

Supplement to HOSDB Evaluations of Taser Devices

Publication No. 64/06



A collection of medical evidence and other source material

Edited by David I Wilkinson

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FIRST PUBLISHED NOVEMBER 2006

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Preface

This supplement is intended to complement the two PSDB reports on evaluations of taser devices published in 2002 and 2005. It is a collection of source material, commissioned during the evaluations, which has not been previously published. It contains seven full reports from the Defence Science and Technology Laboratory, which informed the DOMILL¹ statements on the medical implications of taser use, the Association of Chief Police Officers report on the operational trial and a report on taser compatibility with commercial aircraft systems.

The reports included in this supplement are detailed in the contents list on the following page.

¹ Defence Scientific Advisory Council Sub-committee on the Medical Implications of Less Lethal Weapons Publication No. 64/06

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1 Introduction

The Home Office, the Association of Chief Police Officers (ACPO) and the Northern Ireland Office tasked the Police Scientific Development Branch (PSDB – now the Home Office Scientific Development Branch, HOSDB) with carrying out an evaluation of less lethal technologies. These organisations, along with Her Majesty's Inspectorate of Constabulary (HMIC), the Policing Board of Northern Ireland and the Ministry of Defence, including the Defence Science and Technology Laboratory (Dstl), are represented on the steering group for this project. An Operational Requirement for less lethal tactical options was produced in 2000 and updated in 2001. During a review of available technologies carried out in 2001, electrical incapacitation devices were identified as a priority technology.

The subsequent, extensive evaluation of Taser technology ran from 2001 until 2005. The technical and handling evaluations and international review were carried out by HOSDB. Dstl were contracted to carry out medical assessments, which assisted the Defence Scientific Advisory Council Subcommittee on the Medical Implications of Less-Lethal Weapons (DOMILL) to make a series of statements on the medical implications of the use of Tasers. ACPO ran a 12-month operational trial in 2003-2004. The progress and context of these evaluations and trials can be seen in Figure 1.

During these evaluations HOSDB produced two reports. The first, *PSDB Evaluation of Taser Devices* (Pub 9/02), was released in July 2002. This contained an examination of the benefits and drawbacks of Taser technology as a whole, as well as evaluating the seven Taser models that were available at the time. At the same time, Dstl had produced a review *The medical implications of the use of electrical incapacitation devices (Tasers)* (DSTL/PUB20749), the abstract and executive summary of which was included in the PSDB report as Appendix A. The second report was produced in 2005, *PSDB Further Evaluation of Taser Devices* (Pub 19/05), the contents of which are described later.

As a result of these findings, ACPO proposed a 12-month operational trial of the M26 Advanced Taser with firearms units in five police forces. This proposal necessitated the development of policy and 'guidance to users' under which the trial would operate. This information was used by Dstl to provide *An update on the review of the medical implications of use of Electrical Incapacitation Devices* (DSTL/PUB20750) to DOMILL which assisted in the production of the *First DOMILL statement on the medical implications of the use of the M26 Advanced Taser (December 2002)*, provided to ministers to assist in their decision on whether to proceed with the trial. This statement can be found in the Annex to Appendix E of *PSDB Further Evaluation of Taser Devices* (Pub 19/05).



The operational trial was agreed by ministers and finished in April 2004, when a report commissioned by ACPO (and written by PricewaterhouseCoopers LLP) on the trial was issued. At the same time, a series of studies recommended in the first DOMILL statement (regarding the vulnerability of pacemakers and other implanted medical devices, the effect of drugs of abuse on the susceptibility of the heart to Taser currents and quantitative data on the flow of Taser currents to vulnerable parts of the body) was carried out by Dstl. The reports on these studies, along with evidence from the operational trial and further work by HOSDB were presented to DOMILL to assist in the production of *Second DOMILL statement on the medical implications of the use of the M26 Advanced Taser (July 2004)*. This statement can be found in Appendix E of *PSDB Further Evaluation of Taser Devices* (Pub 19/05).

During this time, one of the Taser manufacturers (Tasertron) had been bought by their competitor (Taser International) and so the M26 Taser became the only law enforcement model available. In May 2003 Taser International launched the X26 and HOSDB were tasked with carrying out an evaluation of this model and comparing it to the M26. Data from this evaluation, along with data from the heart studies already underway, were used by Dstl to produce *The X26 Taser – a review of the experimental and operational data related to an assessment of the medical implications of use* (DSTL/PUB20752). This in turn was used to assist in the production of *DOMILL statement on the comparative medical implications of the use of the X26 Taser and the M26 Advanced Taser*. This statement can be found in Appendix F of the *PSDB Further Evaluation of Taser Devices* (Pub 19/05).

HOSDB also commissioned a report on the Assessment of the M26/X26 Taser Electromagnetic Compatibility with Commercial Aircraft Systems (ERA Report 2004-0241). This information was used, along with HOSDB in-house testing, handling trials, the ACPO report on the operational trials and the DOMILL medical statements to produce the PSDB Further Evaluation of Taser Devices (Pub 19/05).

This supplement is intended to sit alongside the two PSDB reports as a compilation of source material that has not been previously published together. It contains those reports highlighted in yellow in Figure 1. They are the seven full reports from Dstl, the ACPO report on the operational trial and the ERA report on compatibility with commercial aircraft systems.

The next part of this document contains brief descriptions of the contents of the reports, before each is included as an appendix.

2

Report Descriptions

This section gives a brief description of the contents of the reports included in this supplement. Each report has its own executive summary so what follows here are only very broad overviews.

"The medical implications of the use of electrical incapacitation devices (Tasers)."

DSTL/PUB20749 April 2002 This supplement: Appendix A

The executive summary of this report was included as Appendix A of the original *PSDB Evaluation of Taser Devices* (Pub 9/02). The report contained the evidence compiled by Dstl and provided to DOMILL to assist in the production of the *First DOMILL statement on the medical implications of the use of the M26 Advanced Taser (December2002).*

This report was a generic review of the medical implications of the use of electrical incapacitation devices (EIDs), encompassing all Taser models available at the time. It was based on:

- electrical evidence supplied by PSDB
- a '...thorough review of the literature by technical specialists in the fields of electromagnetic modelling, radiofrequency/ microwave safety, neurophysiology and cardiac electrophysiology'
- '...preliminary, innovative computer simulation techniques undertaken by Dstl to provide an indication of the distribution of Taser currents in a simplified model of the body.'

It concluded that the majority of the evidence available related to lowpowered 5-7Watt Tasers and that caution should be used when forming judgements on the 18-26Watt models. It went on to comment on:

- modelling current distribution
- mechanism of desired effect
- pacemakers
- application of Taser outputs to electrical safety criteria
- cardiac arrhythmias low-power Tasers
- cardiac arrhythmias high-power Tasers
- hyper-susceptibility of the heart
- associated trauma
- aftercare.

It then recommended that technical studies be carried out to clarify the nature of further risks of using Tasers by: quantifying magnetic and electric field strengths in the body by using a digital model of the human body; the hypersusceptibility to Taser currents of the heart arising from drugs, acidosis and pre-existing disease; and the vulnerability of pacemakers and other implanted devices. "An update on the review of the medical implications of use of Electrical Incapacitation Devices"

DSTL/PUB20750 30 September 2002 This supplement: Appendix B

This update was produced after the policy and guidance to users were developed by ACPO for the operational trial. It also included information that had been acquired since the release of the first review in April 2002. The report included further published reviews from around the world: a review of deaths reported following Taser use; a report on drug use in the UK; statistics gleaned from the Taser International operational use database; operational use reported directly by other police forces and the results of the PSDB Handling Trials.

It concluded by reiterating the recommendations for further work from the April 2002 review. This report contained the second part of the evidence presented to assist in the production of the *First DOMILL statement on the medical implications of the use of the M26 Advanced Taser (December 2002).*

"Assessment of the effects of Advanced Taser M26 output on active implantable medical devices."

DSTL/PUB20753 31 November 2003 This supplement: Appendix C

This review was undertaken as a result of one of the recommendations made in the December 2002 *First DOMILL statement on the medical implications of the use of the M26 Advanced Taser.* It contained an assessment, based on published material, of the likely effects on the function of implantable devices when an individual is subjected to the M26 Advanced Taser.

It found that there had been limited studies on the effects of 'stun guns'² on cardiac pacemakers, which had shown some temporary effects on their functionality whilst the stun gun was applied. The report considered that implanted cardioverter defibrillators would be affected in the same way as pacemakers. However, due to the way the former operate, the review concluded that they were unlikely to deliver inappropriate therapy. The review found no reports of Tasers affecting other active implantable devices.

The review stated that the age profile of cardiac pacemaker recipients differed significantly from that of the population arrested in situations where a Taser may be deployed. It concluded that the ACPO Operational Guidance did not require significant alteration as result of this report. Although DOMILL should discuss further the short-term change in functionality implications, Dstl's recommendation was that there was no need for further experimental studies on the matter.

 $^{^{2}}$ A stun gun is an electrical weapon where two fixed electrodes, approximately 5cm apart, are pressed directly against the skin of a subject. Tasers fire two probes, attached by wires to the base unit, which attach themselves to the subject at varying ranges.

"Medical implications of the use of the M26 Taser – the effects of drugs of abuse on the cardiac action potential in sheep isolated Purkinje fibres."

DSTL/PUB20751 15 January 2004 This supplement: Appendix D

In the First DOMILL statement on the medical implications of the use of the M26 Advanced Taser (December 2002) the heart was identified as the principal organ at risk in the body when a person is subjected to the Taser. Taser use in the United States has suggested the possibility that the presence of drugs of abuse could contribute to the death of an individual who was subjected to a Taser.

This report assessed the pro-arrhythmic potential of seven drugs of abuse in an *in vitro* heart preparation (sheep isolated Purkinje fibre). This preparation can be used to predict the risk of a particular type of potentially lethal arrhythmia in humans, *torsades de pointes*, associated with an increase in the QT interval of the electrocardiogram.

Seven drugs of abuse were examined:

- cocaine
- cocaethylene
- 3,4-methylenedioxymethamphetamine (MDMA; 'ecstasy')
- (+)-methamphetamine
- morphine
- phencyclidine
- Δ^9 -tetrahydrocannabinol.

Of these, two (MDMA and phencyclidine) produced action potential prolongation, suggesting that they may induce QT lengthening in humans. The report then went on to state that other drugs still have the potential to influence cardiovascular function in other ways. It then compared the results to the scientific literature and concluded that the evidence suggested that '...some frequently used recreational drugs have the potential to contribute to any cardiac-related morbidity or mortality that may arise in the context of Taser use.' However, it went on to note that '...it seems reasonable to assume that this conclusion could be generalised to other emotionally charged and possibly violent confrontations with law enforcement personnel.'

"Modelling Current Flow in the Human Body from the M26 and X26 TASER Devices."

DSTL/PUB20755 October 2005 This supplement: Appendix E

In the *First DOMILL statement on the medical implications of the use of the M26 Advanced Taser (December 2002)* the heart was identified as the principal organ at risk in the body when a person was subjected to the Taser. This work was part of the overall approach taken by Dstl to assess the risk of a cardiac event in someone who was subjected to either the M26 or X26 model. This part of the work involved modelling the path of current flow in

the body using computational electromagnetic modelling (CEM). The data generated for current flow across the heart could then be used to inform a test on a biological model (an isolated guinea-pig heart – *Effects of simulated M26 and X26 Taser waveforms on the guinea-pig isolated heart*. DSTL/PUB20754, Appendix F of this supplement) to establish the risk of ectopic beats and ventricular fibrillation, as well as being used in conjunction with other evidence for an overall view of medical risks.

A three dimensional model of a human male was produced using medical imaging data and input into CEM software. The CEM software turned the model into a 3-D matrix of cells with the appropriate properties and then simulated the passage of an electromagnetic signal through the model.

The most severe scenarios, for both the M26 and X26, led to 20% of the applied current passing through the heart with a peak current density of 0.66 and -0.11 milliamps/mm², respectively. The highest observed current density was observed when one of the contact points was close to the lower frontal lobe of the heart, where the current peak density was spread across a 25mm diameter. The current leaving the heart almost matched the current entering, indicating that there was little net deposition of charge.

As a result of this study, in conjunction with the guinea-pig isolated heart study, it was concluded that it was unlikely that the discharge from M26 and X26 Tasers would influence cardiac rhythmicity by a direct action on the heart, with certain caveats regarding illicit drugs, pre-existing heart disease and other factors.

These studies provided the evidence for the Second DOMILL statement on the medical implications of the use of the M26 Advanced Taser (July 2004), included in Appendix E of the PSDB Further Evaluation of Taser Devices (Pub 19/05) and also part of the evidence used in The X26 Taser – a review of the experimental and operational data related to an assessment of the medical implications of use. DSTL/PUB20752 (Appendix G of this supplement).

"Effects of simulated M26 and X26 Taser waveforms on the guinea-pig isolated heart."

DSTL/PUB20754 15 March 2005 This supplement: Appendix F

In the *First DOMILL statement on the medical implications of the use of the M26 Advanced Taser (December2002)* the heart was identified as the principal organ at risk in the body when a person subjected to the Taser. This report planned to establish the threshold electrical currents of Taser waveforms (of both the M26 and X26 Tasers) required to illicit two types of myocardial responses: ventricular ectopic beats (premature ventricular contractions) and ventricular fibrillation.

The risk of Taser waveforms to the heart was approached experimentally in two stages. Firstly, computational electromagnetically modelling Taser current flow into the heart using a digital mannequin – *Modelling Current Flow in the Human Body from the M26 and X26 TASER Devices.* DSTL/PUB20755. Then, in this report, by application of the modelled

currents into an isolated, spontaneously beating guinea-pig heart to establish the threshold for effects on the cardiac rhythm.

The results of this work indicated that the '...simulated M26 and X26 waveforms, <u>when suitably amplified</u>, are capable of eliciting ventricular ecptopic beats, but not ventricular fibrillation, when applied to the ventricular myocardium of spontaneously beating guinea-pig isolated hearts.' However, the threshold for eliciting these beats was greater than 60-fold the peak current intensity predicted in the heart by the electromagnetic modelling, implying a wide safety margin. The report concluded that it was highly unlikely that either the M26 or X26 Taser would affect the rhythmicity of the heart, although other factors (such as illicit drug intoxication, alcohol abuse, pre-existing heart disease and cardioactive therapeutic drugs) may modify the threshold.

The report finished by recommending a series of measures to monitor Taser use and its after-effects in the population. This was endorsed by the DOMILL statement.

"The X26 Taser – a review of the experimental and operational data related to an assessment of the medical implications of use."

DSTL/PUB20752 20 January 2005 This supplement: Appendix G

The aims of this paper were to 'summarise the available evidence on the characteristics, operational performance and medical assessments worldwide of the X26 Taser' and 'contrast these with the M26 Advanced Taser, thereby provide evidence to assist DOMILL in drafting a statement on the medical implications of use of the X26 according to extant ACPO policy and guidance for the M26.'

It compared the electrical characteristics of the M26 and X26 Tasers before going on to examine experimental work that has been carried out on the X26. It then looked at the evidence provided by *Modelling Current Flow in the Human Body from the M26 and X26 TASER Devices*. DSTL/PUB20755 and *Effects of simulated M26 and X26 Taser waveforms on the guinea-pig isolated heart*. DSTL/PUB20754 (Appendices E and F of this supplement). The report then reviewed the operational data provided by the Taser International operational database and law enforcement agencies, as well as other institutions.

It finished by commenting upon recent research on the M26, the Amnesty International review of police use of Tasers and the matter of XP cartridges.

"Association of Chief Police Officers: Independent Evaluation of the Operational Trial of Taser"

Pricewaterhouse Coopers LLP, on behalf of ACPO Final Report, May 2004 This supplement: Appendix H

From April 2003 to March 2004 an operational trial of Tasers took place in five police forces. The trial was co-ordinated by the ACPO Police use of Firearms Secretariat on behalf of ACPO and at the end of the trial this report was produced, by Pricewaterhouse Coopers LLP, 'to evaluate how successfully Taser devices have been used as a supplementary option to other deployment methods, namely firearms, dogs, baton rounds and irritant spray.'

The report set out the background to the trial and its parameters, described the evaluation methodology and evidence base used, presented the key findings from the analysis of Taser deployment forms and fieldwork visits to pilot forces and gave the main conclusions from the research. The supporting documentation was also included.

"Assessment of the M26/X26 Taser Electromagnetic Compatibility with Commercial Aircraft Systems"

Roger H Smith ERA Report 2004-0241 November 2004 This supplement: Appendix I

This report considered the electromagnetic interference risks associated with the use of the M26 and X26 Tasers on commercial fixed wing aircraft. The report noted that it did not consider the measurements of radiated emissions from Tasers, carried out in laboratory conditions as defined for avionic equipment, to fully represent their real application. It went on to say that some assessment of the practical configuration was made and concluded that Tasers should not affect flight critical systems and should have only a minor detrimental effect on aircraft communications. Aircraft testing confirmed this and also that there was no compromise to radio communications.

The report stated that conducted discharge between earthed metalwork on the aircraft and flight deck instrumentation was very unlikely in practice and that practical testing had generally shown no problems, with the exception of one radio control panel where damage from a probe resulted in the loss of the display.

The report noted that initial work was carried out on the M26 Taser and that the lower output voltage, with less overshoot, of the X26 would mean it had lower emissions than the M26. The report concluded that the use of the M26 or X26 Taser should not impact on aircraft safety.

3 Editor's notes

- (a) The text and contents of the reports included here are reproduced as they were provided to PSDB/HOSDB but they no longer follow an identical pagination. The only changes to the reports that have been made are as follows:
 - Where an included report has an 'appendix' this has been renamed an 'annex', in order to avoid confusion with the appendices of the whole supplement.
 - Where an included report has a contents table, the page numbers have been updated to reflect this document.
 - There have been minor formatting changes to allow the included reports to fit into this supplement, as well as providing some continuity of style. However, the overall appearance of the reports remains the same as the original.
 - The numbers assigned to footnotes may have changed. However, each footnote appears at the bottom of the relevant page and so this should not cause a problem.
 - The numbers assigned to some tables and figures may also have changed but their integrity against references within the text has been maintained.
- (b) Since the company Taser International bought Tasertron, it has acquired ownership of the word 'TASER' and has made it a trademark. However, these reports cover a period that also includes a time when this was not the case. Therefore, HOSDB acknowledges the trademark but in wanting to faithfully reproduce the reports, the terms 'TASER', 'Taser' and 'taser' all appear. They all refer to the same equipment.
- (c) The majority of these reports refer to two Taser units, commonly referred to as the 'M26' and 'X26'. They are the Taser International M26 Advanced Taser and the Taser International Taser X26, respectively.
- (d) Not all of the dates on these reports refer to the order in which the work was carried out. They usually refer, instead, to the dates on which the reports were released. For the correct order, please refer to Figure 1.
- (e) On 1 April 2005, the Police Scientific Development Branch (PSDB) became the Home Office Scientific Development Branch (HOSDB). Both are referred to in this supplement.

Appendix A – "The medical implications of the use of electrical incapacitation devices (Tasers)."

DSTL/PUB20749 April 2002

Executive summary

Background

The Northern Ireland Office (NIO) and Home Office (HO) have requested an independent opinion on the medical implications of the use of electrical incapacitation devices (EIDs) in self-defence and restraint scenarios, and as alternatives to firearms. The independent DSAC sub-committee on the Medical Implications of Less Lethal Weapons (DOMILL) has been requested to provide this opinion. The Defence Science and Technology Laboratory (Dstl) at Porton has produced this report to advise DOMILL on the interactions of EIDs with the body, and the quality and scope of operational and experimental evidence available to develop a medical view on their safety.

Aim

The aim of this report is to provide DOMILL with scientific and clinical evidence on the interactions of a specific class of EID (Tasers) with the human body. It will be used by DOMILL to formulate a statement in May 2002 on the medical implications of the use of Tasers, and to develop a technical plan for the detailed evaluation of Tasers if further research is necessary or desirable.

Scope

Dstl and DOMILL were tasked to provide a definitive medical statement on EIDs by April 2002. The Association of Chief Police Officers (ACPO) and the NIO informed Dstl that no decision would be made on the selection of a specific device before April 2002. DOMILL was therefore requested to provide a generic statement on the medical implications of the use of EIDs, encompassing all types being considered by ACPO and the Police Scientific Development Branch (PSDB). These types were low-power (5-7 W) and high-power (18/26 W) Tasers, employed in the mode of propelling barbed electrodes, and as stun guns with fixed electrodes.

Tests on the electrical output of Tasers were conducted by PSDB and supplied to Dstl in February 2002. The NIO, HO and ACPO were informed that because of the very short timescales, DOMILL's statement would not be based on detailed technical assessments by Dstl of the biophysical interaction of Taser outputs with biological models, nor on laboratory studies on the physiological effects of the coupled current. DOMILL's statement would be based solely on:

- A thorough review of the literature by technical specialists in the fields of electromagnetic modelling, radiofrequency/microwave safety, neurophysiology and cardiac electrophysiology.
- Preliminary, innovative computer simulation techniques undertaken by Dstl to provide an indication of the distribution of Taser currents in a simplified model of the body.

Conclusions

The majority of the safety-related experimental work on Tasers and the clinical experience arising from operational use is with the "low-power" 5-7 W devices. This fact necessitates caution when forming judgements on the modern 18/26 W devices from experience acquired with 5-7 W devices. However, the wattage designation should not be used uncritically to categorise output - peak current and charge transfer are more appropriate and there is disconcerting evidence from the measured outputs that the wattage designation belies the actual output.

Modelling current distribution: Historically, there have been no objective scientific studies (or even ad-hoc studies) to determine the magnitude and distribution in the body (animal or human) of electric currents from Tasers. This knowledge is fundamental to an understanding of the potential interaction of Taser currents with excitable tissues such as the heart. Dstl's modelling revealed information that must be regarded at this stage as indicative only:

With the application of the Taser to the front of the body, the magnetic field strength (an index of current) in the heart was less than those at the body surface, but was still a notable proportion of the surface field. Currents will flow in the heart region; they will not be confined to the peripheral tissues of the body (a claim of the manufacturers and their advisers).

The separation of the Taser electrodes had an effect on the distribution and magnitude of the currents.

Field strengths in the head and spine were a small fraction of the fields at the current injection sites.

The magnetic field strength from the high-power Taser (M26) was approximately twice that of the low-power TE93.

Application of Taser in stun mode to the neck resulted in very high local fields at the contact point when the electrodes were in a vertical orientation. The fields in the heart and thoracic spine area were low. In vertical orientation, the fields in the brain were 3-fold those predicted when the Taser was used with horizontal electrodes.

Mechanism of desired effect: The explanations in the manufacturers' literature regarding the physiological mechanisms of the desired action of Tasers are speculative. Dstl's review is also speculative; it suggests that the most likely explanation is the disruption of neuromuscular control by stimulation of motor axons in peripheral nerves. This may also be accompanied by disruption of the neurophysiological feedback required for maintaining posture, leading to disturbances in posture and balance.

Pacemakers: The available published evidence for the interaction of EIDs with pacemakers and other implanted electrical equipment is contradictory and frequently based on clinical opinion, not experimental evidence. In the limited time imposed for this review, Dstl has been unable to consult with the manufacturers and regulatory bodies on electromagnetic compatibility issues of modern implanted devices. The incidence of pacemaker use is low, particularly in the adult age

group below 60 years of age (probably about 0.4/1000) but it is important that the potential for damage or disturbance be clarified.

Application of Taser outputs to electrical safety criteria: The manufacturers assess the cardiac safety of the Taser pulses by using a US Standard derived for electric stock fences. The VF criteria published in the Standard are not identical to those promulgated by the manufacturers, even though the Standard is cited.

The Taser pulses cannot be applied unquestioningly to the Standard. If expressed in terms of RMS current and duration for a single pulse, the output of the Advanced Taser is below the manufacturers' VF criterion and the Standard's. However, if the pulse repetition frequency is accounted for over a one second period, the Taser output would be above the Standard's criterion. Depending on the approach used to assess the Taser output, it is possible to demonstrate that, according to the electric fence Standard, the Advanced Taser is "safe" or "dangerous".

Cardiac arrhythmias - low-power Tasers: The experimental work undertaken on animals addressing the interaction of Tasers with the heart is poor in terms of statistical design - specifically, the number of animals used. It is not rigorous work. The reports do not contain sufficient information to enable an authoritative review of the quality of the work to be undertaken. The work has not been published in peer-reviewed biomedical journals; there is no evidence that it has been subjected to peer-scrutiny.

There have been a large number of operational uses of low-power Tasers - at least 50,000 are claimed. There have been deaths associated with use of the Taser. One published paper discussed 16 deaths that occurred over a 4-year period in Los Angeles. There were other factors such as pre-existing heart disease and drug use that could have been implicated in the deaths.

On the available evidence, it is considered extremely unlikely that a death has occurred caused directly and exclusively by the electrical output of a low-power Taser.

Cardiac arrhythmias - high-power Tasers: The experimental work on the arrhythmic potential of the Advanced Taser is minimal – a report in the form of a letter on experiments undertaken on a small number of dogs and experiments on one pig. These data have not been published in peer-reviewed journals. The data are not an adequate experimental basis alone for an opinion on whether the electric output of high-power Tasers carries a risk of a serious arrhythmia such as ventricular fibrillation.

High-power Tasers are a relatively modern innovation. One manufacturer has a record of about 2500 exposures with no reported serious injuries. Their company database records about 1600 operational uses; it is difficult to judge the incidence of adverse effects from the data but it appears to be very low. In the period Dec 2001-Feb 2002 there were 3 notified deaths associated with (but not necessarily caused by) use of the Advanced Taser.

The epidemiological evidence for the safety of the M26 Advanced Taser is certainly not as robust as that for the low-power devices. With the lack of substantial historical data of use and inadequate experimental evidence, the high-power Tasers cannot be classed, in the vernacular, as "safe". A precautionary approach is necessary regarding decisions on deployment and operational use. Many agencies in the US (and others worldwide) have recently purchased and deployed the Advanced Taser; experience of use in the field will accrue over the coming months and years. Dstl is also aware that some experimental work on pigs is planned in the US on behalf of a law-enforcement agency (Dstl has not been asked to comment on this work). It would be prudent to await the outcome of the experimental work and the consequences of field use, and re-assess the arrhythmic potential of the high-power Tasers subsequently.

Hyper-susceptibility of the heart: It is thought that certain substances and metabolic conditions such as acidosis (which may be attributed to excessive muscular activity and/or the effects of drugs) may increase the susceptibility of the heart to arrhythmias. "Recreational" drugs such as cocaine and "ecstasy", and pre-existing heart disease may be pro-arrhythmic.

There is no experimental evidence that these pro-arrhythmic factors increase the susceptibility of the heart to Tasers sufficient to cause an arrhythmic event. Nevertheless, there is sufficient indication from the forensic data and the known electrophysiological characteristics of the myocardium (and the effects of certain drugs on it) to express caution regarding use of Tasers on excitable, intoxicated individuals. Guidance to Taser users should reflect the likely increased susceptibility to life-threatening cardiac effects in these individuals. Experimental investigations could also be undertaken to clarify the hazard.

Associated trauma: There are few reported injuries associated with Taser use. Even falls seem to be controlled and the risk of head injury or long-bone fracture will be low. Ocular trauma is a serious hazard with a low risk and should be controlled with guidance to users. The burns at the current injection points are localised and evidently heal without complication.

Aftercare: There is a general consensus in the manufacturers' guidance and in the literature that personnel subjected to Tasers should be taken to hospital and receive a medical examination. Plainly, cardiac investigation is foremost. The barbs should be removed from the skin under medical supervision.

Technical approaches to clarify risks

The requirement for experimental work and/or modelling to clarify both the risks from use of Tasers (in particular the high-power Tasers), and the optimisation of effectiveness balanced with safety is an issue for DOMILL and Ministers.

The key areas requiring clarification are:

Accurate, quantitative estimates of the magnitude of the magnetic and electric field strengths in the body; this would require enhancement of the expedient model developed by Dstl;

Cardiac effects from Taser waveforms, and in particular hyper-susceptibility to Taser currents arising from drugs, acidosis and pre-existing disease; there are *in vitro* tissue models available at Dstl and elsewhere that could be used to address these issues;

The vulnerability of pacemakers and other implanted devices requires a more thorough review; experimental studies to assess electromagnetic incompatibility issues are currently not warranted and should await the outcome of the review.

Introduction

1.1.1 Recommendations from the "Patten Report" into policing in Northern Ireland include two specific items relating to the public-order equipment for Police use [1]. These recommendations, 69 and 70, are:

"69:An immediate and substantial investment should be made in a research programme to find an acceptable, effective and less potentially lethal alternative to the Plastic Baton Round (PBR)";

"70: The police should be equipped with a broader range of public order equipment than the RUC currently possess, so that a commander has a number of options at his/her disposal which might reduce reliance on, or defer resort to, the PBR."

- 1.1.2 In Summer 2000, the Secretary of State for Northern Ireland, in consultation with the Home Secretary, established a UK-wide Steering Group (the Patten Action Team PAT) to lead a research project. The project was to (i) establish whether a less potentially lethal alternative to the baton round is available and (ii) review the public-order equipment which is presently available, or could be developed, in order to expand the range of tactical options available to Operational Commanders.
- 1.1.3 The Steering Group has taken steps to ensure that its work is consistent with the approach being adopted by the Association of Chief Police Officers of England, Wales and Northern Ireland (ACPO). In addition, contact has been made with a range of bodies with relevant expertise, including, for example, the National Institute of Justice and Pennsylvania State University in the US.
- 1.1.4 The terms of Recommendation 69 require the PAT/ACPO teams to address three specific areas acceptability, effectiveness and lethality or minimum force. The criteria for acceptability must be agreed within a UK framework and benchmarked against legal requirements, set out particularly in the "Human Rights Act", 1998. There are three closely linked areas under which acceptability should be considered, these are human rights and legal requirements, ethical and cultural grounds and medical issues. The latter is considered in this report.
- 1.1.5 The PAT/ACPO Steering Group has initiated a research programme entitled "Alternative Policing Approaches Towards the Management of Conflict". One strand of this programme is an in-depth review and assessment of currently available less lethal technologies and those at a development stage [2]. The Police Scientific Development Branch (PSDB) has conducted the technical assessment of commercially available equipment. Five technologies have been classed as Category A (i.e. "devices, which may be the subject of immediate, more in-depth research"):

impact devices; chemical devices capable of being delivered at variable ranges; electrical devices; distraction devices; water cannon.

1.1.6 With regard to electrical devices, PSDB have reviewed a range of commercially available products that use pulses of electricity to incapacitate a target. These Electrical Incapacitation Devices (EIDs) include Tasers, stun guns, electrified riot shields, electrified nets and stun belts. In the report of the Steering Group on Phase 2 of the research programme [2] it was concluded that that only those electrical

devices that could be used at a distance would be considered a priority for further research. Devices such as stun guns, stun batons and electrified shields would not go forward for further testing at present. Electrified nets and stun belts were also been dismissed as a priority. The Taser is probably the best known and most widely available (and used) EID that can be operated at a distance from the target.

1.2 Aim of this review

- 1.2.1 This report reviews the available literature on the medical implications of the use of EIDs in Self Defence and Restraint (SDAR) scenarios, and as alternatives to Firearms. Dstl Porton has prepared this report for submission to the Defence Scientific Advisory Council (DSAC) on the Medical Implications of Less Lethal weapons (DOMILL). The primary role of DOMILL is to provide the Secretary of State for Northern Ireland (and Ministers in the Home Office and Ministry of Defence) with an independent opinion on the medical implications of the use of specific less-lethal (LL) weapons.
- 1.2.2 Dstl and DOMILL have been tasked to provide a final medical statement on EIDs by April 2002. At a meeting of some members of the PAT-ACPO Steering Group on 20 December 2001, Dstl was informed that no decision would be made on the selection of a specific weapon before April 2002. DOMILL was thus requested to provide a "generic" statement on the medical implications of the use of EIDs, encompassing all types being considered by ACPO and PSDB.
- 1.2.3 This report will be used by DOMILL to assist in the formulation of a statement for May 2002 on the medical implications of the use of Tasers, and to assist in the development of a technical plan for the detailed evaluation of EIDs if further research is necessary or desirable.

1.3 Timescales

- 1.3.1 Tests conducted by PSDB on a number of Taser devices have, to date, included accuracy of the projected barbs, electrical output, clothing penetration, flammability issues and handling trials. The technical data was supplied to Dstl in February 2002; the outcome of the handling trials is not available currently.
- 1.3.2 The Steering Group was informed that because of the very short timescales imposed on DOMILL, the statement would not be based on detailed technical assessments by Dstl of the biophysical interaction of Taser outputs with the human body or biological models, nor on laboratory studies on the physiological effects of the coupled current. Therefore, this report is based solely on the results of:
 - a thorough review of the literature by technical specialists in the fields of electromagnetic modelling, RF/microwave safety, neurophysiology and cardiac electrophysiology;
 - preliminary, innovative computer simulation techniques to provide an indication of the distribution of Taser currents in a simplified model of the body.

1.4 Approach

1.4.1 **Literature review:** A detailed search of the world's literature was conducted, by professional information scientists from Dstl's Knowledge Services, employing a number of databases. All codes were selected for their comprehensive array of

aspects relevant to this study, with records drawn from world-wide primary and secondary sources.

- 1.4.2 The literature search included :
 - Medical effects of Taser/EID use;
 - Manufacturers' information;
 - Injuries attributable to electric shock;
 - Technical specifications and patents pertaining to EIDs;
 - Reports on the use of EID's;
 - Legal regulations pertaining to the use of electrical devices.
- 1.4.3 To supplement the literature search, a review of data/articles posted on the worldwide web and in newspapers/periodicals was undertaken, with the aim of ascertaining the type, incidence, severity and cause of injuries attributed to the use of EIDs. Additionally, a number of non-peer reviewed reports were obtained.
- 1.4.4 In total 800 references were collected from the peer-reviewed literature, periodicals and newspapers, patents, trade literature and Internet pages. These were acquired, translated, where appropriate, and read; relevant aspects are reported herein.
- 1.4.5 Knowledge Services staff categorised the resultant references thus:
 - Category 1 : Exact match to search on EID and medical effects;
 - Category 2 : Electrically induced medical effects (any source of electrical charge);
 - Category 3 : EID details, usage and availability (including Patents);
 - Category 4 : Animal models, standards, recommendations for safe usage;
 - Category 5 : Unsubstantiated witness reports.
- 1.4.6 Category 1 and 2 articles provided the bulk of the medical information in this report, with supporting details extracted from Category 3-5 articles. A review was also conducted of EID manufacturers' claims, pertaining to the use of Tasers, published or proposed guidance to users and the electrical output of a range of devices. Taser manufacturers were contacted and specific information requested.
- 1.4.7 Modelling of current distribution: A preliminary assessment of current flow in the body, during the application of an EID, either by projected barbs (Taser) or fixed electrodes (stun guns) was conducted. This task involved the use of complex, novel 3-D computer simulation techniques, and drew on capabilities developed within MOD programmes. This was a technically demanding undertaking achieved within a very short period (2 months) and is limited in its scope. It is described in Section 5.

1.5 Report Structure

- 1.5.1 This document is structured thus:
 - An appreciation of the background to the task, its aims and objectives is in Section 1;
 - Section 2 summarises the claims of the manufacturers with regard to the mechanism of effect of Tasers, and their safety;
 - Guidelines for the use of Tasers, and the scale of their deployment and use are in Section 3;
 - A review of the neurophysiological basis of their intended effects, and the electrophysiology of the heart (the principal site of potential adverse effects) is provided is Sections 4 and 5 respectively;
 - The application by the manufacturers of the Taser electrical output to safety standards for electric shock is reviewed in Section 6;
 - Section 7 presents the results of mathematical modelling undertaken by Dstl to assess the distribution and magnitude of currents from Tasers in the body;
 - Sections 8 and 9 review the available experimental work on the safety of EIDs, and the clinical consequences of operational use by police forces in the US;
 - The conclusions of the study are in Section 10, and Section 11 summarises technical approaches for clarifying specific issues related to safety.
 - Six annexes provide details on: commercial Taser technology (A), the neurophysiology of nerve and muscle (B), ventricular fibrillation (C), the measured output of various commercial Tasers (D), the guidance to users offered by the manufacturers (E), and the computational approach used by Dstl in the modelling of Taser currents in the body (F).

2 Manufacturers' and users' claims

- 2.1.1 This section provides an overview of the <u>claimed</u> effectiveness of Electrical Incapacitation Devices (EIDs), medical safety and recommended training. Also included is a section on key safety points published by Tasertron. Information was obtained primarily from manufacturers' marketing materials, patents and media reports. Murray and Resnick provide a wide-ranging overview of Tasers and stun guns in their book "A Guide to Taser Technology" [3].
- 2.1.2 EIDs, frequently referred to generically as Tasers, are battery powered devices which use a series of low (theoretical) average current, high voltage electric shocks to effect incapacitation. There are two general EID types: (i) devices that propel the electrodes to the target (Tasers), (ii) devices with fixed electrodes (stun guns). Some Tasers may also be operated in stun mode with fixed electrodes. Stun guns have not been selected as a priority for further research [2], but it is envisaged that the UK Police may wish to use Tasers in this manner. A description of the various models of Tasers from the two manufacturers (Taser International and Tasertron) is provided in Annex A.
- 2.1.3 **Specifications:** With regard to equipment specifications, Tasertron claim that Taser device's electronic parts are subject to "standard engineering tolerances, which may vary electrical outputs and inputs plus or minus 20 percent from Taser to Taser". In engineering terms, these are very wide tolerances. Pulse rates (the pulse repetition frequency p.r.f.) are highly variable (see Annex D) and the manufacturer claims that a range of 8-22 Hz is acceptable, and equally effective.
- 2.1.4 **Range & output:** Tasers operate in the following manner: a cartridge is attached to the front end of the weapon, which contains two barbs (the electrodes) each of which is attached to a coiled length of wire. The barbs are fired and attach themselves to the skin or clothing of a targeted individual. When the barbs attach to a person and the trigger is pressed, a current is passed down the wires and through the person's body between the two barbs.
- 2.1.5 The output of the Taser depends on the model, and the location of the current injection barbs on the body. With the models evaluated by PSDB (across a 1,000 Ohm load), the peak current range was found to be 6-12 A, with a pulse duration of 15-30 μ s and pulse repetition frequency (p.r.f.) of 9-38 Hz (Annex D). Taser technologists class the current as DC. The optimal dart locations for effectiveness are upper torso and lower abdomen [3].
- 2.1.6 The range of the devices is limited to the maximum length of wire contained within a cartridge. Most references quote a range of 15-21 feet (4.6 to 6.4 m) [2;4-6]. Manufacturers claim that the devices are capable of being effective upon a target through up to 2 inches of clothing (by electricity arcing across the air gap between skin and clothes) [7]. The Taser International Advanced Taser (M26) is claimed to penetrate two inches of clothing, including leather and many bullet-proof vests [8]. One report claims penetration through six inches of clothing [9].

2.2 Effectiveness

2.2.1 Tasertron representatives have indicated that the minimum distance between electrodes "to ensure best effect" is four inches (10cm) [10]. Operational information from Canadian police officers suggests that best effects are achieved

with a minimum of six inches separation of the barbs [10]. Vogel (US Police Training Bureau) in "Tasertron Effects" [11], suggested that a range of 4 to 12 feet be used to "install one dart each on opposite sides of the spinal column, to maximise neurological interruption".

2.2.2 Incapacitation of a subject is claimed within half a second for the M26 [12], or instantaneous, e.g. Tasertron TE93 [4]. The training bulletin of the LAPD [Ref. 4 in [13]], records that a person can be immobilised with two to three seconds of applied power. The power may be repeated as required to maintain immobilisation. Continuous application of the current is not advised, for it "could result in respiratory arrest". Recovery from being shot with a Taser is reportedly rapid.

2.3 Mechanism of effect

- 2.3.1 EIDs are reported to immobilise an attacker by "confusing" the neuromuscular impulses transmitted through the central nervous system (CNS) by the brain [14]. However, the mechanism is not well understood; claims are made by manufacturers that are not supported by scientific evidence.
- 2.3.2 There are many descriptions in the literature relating to the effects of a Taser on a subject:
 - "muscle control is lost and subjects usually fall to the ground or "freezes" to the spot" [15];
 - "an immediate cessation of aggressive activity" [11];
 - "the Taser wave travels into the CNS, producing temporary loss of muscle control";
 - "when darts hit, 50,000 volts of electricity is flashed into the victim, incapacitating them by causing violent muscle spasms" [16].
- 2.3.3 The Advanced Taser (M26) employs "EMD (electro-muscular disruption) technology" [7;12]. EMD weapons "use a powerful 18-26 watt electrical signal to completely override the CNS and directly control skeletal muscles. The EMD effect causes an uncontrollable contraction of muscle tissue, allowing physical debilitation of the target, regardless of pain tolerance or mental focus". "The weapons affect the CNS by imitating electrical impulses used to communicate with the human body, therefore a hit anywhere on the body can be effective".

2.4 Safety – general comments

- 2.4.1 The M26 uses 26 W power and (nominally) 50,000 volt pulses, which are claimed to be "well within electrical safety standards" [7]. Tasertron in their literature [4] state that the Taser "will not affect the heart, output is well below the level established as safe for electrified cattle fences". This statement is supported by "the full output of the (TE93) Taser was passed through the heart of a rhesus monkey with no harmful effects" [17]. Tasertron also state that the Taser "will not interfere or damage modern pacemakers, designed to withstand electrical defibrillation pulses hundreds of times stronger than Taser output" [4].
- 2.4.2 Vogel in "Tasertron Tactics" [11] stated that the Tasertron TE86 "transmits a series of high voltage, yet very low energy pulses of 50,000 volts from a 7.2 volt nicad battery. The pulse of 50 kV occurs at a rate of 10-20 pulses per second. No one blow/pulse is powerful enough to do any serious damage, yet it ensures the adversary is off balance, confused and unable to aggress".

- 2.4.3 "Voltage travels through one dart to the body and seeks to complete the circuit by reaching the second dart. In between the two darts the voltage travels through muscle and nerves, well below any danger level (1/10th that level) and produces disorientation, loss of motor control and muscle and nerve spasms that are uncontrollable. The subject losses the ability to fight; typically they will revert to a kneeling and then prone position in a very slow fashion, while receiving the voltage".
- 2.4.4 Taser International claim that there are no long-term effects relating to the use of the M26, only "minor skin irritation" [10]. Tasertron also state that a target can be brought down by a Taser hit "without permanent harm or serious after-effects" [4]. They also state that the subject may be "dazed for some minutes, but no permanent damage". Additionally, the Taser "does not destroy nerves, muscles and other body elements, it simply uses them in their natural mode".
- 2.4.5 Under the heading "Medical Findings" in the Air Taser Users' Manual, Taser International claim: (i) The Air Taser (a 7 W device) does not produce enough power to damage nervous tissue. It simply produces electrical signals, confusing the nervous system by overloading the nerve fibres with meaningless signals. No deaths of this nature have been reported. (ii) The nine-volt battery of an Air Taser does not produce enough power to cause any more than perhaps slight surface burns. Testing in hospital settings has shown that the Taser does not cause burns. (iii) Dr. Robert Stratbucker performed tests by applying the T-Wave (their terminology for the Taser output), pulsed wave-form directly to the cardiac tissue and found "no effect on cardiac rhythm or pumping." He also tested the T-Wave on cardiac pacemakers. He found pacemakers were only affected when the pulse wave was placed in direct contact with the pacemaker. Once the pulse was terminated, the pacemaker returned to its regular rhythm. The designs of pacemakers withstand the electrical defibrillators that are several hundred times stronger than Taser pulses. Tests at the Cordis Medical Laboratory in Florida have evidently confirmed this.
- 2.4.6 Tasertron state that the "chances of inflicting serious injury with a Taser are virtually zero". This is because the weapon's effectiveness is based not on impact, body penetration or even contact with the subject's skin. Instead it "employs a pulsating electrical current to induce involuntary muscle spasm and resulting loss of motor control. Electrical charge is well within the medically established safe range for humans. It does no harm to nerves, muscles or any part of the body". The article cites medically supervised human volunteer trials, which concluded that the Taser's "electrical current is non-lethal when the weapon is used, as directed, on the average healthy adult".
- 2.4.7 Tasertron claim that "the human heart, which has a high electrical capacitance, is unresponsive to the low current and high frequency outputs of the Tasertron device. The low current levels can not damage the heart muscles, and as the heart has a high electrical capacitance, the current does not directly affect its beat. It is responsive only to much lower frequencies than the output produced by Tasertron devices". They also state "further, reasons that the current will not penetrate to vital organs and only directly affect the peripheral neuromuscular system is the surface phenomena associated with high frequency outputs like the Tasertron device's output. Rapidly colliding electrons strike each other in such a manner that they are forced to a conductor's surface" [18]. Other alleged evidence of the assertion that the Taser pulse does not penetrate to the internal organs is that "although the Taser electrodes usually hit between upper torso and thigh, there are no reports of vomiting or loss of bladder control from the Taser application" [19].

- 2.4.8 The manufacturers frequently point out that the "power" output of the Taser is only 0.3 to 0.8 joules (the joule is not a unit of power presumably they mean energy), and this should be compared to an external heart defibrillator generating 200 to 400 joules [19].
- 2.4.9 Tasertron's Legal Reference Section [20], records that people who have been subjected to hits from a Taser reported "only slight headaches and some nausea after the immediate pain from the Taser darts had ceased". The report subsequently stated "other than sustained long-term anger, no psychological effects appear to have been suffered by the targets of Taser guns".
- 2.4.10 Taser darts (barbs) "can not penetrate into the body, to cause internal injury; at most only a ¹/₄ inch needle point will penetrate the skin" [4]. The darts have less energy "than a spring propelled BB (ball-bearing) and will not damage a window-pane or penetrate heavy cardboard. A shoulder on the dart prevents penetration greater than ¹/₄ inch".
- 2.4.11 Taser International, in their literature, claim that in "over twenty years field use, there has never been a death attributed directly to Taser technology" [12].
- 2.4.12 The Air Taser Users' Manual states that "the actual effectiveness in the field of the Taser[®] matches or surpasses those for handguns with an 86% instant incapacitation rate versus approximately 72% for handguns (based on percentage of targets which are immediately knocked down. Further, this sample is biased against the Taser[®] as the vast majority (86% in one study) of the people who were hit by a Taser were on the drug PCP. Note that people on PCP frequently do not feel pain and are infamous for their capability to absorb bullets without going down. The Taser[®] is the Los Angeles Police Department's weapon of choice for those on PCP and the mentally deranged".
- 2.4.13 The manual also notes that the nervous systems of animals are greatly different to those of humans. The Air Taser is designed to be effective on a human attacker. Accordingly, it will not be as effective at incapacitating an animal as it is on a human being. The Air Taser should not be used as sole protection from "wild, uncontrollable, or attacking animals".

2.5 Safety notices – Tasertron

- 2.5.1 Tasertron recommend that every Taser device user should be thoroughly familiar with 41 safety notices, which should be strictly adhered to [3;21]. The key points pertinent to biomedical and health effects promulgated by Tasertron are:
 - Users must be aware of the area where a subject might fall, to prevent injury.
 - Tasers should not be used around flammable liquids, gases, solvents or any substance or objects, which a spark could cause to burn or explode. Similarly, they should not be used on a person who has any flammable liquid or other material on his/her body irritants (such as pepper spray and CS spray) may be flammable, depending on the solvent.
 - Care should be taken not to hit a subject in the face, particularly the eyes; blindness in one or both eyes may likely occur. High voltage electricity even near the eyes can cause delayed cataract formation. Should a dart impact or lodge in the face or eye, users should not try to remove it.
 - The neck should be avoided as a target; a dart in a blood vessel such as the carotid artery could cause uncontrolled bleeding and other life-threatening complications.

- Users should avoid striking a man in his penis or testes or hitting a woman's breast. Users should not attempt to remove the darts from these areas.
- Although the Taser device's current is well below the level considered lethal to normal healthy adults (the view of Tasertron), it is "not a medical certainty that it will not effect the heart of certain susceptible individuals with debilitated hearts".
- Users should avoid using Tasers on: "people in wheelchairs or in charge of a vehicle; people known to have diseased or weak hearts; debilitated or elderly people; children or adults under 80 pounds; people with obvious or known neuromuscular disorders; people known to be wearing pacemakers; people in danger of falling to their deaths or being caught in dangerous equipment or machinery". Murray and Resnick [3] also adds "women known to be pregnant".
- The Taser has been "tested and found to be well below those levels considered to be lethal". Nevertheless, Tasertron warn that its use could lead to death or injury of people, including bystanders, through secondary injuries like falls and explosions.
- The Taser may cause a "mild and transient" increased heart rate and blood pressure after its use; "defective, diseased or debilitated" hearts will have extra demands upon them.
- With regard to pacemakers, Tasertron warn that "Pacemakers are designed to withstand currents from a defibrillator, which are greatly in excess of the Taser current, but certain interactions between Taser current and certain types of pacemaker are a theoretical possibility and could lead to complications. Such events, however rare or unlikely, demand extreme caution when considering the use of a Taser device on a subject known to be wearing a pacemaker".
- Taser should be used singly on a subject and should not be used in combination with another electrical device "Current levels might exceed the safe level, especially with medically compromised people".
- The Taser device is an electronic device (it should not be classed as a medical device) and when used by an untrained or improperly trained individual, should be considered a dangerous device.

2.6 Training & tactics

- 2.6.1 In Canada, Taser users are required to undertake an eight hour initial course (Taser International recommend four hours), before being authorised to use the equipment. Re-training is required every three years, and lasts four hours. Great emphasis is placed on medical awareness and aftercare [10]. Tasertron [11] describe the training modules for the use of their weapons as "comprehensive, yet short". There is a one-day Instructor Course (written exam, oral delivery, on a Taser related subject, and manipulation/marksmanship trials) and a Basic Operators' Course, of four hours duration, which is updated every six months with a one hour refresher. The BBC indicate that UK Police will receive one day training [22].
- 2.6.2 With regard to tactics, Vogel [11] noted that the Taser is "ideally suited for custody situations, in which no deadly threat exists, but a high risk of severe physical resistance, which will be difficult to overcome is present". Tasertron suggest that when targeting an assailant, the user aims at the chest or the back, which is "most effective and reduces the risk of a hit to the head" [4].

3 Deployment and guidance to users

3.1.1 Aspects of the guidance to users offered by Tasertron, Taser International and Nova are provided in Annex E.

3.2 ACPO guidance

- 3.2.1 At present there is no formal specific guidance to UK users. ACPO are reluctant to draft guidance, without the independent medical statement. Conversely, DOMILL require guidance to users in order to formulate an opinion. The following non-endorsed guidance was provided to Dstl to inform the DOMILL deliberations [23].
- 3.2.2 In ideal conditions, the aim point (for the top barb) will be either the mid-point of the nipple line at the front or somewhere between the shoulder blades at the back. This is to ensure that the barbs hit "appropriate parts of the body, i.e. upper chest/back, stomach/buttocks and upper parts of the lower limbs". The back is likely to be seen as a useful target, since the clothing tends to be tight around this area and should negate any problems relating to passage of current through loose clothing.
- 3.2.3 The Taser, in normal mode, is likely to be used at distances of 1 m (perhaps closer, if the circumstances dictate) and up to the maximum operating distance of approximately 7 m. The head and neck should be avoided (if possible), due to the perceived increased risk of injury to, for example, the eye.
- 3.2.4 Users will seek guidance from Dstl and DOMILL on the vulnerable parts of the body, and on operational scenarios which may result in injury or an increased risk of injury to the target; this will inform users when considering an appropriate strategy.
- 3.2.5 In addition to the normal mode of operation (electrodes propelled to the target), the Taser may be used in a stun mode (with barb cartridge removed). It is considered likely that the UK Police will use the device in this mode in at least three scenarios.
 - a. As an alternative to pressure point compliance techniques, e.g. in public-order scenarios, where people sit down in the middle of the road or hold onto street furniture and refuse to move;
 - b. When the Taser barbs fail to attach to the target and the subject continues to move towards the officer. With Taser International products, the Taser can be used in the stun mode, where the barbs have been fired and the cartridge is still attached to the device;
 - c. When the officer is unable to load a cartridge before the subject attacks/engages them at very close range, i.e. where a subject puts an officer on the ground.
- 3.2.6 In scenario (a), it is anticipated that the stun would be applied to the arms, legs or, possibly, chest. In scenarios (b) and (c), the point of application would depend on where the officer could target, having been overpowered or about to be overpowered.

3.3 Incidence of deployment and use

- 3.3.1 Dstl has sent e-mails to Taser International and Tasertron posing the following questions:
 - How many law enforcement agencies world-wide have Tasers available to their officers?
 - How many countries are they deployed in?
 - What proportion of police authorities in North America deploy the Taser?
 - How many operational, and how many voluntary uses of Taser technology have occurred since the development of the technology (5-7 W and 18/26 W devices)? Specifically, how many operational and voluntary deployments of 18/26 W Tasers have there been?
 - How many operational and voluntary uses of Taser occurred in 2001?
 - How frequently is the "stun" mode of the Taser used (i.e. fixed electrodes)?
- 3.3.2 Taser International supplied a spreadsheet [24], showing 1089 agencies in the US (out of a total of about 12000) that deploy the Advanced Taser (M26); a further 253 are evaluating it, and 50 international agencies in 11 countries are deploying or evaluating the Advanced Taser. Taser International stated that the spreadsheet was out of date and that number of US agencies deploying the Advanced Taser is currently about 1300 [25].
- 3.3.3 A database of 1608 reports of the operational use of the Advanced Taser by police was also provided. The company estimated that only 20% of operational uses were reported to them. The Los Angeles Sheriffs' Department and the Los Angeles Police Department each have 500 units. These users, and others such as Seattle Police and the Royal Canadian Mounted Police do not report use "for liability reasons". About 50% of all operational uses occurred within the last year.
- 3.3.4 In addition to over 200 police officers who had volunteered to be exposed to the output of the Advanced Taser, about 90% of nearly 5000 certified law enforcement instructors who completed their training course volunteered to be exposed. By a calculation that assumed the number of police officers in classes subsequently taught by these instructors, the company estimates that about 10,000 people have had voluntary applications of the Advanced Taser.
- 3.3.5 Data subsequently supplied by the company on CD shows the breakdown of modes of operation of the Advanced Taser in 1534 uses (presumed operational, but not stated) [Table 1]. Sixty three percent of the uses resulted in deployment of the darts; in 16% of cases, the device was used in stun mode.

Mode	Number			
Not stated	60			
Darts fired	965			
Laser only	225			
Spark demonstration	34			
Application in stun mode	250			

Table 1; Modes of use of Advanced Taser

3.3.6 Taser International entered the law-enforcement market in 1998 and their sales have principally been the high-power Advanced Taser. Their commercial rivals Tasertron made the 7W Tasers and according to Taser International did not keep good records, but since their introduction in 1974, the number of 10,000 uses of 7W

Tasers has been "bantered about" and "seems reasonable", according to the CEO of Taser International.

3.3.7 At the time of writing, Tasertron had not replied to the e-mail sent by Dstl. However, in a (undated) document acquired from the company on another occasion, Tasertron state that the Taser (presumably 5-7 W) has been deployed over 50,000 times, with up to a 90% success rate, and "no fatalities due to the Taser wave" [19]. They claim that there are over 400 major law enforcement/correction users in the US. McNulty [26] (a former Vice-President at Tasertron) repeats the claim that there have been 50,000 uses over twenty years (with no fatalities "showing that the standard power Taser (0.6 J) is safe"). The subjects ranged from a 12 year old boy (attempting suicide), to 70 year old men. The first US police department to deploy the Taser was that in Los Angeles; there were 600 uses in 1986 alone [3].

4 Interaction with nervous tissue and skeletal muscle

- 4.1.1 There is no objective, scientific information in the peer-reviewed literature on the neurophysiological basis of the mechanism of action of Tasers. This section speculates on the possible interactions.
- 4.1.2 Figure 1 is a representative single pulse from a Taser [27]. It is classed as a damped sinusoid. The magnitude of the pulse is dependent on many factors, such as the resistance of the load and the specification of the particular device. The outputs of a number of Taser types are presented in Annex D. The pulse is repeated up to about 38 times each second (pulse repetition frequency p.r.f.)



Figure 1; A single representative Taser pulse

4.2 Incapacitation from Tasers and stun guns

- 4.2.1 It is reasonable to assume that any incapacitation system based on electrical current or voltage must act on electrically active tissues (e.g. nerve, skeletal muscle or heart), and also that any undesirable side effects would be related to these. Before considering the mechanisms of action (and safety) of these systems, it is therefore important to review the physiology of excitable cells. Annex B provides an overview.
- 4.2.2 Tasers and stun guns function as high-voltage, low-current stimulators that can cause involuntary muscle contractions and sensory responses, such as various degrees of pain and the feeling of exhaustion [28]. From the published literature however, the precise mechanism by which these devices incapacitate does not appear to be well understood. According to the Air Taser literature, the voltage is mainly an indication of how far a spark can jump and therefore how much clothing the stun device can penetrate when the spark must penetrate fabric: as a "rule of thumb," 28,000 Volts will penetrate one inch. This is stated to be the only true benefit of using high voltages, as the effectiveness of electronic output is more dependent on current, power and frequency, than on voltage.
- 4.2.3 From viewing video clips of persons subjected to Taser discharges in both controlled and field situations, it is apparent that there is a difference between the 5-7W (0.3 J per pulse) low power Tasers and the newer 26 W (1.76 J per pulse) device. The low power devices do not completely incapacitate the subject and it is possible for the subject to overcome the effects of the Taser. In contrast, the discharge from a 26 W Taser (the so-called "Electro-Muscular Disruption" weapon,

EMD) produced a very rapid (1-2 s) incapacitation of all the subjects shown in the video clips. This appeared to be due to a loss of control of postural muscles, in most cases apparently caused by a rigid tetanic contraction of one or both legs. This has been described as a "controlled fall" in the manufacturer's literature, although in many cases the subjects did not appear to have control in the way they fell. In none of the cases shown did the subject appear to lose consciousness, although most subjects received 1-2 s of discharge, rather than the usual operational duration of 5 s or longer.

- 4.2.4 In the case of Michenfelder vs. Sumner *et al.* [29], Magistrate Atkins "noted that the inmates who have been subjected to hits from Taser guns reported only slight headaches and some nausea after the immediate pain from the Taser darts had ceased. Other than 'sustained long term anger', no psychological effects appear to have been suffered".
- 4.2.5 Tony Bleetman, a consultant at Birmingham's Heartland Hospital, was shot with a Taser as part of his review (funded by Taser International) of the medical safety of the M26 Advanced Taser. He described his experience [30]: "When I was shot with a Taser I remained fully conscious throughout. I was aware of feeling the ground but not understanding why. The next sensation was that of overwhelming pain."
- 4.2.6 The inventor of the Taser (John Cover) had the device inflicted upon him "hundreds of times". Torso stimulation was not necessarily painful, but when darts were taped on the lower leg across joints, the pain was "excruciating" [3]. Cover believed that torso applications could affect the brain "blocking conscious recognition of it [the pain]".
- 4.2.7 The effects of stun guns have been reported to increase with duration of application [28]. With the electrodes 5 cm apart, applications of up to 0.5 s will cause the victim to be startled and repelled. 1–2 s of discharge of current will cause the victim to fall, commonly in a slow, semi-controlled fashion. The degree of sensation evoked by these devices can result in a response that far outlasts the duration of the current, so discharges of 3–5 s may leave the victim immobilised, dazed and weak for 5–15 min. [31]. In most people, a stun gun applied for 4–5 s under the rib cage will bring them to their knees and weaken them [3].
- 4.2.8 In stun guns, the electrodes are usually about 5 cm apart, but darts from Tasers diverge when fired, so that the separation between the probes when they strike the target can be between 3 and 35 inches (7.5-95 cm, Table 2); in the PSDB tests, the maximum barb separation was a mean of 79 cm with a 20 ft (6.1 m) range [2]. At the stated optimum performance distance of the Air Taser (7-10 ft, 2-3 m), the probe separation will be 12-17 inches (30-40 cm).
- 4.2.9 The wider the distance between them when they land on the target, the greater the effect [3]. For example, electrodes 5 cm apart applied directly over the vastus lateralis muscle do not inhibit voluntary function of the muscle during stimulation or afterwards. After about 5 s of application of the stun gun, individuals who have been trying to resist will stop doing so, presumably because of pain or fatigue. By contrast, Taser darts placed 10 inches (25 cm) apart (the distance reached if fired from about 6ft, 2m) over the vastus lateralis in the same person are reported to lock the leg in the flexed position, typically leading him or her to surrender (the vastus lateralis is an extensor muscle, part of the quadriceps extensor in the femoral region and so the "flexed" description is curious).

Distance to Target (feet)	2	5	7	10	15	21
Spread between probes (inch)	3	8	12	17	25	35

Table 2; Spread to distance chart for the Advanced Taser (from [32])

4.3 Potential mechanisms for incapacitation

- 4.3.1 The potential mechanisms of incapacitation of subjects include:
 - a. stimulation of motor nerves controlling muscles;
 - b. direct stimulation of muscles;
 - c. stimulation of sensory nerves;
 - d. stimulation of the central nervous system (CNS).

Each of these is considered below.

4.3.2 Stimulation of motor nerve fibres

- 4.3.2.1 Many motor, sensory and mixed nerves are located quite close to the surface of the body and are likely to be susceptible to externally applied electric fields. Large calibre myelinated A α motor nerve axons have the lowest thresholds of all the axons in a peripheral nerve (Annex B). If an electric field is applied across a nerve, therefore, the motor axons which innervate skeletal (voluntary) muscle fibres will be activated at lower field intensities than the other axons in the nerve. This is consistent with the claims that systems such as the Advanced Taser can produce incapacitation by inducing muscle contractions in the target.
- 4.3.2.2 According to the manufacturers, "conducted energy weapons with power output greater than 14 watts are designated as Electro-Muscular Disruption (EMD) weapons due to the fact that they directly control the skeletal muscles. This EMD effect causes an uncontrollable contraction of the muscle tissue, allowing the M-series to physically debilitate a target regardless of pain tolerance or mental focus" [32]. The manufacturers go on to say that the Air Taser "overrides the nervous system" because the Taser Waves are "quite similar to those used by the human body for communication".
- 4.3.2.3 The Taser waveform is claimed to mimic the action potential in nerve fibres, but this may be misleading. In reality, the Taser output appears to be an overdamped unipolar transient consisting of a number of cycles, depending on the impedance into which the Taser is discharged: as the resistance is increased the number of peaks in the waveform decreases [33]. For nerve and muscle stimulation, the important factors are strength and duration of the voltage or current pulse.
- 4.3.2.4 The claims of the manufacturers that the target "loses control of the neuromuscular system and cannot perform co-ordinated action" are thus consistent with the characteristics of motor nerves. This is also consistent with the signs of sustained tetanic stimulation apparent in persons subjected to Taser discharge, which results in rigidity of the affected area, similar to muscle cramps.
- 4.3.2.5 Often, the targets collapse slowly in a semi-controlled fashion [28]. This raises the possibility that sensory $A\alpha$ fibres could also be affected. These carry proprioceptive information about the positions of muscle and limbs, so that interference with these fibres would disrupt postural control. Furthermore, motor nerves also contain $A\gamma$ fibres which control the contractile elements of muscle

spindles, specialised sensory elements which set muscle tone by a servo-like feedback loop. These have a somewhat higher threshold for excitation than the A α fibres, but have a profound influence on postural control.

4.3.3 Direct stimulation of muscles

4.3.3.1 Skeletal muscle fibres generally have a higher stimulation threshold than the motor axons and motor nerve terminals innervating the muscle (Figure 2). In this Figure, the left-hand curve represents data for indirect stimulation via motor nerve fibres. The right-hand curve represents data for direct stimulation of muscle fibres, when nerve-muscle transmission is blocked by curare.



Figure 2; Strength-duration curve for stimulation of a cat skeletal muscle with an intramuscular electrode. From [34]

- 4.3.3.2 This property is often exploited for field stimulation of *in vitro* muscle preparations in which the nerve is not easily accessible: when a short electric pulse is applied across the muscle between two metal plates, indirect contractions of the muscle can be induced by excitation of the motor nerve terminals at low field intensities. The indirect nature of the contractions can be demonstrated by the application of curare, which inhibits synaptic transmission between the nerve terminals and the muscle fibres and so blocks contraction. Higher field intensities are then required to evoke contraction by direct stimulation of the excitable muscle fibre membranes.
- 4.3.3.3 Given the considerable separation in the strength-duration relationships between muscles and motor nerves, it is unlikely that the short-duration Taser pulses could evoke contractions by direct stimulation of muscle fibres without also stimulating motor nerve terminals within the same muscle.

4.3.4 Stimulation of sensory nerves (pain)

4.3.4.1 The largest calibre sensory nerve fibres, which fall into the Aβ category, mediate non-noxious sensory modalities such as touch and pressure (Annex B). These have quite low stimulation thresholds and are likely to be activated by electric fields from Tasers and other devices. In contrast, painful sensations are mediated by nociceptive A δ and C fibres. The latter are unmyelinated and have slow conduction velocities. Both types of fibre have rather high stimulation thresholds (typically several times that of A $\alpha\beta$) and are therefore less likely to be activated by short electric pulses; however, the sensory receptors for pain are free nerve endings in the epidermis and these are likely to be activated in the area around the Taser darts. Therefore, it is probable that there will be at least some localised pain in the part of the body hit by the probes. Indeed, in the case of Michenfelder vs. Summer *et al* [29], it was concluded that "The evidence indicates that the Taser darts draw blood and cause pain where they hit the target person".

- 4.3.4.2 The actual degree of pain caused by a Taser is unclear. The Air Taser web-site quotes the results of a study at the King/Drew Medical Center in Los Angeles, on patients admitted to the Emergency Department after being shot with a Taser between July 1980 and December 1985. This indicated that the Taser did not cause conscious pain (however, 92% of the patients stated that they could not remember being subjected to the Taser, see below). The quote goes on to state: "In contrast, pepper and chemical sprays are known to cause tremendous pain, which is the primary means of causing the target to stop". Another quote from the web-site states that "Occasionally, police departments have been charged with the pretence that an officer applied the charge too long and tormented the target (even though there is no pain sensation *per se* with the Taser)".
- 4.3.4.3 In contrast, Bleetman [30;35] stated that he had a sensation of overwhelming pain after being shot with a Taser. A behavioural study on trained monkeys [36] concluded that pain may have been the major direct consequence of the 0.3 J (i.e. lower energy) Taser pulse which affected their performance of set tasks.

4.3.5 Stimulation of the Central Nervous System

- 4.3.5.1 Direct stimulation of the central nervous system (CNS) the brain and spinal cord would be expected to produce effects such as unconsciousness and electrographic seizures similar to those seen in epileptics. The NIO/ACPO report on Phase 2 of the Alternative Policing Approaches programme [2] surmised that it is unclear whether the Taser may produce such direct effects on the brain. Bleetman's description of being shot with a Taser stated that he remained fully conscious throughout, although he also stated that he was "aware of feeling the ground, but not understanding why". In the study at the King/Drew Medical Center in Los Angeles, 92% of the patients who had been shot with a Taser stated that they had total amnesia about the event and could not remember being subjected to the Taser. This may reflect indirect consequences of the peripheral actions of the Taser discharge, rather than a direct effect on the central nervous system.
- 4.3.5.2 Summers and Cover (cited in Murray [3] believe that the Taser pulse may affect the CNS and block conscious pain; additionally, it may cause mood changes. Cover also speculates that the current may break up PCP molecules, a perhaps fanciful explanation of the experience of the LAPD ("PCP intoxicated persons subjected to Tasers are "back to their norm" in hours, compared to days for non-"tasered" PCP users").

4.4 Conclusion

4.4.1 The cause of the collapse and incapacitation in subjects shot with Tasers is unclear. The most likely explanation appears to be disruption of neuromuscular control by stimulation of motor axons in peripheral nerves, possibly accompanied by disruption of proprioceptive inputs from muscle spindles, leading to disturbances in
posture and balance (the "semi-controlled fall" described in subjects of Taser use). The significance of painful stimulation by the Taser is not clear. Direct effects on the CNS do not appear to be involved, although there are reports of headaches and amnesia following Taser hits.

5 Neurophysiological basis for interaction with the heart

5.1.1 The section reviews the electrophysiology of the heart, the charge transfer from transcutaneous external pacemakers (TEP) and provides a basis for possible increases in susceptibility of the heart arising from drugs such as "ecstasy".

5.2 Normal heart function

5.2.1 The effective pumping action of the heart is critically dependent on the organised spread of excitation from the pacemaker cells of the sinoatrial node (located in the wall of the right atrium near the inlet of the superior vena cava), through the right and left atria, and into the ventricles via the atrioventricular node, bundle of His and the Purkinje fibre network (see Figure 3).



Figure 3; Anatomy of the conduction pathway

5.2.2 The ECG comprises three principal components: the P wave (corresponding to atrial contraction), the QRS complex (initiation of ventricular contraction or systole), and the T wave (ventricular relaxation or diastole). Sometimes a small U wave can be measured immediately after the T wave. The ECG actually represents the extracellularly recorded averaged activity of many millions of individual heart cells. Figure 4 depicts the relationship between the ECG waveform and the action potential waveform in atrial (A) and ventricular (V) muscle cells. Note in particular the QT interval of the ECG – this is the time interval between the Q wave and the end of the T wave. The determinant of the QT interval is the duration of the action potential in individual ventricular cells – this will be discussed later in the context of drug-induced QT prolongation as a putative contributory factor in possible Taser-induced arrhythmias.



Figure 4; The ECG

- 5.2.3 Clearly, anything with the potential to disrupt the orderly flow of electrical excitation through the heart also has the potential to compromise the circulation of blood and, therefore, the function of every other physiological system in the body.
- 5.2.4 Both the rate and the force of contraction are subject to control from the autonomic innervation to the heart: the parasympathetic vagus nerve (which slows the heart rate and decreases contractility) and the sympathetic cardiac nerve (which elevates heart rate and increases contractility). The heartbeat is also subject to modulation by circulating catecholamines (adrenaline and noradrenaline released from the adrenal glands), the effects of which resemble those of sympathetic nerve activity.

5.3 Automaticity and the specialised role of pacemaker tissue

- 5.3.1 The spread of excitation in the normal heart begins in the sinoatrial (SA) node, which is made up of cells displaying a property known as *automaticity* – even if all external influences and connections to these cells are removed, they spontaneously generate action potentials. Cells in the SA node are not the only ones in the heart to possess automaticity (cells of the atrioventricular node, His bundle and Purkinje fibre network also display this property). However, what makes the SA node the focus for initiation of each heart beat is the fact that the cells in this node generate action potentials at a faster rate (generally 60-100 action potentials per minute). For this reason, the SA node is referred to as the *primary pacemaker*, while the other areas are referred to as *latent pacemakers*.
- 5.3.2 If the SA node fails to generate electrical impulses at its normal rate or stops functioning entirely, or if the conduction of electrical impulses is blocked for any reason, latent pacemaker cells in the atrioventricular (AV) node will usually assume the role of the heart's pacemaker but at a slower rate (usually 40-60 beats per minute). Similarly, if the AV node is diseased (and therefore unable to take over the role of pacemaker), the heart may be paced at an even slower rate (<40 beats per minute) by His or Purkinje tissue.

5.4 Disturbances of cardiac rhythm

5.4.1 Whereas in the normal heart the SA node is responsible for initiating the heartbeat, under certain circumstances cardiac cells in *any* part of the heart (even non-

pacemaker cells) may take on the role of pacemaker and start generating electrical impulses. In these circumstances, the part of the heart generating the abnormal activity is known as an *ectopic focus*, and this can result in ectopic beats and rhythms (e.g. premature contractions, tachycardias, flutters and fibrillations). The three principal mechanisms responsible for ectopic beats and rhythms are: enhanced automaticity, re-entry and triggered activity. Table 3 lists the mechanisms and their common causes:

Mechanism of arrhythmia	Characteristics	Common causes				
Enhanced automaticity	abnormal condition of latent pacemaker cells in which firing rate is increased non-pacemaker cells may acquire automaticity under certain conditions	raised catecholamines (noradrenaline and adrenaline), digitalis toxicity, atropine, hypoxia, hypercapnia, myocardial ischaemia and infarction, low plasma K^+ or Ca^{2+} , heating and cooling of the heart				
Re-entry	flow of excitation delayed or blocked in one or more segments of the conduction system while rest of conduction system is normal	myocardial ischaemia, raised plasma K ⁺				
Triggered activity	abnormal condition of latent pacemaker and non-pacemaker cells in which cells may fire more than once in response to a single stimulus	raised catecholamines, digitalis toxicity, atropine, hypoxia, myocardial ischaemia or injury, stretching and cooling of the heart				

Table 3; Mechanisms and common causes of arrhythmias

- 5.4.2 The principal mechanism involved in any arrhythmia induced by the current discharged from a Taser device is most likely to be triggered activity (initiated by external pacing of the heart), although other secondary arrhythmogenic mechanisms could come into play (e.g. enhanced automaticity mediated by catecholamines released during the emotionally charged events surrounding the use of the Taser). Other contributory factors may include pre-existing heart disease (e.g. myocardial infarction or congenital long QT syndrome) and the presence in the circulation of drugs (prescription or drugs of abuse) which may exert pro-arrhythmic effects. In the case of the latter factor, of particular concern would be drug-induced prolongation of the QT interval (also known as acquired long QT syndrome). This is discussed in more detail later.
- 5.4.3 To understand how electric shock could induce arrhythmias, it is first necessary to consider the property of myocardial cells known as the *refractory period*.

5.5 The refractory period of cardiac cells

- 5.5.1 The excitability of heart tissue, defined as its ability to respond to a normal (or externally applied) stimulus, varies during the different phases of the cardiac cycle. Four states of excitability have been defined experimentally:
 - the *effective refractory period* (defined as that period during the cardiac cycle during which a stimulus, no matter how strong, fails to produce a propagated electrical response);
 - the *relative refractory period* (defined as the period during which a propagated action potential can be elicited, but the stimulus required to do so is greater than that needed to elicit a similar response in diastole);
 - the *supernormal period* (defined as the short time after the relative refractory period during which the stimulus threshold required to elicit a propagated action potential is actually lower than in diastole);

- the *period of normal excitability* (which extends from the end of the supernormal period to the beginning of the next action potential).
- 5.5.2 Figure 5 demonstrates the relative refractory period in a sheep isolated cardiac Purkinje fibre (Dstl data). The fibre was paced by paired stimuli set at varying interstimulus intervals. The first stimulus elicited an action potential, while the second stimulus failed to elicit an action potential until the interstimulus interval was set at 340 ms.



Figure 5; A second stimulus at 100 ms (left) or 300 ms (centre) fails to elicit a response, while the stimulus at 340 ms (right) initiates a new action potential (data from sheep Purkinje fibre recorded at Dstl Porton Down). Abscissa = time in seconds; ordinate = membrane potential in volts.

5.6 Excitability during the cardiac cycle and susceptibility to arrhythmia

- 5.6.1 The significance of the refractory periods is that an externally applied electric shock of sufficient power is highly unlikely to trigger an ectopic heartbeat if it occurs during the absolute refractory period. How5ver, shocks occurring during the other three periods have the potential to precipitate triggered activity.
- 5.6.2 Moreover, the probability of an arrhythmia of this type being induced is likely to be enhanced by the presence of raised catecholamines, such as might be anticipated in the context of use of a Taser device (i.e. a highly emotionally charged event).

5.7 Use of transcutaneous pacemakers to drive the heart with chest surface electrodes

- 5.7.1 Before discussing how (and whether) discharge from a Taser device could influence the electrical activity of the heart, it is informative to consider how transcutaneous external pacemakers (TEPs) work. TEPs are medical devices designed to deliver controlled pulses of current from a pair of paddle electrodes attached to the chest and, in this way, pace the heart. The devices are used as a temporary measure for the treatment of symptomatic bradycardia and for so-called overdrive pacing of certain tachycardias). They may also be used to drive the heart after cardiac arrest. By sending a current of controlled amplitude, width and frequency through the chest wall, the TEP is able to entrain the heartbeat (a process termed *capture*).
- 5.7.2 In its early form in the 1950s, the TEP used a pair of 3 cm metal electrodes secured to the chest wall which delivered 1-2 ms, 120 V alternating current impulses. In 1981, P.M. Zoll patented and introduced a TEP device with a longer pulse duration (40 ms) and a larger electrode surface area (80 cm²) [37]. These modifications reduced the current required to capture the heart and increased the comfort of the patient (reduced pain as a result of less involvement of the chest musculature). In 1982, the US Food and Drug Administration approved the use of the Zoll TEP.
- 5.7.3 The TEPs electrodes are polarised, and it is important that they are positioned correctly. The TEP electrodes are generally sited in one of two configurations:

- anterior-posterior (the anterior electrode [-ve] placed on the left anterior chest over the apex of the heart, the posterior electrode [+ve] placed on the left posterior chest beneath the scapula and lateral to the spine at the heart level);
- anterior-lateral (the anterior electrode placed in the right subclavicular area lateral to the sternum [+ve], the lateral electrode [-ve] placed on the left chest just lateral to the left nipple and in the midaxillary line).
- 5.7.4 In use, the electrodes are positioned and, starting from zero current and a pacing rate of 60-90 beats per minute, the current is gradually increased until capture is confirmed. Most patients achieve capture at currents of 50-90 mA, although threshold varies markedly between individuals. Capture thresholds are not related to body surface area or weight. Interestingly, in a study in which lateral-lateral placement of electrodes (left and right midaxillary lines) was investigated, capture was rarely obtained [38]). Also, if the electrodes are placed in the wrong polarity the capture threshold is markedly increased.
- 5.7.5 The atrial pacing threshold in humans is generally much higher than that for the ventricles. The result of this is that the current required to simultaneously pace the atria and ventricles is too high to be tolerated. For this reason, the pacing of the heart by TEP is regarded as a temporary measure, as the result of pacing of the ventricles alone is a drop in the cardiac output of around 30%.
- 5.7.6 As mentioned above, early TEPs used short duration pulses (1-2 ms) these resemble neuronal rather than cardiac action potentials, and there was significant (and painful) stimulation of skeletal muscle. In his early research, Zoll (see [37]) discovered that increasing the duration of the current from 1 ms to 4 ms resulted in a 3-fold reduction in the current required for captured. Increasing from 4 ms to 40 ms further halved the capture current. Increases in pulse duration above 40 ms gave no further benefit in terms of reduction of capture threshold. Commercial TEPs use either 20 or 40 ms pulse widths.

5.8 Defibrillators – resynchronisation of myocardial excitability

- 5.8.1 While TEPs are designed to provide a continual pacing drive to the heart, defibrillators are designed to restore normal rhythm in a fibrillating heart through the application of a short duration, high intensity shock. The defibrillation mechanism involves the collective depolarisation of all excitable regions of the fibrillating heart, which then forces the myocardial cells into an absolute refractory state from which they can then synchronously recover (and thereby revert to normal rhythmic activity.
- 5.8.2 The defibrillation waveform is half to a quarter of the duration of a TEP waveform. The current, however, is much higher (15-50 A *versus* 50-150 mA in the TEP).

5.9 Tasers and the heart

5.9.1 In the context of electric shock, the factor that is most likely to kill a person is ventricular fibrillation (VF), a condition in which the electrical and mechanical activity of the heart becomes chaotic and ineffectual (VF is discussed in more detail in Annex C). Without intervention (in the form of cardiopulmonary resuscitation), the resulting loss of cardiac output will lead to death within minutes. Although VF is most often associated with an underlying pathology (e.g. myocardial infarction or long QT syndrome), it may also be precipitated by electrical current. In fact, VF is considered to be the main cause of death from electric shock [39].

5.9.2 In terms of the cardiac cycle, the so-called *vulnerable period* occurs during the repolarisation phase of the action potential (corresponding to the relative refractory period which, in turn, corresponds to the T wave of the ECG). A current of sufficient magnitude and duration occurring during the vulnerable period can precipitate VF [34]. The figure below illustrates the relationship between the cardiac cycle, vulnerable period and VF.



Figure 6; Vulnerable period of the ECG and triggering of VF

5.9.3 The susceptibility of the heart to VF arising from Taser currents is discussed in Section 0 below. The increased susceptibility during the T wave will become relevant with a repetitive pulse such as that from a Taser. However, the magnitude of the increased susceptibility is not known. Link showed in a pig model that the duration of the vulnerable period was only about 15 ms before the peak of the T wave, for mechanical impact [40]. If this is applicable to electric shock, it is a small "window" for the Taser pulse to interact with. Kohl has expressed the view that this peak is too short to be explained by changes in cardiac mechanics [41]. The duration of the vulnerable period may be greater than this.

5.10 Additional considerations in possible Taser-induced arrhythmia

5.10.1 **Drugs:** Many prescription medications (see www.torsades.org) predispose the heart to a particular type of arrhythmia known as *torsades de pointes* ('twisting of the points' – see Figure 7).

Figure 7; The ECG in "torsades de pointes"

5.10.2 This arrhythmia, which is potentially lethal unless it spontaneously reverts to normal rhythm, is associated with a prolonged QT interval which, in turn, arises from an increased duration of the action potential at the level of the individual myocardial cell. Clinically, the phenomenon by which certain drugs increase the QT interval is termed *acquired long QT syndrome*. Examples of prescription drugs known to induce QT prolongation are terfenadine (a hay fever remedy that has been withdrawn from the market), cisapride (a gastroprokinetic drug – also withdrawn) and amsacrine (an antileukemic drug – still in use). There are countless other examples and drug regulatory bodies world-wide now insist that all new drugs are tested for QT prolonging activity prior to first administration to humans. Interestingly, there are also several forms of *congenital long QT syndrome* that arise from mutations in genes that control expression of sodium or potassium channels involved in shaping the cardiac action potential – these syndromes are a frequent cause of sudden death in affected individuals.

- 5.10.3 One of the drugs of abuse that has been associated with deaths occurring in the context of Taser use is phencyclidine (PCP). There is very little in the scientific literature concerning the effects of PCP on the heart: PCP has been reported to induce prolongation of the action potential in frog isolated ventricular muscle [42] and to increase the force of contraction and induce marked action potential prolongation in rat and guinea-pig isolated heart muscle [43]. An action potential prolonging effect of PCP has also been observed in guinea-pig isolated ventricular myocytes [44]. This action potential prolonging effect of PCP can be construed as a pro-arrhythmic mechanism [45] and, if reproduced in man, could conceivably reduce the threshold of the myocardium to arrhythmia induced by electric shock.
- 5.10.4 More commonly used drugs of abuse in the UK are cocaine and ecstasy (methylenedioxymethamphetamine or MDMA), both of which have been associated with effects on the heart (mediated either directly or indirectly, via the autonomic innervation to the heart) Table 4. They could also predispose the heart to arrhythmia from electric shock.

Drug	Direct effects on heart				
Cocaine	 – QT prolongation [46] – acidosis, QT prolongation, conduction defects [47] 				
MDMA	– QT prolongation [48] – fatal arrhythmia [49]				

Table 4; Effects of cocaine and MDMA (ecstasy) on the heart

5.10.5 Acidosis: Fish believes acidosis may predispose to arrhythmias from Tasers [28]. Dstl has been unable to find evidence in the literature to suggest that acidosis *per se* will prolong the QT interval. There is evidence that acidosis is a factor in sudden cardiac death (which may be due to ventricular fibrillation) and cardiac arrest and, in this regard, acidosis is one of a number of factors that could contribute (listed in the section on "ventricular fibrillation" in www.e-medicine.com). Wang [47] suggests that cocaine-induced acidosis can induce conduction delays in the heart (a wide QRS complex – pro-arrhythmic) reversed by measures designed to correct blood pH.

6 Taser output applied to electrical safety criteria

6.1.1 This section discusses the use of electrical safety criteria by the manufacturers, and offers a critique of the use of these criteria for Taser waveforms.

6.2 Taser manufacturers' use of safety criteria

6.2.1 Taser International has provided cardiac safety information for their products in graphical form Figure 8. This graph and others are widely reproduced and are used to support statements on Taser safety. The graph shows that the Advanced Tasers and the low-power Air Taser are below the "Heart Safety" line. The graph appears to be largely based on the US Underwriters' Laboratories standard: UL 69 - Standard for Electrical Fence controllers [50]. A Taser is not an electric fence controller, and it is appropriate therefore to review the use of this standard for the Taser output, and the rationale expressed by the companies for the values of "Body Current" and "Pulse Width" applied to the graph.



Figure 8; Taser International's graph for heart safety

6.2.2 Figure 9 is taken from the standard - *Supplement SA* - *Alternative evaluation program for electric fence controllers*; this is an alternative method to that expressed in the body of the standard for safety assessment (the method in the body of the standard will be discussed later). Remarkably, the Standard does not disclose the clinical basis of the line – it could be ventricular fibrillation, or "let-go" current. Taser International state it is VF [51].



Figure 9; Graph of current against pulse length in the UL 69 electric fence controller's standard. (Current is RMS - UL69- Electric Fence Controllers)

6.2.3 Dstl has assumed that this graph in the Standard is the basis for the graph used by Taser International. However, there are certain inconstancies between the graphs from the Taser manufacturer (Figure 8) and the UL 69 graph (Figure 9). The two lines are re-plotted in Figure 10.



Taser Manufacturers Safety Graph Vs UL 69 Figure SA5.1 Graph

Figure 10; Comparison of Taser International criteria and UL 69

6.2.4 The criteria are not identical, even though Taser International cite the UL Standard:

• The UL 69 graph is only plotted to 0.0001 s, implying it is only valid to this point;

- The Taser manufactures appears to have extrapolated the UL 69 graph to include pulses of shorter duration (i.e. Taser pulses). This could be erroneous. Extrapolation of the UL 69 graph to 0.00001 s intercepts the y axis at 30000 mA. The equivalent interception point on the Taser manufacturers line is at 20000 mA;
- The plateau region of the graph appears to be at 300 mA on the Taser manufacturers' line but at 500 mA on the UL 69 graph;
- The plateau on the Taser manufacturers' line appears to run from 0.004 to 0.02 s and the UL 69 plateau appears to run from 0.004 to 0.05 s
- 6.2.5 The Taser manufacturers also make use of another graph claimed to originate from the UL 69 standards (Taser International file CD-ROM ver 6.0 and pg. 13 of the Air Taser 34000 user manual www.taser.com). (Figure 11)



Figure 11; Safety graph used by Taser International; Taser Output probably refers to the Air Taser

6.2.6

Figure 11 resembles Figure 22.1 from the UL 69 Standard (Figure 12).



Figure 12; Figure 22.1 from the UL 69 standard

Publication No. 64/06

6.2.7 The two lines are plotted in Figure 13; they are not identical. Also included in this figure is the value used by the manufacturer for the (assumed) Air Taser 34000.



Taser Manufacturer's Safety Plot vs Figure 22.2 UL 69 Electric Fence Controller Standard

Pulse Duration (Seconds)

Figure 13; Comparison of manufacturer's safety line (upper) and line in Fig 22.2 from UL 69 (lower).

- 6.2.8 There are several reasons that these inconsistencies may have occurred:
 - Incorrect transcription of the UL 69 standard by the manufacturer:
 - The manufacturer using an older version of UL 69 (the original version is dated 1939; Dstl has not yet been able to acquire this document);
 - The manufacturer used a different Underwriters Laboratories standard than UL 69 (although the accompanying text to the graph indicates it is for electric fence safety standards).
- 6.2.9 Regardless of the inconsistencies in the manufacturer's graphs when compared to the UL 69 graphs, is it valid to use the UL69 standard to estimate the risk from Taser impulses?

6.3 Application of the UL 69 standard to Taser output

6.3.1 Whilst manufacturers may have made best efforts to estimate the safety of their products (considering the considerable lack of information in impulse current hazards) the application of the UL 69 graphs for the estimation of VF hazard from Taser pulses is not straightforward. The standard specifies testing of the fence into a 500 Ohm load and refers to the type of pulse the standard applies to thus:

22.1.2 The output of a fence controller shall be a series of pulses separated from each other by off intervals. Each pulse may be unidirectional or oscillatory. A fence controller shall not have a continuous (uninterrupted) output. The maximum on time shall not exceed 1 second. *22.1.2 effective May 20, 1993*" 22.1.3 A minimum of ten randomly selected current pulses shall be measured. All shall comply with the limits specified in Figure 22.1. Current pulses that are not simple unidirectional pulses or decaying oscillatory current waveforms shall be the subject of a special investigation to determine acceptability. 22.1.3 effective May 19, 1995

This indicates that the standard is intended to address damped sinusoidal pulses (the Taser is such a pulse) and on this basis, it could be construed that the standard could have applicability to Tasers.

6.3.2 The U.S. Consumer Product Safety Commission (CPSC) undertook a review of the Taser in the 1970's. Tasertron include documents in their Medical Safety Information that discuss this report; in a letter dated Feb 12th 1976 to a Mr Zylich (CPSC) from a Prof. Bernstein an appendix is included which discusses the reference material supplied by the Taser manufacturer:

The relationship determined by Prof. Dalziel (current time relationship for non-fibrillating shock $I_{rms} = \frac{150}{\sqrt{T}}$ with current in mA and T the pulse

duration) and applies only to 60Hz shock with a valid time range of 8.3 mS to 5 S. It cannot be used for periods less than one half cycle of a 60Hz wave or 8.3mS. This relationship cannot be used directly for the Taser type output.

A mistake has been made in quoting a figure of 4 mAs output as safe according to the Underwriters Laboratories. In UL 69 graph 1 page 18 [this must refer to an older version of UL69] shows that a maximum of 4mAs is allowed for shocks with a pulse on period of 0.1 to 0.2 s. For shorter duration shocks the allowable value is reduced, i.e. for a pulse duration of 0.03 s, the allowable value is 2mAs.

Once again it is important to note that the UL standard allows about one pulse per second compared to the TASERS 13 pulses per second.

- 6.3.3 The following points emerge from Prof. Bernstein's comments:
 - The Root Mean Square (RMS) value of current is the value of equivalent direct current that would produce the same power dissipation in a given resistor. For sinusoidal, damped sinusoidal or unipolar (monophasic) transients, equivalent RMS currents can be derived by equating energy in the pulse.
 - For pulses of tens of microsecond duration i.e. less than 8.3 ms, it would not be possible to define over which part of a cycle the pulse was defined. That is, defining a 30 microsecond pulse (i.e. Taser) at the peak of the cycle or near the crossing, point of the cycle would give different values of RMS current.
 - The present UL 69 also defines off times for the pulse of 1 second, that is a PRF of 1Hz. The p.r.f. of Taser devices varies between device design with the M26 Advanced Taser having a p.r.f of 38 Hz.
 - The physiological basis for the selection of p.r.f. does not appear to be understood by Taser manufacturers and is probably driven by engineering solutions to pulse generation.
 - Information from PSDB indicates variable p.r.f. from the same device and the possibility of p.r.f. changing with the availability of energy stored in the battery. This raises the question as to what is the output from a particular device its consistency in operation?

6.3.4 The UL69 standard does have an additional data to take into multiple pulses within the 1 s period - Figure 23.2 of UL 69, reproduced as Figure 14. The p.r.f. specified for testing are 1, 2, 3, 5,10, 20, 60 and 120 Hz. An equation is offered:

$$I \bullet 20T^{0.7} (PRF^{0.5})^3$$

where I is the RMS current of the half wave of the pulse in A, T is the pulse duration in seconds; and PRF is the pulse repetition frequency.



Figure 14; Figure 23.1 from UL 69 showing lines for different PRF

- 6.3.5 The M26 Taser has a pulse duration of approximately 40 μ s and a p.r.f. of 38 Hz (Annex D). UL 69 specifies a 500 Ohm load. PSDB have calculated that the RMS current of the M26 into a 470 Ohm load is about 12 A (RMS). This gives a position on the UL69 graph (figure 22.2 in UL 69) the black cross in Figure 15 below the manufacturers' version of the safety criterion. However, if the RMS current is calculated over a second as in the UL 69 standard (fence controller standard expects one pulse per second) then the RMS current will be 23 mA. Additionally, the M26 has p.r.f. of 38Hz and therefore 38 times this energy is will be transferred over a 1 s period. This results in an RMS current of 145.8 mA. These values are plotted on Figure 15 23 mA is the purple cross and the 145.8 mA is the filled brown circle, both on the 1 s pulse duration. They exceed the manufacturers' version of the standard.
- 6.3.6 Taking the PSDB data at 12 amps RMS and 40 µs duration puts the M26 Advanced Taser between the 10 Hz and 6 Hz lines of UL69 figure 23.1 (black cross in Figure 15). As the M26 has a p.r.f. of 38 Hz then this indicates the M26 exceeds the safety criterion. If the p.r.f. effects are ignored then the M26 would be below the UL 69 Figure 22.2 line and would be just in the "safe" zone (the purple line that goes to 1 s).
- 6.3.7 As Figure 15 shows, by applying the UL 69 standard in different ways, it is possible

³ It is assumed by Dstl that the \bullet symbol is a proportionality symbol.

to show the M26 is "safe" or "dangerous". The problem is the interpretation of UL 69 to the Taser output.



TASER Manufacturers Safety Plot vs UL 69 Figure 22.2 Plot with Taser Data

Figure 15; Application of Taser output to UL 69 and manufacturers safety line – the effect of p.r.f.

6.3.8 One way to assist resolving this problem is to determine how the UL 69 standard was derived. Figure 14 in "Effect of Electric Shock on the Heart" Ferris et al (1936) [52] is revealing; it depicts data for the minimum current to cause VF in sheep from 60 Hz mains with pulses of differing duration. It is reproduced below in Figure 16



Figure 16; VF threshold in sheep from 60 Hz (Fig. 14 in [52])

6.3.9 The concern here is that the derivation of RMS currents from transients to assess their safety "hides" a lot of the information in the pulse. That is, a short high amplitude pulse with high PRF could have the same RMS current as a low amplitude pulse with low PRF. Biological studies indicate that strength duration curves for excitable tissue are particularly relevant for Taser safety studies. Applying RMS current to these curves may result in misinterpretation of the consequences of humans being exposed to Taser pulses.

6.4 Alternatives to UL69

- 6.4.1 The application of the electric fence safety standards to Tasers is probably not appropriate. Criticism is easy; solutions are more difficult. In the literature, two alternative hypotheses are put forward:
 - Roy and Podgorski [53] concluded that charge transfer (A x s) was the metric to cause ventricular fibrillation (for stun guns). This reflected earlier work by Roy *et al* [54] when pulses as short as 200 ns duration could cause VF in isolated rabbit hearts. However, Roy pointed out that during the activation of the stun guns, the ECG readout was obliterated so only secondary indicators of arrhythmias such as arterial blood pressure could be assessed.
 - Dalziel [55] proposed the hypothesis that the energy in the pulse was the most important criterion. This appears to support Roy's work on charge transfer, as the charge carries the energy.
- 6.4.2 These data are not sufficiently advanced to enable their use currently in the assessment of the hazards from the Taser waveform.
- 6.4.3 There are no appropriate VF safety standards for very short duration current transients repeating many times each second i.e. Tasers.

7 Modelling the current flow in the body

- 7.1.1 The modelling work was undertaken to determine the paths taken in the body by electric currents from low- and high-power Taser devices. The Taser output was applied to the model in dart mode (propelled barbs) and in stun mode (fixed electrodes). The primary purpose was to estimate the current passing through the heart, brain and spine.
- 7.1.2 The approach taken was to develop a simple representation of the human body, and then consider the distribution of electrical currents, for a range of input points (barb/stun electrode locations). The model used a complex computational electromagnetic modelling code to predict the paths and magnitudes of currents flowing in the body. Annex F presents details of the technical approach undertaken, and the limitations and assumptions of the modelling approach. It is important to note that the results presented in this section can only be considered indicative, and should not taken out of the context of these limitations.
- 7.1.3 The model development and execution required innovative scientific endeavour. It relied heavily on an investment by MOD/Dstl into electromagnetic modelling of the human body exposed to non-ionising radiation (for RF safety studies). Development of the model to address Taser pulses was a notable challenge, particularly within the time-scales imposed by the NIO and ACPO for assessment of the medical hazards of Taser devices.
- 7.1.4 A review of the literature showed that the modelling of the distribution of Taser energy in the body had never been undertaken before. In view of the oft-quoted claims that the Taser currents flow in superficial tissues with minimal distribution to the heart, and the obvious relevance of an assessment of the current distribution to safety evaluation, Dstl considered that the modelling was essential, even if the veracity of the model was constrained by time, and by difficulties encountered in developing and implementing the model.

7.2 The model

7.2.1 Figure 17 is a section of the model to reveal the components. The head consists of a brain, which is enclosed by a skull, and then a layer of skin. The torso is comprised of lungs and a heart, which is enclosed by muscle, and a layer of fat and then skin. The legs consist of bone and layers of muscle and skin. The arms consist solely of muscle.



Figure 17, A section of the model

7.3 Aims of the modelling

- 7.3.1 The principal aims of the modelling were to:
 - a. Estimate the magnitude and proportional distribution of currents in the heart, brain and spinal region from a Taser device;
 - b. Determine the effect on these parameters of:
 - changes in the separation of the current injection electrodes (barbs);
 - application in stun mode with the fixed electrodes (5 cm separation);
 - c. Compare the effects of low- and high-power Taser devices.

7.4 Scenarios modelled

- 7.4.1 The number of simulations undertaken was constrained by difficulties in model development, and the long run times (simulations took 5-35 hours to run, depending upon the resolution of the model). The following simulations will be discussed in this report:
 - 1. The first four simulations modelled the application of the upper dart to the chest wall overlying the heart. This dart was fixed. The lower dart was placed at four locations below the fixed upper dart:
 - 225 mm (Figure 18);
 - 378 mm;
 - 601 mm (left leg);
 - 786 mm (left leg) (Figure 19).

These dimensions were the average dart separations noted in trials by PSDB at various ranges from an (unspecified) Taser [2]

2. The fifth simulation modelled the scenario when the Taser was used in stun mode against the neck, with the electrodes in a vertical orientation.

- 3. The sixth simulation modelled the same scenario but the contact points of the two electrodes were applied horizontally at the same height (Figure 20).
- 4. The simulations outlined above were undertaken using the 7W TE93 Taser, and the 26 W Advanced Taser (M26).



Figure 18; Taser dart separation of 225 mm on the anterior chest



Figure 19; Taser dart separation of 786 mm; the lower electrode is on the left leg



Figure 20; Electrodes in stun mode applied horizontally to the "neck"

7.4.2 The simple model did not have a neck *per se* and the stun gun electrodes were applied to the bottom of the sphere representing the neck/head (Figure 20).

7.5 Magnetic field strengths (current index)

- 7.5.1 The data below in the Figures and Table are shown as magnetic field strengths in units of A/m. For the purposes of this discussion, this is an index of the <u>current</u> flowing in the body.
- 7.5.2 Figure 21 is a transverse section through the chest and arms at the height of the upper Taser electrode (the dark vertical line). The lower electrode was 378 mm below this level. The large uniform field at the upper part of the figure is predominantly radiation into the air surrounding the body; radiation out of the body is also evident at the bottom of the figure. Current has entered the body on the front surface and is evident at the area representing the heart; it is not simply flowing in the periphery as manufacturers claim. The red vertical line passing through the body is an artefact of the computer modelling, and has no physical significance.



Figure 21; Magnetic field strength, transverse slice of the thorax at heart/upper electrode level; lower electrode is 378 mm below this level

7.5.3 Figure 22 shows the same section with the lower electrode on the left leg, 786 mm below the upper electrode overlying the heart. With the longer current path length, the current is more uniformly distributed within the body (the elliptical torso can just be discerned) and radiates more efficiently into the air behind the body.



Figure 22; Magnetic field strength, transverse slice of the thorax at heart/upper electrode level; lower electrode is 786 mm below this level.

7.5.4 At specific locations within the body (Figure 34 in Annex F), the change in magnetic field strength (current index) with time may be extracted. The Figures below are illustrative. Figure 23 shows the field strength in the heart for the high-power M26 Taser, and the low-power TE93 (note that the scales on the Y-axis are different). The bold line shows the field strength at the upper barb location on the

surface; the lighter line is the field in the heart. Note that the field in the heart is close to the magnitude of that on the surface and that the fields from the M26 are greater than those from the TE93.



Figure 23; Magnetic field strength at the contact point (bold line) and in the heart (light line); M26 (left) and TE93 (right) – 225 mm separation

7.5.5 Figure 24 shows the field strengths in the head and spine from the M26; the fields at both these locations are very small, and barely discernible at the bottom of the plots.



Figure 24; M26 – light line is the magnetic filed strength in the head (left) and spine area (*right*) – 225 mm separation

7.5.6 Increased separation of the Taser darts reduced the magnetic field strengths in the heart - Figure 25 shows the heart field (light grey line) with 786 mm separation. This should be compared with Figure 23 (right) that show the heart fields from the TE93 with 225 mm separation.



Figure 25; Magnetic field strength at the contact point (bold line) and in the heart (light line); TE93 - 786 mm separation

7.5.7 When the Taser was applied in stun mode to the neck, the orientation of the device had a significant effect on the fields at the application point (Figure 26 – note the difference in the Y-axis scales). The vertical application resulted in higher fields.



Figure 26; Stun mode application to the neck – fields at the contact point (bold) and in the heart (light) - horizontal (left) and vertical application (right)

7.5.8 The compiled data for the simulations is presented in Table 5. Data for the M26 and TE93 are presented as absolute values of predicted magnetic field strength, and as ratios.

Simulation	M26 – Taser				TE93 – Taser			Ratio M26/TE93				
	Input	Heart	Head	Spine	Input	Heart	Head	Spine	Input	Heart	Head	Spine
Stun - Neck	21.5	3.7	8.8	1.2	10.2	1.8	4.5	0.5	2.1	2.1	2.0	2.4
- Horizontal												
Stun - Neck	154.0	4.0	25.0	4.0	77.0	2.0	12.5	2.5	2.0	2.0	2.0	1.6
-Vertical												
Torso - 225	66.0	49.0	1.5	2.0	33.5	24.5	0.7	1.5	2.0	2.0	2.1	1.3
Torso - 378	67.0	49.5	1.5	2.0	33.5	24.5	0.7	1.5	2.0	2.0	2.1	1.3
Torso - 601	50.5	41.5	1.5	3.0	25.5	20.5	1.0	1.7	2.0	2.0	1.5	1.8
Torso - 786	51.0	40.5	1.5	3.0	25.5	20.3	1.0	1.6	2.0	2.0	1.5	1.9

Table 5; Magnetic field strength (A/m) in the body from Taser pulses

7.5.9 The key points emerging from these data, are that on the basis of the modelling (the limitations of the model are declared in Annex F):

- a. With the application of Taser to the front of the body, the fields (current index) in the heart are less than those at the surface ("Input" in the table), but are still a notable proportion of the surface field. Currents will flow in the heart region; they are not confined to the surface of the body (a claim of the manufacturers' and their advisers).
- b. The placement of the electrodes can have an effect on the distribution and magnitude of the currents. Increasing the inter-electrode distance will reduce the fields at the skin site and at the heart, but over the range 225 mm to 786 mm, the reduction in predicted field strengths was not great (49 A/m to 40.5 A/m in the heart for the M26 for example).
- c. Field strengths in the head and spine were a small fraction of the fields at the current injection sites.
- d. The M26/TE93 field strength ratios were nearly always approximately 2, except for the spinal region. This departure from 2 may be attributed to the spinal values being small relative to the input values, and consequently making it difficult to read the spinal values from the plots with any degree of accuracy. Note that the model does not have any frequency dependence in the dielectric properties of the tissues and the conductivities of the tissues are likely to dominate the distribution of current.
- e. Application of Taser in stun mode to the neck can result in very high local fields at the contact point when the electrodes are in vertical orientation. The fields in the heart and thoracic spine area are likely to be low. In vertical orientation, the fields in the brain may be 3 times those when the Taser is used in horizontal electrode orientation.
- 7.5.10 It is important to note that Dstl has not been able to ascribe physiological effects to the absolute field strengths presented in Table 5; due to the limitations of the model, the values are indicative only at this stage.

8 Experiments on animals and volunteers

8.1.1 This section reviews experimental work on animals and studies on volunteers assessing the safety issues associated with Taser and stun gun use. Most of the (rather few) studies on the cardiovascular consequences of their use, using experimental animals, have focussed on the potential for the induction of ventricular fibrillation (VF). The physiological basis of VF and the rationale for VF threshold standards are summarised in Annex C.

8.2 Tasers

- 8.2.1 Tasertron state that they started "extensive animal testing" in 1968 (no details offered); in 1970, ten times the normal Taser output was passed through a 150 pound boar without affecting its heart (no details presented) [19]. "Knock-down" tests on a bull and a bison showed "no harm" [19].
- 8.2.2 The Taser Munition Medical Overview [19] describes tests on humans which were undertaken by Summers during 1970-1972. There were no injuries in five test subjects ECG and blood pressure were recorded. No other details are presented.
- 8.2.3 The earliest fully documented tests of the effects of Tasers on experimental animals took place at the US Army Engineering Laboratory at Aberdeen Proving Ground in 1974 [36]. Five rhesus monkeys were trained to repeatedly press a lever switch on an avoidance schedule, i.e. they were subjected to electric shocks (not from the Taser) until they pressed the response switch. Tasers (0.3 J pulses) were used against the animals to determine if the behaviour could be disrupted. The primates were only fully incapacitated when the Taser pulses were applied across the head for greater than 1 s. The mechanism of the disruption of behaviour was unclear, but it was not due to tetany. There was no investigation of benign or adverse cardio-pulmonary or neuro-physiological effects arising from Taser use.
- 8.2.4 The Medical Safety Information for the M26 Advanced Taser [51] contains a preliminary report, in the form of a letter, on five dogs subjected to Air Taser and Advanced Taser; a full report was never produced [24]. Stratbucker and McDaniel at the Division of Cardiothoracic Surgery undertook the tests at an unnamed hospital in Missouri. The primary aim of the tests was to estimate the risk of inducing VF. Electrodes were placed within and on the thorax to "maximize the potential for adverse cardiac electrical interactions".
- 8.2.5 Sixteen Air Taser applications and 192 applications (14,000 pulses) of Advanced Taser on the external thorax failed to induce VF. Both direct contact and arcing (i.e. clothing stand-off) applications were employed. In three dogs, needles were inserted through the chest wall, such that their points "just contacted" the surface of the heart. Thirteen applications of the Advanced Taser into the needles failed to elicit VF; the duration of the applications was not stated.
- 8.2.6 There is no description of any other physiological measurements undertaken on the animals, nor whether the applications of the Taser induced any arrhythmias, or adverse/benign physiological effects.
- 8.2.7 Pharmacological manipulations were undertaken in some animals:
 - "Medium" and "high" doses of epinephrine, and isoproterenol were administered to "sensitize" the heart to the applied currents; no instances of

VF were observed (the number of animals employed or the number of tests undertaken are not declared);

- In one animal, "toxic" doses of Ketamine (a PCP analogue [56]) were administered; the Advanced Taser did not elicit "untoward cardiac effects".
- 8.2.8 On the basis of these tests (and studies undertaken using stun guns at the University of Nebraska in the 1980's) Stratbucker and McDaniel conclude that the risk of inducing VF by surface application of the Advanced Taser is very small.
- 8.2.9 Tasertron warn that there have been no adequately documented human Taser tests under medical supervision conducted for exposures longer than 30 s [19].

8.3 Fixed electrodes

- 8.3.1 At the University of Nebraska, Stratbucker [57] applied a stun gun to the heart and chest of a pig. The model used was an XR 5000, claimed as generating peak current of 20 A in each pulse (20,000 Ohm load) and a p.r.f. of 20 Hz. Although not stated, it would appear that a single pig was used for all the tests. When the stun gun output was delivered to the right ventricle of the heart through a bipolar catheter, there was no effect on cardiac rhythm and output, as determined by ECG and measurement of arterial blood pressure. Increased electrical susceptibility of the heart was induced with epinephrine, and the stun gun also failed to induce VF under these circumstances. The heart of the animal was paced with an external pacemaker; the stun gun applied to the body failed to disturb the rhythm (with the pacemaker in a non-sensing mode), however when the shocks were applied directly to the pacemaker, erratic pacing (extra-systoles) occurred.
- 8.3.2 With the pacemaker in a "inhibited mode", i.e. sensing cardiac activity, aberrant pacemaker function was noted when the stun gun was applied anywhere on the body. Stratbucker stated that: "Although this mode of pacer operation is the most commonly employed in practice, the degree of susceptibility noted is unlikely to cause serious clinical problems because the pacer is most unlikely to be temporarily inhibited and therefore produce few if, any pulses, of its own during this time."
- 8.3.3 Stratbucker estimated the chance of a serious medical problem with the pacemaker as less than 1 in 100, and with the incidence of pacemaker use in the early 1980's, a risk of serious adverse effects of less than one in a million was offered.
- 8.3.4 Roy and Podgorski [53] applied the output of two types of stun gun to the chest of pigs. The two devices employed were those giving the lowest and highest energy output from a selection of five commercially available stun guns. The stun gun discharges were applied to:
 - closed chest;
 - pericardium of the exposed heart;
 - the closed chest of a pig containing a subcutaneous pacemaker.

The number of exposures undertaken and the number of pigs used was not declared.

8.3.5 On the closed chest, there was burning of the skin, but changes in cardiac rhythm only occurred with discharges from the high-energy device. If this device was applied through towels (simulating clothing, and resulting in arcing), asystole occurred for the duration of the application. When the stun guns were applied directly to the pericardium of the exposed heart, cardiac arrhythmias occurred with

the low-energy device, and VF with the high energy gun. In the pig with the implanted pacemaker, VF occurred immediately upon application of the current.

- 8.3.6 Roy had shown previously [54] that transients applied directly to the heart would cause cardiac "stimulation" with a charge transfer of 3.4 μcoulombs/cm² and VF at 10 times that value. The charge transferred by the stun gun units tested transferred 0.57-27.5 μcoulombs/cm² (assuming an effective current transfer area of 25 cm²) and on this basis the VF with direct cardiac exposure was unsurprising.
- 8.3.7 In 1993, Stratbucker [58] reported further tests on seven types of stun guns from five manufacturers. The p.r.f. ranged from 5-20 Hz; other details of output were not presented, except for two models with peak voltage outputs (across a 20,000 Ohm load) of 50 kV and 80 kV. Twenty volunteers were exposed on the volar aspect of the forearm. All showed 3-5 mm diameter punctate reddening of the skin; no burns were noted.
- 8.3.8 Two 60 kg pigs had bipolar pacing electrodes inserted into the right ventricle of the heart. A 50 kV stun gun (identity not declared) was applied 10 times in 3-5 s bursts to the endocardium, through the catheter. There was no evidence of alteration in heart rhythm or variation in blood pressure (no data presented). The tests were repeated on the heart of a pig, following administration of epinephrine. No "malignant" rhythms were noted when the stun gun was applied (no data presented).
- 8.3.9 These results were at variance with those of Roy [53], and Stratbucker ascribed the difference to "dissimilar current density patterns associated with differing application techniques" (Roy applied the stun guns directly to the myocardium).
- 8.3.10 **Cadavers and volunteers:** Denk *et al* [59] applied various types of stun guns to cadavers and volunteers (the cadavers were used to determine the effective skin resistance). Four volunteers were exposed to shocks from three devices, classed as low, medium and high energy (17, 24 & 93 μ W.s [i.e. μ Joules] respectively). The stun guns were applied to the lower arm, thigh and "heart area". The pain was classed as "unpleasant" and the volunteers were content to be exposed again. The ECG and blood pressure showed no changes before and after application of the stun guns (they could not be recorded during application). There was local reddening of the skin and this disappeared after 1 hour. Denk cited work by Giebe [60] (which Dstl has been unable to acquire) in which electrodes (presumably from a stun gun) were applied to the heart area and produced "major ECG changes". Denk speculated that the difference between his data and Giebe's could be ascribed to the pig model test conditions and local field effects.
- 8.3.11 Overall, Denk concluded that the risk of initiating VF was low, but if the electrodes were applied close to the heart, the disturbances of rhythm were possible, particularly in people with pacemakers and persons under the influence of drugs that affect heart rhythm. He regarded the stun guns tested as having "limited effectiveness".

8.4 Histological evidence of injury to skin

8.4.1 Stun guns and other electrical devices have been used for torture. Research has been undertaken pertaining to their effects on skin, assessed histologically, both immediately after exposure and several months later. Karlsmark *et al* [61-62] applied electrical (DC and 50 Hz AC) and thermal energy to the skin of anaesthetised pigs and biopsied the skin up to 65 days after exposure. One of the

late characteristic sequelae of electrically injured skin was the deposition of calcium salts beneath DC electrical cathodes [62]. This effect was also observed with higher levels of AC current [61]. They concluded that collagen calcification is highly indicative of electrical injury (in the absence of a history of skin exposure to calcium salts).

- 8.4.2 Seta [63] applied a stun gun (Nova XR-5000) to the skin of anaesthetised pigs, for between 1 s and 10 s and then immediately sampled the skin for examination by light and electron microscopy. Gross and histological changes were more marked with the longer periods of application. The surface exhibited a white central region surrounded by erythema. The histological examination revealed features consistent with mild electrical shocks and a thermal component.
- 8.4.3 In an investigation on the use of a stun gun in the murder of a young woman (who was also strangled) Ikeda [64] exposed "slightly anaesthetized" pigs to the output of a MRT 502R stun gun. The stun gun was applied before and after death. Applications after death left no marks [64-65]; those applied before death resulted in small defects in the epithelium small and dark-stained or vesicular nuclei of the epithelial cells and hyperaemia of the capillaries in the stratum papillae of the cutis.

8.5 Pacemakers

- 8.5.1 The prevalence of pacemakers in the US adults was 2.6 per 1000 in 1988; within the 18-64 age group, this fell to 0.4 per 1000 persons [66]. Implantation rate in the UK is about 0.42 per 1000 [67].
- 8.5.2 Electric shocks can interact with pacemakers in three possible ways (i) a transient alteration in output, arising from direct interaction with the pacemaker, or its feedback, (ii) if the shock is strong enough, there may be permanent damage to the pacemaker, which can lead to changes in rate and magnitude of output, (iii) current passing down the pacemaker lead to the endocardium may cause damage at the lead/tissue interface (this may then raise the pacing threshold).
- 8.5.3 Murray and Resnick [3] reproduce a letter (dated May 1976) from BH Barkelow, a biomedical and electrical engineer to John Cover, the inventor of Taser technology. Barkelow reviewed the interaction of the Taser pulse with fixed rate and demand pacemakers. He estimated the charge in the pulse as 0.04 mA s; the charge in the Taser pulses measured by PSDB (1,000 Ohm load) ranged from 0.1-0.38 mA s (Annex D). On the basis of "microshock electrocution" experiments in dogs, he would not expect the externally applied Taser output extant at that time to be electrically dangerous. On the premise that pacemakers are built to withstand a cardiac defibrillator, he considered it extremely unlikely that a pacemaker would be damaged by a Taser output.
- 8.5.4 However, with "R-wave synchronous" and "R-wave inhibited demand" pacemakers, designed to counter bradycardia and tachycardia respectively, the Taser pulse could be interpreted as cardiac activity. With regard to the former, Barkelow considered that as a result of a fixed upper rate for pacemaker pulsing, "Hopefully...[this] limit as a fail-safe mechanism will not be dangerous to the patient". With inhibited demand pacemakers, a Taser-induced reduction in pacing frequency could with "anaerobic exercise [*from the Taser*], and at the same time lowering the patient's heart rate to...[its] intrinsic rhythm by inhibiting pacemaker function, be dangerous".

- 8.5.5 Roy [53] and Stratbucker [57] undertook experiments on animals paced with internal and external pacemakers; these experiments are described above in paras. 8.3.4 and 8.3.1 respectively.
- 8.5.6 Moraes [68] studied the effects of two "autodefense devices" (specifications not reported, but presumed to be a form of stun gun) on three explanted and one external pacemaker. All tested pacemakers were severely affected by the "autodefense devices", but with a duration of less than 5 s, the effects were not permanent, and the pacemakers returned to normal operation as soon as the electrical interference ceased. With the explanted pacemakers, the interference was evident up to 12 cm away. Moraes concluded that there was a potential danger to patients with pacemakers, and that users of "autodefense devices" should adhere to the written instructions of a 5 s duration of use.
- 8.5.7 Hendry from the University of Ottawa Heart Institute provided a medical opinion on the Advanced Taser for the Ottawa Police (Tactical Team Operations) [51;69]. He concluded that based on the information supplied to him (not disclosed), that "I cannot see that it should provide any increased risk to patients with either pacemakers or implantable defibrillators". The rationale for this conclusion was not provided; Dstl has acquired Dr Hendry's contact details from the Ottawa Police, but has been unable to contact Dr Hendry.
- 8.5.8 The Tasertron FAQ list [17] states that to satisfy members of the California State Assembly, staff members of the Sutter Memorial Hospital in Sacramento sponsored a test at the Cordis Medical Laboratory in Florida, which apparently validated that the Taser (presumable 5-7 W) would not damage a pacemaker. The FAQ did not discuss if the Taser pulse <u>affected</u> a pacemaker, as opposed to damaging it. Dstl has not been able to acquire a report on the cited test.

9 Reported clinical consequences of operational use

9.1.1 This section describes the clinical effects in patients subjected to Tasers, and summarises the pathology and alleged cardiovascular and metabolic effects in fatalities occurring following Taser use.

9.2 Low power Tasers (5-7 W)

- 9.2.1 Koscove described the Taser as a "new emergency medical problem" [70]. It is difficult to determine from the paper whether he had personal experience of the medical issues associated with the Taser or was speculating. The greatest potential injury identified by Koscove was penetration of the globe of the eye by the dart, although he stated that whether total loss of the eye would occur, either from the mechanical trauma or the passage of the current was not known. He recommended three methods for removing Taser barbs from the skin.
- 9.2.2 In an study (not cited in the references in the paper), in which a single volunteer was subjected to a Taser application for 3 seconds, it was noted that there was a "mild" elevation of blood pressure that lasted approximately 2 minutes, and a "mild" increase in heart rate that lasted 3-4 minutes. No "significant" arrhythmias were noted.
- 9.2.3 The key points from his review in 1985 are that:
 - Although the Taser appeared to be under the VF threshold on the basis of the 60 Hz susceptibility criteria [39] (and employing assumptions on the application of Taser waveforms to these criteria), the effects of the device on individuals with coronary artery disease, conduction disease, pre-existing arrhythmias, use of alcohol or other drugs, were not known.
 - No case of a victim with an implanted pacemaker had been reported up to that date. However, Koscove speculated that: (a) the Taser current could be coupled into the pacemaker and its lead and thereby interact directly with the myocardium (where the VF threshold may be lower); (b) the pacemaker could be inhibited by sensing the Taser energy as normal cardiac activity; (c) the software of the pacemaker could be disrupted.
 - Due to the lack of human clinical data, Koscove recommended that "acute life threatening problems (e.g. potential cardiac injury or arrhythmias) should be assessed, particularly in patients with known cardiac disease". He was ambivalent whether patients should be admitted for cardiac evaluation and monitoring.
 - Falls in persons subjected to Tasers were a potential source of injury.
 - An ECG was advisable.
- 9.2.4 Overall, the review is speculative and presents little evidence of significant clinical problems associated with use.
- 9.2.5 Ordog [13] conducted a prospective case study of all patients brought into the emergency department of the King/Drew Medical Centre in Los Angeles who had been subjected to a Taser; 218 patients over a 5 year period were reviewed. These data were compared to a group of 22 patients shot by police officers using a handgun (0.38 Special) over a concurrent 3 year period.
- 9.2.6 Eight six percent of the patients that had been subjected to Taser had a history of recent (same day) use of PCP; 70% had positive blood levels of PCP and 64% had

signs of PCP intoxication. Thirty eight percent has associated injuries - stab wounds (11 patients) and multiple lacerations.

- 9.2.7 Between one and four darts were present in the patients. The majority were present in the posterior chest (39%), with remarkably few in the anterior chest (4%). Twenty three percent were in the lower limbs. It is notable that darts were also found in the scalp (2%) and face (1%).
- 9.2.8 Three of the patients suffered asystole; there were no cardiac arrhythmias in the remaining patients (although ECGs were only undertaken on 38% of patients). The patients with asystole arrived at the emergency department in that condition. All had high levels of PCP in the blood. One of the patients had a previous cardiac history: sick sinus syndrome with mitral valve prolapse, and a history of arrhythmias. All three suffered cardiac arrest after application of the Taser, two within 5 and 15 minutes, and the third after 25 minutes. The coroner's report stated that death was due to phencyclidine toxicity, with no evidence of myocardial damage, airway obstruction or other pathology.
- 9.2.9 Thirty eight percent of the 218 Taser patients had contusions, lacerations and abrasions (probably pre-existent and associated with bizarre behaviour from the PCP use). One percent exhibited mild rhabdomyolysis and myoglobinuria. One patient developed testicular torsion after use of the Taser and another claimed he was sterile after receiving Taser shocks to the scrotum. Fifteen percent were admitted to hospital for the management of medical condition, predominantly stab wounds; 30% were admitted on "involuntary 72 h psychiatric hold". Only one patient required hospital admission for the effects of the Taser (believed to be the patient with rhabdomyolosis, but this is not clear in the paper). It is notable that 92% of the patients could not recall being subjected to the Taser.
- 9.2.10 The mortality and long-term morbidity of the 218 people subjected to the Taser by police were compared to those of the 22 patients shot with the handgun. Unsurprisingly perhaps, the mortality rates and long-term morbidity rates for people subjected to Taser were significantly lower than in those shot with handguns (mortality 1.4% vs. 50% respectively; morbidity 0% vs. 50%). Twenty five percent of the patients shot with a handgun had evidence of recent use of PCP, alcohol or cocaine.

9.2.11 Ordog concluded that:

- The Taser could not be held "solely responsible" for the three deaths in the group of patients subjected to Taser; he believed the PCP levels to be "toxic" and suggested that a mortality rate of 1% would probably be associated with the degree of intoxication present in the patients.
- Other speculative injuries such as penetration of major blood vessels, ocular injury, interference with cardiac pacemaker, myocardial infarction and cardiac arrhythmias were not observed in the series of 228 patients.
- The lower mortality of the Taser saved the lives of patients who may have otherwise have been shot with handguns.
- 9.2.12 In a comment on Ordog's study, Koscove [71] cautioned that the police model Taser had greater output (approximately 6 mA) than the model available for purchase (in 1985) by members of the public (estimated at 3 mA). The police model had not undergone formal review by an independent agency, such as the US Consumer Product Safety Commission, and the current applied to the victims of the police Taser was not known.

- 9.2.13 A bizarre case of deliberate ingestion of a Taser dart is presented by Koscove [72]. The dart emerged naturally during the patient's fourth day in hospital; he was asymptomatic at the time. Koscove offered guidelines on management for a similar occurrence; there is no evidence in the literature that Taser dart ingestion has occurred subsequently.
- 9.2.14 Notwithstanding the three fatalities described by Ordog, Kornblum's paper in 1991 is the first, and indeed last comprehensive review of fatalities associated with the use of Tasers [73]. Kornblum was the Chief Medical Examiner-Coroner for Los Angeles. In the period 1983-1987, 16 deaths associated with the use of the Taser were recorded in Los Angeles County (the total number of persons attacked with Taser during this period is not presented). All were males within the age range 20-40 years, and were evidently known to use illegal drugs. They were unarmed or armed with weapons of low lethality (screwdriver, frying pan) and all were exhibiting "bizarre and unusual behaviour"; 14 of the 16 Taser victims were not threatening other people. According to Kornblum, this pattern of behaviour was usually considered by police to be consistent with PCP use.
- 9.2.15 The time interval between Taser application and death ranged from 15 minutes to 3 days; 5 deaths occurred at 15 minutes, 3 at 30 minutes and 3 at 45 minutes. Between one and eight Taser dart wounds were present on the bodies; three victims also had gunshot wounds and four had bone fractures. Four patients had "enlarged hearts" and there was one case of degeneration of the mitral valve this patient had a history of mitral valve prolapse, cardiac arrhythmia and syncope.
- 9.2.16 PCP was "found" in eight cases (details not provided), cocaine in six and amphetamines in one. In three cases, drugs were not detected. On the basis of the levels of drugs detected in the bodies (data not provided), Kornblum concluded that the cause of death could be attributed to the drugs in 13 of the 16 cases. One man was shot to death after being subjected to the Taser.
- 9.2.17 Two cases were certified as having been caused by electrical injury:
 - A 35 year old male (Case 3) who died of "cardiac arrhythmia, sick sinus syndrome, prolapse of the mitral valve, and electrical (Taser) stimulation under the influence of PCP". The man died 45 minutes after one Taser cassette (presumably 2 darts) had been used on him. Kornblum states that the multiple application of Taser should not have been a determining factor in this death because electrical current is "not cumulative". As the Taser had little effect on the behaviour of the man (it is implied that the fact that the victim was standing in water was relevant), Kornblum surmises that "this death clearly fits into the cocaine category".
 - A 37 year old male (Case 6) who had been attacked with seven Taser cassettes (8 darts) and died 45 minutes after Taser use; the cause of death was "cardiac arrest due to multiple Taser wounds/acute cocaine intoxication". This victim had an enlarged heart and a history of heart disease (systolic murmur [mitral valve prolapse], cardiac arrhythmia and an episode of syncope). This patient had been advised to have a pacemaker fitted, but refused. PCP was found in blood, bile and liver and the cause of death "could be attributed to PCP", but Korblum considered that the victim's heart could have suffered an arrhythmia from a number of factors: PCP, excitement and/or Taser use.
- 9.2.18 None of the 16 dead showed injuries consistent with a fall (that could have arisen from Taser use), but all showed injuries (abrasions, lacerations) consistent with a struggle with police officers.

- 9.2.19 Although the paper is a relevant account of fatalities associated with Taser use, it is devoid of objective evidence to assign the majority of the deaths to drug abuse a theme taken up by Allen [74], a former Deputy Medical Examiner in Los Angeles. Allen's principal point is that Kornblum had entirely ignored the logical conclusion of his study that certain medical conditions and drug use could increase the risk that the Taser could be lethal. His principal criticisms of Kornblum were:
 - The location of the Taser barbs on the bodies was not reported this would allow a judgement of the current path with respect to the heart. The duration of (AC) current application is an important factor in the risk of VF and the failure to present the duration of Taser applications was an important omission.
 - Kornblum did not present the drug concentrations in the tissues of the bodies; it would have been informative to compare the mean drug concentrations with the supposed overdose deaths associated with Taser use, with a group of patients not associated with Taser use.
 - The interval between Taser use and death reported by Kornblum was not relevant; more pertinent would have been the interval between Taser use and collapse. Kornblum provided no information regarding on-scene events related to any observation of collapse and recovery, observation of asystole or of other cardiac dysrhythmias.
 - Allen was the Deputy Medical Examiner involved in Case 6 (described in 9.2.16). The victim evidently collapsed immediately after the last Taser application and could not be resuscitated by paramedics. Kornblum's description of a 45 minute period between Taser use and death was misleading. Allen stated that "death was immediate and [a] direct result of the Taser".
 - If the deaths that could be reasonably attributed to gunshot wounds, blunt trauma or physical restraint were removed from the 16 reported, there were, in Allen's view, nine individuals in which the Taser was a contributory factor. There was no evidence that any of the individuals recovered from Taser use, and later died of drug effects.
- 9.2.20 Allen concluded that whilst Tasers may be "generally safe" in healthy adults, preexistent heart disease, psychosis and use of drugs, such as PCP, alcohol and cocaine may substantially increase the risk of fatality.
- 9.2.21 Allen alleged that pathologists in Los Angeles were under pressure from law enforcement agencies to exclude the Taser as a cause of death. Dstl has been unable to find in the literature any subsequent refutation of this allegation or a response to the technical criticism of Kornblum's paper.
- 9.2.22 More recently, Fish and Geddes [28] reviewed the Taser medical literature in the light (according to them) of plans by the Metropolitan Police to introduce Tasers. No new information on clinical consequences of use was presented, but they did focus on the metabolic consequences of Taser use *per se* and the metabolic status of agitated or intoxicated individuals on whom the Taser may be used. Specifically, metabolic acidosis arising from physical activity may increase the potential for ventricular dysrythmias (see Section 5), particularly in the presence of phencyclidine (PCP) and cocaine. Although individuals in a quiescent, relaxed state after Taser use and exertion would be expected to compensate the metabolic acidosis quickly, those that remain agitated or are restrained in a way that could compromise normal breathing may remain vulnerable from potentially fatal quantities of ingested drugs. They recommend that the acid-base status of patients

subjected to Taser should be checked if they are agitated or unwell, and steps should be taken to restore the normal status.

- 9.2.23 They concluded that whilst the Taser may be classed as less likely to cause injury or death in individuals (compared to conventional guns) and to provide more effective restraint, research is required on:
 - Cardiac effects arising from Taser use on patients with pacemakers;
 - Injury thresholds (detail and scope not specified);
 - Damage to nerves;
 - Methods of stratifying people at risk of respiratory of cardiac arrest.

Finally, "the mechanisms of injury by Tasers should be compared with those of physical and chemical methods of restraint, so that the safest method can be used for any specific situation". Presumably the primary purpose of this activity would be to identify vulnerable groups for each restraint type, and to inform guidance to users.

- 9.2.24 McNulty (a former Vice-President of Tasertron, but now working as an independent consultant) provided Dstl with a presentation by Dr G. Taylor (an anaesthetist from California and Staff Medical Consultant for Tasertron) [75]. Some pertinent points on medical safety made by Taylor were:
 - Taser subjects are conscious and able to control their airway; there are no effects of the Taser on the body wall or diaphragm. Pain will lead to hyperventilation. Taylor implied that respiratory acidosis (and hypoxia) are unlikely;
 - Taser subjects are not like those suffering "status epilepticus"; they are conscious, ventilating freely and protecting their airways;
 - The electrical parameters are "insufficient to induce seizures" and there have been no reports of Taser-induced convulsions;
 - Tasers are "electrically unsuited both qualitatively and quantitatively" to induce heart rhythm disturbances.
- 9.2.25 **Miscarriage:** An alleged case of miscarriage following application of Taser at 12 weeks of pregnancy was presented by Mehl [76]. The duration of the exposure was reported from various sources present as between 3 and 10 s. One of the darts landed on the abdomen. Mehl concluded that there was a causal link between the exposure to the Taser, and the miscarriage some 7 days later, and rejected the view that the currents did not necessarily pass through the uterus Stratbucker states that, in effect, the foetus is in a Faraday Cage. Dstl's view is that this is not true; the uterus and amniotic fluid will have conductivities similar to muscle and this would not preclude current flow reaching the foetus.
- 9.2.26 Tasertron claim that the Taser was used on two women in the latter stages of pregnancy; neither of the women, nor their foetuses were harmed [19].
- 9.2.27 **Burns:** The passage of current into the body through Taser darts will result in very localised burns. After 4-5 s application, a small blister may form at the negative pole; after about 6-7 s a blister may form at the other electrode. They apparently heal in a week or two without scarring [3].
- 9.2.28 Flammable materials: PSDB reported tests in which they dispensed the contents

of an (inert) CS spray, which contained the solvent MIBK, onto a dummy clothed in a sweatshirt. Upon use of the Taser, the sweatshirt caught fire in two out of seven tests [2]. They concluded that there is a serious risk of ignition if the Taser is fired at a target contaminated with a flammable solvent; they also advise caution about the use of the Taser in flammable environments, such as petrol stations. Tasertron warn about use in flammable environments [21].

9.3 High power (26 W) Tasers

- 9.3.1 The Medical Safety Information for the M26 Advanced Taser from Taser International [51] is a compilation of limited experimental work on animals (reported by Stratbucker Associates⁴) using (curiously) the <u>7 Watt</u> Air Taser 34000 system.
- 9.3.2 The work with the Air Taser was designed to establish a margin of safety for the device, by altering the output and observing the physiological responses in experimental animals (pigs). A single 18 kg pig was anaesthetised with Ketamine/Xylazine exposed to Taser shocks by electrodes on the left hindquarter, anterior abdomen (vertically at the umbilicus) and vertical and transverse orientations at the cardiac apex. By altering the capacitor value in the Air Taser (4 values) and the battery input (9, 18 or 27 volts), the pulse interval was modified and ranged from 44 to 1000 ms. The peak current varied little between the 3 battery voltage groups, but changed with capacitor value and ranged from 8-18 Amps (into a 1000 Ohm load). Pulse width varied from 6-13 μs.
- 9.3.3 Forty-eight discharges lasting 5 seconds were applied to the animal. There was no case of cardiac ectopics or myocardial injury. This was based on ECG; there is no evidence that biochemical markers of myocardial injury were employed, or that the animal was autopsied (the animal was allowed to recover). Respiration was inhibited during some of the applications to the chest, but returned spontaneously. Heart rate and respiratory rate increased and returned to normal. Stratbucker concluded that on the basis of the tests using increased capacitance (4-fold) and battery power (3-fold) on the single animal, that there is an "adequate margin of safely" for the standard (7W) Air Taser 34000.
- 9.3.4 Also included in the Medical Safety Information for the M26 Advanced Taser pack is a preliminary report, in the form of a letter, on five dogs subjected to Air Taser and Advanced Taser; this is discussed in para 0 and following. On the basis of these and other tests, they concluded that that the risk of inducing VF by surface application of the Advanced Taser was very small.
- 9.3.5 In a long catalogue of 2486 voluntary human exposures⁵ (and a small number of operational involuntary exposures) to the Advanced Taser, there were no "injuries" directly from Taser (one person bruised a shoulder during a fall). There was "slight surface irritation of the skin similar to sun burns" (most of the volunteers had the electrodes taped to the skin).
- 9.3.6 In a letter from Dr P Hendry (University of Ottawa Heart Institute) to a Canadian police officer, Hendry declared that based on the medical information provided to him, he would "be favored to use this system, regardless of any cardiac condition, when compared to the alternative or violent way to incapacitate an offender". The

⁴ Dr Stratbucker is the Medical Director at Taser International.

⁵ Presented in a database provided on CD to Dstl by Taser International – this figure is greater than that in the published hardcopy [49].

technical basis of these conclusions was not declared.

- 9.3.7 Three cases of in-custody deaths occurring within a three month period (December 2001 to February 2002) following use of the Advanced Taser led to statements from the manufacturers, Taser International [56;77]. These incidents were:
 - A 27-year-old violent male (vomiting blood) attacked twice with the Advanced Taser in stun mode. He was subdued, but went into cardiac arrest during transport to hospital. According to the coroner, the levels of cocaine in the man's body were "off the scale". The cause of death was declared as a cocaine overdose by the coroner.
 - A 31 year old "drug, crazy" male who was expressing bizarre behaviour and "looked like he was under the influence of PCP". He was attacked several times by the Taser, although the details are not clear. He was subdued by the Taser, but then had difficulty breathing. It is not declared when he died, but it is implied that this was some time after the Taser application. In April 2002, the Medical Examiner's report declared that the Taser did not kill the man [78].
 - A large male stood naked in freezing weather, holding a knife. He was attacked by the Taser, handcuffed and placed in a vehicle for a journey to hospital. Although initially conscious and "ranting", he became unconscious and died on the way to hospital. Cocaine and alcohol were present in his body; the coroner's report had not been released in February 2002.
- 9.3.8 In an energetic defence of the use of the Advanced Taser, Smith concluded that:
 - If a victim has injected toxic levels of drugs, the Taser will not stop the biochemical processes that will ultimately cause the death;
 - If the Taser directly caused death, death would be immediate;
 - If there is a delay between Taser application and death, there is no plausible way that the electrical output of the Taser could be the causal factor;
 - There has never been a death caused by the Taser;
 - Taser is a life-saving technology (compared to conventional methods of defence and restraint); he calculated that Tasers have saved 500 lives.
- 9.3.9 In a further defence of the Advanced Taser implicated in these deaths [56], Stratbucker reviewed Kornblum [73] (but not Allen's critique of Korblum's paper [74]) and stated that Tasers did not cause or contribute to deaths in this series. The Kornblum series of fatalities were attacked with 5-7W Tasers manufactured by Taser International's current competitor, Tasertron. Stratbucker stated, rather truthfully, that: "it would be unrealistic to draw any conclusions concerning the relative safety and efficacy of the Advanced Taser (M26) based upon the outdated, very different weapon system reported in the Journal of Forensic Sciences " [the Kornblum paper] – it is even more curious therefore for the 7W Air Taser experiments to be present in the M26 Medical Safety Information.
- 9.3.10 Bleetman and Steyn [35] from the Birmingham Heartlands Hospital were commissioned to review the Advanced Taser by the manufacturer, Taser International. They reviewed 75 publications on the usage of "electronic restraint devices" and the medical hazards of electricity. They were unable to find any publications in the peer-reviewed literature on the medical effects of the Advanced Taser (and neither has Dstl).
- 9.3.11 They surmised that the current from the Advanced Taser did not penetrate into the internal organs, but stayed near the surface of the body. The biophysical basis of this (probably incorrect) statement was not given. Thus, they believed that the electrical delivery of the Advanced Taser (and therefore its injury potential) was likely to be different from other modes of electrical delivery (not specified).
- 9.3.12 Overall, the review is thorough and objective, but (unsurprisingly) provides little new insight. The dismissal of the risk to pregnant women from the device (presumably instigated by the case of Mehl [76]) was founded on a communication from Stratbucker that the uterus and amniotic fluid represents a Faraday Cage therefore "there cannot be an electric field within them" which thus implies that the foetus is safe. We cannot currently judge whether the foetus is safe or not, but the assertion that it lies within a Faraday Cage is incorrect. The dielectric constants of the uterus, amniotic fluid and foetus will be similar; the foetus will not be absolved from passage of current of some (unknown) magnitude. Bleetman also recounted his personal experience of a 0.5 –1 s application of the Advanced Taser. He suffered no chest pain or palpitations, did not lose consciousness, but was unable to move. He did not desire another application of the Taser.
- 9.3.13 They concluded that on the basis of the literature pertaining to 5-7 W Tasers:
 - There was little accurate information on the coupling of energy to the internal organs; the reported confinement of the Advanced Taser current to the skin needed to be proven.
 - It would be very difficult to determine absolute safety for this type of weapon, and there was conflicting information of VF, cardiac standstill and the vulnerability of pacemakers.
 - Elderly subjects and those with pre-existing heart disease are "perhaps" at an increased risk of cardiac complications and death.
 - There was not enough information of the risk to those with implantable defibrillators or pacemakers; they then stated that the risk is probably quite small.
 - The deaths described in the literature could not be conclusively linked directly to the use of the [low power] Taser.
 - More work was required to record the effects of the Taser on physiological variables and ECG (but they saw little benefit in testing on animals).
 - The Taser (output not specified) was most unlikely to cause permanent physical problems in healthy individuals; use of the Taser had a lower injury potential than unarmed defensive tactics, baton strikes and the use of police dogs.

There is some ambiguity in the conclusions in whether they consider them applicable to the high power Advanced Tasers, or Tasers in general.

- 9.3.14 A former Vice-President of Tasertron (now working as an independent consultant, JF McNulty) stated in a letter to Dstl [26] that "there is a point were a badly debilitated person might die from stress related causes" following use of high-power Tasers, but "might live if the lower power Taser had been used".
- 9.3.15 **Therapeutic use:** A patient found without a pulse and apnoeic by police officers was apparently resuscitated by the application to two stun guns held across the chest [79]. Whether the patient had a serious arrhythmia was not known (a cardiac monitor was not available prior to the application of the stun guns) and so it cannot

be stated that the devices had a direct effect on the heart; the pain of the application could have improved the respiratory endeavours of the patient.

9.4 Fixed electrodes (stun guns)

9.4.1 Stun guns have been used for the abuse of children. Frechette [80] reported a case and commented that given the subtlety of physical signs, cases may be underrecognised. Most lesions were hypopigmented macules; others were erythematous and raised. A number of types of abuse (such as cigarette burns) or non-abusive clinical causes may cause multiple circular lesions on children. Lesions from stun guns were characterised by being in pairs, separated by 5 cm.

10 Conclusions

- 10.1.1 The majority of the safety-related experimental work on Tasers and the clinical experience arising from operational use is with the "low-power" 5-7 W devices. It is appropriate therefore to partition the conclusions to address "low" and "high" (18/26 W) power devices separately. ACPO's request was that DOMILL should produce a "generic" statement, presumably applicable to all forms of Taser. Plainly, the fact that most of the evidence upon which a judgement can be made on hazards and risks originates from 5-7 W Tasers necessitates caution when forming judgements on the modern 18/26 W devices.
- 10.1.2 Caution is also required regarding the wattage designation. It should not be used uncritically to categorise output peak current and charge transfer are more appropriate and there is disconcerting evidence from the measured outputs that the wattage designation belies the actual output (Annex D).

10.2 General points

- 10.2.1 **Modelling current distribution:** There have been no objective scientific studies (or even ad-hoc studies) to determine the magnitude and distribution in the body (animal or human) of electric currents from Tasers. This knowledge is fundamental to an understanding of the potential interaction of Taser currents with excitable tissues such as the heart. Dstl's modelling has revealed valuable, novel information, but must be regarded at this stage as indicative only. Plainly, additional simulations could be undertaken - these were constrained by time - and the model could be developed further to enhance the confidence in the output.
- 10.2.2 **Mechanism of desired effect:** The explanations in the manufacturers' literature on the physiological mechanisms of the action of Tasers are speculative. Dstl's review is also speculative, and suggests that from a neurophysiological perspective, the most likely explanation appears to be disruption of neuromuscular control by stimulation of motor axons in peripheral nerves. This may also be accompanied by disruption of proprioceptive inputs from muscle spindles⁶, leading to disturbances in posture and balance.
- 10.2.3 **Pacemakers:** The available published evidence for the potential interaction of EIDs with pacemakers and other implanted electrical equipment is contradictory and frequently based on clinical opinion, not experimental evidence. In the limited time imposed for this review, Dstl has been unable to consult with the manufacturers and regulatory bodies on electromagnetic compatibility issues of modern implanted devices. The incidence of pacemaker use is low, particularly in the adult age group below 60 years of age (probably about 0.4/1000) but it is important that the potential for damage or disturbance be clarified.

10.3 Application of Taser outputs to electrical standards

10.3.1 The manufacturers assess the cardiac safety of the Taser pulses by using a US Standard derived for electric stock fences. The VF criteria published in the Standard are not identical to those promulgated by the manufacturers, even though the Standard is cited. There are differences in the position of the line plotted curves relating current, pulse duration and the cardiac injury threshold (presumed VF threshold), and in the inflexion in the curve. The reasons for these dissimilarities are not known. The manufacturers have also extrapolated the Standard's criterion to the

⁶ Feedback sensors that control posture.

very short pulse durations of the Taser output, without justification.

10.3.2 Notwithstanding these differences, the Taser pulses cannot be applied unquestioningly to the Standard. If expressed in terms of RMS current and duration for a single pulse, the output of the Advanced Taser is below the manufacturers' VF criterion and the Standard's. However, if the pulse repetition frequency is accounted for over a one second period, the Taser output would be above the Standard's criterion. Depending on the approach used to assess the Taser output, it is possible to demonstrate that, according to the electric fence Standard, the M26 is "safe" or "dangerous".

10.4 Arrhythmias - low-power Tasers

- 10.4.1 **Experimental work:** The experimental work undertaken on animals addressing the interaction of Tasers with the heart is poor in terms of statistical design specifically, the number of animals used. It is not rigorous work. The reports do not contain sufficient information to enable an authoritative review of the quality of the work to be undertaken. The work has not been published in peer-reviewed biomedical journals; there is no evidence that it has been subjected to peer-scrutiny.
- 10.4.2 **Operational use and use on volunteers:** There have been a large number of operational uses of low-power Tasers at least 50,000 are claimed. There have been deaths associated with use of the Taser. One published paper discussed 16 deaths that occurred over a 4 year period in Los Angeles. There were other factors such as pre-existing heart disease and drug use that could have been implicated in the deaths.
- 10.4.3 On the available evidence, it is considered extremely unlikely that death caused directly and exclusively by the electrical output of a low-power Taser has occurred.

10.5 Arrhythmias - high-power Tasers

- 10.5.1 **Experimental work:** The experimental work on the arrhythmic potential of the Advanced Taser is minimal, being confined to report in the form of a letter on experiments undertaken on a small number of dogs and experiments on one pig. These data have not been published in peer-reviewed journals. The data are not an adequate basis alone for an opinion on whether the electric output of high-power Tasers carries a risk of a serious arrhythmia such as ventricular fibrillation.
- 10.5.2 **Operational use and use on volunteers:** High-power Tasers are a relatively modern innovation. One manufacturer calculated that about 10,000 volunteers may have been exposed to the Advanced Taser (about 2500 recorded) with no reported serious injuries. Their company database records about 1600 operational uses; it is difficult to judge the incidence of adverse effects from the data. In the period from Dec 2001-Feb 2002 there were three notified deaths associated with use of the Advanced Taser; two were subsequently attributed to other causes, the third has not been resolved at the time of drafting this report.
- 10.5.3 The epidemiological evidence for safety of the Advanced Taser is certainly not as robust as that for the low-power devices. With the lack of substantial historical data of use and inadequate experimental evidence, the high-power Tasers cannot be classed in the vernacular as safe. A precautionary approach is necessary regarding decisions on deployment and operational use. Many agencies in the US (and others world-wide) have recently purchased and deployed the Advanced Taser; experience of use in the field will accrue over the coming months and years. Dstl is also aware

that experimental work on pigs is planned in the US on behalf of a law-enforcement agency⁷. It would be prudent to await the outcome of the experimental work and the consequences of field use, and re-assess the arrhythmic potential of the high-power Tasers subsequently.

10.6 Hyper-susceptibility of the heart

- 10.6.1 It is thought that certain substances and metabolic conditions such as acidosis (which may be attributed to excessive muscular activity and/or the effects of drugs) may increase the susceptibility of the heart to arrhythmias. "Recreational" drugs such as cocaine and "ecstasy" may be pro-arrhythmic. Pre-existing heart disease may also lower arrhythmic thresholds. Many of the 16 fatalities associated with use of the low-power Taser had also taken PCP (phencyclidine) prior to the incident PCP is also thought to be pro-arrhythmic. Although in only two of the sixteen deaths was the Taser formally recorded as one of the factors responsible for the deaths⁸, it is possible that the Taser contributed to the death of the individuals who had taken drugs thought to be pro-arrhythmic, or had pre-existing heart disease.
- 10.6.2 There is no experimental evidence that the aforementioned pro-arrhythmic factors increase the susceptibility of the heart to Tasers sufficient to cause an arrhythmic event. Nevertheless, there is sufficient indication from the forensic data and the known electrophysiological characteristics of the myocardium (and the effects of certain drugs on this) to express caution regarding use of Tasers on excitable, intoxicated individuals. Further review is required, and guidance to Taser users should reflect likely increased susceptibility to serious cardiac effects in these individuals. Experimental investigations to clarify hazards could also be undertaken (below).

10.7 Associated trauma

10.7.1 There are few reported injuries associated with Taser use. Even falls seem to be controlled and the risk of head injury or long-bone fracture will be low. Ocular trauma is a serious hazard with a low risk and should be controlled with guidance to users. The burns at the current injection points are localised and evidently heal without complication.

10.8 Aftercare

10.8.1 There is a general consensus in the manufacturers' guidance and in the literature that personnel subjected to Tasers should be taken to hospital and receive a medical examination. Plainly, cardiac investigation is foremost. The barbs should be removed from the skin under medical supervision. One clinical paper recommends correction of acid-base status [28].

⁷ Dstl has received a copy of the research proposal submitted by the contractor to the agency, but has not been asked to comment on it. Dstl does not endorse it.

⁸ There is disagreement on this matter – see Allen [71] and Kornblum [70].

11 Technical approaches to clarify risks

- 11.1.1 The requirement for experimental work and/or modelling to clarify both the risks from use of Tasers (in particular the high-power Tasers), and the optimisation of effectiveness balanced with safety is an issue for DOMILL and Ministers. The key areas requiring clarification are:
 - improved modelling of Taser current distribution in the body;
 - cardiac effects arising from Taser use, in particular hyper-susceptibility;
 - the vulnerability of pacemakers and other implanted devices.

11.2 Modelling of energy distribution in the body

- 11.2.1 Dstl and MOD developed the computer model employed in this review for RF/microwave safety studies. MOD has invested substantial sums in this model, and the NIO and ACPO have benefited from this investment. Use of the RF safety model for Tasers required novel and technically demanding modifications; these were constrained by time and available resources. Nevertheless, the simple model was able to predict the consequences of changes in the characteristics of the Taser/stun application. Because of the geometric simplicity of the model and constraints in software design, the absolute values of magnetic field strength (current index) are undoubtedly incorrect. Of course, the model could be used in its present form to perform additional simulations, such as stun gun application over the thorax, but for quantitative information to compare with published data on cardiac susceptibility to currents, or to inform *in vitro* studies (outlined below), it would require enhancement. For example:
 - The frequency-dependent properties of human tissue would need to be implemented in the model to improve accuracy (some of these data is already being acquired by Dstl for other customers);
 - Greater anatomical accuracy should be implemented;
 - The resolution of the model should be improved; this would require the use of more powerful computer resources and longer run times.

11.3 Cardiac effects and hyper-susceptibility

- 11.3.1 The approach undertaken in safety studies addressing the effects of non-ionising radiation (such as that generated by mobile phones and novel transmitters) is initially to predict the field strength within the body at specific potentially vulnerable organs (for example, the brain). *In vitro* studies may then be undertaken isolated tissues may be exposed to the predicted field strengths to determine the specific effects on the tissue. Pharmacological manipulations may then be undertaken on the tissue to determine whether the effects may be modulated, or to understand the mechanism of the interaction. A similar approach could be used to study the interaction of the Taser output with cardiac tissue.
- 11.3.2 The computer model discussed above would be used to define the fields in the body. *In vitro* studies may then be used to determine the effects of the pulses on excitable tissues (nerve, muscle, heart and brain). *In vivo* studies would present considerable ethical and other difficulties, but the need for these could be reduced or even replaced by carefully designed *in vitro* experiments.
- 11.3.3 Clearly, the most important site of action for the potentially adverse effects of Tasers is the heart. Two standard *in vitro* preparations could be used to investigate these effects. The primary aims would be to determine the effects of currents

induced by Tasers (as derived from modelling) on normal hearts and in the presence of drugs of abuse, such as PCP, cocaine, amphetamine, ketamine and MDMA ("ecstasy"), as well as the associated acidosis.

- The isolated Langendorff-perfused heart would allow measurement of the effects on the physiology of the intact heart, and particularly on the electrocardiogram (ECG). Drugs can be perfused through the heart, but the disadvantage of this preparation would be that it is not possible to know the precise equilibrium drug concentration in the tissue.
- Knowledge of the pro-arrhythmic effects of drugs has advanced exponentially over the last 5 years, driven by the pharmaceutical regulatory authorities. The preparation of choice for regulatory studies is the isolated Purkinje fibre preparation from sheep, dogs or rabbits, one advantage being that the equilibrium drug concentration in the tissue is known. In this preparation, a decrease in the upstroke of the cardiac action potential is indicative of sodium channel block, corresponding to conduction problems, whereas lengthening of the cardiac action potential is predictive of QT interval prolongation and development of the malignant ventricular arrhythmia, *torsade de pointes*.

11.4 Pacemakers and other implanted devices

11.4.1 Plainly, commercial devices could be exposed to Taser outputs in materials representing tissues. Dstl's view is that such an experimental approach is currently not warranted. It is desirable however that a more detailed and diverse review of the electromagnetic compatibility issues of Tasers and implanted devices be undertaken.

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13	Glossary	
ACPO CNS		Association of Chief Police Officers Central Nervous System
DOMILL		DSAC sub-committee on Medical Implications of Less Lethal Weapons
DSAC		Defence Scientific Advisory Council
DTIC		Defense Technical Information Centre
EID		Electrical Incapacitation Device
EMD		Electro-muscular disruption
FDTD		Finite difference time domain
IEC 479		International Electrotechnical Commission
LL		Less-lethal
MDMA		methylenedioxymethamphetamine
NIO		Northern Ireland Office
PAT		Patten Action Team
PBR		Plastic Baton Round
PSDB		Police Scientific Development Branch
PSNI		Police Service of Northern Ireland
p.r.f.		Pulse repetition frequency
RMS		Root mean square
Taser		Thomas A Swift's Electric Rifle
TLM		Transmission line matrix
TEP		Transcutaneous external pacemakers
UL		Underwriters' Laboratory
VF		Ventricular fibrillation

A Annex A: An overview of Taser technology

A.1.1 This Annex is an extract from the PSDB report published in June 2001 on Taser technology [81].

A.2 Introduction

- A.2.1.1 Taser devices operate in the following way: A cartridge is attached to the front end of the weapon, which contains two barbs (the electrodes) each of which is attached to a coiled length of wire. The barbs are fired and attach themselves to the skin or clothing of the targeted individual. When the barbs strike a person, a current can be sent down the wires and through the person's body between the two barb points.
- A.2.1.2 John Cover built the first Taser prototype in 1970. The name Taser was chosen as an acronym for "Thomas A Swift's Electrical Rifle", after the Tom Swift fantasy stories. At this time, North American law enforcement agencies did not show much interest in the device and it was sold mainly to the civilian market. In 1976, some American police departments began successfully using the Taser, which led to further interest by other police departments, and a healthy growth curve within the American law enforcement community has existed ever since. Today, hundreds of police departments in the United States use Taser technology. Canadian police forces first began using Tasers in December 1998, and an increase in use and sales has also followed there.
- A.2.1.3 There are currently two major suppliers of Taser devices to American police forces: Taser International and Tasertron. In many respects, the devices made by each of these manufacturers are very similar as they are essentially designed to do the same thing, however there are some differences that set the two apart. The products available from each company are described below.

A.3 Taser International

- A.3.1.1 Taser International, formerly known as Air Taser, was formed in 1993. Although initially geared towards the civilian market, the company are now heavily promoting their products within the North American law enforcement community following the expiration of Tasertron's exclusive patent right in 1998.
- A.3.1.2 Taser International produces two series of Tasers: the 34000-Series and the M-Series.
 - Air Taser 34000-Series (see Figure 27 (a)): These models are not shaped like firearms. They are 7W systems (pulse energy = 0.44J) and weigh 8-9 ounces (227-255g). These models are single shot and have a detachable single laser sight. They have an automatic 30-second timing cycle that is activated once the darts have been deployed, although this can be turned off at any time by the person controlling the unit.
 - Advanced Taser M-Series (see Figure 27 (b)): This series comprises the M18 model and the M26 model. Both models are shaped like conventional handguns, have single laser sights built in and weigh 18 ounces (510g). The M18 model has a power output of 18W and a pulse energy of 1.76J. The M26 model has a power output of 26W although pulse energy is also reported to be 1.76J. Both models are single shot and have an automatic 5-second timing cycle that is activated once the darts have been deployed, although this can be turned off at any time by the person controlling the unit. This model can be used as a 'touch stun' device when the cartridge is removed. More than 750

North American and Canadian police forces are now believed to be using the M26.

A.3.1.3 All Taser International cartridges use compressed nitrogen as the propellant.



Figure 27; (a) The Air-Taser 34000 series; (b) The Advanced Taser M series

A.4 Tasertron

- A.4.1.1 Tasertron was formed in 1986 and does not sell any of its products to the civilian market. Up until 1998, Tasertron was the only company, under legal agreement, that was allowed to sell Taser technology devices to law enforcement agencies in North America. This legal agreement has since expired and other companies are now allowed to sell their Taser products to this market.
- A.4.1.2 Tasertron currently offers four models of Taser: the TE93, TE86, TE95 and 95HP (See Figure 28).
 - **Models TE86/95:** These models are both two-shot, 5-7W systems weighing 22 ounces (623g). Both models are 9inches (229mm) long and 2 x 3 inches (51 x 76mm) at the firing bay. The only difference between the two models is that the TE95 comes with a mount available to allow the optional dual laser sight to be fitted, while for the TE86 this mount has to be retrofitted. Both devices can use the optional 'Probe Pak' (see below).
 - **Model TE93** (also called the "Taser Partner"): This device is a single shot, 5-7W system weighing 14 ounces (397g). The device is 9inches (229mm) long, 1.5 inches (38mm) at the firing bay and has an optional single or double dot laser sight available. This model has a touch stun capability using the two additional terminals at the top of the unit. The unit also comes with a safety wrist strap that automatically disables the device should a suspect attempt to forcibly disarm the user.
 - **Model 95HP:** The only difference between the TE95 and the 95HP is that the latter is a higher-powered version. This device is a two-shot, 26W-system (pulse energy = 1.6J) weighing 22 ounces (623g). The device is 9 inches (229mm) long, 2 x 3 inches (51 x 76mm) at the firing bay and has an optional dual laser sight available. The optional 'Probe Pak' (see below) can also be used with this model.



Figure 28; Tasertron Models of Taser, a) Model TE86, b) Model TE93, c) Model TE95/95HP

- A.4.1.3 The 'Probe Pak' is an optional accessory offered by Tasertron. It consists of a pair of telescoping antenna-like probes measuring 36" (0.91m), which allow the device to deliver its electrical charge when contact is made with the target and the ends of the probes. These probes are contained within a cartridge that can be fitted in the normal manner in place of a dart cartridge. All Tasertron cartridges use a rifle primer as the propellant.
- A.4.1.4 Because of the exclusive patent held by Tasertron up to 1998, the TE86 and TE95 models have been the most widely used by American law enforcement, with reportedly greater than 50,000 deployments by police and correctional agencies to date.

A.5 Taser International Vs Tasertron

- A.5.1.1 In many respects, Tasertron and Taser International Tasers are very similar and both are intended to perform the same job. With both companies' models, a cartridge is fitted to a hand-held battery operated unit. When fired, it propels a pair of barbed darts attached to two trailing wires at the subject. Once contact is made, it begins discharging a metered and pulsed current through the subject's body resulting in involuntary muscle spasms and severe loss of motor control.
- A.5.1.2 Rival companies often mirror changes that are made to a product. This has been the case with Tasers as both companies now offer both 15ft (4.6m) and 21ft (6.4m) cartridges, whereas previously only 15ft (4.6m) cartridges were available. Both companies also now provide the new higher powered 26W Tasers (with a reported pulse energy of 1.4-1.8 Joules) as well as the older 5-7W systems (note: Taser International also supplies an 18W system).
- A.5.1.3 There are, however, a number of differences between the two companies' products that may affect the users' decision as to which one is most suitable. Tasertron and Taser International products differ in the following ways:
 - Tasertron provide both single and two-shot models while all Taser International models are currently single shot only;
 - Tasertron do not produce any models that resemble a handgun while Taser International provide both models that do and that don't resemble lethal firearms;
 - Tasertron offers both single and dual laser sights that are available on both single and two-shot models the dual laser sights are intended to provide a better judgement of distance and dart angulation by showing where both barbs will land. Taser International currently offers only single laser sights that are intended to show where the top barb will land on the target;

- Taser International has a data port located on the back of the M26. This can be plugged into a computer, with the appropriate software, and downloaded to give information on how often the Taser had been used and the time duration of every activation;
- Tasertron offers a 'Probe Pak' for use on some of their models this provides a touch stun capability at distances of up to 3ft (0.91m);
- Taser International models provide a continuous five or thirty-second burst of electricity when the trigger is pulled, although the user can stop this at any time by flicking the safety switch. Tasertron models, on the other hand, require the firer to keep their finger on the trigger for the entire time that the electricity is to flow (note: there has been a suggestion that Tasertron are considering adding a 7 second timing cycle to their Tasers);
- Tasertron cartridges use a rifle primer as the propellant while Taser International cartridges use compressed nitrogen;
- Tasertron cartridges have a twelve-degree angle of separation between the barbs while the value for Taser International is 8 degrees. This means that, at a given distance, Tasertron barbs will have separated further than their counterparts by Taser International;
- Tasertron cartridges can apparently be loaded upside down and jammed in the Taser unit making it inoperable. This is not a problem for Taser International cartridges as they cannot be loaded upside down;
- When fired, Taser International cartridges will release a large number of small, confetti-like pieces of paper with the serial number of that particular cartridge printed on them. This helps provide evidence of the use of a particular cartridge at a scene. This feature is not currently available with Tasertron cartridges.
- A.5.1.4 In 1999, Sgt. Darren Laur of the Victoria Police Department, Canada, published an 'Independent Evaluation Report of Taser and Air Taser Conducted Energy Weapons'. This report is an unbiased assessment and comparison of the Tasertron and Taser International models of Taser available at that time; it discusses the strengths and weaknesses of each of the models. Many of the important points of the Laur report have been summarised in this document, however a full copy of the report can be found at: http://www.airtaser.com/laur/report.html It is worth noting, however, that although only two years old, this report is already out of date as a number of additions have been made to both companies' list of products since its publication.

B Annex B: An overview of action potentials in nerves and muscle

B.1.1 The electrophysiology of excitable nerve and skeletal muscle cells is summarised in this Annex.

B.2 Resting potential

B.2.1.1 If an intracellular electrode is inserted into a nerve or muscle cell, it is found that the inside of the cell is electrically negative, relative to the outside, by some tens of millivolts. This resting potential arises because of differences in the concentration of ions across the cell membrane, rather like a battery, which results in polarisation of the membrane. For example, in frog muscle cells, the extracellular and (intracellular) ion concentrations in millimolar are sodium 109 (10.4), potassium 2.25 (124) and chloride 77.5 (1.5). These differences are maintained by a combination of active ion pumps and electrochemical gradients.

B.3 Action potential

B.3.1.1 Resting nerve and muscle cells are relatively permeable to potassium ions, hence the resting membrane potential is quite close to the potassium equilibrium potential. When a positive current is applied across the membrane, or the extracellular side is made more negative, the membrane becomes depolarised. If this depolarisation reaches a threshold level, it will trigger an active response of the membrane called the *action potential* (Figure 29).



Figure 29; An intracellular action potential

- B.3.1.2 This is an all-or-none impulse which is propagated along the membrane. It is initiated by the opening of sodium channels, triggered by the depolarisation of the membrane, hence the membrane potential changes rapidly towards the sodium equilibrium potential, which is electrically positive relative to the outside. After about 1 ms, the sodium channels inactivate and voltage dependent potassium channels are activated by the increased depolarisation; this results in the repolarisation of the membrane back towards the potassium equilibrium (Figure 29).
- B.3.1.3 For a short time after the action potential, it is not possible to elicit a second action potential, no matter how strong the stimulus. This is known as the *absolute refractory period*. Following the absolute refractory period, there is a period when it is possible to elicit a second action potential, but the threshold stimulus intensity is higher than usual. During this *relative refractory period*, the second action potential may be reduced in amplitude. The refractoriness limits the upper frequency at

which axons can conduct nerve impulses; *in vivo*, this rarely exceeds 500 per second and is more typically in the range 10-100 per second [34].

B.3.1.4 The threshold for generation of an action potential changes if the cell is hyperpolarised or depolarised. If a constant subthreshold depolarising current is passed into the cell, the threshold slowly rises during the passage of current and then falls again after its cessation. Conversely, when hyperpolarising current is used, the threshold falls. This delayed dependence of the threshold on membrane potential is known as accommodation. One consequence of accommodation is that the threshold current intensity is lower for rapidly rising currents, cf. slowly rising ones. When the rate of rise of current is sufficiently low, the change in membrane potential is too slow to be able to overtake the change in threshold level, and therefore no excitation occurs.

B.3.2 Strength-duration relationship

B.3.2.1 If a nerve axon is stimulated with square constant current pulses, it is found that the threshold stimulation intensity rises as the pulse is shortened. This effect is called the strength-duration relationship (Figure 30). In this Figure, rheobase is the minimum stimulus strength that will produce a response, shown as the asymptote (1). When the stimulus strength is set to $2 \times$ rheobase (2), the minimum stimulus duration that yields a response is the chronaxie (3).



Figure 30; Strength-duration curve for nerve stimulation.

B.3.2.2 The curve is described by the empirical equation

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where I is the intensity of the pulse, t is the length of the pulse, I_0 is the threshold stimulus intensity, when t is large (the *rheobase*), and k is a constant. The pulse length when the threshold stimulus intensity is twice the rheobase is called the *chronaxie*.

B.3.2.3 Equation (1) is similar to that describing the change of voltage across a circuit consisting of a resistance and capacitance in parallel, following the application of a constant current, i.e.

$$V = IR(1 - e^{-t/RC}) \tag{2}$$

where V is the voltage, I the current, R the resistance and C the capacitance. If V is constant, for example if V is regarded as the threshold membrane depolarization, this becomes

$$I \times k = \frac{1}{1 - e^{-t/RC}} \tag{3}$$

which is equivalent to (1); however, this equation involves a number of simplifications. Firstly, the voltage across a passive membrane cannot be described by (2); more complicated relations including both the time constant and space constant must be applied. Secondly, strong currents of short duration produce depolarisations which fall off rapidly with distance from the stimulating electrode, whereas the depolarisations produced by weaker currents of longer duration are more diffuse. Since propagation of an impulse is dependent on local circuits of sufficient intensity, the size of the active region is important, hence the threshold membrane depolarization is higher when smaller areas of membrane are depolarized, and therefore it is higher for brief current pulses than for longer ones. Finally, the existence of local responses complicates the relationship.

B.4 Latency

B.4.1.1 The time between the onset of a stimulus and the peak of the action potential is called the *latency* of the response. This decreases with increasing current strength.

B.5 Compound Action Potential

- B.5.1.1 If a nerve is stimulated at one end and recorded extracellularly at the other, a *compound action potential* can be observed. The size of this potential is proportional to the size of the stimulus over a certain range. This is because the potential is the result of simultaneous action potentials in a large number of axons (each of which itself obeys the all-or-nothing law), which have different thresholds.
- B.5.1.2 If there is sufficient separation between stimulating and recording electrodes, the compound action potential is seen to consist of a number of waves. This is because the nerve contains fibres of different diameters and hence conduction velocities, larger calibre fibres having faster conduction velocities. Erlanger [82] classified vertebrate nerve fibres according to their conduction velocities into three groups, A, B and C, with A being subdivided into α , β , γ and δ (Table 6). C fibres are the unmyelinated axons, i.e. those lacking an insulating fatty myelin sheath produced by Schwann cells. Myelinated A fibres are distinguished from unmyelinated C fibres by faster conduction rates, shorter action potential durations and lower electrical thresholds.

Fibre type	Function	Fibre Diameter (µm)	Conduction Velocity (m/s)	Spike Duration (ms)	Absolute Refractory Period (ms)
Αα	Proprioception, somatic motor	12-20	70-120	0.4-0.5	0.4-1.0
β	Touch, pressure	5-12	30-70	0.4-0.5	0.4-1.0
γ	Motor to muscle spindles	3-6	15-30	0.4-0.5	0.4-1.0
δ	Pain, cold, touch	2-5	12-30	0.4-0.5	0.4-1.0
В	Preganglionic autonomic	<3	3-15	1.2	1.2
C Dorsal root	Pain, temperature, some mechanoreception, reflex responses	0.4-1.2	0.5-2	2	2
Sympathetic	Postganglionic sympathetics	0.3-1.3	0.7-2.3	2	2

Supplement to HOSDB Evaluations of Taser Devices

Table 6; Fibre types in mammalian nerves

B.5.1.3 An alternative classification, by [83], has been widely used for sensory nerve fibres in mammalian muscle nerves, with groups I to IV according to their fibre diameter (Table 7).

Group	Diam eter (µm)	Conductionv elocity (m/s)	Sensory endings
Ia	12-20	72-120	Primary endings on muscle spindles
Ib	12-20	72-120	Golgi tendon organs
п	4-12	24-27	Secondary endings on muscle spindles
III	1-4	6-24	Pressure/pain receptors
IV	Non-myelinated fibres		Pain

 Table 7: The relation between function and diameter in the afferent (sensory) fibres of mammalian muscle nerves.

B.5.1.4 Differences in the strength-duration characteristics determine the sensitivity of nerve and muscle fibres to electrical stimulation. Each calibre of nerve fibre has its own characteristic strength-duration curve (Table 8). For example, large calibre myelinated motor nerve fibres (which stimulate muscle contraction) have lower thresholds than small calibre and unmyelinated pain fibres. Fibres innervating proprioceptors (which are involved in postural feedback control) are intermediate between these.

Fibre diameter (µm)	Threshold (V/m)		
5	24.6		
10	12.3		
20	6.2		

Table 8; Theoretical stimulus threshold for uniform field excitation of a terminated myelinatednerve fibre (monophasic stimulus). Listed thresholds are minimum (rheobase)values for long duration pulsed fields ($t \ge 2ms$). From [84].

B.5.1.5 Motor nerve axons also have lower thresholds than muscle fibres (Figure 2) which allows selective field stimulation of the presynaptic elements in nerve-muscle preparations.

B.6 Synapses

B.6.1.1 Nerve impulses are transmitted between cells across specialised junctions called synapses. An action potential in the presynaptic cell causes the release of a chemical neurotransmitter, which diffuses across the synaptic gap between the cells and binds to specific receptors on the postsynaptic membrane. This opens (or in some cases closes) ion channels that alter the membrane potential, resulting in excitation or inhibition of the postsynaptic cell. The chemical nature of synaptic transmission allows integration (temporal and spatial) and amplification of presynaptic inputs onto a cell. These properties can make synapses in the retina results in a threshold electric field for phosphenes, which is approximately 100 times lower than the rheobase threshold for nerve excitation [85].

C Annex C: Ventricular fibrillation

- C.1.1.1 Ventricular fibrillation is an uncoordinated asynchronous contraction of the ventricular muscle fibres of the heart, in contrast to their normal co-ordinated and rhythmic contraction [86]. The heart seems to quiver rather than to beat. Once a person goes into ventricular fibrillation, their blood circulation ceases, they become unconscious in less than 10 s and can have irreversible brain damage in 4-6 minutes, unless corrective action, such as cardiopulmonary resuscitation is taken. The only way to terminate ventricular fibrillation is to use a defibrillator to reestablish the synchronised beating of the heart muscle.
- C.1.1.2 Ventricular fibrillation can be caused by an electric shock, where the path of current travels through the chest, for instance between two arms or between an arm and a leg. Jaffe [87] quoted a series of papers by Prevost and Battelli from 1899 and 1900, showing that severing of the vagus nerves did not influence the occurrence of cardiac fibrillation. The fibrillation apparently results from a direct action of the current on the muscle fibres or ganglion cells of the heart.
- C.1.1.3 Ferris et al. [52] explored electrically-induced ventricular fibrillation in sheep, using 60 Hz AC shocks of varying duration passed between electrodes on the right foreleg and the left hindleg. They drew a number of conclusions, including the following:
 - Current rather than voltage is the correct criterion of shock intensity, and this current can cause ventricular fibrillation.
 - A current just below the threshold for ventricular fibrillation is the maximum to which humans may be subjected safely. Based upon numerous tests on animals of several species comparable in size to humans, this maximum current is about 0.1 A for a duration of 1 s or more and a pathway between an arm and a leg.
 - The threshold fibrillating current is affected by:
 - Species and size of animal;
 - Current pathway currents between the two arms give a lower threshold than currents between an arm and a leg;
 - Frequency of the current;
 - Relation to cardiac cycle the cardiac T wave is the most vulnerable period (Figure 31);
 - Duration of shock within the sensitive phase of the cardiac cycle, the threshold ventricular fibrillation current for durations of about 0.1 s or less is 10 or more times that for durations of 1 s or more.
 - Successive shocks have no cumulative effect on the susceptibility of the heart to ventricular fibrillation.
 - The susceptibility of the heart to ventricular fibrillation by short shocks increases with current up to several times the threshold, then diminishes, becoming very small at currents of around 25 A.
 - VF caused by short shocks will, in most cases, be arrested by a subsequent electric shock of high intensity and short duration, allowing resumption of beating with no permanent damage.
- C.1.1.4 Atrial or ventricular fibrillation can be induced by electrical stimulation coinciding with late atrial or ventricular systole (relaxation of the cardiac muscle); this is the so-called vulnerable period [85]. During this period, the heart muscle is recovering its excitability following the refractory period. This does not occur in a uniform

manner, and the non-uniformity in the ventricles is maximal preceding the T wave of the ECG. Propagation of an electrically induced wavefront can therefore be initiated in certain directions, thus leading to multiple re-entry, the electrophysiological basis of ventricular fibrillation (Figure 31).



Figure 31; Mechanism of VF associated with the vulnerable period

- C.1.1.5 The upper part of the figure shows the normal ECG curve. The triangle-shaped figures below the ECG symbolise the branched network of the conducting system of the myocardium. Absolute refractory zones of the excitation wave are represented in black, relative refractory zones are hatched. In the vulnerable period, the conduction pathway is still partially refractory, so the wave of excitation generated by electrical stimulation can propagate in only one direction and generate re-entry. The ventricles would be non-excitable if stimulated earlier; at a later time, re-entry is no longer possible because of the normal spread of excitation.
- C.1.1.6 The Taser International website (www.taser.com) shows a graph of body current (mA RMS) versus pulse duration. This uses "internationally recognized safety guidelines for electrical currents" to define a "safe area" which is considered "safe electrical exposure for 2 year old child or a 75 year old man". The manufacturer's claim that the Advanced Taser's output is less than 1/100th of a potentially dangerous level. The danger levels shown on this graph are taken from the Underwriters' Laboratory standard for electric fence controllers and from the IEC 479 threshold for safety.
- C.1.1.7 The data from the Underwriter's Laboratory appear very similar to Figure 8 in Reilly [88], which shows the current threshold for ventricular fibrillation at different durations of a 60Hz stimulus. In this graph, the peak current is shown in normalised units, presumably to account for species differences. These criteria are discussed in detail in Section 0.
- C.1.1.8 A recent review of the safety of stun guns [31] discussed data from the International Electrotechnical Commission, which has "assigned values for the thresholds of

perception, pain and VF for single unidirectional impulses of duration 0.1 to 10ms". Figure 13 in this review shows a graph of the duration of impulse versus the body current threshold for ventricular fibrillation, for a current pathway from left hand to feet. The authors conclude that the primary hazard from a stun gun output is related to the peak current of each impulse, but suggest that "it is not known whether a succession of impulses would increase the risk of ventricular fibrillation" [52].

C.1.1.9 One further concern is that the heart can fibrillate at extremely small current levels if the current is applied directly to the heart; current as low as 0.1 mA can cause the heart to fibrillate under these circumstances [89]. This sensitivity to current is extremely important if a person is catheterised or has a pacemaker with external connections.

D Annex D: Taser outputs

- D.1.1.1 This annex presents a summary of the measured output of Tasertron and Taser International devices. From the measured data, the charge transfer has been calculated (Table 9).
- D.1.1.2 Peak current and voltage values were taken from PSDB measurements provided to Dstl. Only measurements into a 1,000 Ohm load are presented.
- D.1.1.3 Pulse lengths were determined from the damped sinusoidal waveforms produced by PSDB. The length of a pulse was been taken as the time taken for the voltage output to return to the pre-function value any signal noise on a flat signal background has been ignored.
- D.1.1.4 Pulse repetition rates are those supplied by PSDB. Only one p.r.f. value was given for each Taser type, and this is the one used. It is more likely that the measured p.r.f values have a spread rather than being consistently single-valued, and use of this data would enable a more detailed statistical analysis to be carried out.
- D.1.1.5 The charge delivered by a single pulse is the product of the peak current and the pulse length. It is expressed in mA s. The charge delivered by a 1 s pulse train is the single pulse charge multiplied by the p.r.f.; it is also expressed in mA s.

Model	Peak	Peak voltage (kV)	Pulse length	PRF	Single pulse	1s pulse train
	current		(µs)	(Hz)	(charge)	(charge)
	(A)				(mA s)	(mA s)
TE93	6.26	6.35	21.7	10.8	0.136	1.47
TE95	7.12	7.22	15.1	20.8	0.108	2.24
TE86	7.46	7.56	15.4	24	0.115	2.75
TE95HP	8.7	8.83	19.8	16.4	0.172	2.83
34000*	9.86	9.99	34	9.2	0.335	3.08
M18L	12.2	12.37	31.4	24.2	0.382	9.26
M26	9	9.13	30.7	38.2	0.276	10.5

* Air Taser

Table 9; Measured output of Tasers

- D.1.1.6 The supposed high power devices are the TE95HP, M18L and M26, but it is evident from Table 9 that the output characterised in terms of charge transfer for a single pulse (mA s) is low for the TE95HP, compared to the output of the M18L and M26. In contrast, the 7 W Air Taser 34000 has a similar output in a single pulse to the 18-26 W M-series devices. It is plain that the classification of Tasers simply in terms of the wattage designations does not necessarily describe the output.
- D.1.1.7 Tasers may have a wide range of p.r.f., dependent on battery power and other factors. The nominal value for the low power Tasers is 15 Hz; 8-22 Hz is "acceptable" [3].

E Annex E: Guidance to users from manufacturers

E.1.1 This Annex presents excerpts from the guidance to users promulgated by Taser International (for the Air Taser) and Tasertron.

E.2 Taser International – the Air Taser

- E.2.1.1 The following information has been extracted from the Air Taser Users' Manual on their web-site (www.taser.com), and is preceded by "Warning : Read This Before Using".
 - Never point the Air Taser[®] at another person unless in self-defence. The Air Taser performs best from 7-10 ft.
 - Never aim the Air Taser at the eyes or face.
 - Do not fire the Air Taser near flammable liquids and fumes. The Air Taser can ignite gasoline or other flammables. Some self-defence sprays are flammable and would be extremely dangerous to use in conjunction with Air Taser.
 - The Air Taser causes temporary paralysis. This paralysis can be dangerous and even fatal under specific circumstances. For example, someone tasered in a swimming pool would probably drown as they could not swim or support themselves. Due to potential dangers, only use the Air Taser when absolutely necessary to protect your life.
- E.2.1.2 The points extracted above are limited to those with health implications; further points in the Warning cover safety, handling and transport of the device.
- E.2.1.3 Using the Air Taser: The manual recommends the following mode of use:
 - Arm the device by sliding back the Safety Slide.
 - Just like pointing a flashlight, aim directly at the centre of the chest of an attacker. This is the easiest and most effective place to hit.



- Press down the Trigger Switch to fire the probes.
- If the attacker is on the ground and there are no other attackers, place the Air Taser gently on the ground and leave the area as quickly as possible. Law enforcement: disarm and restrain suspect while Air Taser is active. The Air Taser will continue to stun the attacker for a full 30 seconds (it will then take him anywhere from 1 to 30 minutes to fully recover). In self-defence situations, we [Taser International] recommend you leave the area and let the unit do its work.
- If the attacker is not down or there are multiple attackers (or you are attacked from behind), hold the unit firmly and prepare to use it as a stun gun. If for

some reason the attacker is not down (perhaps the probes missed), you may need to use the stun gun feature to defend yourself. Even with the Air Cartridge in place, the Air Taser will continue to function as a stun gun.

• To use the stun gun after firing an Air Cartridge, press down the Trigger Switch to ensure the unit is active, then press the front of the Air Taser firmly against the body of an assailant. The Air Taser works as a stun gun with or without the Air Cartridge in place. Even with the Air Cartridge in place, the metal prongs on the front of the Air Taser will deliver T-Waves directly to the body of the target. Shown below are the most effective places to use the stun gun. In the video, you are instructed to aim for the upper leg, because it may be the easiest place to reach if you are grabbed from behind.



• If the attacker is in front of you, you should attempt to press the Air Taser right into the centre of his chest, or into the nerves under his chin. Note: If the attacker is touching you, the T-Waves will not transmit to you from the attacker. The T-Waves directly travel between the two probes.

E.3 Tasertron

- E.3.1.1 The following information has been extracted from Tasertron's "Taser Device Operation and Instruction Manual" [21]. Chapter 1 : "Manufacturer's Product Notice" states :
- E.3.1.2 No method of restraining an individual is harmless. Obviously, the discharge of a firearm is not. Even when you use supposed less-lethal force, when you grapple a person to the ground, strike them with a baton or take them down with a net, you risk serious traumatic injury and even death to the individual, yourself and bystanders. Injuries from secondary sources alone, such as a fall or heart attack from physical exertion or fright could cause death. Similarly, neither the Tasertron device, nor any other Taser device is harmless.
- E.3.1.3 Similar to other methods of human restraint such as batons, manual restraint, chemical agents, nets and leg grabbers, which also depend upon kinetic force to achieve their desired result, the use of a Taser device could result in trauma to a suspect, operator and/or bystander from uncontrolled falls and secondary injury.
- E.3.1.4 The Tasertron device's electrical current also presents peculiar hazards, which may not be encountered with other restraint methods. These though unlikely, include the following : (i) seizures and convulsions, which can result in additional injury, (ii) vision obstructing cataract formation in eyes (should a dart hit the eye), (iii) interference with or damage to pacemakers and other biomedical aids.

- E.3.1.5 For the TE86, TE93 and TE95 models the manual notes, under the heading "Trigger Switch", that the operator controls the amount of pulsed energy received by the subject. The trigger switch should be held down the minimum time necessary to gain control of the subject.
- E.3.1.6 Deployment : When tactically feasible the Taser should be deployed at the subject's back or, if not possible, the torso area, thereby reducing the risk of a facial or eyeshot. Whenever possible, the Taser should be deployed at the subject's back in order to maximize the target area because the subject's clothing is tighter fitting in the back. When facing the subject, try to gain the subject's compliance by using the laser sighting, together with a verbal warning, as a force presence.
- E.3.1.7 Whenever deploying the Taser, the operator should adhere to the following guidelines:
 - Assume a shooting position.
 - Use the weak hand to deploy the Taser, if alone and armed.
 - Point the Taser at the subject's back or torso.
 - Aim the dual laser sight at the subject's torso (subject may surrender).
 - Issue verbal warnings, if feasible.
 - Disengage the safety switch.
 - Place the shooting finger on the trigger switch.
 - Hold the trigger down until you gain control of the subject, but do not hold it any longer than absolutely necessary (usually between 1 and 10 seconds, depending on the model of the Taser employed and the physiology of the subject).
 - If the Taser is ineffective discharge the back-up cartridge (TE86, TE95 and 95HP).
 - Immediately issue verbal directions to cuffing team and engage the safety switch.
 - If the subject resumes threat reactivate the Taser, if on line.
 - Have several contingency plans and adequate back up ready.
 - Immediately control and stabilise the subject.
- E.3.1.8 The following safety procedures should be conducted as soon as the subject is incapacitated :
 - Establish control quickly and stabilise.
 - Utilise proper restraining equipment.
 - Do not position the subject face down.
 - Turn the subject onto his/her side or into a sitting position to promote free breathing.
 - Immediately render first aid, if necessary.
 - Transport the subject to a medical facility, if necessary.
 - Monitor procedure (never leave the subject unattended).
 - Follow the agency's guidelines when removing the darts from the subject's body.
 - Do not remove a dart from a subject's eye, immediately transport the subject to a physician or surgeon.

• Inform emergency medical technicians and doctors that a Taser device was used.

E.4 Stun Guns

- E.4.1.1 The NOVA Spirit User's Manual, summarised in "A Guide to Taser Technology" [3], details the most effective application points for the use of a stun gun. "As your first choice, touch the muscle that joins the sides of the neck to the shoulders, second choice below the rib-cage and third the upper hip. Try to avoid using the NOVA on the head of an assailant".
- E.4.1.2 Information provided by Stun Tech notes that the head and neck should be avoided; however, the rear base of the neck is designated (by Stun Tech) a primary strike zone. Although it is effective, "it is not prudent and Stun Tech recommends users to avoid this site".

F Annex F: Computational electromagnetic modelling technical approach

F.1 Introduction

F.1.1.1 The modelling work discussed within this report was undertaken attempt to determine the paths taken by an electric current from different Taser devices, and to investigate the currents flowing near and through the heart. The approach taken was to develop a simple representation of the human body, and then consider the distribution of electrical currents, for a range of input points. The model used a computational electromagnetic modelling code to predict the paths and magnitudes of currents flowing in the body.

F.2 Computational Electromagnetic Modelling (CEM)

- F.2.1.1 Analysis and experiment have solved many problems in electromagnetics. The increasing cost of experiments and the increasing complexity of problems to be solved by analysis, combined with the reducing cost of powerful computers, has resulted in computer based numerical modelling techniques becoming increasingly popular in providing solutions.
- F.2.1.2 Computer modelling techniques are divided into two main areas, analytical and numerical. Analytical techniques can be a useful tool when the important EM interactions of the configuration can be anticipated and are generally applicable only in simplified geometries. However, most problems in electromagnetics, particularly when considering modelling the interaction with biological organism, are too complex for analytical solutions to provide meaningful results.
- F.2.1.3 Numerical techniques attempt to solve fundamental field equations directly, subject to the boundary constraints posed by the geometry. A number of different numerical techniques for solving electromagnetic problems are available. Each numerical technique is well-suited for the analysis of a particular type of problem.
- F.2.1.4 The numerical techniques considered for the estimation of Taser currents in the body are space-grid time-domain solutions of Maxwell's equations (which predict electromagnetic phenomena). Firstly, they specify a volume in space were the problem is defined and boundary conditions established. Next the problem space is "discretised" into small volumes or cells, normally cuboids.
- F.2.1.5 The discretisation process is normally called gridding or meshing. Each cell can then have electromagnetic parameters for the material assigned to it such as conductance, permittivity and permeability. A simulated voltage source (e.g. a sinusoid) is then applied at one of the sub-cubes, then the resulting electromagnetic field can be calculated, as it propagates through the mesh, at a series of time-steps. Time-stepping is continued until the desired late-time pulse response is observed at the field points of interest.

F.3 Transmission line matrix (TLM) Method

F.3.1.1 The Transmission Line Matrix (TLM) method is a Finite Difference Time Domain (FDTD) method and belongs to the general class of differential timedomain numerical modelling methods TLM analysis is performed in the time domain and the entire region of the analysis is meshed. However, rather than interleaving E-field and H-field grids like FDTD, a single grid is used and the nodes of this grid are interconnected by virtual transmission lines (Figure 32).

F.3.1.2 Many engineers find the transmission line analogies of the TLM method to be more intuitive and easier to work with. This is because it is easier to visualise the electromagnetic signal propagating through the workspace through materials whose properties are determined in the node by transmission lines rather than the FDTD approach of calculating the fields at each cell using Maxwell's equations.



Figure 32; TLM symmetrical condensed node

- F.3.1.3 As the TLM method uses cubes to model curved surfaces the object being modelled must be "staircased". That is, curved surfaces are approximated by layers of cubes and the surface can take on the appearance of being made up of staircases. For configurations with sharp, acute edges, an adequately staircased approximation necessitates a very small grid size as the fineness of the mesh is generally determined by the dimensions of the smallest features that need to be modelled. This also applies to large objects requiring detailed modelling such as human beings. The volume of the grid must be great enough to encompass the entire object and most of the electromagnetic nearfield.
- F.3.1.4 The problem of having a fine grid with a large volume is the most testing one for computational electromagnetics as this can significantly increase the computational size of the problem and hence cost.
- F.3.1.5 The TLM method has been used to provide solutions for the interaction of electromagnetic radiation with large, complex, inhomogeneous, and irregularly shaped objects in three dimensions, with millimetre range spatial resolution. In particular in bioelectromagnetics for the calculation of whole and partial body exposures to a variety of sources including transient fields such as those of an electromagnetic pulse (EMP).

F.4 Modelling Issues

F.4.1.1 All Taser modelling was completed with the aid of Micro-Stripes, a computational electromagnetics package. Micro-Stripes can give plots of the spatial and phase variation of each of the three components of the electric field strength (E) (units: Vm⁻¹) and the magnetic field strength (H) (units: Am⁻¹), and also their vector magnitudes. Furthermore, Micro-Stripes can give three-dimensional plots of E, H, the Specific Absorption Rate (SAR) (the metric of

electromagnetic field dose in units of Wkg⁻¹), the power density (units: Wm⁻²), and the energy density (units: Jm⁻³). It is the three-dimensional plots that are potentially the most informative, yet are the most computer memory intensive.

F.4.1.2 The approximate dimensions of human organs were taken from Agur [90]; the model included muscle, fat, skin, heart, lungs, brain and the skull. The electrical properties of the various tissue types incorporated within the model were taken from Gabriel [91]. The electrical properties, for all the tissue types, were taken at a frequency of 50 kHz, except for bone where information below 1MHz was unavailable, and so for bone 1MHz data was selected. 50kHz is the dominant frequency of a M26 Taser pulse. However, it must be noted that the dominant frequency of a TE93 Taser pulse is 75kHz, and since the electrical properties were chosen at 50kHz, this is another potential source of error. This will be rectified in any future development of the model – the model will implement a frequency dependant dielectric model for tissue. However, this was not available at the time of the work being undertaken.

F.5 Taser waveforms

- F.5.1.1 At present, Micro-Stripes has no option that allows a user-defined waveform to be input, such as a real Taser pulse obtained from an oscilloscope. Instead, the input waveform is fixed to an approximation of an Dirac delta impulse in the time domain; this approximation has a duration of ≈10ns, and a peak of ≈1GV. Micro-Stripes has the utility to convolve (effectively multiply in the frequency domain) the time domain output with one of four possible functions, namely, the double exponential, the Gaussian, the sinusoidal or a pulse-train (square waves).
- F.5.1.2 Details of the waveform of the Advanced M26 Taser may be found in Kirkbride [33], whereas details of the TE93 Taser were supplied on a CD-ROM from PSDB. Both of the Taser waveforms appear to be approximately a damped sine wave (Figure 32). A computer program was written at Dstl in MATLAB to determine the spectral components of these Taser waveforms.



Figure 32; M26 (left) and TE93 (right) outputs in the time domain

F.6 Data visualisation

F.6.1.1 Micro-Stripes simulation runtime increases with the fourth power of the mesh size; therefore doubling the mesh size would increase the runtime by a factor of sixteen. Thus, the runtime can be potentially enormous. Hence, for these longer runs, it will almost certainly be necessary to run the computer over several days. Furthermore, these long runs will generate massive output files, which could create visualisation problems. Data generated were spatial outputs of electric and magnetic field strength in the body. Maxwell's corkscrew rule allows the electric current paths to be inferred visually from the three-dimensional plots of the magnetic flux lines. Plots were also generated showing the time variations of the magnetic field strengths of both the M26 and TE93 Taser's at specific points in the body.

F.7 Modelling limitations

- F.7.1.1 For this work a very coarse mesh was chosen. This was to reduce the computer runtime to a value that would permit several runs to be made within the project timescales. Despite the coarseness of the mesh, each run took approximately five hours to complete. However, the coarseness of the mesh meant that the discretisation was also very coarse, and so the output perhaps should be regarded as indication only. Nevertheless, despite the underlying coarseness, some conclusions can be made.
- F.7.1.2 The electrical input to the model simulated by Micro-Stripes is an approximation to the impulse function. However, convolving the impulse function with an appropriate function gives an exponential fall-off function. Convolution may be regarded as multiplication in the frequency domain. The parameters for the double exponential function were determined by comparing the waveform of a Taser impulse with a theoretical waveform. However, the M26 and TE93 Taser waveforms are approximately exponentially damped sine waves. The exponent and the principal frequency of this waveform were determined by spectral analysis. These calculated parameters were then input to the Micro-Stripes convolution function.

F.8 Discretised model

F.8.1.1 Figure 33 shows the discrete nature of the model. On the torso, the fat may be seen through the skin. Whereas on the head, both the brain and the skull are visible through the skin. This distortion is a consequence of setting the mesh too coarsely. A finer mesh would resolve this problem, but unfortunately would dramatically increase the runtime. The Taser electrodes are shown as blue cylinders on the chest.



Figure 33; Discrete nature of the model

F.8.1.2 Figure 34 shows a transverse section at the height of the upper Taser electrode and identifies the sites in the lungs, heart, spine area and contact loci that were used to provide estimates of magnetic field strengths. The upper section of the body is removed to make the output points visible. The centre of the heart was 100 mm from the skin surface; the spinal region was designated as 40 mm below the skin of the back.



Figure 34; Sites used to predict field strengths; lungs and heart are visible

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Appendix B – "An update on the review of the medical implications of use of Electrical Incapacitation Devices"

DSTL/PUB20750 30 September 2002

Background

- 1. The Northern Ireland Office (NIO) and Home Office (HO) require an independent opinion on the medical implications of the use of electrical incapacitation devices (EIDs) in self-defence and restraint scenarios, and as alternatives to firearms. The DSAC sub-committee on the Medical Implications of Less Lethal Weapons (DOMILL) was requested to provide this opinion. On behalf of DOMILL, Dstl undertook a review of published information from a wide range of sources on the reported incidence worldwide of injuries associated with the use of EIDs, specifically Tasers and stun guns. DOMILL endorsed Dstl's report and in April 2002, Dstl published its report as Issue 1.0⁹.
- 2. The Official member of DOMILL advised the Steering Group coordinating the NIO and HO requirements that DOMILL would write a formal independent medical statement for the Secretary of State for Northern Ireland (and other Government Ministers) when the Association of Chief Police Officers (ACPO) had formulated policy and Guidance to Users for any proposed operational trial of a Taser. The development of the ACPO document awaited the outcome of a technical assessment and police handing trials of the various Taser systems by the Police Scientific Development Branch (PSDB). The PSDB report has now been published¹⁰ (and can be made available to DOMILL). Consequently, ACPO have now published notes on guidance for police use of the M26 Advanced Taser in a proposed operational trial of the device¹¹. ACPO now intend to approach the Home Secretary to seek approval for the trial. DOMILL have now been formally requested to provide a statement for Ministers.

Aim

3. The aim of this report is to provide DOMILL with information that has been acquired since the publication of the Iss 1.0 report in Apr 2002. This information will be used in conjunction with the April report and the ACPO Guidance to draft a medical statement. The report will also be re-issued by end-Oct 2002 to include the new information, and to incorporate the editorial changes to Iss 1.0 required by DOMILL.

⁹ Cooper GJ et al (2002). The medical implications of the use of electrical incapacitation devices (Tasers). Dstl/CBS/BTP/DOC/594/1.0. UK RESTRICTED.

¹⁰ Donnelly T et al (2002). PSDB Evaluation of Taser Devices. Report 9/02. RESTRICTED-COMMERCIAL.

¹¹ Pre-circulated 25 Sep 02. The M26 Taser. Operational trials involving firearms officers in selected forces. Notes for guidance on police use. ACPO ref. 4th Sep 2002 CSB3. Dstl ref: DSTL/CBS/BTP/PAT-ACPO/MAN/COM/3 dated 23 Sep 02.

Benefits of Taser use

4. DOMILL's focus should address the risk of injury associated with use of Taser technology. However, it is important to note that surveys of Taser use by US and Canadian police have demonstrated a reduction in injuries to police officers when compared to the frequency sustained from conventional self-defence and restraint approaches. Additionally, use of Tasers has provided officers with a less-lethal alternative to the use of handguns and other lethal weapons, thereby reducing the use of lethal weapons against violent or threatening suspects. Tasers have risks; bullets have much greater risks.

Other published reviews

- 5. Bozeman (a physician and educator in Emergency Medicine at the University of Florida) provided Dstl with a draft copy of his review on the medical risks associated with the M26 [1]. The review is brief and objective, but (not surprisingly) provides no new information. He makes two recommendations for further work:
 - Metabolic changes arising from Taser use that may exacerbate the risk of fatal outcome: acidosis and potassium release;
 - Initiation of a national database to track all uses of Taser and medical complications.
- 6. The Joint Non-lethal Weapons Human Effects Center of Excellence (JNLW HECOE) published a review in May 2002 of the human effects (safety and effectiveness) of Taser low and high power [2]. Dstl acquired this document through US/UK Defence exchange agreements. It is a thorough review, and includes Taser outputs measured to support a study (funded by the National Institute of Justice) being undertaken on pigs to determine Taser *effectiveness*. The report makes a number of recommendations. The notable ones from a clinical perspective are:
 - The effects of drugs on Taser effectiveness and morbidity/mortality;
 - The effects of stress hormones on the Taser effect;
 - There should be a formal Risk Characterization using models and frameworks developed by JNLW HECOE.
- 7. Dstl will maintain formal MOD/DOD links with JNLW HECOE and seek to exchange documents and technical work.

Deaths

- 8. Deaths have been associated with Taser use. The April 2002 document described the reported cases and stated that with the Tasers used historically (the "low-power" Tasers), there was no evidence that a death had been directly associated with Taser use drug intoxication was the principal cause of death in the cases reported in the literature. Dstl recommended caution in extrapolating this experience with the low-power Tasers to the modern "high-power" Tasers such as the M26 (used in North America for about 2 years).
- 9. The April report described three deaths associated with M26 use:
- A 27-year-old violent male (vomiting blood) attacked twice with the M26 Advanced Taser in stun mode. He was subdued, but went into cardiac arrest during transport to hospital. According to the coroner, the levels of cocaine in the man's body were "off the scale". The cause of death was declared as a cocaine overdose by the coroner.
- A 31 year old "drug crazy" male who was expressing bizarre behaviour and "looked like he was under the influence of PCP". He was attacked several times by the Taser, although the details are not clear. He was subdued by the Taser, but then had difficulty breathing. It is not declared when he died, but it is implied that this was some time after the Taser application. In April 2002, the Medical Examiner's report declared that the Taser did not kill the man.
- A large male stood naked in freezing weather, holding a knife. He was subjected to the Taser, handcuffed and placed in a vehicle for a journey to hospital. Although initially conscious and "ranting", he became unconscious and died on the way to hospital. Cocaine and alcohol were present in his body; the coroner's report had not been released in February 2002.
- 10. With regard to the last case, a subsequent Associated Press report of the Medical Examiner's investigation stated that the victim (Mr. Spencer) died of a drug overdose, and the Taser did not contribute to his death [3].
- 11. There have been additional Taser-associated deaths reported in the press since the April 2002 report. Dstl is aware of three:
 - A 36 year old man (Mr. Baralla) died as police tried to arrest him in May 2002; he had suffered a heart attack [4]. There was evidence on the man's body that a Taser had been used (type not specified). The reported official cause of death was "sudden death occurring with agitation during necessitated restraint". The report states that the Taser had no bearing on the man's death.
 - An 18 year old man (Mr. Burkett) died of "acute exhaustive mania" [5]. He was shot with a Taser in the morning and in the afternoon of his death, and went into respiratory arrest during a struggle with jail staff. He was described as violent and mentally unstable.
 - A Florida man (Mr. Canady) died at the scene after being subdued with a Taser (type not specified) [6]. The newspaper report states that the Medical Examiner declared that the cause of death was cocaine use and coronary disease.
- 12. **Drug use in UK:** The frequently-quoted retrospective review by Kornblum ([7] stated that 8 of the 16 persons who had died after being subjected to (low-power) Tasers had consumed PCP (phencyclidine); six had taken cocaine. In Ordog's prospective case study of 218 patients who had been subjected to Taser, 86% had a recent (same day) use of PCP; 70% had positive blood levels.
- 13. Dstl requested that PSDB to advise on use of PCP and other "recreational" drugs in UK. PCP is very uncommon in the UK. There have been no submissions of phencyclidine to forensic agencies over the last two years. The following are most frequently used:
 - Cocaine Powder/Crack Cocaine;
 - Heroin (and substitutes i.e. methadone);

- Ecstasy¹² MDMA is the most common component, but tablets have also been found to contain amphetamine/methylamphetamine, ketamine, 2-CB and ephedrine. Tablets containing MDEA and MDA are still seized, but are comparatively rare.
- Methylamphetamine/Amphetamine a greater focus on Amphetamine since availability of Methylamphetamine is judged to be limited in Europe.

Case report

14. A pregnant women was subjected to a Taser and had a stillbirth four days later [8]. An autopsy failed to link the death of the 6 month old foetus to the electric shock.

Operational use – Taser International database

15. Taser International provided a database of operational use of the M26 Taser. The database was dated 14 May 02 and was on Ver 8.0 of their promotional and information disc (file date 11 Aug 02). The reports - numbered 1 to 1704 - were reviewed by a military surgeon attached to Dstl. There was a total of 1645 separate reports of deployments and the field use reports; analysis provided by Taser International stated a success rate of 94.59%. Table 10 shows the compiled information provided by Taser International.

Suspect Injury Level	Number of Incidents
None	1443
Minor	176
Moderate	19
Severe	7
Total	1645

Table 10; M26 associated injury frequency reported by Taser International

- 16. In 800 incidents in which the duration of the Taser application was reported, 55% were for 5 s (i.e. one full programmed cycle for the M26), and 35% had more than one cycle. The remainder were for <5 s (i.e. the officers must have terminated the cycle prematurely).
- 17. Each report in the document was inspected for:
 - a. the suspect injury level indicated (none, minor, moderate and severe); and
 - b. the **injuries described** box, for more detail on the nature of the injury.
- 18. In all reports where the injury level was described as minor or above, the details of the incident, as described by the officer in his contemporaneous notes, was

¹² MDMA is the abbreviation for the chemical name of Ecstasy (3,4-<u>m</u>ethylene<u>d</u>ioxy<u>m</u>ethyl<u>a</u>mphetamine). MDEA

⁽methylenedioxyethylamphetamine) is an analogue of MDMA with similar properties. Pharmacological effects are thought to be due primarily to release of 5-HT in the brain. MDA = methylenedioxyamphetamine. 2-CB is a synthetic substance with the proper name 2,5-dimethoxy-4-bromophenylethylamine. The chemical structure of 2-CB shows similarities to the hallucinogenic drug mescaline. 2-CB is a hallucinogenic substance. 2-CB may be consumed in combination with MDMA. It is usually taken when effects of the latter wear off. Ketamine is an anaesthetic (close analogue to PCP) that produces hallucinations and disorientation - effects may be partly related to block of the ion channel linked to the NMDA (N-methyl-D-aspartate) receptor. Ephedrine is a nasal decongestant which, by virtue of its ability to release noradrenaline, has similar (but weaker) effects to amphetamine.

scrutinised for relevance. Furthermore, reports where the **suspect injury level** was described as none, but that contained details in the **injuries described** box, were also noted. The total number of relevant reports reviewed is shown in Table 11.

Suspect Injury Level	Number of Reports
Minor	173/176
Moderate	19/19
Severe	7/7
Total	199/202

Table 11; Injury reports scrutinised by Dstl

Suspect injury level: SEVERE

- 19. All seven reports detailing severe injury to the suspect were identified. The relevant reports were numbers 190, 223, 274, 606, 858, 1594 and 1595. Reports 1594 and 1595 were identical (duplicates) and so there were only six severe suspect injuries. The injuries described were:
 - Canine and bean-bag (x9) injuries (no. 190);
 - Self mutilation (223);
 - Injuries from the struggle, swarm tactics, baton hits and PPCT (?) deployment (274);
 - Self-inflicted knife wound (606);
 - Gunshot wound from initial confrontation with police (858);
 - Self-inflicted knife wound (1594 & 1595).
 - None of these injuries occurred directly due to the application of the M26 Taser in any modality.

Suspect injury level: MODERATE

- 20. All 19 reports detailing moderate injury to the suspect were identified. The relevant report numbers were: 149, 167, 273, 278, 373, 464, 571, 589, 637, 660, 718, 748, 829, 946, 1255, 1260, 1261, 1660, 1703. Of the above, only two moderate injuries were related to the use of the M26 Taser in any of its modalities. These were:
 - Fall following Taser use with dart deployment leading to a chin laceration requiring stitches;
 - Fall following Taser use with dart deployment leading to a face laceration.
- 21. The other 17 reports comprised injuries sustained prior to the use of the M26 Taser, such as RTA or bar brawl injuries, self-inflicted injuries and some sustained in confrontations with police officers using other methods, such as the straight bat, PR-24 (?), baton rounds and one case of the use of the M26 Taser as a blunt instrument after a failure. There was one unspecified injury in this group, but the M26 Taser had only been deployed in its laser mode in that instance.

Suspect injury level: MINOR

- 22. All 176 reports of minor injuries to suspects were identified. One report was excluded as it was a duplicate of the preceding report, and two reports were deemed irrelevant as they detailed minor injury to an animal, against which the M26 Taser was deployed. The remaining 173 minor injuries could be classified into the following six groups:
 - a. **Falls** following Taser use (usually dart deployment) causing minor injuries, usually described as abrasions, scratches, minor lacerations or cuts, road rash, bumps, swellings and areas of redness.
 - b. **Puncture wounds, burns and marks**. Dart deployment necessarily causes puncture wounds and this fact was occasionally, dutifully documented. More serious puncture wounds were usually caused by uncontrolled, forcible extraction of the dart by the suspect. The use of the M26 Taser in stun gun mode left some burn marks. Other reports just describe skin marks following use of the M26 Taser in any of its modalities.
 - c. **Other conditions**. These were not injuries, but rather one case of chest pain, another of chest pain and difficulty in breathing, and another of numbness to an arm. There were no sequelae or any further details of these cases reported.
 - d. Unspecified injuries.
 - e. **No injury**. This was usually documented because the suspect underwent a routine medical examination after M26 Taser deployment and no injury was then reported by the examiner.
 - f. **Unrelated injuries**. Injuries unrelated to the use of the M26 Taser in any of its modalities.
- 23. This incidence of these MINOR injuries is shown in Table 12.

Injury Category	Number of Injuries	Percentage of MINOR
Falls	23	13
	35	
Puncture wounds		
Burns	9	
Marks	8 (Total 52)	
		Total 30
Other conditions	3	2
Unspecified	13	8
No injury	4	2
Unrelated injuries	78	45

Table 12; Categorisation of MINOR injuries

- 24. There were about 10 reports in which no suspect injury was indicated in the **suspect injury level** box, but the **injuries described** box detailed minor injuries from falls following deployment of the M26 Taser.
- 25. In other reports that stated that there was no suspect injury, the **injuries described** box was annotated with the presence of puncture wounds from the darts or burn marks from the stun gun application in approximately 100 cases. In a further 50 cases

(approximate), injuries unrelated to the use of the M26 Taser were described in this box. There were approximately 30 descriptions of the use of the M26 Taser against animals, mainly dogs, but also several bulls.

Conclusions on the Taser International operational database

- 26. Of the 199 relevant suspect injuries detailed in 1645 uses of the M26 Taser (an injury rate of 12.1%), only 93 injuries (5.7% of the total deployments) could be considered to be caused by M26 use, and subsequent to its use. These consisted of falls as a result of subject incapacitation by the M26 Taser (25, two of which caused moderate injuries), puncture wounds, burns and marks (52, all minor), unspecified minor injuries (13), and others (3). If the puncture wounds, burns and marks total are excluded, as they are expected and unavoidable (52), a total of 41 injuries remain from 1645 deployments of the M26 Taser (an injury rate of 2.5%), the majority from injuries sustained from falls (25). The only moderate injuries were lacerations from falls (2) and there were no serious injuries related to the use of the M26 Taser. There were no deaths reported in this series.
- 27. Risk analysis: In situations where no specific adverse effects have occurred within a sample of known size, it is possible to make inferences regarding the maximum longrun risk. There were 1645 operational reports of the M26 Taser; in 957 of these incidents, darts were fired at the subject (about 30 of these subjects were animals). There were no cases of death, and no cases of severe injury <u>directly</u> attributable to the current flow in the body. Thus, according to Hanley and Lippmann-Hand¹³, we can be 95% confident that the chance of each of these events actually occurring in humans in the long term is, <u>at most</u>, 3 in 927 (i.e. 1 in 309).

Operational use – police forces

- 28. Edmonton Police Service, Canada: A table of 37 uses of M26 Taser during 2001 has been made available to Dstl. Medical information is sparse, but there is a column addressing "Subject Injury". Of the 37 uses, 20 involved deployment of the barbs, and 14 subjects had "minor" injuries. It is not clear whether the data includes incidental injuries not related to Taser use. The Taser was used in stun mode in 10 incidents; five injuries were reported, all classed as "minor".
- 29. Los Angeles Police Department: A Powerpoint presentation made available to Dstl reviews the case for the deployment of the M26 in Los Angeles, supplanting the low power Tasers previously used. In 19 reported uses of the M26, 11 involved firing the barbs and were classed as "effective" in 8 of those incidents. There is no information on adverse medical effects with the M26. It is likely they would have mentioned such events earlier in the presentation, a breakdown on the use of (presumed) low-power systems from Jan 1997-Dec 2001 describing 72 deployments with 41 "effective" incidents is shown. There were no injuries to officers or suspects, other than "puncture wounds", presumably from the barbs.

¹³ Hanley JA, Lippmann-Hand, A (1983). If nothing goes wrong, is everything all right? JAMA, Apr 1, 1983 Vol 249 No 13, 1743-1745.

- 30. Royal Canadian Mounted Police (RCMP): The RCMP and the Canadian Police Research Centre have published a comprehensive report summarising their experience – technical evaluation and operational use – of the M26 Taser [9]. Tests were conducted on 104 volunteers of the law enforcement community; some of the tests involved simultaneous application of two M26 Tasers. The reports also describes the results of an 11 month operational use in which the M26 was used 139 times in 111 incidents.
 - Volunteer studies: The studies were principally focussed on effectiveness; it was rated as 89% effcetive in controlling the volunteers' behaviour. The Taser barbs were either affixed to the subject's skin with tape (93 tests) or fired into the skin (17 tests). The medically relevant observations from the study are: (i) current injection into the back was more effective than frontal use - loss of coordinated muscle control was more notable with rear attack; (ii) the risk of falling to the ground "heavily" was greater in those moving forward when attacked, than those stationary; (iii) no "serious" injuries were noted in the tests; there were no significant medical complications in the 17 volunteers hit with the darts; first and second degree burns were noted in several individuals; the report includes a note by a Medical Officer on the preferred method for barb removal; (iv) three males reported pain in the scrotal area (there has been a claim of testicular torsion from an operational use); (v) there were "no cardiac or respiratory problems"; (vi) the volunteers hit with two simultaneous M26 applications reported no increase in pain or dysfunction, but a larger muscle area was involved; there were no adverse effects.
 - Operational use: In 40% of incidents, barbs were fired; stun mode was used in 47%. The remainder were "voluntary compliance", i.e. the presence of the Taser. It was classed as effective in 78% of incidents in which barbs were fired; in stun mode it was 89% effective. In 63% of incidents the subjects were under the influence of alcohol, 19% were considered to have consumed drugs, and 23% were in a "mental health crisis state". The most serious injury reported was when two sutures were required following barb removal¹⁴. Two patients complained of testicular pain - this led to a recommendation that such individuals should be transported to a medical facility. There were no reports of serious secondary injury from falls, for example. Barb injuries were as expected – some had a 3 cm burn area that resolved within 1-3 days. The report discusses use on mentally impaired individuals in more detail. The British Columbia Schizophrenia Society and the Schizophrenia Society of Alberta monitored the programme; they both passed resolutions supporting the use of Tasers by the police in an effort to reduce the incidence of injury and death within their "client base". In some incidents described in the report, "escalation of force" would have had to be used if the Taser had not been available.
- 31. **Seattle Police Department (SPD)**: SPD have issued a report on their experience of use of the M26 over one year [10]. SPD received their first consignment of 66 M26 Tasers in late 2000. The review considers 106 incidents from 1 Jan 2001- 31 Jan 2002. Two-thirds of the subjects were between the ages of 21 and 40, with the balance split evenly between the 20-and-under age group, and the over-40 age group; 94% were males. In nearly 60% of the 106 incidents, the subject was classed as "impaired". The impairments are shown in Table 13.

¹⁴ There was difficulty in acquiring medical information. The analysis is based on limited reports from the subjects, police observations, and the lack of public complaints.

Supplement to HOSDB Evaluations of Taser Devices

Impairment	Number	Percentage of total
Alcohol	24	22.6%
Chemical/drug	11	10.4%
Drug and alcohol	4	3.8%
Mental illness/delusions	24	22.6%
No apparent impairment	43	40.6%

Table 13; Numbers and types of "impaired" subjects; 106 M26 incidents

32. In 60% of the incidents, the dart (barb) mode was used. The stun mode was used in 27% of cases and both modes were used in 12%. In 68% of incidents, subjects sustained either no injury, or simply puncture wounds from the barbs. Injuries subsequent to Taser deployment were reported in 13% of cases, generally as subjects fell to the ground. In 19% of incidents, injuries to subjects occurred prior to police arrival, prior to Taser deployment, or were self-inflicted. No injuries to subjects were classed as "major", and there were no injuries attributed directly to the Taser itself (other than the barb injuries presumably).

Taser handling trials undertaken by PSDB

- 33. The PSDB report on Taser handling and accuracy trials (Footnote 10) presents information on the accuracy of the M26 (and other Tasers). Sixty four police officers and prison officers from 20 different forces used the Tasers in a trials scenario (i.e. not operationally) employing 17 exercises for example, shooting at moving targets, shooting over or around barriers. Three hundred and nineteen shots were fired with the M26. Both barbs hit the body (excluding head, neck and groin) in 92% of firings. One barb hit the head, neck or groin in 2% of shots, and one or both barbs missed the body in 6% of all shots.
- 34. The M26 Advanced Taser was the most consistently accurate Taser evaluated, and the M26 received the most favourable responses in the questionnaires completed by the officers.

Recommended further work

- 35. DOMILL recommended for further work to clarify aspects of the cardiac risks associated with Taser use:
 - a. improved modelling of Taser current distribution in the body;
 - b. cardiac effects arising from Taser use, in particular hyper-susceptibility from "recreational" drugs;
 - c. the vulnerability of pacemakers and other implanted devices.
- 36. Dstl was requested by the Home Office to clarify the technical approaches required to address these concerns; the response is at Annex A. This work has not yet been funded. Dstl is still in negotiation with the Home Office. It is probable, but not certain, that the work will proceed. Dstl has advised the Home Office that items b. and c. could be undertaken by research providers other than Dstl if they so desired, however Dstl has unique capabilities to undertake item a. and it would be more efficient and cost-effective for that work to be done at Porton.

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Annex A : Programme of work proposed to Home Office on behalf of DOMILL

A1 Modelling Current Flow in the Body

A1.1 Model Enhancements

Due to the geometric simplicity of the initial model constructed by Dstl and constraints in software design, the values of magnetic field strength (current index) reported previously were indicative only (Reference : DSTL/PUB20749). The model could be used in its present form to perform additional simulations, such as stun gun application over the thorax, but to generate quantitative information, to compare with published data on cardiac susceptibility to currents or to inform *in vitro* studies, the model will require enhancement. Such enhancements will incorporate :

- Input of frequency-dependent properties of human tissue, to improve accuracy (some of these data are currently being acquired by Dstl for other customers);
- Greater anatomical accuracy;
- Improved resolution (this will require the use of more powerful computer resources and longer run times).

It is intended that these changes will be implemented and additional simulations performed to generate sufficient data for improved clinical outcomes to be predicted for Taser use.

A1.2 Case Studies

The number of simulations undertaken will be constrained by the long run times associated with this model (simulations can take up to 35 hours to run, depending upon the resolution of the model). It is proposed that Dstl undertake the following simulations, to complement those run previously.

- a. Application of the upper dart to the chest wall overlying the heart, with the lower dart placed **225 mm** below the upper dart.
- b. Application of the upper dart to the chest wall overlying the heart, with the lower dart placed **378 mm** below the upper dart.
- c. Application of the upper dart to the chest wall overlying the heart, with the lower dart placed **601 mm** below the upper dart (left leg).
- d. Application of the upper dart to the chest wall overlying the heart, with the lower dart placed **786 mm** below the upper dart (left leg).
- e. Application of the Taser in stun mode against the neck, with the electrodes in a vertical orientation.
- f. Application of the Taser in stun mode against the neck, with the electrodes in a horizontal orientation (at the same height as Case 5).

The dimensions used in Cases 1 to 4 are the average dart separations recorded in trials conducted by PSDB at various ranges from an (unspecified) Taser; these may be amended, by agreement, following drafting of ACPO's Guidance to Users. The simulations outlined above will be undertaken using waveforms derived from the 7W TE93 Taser (low power), and the 26W M26 Advanced Taser (high power).

A2 Cardiac Effects

A2.1 Scope of Work

The proposed research work is based on established *in vitro* animal models and has been designed to assess the cardiac risks associated with Taser use in the context of **recreational drug intoxication** and **direct heart pacing**.

A2.1.1 Recreational Drug Intoxication

Dstl Biomedical Sciences currently operates an established assay that may be used to evaluate the potential proarrhythmic effects of drugs. The assay, which conforms to the requirements of the UK and US drug regulatory authorities, looks at the effects of drugs on the intracellularly recorded action potential in tissues (Purkinje fibres) isolated from sheep hearts. This assay is suitable for assessing the proarrhythmic risk of both medicinal drugs and other pharmacologically active chemicals (e.g. substances of abuse).

The number of drugs to be tested (and combinations thereof) will be dependent on the requirements of the Home Office; for planning purposes it has been assumed that seven drugs (cocaine, cocaethylene, ecstasy, methamphetamine, heroin, phencyclidine and cannabis) will be evaluated.

By examining the effect of the drug on various characteristics of the action potential (in particular its duration), it is possible to make reasonable predictions about the likelihood of the drug inducing acquired LQTS in humans, and tentative predictions about the likelihood of inducing torsades de pointes arrhythmia. Any effects of the drug at the concentrations tested *in vitro* can be related back to the typical plasma concentration range likely to be found in humans. In instances where a drug is found to increase action potential duration in the sheep Purkinje fibre (at concentrations likely to be found in humans), it would not be an unreasonable extrapolation to assume that the intoxicated individual may be more susceptible to development of potentially lethal arrhythmia in the context of Taser use than if the individual had not been intoxicated.

A2.1.2 Direct Heart Pacing

The modelling studies preceding this part of the proposed research work would provide an estimate of the current levels and waveform shape that the heart is likely to be exposed to following Taser shock. These currents/waveforms could then be reproduced *in vitro* and their effects on isolated hearts investigated. The most appropriate biological preparation is the isolated, perfused heart (Langendorff preparation), in which the heart is suspended in a volume conductor (physiological salt solution) through which the ECG may be measured. Additionally, drugs may be perfused though the heart (via the coronary circulation) and their influence on the heart's susceptibility to Taser discharge explored. The most suitable preparations for this work would be rabbit or guinea-pig heart. The rat heart is not suitable as the ionic currents underlying the action potential differ from those in guinea-pig, rabbit and humans.

These studies will ascertain whether or not a Taser-like discharge, if appropriately timed during the cardiac cycle, can modulate normal electrophysiology (i.e. induce extrasystoles and arrhythmias). As a refinement to this model, the effect of drugs on this Taser-induced modulation would be investigated (especially if any of the substances of abuse, evaluated in Section A2.1.1, test positive for action potential prolongation).

A3 Pacemakers and Other Implanted Devices

Plainly, commercial devices could be exposed to Taser outputs in materials representing tissues. Dstl's view is that such an experimental approach is currently not warranted. It is

desirable, however, that a more detailed and diverse review of the electromagnetic compatibility issues of Tasers and implanted devices be undertaken.

Such a review will be conducted by professional information scientists from Dstl's Knowledge Services, from a range of sources, including peer-reviewed literature, periodicals and newspapers, patents, trade literature and the world-wide web.

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Appendix C – "Assessment of the effects of Advanced Taser M26 output on active implantable medical devices."

DSTL/PUB20753 31 November 2003

Executive Summary

The Defence Scientific Advisory Council (DSAC) sub-committee on the Medical Implications of Less Lethal Weapons (DOMILL) has produced a statement on the medical implications of the use of the Advanced Taser M26 [1], which was published in December 2002. The statement recommended that a programme of research be undertaken to clarify some of the potential effects on the human body of the output of an Advanced Taser M26 unit. One of the recommendations made was that a review of the vulnerability of pacemakers and other implanted devices should be carried out.

This review has been prepared by the Biomedical Sciences Department, Defence Science and Technology Laboratory, to address this recommendation. It contains an assessment, based on published material, of the likely effects on the function of implantable devices that may arise as a result of application of the output of an Advanced Taser M26 to a person wearing such a device.

There are no reports in the published literature of persons wearing pacemakers being subjected to the output of an Advanced Taser M26 device. There is little independent published information that deals directly with the effects of Taser output on implantable devices. Limited studies have been reported on the effects of "stun guns" on explanted cardiac pacemakers. These studies have shown that there are some effects on the functionality of the pacemaker, such as reversion to fixed asynchronous mode, but the effect is temporary and ceases when the "stun gun" is removed.

The effects of Taser output on implantable cardioverter defibrillators are likely to be similar to those on cardiac pacemakers. The nature of the cardiac rhythm sampling process (i.e. two samples approximately 10 seconds apart) indicate that application of a Taser for a period of 5 seconds is unlikely to result in inappropriate therapy delivery.

The effect of Taser output of other active implantable devices, such as cochlear implants and nerve stimulators, has not been reported. It is unlikely that the effects will be long-term or life-threatening, although patient distress is possible in the event of device malfunction. There have been two deaths associated with use of diathermy in patients with neurostimulators.

The age profile of cardiac pacemaker recipients is significantly different from both the overall population and that of persons arrested in situations where a Taser may be deployed. The probability of an individual wearing a pacemaker being present in such a situation is therefore likely to be considerably lower than the overall incidence of pacemakers in the population (0.45%).

The ACPO Operational Guidance document does not require significant alteration to take into account the recommendations of this report. The clinical significance of short-term changes in

implant function should be discussed further by DOMILL. Dstl's view is that there is no requirement to undertake experimental studies on the vulnerability of active implanted devices to the output of the Advanced Taser M26 unit.

1 Introduction

- 1.1 The Defence Scientific Advisory Council (DSAC) sub-committee on the Medical Implications of Less Lethal Weapons (DOMILL) has produced a statement on the medical implications of the use of the Advanced Taser M26 [1], which was published in December 2002.
- 1.2 The statement recommended that a programme of research be undertaken to clarify some of the potential effects on the human body of the output of an Advanced Taser M26 unit. One of the recommendations made was that a review of the vulnerability of pacemakers and other implanted devices should be carried out. DOMILL noted that experimental studies were not warranted at the time of publication of the statement, and should not be carried out until the result of the review is known.
- 1.3 This review has been prepared by the Biomedical Sciences Department, Defence Science and Technology Laboratory, to address this recommendation. It contains an assessment, based on published material, of the likely effects on the function of implantable devices that may arise as a result of application of the output of an Advanced Taser M26 to a person wearing such a device.
- 1.4 A summary of the output of the Advanced Taser M26 device is included (Section 2). A more comprehensive report of the output properties of the device may be found in related documentation [2,3]. Recently published statistics on field use of the Advanced Taser M26 unit in the law enforcement role in the United States are included in this section.
- 1.5 The implanted devices examined in this review include cardiac pacemakers, cardioverter defibrillators, cochlear implants and other implantable neurostimulatory devices, such as phrenic and vagal nerve stimulators (Section 3). Published material on the construction of the devices [4,5] has been consulted to assess the likely consequences of Taser barb impact on the device. This is followed by an assessment of available published information on the observed interference of external electromagnetic fields with active implantable devices (Section 4).
- 1.6 This document also contains a brief assessment of the probability of a person wearing an active implantable device being present in a situation where a Taser may be deployed. This draws upon a comparison of the age profiles of the overall United Kingdom population that of pacemaker and implantable cardioverter defibrillator wearers and Home Office data on the age profile of persons arrested during incidents where firearms teams have been deployed (Section 5).
- 1.7 The findings of the study are brought together in Section 6 (Conclusions), and recommendations for minor changes to current guidance and for a further review are highlighted in Section 7 (Recommendations).

2 Summary of the output of the Advanced Taser M26 device

2.1 Introduction

- 2.1.1 A Taser is a battery-powered electrical incapacitation device (EID). It uses a series of low average current (the current pulses are up to 10 A, and last for a few microseconds), high voltage electric pulses to cause incapacitation in the target individual. Two barbed electrodes, each of which is attached to a coiled wire (of length 6-7 m), are propelled towards the target from a cartridge attached to the front end of the weapon. The barbs attach to the skin or clothing of the target individual.
- 2.1.2 When the device is fired, an electrical pulse train is passed down the wires and through the target's body. The voltage output characteristics depends on the model of Taser and the separation of the barbs on the target. Barb separation distance governs the electrical resistance of the current pathway between the barbs, and thus, from Ohm's Law, the voltage characteristics for a constant current.
- 2.1.3 The mechanism of incapacitation has yet to be fully determined. The manufacturer (Taser International, Arizona, US) claims that "[The Taser devices].... use a powerful 18-26 Watt electrical signal to completely override the CNS¹⁵ and directly control skeletal muscles. The [electromuscular disruption] effect causes an uncontrollable contraction of muscle tissue, allowing physical debilitation of the target, regardless of pain tolerance or mental focus".
- 2.1.4 The output of the Advanced Taser M26 device is given in a previous Dstl report [2]. Across a 2 k Ω load, the device has an output of :
 - up to 15 A peak current.
 - a pulse width of up to $20 \times 10^{-6} \text{ s} (20 \text{ }\mu\text{s})$.
 - a pulse repetition rate of 35-40 Hz.
 - a voltage output of approximately 20 kV.

The waveform is a damped half sinusoid. The energy per pulse lies between 1.4 and 1.8 J. The manufacturer claims a power output of 26 W.

- 2.1.5 The Taser barb is reported to strike the target with a maximum kinetic energy of 1.5J. The range of the devices is limited by the wire contained within the cartridge this is between 6 and 7 metres for the Advanced Taser M26 unit. The reported optimal dart locations for effectiveness are the upper torso and the lower abdomen.
- 2.1.6 The devices are capable of being effective on a target through up to 5 cm of clothing (apparently by electricity arcing across the clothing-skin interface). The length of the barb on the electrode is approximately 10 mm.

2.2 Data on operational use of Advanced Taser M26 units

2.2.1 The statistics quoted in this section were presented by Taser International to an international conference in May 2003 [6]. The material presented was based on 2050 field reports from use of Advanced Taser M26 devices in the United States, received by Taser International in the period 2000-2003.

 $^{^{15}}$ CNS = central nervous system

- 2.2.2 The statistics quoted are based on usage in the United States. Incidents where the subject possessed a weapon (blunt or edged) or a firearm accounted for just over 20% of the total US deployments.
- 2.2.3 A total of 90% of reported instances of Taser use, that included an estimation of the exposure time to the target subject, reported discharge times of at least 5 seconds.
- 2.2.4 Eighty-one percent of reported cases involved Taser deployment from a range of less than 3 metres. 86.1% of deployments included the use of a single shot. Instances of up to five shots being required to incapacitate a target were reported.
- 2.2.5 Ninety-eight percent of reported cases involved no, or minor, injury to the suspect following Taser deployment.

3 Implantable electrical devices

3.1 Introduction

3.1.1 The range of implantable electrical devices examined in this report includes cardiac pacemakers, implantable cardiac defibrillators, cochlear implants and other implantable nerve stimulators.

3.2 Cardiac pacemakers

- 3.2.1 The first artificial pacemaker was implanted in 1958 [7,8]. Development of the devices by introduction of transistors and integrated circuit technology was rapid, and modern devices contain complex circuitry which enable the device to be of maximum therapeutic use to the individual patient.
- 3.2.2 The majority of modern cardiac pacemaker devices are used to treat patients with symptomatic bradycardia, although anti-tachycardia pacing is becoming more common. The overwhelming majority of pacemakers are "demand" units, in which the heart output is monitored and pacing is only delivered in the absence of normal patient cardiac activity. The device may be programmed to adjust sensitivity according to the patient's cardiac output, and the magnitude of the pacing pulse may be altered to suit each individual patient. The units may be rate-responsive, in that input from other sensors (e.g. blood temperature or respiratory rate) may be used to adjust the rate of pacing (for example, during exercise).
- 3.2.3 Modern pacemaker units consist of a pulse generator (which contains the battery power source, the sensing and pacing circuits and the lead connection block) and the pacemaker leads. Depending on the desired functionality of the model, there may be up to three leads connected to the pulse generator, although the normal case is for one lead.
- 3.2.4 The pulse generator is connected to the myocardial tissue by the pacemaker lead, which consists of a sensor electrode, a wire and surrounding biocompatible insulation material. The lead may be unipolar (a single wire carries the pulse to the electrode, and the circuit back to the pulse generator is completed by the body tissue) or bipolar (two wires in a coaxial arrangement one carries the pulse to the electrode, the other completes the circuit back to the pulse generator). The lead is fixed to the myocardial tissue using a screw-in tip, or a barb-type end piece.
- 3.2.5 Single chamber devices, where both the sensing and pacing processes are carried out on either the atrium or (more commonly) the ventricle, are most commonly used in antibradycardia pacing. Dual chamber devices, where sensing and pacing may be carried out on separate chambers (depending on the selected functionality), allow atrioventricular synchronisation, an increase in stroke volume (and therefore cardiac output) and decrease in tachycardias when compared to single chamber devices. Dual chamber pacing is the most common type of pacing, although these are more expensive than single chamber units and do not offer appropriate pacing therapy for all patients.
- 3.2.6 Dual chamber devices have two separate leads one for sensing, the other for pacing. There is the possibility of "crosstalk" between the two functions a signal originating from the atrium could be sensed by the ventricular system and inhibit correct function. Cross-talk could be a problem in subjects exposed to Taser output

in that the Taser output could be interpreted as an atrial event. Manufacturers have used several approaches to reduce cross-talk in their products [7,8].

3.3 Implantable cardioverter defibrillators (ICDs)

- 3.3.1 The function of an ICD is to respond to the onset of ventricular fibrillation by depolarising most of the ventricle, thereby allowing an organised rhythm to return. It consists of a generator, which is usually implanted within the abdominal wall, and a subcutaneous sensing/therapy lead. Depending on the model, sensing and therapy may require separate leads, but modern devices incorporate both functions into the same lead.
- 3.3.2 The first generation of ICDs were introduced in the mid-1980s. Early models were able to detect ventricular tachyarrhythmia (VT) and ventricular fibrillation (VF), and after an elapsed period of time (a few seconds), the capacitor in the generator would be charged and would then deliver a non-synchronised shock of 25-30 Joules until the tachycardia was terminated.
- 3.3.3 Modern ICDs are multi-functional, and are able to deliver "tiered therapy". They can provide anti-tachycardia pacing for painless termination of monomorphic ventricular fibrillation, programmable cardioversion, back-up bradycardia pacing (in a similar manner to a cardiac pacemaker) and high-energy defibrillation.
- 3.3.4 The ICD constantly monitors the heart rate, and if the rate rises above a preprogrammed value (usually about 240 beats per minute), then the capacitor is charged. The heart rate is then sampled a second time a few (5 to 10) seconds later, and if the rate is still above the threshold value then defibrillation therapy is initiated. Should the rate fall below the threshold value on the second sampling phase, then therapy will not be initiated and the capacitor is discharged into a suitable resistance within the generator body.
- 3.3.5 Following defibrillation, other therapies may be delivered. For example, some patients successfully converted out of VT or VF are found to suffer marked sinus bradycardia, and pacing is required. In such cases, the ICD is able to deliver pacing in a similar manner to a cardiac pacemaker.
- 3.3.6 The construction standards of cardiac pacemakers and ICDs are similar, and they contain similar detection circuitry. However, the ICD contains a larger capacity power source and a capacitor to store charge.

3.4 Cochlear implants [9]

- 3.4.1 Cochlear implants function by directly stimulating undamaged nerve fibres in the inner ear, thereby producing a sense of sound to the wearer. They are used in patients who have severe to profound hearing loss and who do not benefit from use of conventional hearing aids.
- 3.4.2 The implant consists of three parts the receiver, headpiece and speech processor. Only the receiver is implanted into the body. It is a disk-shaped assembly, 10-15 mm in diameter, which is placed under the skin behind one ear. There is a wire leading from the receiver to an electrode placed in the fluid in the inner ear. The headpiece is worn externally just behind the ear, and contains a microphone and a transmitter. The speech processor, which processes the microphone input, may be worn behind the ear or on a belt.

3.4.3 Bilateral implants are rare – the favoured surgical technique is to fit an implant to one ear only. There are about 4 000 units fitted to patients in the United Kingdom at the present time, which are divided roughly equally between adults and children [9].

3.5 Other nerve stimulatory devices

- 3.5.1 There is a wide range of neurostimulators in use for functional electrode stimulation, control of pain, movement of limbs through muscle or nerve stimulation, deep brain stimulation (to control involuntary tremors), control of bladder/bowel function, control of diaphragm movement (phrenic nerve stimulators) and vagus nerve stimulation for the control of epileptic seizures. Drug diffusion pumps are implanted into patients to control the delivery of medication.
- 3.5.2 The neurostimulators may be implanted in the abdomen, upper chest region, or within or adjacent to limbs. Leads and electrodes run subcutaneously to the target site from the neurostimulator.
- 3.5.3 Device malfunction through interference could potentially cause pain or discomfort to the patient. Nerve fibre endings and other tissue near to the electrodes could also be damaged by direct or induced high current density arising from interference from external sources.
- 3.5.4 Few studies have been published which specifically investigate the effect of electromagnetic interference on neurostimulators. However, the neurostimulatory units are constructed to similar standards as cardiac pacemakers [10], and so the effects of external electromagnetic interference is likely to be similar.
- 3.5.5 The numbers of such devices in use in the UK at the present time is not known precisely.

3.6 Physical vulnerability of devices to malfunction caused by M26 Taser

3.6.1 Cardiac pacemakers

- 3.6.1.1 The pulse generator is normally situated in a pocket fashioned by separating the pectoral muscle fascia from the overlying subcutaneous tissue. The depth of the pocket below the skin is typically 5 10 mm, and so it is possible for the Taser barb to strike the pulse generator housing, following penetration of the skin.
- 3.6.1.2 The dimensions of the pulse generator casing are of the order of 50 (H) x 50 (L) x 10 (D) mm. Example dimensions of units are :
 - CCS Maestro II Series 200 pulse generators [11] 49 x 46 x 6 mm;
 - Medtronic Sigma SR 200 pulse generators [12] (pictured in Figure 1) 42 x 51 x 7 mm.
- 3.6.1.3 The surface area presented by the casing is therefore of the order of 2 500 mm². This compares with a typical adult body surface area of 1 730 000 mm² [13].



Figure 1 Medtronic Sigma SR 200 pulse generator (by permission of Medtronic UK Ltd, Watford)

- 3.6.1.4 The casing of the pulse generator is normally made of titanium, coated with a thin layer of biocompatible polymeric material (such as Parylene). The casing material is manufactured to withstand three mutually perpendicular shocks of a peak acceleration of 5000 ms⁻² for a duration of 1 ms [4,5].
- 3.6.1.5 The impact of a Taser barb (kinetic energy of less than 2 J) with a casing that withstands the mechanical shock test is unlikely to result in a rupture of the pulse generator case, although it may result in a scratch to the outer polymeric layer.
- 3.6.1.6 The lead connector block on the end of the pulse generator (at the top of the pulse generator in Figure 1) may be struck by the Taser barb. The surface area of the connector block is approximately 5 % of the frontal area of the pulse generator. Impact of the barb with the connector block is very unlikely to result in damage, since the connector block is subject to the same mechanical shock test as the rest of the pulse generator.
- 3.6.1.7 Damage to a pacemaker lead may result from the lead being struck by the Taser barb. The pacemaker lead lies within a protective outer sheath. Should the sheath be ruptured by the Taser barb, it is possible that a direct electrical connection may be formed between the Taser barb and the pacemaker lead, which is likely to result in direct passage of the Taser output waveform into the heart. The probability of damage to the lead is extremely low (only a small length of lead is within 10 mm of the skin, and much of the lead is shielded from impact by the pulse generator), and so the probability of direct passage of the Taser output waveform to the myocardial tissue by this route is low.
- 3.6.1.8 The only other part of the pacemaker lead that is potentially vulnerable to barb strike is the short length near to the connector terminal. Any slack part of the lead is coiled behind the pulse generator (and is therefore not vulnerable to barb strike), with the remainder of the lead path being transvenous (through the cephalic or subclavian vein).
- 3.6.1.9 Most modern cardiac pacemakers may be reprogrammed using a telemetric link with the pulse generator. The process is non-invasive, but requires specialist equipment. The majority of devices can only be reprogrammed after a certain code

is given via the telemetry link, in order to minimise instances of accidental reprogramming to a different function mode. Reprogramming by direct impact of the Taser barb with the pulse generator is therefore extremely unlikely.

3.6.1.10 Temporary or permanent loss of function of a cardiac pacemaker through physical damage to the device is likely to have significant clinical consequences, which may be life-threatening depending on the patient and nature of the therapy.

3.6.2 Implantable cardioverter defibrillator

- 3.6.2.1 The construction is similar to that of a cardiac pacemaker. The generator is implanted in the abdominal wall, and has at least one lead between the generator and the myocardial tissue. The generator is very unlikely to be penetrated by barb strike. Rupture of the lead casing or generator/lead connector block, resulting in a direct electrical pathway to the heart through the lead is possible, but very unlikely.
- 3.6.2.2 Temporary or permanent loss of function of the ICD through physical damage to the device is likely to have life-threatening consequences for the patient. The probability of loss of proper function from exposure to Taser output is low, as damage resulting from impact is unlikely.

3.6.3 Cochlear implants

- 3.6.3.1 The implanted part of the device is very unlikely to be impacted by a Taser barb, as it lies within the inner ear. The outer ear protects the implant site from external impact, and impact on the outer headpiece is unlikely to cause significant damage to the casing. Impact on the processing unit, which is worn behind the ear or on the belt, is more likely. The manufacture standard of the casing is similar to that of cardiac pacemakers [14], so damage is unlikely. There is the possibility of the Taser barb striking the lead connecting the processing unit and the outer headpiece, although this is unlikely.
- 3.6.3.2 Loss of function from a cochlear implant is unlikely to have life-threatening consequences for the patient. The loss of function may cause considerable patient distress, which may have other physical consequences depending on the individual patient.

3.6.4 Other neurostimulatory devices

- 3.6.4.1 Such devices are implanted at locations appropriate for function. Vagal nerve stimulators consist of a generator (usually placed in an internal subclavicular pocket, similar to cardiac pacemakers), connected to the vagus nerve in the neck by two electrodes. Phrenic nerve stimulators consist of electrodes connecting the stimulator to the phrenic nerve. The electrodes exit the body, usually in the shoulder region, and are connected to a generator which is external to the body.
- 3.6.4.2 There is the possibility of the leads being ruptured by the Taser barb, with subsequent loss of delivery of therapy. The generators are constructed to similar standards as cardiac pacemakers [14], and the likelihood of penetration of the generator body is low.
- 3.6.4.3 It is possible that, for all neurostimulatory devices, the lead could become detached from the generator as a result of violent movement of the subject during application of the Taser output. The clinical result of loss of neurostimulation depends on the nature of the device and the patient.

- 3.6.4.4 Loss of function from a phrenic nerve stimulator is very likely to result in loss of respiratory function. A short-term loss of function (of the order of a few seconds) is unlikely to result in significant harm to the patient as long as correct function is re-established as soon as possible.
- 3.6.4.5 Temporary or permanent loss of function of a vagal nerve stimulator may result in the patient suffering seizures, which may be life-threatening depending on the severity and nature of the seizure. The precise clinical nature of the seizure, and the consequences arising from it, depends on the individual patient. It is possible that the patient's response to application of the Taser waveform may include a seizure, arising from loss of vagal control.
- 3.6.4.6 Loss of function of other active implantable neurostimulatory devices is unlikely to have life-threatening consequences, although any adverse consequences are likely to result in a degree of patient distress. The clinical nature of response to malfunction will depend on the function of the device and the patient.
- 3.6.4.7 Conduction of the Taser output into the brain via a neurostimulator lead is a possibility. Such an event is likely to cause significant localised electrode tip heating, which may result in lesions in the brain tissue. A major international manufacturer of neurostimulatory devices (Medtronic) has confirmed that such effects have been observed following the application of diathermy to a patient wearing a neurostimulatory device, which resulted in patient coma.

3.6.4.8 Information is available regarding two incidents

- A patient with bilaterally implanted deep brain stimulators died as a result of brain tissue damage incurred following diathermy treatment to hasten recovery from teeth extraction. The patient was 70 years old, was wearing the DBS to reduce Parkinsonian tremors and was wearing a Medtronic 7424 unit attached to two 3387 quadripolar electrodes.
- An apochryphal report that a patient with implanted neurostimulators underwent diathermy for severe kyphosis, and after suffering a sudden change in mental state and neurological deficits, eventually died as a result of brain tissue damage. This wasn't reported in the open literature, and it's proving a bit difficult to track down any more details.
- 3.6.4.9 In both cases, MRI scans revealed significant brain tissue damage around the neurostimulator electrode sites. For the first incident, the diathermy frequency was 27 MHz, pulse duration was 100 microseconds, pulse rate was variable (patient injury was reported at 4.1 kHz PRF), power output was about 25 W (these are appropriate settings).
- 3.6.4.10 Ruggera *et al* [27] showed that the specific absorption rate levels attainable in tissue simulant contacting the end of neurostimulator (and pacemaker) leads following exposure to simulated diathermy treatment was very high (several thousand W/kg), with temperature rises of several degrees Celsius per second.
- 3.6.4.11 The power levels involved in diathermy are significantly higher than for the Taser output, and so it is unlikely that the effect of a Taser will be identical to that of diathermy application. In the absence of any firm data regarding the temperature rise of the electrode tips during passage of the Taser output waveform, the likelihood of adverse effects such as brain tissue damage should be assessed as significant.

- 3.6.4.12 No reports of such occurrences have been made in the open literature since the introduction of Tasers into United States police service. The likelihood of a neurostimulator wearer being present in a situation where Tasers may be used is no higher than that of a non-wearer, and may well be significantly less. The likelihood of the Taser barb penetrating the lead and making a direct electrical connection with the electrode tip is very low, as the lead dimensions are small in relation to the torso dimensions.
- 3.6.4.13 The overall probability of such an adverse effect is therefore assessed as being low, although further investigation into the extent of the likely tissue damage from passage of a Taser output waveform through a neurostimulator lead and electrode would be desirable.

4 Electrical vulnerability to output of Advanced Taser M26 unit

4.1 Introduction

- 4.1.1 Electromagnetic interference with active implanted medical devices is an area of considerable research and development, due to the near certainty of persons encountering electromagnetic fields on a daily basis, both in the household and elsewhere.
- 4.1.2 There is an international standard [4] which cardiac pacemakers must satisfy before they are approved for implantation. This standard noted that the issue of immunity to electromagnetic interference was "under consideration".
- 4.1.3 A draft European standard concerning active implantable medical devices is in preparation at the time of writing [5]. This standard is more specific than the extant standard (ISO 5841-1:1989) [4] in terms of measuring the effect of external electromagnetic fields on cardiac pacemakers, since it specifies a frequency range over which the device shall be tested.
- 4.1.4 Sub-clause 27.1 of the draft standard [5] states that "implantable devices shall not cause any harm because of susceptibility to electrical influences due to external electromagnetic fields, whether through malfunction of the device, damage to the device, heating of the device, or by causing local increase of induced electrical current density within the patient". Test signals are specified (sub-clause 27.2) within the range 16.6 Hz and 20 kHz (1 V peak to peak amplitude), and a carrier signal of 500 kHz with amplitude modulation at 130 Hz (double sideband with carrier) with a maximum peak-to-peak voltage of 2 V.
- 4.1.5 The current standard [4] specifies that a cardiac pacemaker shall not be affected by the operation of an external cardiac defibrillator on the device wearer, provided that the defibrillator paddles are not directly above or immediately adjacent to the pulse generator. The typical output of an external defibrillator exceeds 300 J (at 150 V).
- 4.1.6 There is a lack of accessible published information that specifically deals with the issue of vulnerability of pacemakers and other implantable devices to Taser outputs. No experimental data has been made available in support of Taser International's claims, although some appears to be in existence, since it is referred to in the manufacturer's literature [15].
- 4.1.7 This information has been used by the manufacturers of the M26 Advanced Taser to state that since the output of the Taser device is "only" 0.3 J, then there is little risk of pacemaker damage from the Taser output [15,16]. This statement should be read in the knowledge that this output estimate may be a considerable understatement.

4.2 Cardiac pacemakers

- 4.2.1 There are relatively few published articles on the subject of the effects of electrical incapacitation devices on cardiac pacemakers. No paper is known to the author which specifically deals with the effects of Taser output on implantable electrical devices, and there are no published reported instances of Taser units being deployed against persons wearing active implantable devices.
- 4.2.2 Manufacturers of Taser units have made several claims regarding the effects of Tasers on pacemakers. Taser International have stated [15] that the Taser "will not

interfere or damage modern pacemakers", since they are "designed to withstand defibrillation pulses hundreds of time stronger than Taser output". Taser International also claims [15] that "the output has also been tested to be significantly lower than necessary to damage cardiac pacemakers", but no data or reference to a test report is given.

- 4.2.3 Taser International have stated [6,17] that "any modern pacemaker is designed to withstand electrical defibrillator pulses, which are hundreds of times stronger than the output of the Taser. To satisfy members of the California State Assembly, staff members of the Sutter Memorial Hospital in Sacramento, sponsored an actual test at the Cordis Medical Laboratory in Florida, which verified that the Taser will not damage a pacemaker". It is not clear what form these tests took or how they were carried out, since the report is not available.
- 4.2.4 Sergeant Darren Laur of the Victoria Police Department, British Columbia, Canada has independently evaluated several Taser units, and has reported his findings [17]. The study mentions that staff from the University of Ottawa Heart Institute undertook a review of all the US medical research on Taser units published up to 1999, and the review concluded that "the system appears to be safe". The report is not accessible, and Sgt Laur has been contacted with a view to obtaining a copy of the report, but it has yet to be received.
- 4.2.5 A need for further research into the cardiac effects that Tasers and related devices would have on people with pacemakers has been identified in an article by Fish and Geddes [18].
- 4.2.6 A study by Moraes [19] reports the effects of two electronic "autodefense" devices ("stun guns" rather than Tasers) on a small number of cardiac pacemakers. It found that the function of the pacemakers tested were significantly affected by the output of the devices, but were they were not permanently affected and the pacemakers return to the correct action as soon as the interference from the autodefense device ceased.
- 4.2.7 The full electrical output characteristics of the autodefense devices were not quoted in the study. Both were of the "stun gun" type manufactured by ITM (São Paulo, Brazil), and contained similar circuitry and therefore presumably produced similar output waveforms. They function through passage of a waveform into the target through direct contact with the device, although the nature of the waveform was not specified in the study. The manufacturer [20] quotes an output of 50 kV and 2 x 10-6 A (2 μ A), but the frequency of the output is not specified.
- 4.2.8 The maximum distance between the autodefense device and the pacemaker at which interference with pacemaker function was observed was 12 cm (Biotronik Diplos M05 pacemaker). This corresponds to a circular area of 452 cm2 around the pacemaker site. This result was obtained from an explanted device, so the influence of the surrounding tissue was not investigated.
- 4.2.9 The effects of the interference were change of pacemaker frequency (including random pulse generation in some cases) and reversal of working condition (from inhibited to uninhibited, or vice-versa). The duration of the effects on the pacemaker was similar to that of the stimuli, and the pacemakers returned to correct function as soon as the interference stimulus was removed.
- 4.2.10 It is unlikely that change of function to fixed asynchronous mode for a period of 5 seconds, followed by reversion to normal mode, will result in significant injury or

harm to the pacemaker wearer. The wearer may feel some discomfort arising from temporary change of function, but this is very likely to be significantly outweighed by the discomfort arising from the effects of the autodefense device. It is especially notable that no permanent damage was caused to any of the pacemakers examined, and they returned to normal function after the stimulus was removed.

- 4.2.11 The effect of extraneous 50 Hz electrical interference on pacemakers has been the subject of a number of investigations. Astridge et al [21] have studied the effects on a number of implanted pacemakers using electrical waveforms (240 V, maximum of 600 μ A), applied to patients under controlled conditions. Pacemaker behaviour was monitored using telemetry and intracardiac electrograms. Pacemaker function was observed to be affected in most of the units tested (manufactured by Intermedics, Siemens Pacesetter and Telectronics), although not all showed similar susceptibility to the waveforms used, as two models manufactured by Medtronic were found to have a significantly higher interference threshold than the other units tested.
- 4.2.12 In those units which were affected, an onset of noise reversion mode was observed, preceded by a short window of inappropriate function. Some of the subjects in the study reported dizziness (associated with pacemaker inhibition) or palpitations (associated with accelerated pacing), but the effects were temporary. Inappropriate pacemaker acceleration induced by atrial malsensing may cause some discomfort or provoke angina, but these are short-term effects.
- 4.2.13 The response of the units to electrical noise was observed to depend on the model. Most units studied (Telectronics Quadra, Siemens Pacesetter Paragon II and Intermedics Cosmos II) reverted to DOO (dual chamber pacing, both chambers paced at fixed asynchronous rate) mode if noise is sensed on the ventricular channel. If noise is sensed on the atrial channel, the Telectronics and Siemens units reverted to DOO mode, but the Intermedics device reverted to VVI (ventricular pacing, ventricular sensing, inhibited mode) mode. A Medtronics Minuet 7108 unit was found to have a significantly higher interference threshold than the other units tested (120 μ A as opposed to less than 100 μ A), and a Medtronics Elite unit was found to be unaffected during the interference trials.
- 4.2.14 Reversion to the modes specified is very unlikely to result in long-term harm to the pacemaker wearer, although some short-term adverse effects were reported by Astridge. The devices reverted to their normal clinically programmed mode when the source of electrical interference was removed. No permanent damage to the pacemaker units (leads or pulse generators) was reported.
- 4.2.15 Astridge noted that the current levels at which interference was observed was significantly higher for devices operating in bipolar mode than for those operating in unipolar mode. The difference in sensitivity arises since bipolar systems have higher impedances (and therefore voltage thresholds) than unipolar systems.
- 4.2.16 Reprogramming of the unit to an alternative pacing mode (see Section 3.6.1.9) is very unlikely, since the function may only be changed using specialist equipment. The effects on pacemakers noted in the studies by Moraes [19] and Astridge [21] were temporary, and it was evident that no permanent effects had occurred since all the pacemakers reverted to their pre-programmed modes after interference had ceased.
- 4.2.17 Astridge [21] noted that cross-talk was not conclusively observed during electrical interference trials.

4.3 Implantable cardioverter defibrillators

- 4.3.1 Little, if any, information has been published on the effects of Advanced Taser M26 output on implantable cardiac defibrillators (ICDs). The manufacturers claim that "it is extremely unlikely that ... M26 operation could damage an implanted pacemaker or implantable cardioverter defibrillator" [16]. It seems that this claim is based on the requirement for such devices to withstand the output of external defibrillators in a similar manner to cardiac pacemakers [4,5].
- 4.3.2 Embil *et al* [22] have published a study of a patient wearing an ICD (a Medtronic Model 7217B unit) who returned to work in an "electrically hostile" environment following implantation. The environment contained low frequency (70 Hz) high field strengths (up to 3 Gauss), although body current flow in the subject was not reported. There were no reported therapy events delivered by the ICD during exposure of the worker, so it was concluded that the high field environment had no effect on the ICD.
- 4.3.3 ICDs are manufactured to similar standards as cardiac pacemakers, and so may be regarded as being as vulnerable to external electrical interference. However, there are differences in the sensing and therapy delivery processes between the two types of implantable device. The principles of operation of an ICD are given in Section 3.3.4.
- 4.3.4 The time gap between the two ICD sampling periods is longer than the duration of the Taser output (10 seconds, as opposed to a maximum of 5 seconds for a single Taser shot). If the ICD senses the Taser output as being ventricular fibrillation, then the capacitor will charge up to a pre-set value. The second sampling period, which is at least 10 seconds later, will not be sensed as ventricular fibrillation and so the defibrillation therapy will not be delivered (the capacitor will be discharged slowly into a load resistor).
- 4.3.5 If multiple applications of 5 second duration Taser outputs are used in an operational situation, as has been described in operational reports [6], then the probability of triggering an adverse effect is increased.

4.4 Cochlear implants and other neurostimulatory devices

- 4.4.1 No published studies of the effects of Taser use on subjects wearing cochlear implants or other active implantable neurostimulatory devices have been located.
- 4.4.2 There are no specific standards set down for other active implantable medical devices at the present time in respect of immunity from electromagnetic interference. Draft standards based on those extant for cardiac pacemakers are under consideration, but they have yet to be published for consultation.
- 4.4.3 No firm conclusions may therefore be drawn on the potential effect of Advanced Taser M26 unit output on these devices, owing to lack of published data or performance standards. The draft standards are based upon those that apply to cardiac pacemakers, and it may be reasonable to assume that the response of these devices to Taser output may be similar to that of cardiac pacemakers.

5 Incidence of implantable cardiac device use in the population

5.1 Introduction

- 5.1.1 The incidence of use of implantable devices in the UK population is an important factor in the risk assessment of use of Taser device on wearers of such implants, since it provides an indication of the likelihood of a Taser target wearing such a device.
- 5.1.2 Cardiac pacing devices (pacemakers) and implantable cardioverter defibrillators (ICDs) are considered separately, although the lack of age profile data on ICDs makes a similar comparison difficult at the present time.
- 5.1.3 There is little available published data on the number of neurostimulators in use in the United Kingdom, and so this section is restricted to cardiac devices.

5.2 Number of implantable devices

- 5.2.1 The 1998-99 National Pacemaker Database Annual Report [23] puts the number of implants in the database at 273 949, with 205 000 patients in follow-up (i.e. in contact with an implant centre). The larger value corresponds to a figure of 4643 implants per million of population, or 0.46%, whilst the lower figure (patients in follow-up) corresponds to a figure of 3475 implants per million of population, or 0.35%.
- 5.2.2 The number of implantable cardiac defibrillators in use in 1999 has been estimated at 4123 [23]. This corresponds to 70 per million of population, or 0.007%. No data is available on the age profile of the recipients of ICDs, but the mean age of receipt (59.7 years) is significantly less than that of pacemakers (74.5 years).
- 5.2.3 Small inaccuracies in the compilation of the database due to incomplete reporting are unlikely to significantly affect these figures.

5.3 Age profile data

- 5.3.1 Data on the age of patient on first implant in 1999 has been obtained [23]. This has been used to create an age profile of persons in receipt of implants.
- 5.3.2 Data on the general population has been obtained from the 2001 UK National Census [24]. This gives information on the number of UK citizens in five year bands, from 0-4 years to 90+ years.
- 5.3.3 Table 1 is a comparison of the implant age profile data and that of the general population. The general population data for the lowest two age ranges have been recalculated to match the age divisions used in the implant survey. Any errors in this process are unlikely to have a significant impact on the figures shown.

Age	Implant recipients / %	Overall population / %
0-13	0.6	17.3
14-40	2.3	36.0
41-60	9.1	26.1
61-80	54.1	16.6
81 and above	33.9	4.1

Table 1: Comparison of implant recipient profile with overall population profile.

5.4 Analysis of data

5.4.1 Table 1 clearly shows that the overall rate of cardiac pacing implant use in the population (0.45%) is not evenly distributed across the population, and that the incidence of pacemakers is highest in persons between 61 and 80 years of age. The population of implant recipients is clearly skewed towards older age, when compared with that of the general population.

5.5 Conclusions

- 5.5.1 The great majority of recipients of cardiac pacing devices are aged over 60 years. Intuition suggests that this age group has a low probability of coming in contact with the police in a conflict situation, i.e. one which may result in the use of a Taser.
- 5.5.2 It is unlikely that the age profile of persons arrested by the police matches that of the general population. Home Office data [25], which does not provide a detailed age breakdown of persons arrested over 21 years of age, indicates that 42% of those arrested are under 21 years of age. This should be compared with a figure of 26.6% for this age group in the UK population [24].
- 5.5.3 The overall rate of incidence of implant receipt (0.45%) is therefore not a good guide to the likelihood of the implant recipient coming into contact with the police in a conflict situation. It is very likely to be significantly less than this figure. The assumption of a lower probability is supported by the fact that in over 20 years of service and many thousands of deployments in the United States, not a single incident involving a Taser applied to an implant recipient has been published in the open literature.

6 Conclusions

- 6.1 There are no reports in the published literature of persons wearing pacemakers being subjected to the output of an Advanced Taser M26 device. There is little independent published information that deals directly with the effects of Taser output on implantable devices.
- 6.2 The manufacturers of the Advanced Taser M26 appear to have carried out a brief review of the effect of the output of the M26 Taser on pacemakers and ICDs. This assessment has been based on the ability of implantable devices to withstand external defibrillator pulses. This assessment is only of limited value, since the Taser output waveform is very different to that of an external defibrillator and the assessment is not based on practical measurements.
- 6.3 Studies on the effects of stun gun output on implantable pacemakers have shown that the function of the pacemaker is affected by the output of the device, but the effect is temporary and only lasts for the duration of the stun gun output. No permanent damage to the pacemakers tested was reported. The clinical effect of short-term incidence of change of pacemaker function to fixed asynchronous mode was not reported in the study.
- 6.4 An examination of the function of cardiac pacemakers, combined with an examination of the international standards to which they are constructed, as given in Section 3 of this report, indicates that physical damage to the pacemaker from a Taser dart is very unlikely. The most vulnerable part of the pacemaker is the connection between the pulse generator and the lead, but penetration of this by the Taser dart is very unlikely, owing to its small size in relation to the torso and attenuation of the impact kinetic energy of the Taser dart by clothing and skin. Physical damage to the pacemaker lead may result in failure to deliver appropriate therapy, and/or direct passage of the Taser waveform to the myocardial tissue. Either or both of these may result in a situation where proper cardiac function is compromised, and must be regarded as immediately life-threatening.
- 6.5 The situation for ICDs in terms of physical damage from the Taser barb is similar to that of cardiac pacemakers, i.e. physical damage is very unlikely. However, either damage to the connector lead, or malfunction of the pulse generator (or both) is likely to result in a life-threatening situation.
- 6.6 The implanted part of a cochlear implant is very unlikely to be vulnerable to Taser dart strike, since it is protected by the outer ear. The parts of the system that are outside the body are more vulnerable to the Taser dart, but the processor casing is very unlikely to be penetrated. Malfunction of any part of the system is, however, unlikely to be life-threatening unless the Taser waveform is passed directly into the brain via the auditory nerve. The probability of this event occurring is low.
- 6.7 The situation with other implantable devices is similar to that for cochlear implants. System components that are outside the body are vulnerable to Taser barb strike, but are unlikely to be damaged. Connection leads may be damaged or severed by the Taser barb, but the probability of this is low. The clinical effects of device malfunction depend on the device and the nature of the therapy to be delivered.
- 6.8 The effects of Taser output on the function of cardiac pacemakers are unlikely to be permanent. The limited number of studies that have been reported on devices similar to Tasers [19] indicate that effects are likely to be limited to reversion to

asynchronous pacing mode, and that these effects are temporary. There is the possibility of "crosstalk" affecting proper function of the pacemaker, but studies [21] have shown that such interference is unlikely in the presence of time-varying electric fields.

- 6.9 The effects of Taser output on implantable cardioverter defibrillators are likely to be similar to those on cardiac pacemakers. The nature of the cardiac rhythm sampling process (i.e. two samples approximately 10 seconds apart) indicate that application of a Taser for a period of 5 seconds is unlikely to result in inappropriate therapy delivery.
- 6.10 The effect of Taser outputs of other active implantable devices, such as cochlear implants and nerve stimulators, has not been reported. It is unlikely that the effects will be long-term or life-threatening, although patient distress is possible should the devices malfunction.
- 6.11 The age profile of cardiac pacemaker recipients is significantly different from the overall population and that of persons arrested in situations where a Taser may be deployed. The probability of an individual wearing a pacemaker being present in such a situation is therefore likely to be considerably lower than the overall incidence of pacemakers in the population (0.45%).

7 **Recommendations**

- 7.1 All persons exposed to the output of an Advanced Taser M26 unit should be examined by a medical professional as soon as possible after the exposure incident. This is fully addressed in Sections 11.6 and 11.7 of the ACPO¹⁶ Operational Guidance document [26], and no changes are required.
- 7.2 The need for immediate referral to a hospital where officers are informed or come to believe that a person to whom the Taser has been applied is wearing a cardiac pacemaker is contained in Section 11.6 of the Operational Guidance document [26]. It is recommended that this section is altered to refer to other active implantable devices, and not just cardiac pacemakers.
- 7.3 In order to minimise the probability of the implanted device being located in the current path taken by the Taser output, the Taser barbs should not be aimed at the head or the pectoral area. This is addressed in section 9.5 of the Operational Guidance document [26], and no changes are required.
- 7.4 The clinical significance of short-term reversible changes in pacemaker function should be discussed by DOMILL. The literature reviewed for this report suggests that there may be some physiological effects arising from change of pacemaker function to noise reversion mode, but further investigation is required to assess the extent and short-and long-term significance of these effects. The view of the clinical neurophysiologist advising DOMILL on Taser should be obtained.
- 7.5 Dstl's view is that, on balance, there is no requirement to undertake experimental studies on the vulnerability of active implantable medical devices to the output of the Advanced Taser M26 unit.

¹⁶ ACPO – Association of Chief Police Officers

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Appendix D – "Medical implications of the use of the M26 Taser – the effects of drugs of abuse on the cardiac action potential in sheep isolated Purkinje fibres."

DSTL/PUB20751 15 January 2004

Executive summary

Background

The work described in this report was performed under contract to PSDB¹⁷ and forms part of the assessment of the potential health risks associated with use of the Taser electrical incapacitation device. In a Dstl review¹⁸ of the medical implications of Taser use, the heart was identified as the principal organ at risk of being adversely influenced by the Taser current and a cardiac risk assessment strategy was put forward.

One aspect of the proposed strategy was predicated on the observation that many of the individuals targeted by Tasers in the US were concurrently intoxicated with drugs of abuse and that, where deaths had occurred in association with Taser use, the presence of drugs was considered to be a confounding factor in establishing causation. The question therefore arose as to whether intoxication by drugs could, irrespective of Taser deployment, predispose the heart to potentially lethal rhythm disturbances which, in the context of an emotionally charged confrontation, may have serious adverse consequences.

The present report describes the findings of the part of the cardiac risk assessment designed to evaluate any intrinsic pro-arrhythmic¹⁹ actions of a series of common substances of abuse. The second part of the cardiac risk assessment will look at the effects of a Taser-like discharge directly applied to the myocardium in an isolated and perfused whole heart preparation. The outcome of this will form the basis of a separate report.

Requirement and Scope of Work

PSDB has tasked Dstl with assessing the pro-arrhythmic potential of seven drugs of abuse in an *in vitro* heart preparation (sheep isolated Purkinje fibre). Drug-induced prolongation of the intracellularly recorded action potential in this preparation is thought to be predictive of the risk of development of a particular type of potentially lethal arrhythmia in humans, termed *torsades de pointes*²⁰. This ventricular arrhythmia can be fatal if it fails spontaneously to revert to normal rhythm.

Seven drugs of abuse have been examined for their ability to prolong the cardiac action potential in sheep isolated Purkinje fibres. This report will contribute to the overall understanding of the cardiac risk associated with Taser deployment on individuals intoxicated with substances of abuse.

²⁰ The development of *torsades de pointes* is associated with an increase in the QT interval of the electrocardiogram which, at the level of the single heart cell, is caused by prolongation of the action potential.

¹⁷ Police Scientific Development Branch of the Home Office.

¹⁸ Report reference DSTL/PUB20749.

¹⁹ The term 'pro-arrhythmic' denotes an action of a drug that predisposes the heart to disturbance of rhythm.

Main Findings

Seven substances of abuse have been studied for their effects on the intracellularly recorded action potential in sheep isolated Purkinje fibres, namely, cocaine, cocaethylene, 3,4-methylenedioxymethamphetamine (MDMA; "ecstasy"), (+)-methamphetamine, morphine, phencyclidine and Δ^9 -tetrahydrocannabinol. The drugs were studied over concentration ranges relevant to those found in the plasma of intoxicated individuals.

The following action potential parameters were monitored: APD_{50} and APD_{90} (action potential duration at 50% and 90% repolarisation), V_{max} (maximum rate of rise of the action potential upstroke), diastolic membrane potential and action potential amplitude (APA). Of particular relevance to pro-arrhythmic potential is prolongation of the APD.

Following a period of stabilisation, fibres (four per treatment group) were exposed to each concentration of drug for 30 minutes using a cumulative dosing protocol. Fibres were stimulated at 1 Hz throughout. The effects of the drugs were compared statistically with a time-and vehicle-matched control group exposed to 0.01%, 0.019% and 0.109% v/v dimethylsulphoxide (a solvent commonly used in biological studies to dissolve drugs).

- Cocaine (0.01, 0.1, 1 μM), (+)-methamphetamine (0.05, 0.5, 5 μM) and the heroin metabolite, morphine (0.05, 0.5, 5 μM), had no statistically significant effect on any of the monitored cardiac action potential parameters.
- Δ^9 -tetrahydrocannabinol (0.01, 0.1, 1 µM) induced a small (+4.8%) increase in APD₉₀, when applied at 0.1 µM (*P* < 0.05), but prolongation was not evident at 1 µM.
- **MDMA** (0.1, 1, 10 μ M) induced a moderate (+12.1%) increase in APD₉₀ at the highest concentration (*P* < 0.05).
- **Phencyclidine** (0.05, 0.5 and 5 μ M) exerted a concentration-dependent prolongation of the action potential: APD₉₀ was increased by +7.5% at 0.5 μ M and by +30.7% at 5 μ M (both *P* < 0.001). An increase in APD₅₀ (+22.8%; *P* < 0.01) was also observed at the highest concentration.
- **Cocaethylene** (0.1, 1, 10 μ M) is a major metabolite formed when cocaine is used concurrently with alcohol. Cocaethylene (10 μ M) induced profound decreases in APD₅₀ (-39.0%) and APD₉₀ (-23.8%) (both *P* < 0.001). APA was also reduced (-7.2 mV) at the highest cocaethylene concentration (*P* < 0.01).

Conclusions

Seven recreational drugs or their active metabolites have been examined in an *in vitro* heart preparation for their potential to induce a malignant ventricular arrhythmia known as *torsades de pointes*.

Two of the drugs tested (MDMA and phencyclidine) produced action potential prolongation, suggesting that they may induce QT prolongation in humans and thereby raise the risk of development of *torsades de pointes*.

Although cocaine, cocaethylene and (+)-methamphetamine did not induce action potential prolongation, a critical review of the scientific and clinical literature revealed that these drugs still have the potential to influence cardiovascular function in a way that could precipitate a life-threatening cardiac event.

The clinical literature suggests that morphine (the principal metabolite of heroin) and Δ^9 -tetrahydrocannabinol (the principal psychoactive component of cannabis) are relatively benign in terms of cardiovascular toxicity. This is further borne out by their relative lack of effect in the present study.

The results from the study, together with evidence from the literature, suggest that some frequently used recreational drugs have the potential to contribute to any cardiac-related morbidity or mortality that may arise in the context of Taser use. Furthermore, it seems reasonable to assume that this conclusion could be generalised to other emotionally charged and possibly violent confrontations with law enforcement personnel.

The adverse cardiac effects produced by any individual drug are dependent on several factors including dose consumed, co-use with other drugs (including pharmaceutical drugs and ethanol) and pre-existing heart disease. Genetic factors and gender will undoubtedly also play a role in determining the adverse drug reaction profile in individual users. This complex interplay of multiple risk factors could conceivably contribute to any cardiac-related morbidity or mortality associated with Taser use against drug-intoxicated persons. The authors do not believe that knowledge of a person's drug intoxication status can rationally be used to make field-based decisions on Taser use. However, officers should be aware that the risk of any adverse response in the aftermath of Taser deployment may be higher in drug-impaired individuals and, accordingly, they should be vigilant of any unusual signs exhibited (or symptoms reported) by the apprehended person that may indicate the need for early medical intervention.

Recommendations

It is recommended that on the basis of these data:

- The extant DOMILL statement on the medical implications of the use of the M26 Advanced Taser (DSTL/CBS/BTP/PAT-ACPO/MAN/REP/4 dated 9 Dec 02) does not currently require amendment;
- The ACPO Taser Operational Trial Guidance (25 Feb 03) and ACPO Taser Training Module (25 Feb 03) do not require amendment.

Subsequent studies will determine whether the Taser current can modify cardiac rhythm by a direct effect on the myocardium. It is recommended that the effect on the threshold for Taser-induced adverse cardiac events of the drugs that extended QT interval, be assessed. Subsequent to these studies, the DOMILL statement should be reviewed again.
1 Introduction

1.1 Rationale behind the present study

- 1.1.1 The work described in this report was performed under contract to the Police Scientific Development Branch (PSDB) of the UK Home Office. It forms part of the assessment of the potential health risks associated with use of the Taser electrical incapacitation device. In a review by Dstl of the medical implications of Taser use²¹, the heart was identified as the most important organ likely to be adversely affected by the Taser current and a cardiac risk assessment strategy was proposed by Dstl. This strategy was also declared by DOMILL²² in a statement on the Medical Implications of M26 Taser use (December 2002), placed in the House of Commons Library. The risk assessment strategy encompassed the following approaches:
 - A review of possible effects of Taser deployment on the function of cardiac pacemakers and other less commonly encountered electronic implantable devices.
 - Computer modelling of Taser current distribution within the human body, in an effort to determine the shape and magnitude of the waveform arriving at the heart.
 - Investigation of the effect of the modelled Taser waveform on electrical activity in the perfused guinea-pig heart *in vitro*.
 - Investigation of a series of substances of abuse for pro-arrhythmic actions in the sheep isolated cardiac Purkinje fibre preparation *in vitro*.
- 1.1.2 This last approach was driven by the observation that many of the individuals targeted by Tasers in the US were intoxicated with drugs of abuse and that, where deaths had occurred in association with Taser use, the presence of drugs proved to be a confounding factor in establishing causation [Ordog *et al.*, 1987]. The question therefore arose as to whether intoxication by drugs could, independently of Taser deployment, predispose the heart to a potentially lethal rhythm disturbance which, in the context of an emotionally charged confrontation, could tip the balance between life and death.
- 1.1.3 The present report describes the findings of the part of the cardiac risk assessment designed to evaluate any intrinsic pro-arrhythmic²³ actions of a series of common substances of abuse. The second part of the cardiac risk assessment will look at the effects of a Taser-like discharge directly applied to the myocardium in an isolated and perfused whole heart preparation. The outcome of this will form the basis of a separate report.

1.2 Study objective

- 1.2.1 The purpose of this study is to evaluate the electrophysiological effects of a series of commonly used substances of abuse on the action potential recorded in sheep isolated cardiac Purkinje fibres. Effects on the following action potential parameters were investigated (see Figure 1):
 - Action potential duration at 50% and 90% repolarisation (APD₅₀, APD₉₀).
 - Maximum rate of rise of the action potential upstroke (V_{max}).
 - Action potential upstroke amplitude.
 - Diastolic membrane potential (DMP).

²¹ Report reference DSTL/PUB20749

²² DOMILL : Defence Scientific Advisory Council (DSAC) sub-committee on the Medical Implications of Less Lethal Weapons.

²³ The term 'pro-arrhythmic' denotes an action of a drug that predisposes the heart to disturbance of rhythm.



Figure 35: Parameters of the action potential

- 1.2.2 The seven substances of abuse selected for study were cocaine, cocaethylene²⁴, 3,4-methylenedioxymethamphetamine (MDMA, "ecstasy"), methamphetamine ("speed"), morphine²⁵, phencyclidine (PCP, "angel dust"), Δ^9 -tetrahydrocannabinol (principal active component of cannabis).
- 1.2.3 The hERG channel blocking drug, *dl*-sotalol hydrochloride, was used as a reference item to confirm the sensitivity of the test system to a compound with well-established action potential prolonging effects.

1.3 The heart – basic principles

1.3.1 The effective circulation of the blood is critically dependent upon the synchronised and regular contraction of the heart. Under normal circumstances each contraction is initiated by a wave of electrical activity (termed depolarisation) which emanates from specialised pacemaker cells located in the sinoatrial node (Figure 2). This wave of depolarisation travels down the atria causing them to contract (the right atrium sending deoxygenated blood in the right ventricle and the left atrium sending freshly oxygenated blood into the left ventricle). At the same time, the wave of depolarisation is transmitted to the atrioventricular node, via internodal conduction fibres. The atrioventricular node represents the "point of entry" of the wave of depolarisation into the ventricular conducting system. A network of specialised conducting tissue comprising the bundle of His, the left and right bundle branches and the Purkinje fibres, then ensures that the wave of excitation is transmitted in a co-ordinated way throughout the ventricles (the left ventricle sending freshly oxygenated blood into the systemic circulation, while the right ventricle sends deoxygenated blood into the pulmonary circulation). Relaxation (repolarisation) of the atrial and ventricular tissues follows the wave of depolarisation and the cycle is then ready for the initiation of another contraction.

²⁴ Cocaethylene is a metabolite formed when cocaine and alcohol are consumed concurrently [Rafla & Epstein, 1979; Smith, 1984].

²⁵ Heroin (diacetylmorphine) is rapidly converted firstly to 6-monoacetylmorphine and then to morphine [Boerner et al., 1975; Inturrisi *et al.*, 1986; Cone *et al.*, 1991; Jenkins *et al.*, 1994; Rentsch *et al.*, 2001]. For this reason morphine, rather than heroin, was selected for study.



Figure 36: Structure of the heart

1.4 Electrophysiological basis of the electrocardiogram (ECG)

1.4.1 The wave of depolarisation that accompanies each contraction of the heart may be readily monitored via ECG electrodes attached to the skin. Conventionally,



electrode leads are attached to the arms, legs and chest and the ECG is derived by recording from various permutations of these leads. A typical ECG signal might appear as shown in Figure 3 (*lower trace*). The signal generated during contraction of the atria is known as the P wave, while that generated during contraction of the ventricles is termed the QRS complex. The signal generated when the ventricles relax (a process known as repolarisation) is termed the T wave. Repolarisation of the atria is not seen in the ECG, partly because of the smaller muscle mass (and therefore weaker signal) and partly because any signal is swamped by the larger signal from the ventricles.

Figure 3: Electrophysiological basis of the ECG

At the level of the individual heart cell, depolarisation and repolarisation may be monitored using an intracellular electrode. The signal measured in this

way is termed the cardiac action potential (*upper traces* in Figure 3). The ECG trace corresponds to the time-averaged activity of individual heart cells, the main difference between the cardiac action potential and the ECG being that the latter is effectively a mathematically differentiated form of the intracellularly recorded signal.

1.5 Ionic currents underlying the cardiac action potential

Cardiac action potentials are shaped by the ion channel composition of the cell membrane. Figure 4 shows some of the principal voltage-dependent currents involved in this shaping (the



Figure 4: Currents shaping the action potential

term *voltage dependence* refers to the dependence of channel opening and closing on the membrane potential).

The initial fast upstroke depolarisation is formed by the rapid influx of Na⁺ ions into the cell through voltage-dependent Na⁺ channels. As these Na⁺ channels close, various types of Ca²⁺ and K⁺ currents come into play. When Na⁺ and Ca²⁺ currents flow the membrane potential becomes less negative (i.e. becomes depolarised and <u>more</u> excitable). Conversely, when K⁺ currents flow the membrane potential becomes more negative (i.e. becomes hyperpolarised and <u>less</u> excitable).

The channel of most relevance to the present study is the channel that conducts the I_{Kr} current. This current, also known as the rapid activating delayed rectifier K^+ current, is the principal determinant of the duration of the cardiac action potential – it is responsible for repolarisation of the action potential.

When the contribution of the I_{Kr} current to repolarisation is reduced (as can happen if the channel is blocked by a drug molecule), the action potential

duration becomes increased. It is this increase that has the potential to be dangerous (see Section 1.7).

1.6 Cardiac action potential duration determines the QT interval

1.6.1 The QT interval of the ECG is the time interval between ventricular depolarisation and ventricular repolarisation (Figure 3). At the cellular level, anything that increases action potential duration will simultaneously increase the QT interval.

1.7 Why should QT interval prolongation be a cause for concern?

1.7.1 QT interval prolongation can be either congenital (so-called long QT syndrome) or acquired (i.e. induced pharmacologically). Congenital long QT syndrome, which has been estimated to afflict 1 in 5000 of the population [Kass & Moss, 2003], can arise from mutations in the gene encoding the cardiac Na⁺ channel (leading to a failure of the channel to switch off during the plateau phase of the action potential) or mutations in the genes encoding the channels conducting I_{Kr} and I_{Ks} (leading to a reduced contribution of these currents to repolarisation) [Kass & Moss, 2003]. People with congential long QT syndrome are at increased risk of developing a

malignant ventricular arrhythmia (called *torsades de pointes*) and experiencing sudden cardiac death [Kass & Moss, 2003].

1.7.2 Acquired QT interval prolongation (i.e. prolongation induced as a side-effect by therapeutic drugs) has attracted much interest over the past ten years, partly because it has the potential to affect a much larger number of people and partly because many drugs have been found to prolong QT interval [Redfern *et al.*, 2003]. The most common mechanism of

QT interval prolongation by pharmaceutical drugs appears to be inhibition of the delayed



Figure Figure 5: ECG showing *torsades de pointes* arrhythmia

rectifier potassium channel that is responsible for conducting I_{Kr} [Yapp & Camm, 2000; Belardinelli *et al.*, 2003; Redfern *et al.*, 2003].

1.8 Many pharmaceutical drugs block I_{Kr} as a side-effect

- 1.8.1 Drug-induced increase in action potential duration and QT interval (via block of I_{Kr}) is exploited clinically to treat certain types of arrhythmia. However, there are many pharmaceuticals that induce QT interval prolongation as a sideeffect, and many of these have been associated with the development of torsades de pointes (see www.torsades.org for a regularly updated list). Examples of drugs that are generally accepted by regulatory authorities to increase the risk of *torsades de pointes* are the antibiotic, erythromycin, and the antipsychotic, haloperidol. In total, there are more than 30 clinically used drugs for which there is strong evidence for a link to the development of torsades de pointes and at least that number again that are regarded as potential pro-arrhythmics. The molecular diversity of the many pharmaceutical compounds that block I_{Kr} , prolong the cardiac action potential, increase QT interval and elevate the risk of torsades de pointes, is evidence that the structural requirements for block of the ion channel that conducts I_{Kr}^{26} are not rigorous.
- 1.8.2 Drug-induced *torsades de pointes* has become such a high profile safety issue over the past five years that international pharmaceutical regulatory authorities now insist that all new pharmaceutical compounds are tested for their arrhythmogenic potential in both *in vivo* and *in vitro* test systems [ICH, 2002²⁷].

1.9 Reverse rate-dependency of I_{Kr} block

1.9.1 The phenomenon of reverse rate-dependency refers to the observation that most blockers of I_{Kr} induce a bigger prolongation of the cardiac action potential at slower heart rates than at faster heart rates. As prolongation of the action potential underlies QT prolongation and, since QT prolongation is associated with development of *torsades de pointes*, the implication is that *torsades* is more likely to develop at a slower heart rate.

²⁶ In humans the channel that conducts I_{Kr} is termed the hERG channel. hERG is an abbreviation of human ether-àgo-go related gene (in reference to a mutation in the analogous drosophila gene, in which there is ether-induced leg shaking behaviour). ²⁷ ICH is the contracted abbreviation for the International Conference on Harmonisation of Technical Requirements

²⁷ ICH is the contracted abbreviation for the International Conference on Harmonisation of Technical Requirements for Registration of Pharmaceuticals for Human Use. It comprises regulatory authorities and pharmaceutical industry experts from Europe (including UK), Japan and the US. ICH produces guidelines relating to pharmaceutical product registration. The guideline relating to the testing of drugs for pro-arrhythmic risk is referred to as 'ICH S7B' (downloadable from the safety pharmacology guideline section at www.ich.org).

1.10 In vitro test systems for predicting pro-arrhythmic effects of drugs

- 1.10.1 The two *in vitro* test systems most commonly used for screening pharmaceutical drugs for potential pro-arrhythmic properties are:
 - Intracellular recording of the action potential in isolated cardiac Purkinje fibres.
 - Patch clamp recording of hERG currents expressed in single cells.
- 1.10.2 The two test systems are complementary. The advantage of the Purkinje fibre preparation is that the response evaluated (namely, action potential prolongation) can be directly related to QT interval prolongation. The disadvantage is that the test system is not human-derived and that it may be difficult to interpret the effects of drugs with actions on multiple currents. The advantage of the hERG current test system is that it provides a measure of the effect of a drug on a human-derived ion channel, although any effect seen must then be interpreted in terms of implications for the whole heart. The potency with which a drug blocks the hERG current is expressed in terms of its IC_{50} (the concentration of drug inhibiting the current by 50%).

2 Materials and methods

2.1 Test system

2.1.1The test system consisted of cardiac Purkinje fibres isolated from the left ventricles of male sheep (offspring of Charollais ram x mule ewe) bred on Dstl Farm. A total of 72 sheep were culled during the period 7 July 2003 to 4 November 2003, of which fibres from 34 sheep hearts contributed to the final dataset (the fibres from the remaining 38 animals being excluded on the basis of poor quality intracellular impalements or spontaneous activity). The weight range of the 34 sheep used in the study was 51.1 ± 13.2 kg (mean \pm SD). Sheep were killed in the Dstl Farm slaughterhouse by captive bolt stunning, followed immediately by exsanguination. The chest was opened and the heart rapidly removed and submerged in cold physiological salt solution (PSS), pregassed with 95% $O_2/5\%$ CO₂, in order to expel as much blood as possible. The left ventricle was opened and free-running Purkinje fibres isolated and transferred to screw-capped glass vials containing chilled pre-gassed PSS. The time interval between captive bolt administration, isolation and subsequent transfer of fibres to chilled PSS was $7.3 \pm 1.1 \text{ min} (\text{mean} \pm \text{SD})$. Isolated fibres were transported to the study laboratory, where they were transferred to a holding chamber containing gassed PSS at ambient temperature (approximately 21°C). The composition of the PSS was (in mM): NaCl 129.0, KCl 4.0, CaCl₂ 1.8, MgCl₂ 1.1, NaH₂PO₄ 1.0, NaHCO₃ 20.0, Dglucose 11.0. The buffer was gassed with a mixture of 95% O₂ and 5% CO₂.

2.2 Recording of cardiac action potentials

2.2.1 After at least 30 minutes equilibration at room temperature, Purkinje fibres were transferred to a two channel recording chamber (one fibre per channel – see Figure 6).



Figure 6: Two channel recording chamber

Each fibre was pinned to the Sylgard base of the chamber using entomological pins and positioned over a pair of silver stimulation electrodes, which were used to pace the fibres at a frequency of 1 Hz. The recording chambers were perfused at about 10 ml/min with gassed Tyrode solution at approximately 36°C. Electrical pacing was started at least 15 minutes after transfer of the fibres to the recording chamber using square-wave constant voltage pulses of

about 0.05 ms duration and intensity about 20% above the threshold for eliciting contraction of the fibre (visible under the dissection microscope). Fibres were impaled using glass micropipettes filled with 3 M KCl. Cardiac action potentials were then monitored over the course of the next 15-30 minutes and, if they appeared stable, the experiment was continued.

2.3 Experimental design

Treatment	Concentrations		
dimethylsulphoxide (DMSO) vehicle	0.01% v/v	0.019% v/v	0.109% v/v
cocaine	0.01 µM	0.1 µM	1 μΜ
cocaethylene	0.1 µM	1 μΜ	10 µM
MDMA ('ecstasy')	0.1 µM	1 µM	10 µM
(+)-methamphetamine ('speed')	0.05 μΜ	0.5 μΜ	5 μΜ
morphine	0.05 μΜ	0.5 μΜ	5 μΜ
phencyclidine	0.05 μΜ	0.5 μΜ	5 μΜ
Δ^9 -tetrahydrocannabinol	0.01 µM	0.1 μΜ	1 µM

2.3.1 The study comprised 8 treatment groups:





Figure 7: Time-course of experiment

- 2.3.2 Once the cardiac action potential appeared to be stable, a 'pre-control' measurement of the five action potential parameters was made (Figure 7). A 'control' action potential was taken 15 minutes later. Drug was then applied at the low, medium and high concentrations (30 minutes at each concentration).
- 2.3.3 If there was little or no effect of the test drug after 30 minutes perfusion with the highest concentration, a reference drug (30 μ M *dl*-sotalol hydrochloride) was administered towards the end of the experiment to confirm the sensitivity of the test system. *dl*-Sotalol is a well-established inhibitor of the K⁺ current, I_{Kr}, that is primarily responsible for determining the duration of the action potential (see Section 1.5).

2.4 Reverse rate-dependency experiments

2.4.1 Where a test drug was found to induce action potential prolongation, this effect was examined in closer detail. Reverse rate-dependency (see Section 1.9) was examined by comparing the prolongation produced by the highest concentration of the drug at two pacing frequencies: 1 Hz and 3 Hz. A drug displaying the characteristics of reverse rate-dependent prolongation would be expected to induce a larger prolongation at 1 Hz than at 3 Hz.

2.5 Data acquisition

2.5.1 Action potential data were digitised at a sampling rate of 25 kHz using the *eDacq* (Version 1.1.17) data acquisition system (Electro-Medical Measurement Systems, Unit 12 Woolmer Way, Bordon, Hampshire GU35 9QF, UK).

2.6 Data analysis

- 2.6.1 Digitised action potentials were analysed by the data acquisition software to derive the following parameters: APD_{50} , APD_{90} , V_{max} , diastolic membrane potential and upstroke amplitude (Figure 1). Average values for the parameters were obtained from 29-30 action potentials at each of the relevant time points (indicated by the vertical down arrows in Figure 7).
- 2.6.2 For each parameter, the change from the respective control value for each fibre in each treatment group was derived. (The control value for each parameter was taken from the action potential captured at the '0 minutes' time point in Figure 7). For APD₅₀, APD₉₀ and V_{max} , the changes from control were calculated as a percentage, while changes from control for upstroke amplitude and diastolic membrane potential were calculated in absolute units (mV).

2.7 Statistical analysis

- 2.7.1 For each of the parameters, the data from the seven test drug groups and the DMSO vehicle group (changes from control at the 30, 60 and 90 minute time points) were initially analysed by a multivariate analysis of variance procedure (MANOVA) followed, where an overall statistically significant interaction was detected, by a one-way ANOVA (to determine at which of the three concentrations the significant interaction occurred). Finally, the Tukey-Kramer Multiple Comparison test was performed to determine which of the test drug treatments differed significantly from DMSO vehicle.
- 2.7.2 Statistical analysis was performed using NCSS software (Kaysville, Utah; <u>www.ncss.com</u>).

2.8 Test drugs and DMSO vehicle

2.8.1 Details of the test drugs are given in Table 2. All test drugs were sourced from Sigma-Aldrich UK. The drugs were initially formulated in dimethylsulphoxide (DMSO) at 1000-fold the highest concentration to be tested (see Table 1). A ten-fold dilution of the initial formulation (in DMSO) was also prepared. Appropriate volumes of these formulations were added to the PSS perfusing the fibres in order to achieve the final desired concentrations.

Supplement to HOSDB Evaluations of Taser Devices

Test drug	Lot No.	Formu	lations
cocaine hydrochloride	59H0640	1 mM	0.1 mM
cocaethylene base	50K4056	10 mM	1 mM
MDMA hydrochloride ('ecstasy')	112K4095	10 mM	1 mM
(+)-methamphetamine hydrochloride ('speed')	052H0132	5 mM	0.5 mM
morphine sulphate pentahydrate	102K1353	5 mM	0.5 mM
phencyclidine hydrochloride (PCP)	033K4070	5 mM	0.5 mM
Δ^9 -tetrahydrocannabinol base (Δ^9 -THC)	092K8800	1 mM	0.1 mM

Table 15: Test drugs

2.9 Justification for selection of test drug concentrations

2.9.1 Each of the drugs was examined over a three orders of magnitude range of concentrations (Table 1). These concentration ranges were designed to bracket plasma concentrations that have been reported in users (see Table 3).

Test drug	Reported plasma concentration range (µM)	Reference	
cocaine	0.053 - 0.43	Williams et al. (2000)	
cocaethylene	0.78	Bailey (1996)	
MDMA ('ecstasy')	0.12 – 1.65 1.8	Samyn <i>et al.</i> (2002) Helmlin <i>et al.</i> (1996)	
(+)-methamphetamine ('speed')	0.09 - 2.01	Schepers et al. (2003)	
morphine (heroin metabolite)	0.12 - 2.17	Darke et al. (1997)	
phencyclidine (PCP)	0.04 - 3.34	Bailey (1979)	
Δ^9 -tetrahydrocannabinol	0.02 - 0.09	Cone & Huestis (1993)	

Table 16: Plasma levels of drugs reported in humans

3 Results

The effects of each drug are compared graphically with the effects seen in the DMSO vehicle group (graphs show means \pm s.e. mean; 4 fibres per data point). The effects of drug treatment are expressed in the text as mean differences from the DMSO group \pm s.e. mean difference.

3.1 Cocaine

3.1.1 The effects of cocaine on the five action potential parameters are shown in Figure 8. There were no significant differences between the effects seen with cocaine and those seen with DMSO vehicle.



Figure 8: Effects of cocaine on the cardiac action potential

3.2 Cocaethylene

3.2.1 When applied for 30 minutes at the highest concentration (10 μ M), cocaethylene induced statistically significant reductions in APD₅₀ (-39.0 ± 7.6%; *P* < 0.001), APD₉₀ (-23.8 ± 5.1%; *P* < 0.001) and action potential amplitude (-7.2 ± 1.9 mV; *P* < 0.01) relative to the DMSO vehicle group (Figure 9).



Figure 9: Effects of cocaethylene on the cardiac action potential

3.3 MDMA (ecstasy)

3.3.1 When applied for 30 minutes at the highest concentration (10 μ M), MDMA induced a statistically significant increase in APD₉₀ (+12.1 ± 2.8%; *P* < 0.05) relative to the DMSO vehicle group (Figure 10).



Figure 10: Effects of MDMA on the cardiac action potential

3.4 (+)-Methamphetamine ('speed')

3.4.1 The effects of (+)-methamphetamine on the five action potential parameters are shown in Figure 11. There were no significant differences between the effects seen with (+)-methamphetamine and those seen with DMSO vehicle.



Figure 11: Effects of (+)-methamphetamine on the cardiac action potential

3.5 Morphine

3.5.1 The effects of morphine on the five action potential parameters are shown in Figure 12. There were no significant differences between the effects seen with morphine and those seen with DMSO vehicle.



Figure 12: Effects of morphine on the cardiac action potential

3.6 Phencyclidine (PCP)

3.6.1 Relative to the DMSO vehicle group, phencyclidine $(0.5 \ \mu\text{M})$ induced a statistically significant increase in APD₉₀ (+7.5 ± 1.5%; *P* < 0.001). When applied at the highest concentration (5 μ M), phencyclidine induced statistically significant increases in both APD₅₀ (+22.8 ± 3.0%; *P* < 0.01) and APD₉₀ (+30.7 ± 2.8%; *P* < 0.001) relative to the DMSO vehicle group (Figure 13).



Phencyclidine concentration (µM)

Figure 13: Effects of phencyclidine on the cardiac action potential

3.7 Δ^9 -Tetrahydrocannabinol (Δ^9 -THC)

3.7.1 Δ^9 -THC (0.1 µM) induced a small, but statistically significant, increase in APD₉₀ relative to the DMSO vehicle group (+4.8 ± 0.9%; *P* < 0.05). This apparent increase did not carry through to the highest concentration tested (Figure 14).



Figure 14: Effect of Δ^9 -THC on the cardiac action potential

3.8 Reverse rate dependency of the APD prolongation induced by PCP and MDMA

- 3.8.1 The reverse rate dependent effects of PCP and MDMA were investigated in two fibres.
- 3.8.2 Phencyclidine (PCP) : The APD₉₀ values of the action potential before exposure to PCP were 276 ms, at a pacing frequency of 1 Hz, and 248 ms at 3 Hz pacing (Figure 15; upper traces). After application of 5 μM PCP for 30 minutes, the APD₉₀ values at 1 Hz and 3 Hz were 333 ms and 262 ms, respectively. The increases in APD₉₀ were 57 ms at 1 Hz pacing and 14 ms at 3 Hz pacing.



Figure 15: Reverse rate dependent prolongation by PCP

3.9 Effect of the reference drug, *dl*-sotalol, on the action potential

- 3.9.1 dl-Sotalol (30 µM) was applied towards the end of all the experiments in which the test drug failed to increase APD₉₀. The effects of *dl*-sotalol on APD₉₀ are summarised in Figure 17. The figure shows the mean percentage changes (± s.e. mean) in diastolic membrane potential (DMP), action potential amplitude (APA), APD₅₀, APD₉₀ and V_{max} induced by 30 µM *dl*-sotalol applied after the effect of the highest concentration of test drug (or DMSO vehicle) had been recorded. The positive APD₉₀ response to *dl*-sotalol indicates that the fibres in all treatment groups were capable of responding to inhibition of I_{Kr} with a prolongation in action potential duration.
- 3.9.2 Interestingly, when *dl*-sotalol was applied to fibres which had been treated with cocaethylene, the reference drug failed to induce prolongation. Potential reasons for this lack of effect are considered in Section 4 (Discussion).

3.9.3 *dl*-Sotalol was not applied to fibres which had been treated with MDMA or PCP (see Section 2.3).



Figure 17: Effect of *dl*-sotalol on the cardiac action potential

4 Discussion

4.1 Introduction

- 4.1.1 A series of illicit drugs has been tested in an *in vitro* heart preparation to gain insight into their potential pro-arrhythmic effects and thereby to assist understanding of any health risks associated with Taser deployment and use. Not withstanding the use of the Taser, the results also have wider implications, as they suggest a potential cardiac risk for three of the tested drugs that hitherto had not been systematically evaluated either clinically or in the laboratory.
- 4.1.2 The drugs tested in the present study were selected after discussions between Dstl and the Police Scientific Development Branch (PSDB). The list includes some of the most common drugs abused by the highest use age group (16-24 year olds; see Table 4). Also included were cocaethylene (a metabolite formed when cocaine and alcohol are consumed concurrently) and PCP which, although rarely abused in the UK, is used in the US and has been associated with Taser fatalities (Ordog *et al.*, 1987; Kornblum & Reddy, 1991).

H.O. report 'Findings 229'*	Drug evaluated in study	Percentage of 16-24 year olds ²⁸	Estimated number of users (16-24 year olds) ²⁹
cannabis	Δ^9 -tetrahydrocannabinol base (Δ^9 -THC)	16.2	1,497,000
ecstasy	3,4-methylenedioxymethamphetamine hydrochloride (MDMA)	2.6	312,000
cocaine	cocaine hydrochloride	1.9	270,000
amphetamines	(+)-methamphetamine hydrochloride ('speed')	1.7	216,000
heroin	morphine sulphate pentahydrate (heroin metabolite)	0.1	12,000
	cocaethylene base (not cited in <i>Findings</i> 229*)	not applicable	not applicable
	phencyclidine hydrochloride (not cited in <i>Findings 229*</i>)	not applicable	not applicable

Table 17 Prevalence of drug misuse. *Adapted from H.O. publication "Prevalence of drug use: key findings from the 2002/2003 British Crime Survey" (*Findings 229*).

4.1.3 The effect of each of the test drugs on the action potential in ovine isolated cardiac Purkinje fibres is discussed separately.

4.2 Cocaine

4.2.1 Cocaine had no effect on the cardiac action potential over the concentration range tested (0.01 to 1 μ M). This null finding contrasts with reports in the literature of cocaine-induced action potential prolongation in feline isolated ventricular myocytes (significant prolongation at 10 μ M; Kimura *et al.*, 1992)

²⁸ Estimates are based on a single month in 2003.

²⁹ Estimates are based on 2002 figures.

and guinea-pig isolated ventricular myocytes (significant prolongation at 3 μ M; Clarkson *et al.*, 1996). However, the study deliberately set out to constrain the top end of the range of cocaine concentrations tested to a value which was marginally above the top end of the range of concentrations measured in a sample of cocaine users (0.43 μ M; Williams *et al.*, 2000). Concentrations as high as 20 μ M have been measured in the plasma of cocaine overdose fatalities (Mittleman & Wetli, 1984), but the authors consider it improbable that such high plasma concentrations would be encountered in individuals likely to be confronted with a Taser. Nevertheless, it is conceivable that had a cocaine concentration of 1 μ M been exceeded, then an action potential prolongation in the sheep Purkinje fibre preparation would have been encountered.

- 4.2.2 Cocaine has been reported to block hERG currents with IC50 values reported to be 4.4 μ M (Ferreira et al., 2001), 5.6 μ M (O'Leary, 2001) and 7.2 μ M (Zhang et al., 2001). These observations are consistent with the reports of action potential prolongation described above.
- 4.2.3 There is some evidence of cocaine-induced QT prolongation in humans (Perera et al., 1997; Singh et al., 2001), together with lethal arrhythmia (Gamouras et al., 2000).
- 4.2.4 Possibly of greater relevance to the health risks of cocaine than QT prolongation is the observation that the risk of acute myocardial infarction is elevated by nearly 25-fold during the 60 minutes following cocaine use (Mittleman et al., 1999). The likely mechanisms underlying this are related to the well-established pharmacological actions of cocaine on the cardiovascular system. By inhibiting re-uptake of the neurotransmitter, noradrenaline, at post-ganglionic synapses of the sympathetic nervous system, cocaine elevates levels of noradrenaline, which then leads to over-stimulation of receptors (termed α and β -adrenoceptors) located on blood vessels and in the heart. The net result of this excess activity in the sympathetic nervous system is that blood pressure, heart rate and left ventricular contractility are raised and coronary blood vessels become constricted (for references see Mittleman et al., 1999). Cocaine may also promote platelet aggregation and thrombus formation (see Mittleman et al., 1999).
- 4.2.5 The risk of cocaine-related acute myocardial infarction is elevated both in individuals with no history of heart disease and in those with pre-existing heart disease, although the risk is higher in the latter group (Minor et al., 1991; Mittleman et al., 1999). Nevertheless, about 90% of those patients presenting with cocaine-induced myocardial infarction have no known history of heart disease (Bunn et al., 1992). It has been reported that the mortality rate from cocaine-induced myocardial infarction is 10% (Cregler, 1991).
- 4.2.6 Of relevance to the potential adverse cardiac effects of cocaine in the context of an individual involved in a Taser confrontation (or indeed any potentially violent confrontation with the police) is the finding that heavy physical exertion in itself may trigger acute myocardial infarction (Mittleman et al., 1993). The potential risk to the cocaine user is therefore two-fold: risk from the intrinsic adverse cardiovascular effects of cocaine coupled with the risk imposed by physical exertion (e.g. resisting arrest).

4.3 Cocaethylene

4.3.1 Cocaethylene had no effect on the cardiac action potential at the low and medium concentrations tested (0.1 μ M and 1 μ M), but produced a profound

shortening at the highest concentration (10 μ M). This finding is consistent with *in vivo* studies in dog in which cocaethylene induced marked dosedependent decreases in myocardial function at plasma concentrations ranging from about 5 to 20 μ M (Wilson *et al.*, 1995).

- 4.3.2 Although cocaethylene has been reported by Ferreira et al. (2001) to block hERG currents (IC50 = 1.2μ M) more potently than cocaine (IC50 = 4.4μ M), no action potential prolongation was seen in the present study. The authors suspect that the profound shortening of the cardiac action potential observed at the highest concentration was due to a blocking action of cocaethylene on Na+ and/or Ca2+ channels. Such an interpretation would be consistent with the significant decreases in APD50, APD90 and action potential amplitude, and with the trend towards a decrease in Vmax and small depolarisation of the diastolic membrane potential. Moreover, the failure of the reference drug, dlsotalol, to increase the action potential duration in fibres which had been treated with cocaethylene, implies that the IKr channel may have already been blocked by cocaethylene.
- 4.3.3 Thus, the overall picture from the Purkinje fibre studies is that cocaethylene is a non-selective blocker of several ion channels involved in generating the cardiac action potential.
- 4.3.4 Cocaethylene is a psychoactive metabolite of cocaine that is formed by hepatic transesterification of cocaine in the presence of ethanol (Rafla & Epstein, 1979; Smith, 1984). It has been speculated that the production of cocaethylene is responsible for the apparent 25-fold increase in risk of sudden death in individuals who co-use cocaine and ethanol (Bunn & Giannini, 1992).
- 4.3.5 When administered to human volunteers under clinically controlled conditions, cocaethylene and cocaine both induced increases in systolic blood pressure, although cocaethylene induced smaller increases in heart rate than equivalent doses of cocaine (Hart et al., 2000).
- 4.3.6 If the effects of cocaethylene on the sheep isolated Purkinje fibre preparation translate directly into humans, then one might anticipate that the metabolite had the potential, at least at higher plasma concentrations, to induce adverse changes in cardiac electrophysiology and predispose the heart to arrhythmia.

4.4 MDMA ("ecstasy")

- 4.4.1 At the highest concentration tested (10 μ M), MDMA prolonged APD₉₀ by about 12%. No other parameters were affected. This effect of MDMA displayed the reverse rate dependency characteristic of blockers of the ion channel that conducts I_{Kr}.
- 4.4.2 Under controlled clinical conditions, "recreational" doses of MDMA (75 or 125 mg orally) induce increases in systolic blood pressure (up 25-35 mmHg) and diastolic blood pressure (up 10-20 mmHg), an increase in heart rate (up 10-25 bpm), and an increase in body temperature (up 0.2-0.6°C) (Mas et al., 1999). In this study, the peak plasma concentration (Cmax) of MDMA in both dose groups was achieved within 2 to 2.5 hours after dosing: average Cmax of 0.8 µM after 75 mg dose and 1.4 µM after 125 mg dose (Mas et al., 1999). Unfortunately, no ECG data were collected during this study.
- 4.4.3 There is a single case report in the clinical literature where QT prolongation has been attributed to MDMA ingestion (Drake & Broadhurst, 1996). The authors describe an instance of a 25 year old man who was admitted to

hospital 5 hours after taking a single MDMA tablet. On arrival at the hospital the individual was "agitated, dehydrated, pyrexial (temperature 39°C) and sweating, with a pulse rate of 140/min and a blood pressure of 200/100 mmHg". ECGs taken at 8 and 24 hours after admission showed a rate corrected QT interval of 640 ms. (A rate corrected QT interval of <430 ms is considered normal in adult males. A QT interval >450 ms is considered to be prolonged.) Plasma concentrations of MDMA were not determined.

- 4.4.4 Drake & Broadhurst (1996) speculated that the QT prolongation induced by MDMA may have resulted from a direct action of the drug on ventricular muscle. The present data, obtained in the sheep cardiac Purkinje fibre preparation, lends support to this hypothesis. There are no reports in the scientific literature in which the effect of MDMA on hERG currents has been investigated.
- 4.4.5 Dowling et al. (1987) reported on five deaths associated with MDMA abuse. One of the deaths (Case 4) involved a previously healthy 18 year old female who had ingested approximately 150 mg of MDMA together with "an unknown amount of alcohol within a 60 to 90 minute period". She collapsed shortly afterwards and, on arrival of the paramedics, she was found to be in ventricular fibrillation. She was pronounced dead after attempts at resuscitation failed.
- 4.4.6 A case of sudden cardiac death linked to MDMA was reported by Suarez & Riemersma (1988). The individual, a 34 year old male, suffered from an untreated pre-existing heart condition known as Wolff-Parkinson-White syndrome. In this syndrome an anatomical defect between the atria and the ventricles enables the wave of excitation to bypass the atrioventricular node (see Section 1.3) and to activate the ventricles prematurely (Esberger et al., 2002). The individual had taken MDMA some hours before complaining of palpitations. His partner awoke in the early hours of the next day to see him gasping and convulsing. Upon arrival of the medical team he was found to be in ventricular fibrillation and resuscitation attempts were unsuccessful. The blood level of MDMA at autopsy exceeded 10 μM. It is conceivable, therefore, that MDMA cardiotoxicity, complicated by existing heart disease, precipitated the ventricular fibrillation.
- 4.4.7 Greene et al. (2003) reported on seven individuals (six 17-23 year old males and one 18 year old female) who had taken MDMA at the same nightclub and who were subsequently admitted to hospital with symptoms and signs of MDMA intoxication. One male individual (Case 1), who died from cardiac arrest one hour after admission, displayed a QRS complex of 230 ms (normal range 60-100 ms). His plasma MDMA level was 13.4 μ M. A second male individual (Case 2), who had a plasma MDMA level of 5.2 μ M, also displayed a prolonged QRS complex (217 ms). This patient died from liver failure 58 hours after admission. Although the electrocardiographic changes seen in these two fatalities may have resulted from a direct effect of MDMA on the heart, it is also possible that the QRS changes were secondary to the raised serum potassium levels in these two cases (7.7 mM in Case 1, 8.0 mM in Case 2; normal range is 3.5-5.0 mM).
- 4.4.8 MDMA is metabolised primarily by the liver cytochrome P450 enzyme, CYP2D6 (de la Torre et al., 2000). This has two potentially important implications. Firstly, within the population there is an ethnicity-related genetic variation (known as polymorphism) in the CYP2D6 enzyme, such that the population can be divided into 'extensive metabolisers' (estimated to

comprise 75-85% of the caucasian population), 'intermediate metabolisers' (10-15%), 'poor metabolisers' (5-10%) and 'ultrarapid metabolisers' (1-10%) (Meyer, 2000). Thus, despite ingestion of identical doses of MDMA, the poor metaboliser would be expected to experience a higher peak plasma concentration of the drug than the extensive metaboliser, with the consequence that signs of toxicity may be more likely to appear in the poor metaboliser (Burgess et al., 2000). Secondly, a large number of therapeutic drugs are also metabolised by the CYP2D6 enzyme (e.g. many antidepressant and antipsychotic drugs) and, if these were to be co-used with MDMA, both drugs would compete with the same enzyme (with the result that plasma levels of both drugs may be elevated). Again, the raised plasma MDMA levels would be more likely to lead to toxicity.

- 4.4.9 A further complicating factor in the behaviour of MDMA is the reported phenomenon of its non-linear pharmacokinetics (de la Torre et al., 2000). The consequence of this is that the plasma concentration of MDMA does not increase in proportion to the ingested dose. Instead, a small increase in the oral dose of MDMA can induce a disproportionately large increase in plasma concentrations (de la Torre et al., 2000). Thus, an individual who fails to achieve the desired 'high' following a single MDMA tablet, could ingest a second tablet and potentially achieve inappropriately high plasma concentrations.
- 4.4.10 The action potential prolonging action of MDMA in the sheep isolated Purkinje fibre preparation occurred at an MDMA concentration of 10 μ M. It is apparent from the studies cited above that this concentration is more likely to be at the toxic, rather than the recreational, end of the spectrum. It also raises the question of how likely it is that an individual with such high levels of MDMA circulating in the blood will need to be restrained using a Taser (as opposed to conventional physical methods).
- 4.4.11There is no consensus of opinion as to how much action potential prolongation is required for a drug to be considered as presenting a risk for the development of torsades de pointes arrhythmia. If MDMA were a conventional therapeutic drug being developed by a pharmaceutical company, the results from the sheep Purkinje study would suggest that the potential exists for the drug to induce ventricular arrhythmia at a concentration only 10-fold above that required for its 'therapeutic' effects. In pharmaceutical terms, this is not a particularly wide margin of safety. The pharmaceutical company would want to further evaluate this potential pro-arrhythmic effect in two ways. Firstly, they would want to establish the potency of MDMA to inhibit hERG currents. Secondly, they would want to perform in vivo studies either in dog or non-human primates instrumented for recording of cardiovascular parameters (electrocardiogram and blood pressure). All of these studies would be performed prior to Phase I clinical trials (i.e. the first introduction into humans), and they would be used to inform the strategy for the subsequent clinical studies that all drugs have to undergo prior to licensing.
- 4.4.12 Balanced against all the scientific evidence discussed above is the real-world experience with MDMA. This would tend to suggest that MDMA is relatively non-toxic (at least in respect of short-term life-threatening events). This is evidenced by the relatively few accounts of MDMA-associated morbidity and mortality reported in the international scientific literature despite the vast number of abusers (an estimated 312,000 16-24 year olds in the UK alone in 2002 see Table 4).

4.4.13 The authors would conclude that an individual using MDMA recreationally may be at an increased risk of suffering an adverse cardiac event, but that further studies are necessary to estimate the magnitude of that increased risk.

4.5 (+)-Methamphetamine ('speed')

- 4.5.1 (+)-Methamphetamine had no effect on the cardiac action potential over the concentration range tested (0.05 to 5 μ M). This lack of action potential prolongation is consistent with the absence of any reports in the scientific literature of (+)-methamphetamine-associated QT prolongation or associated *torsades de pointes* arrhythmia.
- 4.5.2 (+)-Methamphetamine, like MDMA, belongs to the class of substances collectively referred to as amphetamines (Figure 18). The psychoactive action of amphetamines is mediated primarily by stimulating release of the neurotransmitters, noradrenaline and dopamine, from nerve terminals in the brain (Rang *et al.*, 1999). In this regard, amphetamines exert an equivalent pharmacological effect to cocaine, which also increases levels of noradrenaline and dopamine by blocking uptake of these neurotransmitters into nerve terminals (Rang *et al.*, 1999a). The effects on the cardiovascular system of these three drugs are very similar, with both blood pressure and heart rate being elevated (Downing, 1986; Perez-Reyes *et al.*, 1991a,b; Mittleman *et al.*, 1999).



methamphetamine

MDMA

Figure 37 Structures of methamphetamine and MDMA

- 4.5.3 The main cardiotoxic effects of (+)-methamphetamine and its primary metabolite, amphetamine, appear to be cardiomyopathy (O'Neill *et al.*, 1983; Jacobs, 1989; Hong *et al.*, 1991) and myocardial infarction (Packe *et al.*, 1990; Hong *et al.*, 1991; Ragland *et al.*, 1993; Waksman *et al.*, 2001). In a review of 413 methamphetamine-related deaths, Karch *et al.* (1999) noted a strong association between methamphetamine use and coronary artery disease. (For a recent review of the cardiovascular consequences of amphetamines and other drugs of abuse the reader is referred to Frishman *et al.*, 2003a,b).
- 4.5.4 Nishida *et al.* (2003) published an interesting case report involving a 51 year old male methamphetamine abuser who unexpectedly died while being arrested. The autopsy revealed pathological lesions in the cardiac conduction system which the authors attributed to chronic methamphetamine abuse. They concluded that a methamphetamine abuser with such lesions could easily have died suddenly upon experiencing emotional stress. The significance of this observation in the context of a Taser confrontation is clear (see also Mittleman *et al.*, 1993).
- 4.5.5 Although no signal for QT prolongation by methamphetamine was detected in the sheep Purkinje fibre preparation and there are no reports of

methamphetamine-induced QT prolongation in the clinical literature, other cardiotoxic effects are apparent with this drug which are likely to increase the likelihood of morbidity and mortality in abusers. The risk of an adverse event is likely to be elevated further in emotionally charged circumstances.

4.5.6 Like MDMA, methamphetamine is metabolised by the polymorphic liver enzyme, CYP2D6 (Lin *et al.*, 1997). As discussed in Section 4.4 in relation to MDMA, this could have implications for the toxicity of methamphetamine in any given individual.

4.6 Morphine (heroin metabolite)

- 4.6.1 Morphine (0.05 to 5 μM) had no effect on the action potential in sheep isolated Purkinje fibres. Heroin (diacetylmorphine) is rapidly converted firstly to 6-monoacetylmorphine and then to morphine (Boerner *et al.*, 1975; Inturrisi *et al.*, 1986; Cone *et al.*, 1991; Jenkins *et al.*, 1994; Rentsch *et al.*, 2001). For this reason morphine, rather than heroin, was selected for study.
- 4.6.2 Morphine is relatively free of effects on the cardiovascular system. Marsch et al. (2001) investigated the effects of intravenously injected morphine in 18 healthy male subjects aged 18 to 45 years. When morphine was injected to achieve a peak plasma concentration of 0.7 μ M, systolic and diastolic blood pressure and heart rate were not significantly altered.
- 4.6.3 There are no published clinical reports of morphine- or heroin-induced QT prolongation or torsades de pointes arrhythmia.
- 4.6.4 In a review of cardiovascular manifestations of substance abuse, Frishman *et al.* (2003b) concluded that the direct cardiovascular effects of heroin (and presumably morphine) did not seem to play a major role in the cause of morbidity or mortality associated with the drug.
- 4.6.5 The predominant adverse side-effect of morphine and related opioids is respiratory depression, mediated by an action of the drug in the brainstem (Rang *et al.*, 1999b). Respiratory depression can be seen at therapeutic analgesic doses and is believed to be the commonest cause of death in acute opioid poisoning (Rang *et al.*, 1999b). It is conceivable that the profound respiratory depression and hypoxaemia that would result from ingestion of higher doses of morphine (and heroin) could lead to secondary effects on cardiac electrophysiology. However, the authors believe that any individual intoxicated with morphine (or heroin) to the extent where respiration is significantly depressed is unlikely to present a threat to the police and is therefore unlikely to require use of a Taser.
- 4.6.6 Methadone is a synthetic derivative of morphine that is used therapeutically as a means of treating morphine and heroin dependence (Rang *et al.*, 1999b). Two recent publications suggest that methadone inhibits hERG currents, prolongs the QT interval in human subjects, and has been associated with the development of *torsades de pointes* arrhythmia (Krantz *et al.*, 2002; Kornick *et al.*, 2003). On this basis, it may be surmised that individuals involved in a methadone rehabilitation programme may present with an increased risk of developing *torsades de pointes* arrhythmia, especially in the context of an emotionally charged and potential violent confrontation with the police (Mittleman *et al.*, 1993).
- 4.6.7 Levomethadyl (ORLAAM[®]), like methadone, has been used to treat opioiddependent individuals. The drug was withdrawn in the UK and rest of Europe

in 2001, because of an unacceptably high incidence of life-threatening cardiotoxicity (including QT prolongation and *torsades de pointes*^{30,31}). For the same reason, the manufacturer of levomethadyl voluntarily withdrew the drug from the US market in August 2003³².

4.7 Phencyclidine (PCP, "angel dust")

- 4.7.1 PCP (0.05, 0.5 and 5 μ M) induced a concentration-dependent prolongation of the cardiac action potential: APD₉₀ was increased by 7.5% at 0.5 μ M and by 30.7% at 5 μ M. An increase in APD₅₀ of 22.8% was also observed at the highest concentration. This effect of PCP displayed the reverse rate dependency characteristic of blockers of the ion channel that conducts I_{Kr} (Section 1.9).
- 4.7.2 PCP has been reported to induce prolongation of the action potential in frog isolated ventricular muscle (D'Amico *et al.*, 1983) and to increase the force of contraction and induce marked action potential prolongation in rat and guineapig isolated heart muscle (Temma *et al.*, 1985). An action potential prolonging effect of PCP has also been observed in guinea-pig isolated ventricular myocytes (Hadley & Hume, 1986).
- 4.7.3 There are no reports in the literature in which PCP block of hERG currents has been evaluated. Similarly, there are no reports of PCP-induced QT prolongation in either animal or human studies.
- 4.7.4 The contrast between the animal studies (action potential prolongation) and clinical experience (no published reports of QT prolongation) suggests, among other things, that potential PCP-induced QT prolongation has not been investigated in humans or that the pharmacological response in animals does not translate into humans. Circumstantial support for the former interpretation is given by the possibility that the tachycardia accompanying PCP intoxication may mask any QT prolongation due to the reverse rate dependence of the phenomenon.
- 4.7.5 Of interest are two reports concerning fatalities associated with neck hold restraint in PCP users (Lerner & Burns, 1986; Mercy *et al.*, 1990). Neck hold restraint results in carotid artery compression and carotid sinus stimulation which, in turn, produces a reflex slowing of the heart rate. Although entirely speculative, if the human cardiac I_{Kr} channel is blocked by PCP, the reverse rate dependence of block could mean that any prolonging action of PCP would be exaggerated at the slower heart rate. This would have the effect of increasing the risk of development of *torsades de pointes* (Redfern *et al.*, 2003).
- 4.7.6 In humans (Barton *et al.*, 1981) and squirrel monkeys (Byrd, 1987), PCP induces increases in blood pressure and heart rate. This response will increase myocardial oxygen demand and would conceivably increase the risk of a coronary event, at least in those individuals with pre-existing heart disease.
- 4.7.7 Although PCP does not feature significantly as a drug of abuse in the UK (see Table 4), its action in the sheep cardiac Purkinje fibre preparation was examined because of its reported association with several Taser-related fatalities in the US (Ordog *et al.*, 1987; Kornblum & Reddy, 1991). The

³⁰ www.emea.eu.int/pdfs/human/press/pus/3891800en.pdf

³¹ Deamer *et al.* (2001); Katchman *et al.* (2002)

³² http://www.fda.gov/cder/drug/shortages/orlaam.htm

findings, if they translate from sheep cardiac tissue into humans, suggest that PCP may sensitise the heart to development of *torsades de pointes*, although further *in vitro* and *in vivo* studies would be required to give weight to this hypothesis.

4.8 Δ^9 -Tetrahydrocannabinol (Δ^9 -THC)

- 4.8.1 With the exception of a small, but statistically significant, 4.8% increase in APD₉₀ at the medium concentration tested (0.1 μ M), Δ^9 -THC was without effect on the cardiac action potential in the sheep Purkinje fibre preparation. It is believed that the apparent increase in APD₉₀ is most likely to be a statistical anomaly rather than a biologically significant action of the drug on the basis that the prolongation did not carry through to the highest concentration tested. However, in the absence of further experimentation the possibility that Δ^9 -THC has a biphasic effect on APD₉₀ can not be discounted.
- 4.8.2 There are no reports in the scientific literature concerning the effects of Δ^9 -THC on cardiac potential duration or hERG currents. No incidences of Δ^9 -THC-related QT prolongation or *torsades de pointes* have been reported.
- 4.8.3 When administered to humans, Δ^9 -THC increases heart rate and blood pressure (Jones, 2002; Sidney, 2002). This action would be expected to elevate myocardial oxygen demand with potential implications for individuals with pre-existing heart disease. Nevertheless, there are no published reports in which adverse cardiovascular events have been unequivocally attributed to Δ^9 -THC (i.e. marijuana) use (Frishman *et al.*, 2003). In terms of inducing adverse cardiovascular events, both marijuana and its principal psychoactive component, Δ^9 -THC, appear to be relatively benign (Frishman *et al.*, 2003).
- 4.8.4 On the basis of the clinical and scientific evidence, the authors do not consider that this widely abused drug constitutes a significant cardiac risk factor.

4.9 *dl*-Sotalol

4.9.1 dl-Sotalol, a well-characterised blocker of I_{Kr} (see Section 1.5), was used as a positive control in experiments in which the test drug failed to increase action potential duration. As may be seen in Figure 17, *dl*-sotalol produced the expected prolongation, thereby confirming that the lack of effect of cocaine, morphine, Δ^9 -THC and (+)-methamphetamine was not due to a lack of sensitivity of the experimental preparations.

4.10 The influence of gender on the incidence of *torsades de pointes*

4.10.1 It has become increasingly clear that females are more prone than males to developing QT prolongation and *torsades de pointes* arrhythmia following medication with certain pharmaceutical drugs (Drici & Clement, 2001). Indeed, it has been estimated that two-thirds of the cases of drug-induced *torsades de pointes* occur in women (Drici & Clement, 2001). It is conceivable, therefore, that QT prolongation induced by drugs of abuse may pose a particular risk to women.

5 Summary and conclusions

- 5.1 Seven recreational drugs, or their active metabolites, have been examined in an *in vitro* heart preparation for their potential to induce a malignant ventricular arrhythmia known as *torsades de pointes*.
- 5.2 Two of the drugs tested (MDMA and phencyclidine) produced action potential prolongation, suggesting that they may induce QT prolongation in humans and thereby raise the risk of development of *torsades de pointes*.
- 5.3 Although cocaine, cocaethylene and (+)-methamphetamine did not induce action potential prolongation, a critical review of the scientific and clinical literature revealed that these drugs still have the potential to compromise cardiovascular function in a way that could precipitate a life-threatening cardiac event.
- 5.4 The clinical literature suggests that morphine (the principal metabolite of heroin) and $\Delta 9$ -tetrahydrocannabinol (the principal psychoactive component of cannabis) are relatively benign in terms of cardiovascular toxicity. This is further borne out by their relative lack of effect in the present study.
- 5.5 This study, which was undertaken in an attempt to understand the medical implications associated with deployment of Taser incapacitation devices, was predicated on empirical observations in the United States that many of those involved in Taser-related confrontations were under the influence of drugs of abuse. The results from the study, together with evidence gleaned from the literature, suggest that some frequently used recreational drugs have the potential to contribute to any cardiac-related morbidity or mortality that may arise in the context of Taser use. Furthermore, it seems reasonable to assume that this conclusion could be generalised to other emotionally charged and possibly violent confrontations with law enforcement personnel.

6 Recommendations

- 6.1 The Purkinje study and review of the clinical literature serve to reinforce the notion that several drugs of abuse have the potential to adversely to affect heart function (increased risk of arrhythmia and myocardial infarction).
- 6.2 The adverse cardiac effects produced by any individual drug are dependent on several risk factors, including dose consumed, co-use with other drugs (including pharmaceutical drugs and ethanol) and pre-existing heart disease. Genetic factors (liver enzyme polymorphisms) and gender will undoubtedly also play a role in determining the adverse drug reaction profile in individual users. This complex interplay of multiple risk factors could conceivably contribute to any cardiac-related morbidity or mortality associated with Taser use against drug-intoxicated persons. Nevertheless, given that the priority is to restrain an individual posing a threat to themselves and others, the authors do not believe that knowledge of a person's drug intoxication status can rationally be used to make field-based decisions on Taser use. However, officers should be aware that the risk of any adverse response in the aftermath of Taser deployment may be higher in drug-impaired individuals and, accordingly, they should be vigilant of any unusual behaviour displayed by the apprehended person that may signal the need for early medical intervention. These signs may include profuse sweating, chest pain, loss of consciousness, persistent laboured breathing, seizures.
- 6.3 With regard to the extant DOMILL statement on the medical implications of the use of the M26 Advanced Taser (DSTL/CBS/BTP/PAT-ACPO/MAN/REP/4, dated 9 December 2002), the results of the study serve to support the view in the statement that (para. 28):

"There is no experimental evidence that the aforementioned pro-arrhythmic factors [pre-existing heart disease and pro-arrhythmogenic drugs] increase the susceptibility of the heart to low- or high-power Tasers specifically, sufficient to cause an arrhythmic event. Nevertheless, there is sufficient indication from the forensic data and the known electrophysiological characteristics of the heart (and the effects of certain drugs on this) to express a view that excited, intoxicated individuals or those with pre-existing heart disease could be more prone to adverse effects from the M26 Taser, compared to unimpaired individuals."

6.4 Similarly, it is considered that the overall view (para. 29) is supported:

"... From the available evidence on the use of the device, the risk of life-threatening or serious injuries from the M26 Advanced Taser appears to be very low".

6.5 The ACPO Taser Operational Trial Guidance (25 February 2003) [para. 11.9] states:

"Experience from the use of Tasers in other countries, which is supported by medical assessment in the UK, has shown that the persons most likely to be at greatest risk from any harmful effects of the Taser device are those also suffering from the effects of drugs or who have been struggling violently. There are cases where such persons exposed to the effects of Taser have died some time after being exposed although the cause is unlikely to have been Taser itself. For this reason, such persons should be very closely monitored following exposure to the effects of the Taser. In addition, and as highlighted in other guidance, if there is any suspicion at all that the violent behaviour of any subject is being caused by excited delirium, they should be treated as a medical emergency and conveyed directly to hospital". The ACPO Taser Training Module (25 Feb 03), Chapter 10, paras 1.2(3) and 1.2(4) state:

"The effects of Taser on the heart have not been thoroughly investigated. Certain substances or metabolic conditions may increase the susceptibility of the heart to arrhythmia e.g. pre-existing heart disease or use of recreational drugs. There is no experimental evidence that these factors increase the susceptibility of the heart to Taser sufficient to cause arrhythmic event, however caution should be expressed regarding the use of Taser on excitable, intoxicated individuals".

It is recommended that these statements are retained unamended.

6.6 Subsequent studies will determine whether the Taser current can modify cardiac rhythm by a direct effect on the myocardium. It is recommended that the effect on the threshold for Taser-induced adverse cardiac events of the drugs that extended QT interval, be assessed. Subsequent to these studies, the DOMILL statement should be reviewed again.

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Appendix E – "Modelling Current Flow in the Human Body from the M26 and X26 TASER Devices."

DSTL/PUB20755 October 2005

Executive Summary

The Northern Ireland Office (NIO) and Home Office (HO) of the Government of the United Kingdom requested an independent opinion on the medical implications of two electrical incapacitation devices (EIDs) as alternatives to firearms in certain law enforcement roles. The independent Defence Scientific Advisory Council (DSAC) sub-committee on the Medical Implications of Less Lethal Weapons (DOMILL) provides this opinion. On behalf of DOMILL, the Defence Science and Technology Laboratory (Dstl) at Porton Down was tasked with assessing the risk of adverse cardiac events from the M26 and X26 TASER devices (TASER International Inc).

The approach taken by Dstl was to model the path of current flow in the body from both devices using computational electromagnetic modelling (CEM). In particular, the current flow in the heart was predicted, and these data would then enable application of appropriate currents to a biological model: an isolated beating heart preparation (the Langendorff preparation). Using this approach, the risk of ventricular ectopic beats and ventricular fibrillation could be assessed.

Data generated by the modelling could then be assessed in conjunction with other evidence (e.g. epidemiological data) concerning the risks of the TASER devices to enable an overall medical view on their risks to be developed and offered to Government by DOMILL.

Using medical imaging data, a three dimensional approximation to a human male was produced. This model - the Dstl Boolean Man - was input to computational electromagnetic modelling (CEM) software. The principle of operation of the CEM software is to discretise the model into a 3-D Cartesian mesh, generating a 3-D matrix of cells or voxels and then apply boundary conditions (e.g. material properties) and time march an electromagnetic signal through the model. The principal solution method used on each cell is the Transmission Line Matrix (TLM) method.

Four exposure scenarios were simulated based on firing trials by the Home Office Scientific Development Branch of the Home Office with ranges between 1.5 to 6.1 Metres (5-20ft) plus two direct contact stun mode scenarios. The study showed that:

- In the most severe scenario, about 20% of the M26's applied current passes through the heart with an absolute peak current density of about 0.66 milliamps/mm² during the M26's 50 micro second pulse;
- In the most severe scenario, about 20%, of the X26's applied current passes through the heart with an absolute peak current density of about 0.11 milliamps/mm² during the 120 micro second pulse;
- The highest observed current density at the heart is when one of the TASER contact points (i.e. simulated TASER dart) is close to the lower frontal lobe of the heart.

- The current leaving the heart almost matches the current entering the heart at any one time indicating that there is little net deposition of charge;
- In the most severe scenario, the current density peak is spread across a circle of approximately 25mm diameter on the heart's lower lobe and centred just below the line of the TASER upper probe.

A number of recommendations concerning modelling of the TASER current flow are included in the report should further studies be required.

The values of current density (and waveform shape) determined by this modelling study were programmed into a TASER simulator for the biological testing phase of this safety study using an isolated beating guinea pig heart (Langendorff preparation).

On the basis of the Langendorff preparation study it is considered unlikely that the discharge from the M26 and X26 TASER devices will influence cardiac rhythmicity by a direct action on the heart. The possibility that other factors (e.g. illicit drug intoxication, alcohol abuse, preexisting heart disease and cardioactive therapeutic drugs) may modify the threshold for generation of cardiac arrhythmias cannot be excluded. Similarly, other responses to TASER deployment (e.g. arrhythmias precipitated by stress- or exercise-induced catecholamine release) may, in themselves, predispose to an adverse cardiac outcome independent of the primary (electrical) action of the TASER devices.

Accordingly DOMILL subsequently issued a statement³³ to ministers and based on this evidence and other supporting information, the Home Secretary authorised use of M26 or X26 TASER devices in Great Britain within ACPO Policy and Guidance.

Statement on the comparative medical implications of the use of the X26 TASER and the M26 Advanced TASER, Dstl/BSC/BTP/DOC803, 7th March 2005

1 Introduction

1.1 Contractual

1.2 Background

Recommendations from the "Patten Report³⁴" into policing in Northern Ireland include two specific items relating to the public-order equipment for Police use. These Recommendations, 69 and 70, were:

"69: An immediate and substantial investment should be made in a research programme to find an acceptable, effective and less potentially lethal alternative to the Plastic Baton Round (PBR)";

"70: The police should be equipped with a broader range of public order equipment than the RUC currently possess, so that a commander has a number of options at his/her disposal which might reduce reliance on, or defer resort to, the PBR."

In Summer 2000, the Secretary of State for Northern Ireland, in consultation with the Home Secretary, established a UK-wide Steering Group (the Patten Action Team – PAT) to lead a research project. The project was to (i) establish whether a less potentially lethal alternative to the baton round is available and (ii) review the public-order equipment which is presently available, or could be developed, in order to expand the range of tactical options available to Operational Commanders.

The Steering Group has taken steps to ensure that its work is consistent with the approach being adopted by the Association of Chief Police Officers (ACPO) of England, Wales and Scotland and the Police Service of Northern Ireland (PSNI). In addition, contact has been made with a range of bodies with relevant expertise, including the US National Institute of Justice and Pennsylvania State University, through the International Law Enforcement Forum.

The terms of Recommendation 69 require the PAT/ACPO teams to address three specific areas – acceptability, effectiveness and lethality or minimum force. The criteria for acceptability must be agreed within UK framework and benchmarked against legal requirements, set out particularly in the "Human Rights Act", 1998. There are three closely linked areas under which acceptability should be considered; these are human rights and legal requirements, ethical and cultural grounds and medical issues. The latter is considered in this report, with regard to Electrical Incapacitation Devices (EID).

The PAT/ACPO Steering Group initiated a research programme entitled "Alternative Policing Approaches Towards the Management of Conflict". One strand of this programme was an in-depth review and assessment of currently available less lethal technologies and those at a development stage³⁵. The Police Scientific Development Branch (PSDB) has conducted the technical assessment of commercially available equipment. Five technologies have been classed as Category A (i.e. "devices, which may be the subject of immediate, more in-depth research"):

impact devices;

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A New Beginning: Policing in Northern Ireland, The Report of the Independent Commission on Policing for Northern Ireland, September 1999.

Patten Report Recommendations 69 And 70 Relating To Public Order Equipment, A Research Programme Into Alternative Policing Approaches Towards The Management Of Conflict, Second Report prepared by the PAT/ACPO Steering Group December 2001

- chemical devices capable of being delivered at variable ranges;
- electrical devices;
- distraction devices;
- water cannon.

With regard to electrical devices, PSDB have reviewed a range of commercially available products that use pulses of electricity to incapacitate a target. These EID's include TASER, stun guns, electrified riot shields, electrified nets and stun belts. In the report of the Steering Group on Phase 2 of the research programme³⁵ it was concluded that that only those electrical devices that could be used at a distance would be considered a priority for further research. Devices such as stun guns, stun batons and electrified shields would not go forward for further testing at present. Electrified nets and stun belts were also dismissed as a priority. The TASER is probably the best known and most widely available (and used) EID that can be operated at a distance from the target.

The Northern Ireland Office and Home Office therefore, requested an independent opinion on the medical implications of the use of electrical incapacitation devices (EID) in self-defence and restraint scenarios, and as alternatives to firearms. There is no role for TASER devices in crowd control scenarios. The independent DSAC subcommittee on the Medical Implications of Less Lethal Weapons (DOMILL) was requested to provide this opinion. The Defence Science and Technology Laboratory (Dstl) was tasked to produce a report to advise DOMILL on the interactions of EID with the body, and the quality and scope of operational and experimental evidence available to develop a medical view on their safety.

Initially, computational electromagnetic modelling³⁶ (CEM) was employed to gain a qualitative understanding of the distribution of currents in the human body from existing low power (~7 Watts power, and a good understanding of injury epidemiology) and newer high power devices (~26 Watts power and little data on injury epidemiology). Results indicated higher currents near the heart from the higher power devices modelled. However, there was no indication from the model what biological effect this increase would have. As a result it was recommended to undertake a quantitative study with a more anatomically accurate model. Data from this model would then be fed into biological models to predict biological effects and any possible clinical effects.

1.3 The M26 and X26 TASER Devices

TASER devices are electrical incapacitation devices that fire two darts connected to the main TASER body via thin conducting wires. On hitting the target the device sends a series of electrical impulses at high voltage intended to incapacitate the target. The mechanism of action is not well understood but the most likely explanation is the disruption of neuromuscular control by stimulation of motor axons in peripheral nerves. This may also be accompanied by disruption of the neurophysiological feedback required for maintaining posture, leading to disturbances in posture and balance.

Two devices were recommended by PSDB to the PAT/ACPO team, namely the M26 and X26 TASER devices (Figure 1) produced by TASER International Inc, Arizona, USA. The M26 was introduced to the law enforcement community first

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DOMILL statement on the medical implications of the use of the M26 Advanced TASER, Dstl/CBS/BTP/PAT-ACPO/MAN/REP/4/ 9th December 2002

and UK Police forces determined that the TASER had the potential to be alternatives to firearms in certain roles. The results described here, enabled DOMILL to issue a statement³⁶ on the safety of the M26. On 30 January 2003 the Home Secretary gave authority to proceed with an operational trial of the M26 as a less lethal option in incidents at which authority to use firearms had been granted. The operational trial began on 21 April 2003 for an initial period of 12 months, with five police constabularies taking part. Only trained firearms officers would use the M26.

During the trial period, under recommendations made by DOMILL, further research was undertaken to clarify the cardiac hazard associated with the use of the M26 on individuals with cardiac hypersusceptibility.

In May 2003, the manufacturers of the M26, TASER International Inc, introduced another TASER weapon – the X26. ACPO expressed the view that the X26 may have operational benefits over the M26 and requested that PSDB conduct a handling trial, similar to that undertaken on the M26 prior to its introduction. Subsequent to the X26 handling trial the Home Office requested that DOMILL prepare a statement on the medical implications of the use of the X26. This led, via DOMILL, to the study described in this report being undertaken by Dstl.



Figure 38 - The M26 and X26 TASER devices (figure courtesy of PSDB)

Technical specifications from the manufacturer are detailed in Table 18 and Table 19.

Model	ADVANCED TASER M26 (Law Enforcement) Model # 44000				
Power Output	50,000 Volt (est.); 26 Watts; 162mA (Irms) and 1.76 Joules per pulse energy				
Power Input	12 VDC: 4-6 A				
Power Supply	8 AA Nickel Metal Hydride (NiMH) 1.2-Volt rechargeable batteries or hi-				
	output 1.5 Volt alkaline batteries, self-contained inside polyethylene battery				
	tray, with reverse insertion prevention feature.				
Aiming Mechanism					
Mechanical	Fixed front and rear "fin and blade" sights, optimised at 13 foot range.				
Optical	650 Nm wavelength, daytime laser sight, optimised at 13 foot range.				
Housing					
Dimensions	6.5" x 1.4" x 5.9" (inches).				
Material	Bayblend T 85 MN 901510 (PC/ABS Blend). No mold release used during				
	moulding process.				
Safety Levers	Ambidextrous safeties				
Material	rial Bayblend T 85 MN 901510 (PC/ABS Blend). No mold release used during				
	moulding process.				
Activation Switch					
Material	High durability black Santoprene, shore A				
Laser Lens					
Material	Optically clear polycarbonate.				
Other Features					
On Board Memory	Fast recording EEPROM chip records 585 firings, date and time.				
Battery Indicator	Indicator High visibility red LED calibrated for alkaline batteries.				
Yellow Coloration	ow Coloration Left and right side yellow polycarbonate decals with P.S.A. that adheres to				
Kit	Kit sides of the weapon, in order to mark it as less-lethal.				
Air Cartridges	21-foot and 15-foot interchangeable cartridges made of polycarbonate plastic.				
	Uses 1800 P.S.I. compressed nitrogen. Wire is proprietary insulated copper-				
	steel				
1	Steel.				

Table 18 - M26 TASER specifications

	TASER X26E (Law Enforcement) Model # 26000		
Model			
	175 cm3 (10.7 cubic in.)		
Size	15.3 cm x 8.2 cm x 3.3 cm (6.0" x 3.2" x 1.3")		
Weight	175 grams (0.45 pounds / 7 ounces)		
Incapacitation	105 MDU's (Muscular Disruption Units)		
Power Output	Shaped Pulse Discharge		
	50,000 Peak Voltage		
	2.1 Milliamps Average Current (0.0021 Amperes)		
	151 Milliamps Root Mean Square Body Current (0.151 A Irms)		
Range	0-7 Meters (0-21 ft) plus contact stun backup capability		
Digital Power	Power Source w. Lithium Energy Cells and Digital Memory		
Magazine (DPM)	6 Volt Input, 10 yr shelf life, 300 firings at 25°C		
Indicator	99% - 00% Remaining Energy Level		
Digital Pulse	Automatic 5 sec burst (interruptible)		
Controller (DPC)	0-2 seconds: 19 pulses per second		
()	2-5 seconds: 15 pulses per second		
Clothing	Up to 5 cm (2 inches)		
Penetration			
Temperature Range	-20 C (-05°F) to 50 C (122° F)		
USB Dataport	Stores Time, Date, Duration, Temperature, & Energy Cell Status of		
System	over 1,000 firings. Data accessed through USB into encrypted secure		
	".x26" file format on Windows PC (Windows® 2000, XP, or ME)		
Target Illumination	650 nm laser sighted to center grouping at 13 feet plus two super bright		
	LED's for Low Intensity Illumination (LIL)		
Cartridges	15 or 21 ft. range, 1800 psi nitrogen propellant, classified by		
	U.S.B.A.T.F. as non-firearm, reversible design with 8° probe separation		
	angle.		
Central Info Display	2 Digit LED displays fuel level, burst time, warranty expiration,		
(CID)	illumination status		
Safety	Ambidextrous levers with Safe "S", Fire "F" markings		
Holster	eXoskeleton molded polymer and stainless steel holster included.		
	Ambidextrous (shipped in rt. hand configuration).		
Patents	U.S. #5,078,117; U.S. #5,771,663 and others pending U.S. and Worldwide.		
Warranty	1 year standard, extended warranties available		

Table 19 - X26 TASER specifications

1.3.1 The M26 and X26 waveforms

The M26 generates a high voltage waveform with a current of about 10-12 amps, depending on the load the TASER is fired into. The waveform, shown firing into an ~48 Ω load, (see Figure 39, note the y-axis has been expanded and the graph does not show the high frequency spikes which are most likely a measurement artefact) appears to be, essentially, a damped sinusoidal waveform (50kHz fundamental) of approximately 40 µs duration.

Supplement to HOSDB Evaluations of Taser Devices



Figure 39 - Resultant waveforms for the X26 and M26 discharged into (of the order of) a 48 Ohm resistor

The peak voltage is probably just under 1000 Volts. The high voltage pulses overlaying the M26 pulse are discussed later. The X26 waveform is a fast damped sinusoidal signal (the "Arc Phase" of the "Shaped Pulse³⁷"), of approximately 120 kHz, at the start superimposed on a unipolar double exponential pulse (see Figure 39). The pulse is of lower amplitude than the M26 peak, about 300 Volts. In this case the peak is not instrumentation noise but the fast initial sinusoidal waveform – however, there is some noise overlaying the X26 waveform. The X26 pulse is also of longer duration, approximately 120 µs.

1.3.2 Electrophysiological considerations

Excised nerves are regularly used in electrophysiology experiments and the stimulating electrode emits an electrical pulse (or trains of pulses) of a certain strength (amplitude) and duration. The classes of pulse used in electrophysiology research are as follows:

- Biphasic (single cycle sinusoid or square wave positive and negative);
- Monophasic (half cycle sinusoid or square wave positive or negative);
- Alternating current (sinusoid or square wave and of different frequencies)

The responses of nerves to pulses of different strengths and duration enable curves to be plotted (see Figure 40).



Figure 40 - Strength duration curves for nerves

Two important features from can be seen from Figure 40. Firstly it is possible to selectively stimulate different nerves types (different functions) and, secondly, at shorter pulse duration the stimulation current (or voltage) increases dramatically – in fact the curves are hyperbolae. So the significant increase in the duration of the X26 waveform compared to the M26 waveform means that it may be able to stimulate the same nerves as the M26 but at lower voltage. More of this is discussed in the Dstl report³⁸ on the electrophysiological aspects of this programme.

1.3.3 Waveform Measurement Artefacts?

There are high amplitude, short duration spikes superimposed on the M26 and X26 waveforms. These spikes or noise are most likely measurement artefacts and there is evidence to support this.

The relationship for the DC breakdown field, E (V/m), of a uniform gap can take the form:

$$E = 24.5 p + \frac{6.7 p^{\frac{1}{2}}}{d^{\frac{1}{2}}}$$

Equation 1

Where *p* is the pressure in atmospheres and *d* is the gap spacing in centimeters.

Applying Equation 1 to the M26 and X26 (1.4 inch or 3.55 cm electrode separation) indicates an electric field strength, E, of up to 100kV across the electrodes. Fast risetime pulses can increase the breakdown voltage of air gaps but the TASER waveform risetime would only do this by a few percent.

The TASER electrodes are not a uniform gap and the field is not DC. These factors can considerably <u>reduce</u> the output voltage across the electrodes. Even if field enhancement factors are not taken into account the calculated field strength is

Effects of simulated M26 and X26 TASER waveforms on the guinea-pig isolated heart. DSTL/PUB20754

considerably <u>lower</u> than that observed on the waveform spikes. This information indicates that the spikes superimposed on the TASER waveform are measurement artefacts. A full investigation into the field enhancement factors of the TASER electrodes was considered outside the scope of the programme.

It was also noted that the spikes occur at regular intervals across the TASER waveform. This appears strange, as it is unlikely anything is "switching" in the TASER during the production of one waveform. Again it suggests it is more likely to be some kind of interference in the measurements system.

Once the gap has broken down, there will be ionised air between the electrodes this will allow the gap to breakdown at lower voltages, below that indicated in the spikes. This further supports the view that the spikes are measurement artefacts.

Dstl has experience of measurement artefacts in past research into EID, due to the difficulties in measuring high voltages, as corona and arcing can occur and interfere with instrumentation. The present Dstl approach is not to use a resistor network voltage divider, but to use a calibrated electric field probe. In this case (see Figure 4) a wire connected to the output of a stun gun is used and passed over an EG&G CFD-1 conformal dipole D-dot probe. The probe signal is fed into a Digital Storage Oscilloscope (DSO), via an analogue fibre optic telemetry link (FOL³⁹). Active integration built into the FOL enables integration of the signal correcting for the differential signal from the probe. The DSO is located either inside a shielded box with a filtered power supply or within a shielded room designed for electromagnetic compatibility (EMC) testing. This approach allows remote (electrically isolated, so inherently safe) measurements of high voltage sources without the problems of arcing that a voltage divider can sometimes create.



Figure 41 - Stun gun output measured with calibrated field probe

Pulse Power and Measurement Ltd.



Figure 42 - Dstl measurements of a stun gun output showing no noise.

Figure 42 shows the output of the D-dot probe via the FOL compared to direct measurement with a (Poynting High Voltage Ltd) potentiometer (voltage divider) also measured via a FOL connected to a DSO in a shielded room. By comparing the D-dot measurements with the potentiometer is one way in which the D-dot probe can be calibrated. As a result of this approach measured waveforms are smooth with no high amplitude, short duration, spikes.

Another way to reduce artefacts is to submerge the resistor network (if using a voltage divider) in transformer oil. However, sometimes the "noise" source can come from inside the device and interference can still occur on unshielded instrumentation.

It was concluded that the short duration high voltage spikes superimposed on the TASER waveform were measurement artefacts.

1.4 Approach taken for safety assessment

Historically, there have been no objective scientific studies (or even ad-hoc studies) to determine the magnitude and distribution in the body (animal or human) of electric currents from TASER devices. This knowledge is fundamental to an understanding of the potential interaction of TASER currents with excitable tissues such as the heart. Dstl's earlier modelling studies⁴⁰ revealed information that must be regarded as indicative only.

Therefore, the approach taken to obtain quantitative results was to model the current flow in a more anatomically accurate model of the human body, using computational electromagnetic methods. The derived currents into the heart would then be injected into an isolated beating (guinea pig) heart preparation. This approach required quantitative data, in addition to the earlier qualitative date acquired using CEM techniques.

Computer Modelling of TASER-Induced Electric and Magnetic Fields J. F. Disley, S. J. Holden, The 5th International Workshop on Computational Electromagnetics in the Time Domain (CEM-TD 2003) 17-19 June 2003, Halifax, Nova Scotia

Supplement to HOSDB Evaluations of Taser Devices

Using this approach, the risk of ventricular ectopic beats and ventricular fibrillation could be assessed. Data generated by the modelling could then be assessed in conjunction with other evidence (e.g. epidemiological data) concerning the risks of the TASER devices to enable an overall medical view on their risks to be developed and offered to Government by DOMILL.

2 Developing the model

2.1 Computational Electromagnetics

Most problems in electromagnetics have traditionally been solved by analysis and experiment. The increasing cost of experiments and the complexity of problems to be solved by analysis, combined with the reducing cost of powerful computers, has resulted in computer based numerical modelling techniques becoming increasing popular in providing solutions.

Numerical techniques attempt to solve fundamental field equations directly, subject to the boundary constraints posed by the geometry. A number of different numerical techniques for solving electromagnetic problems are available. Each numerical technique is well-suited for the analysis of a particular type of problem.

The numerical techniques considered for this work are space-grid, time-domain solutions of Maxwell's Equations (the latter define electromagnetics). This approach firstly, identifies a volume in space where the problem is defined and boundary conditions established. Next the problem space is discretised into small volumes or cells, normally cuboids. The discretisation process is referred to as gridding or meshing. Each cell can then have electromagnetic parameters for the material assigned to it such as conductance, permittivity and permeability. A simulated voltage source (e.g. a sinusoid) is then applied at one of the sub-cubes. The resulting electromagnetic field can then be calculated, as it propagates through the mesh, at a series of time-steps. Time-stepping is continued until the desired late-time pulse response is observed at the field points of interest.

There are several solutions methods available to solve the fields in each cube; the most popular are of the class of Finite Difference Time Domain (FDTD) methods. The principal solution methods in this area are the Transmission Line Matrix Method (TLM⁴¹) and the Yee⁴² cell. Although both methods are by definition FDTD methods the convention is to refer to the Yee cell method as FDTD and the TLM method as TLM. That convention will be observed here.

2.1.1 Finite Difference Time Domain (FDTD)

The FDTD method has become one of the most extensively used numerical procedures for bioelectromagnetic computations. The Finite Difference Time Domain (FDTD) method is a direct solution (by discretisation) of Maxwell's time dependent curl equations. It uses simple central-difference approximations to evaluate the space and time derivatives algorithm. The FDTD method was first proposed by Yee⁴². The method discretises the three dimensional space that is under consideration (meshing), into small cubes. Each cube can have a value of conductance, permittivity and permeability.

The region being modelled is represented by two interleaved grids of discrete points. One grid contains the points at which the magnetic field is evaluated. The second grid contains the points at which the electric field is evaluated. A basic element of the FDTD space lattice is shown in Figure 43.

Johns, "A symmetrical condensed node for the TLM method", IEEE Transactions on Microwave Theory and Techniques, 1987, Vol. 35, No. 4, pp 370-377.

41

Yee, K. S., Numerical solutions of initial boundary value problems involving Maxwell's equations in isotropic media, IEEE Trans. Ant. Propagation, 14, 303, 1966

The FDTD method is a time stepping procedure. A simulated voltage source is applied at one of the sub-cubes. Most FDTD codes use a pseudo Dirac⁴³ delta function to excite the model volume, exciting a wide range of frequencies. The resulting electromagnetic field can be calculated, as it propagates through the mesh, at a series of time-steps. The solution to Maxwell's Equations is completed when the steady-state behaviour is observed at each lattice cell.



Figure 43 - Yee Cell for FDTD

Special absorbing elements are used at the outer boundary of the lattice in order to prevent unwanted reflection of signals that reach this boundary.

The FDTD technique has the following characteristics:

- It can be utilised in frequency dependent non-linear and isotropic materials.
- The required computer storage and running time is proportional to the electrical size of the volume being modelled and grid resolution.
- Normally, this mesh must be uniform, so that the mesh density is determined by the smallest detail of the configuration.
- Values of conductance, permittivity and permeability assigned to each field component in each cell define the position and electrical properties of the scatterer.
- FDTD techniques, unlike many FE techniques, work in the time domain. This makes them very well-suited to transient analysis problems.
- FDTD techniques are superior in modelling unbounded problems than finite element modelling codes.
- Experience has shown that with care, field intensities have been predicted to within 2.5% accuracy relative to known analytical and experimental bench marks.
- One disadvantage of this technique, is that the problem size can become large for certain modelling scenarios.

R. N. Bracewell. The Fourier Transform And Its Applications. McGraw- Hill Book Co. (**1986**).

 Additionally, when approaching boundaries of materials errors can occur due to the method of field calculation the Yee-cell uses. Methods to overcome this have been derived, but can increase the complexity and memory requirements of the model.

As the FDTD technique uses cubes to model curved surfaces the object being modelled must be staircased. That is, the curved surface is approximated by layers of cubes and the surface can take on the appearance of being made up of staircases. For configurations with sharp, acute edges, an adequately staircased approximation should have a very small grid size as the fineness of the mesh is generally determined by the dimensions of the smallest features that need to be modelled. This also applies to large objects requiring detailed modelling at high frequencies, such as aircraft or humans at microwave frequencies. The volume of the grid must be great enough to encompass the entire object and most of the near-field.

A fine grid with a large volume is the most testing problem for computational electromagnetics (CEM) as this can significantly increase the computational size of the problem and hence cost.

The FDTD technique has been used to provide solutions for the interaction of electromagnetic radiation with large, complex, inhomogeneous, and irregularly shaped objects in three dimensions, with millimetre range spatial resolution. In particular, it is used in bioelectromagnetics for the calculation of whole and partial body exposures to a variety of sources, including transient fields such as those of an electromagnetic pulse (EMP).

2.1.2 Transmission line matrix (TLM) Method

The Transmission Line Matrix (TLM) method is similar to the FDTD method in terms of its capabilities, but its approach is different. As with FDTD, analysis is performed in the time domain (although frequency domain TLM codes now exist) and the entire region of the analysis is meshed. However, rather than interleaving E-field and H-field grids like FDTD, a single grid is used and the nodes of this grid are interconnected by virtual transmission lines.

Excitations at the source nodes propagate to adjacent nodes through these transmission lines at each time step. Each node is connected to its neighbouring nodes by a pair of orthogonally polarised transmission lines. The point at which the transmission-lines intersect is referred to as a node and the most commonly used node for 3-dimensional work is the symmetrical condensed node (see Figure 44).

The symmetrical condensed node formulation introduced by Professor P.B. Johns⁴¹, of the University of Nottingham, has become the standard for three-dimensional TLM analysis. At each timestep, voltage pulses are incident upon the node from each of the transmission lines. These pulses are then scattered to produce a new set of pulses, which become incident on adjacent nodes at the next timestep. The relationship between the incident pulses and the scattered pulses is determined by the scattering matrix, which is set to be consistent with Maxwell's Equations.

Many engineers find the transmission line analogies of the TLM method to be more intuitive and easier to work with, as the electromagnetic signal propagates through the workspace through materials whose properties are determined in the node by transmission lines. This compares with the FDTD approach of calculating the fields at each cell using Maxwell's equations.

Characteristics of the TLM are:

- Material properties are assigned by changing the dielectric properties of the transmission lines;
- Lossy media can be modelled by introducing loss into the transmission line equations or by loading the nodes with lossy stubs;
- Absorbing boundaries are easily constructed in TLM meshes by terminating each boundary node transmission line with its characteristic impedance;
- The fundamental development of TLM has continued with the introduction of hybrid nodes, a multigrid mesh and the supercondensed node.



Figure 44 - TLM symmetrical condensed node

The disadvantages of the TLM method are similar to the FDTD method. In addition, the TLM method requires more computer memory per node than other techniques. However, when modelling complex boundary geometries it has the advantages of calculating both E and H at every boundary node.

For this work programme a developed version of a commercial TLM code was used, specifically Flomerics Microstripes. The UK Ministry of Defence (MoD) amongst others, has driven the development of this code over several years (and with many applications in mind) in several key areas:

- An easy to use interface capable of importing geometries and models in computer aided design (CAD) formats, such as ACIS⁴⁴;
- A frequency dependent Debye material model;
- A tissue database of approximately 44 tissues up to 20 GHz (the upper frequency depending on computer resources);
- A wire and wire bundle model;
- A number of sources including free space plane wave and wire;
- A number of output methods including time domain point output and space domain (frequency and time domain).

2.2 Development of the Dstl Boolean Man

In order to develop the model the first item required was a representation of the human geometry including internal organs. This undertaking was most difficult and the best course of action was to build a model based on medical imaging data^{45,46}.

Suitable magnetic resonance imaging (MRI) and computed tomography (CT) data was obtained⁴⁷. These data were processed by special software to take 2-D axial layers (see Figure 45 with tissues identified) and build 3-D model of the human with the individual tissues modelled, a process known as segmentation (see Figure 46).



Figure 45 - A 2-D medical image with individual tissues highlighted

44	ACIS is made up of the initials of the three founding members of Three-Space Ltd, Cambridge,
	England (Alan Grayer, Charles Lang and Ian Braid).
45	Dimbylow PJ, 1995, the development of Voxel Phantoms for Electromagnetic Dosimetry. In
	Voxel Phantom Development, PJ Dimbylow, Editor, Proceedings of an International Workshop
	held at NRPB.
46	"Three Dimensional Computer Modelling Of The Human Anatomy" IV World Congress of
	Biomechanics, Calgary, Alberta, Canada August 4-9. Dr Panos Diamantopolous, University of Sussex,
	Bio-Medical Modelling Unit, School of Engineering, University of Sussex, Falmer, Brighton, Sussex,
	BN1 9QT, Simon Holden, RF Biological Effects, Biophysics, Dstl Chemical and Biological Sciences,
	Porton Down, Salisbury, Wilts, SP4 OJQ.
47	Anonymised data supplied by the Royal Hospital, Haslar.
196	Publication No. 64/06



Figure 46 - A reconstruction after segmentation showing individual organs modelled in 3-D

In this approach it was hoped to completely segment out all the tissues as the 2-D data was accessed further down the vertical axis of the body. However, two issues arose. Firstly, it took considerably more manual input than anticipated to identify tissue boundaries. Secondly, due to errors in manual or automatic identification of tissue boundaries, air gaps were appearing between tissues. The latter would severely affect results.

An alternative approach was then taken. Individual organs were segmented out of the data as separate entities. Then advantage was taken of a feature of the Microstripes software which, enables models (usually using primitives, for example spheres or cylinders) to be built using Boolean operations. In this way the model was built by adding and subtracting (the volumes of) organs to form the model. This resulted in a multiple tissue, heterogeneous man model with no air gaps between the organs (Figure 47), referred to as the Dstl Boolean man model.



Figure 47 - The Dstl Boolean man

Due to the Boolean process it was much more difficult to segment all the organs, for this reason only a limited number of the major organs and tissues were identified:

- Fat;
- Muscle;

- Skeleton;
- Brain (grey matter);
- Heart;
- Intestine;
- Kidneys;
- Liver;
- Lung (inflated);
- Pancreas;
- Spinal cord;
- Stomach.

At the time of the model development it was not possible to model skin. It was not possible to segment out the skin as a tissue; when discretised into cubes the skin would require a certain number of cells to give valid results. This would mean it could be very thick when compared to the other tissues. In most scenarios it was rationalised that the TASER probe barbs would penetrate the skin into the underlying fat (see the section on material properties).

2.3 TASER Exposure Scenarios

2.3.1 Background

It was considered important to characterise likely exposure scenarios such as range of engagement and barb separation. The data would:

- Provide information on how many simulations would need to be run (probe positions);
- Enable estimation of the impedance between the probes and thus what the waveform should be used in the model (the TASER waveform shape changes when it is fired into different loads);
- Assist in determining what fixed material properties are assigned to the tissues, as it was not possible to use the frequency dependent Debye model of the tissues.

2.3.2 **PSDB Firing Trials**

PSDB (now HOSDB) conducted extensive handling trials on the M26 and X26 TASER with a number of cartridge types. The following Figure 11 and Figures 12 show example results extracted from the Phase 3 Patten Recommendations report^{48,49} (the XP cartridge has longer dart probes and is currently not used by UK Police Forces).

Patten Report Recommendations 69 and 70 relating to public order equipment: Phase 3 Report, December 2002.
PSDD Further Evolution of TASER Devices Publication No. 10/05, D. I. Williams

PSDB Further Evaluation of TASER Devices, Publication No 19/05, D. I. Wilkinson, PSDB, 2005.



Figure 48 - M26, X26 and X26 with XP cartridge at 5 ft range.



Figure 49 - M26, X26 and X26 with XP cartridge at 20ft range.

The trial, first undertaken with the M26, at ranges of 5, 10, 15 and 20 ft (1.5, 3.0, 4.6 and 6.1m) used 64 officers from 20 Police Forces and the Prison service and expended over 1200 cartridges. This trial generated six exposure scenarios to be modelled:

- TASER waveform application, via barb electrodes on wires to torso, with an electrode separation of 225 mm;
- TASER waveform application, via barb electrodes on wires to torso, with an electrode separation of 378 mm;
- TASER waveform application, via barb electrodes on wires to torso, with an electrode separation of 601 mm;
- TASER waveform application, via barb electrodes on wires to torso and upper leg, with an electrode separation of 786 mm;
- TASER waveform application, by electrode contact with neck ("Stun mode"), electrodes aligned in horizontal plane; and
- TASER waveform application, by electrode contact with neck ("Stun Mode"), electrodes aligned in vertical plane.

Trials with the X26 TASER showed very similar results to the M26 TASER so it was decided that only the 225 mm scenario would be modelled (this scenario gave the highest currents into the heart) for the X26 also.

2.3.3 Calculation of body impedance for TASER modelling scenarios

As the modelling exposure scenarios (where the darts go) for six conditions had now been established, it was necessary to determine the impedance between the darts in each scenario to select the appropriate input waveform.

Calculations of the impedance values for each of these six scenarios have been made using a number of assumptions. These assumptions were:

- The TASER barbed electrodes have completely penetrated the skin (corneum stratum and epidermis). In this case, contributions from skin impedance may be ignored. This does not apply to the two direct stun scenarios, as barb electrodes were not used. It should be noted that the Dstl Boolean Man used in the computer model did not include a skin component, so the assumption of skin penetration is in line with the model;
- The overall hand to foot impedance of the human body is 750 Ω . Overall body impedance depends on body constitution, body size, gender and age of the subject, and it has also been observed to be frequency-dependent⁵⁰. At the frequencies used in the modelling (see later section), the mean overall body impedance for hand to feet contact is approximately 750 Ω^{51} ;
- The distribution of impedance within the body is as determined by Freiberger⁵²;
- The skin is moist. Dry skin has significantly higher impedance than wet skin, and this would make a significant difference in the neck contact scenarios. It has been presumed that the skin is moist, though dry skin values are included in Table 20 for comparison. Dielectric breakdown of the skin has been presumed to be absent. This would significantly reduce the impedance of the skin:
- Neck tissue consists of skin and underlying muscle skeletal and other contributions have been ignored. The muscle has been assumed to be oriented vertically. The conductivity of muscle tissue is directional, with conductivity along the orientation of the muscle fibres being significantly higher than that in a transverse direction. However, the dominant contribution is from the skin impedance in this case, as the electrodes do not penetrate the skin. The Dstl Boolean man model did not model the skin. However, this is mitigated by the conductivity of wet skin being very similar to fat at the modelled TASER frequencies (this will be discussed more in later sections);
- For the neck contact scenarios, the TASER electrode spacing is 25 mm, and the electrode contact area is 5 mm².

Based on these assumptions, the impedance values between the electrodes in each of the six scenarios used in the modelling are given in Table 20.

⁵⁰ "Applied Bioelectricity", J P Reilly, Springer-Verlag, 1998.

"The electrical resistance of the human body to commercial direct and alternating currents", R Freiburger, Springer-Verlag, 1934.

Osypka P (1963) Quantitative investigation of current strength, duration, and routing in ac electrocution accidents involving human beings and animals. *Elektromedizen* 8

Scenario	Impedance / Ω	Notes
TASER barbs on torso,	6.3	
225 mm separation		
TASER barbs on torso,	12.7	
378 mm separation		
TASER barbs on torso,	29.0	
601 mm separation		
TASER barbs on torso/upper leg,	43.1	
786 mm separation		
TASER electrodes on neck, horizontal	1.7 (50 kHz)	Dry skin value 146.7 Ω (50
		kHz)
TASER electrodes on neck, vertical	1.4 (50 kHz)	Dry skin value 146.6Ω (50
		kHz)

Table 20 - Calculated impedance values for TASER waveform application scenarios

PSDB provided waveform data from measurement trials in which the TASER was fired into loads with a range of impedance values. The lowest value of impedance used by PSDB was ~48 Ω . Therefore, it was decided to adopt the input waveform measured when the M26 and X26 TASER devices were fired into this impedance. This is a reasonable approach as a TASER is a current source. That is, it has a high output impedance, meaning that any impedance it fires into does not appreciably change (although there is some change) the current amplitude unless it is a significant percentage of the TASER output impedance (See PSDB data in Figure 13).This means the maximum current output occurs at the lowest impedance, thus TASER devices are inherently current limited by design.



Showing Mean Peak Current against increasing Load Resistance for the Taser International M26 Taser under local conditions for 5 different units

Figure 50 - Mean Peak current form the M26 TASER fired into different Impedance values

Adopting the waveform for the TASER discharged into a 48 Ω impedance, rather than the range observed in the literature (1.4 to 146.7 Ω , Table 20) will predominantly affect the damping function of the waveform rather than the peak current, see Figure 14. The electrophysiological effect of this is unknown but is discussed in the Dstl report³⁸ on the electrophysiological study of this programme.



51 - The effect of impedance on the damping of the M26 TASER waveform.

2.4 Material properties of the model

The TLM software has the capability of modelling 44 tissues using a frequency dependent Debye^{53,54} model of the dielectric behaviour of the tissue (note: the dielectric behaviour of mammalian tissue is frequency dependent). However, for this application it was not possible to use this type of material model for the following reasons;

- The tissue models are primarily based on data taken at high frequencies;
- There is a lack of useful data at the frequencies (contained with the spectra) of the M26 and X26 TASER pulses;
- The Debye material models implemented in the TLM software could not be extended to the TASER pulse frequencies even if the data was available.

Therefore, the models were run at fixed frequencies and it was necessary to define the frequencies at which to run the model. For the M26, this decision was straightforward, as the M26 waveform is damped sinusoidal waveform of approximately 40 μ s duration with a 50kHz fundamental frequency, which dominates the pulse shape. Therefore, it was decided to run the model with material properties fixed at 50kHz.

The X26 waveform is different to the M26 waveform and consists of a faster damped sinusoidal signal of approximately 120 kHz, at the start superimposed on a unipolar double exponential pulse duration, probably about 120 μ s. As the unipolar

⁵³ Generalized material models in TLM .I. Materials with frequency-dependent properties, Paul, J.; Christopoulos, C.; Thomas, D.W.P.; Antennas and Propagation, IEEE Transactions on, Volume 47, Issue 10, Oct. 1999 Page(s):1528 - 1534

⁵⁴ Modelling of Debye material in 1-D and 2-D TLM schemes. J. Paul, C. Christopoulos, D. W. P. Thomas. International Symposium on Electromagnetic Theory, URSI Commission B, Thessaloniki, Greece, May 1998.

pulse element of the X26 pulse dominates the overall waveform it was decided to run simulations with the material models set to the fundamental frequency of this waveform that is the reciprocal of the duration - in this case 8333.33 Hz.

At these frequencies there is a distinct lack of data on the dielectric properties of tissue. In addition, the majority of the data is for *in-vitro* (i.e. dead excised) animal tissue not *in-vivo* (living) or indeed human (although what measurements have been made show most mammalian tissue compare well between species). Another confounding factor is that data at low frequencies is often measured using techniques which, can suffer from electrode polarisation effects⁵⁵. This can obscure the true values of the data.

To this end, tissue property values were generated using a 4-Cole-Cole^{56,57,58} parametric model of the dielectric properties of tissue. This model is based on the present database on the dielectric properties of tissue produced by Gabriel and Gabriel⁵⁹ and is available at the Brooks Air Force Base (AFB) website⁶⁰. A useful online application for generating the data, using the 4-Cole-Cole model, is available at the website of the Institute for Applied Physics "Nello Carrara" - Florence, Italy⁶¹.

Although discussion of the limitations of the present database have been made earlier it should be pointed out that this presently provides the best estimate based on current knowledge, even though data is scarce below 1MHz. Dstl (in conjunction with Microwave Consultants Ltd) has been working on generating a new database to rectify some of the limitations of the current database but unfortunately the data was not available at the time of the TASER model construction.

The material properties used are shown in Table 4.

Bioelectrical impedance techniques in medicine. Part I: Bioimpedance measurement. Second section: Impedance spectrometry. Rigaud B, Morucci JP, Chauveau N. Crit Rev Biomed Eng. 1996;24(4-6):257-351 56 The dielectric properties of biological tissues: III. Parametric models for the dielectric spectrum of tissues. Phys Med Biol. 1996 Nov;41(11):2271-93. 57 An FDTD algorithm for transient propagation in biological tissue with a Cole-Cole dispersion relation

Schuster, J.W.; Luebbers, R.J.; Antennas and Propagation Society International Symposium, 1998. IEEE Volume 4, 21-26 June 1998 Page(s):1988 - 1991 vol.4

⁵⁸ Parameterization of media dispersive properties for FDTD, Mrozowski, M.; Stuchly, M.A.; Antennas and Propagation, IEEE Transactions on Volume 45, Issue 9, Sept. 1997 Page(s):1438-1439.

⁵⁹ Compilation Of The Dielectric Properties Of Body Tissues At RF And Microwave Frequencies, Camellia Gabriel, PhD and Sami Gabriel, MSc, Physics Department, King's College London, London WC2R 2LS, UK June 1996, Final Report for the Period 15 December 1994 - 14 December 1995, Prepared for AFOSR/NL Bolling AFB DC 20332-0001

⁶⁰ http://www.brooks.af.mil/AFRL/HED/hedr/reports/dielectric/Report/Report.html

⁶¹ http://safeemf.iroe.fi.cnr.it/tissprop/

	Propertie	es for M26	Properties	for X26
Tissue Name	Cond (S/m)	Relative	Cond (S/m)	Relative
		permittivity		permittivity
Fat	0.026000	187.00	0.023774	1383.90
Muscle	0.559000	3500.00	0.339780	30607.00
Skeleton	0.030500	209.00	0.020409	585.55
Brain (grey matter)	0.072300	3260.00	0.113470	26349.00
Heart	0.193000	22200.00	0.149570	82498.00
Intestines	0.559000	3500.00	0.557560	49451.00
Kidneys	0.168000	14500.00	0.135380	45234.00
Liver	0.072900	14100.00	0.051786	32307.00
Lung (inflated)	0.073800	4880.00	0.092128	20432.00
Pancreas	0.559000	3,500	0.529320	10483.00
Spinal cord	0.072300	3260.00	0.039949	39469.00
Stomach	0.753000	655.00	0.529310	9991.70

Table 21 - Tissue properties used in the M26 and X26 TASER models.

It was not possible to model skin in the Dstl Boolean man model. However, this was considered inconsequential as:

- The TASER electrodes were modelled as completely penetrating the skin as observed in the majority of operational use scenarios;
- The conductivity of fat is very similar to wet skin at 50 kHz (using the 4-Cole-Cole model);
- The conductivity of fat is higher than wet skin at 8.333 kHz (using the 4-Cole-Cole model) and so the fat would dominate the observed impedance of this scenario.

2.5 Development of the Simulated TASER in the model

Initially the model represented the TASER as a pair of metal wires joined externally by a fixed impedance (using the TLM "wire" model). However, the software effectively treated such wires as insulated at the ends when connected to a dielectric (tissue) which, resulted in it predicting that there would be virtually no electrical energy transmitted through the body. As a consequence, a thin metal pad covering the surface of a single discretised cuboid was added to the end of each wire. This model was used to investigate the effect of the M26 with different exposure scenarios and to provide the preliminary results. Six pairs of scenarios were modelled for the M26. These are illustrated in Figure 52.

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Figure 52 - The Six TASER Contact Positions or Scenarios Modelled

In the results, it was evident that the spatial distribution of current density exhibited significant numerical noise. This was extensive enough to conclude that the preliminary results should be considered to be guides to orders of magnitude only. This was particularly so for the two stun modes where it was apparent that the peak current densities were probably almost entirely due to this noise.

Discussion with the TLM modelling software developer, Flomerics, advised that this was probably due to numerically valid but physically unrealistic, modes of propagation dominating the results. They recommended the replacement of the metal pads by metal blocks. Initially blocks occupying single discretised cuboids were implemented. The noise persisted and Flomerics subsequently recommended extending the blocks to two cuboids deep and to place them such that they were not placed edge to edge. It transpired that in some cases the corner of the block, while surrounded by one material touched another material only along an edge.

At the same time Flomerics recommended increasing the external impedance between the two TASER wires. Whilst this change was later shown to have little impact on the noise, applying both recommendations was effective in reducing the noise to acceptable levels. As a consequence, the resultant models were used to obtain the M26 and X26 results presented in this report.

As the preliminary results had demonstrated that the highest current flow observed on the heart was primarily influenced by the probe nearest to it and that the Torso 225 (waveform applied to the torso with an electrode separation of 225 mm) case gave the greatest current flows, studies with the probes modelled as metal blocks were limited to that case. The evolution of the TASER probe model is shown in Figure 53, the figure shows the torso as either black or red (depending on viewing aspect) and the simulated TASER as two blue electrodes connected by a blue wire. The figure shows (moving down the figure) how the model of the TASER was developed from direct wire contact into the torso, to metal pads, to 1*1*1 metal cubes, to the final 1*2*1 metal cubes.



Figure 53 - Evolution of TASER Probes Torso 225 Position

2.6 The TASER Stimuli

The measured TASER output data provided by PSDB showed high amplitude, short duration current spikes superimposed over the overall waveform. This is believed to be due to a measurement artefact rather than from the TASER itself (see section 1.3.3). As a consequence, these spikes were smoothed out. At the same time the sampling interval was reduced to make the time required for subsequent analyses more practical, i.e. post processing convolution.

The supplied M26 and X26 TASER data and the smoothed equivalents used in the analysis are presented in Figure 54 and Figure 55. Note that while the time scales are the same, the current scales are different.



M26 Taser Stimulus (48 ohm load)

Figure 54 - M26 TASER Applied Stimulus



X26 Taser Stimulus (46.4 ohm load)

2.7 Estimating the Response to TASER Stimuli

The TLM software stimulus is a pseudo Dirac delta function (a mathematical model of a theoretical function). The Dirac delta function⁴³ can be considered as the theoretical concept of an infinitely short pulse that integrates to unity. It has the advantage of stimulating all frequencies in a model, i.e. its spectra is unity high and infinite in extent both positively and negatively. To stimulate the TASER model the TLM software applies a pseudo Dirac delta function shaped current pulse between

Figure 55 - X26 TASER Applied Stimulus

the TASER probes. As a result the model output is the response to a pseudo Dirac delta function and not a TASER pulse. To obtain the required information (response of the model to a TASER pulse) it was necessary to perform a mathematical based post process known as convolution.

Convolution is a time domain process, but is analogous to multiplying two spectra or functions in the frequency domain. Convolving the Dstl Boolean man model's response to the pseudo Dirac delta function at any output point with the measured TASER current yields the model's response to a TASER.

The convolution was more complex than in many problems due to the different sampling intervals and pulse duration of the currents applied by the TASER and the model's response to the pseudo Dirac delta function. This, though, was managed by extending the discrete Fourier transforms to enable the alignment of the frequency components of the TASER and the model's response to the pseudo Dirac delta function by interpolation. This, in turn, enabled the convolution to be directly computed.

The time period that the TLM model simulated was short, relative to the duration of the TASER pulse. This meant that the response to the TASER dominant low frequency components was based on interpolation of the direct current and lowest frequency components of the model's response to the pseudo Dirac delta function. While such interpolation may seem undesirable, it is essentially the same as zero padding the model's response to the pseudo Dirac delta function. Provided that the response has decayed to zero the approach is valid. Note, though, that zero padding alone will not produce aligned frequency components unless the larger time step is an integer multiple of the smaller. As that was not the case zero padding alone would not have sufficed for all results presented in this report.

In the case of the results for the X26 TASER, however, at some monitor points the model's response to the pseudo Dirac delta function had nearly, but not quite decayed to zero. There was some concern about this affecting results as this would mean the waveform was already convolved with a top hat function⁶². In fact any sampling process with a digital storage oscilloscope convolves the waveform with a top-hat function and the Shah⁶³ sampling function. With TASER type transient waveforms by careful selection of the timebase the effects of this can be ignored. Obtaining the X26 results had already required extensions to the period simulated (to facilitate the convolution process) this resulted in the simulation taking approximately one week (twin Pentium Xeon workstation with multithreaded processors and 4 Gbytes of memory). It was decided that the effect of such a slight lack of final decay would be insignificant. The X26 results were accepted as is, allowing the biological test phase to begin without delay. The convolution method, including the discrete Fourier transform calculations, is outlined in Appendix A. The sampling intervals and related information for the simulations are listed in Table 5.

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Top Hat Function – is a sampling function of width and height. If, for example, an oscilloscope was used to sample a sinusoidal current the resultant spectra would be a sinc function rather than a sine line at the appropriate frequency. This is because during the sampling process the sine wave was convolved with the top hat function corresponding to the time window of the oscilloscope. The Fourier transform of the top-hat function is a sinc function, in this case multiplied by the spectra of the sine wave. Bracewell, R. "The Sampling of Replicating Symbol - *The Fourier Transform and It's Applications*,

New York: McGraw-Hill, pp. 77-79 and 85, 1999.

	Properties for M26	Properties for X26
TASER Sampling Interval (secs)	10-7	$2 * 10^{-7}$
TASER Pulse Duration (secs)	$6.54 * 10^{-5}$	$1.858 * 10^{-4}$
TLM Model Output Interval (secs)	10 ⁻⁸	$5 * 10^{-8}$
TLM Model Output Duration (secs)	$1.25 * 10^{-6}$	$1.125 * 10^{-5}$
TLM Model Output Time Steps	126	225

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Table 22 - Sampling intervals and related information for TASER devices

The two pseudo Dirac delta function stimuli that the TLM model generated and used for the two TASER models are illustrated in Figure 56 and Figure 57. Note the different time scales.



Figure 56 - M26 TLM Model Dirac Delta Function Stimulus



X26 TLM Model Stimulus

Figure 57 - X26 TLM Model Dirac Delta Function Stimulus

Examples of the TLM model's responses to the pseudo Dirac delta functions are illustrated in Figure 21 and Figure 22. Both of these examples are from the output monitor point in line with the upper TASER probe for the Torso 225 case. Again, note the different time scales.



M26 TLM Model Electric Field Into Heart In Line with Upper Taser Probe Unconvolved Response to Dirac Delta

Figure 58 - M26 TLM Model Specimen Response to Dirac Delta Function Stimulus



X26 TLM Model Electric Field Into Heart In Line with Upper Taser Probe Unconvolved Response to Dirac Delta

Figure 59 - X26 TLM Model Specimen Response to Dirac Delta Function Stimulus

The equivalent responses to the TASER stimuli obtained by convolution are illustrated in Figure 60 and Figure 61. Note that the time scales have been made the same, but the electric field scales are quite different.



M26 TLM Model Electric Field Into Heart In Line with Upper Taser Probe Response to Taser Stimulus From Convolution

Figure 60 - M26 TLM Model Specimen Response to TASER Stimulus Obtained by Convolution



X26 TLM Model Electric Field Into Heart In Line with Upper Taser Probe Response to Taser Stimulus from Convolution

Figure 61 - X26 TLM Model Specimen Response to TASER Stimulus Obtained by Convolution

2.8 Model Output: Evaluating the Current Distribution

The TLM software presents three orthogonal components of the electric and magnetic field's at each of the output monitor points. The electric field components at the monitor points covering the surface of the heart were used to calculate the current density distribution into the heart and the total current passing through it. Current density is related to the electric field (Equation 2).

Current Density (Amps / m^2) = conductivity (S/m) * electric field (V/m) - Equation 2

This gave the three current density components at each of the output monitor points. Each of the monitor points is at the centre of a cuboid and the current density components were converted to current components by multiplying them by the area of the applicable cuboid face (see Figure 62).



Figure 62 - CAD model of the heart, Discretised Heart and Heart Output Points (Blue). Note that the veins and arteries included as part of the heart model were excluded from the heart output points. Also note that the heart output points form a closed surface.

Each of the monitor point cuboids covering the surface of the heart can have between one and five faces that actually form part of the outer surface of the discretised heart (see Figure 62). Summing the current components across these surface faces, with due allowance for sign, yields the net current retained by the heart. That, it transpires, is very near to zero, the charge passing through the heart rather than being retained by it. As a consequence, it was decided to apply Kirchoff's⁶⁴ Law to independently sum the current components entering the heart and those leaving it. Treating the former as always positive and the latter as always negative, the current passing through is the algebraic sum of the two.

Unfortunately, the individual current components switch direction at different times at different monitor points. That is, they are not all in phase around the surface of the heart, and so there is no absolutely correct way to combine the resulting time histories into a "waveform" representing the current passing through the heart. This "current" passing through the heart would not be physically meaningful either, as there is no one injection point, but a diffuse flow over the entire heart.

The current components crossing the cuboid faces at a single monitor point can be summed and divided by the equivalent area to obtain a resultant local current density.

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Kirchoff's 1st Law states that the current flowing into a junction in a circuit (or node) must equal the current flowing out of the junction. This law is a direct consequence of the conservation of charge. Since no charge can be lost in the junction, any charge that flows in must ultimately flow out.

Whilst it is clear how to sum the current components, there are a few ways to define the area that should be used to define the surface of the heart given the cuboid shape of the monitor points on the surface of the discretised heart. In the end, it was decided to sum the areas of the exposed faces, despite the fact that this will tend to slightly overestimate the area of the equivalent non-discretised surface (Figure 62).

It was also decided to independently present the current density into the heart and out of the heart at each monitor point. Where a monitor point has only one exposed face, then one of these densities will be the same as the resultant density while the other will be zero. However, where a monitor point has more than one exposed face there can be current components both entering and leaving the heart. The resultant density into the heart for an individual monitor point was obtained by summing only those current components that were into the heart and dividing the total by the combined area of the faces across which current flowed into the heart. The resultant current density out of the heart was obtained in similar fashion.

The current densities around the heart were scanned⁶⁵ to establish the peak current densities into and out of the heart at each point during the simulations. The waveforms of current densities into and out off the heart were then spliced together to provide a single current density waveform for use in the Langendorff preparation part of the study.

The method of calculating the current densities is described in detail in Appendix B.

2.8 Presentation of Current Distributions

Presenting the current distributions in a manner that enabled the flow of the energy to be visualised proved a significant challenge, not least because there were 752 output monitor points placed around the heart. Also, early attempts were hampered by significant spatially distributed numerical noise in the results.

As a consequence, it was eventually decided that viewing contours of the currents into and out of the heart and the current density components in the three orthogonal directions were both relevant. Software was developed that enabled these to be viewed from any or all of the six orthogonal directions ($\pm x$, $\pm y$, $\pm z$) and at any time during the simulation.

The results, as illustrated in Figure 63, gave a graphic indication of the location and spread of the peak current density.

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Scanned via proprietary software produced by Mathshop Ltd.



Figure 63 - M26 TASER - Torso 225 Scenario - TASER Probe 1*2*1 Metal Block Model Current Density Components Viewed from All Directions Time of Peak Current into the Heart

However, this method of displaying data did not always readily illustrate the shape of the current distribution around the heart. To this end, profiles showing the relative size and orientation of the current density components around the surface were developed and these were generated using Microsoft Excel macros, see Figure 64.



Current Density Directi ved From

Current Density Direction And Magnitude On The Surface Of The Heart As Viewed From Model's Left. X (+ve leftwards) = 375.65925 mm



Current Density Direction And Magnitude On The Surface Of The Heart As Viewed From Front Of Model. Y (+ve aftwards) = 173.50565 mm



Figure 64 -M26 TASER - Torso 225 Scenario - TASER Probe 1*2*1 Metal Block Model. Time of Peak Current into the Heart

- Horizontal slice in plane of TASER probe (a)
- Vertical slice fore-aft in plane of TASER (b)
- Vertical slice across heart three cuboids into discretised heart (c)
3 Results

The objective of the study was to provide an assessment of the electric current to the human heart and to provide waveforms that could be used on an isolated Langendorff perfused guinea pig heart to simulate the effect of TASER firings.

This was simulated in six scenarios. However, as previously outlined in the description of the TLM model and the analysis, it was necessary to refine the contact probe model to eliminate significant spatially distributed numerical noise from the results. Unfortunately, while noise was apparent, its extent did not become truly appreciated until the profile presentation, illustrated in Figure 64, was developed.

It became clear that the heart was subjected to the greatest current flow through it when the upper TASER probe was in line with the front of the heart. Given that, and the time taken for each analysis, only the results for the most severe case were re-evaluated with the improved TASER probe model.

3.1 M26 TASER: Effect of Different Contact Positions

Preliminary results were produced for each of the six pairs of TASER probe contact positions. These were obtained with the probes modelled as thin wires with metal pads at the ends. As a consequence, the values presented in this sub-section should be treated as guides rather than definitive results.

The waveforms of the currents passing through the heart show that the most current passes through the heart and that peak densities occur when one of the TASER contact points is close to the heart's lower frontal area.

The case when the probes are closest together shows a slightly higher current than the others, but whether this is due to the spatially distributed numerical noise was not investigated. Regardless, this scenario was taken as imposing the greatest current load on the heart, as might be expected, and was the only one used for subsequent investigations.

The effect of the spatially distributed numerical noise is more apparent in the peak current density waveforms presented in Figure 65. In this case the densities for the stun mode vertical scenario in particular seemed disproportionately high. This was the incentive for developing the profile display, which more graphically illustrated the noise. It is apparent in both Figure 66 and Figure 67, the latter being for the stun mode vertical.

Note that the profile slices presented for the stun mode vertical scenario were chosen to illustrate the spatially distributed numerical noise rather than the true shape of the current profiles. Figure 67 demonstrates that apart from the noise the current densities were effectively zero. In essence, the current densities reported for the two stun modes were essentially a representation of the noise levels. Also, noise was a significant component of the results in the other cases as Figure 66(b) illustrates.



M26 Taser - Wave Forms of Peak Current Density on Surface of Heart

Figure 65 - M26 TASER - All Scenarios - TASER Probe Metal Pad Model Waveforms of Peak Current Density on the Surface of the Heart (Note that spatially distributed numerical noise added significant errors to these curves) Current Densi



Figure 66 - M26 TASER - Torso 225 Scenario - TASER Probe Metal Pad Model

Time of Peak Current into the Heart

- (a) Horizontal slice in plane of TASER probe
- (b) Vertical slice fore-aft in plane of TASER
- (c) Vertical slice across heart three cuboids into discretised heart



Current Density Direction And Magnitude On The Surface Of The Heart As Viewed From Above Model. Z (+ve upwards) = 1372.4992 mm

Figure 67 - M26 TASER - Stun Mode Vertical Scenario - TASER Probe Metal Pad Model

Time of Peak Current into the Heart

- (a) Horizontal slice in plane of TASER probe
- (b) Vertical slice fore-aft in plane of TASER
- (c) Vertical slice across heart three cuboids into discretised heart

3.2 M26 TASER: Elimination of Numerical Noise

The spatially distributed numerical noise, as discussed in the outline of the model and the TLM software, was eliminated by replacing the metal pad model for the TASER probe tip with, first a 1*1*1 element metal block and, subsequently, a 1*2*1 element metal block.

The improvements are illustrated by the change in the contours and profiles of the current density components. This improvement enabled the contours to illustrate the extent of the spreading of the current density.

The contours are presented for the torso 225 scenario for all three probe models in Figure 31 (showing noise reduction with improvements in the TASER barb design). The profiles for the 1*2*1 element metal block are presented in Figure 69 (showing the resultant low noise). This noise reduction achieved by development of the TASER probe model allowed definitive results to be generated.



Figure 68 - The effects of modification of the simulated TASER probes on numerical noise.

Current Density Direction And Magnitude On The Surface Of The Heart As Viewed From Above Model. Z (+ve upwards) = 1297 mm



Current Density Direction And Magnitude On The Surface Of The Heart As Viewed From Model's Left. X (+ve leftwards) = 375.65925 mm



Current Density Direction And Magnitude On The Surface Of The Heart As Viewed From Front Of Model. Y (+ve aftwards) = 173.50565 mm



Figure 69 - M26 TASER - Torso 225 Scenario - TASER Probe 1*2*1 Metal Block Model

Time of Peak Current into the Heart

- (a) Horizontal slice in plane of TASER probe
- (b) Vertical slice fore-aft in plane of TASER

Vertical slice across heart three cuboids into discretised heart

3.3 M26 TASER: Worst Case Assessment

As previously outlined, the Torso 225 contact position/scenario presents the highest current density on the heart. For that case the waveform of the peak current density is presented in Figure 70, the current density contours in Figure 71 and the profiles in Figure 72.

From these it was deduced that:

- The absolute peak current density is about 0.66 milliamps/mm² during the M26's 2¹/₂ cycle, 50 micro second pulse.
- The current density peak is spread across a circle of the order of 25mm diameter on the heart's lower lobe and centred just below the line of the TASER upper probe.



M26 Taser - Wave Form of Peak Current Density on Surface of Heart

Figure 70 - M26 TASER - Torso 225 Scenario - TASER Probe 1*2*1 Metal Block Model Waveform of Peak Current Density on the Surface of the Heart



Figure 71 - M26 TASER - Torso 225 Scenario - TASER Probe 1*2*1 Metal Block Model Current Density Components Viewed from All Directions Time of Peak Current Into the Heart



Figure 72 - M26 TASER - Torso 225 Scenario - TASER Probe 1*2*1 Metal Block Model time of Peak Current density Into the Heart

- (a) Horizontal slice in plane of TASER probe
- (b) Vertical slice fore-aft in plane of TASER
- (c) Vertical slice across heart three cuboids into discretised heart

3.4 X26 TASER: Worst Case Assessment

As the M26 had shown the Torso 225 contact position/scenario presents the highest current density on the heart, this was the only simulation undertaken for the X26 modelling. For this case the waveforms of the peak current density are presented in Figure 73, the current density contours in Figure 74 and the profiles in Figure 75.

From these it was deduced that:

- The highest observed absolute peak current density passing through the heart is 0.11 milliamps/mm² during the X26's 120 microsecond pulse.
- The current density peak is spread across a circle of the order of 25mm diameter on the heart's lower lobe and centred just below the line of the TASER upper probe.



Figure 73 - X26 TASER - Torso 225 Scenario - TASER Probe 1*2*1 Metal Block Model Waveform of Peak Current Density on the Surface of the Heart



Figure 74 - X26 TASER - Torso 225 Scenario - TASER Probe 1*2*1 Metal Block Model Current Density Components Viewed from All Directions Time of Peak Current Into the Heart



Figure 75 - X26 TASER - Torso 225 Scenario - TASER Probe 1*2*1 Metal Block Model Time of Peak Current Into the Heart

- (a) Horizontal slice in plane of TASER probe
- (b) Vertical slice fore-aft in plane of TASER
- (c) Vertical slice across heart three cuboids into discretised heart

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Transposing the modelled current density to the Langendorff preparation

The contour maps of the current densities for the M26 and X26 TASER are not quite constant across the 25 mm area estimated. In fact the current density varies over the entire heart. To represent this in the guinea pig heart (Langendorff perfused heart) would mean an array of electrodes all over the heart injecting a different waveform phase adjusted with the other electrodes to exactly reproduce what is observed in the model. This is not feasible in practice.

The approach taken to inject the current into the guinea pig heart (Langendorff preparation) was to assume that the current density was constant over the 25 mm area (and therefore a worst case scenario). This current would be injected into the guinea pig heart with an electrode suitably scaled to give the same area as would be seen in the human heart.

This approach only modelled the input current density. To model the output current flow would mean returning to the original problem of requiring an array of electrodes all over the heart injecting a different waveform. The approach taken here was to use the physiological solution used to perfuse the heart with oxygen as the output electrode. This approach would simulate as closely as practically possible the diffuse current exiting the heart. This experimental set up is shown in Figure 76. More of this is discussed further in the Dstl report³⁸ on the electrophysiological aspects of this programme.



Figure 76 - Langendorff preparation with a guinea pig heart, showing simulated TASER electrodes

5 Conclusion

Using computational electromagnetics to model the flow of the TASER current into the human body it was predicted that:

- In the most severe scenario, about 20% of the M26's applied current passes through the heart with an absolute peak current density of about 0.66 milliamps/mm² during the M26's 2¹/₂ cycle, 50 micro second pulse.
- In the most severe scenario, about 20%, of the X26's applied current passes through the heart with an absolute peak current densities of about 0.11 milliamps/mm² during the X26's 4 cycle, 120 micro second pulse.
- The highest current density is when one of the TASER contact points is close to the lower frontal lobe of the heart.
- The current leaving the heart almost matches the current entering the heart at any one time indicating that there is little net deposition of charge.

This work has been undertaken on a model which can be defined as "*a simplification* of a system to aid in calculations and predictions". There are therefore a number of important caveats on this study and these should be noted when using the results presented:

- The Dstl Boolean man has modelled only 12 tissues;
- Due to the lack of frequency dependent tissue property data over the range of the TASER waveform spectra frequencies, fixed frequency material models were used. The fixed frequency data was derived from parametric models of the frequency dependent response. The models themselves are based on *in-vitro* data (i.e. dead excised tissue) and not living tissue (*in-vivo*);

It is likely that the problems with the spatially distributed numerical noise found during the TASER probe development would probably not have occurred if the discretisation was finer.

The TLM modelling code has been developed without a validation and verification programme, there were no specific physical validation exercises undertaken for the model development. However, sufficient analysis has been undertaken to be comfortable that the TLM model produces results that represent the current density levels in the heart from a TASER.

6 **Recommendations**

Any future studies that may be required to assess future EID, such as TASER, should preferably incorporate the following enhancements:

- Data should be acquired *in-vivo* at low frequencies suitable to input to the TLM modelling code;
- Any future simulations should be run with a Dstl Boolean man with more tissues modelled;
- Any future simulations should be run with a more finely discretised model;
- It is recommended that in any future study a validation and verification programme should take place;
- To aid in the transposition of the current density contours from the model of the human heart to the *in-vitro* guinea pig heart it is recommended that future studies include the modelling of the test set-up to evaluate in more detail its relationship to the human model.

The post processing has been rendered direct so that results can be made available within a few hours of the running of the TLM software. However, there are three aspects that would make the reviewing of different scenarios simpler:

- Firstly, the covering of the heart with output points, while semi-automated, is a significant task and tends to discourage changes that would force rediscretisation of the mannequin model. Further automation would be useful prior to future studies. If possible the TLM software should be altered to allow surface current plots on a dielectric.
- Secondly, if the TLM software was able to model the variability of the material properties at low frequencies, the same Dirac delta function responses could have been used to obtain the M26 and X26 TASER responses. That would enable evaluations of new TASERs to be provided much more quickly. Also, it would allow the TLM software runs to require fewer compromises for speed as fewer runs would be necessary.
- Finally, the post processing involves seven operations and should be streamlined.

Annex A Convolution to Obtain Response to TASER Stimulus

The Flomerics Microstripes program uses the TLM model to calculate the response of the model to a Dirac delta function stimulus. When the simulation is complete the output consists of the electric field response to that in the x, y and z directions for each output cell at each time step. To obtain the response due to the TASER stimulus, the model output must be convolved with the TASER stimulus.

Convolving the model data with the TASER stimulus involves finding the discrete Fourier transforms of the two sets of data. With the model data and TASER stimulus having different sampling intervals and number of samples, it was necessary to extend the usual Fourier transform equations to obtain the transforms for the model data and the TASER stimulus at a common set of frequencies.

This Appendix describes the method used to obtain the Fourier transforms and to subsequently convolve them to produce the response to the TASER stimulus.

A.1 Fourier Transforms

The Fourier transform of a function, f(t), is a function of frequency, v. It is defined as [1]

$$\boldsymbol{F}[\boldsymbol{v}] = \int_{-\infty}^{\infty} f(t) \exp\left(-i\,2\,\pi\,\boldsymbol{v}\,t\right) dt \tag{1}$$

To obtain the original function from the Fourier transform use the inverse Fourier transform which is defined as

$$f(t) = \int_{-\infty}^{\infty} \boldsymbol{F}[\nu] \exp(i 2\pi \nu t) d\nu$$
⁽²⁾

A.2 Discrete Fourier Transforms

In practice a signal cannot be measured at every point in time but only at a discrete set of points. The points at which the signal is measured are usually equally spaced and the interval between them is known as the sampling rate, Δt , The sampled function is then only known at the sample points and can be written as

$$\boldsymbol{f}_{k} \equiv f(\boldsymbol{t}_{k}), \quad \boldsymbol{t}_{k} \equiv k \,\Delta \, \boldsymbol{t} \tag{3}$$

where k = 0, ..., N - 1 and N is the number of samples.

The result of the discrete Fourier transform gives output at a discrete set of frequencies, v_n , Substituting for t_k and v_n into equation (1), the discrete approximation of the Fourier transform integral is

$$\boldsymbol{F}'_{n} \equiv \boldsymbol{F}'(\boldsymbol{v}_{n}) = \sum_{k=0}^{N-1} \boldsymbol{f}_{k} \exp\left(-i 2 \pi \boldsymbol{v}_{n} \boldsymbol{t}_{k}\right) \Delta \boldsymbol{t}$$
(4)

The discrete Fourier transform is then defined as

$$\boldsymbol{F}_{n} \equiv \boldsymbol{F}(\boldsymbol{\nu}_{n}) = \sum_{k=0}^{N-1} \boldsymbol{f}_{k} \exp(-i2\pi\boldsymbol{\nu}_{n}\boldsymbol{t}_{k}) = \frac{\boldsymbol{F}'(\boldsymbol{\nu}_{n})}{\Delta t}$$
(5)

Using this equation given a function, f_k at a set of times, t_k , the transform F_n at a set of frequencies v_n can be found.

Usually, the transform⁶⁶ is calculated at the set of frequencies, v_n defined by

$$v_n = \frac{n}{N\Delta t}$$

$$n = -(N/2+1), \dots, N/2$$
(6)

Substituting this set of frequencies and $t_k = k\Delta t$ into the above equation the traditional discrete Fourier transform formula is

$$\boldsymbol{F}_{n} = \sum_{k=0}^{N-1} \boldsymbol{f}_{k} \exp\left(\frac{-i2\pi k n}{N}\right)$$
(7)

Note that the calculation of the transform is not restricted to this set of frequencies as equation (5) applies to any set. The frequency can be chosen to match the requirements or the input can be zero padded, thus increasing N and the number of frequencies. Neither of these changes the value of the transform at the set of frequencies above, but both effectively interpolate to find the value of the transform at the other frequencies. However, as the input data was sampled at an interval, Δt , no information about the function at frequencies above its Nyquist frequency of $1/(2\Delta t)$ exists. This gives us a practical upper limit in using these equations.

In general even if the input is real, the transform will be a complex function. It is useful to be able to calculate the real and imaginary parts separately. The transform can be split into real and imaginary parts as,

$$\operatorname{Re}[\boldsymbol{F}_{n}] + i\operatorname{Im}[\boldsymbol{F}_{n}] = \sum_{k=0}^{N-1} (\operatorname{Re}[\boldsymbol{f}_{k}] + i\operatorname{Im}[\boldsymbol{f}_{k}]) \exp\left(\frac{-i2\pi kn}{N}\right)$$

$$= \sum_{k=0}^{N-1} (\operatorname{Re}[\boldsymbol{f}_{k}] + i\operatorname{Im}[\boldsymbol{f}_{k}]) \left[\cos\left(\frac{2\pi kn}{N}\right) - i\sin\left(\frac{2\pi kn}{N}\right)\right]$$

$$= \sum_{k=0}^{N-1} \left(\operatorname{Re}[\boldsymbol{f}_{k}] \cos\left(\frac{2\pi kn}{N}\right) + \operatorname{Im}[\boldsymbol{f}_{k}] \sin\left(\frac{2\pi kn}{N}\right)\right)$$

$$+ \sum_{k=0}^{N-1} \left(i\left(\operatorname{Im}[\boldsymbol{f}_{k}] \cos\left(\frac{2\pi kn}{N}\right) - \operatorname{Re}[\boldsymbol{f}_{k}] \sin\left(\frac{2\pi kn}{N}\right)\right)\right)$$
(8)

therefore the real and imaginary parts of the transform are

$$\operatorname{Re}[\boldsymbol{F}_{n}] = \sum_{k=0}^{N-1} \operatorname{Re}[\boldsymbol{f}_{k}] \cos\left(\frac{2\pi k n}{N}\right) + \operatorname{Im}[\boldsymbol{f}_{k}] \sin\left(\frac{2\pi k n}{N}\right)$$

$$\operatorname{Im}[\boldsymbol{F}_{n}] = \sum_{k=0}^{N-1} \operatorname{Im}[\boldsymbol{f}_{k}] \cos\left(\frac{2\pi k n}{N}\right) - \operatorname{Re}[\boldsymbol{f}_{k}] \sin\left(\frac{2\pi k n}{N}\right)$$
(9)

Once the transform has been calculated the original function can be regained by applying the inverse discrete Fourier transform. The inverse discrete Fourier transform is found as the discrete approximation to the inverse Fourier transform integral given in equation (2). The integral can be approximated by using,

W. H. Press, S. A. Teukolsky, W. T. Vettering and B. P. Flannery. Numerical Recipes in C.Cambridge University Press. (1992).

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$$d v \approx \Delta v_n = v_{n+1} - v_n = \frac{1}{N \,\Delta t} \tag{10}$$

Giving the discrete approximation to the integral as

$$f_{k} = \frac{1}{N\Delta t} \sum_{n=0}^{N-1} F'_{n} \exp(i2\pi v_{n}t_{k})$$
(11)

From equation (5), $F'_n = \Delta t F_{n,,}$ so that

$$f_{k} = \frac{1}{N\Delta t} \sum_{n=0}^{N-1} \Delta t F_{n} \exp(i2\pi v_{n}t_{k})$$

$$= \frac{1}{N} \sum_{n=0}^{N-1} F_{n} \exp(i2\pi v_{n}t_{k})$$
(12)

Note that when using this equation, the period of f_k will be equal to $T = (N-1) \Delta t$, where *N* is the number of frequencies used and Δt is the sampling interval used when applying equation (6). If the standard set of frequencies and time are used then $v_n t_k = nk/N$ and the formula becomes the standard inverse transform formula,

$$\boldsymbol{f}_{k} = \frac{1}{N} \sum_{n=0}^{N-1} \boldsymbol{F}_{n} \exp\left(\frac{i 2\pi n k}{N}\right)$$
(13)

However the set of times is not restricted to, $t_k = N\Delta t$, this can be varied to either extrapolate or interpolate the output function. Extrapolation will reflect the periodicity assumed in generating the forward transform. Interpolation will reflect that sine and cosine functions are being used to interpolate. Also note that the interpolation will appear more natural if the frequencies are defined by equation (6), rather than the sometimes used alternative of $v_n = n/(N\Delta t)$, n = 0, ..., N - 1.

The inverse transform can be split into real and imaginary components as

$$\operatorname{Re}[\boldsymbol{f}_{k}] = \sum_{n=0}^{N-1} \operatorname{Re}[\boldsymbol{F}_{n}] \cos\left(\frac{2\pi kn}{N}\right) - \operatorname{Im}[\boldsymbol{F}_{n}] \sin\left(\frac{2\pi kn}{N}\right)$$
$$\operatorname{Im}[\boldsymbol{f}_{k}] = \sum_{n=0}^{N-1} \operatorname{Re}[\boldsymbol{F}_{n}] \sin\left(\frac{2\pi kn}{N}\right) + \operatorname{Im}[\boldsymbol{F}_{n}] \cos\left(\frac{2\pi kn}{N}\right)$$
(14)

Also note that if the forward transform is multiplied by a constant *C* as,

$$\boldsymbol{F}_{\boldsymbol{n}} = C \sum_{i=0}^{N-1} f_k \exp\left(\frac{-i2\pi kn}{N}\right)$$
(15)

Then to regain the original function the inverse will have to be multiplied by a factor, D, such that DxC = 1/N. So in this case the inverse would be defined as

$$f_{k} = \frac{1}{CN} \sum_{k=0}^{N-1} F_{n} \exp\left(\frac{i2\pi k n}{N}\right)$$
(16)

The function $\exp(-i2\pi kn/N)$ that occurs in the traditional expression of the forward transform is periodic with a period of *N*, to show this consider

$$\exp\left(\frac{-i2\pi k (n+N)}{N}\right) = \exp\left(\frac{-i2\pi k n}{N}\right) \exp\left(-i2\pi k\right)$$
$$= \exp\left(\frac{-i2\pi k n}{N}\right) \left[\cos\left(2\pi k\right) - i\sin\left(2\pi k\right)\right] (17)$$
$$= \exp\left(\frac{-i2\pi k n}{N}\right)$$

This implies that the discrete Fourier transform of a function is periodic in the frequency domain with a period of *N*.

A.3 Convolution

The convolution of two functions g(t) and h(t) is defined as [1].

$$f * g = \int_{-\infty}^{\infty} f(u) g(t-u) du$$
(18)

From this it can seen that f * g is a function of time and also that the convolution is commutative, i.e. f * g = g * f. The discrete version of this is

$$(f * g)_{j} = \sum_{k=-M/2+1}^{M/2} g_{j-k} f_{k}$$
(19)

The convolution theorem states that the Fourier transform of the convolution integral is equal to the product of the Fourier transforms of the functions f(t) and g(t). This can be written as

$$f \ast g \to F G \tag{20}$$

where \rightarrow has been used to denote transforms to. The convolution of two functions can therefore be found by calculating the Fourier transform of the two transforms, multiplying the transforms and then inverse transforming the resulting product. When using the discrete Fourier transform the convolution theorem becomes

$$f * g \to \sum_{i=0}^{N-1} \boldsymbol{F}_i \boldsymbol{G}_i \tag{21}$$

Therefore for two functions f and g, to find their convolution, first calculate their transforms F_n and G_n . Then multiply the transforms to form H_n . To get an approximation of the convolution integral the Δt factors must be included in the forward and inverse transforms. This gives

and

$$h_{k} = \frac{1}{N\Delta t} \sum_{n=0}^{N-1} \boldsymbol{H}'_{n} \exp\left(\frac{i2\pi kn}{N}\right)$$

$$= \frac{\Delta t\Delta t}{N\Delta t} \sum_{n=0}^{N-1} \boldsymbol{H}_{n} \exp\left(\frac{i2\pi kn}{N}\right)$$

$$= \frac{\Delta t}{N} \sum_{n=0}^{N-1} \boldsymbol{H}_{n} \exp\left(\frac{i2\pi kn}{N}\right)$$
(23)

Also note that if a factor C_f was applied to the forward transform of f and a factor C_g was applied to the forward transform of g then a factor $1/C_fC_g$ has to be applied to the inverse transform of the product of the transforms.

As the forward and inverse transforms are periodic functions the discrete convolution will also be periodic. It can be shown⁶⁷, that the period of the convolution is T_c equal to $T_f + T_g$. If our output period is less than this, the convolution function in separate periods will overlap resulting in what is known as wrap-around error. To avoid wrap-around error the input functions can be padded with zeros to the required period or equivalently the number of frequencies calculated can be increased. When both functions are similarly sampled, the number of points to pad to or the number of frequencies to use can be found by

$$T_{c} = (N_{c}-1)\Delta t$$

$$T_{f}+T_{g} = (N_{f}-1)\Delta t + (N_{g}-1)\Delta t$$
(24)

as
$$T_{\rm c} = T_{\rm f} + T_{\rm g}$$
,
 $(N_c - 1)\Delta t = (N_f - 1)\Delta t + (N_g - 1)\Delta t$ (25)

so that N_c is given by

$$N_{c} = N_{f} + N_{g} - 1 \tag{26}$$

A.4 Convolution of two functions with different sampling rates and number of samples

Given two input signals f_t and f_m (for the TASER and model respectively) consisting of N_t and N_m samples that have sampling intervals of Δt_t and Δt_m . The minimum period, T_c , required to avoid wrap around errors in the convolution is given by

$$T_{c} = T_{m} + T_{t}$$

= $(N_{m} - 1)\Delta t_{m} + (N_{t} - 1)\Delta t_{t}$ (27)

The number of frequencies required to generate the convolution is given by

$$N_{c} = 1 + \frac{(N_{t} - 1)\Delta t_{t}}{\Delta t_{c}} + \frac{(N_{m} - 1)\Delta t_{m}}{\Delta t_{c}}$$
(28)

R. C. Gonzalez and R. E. Woods. Digital Image Processing. Addison-Wesley Publishing Company. (1993).

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As shown earlier the transform of a function can be calculated at any frequency up to its Nyquist frequency, $v_{max} = 1 / (2 \Delta t)$. No information about the transform can be found above this frequency. However the two functions have different sampling intervals and therefore different Nyquist frequencies. For the convolution the two transforms have to be multiplied. The product will contain no information for frequencies greater than the smaller of the two Nyquist frequencies. This frequency is given by $v_{max} = 1 / (2 \Delta t_c)$, where Δt_c is the larger of the two sampling intervals, i.e $\Delta t_c = max(\Delta t_b \Delta t_m)$. Therefore for the convolution the set of frequencies are given by based on N_c as defined in the equation above and Δt_c . These frequencies are given by

$$v_{n} = \frac{n}{N_{c} \Delta t_{c}}$$
(29)
$$n = -(N_{c}/2+1), ..., (N_{c}/2)$$

The discrete Fourier transform (F_m and F_t) of each function (f_t and f_m) at this set of frequencies can now be calculated using

$$\boldsymbol{F}_{\boldsymbol{m},\boldsymbol{n}} = \sum_{k=0}^{N_m - 1} \boldsymbol{f}_{\boldsymbol{m},\boldsymbol{k}} \exp\left(-i \, 2 \, \boldsymbol{\pi} \, \boldsymbol{v}_n \, \boldsymbol{k} \, \Delta \, \boldsymbol{t}_m\right) \tag{30}$$

where $f_{m,k} \equiv f_m(t_k)$, and

$$\boldsymbol{F}_{t,n} = \sum_{k=0}^{N_t-1} \boldsymbol{f}_{t,k} \exp\left(-i 2\pi v_n k \,\Delta t_t\right)$$
(31)

where $f_{t,k} \equiv f_t(t_k)$. These transforms are now multiplied together to form $H(v_n)$,

$$\operatorname{Re}[\boldsymbol{H}_{\boldsymbol{n}}(\boldsymbol{f}_{n})] + i\operatorname{Im}[\boldsymbol{H}_{\boldsymbol{n}}(\boldsymbol{f}_{n})] = (\operatorname{Re}[\boldsymbol{F}_{\boldsymbol{m},\boldsymbol{n}}] + i\operatorname{Im}[\boldsymbol{F}_{\boldsymbol{m},\boldsymbol{n}}])(\operatorname{Re}[\boldsymbol{F}_{t,\boldsymbol{n}}] + i\operatorname{Im}[\boldsymbol{F}_{t,\boldsymbol{n}}]) \quad (32)$$

so that

$$Re[\boldsymbol{H}(\boldsymbol{v}_n)] = Re[\boldsymbol{F}_{m,n}]Re[\boldsymbol{F}_{t,n}] - Im[\boldsymbol{F}_{m,n}]Im[\boldsymbol{F}_{t,n}]$$

$$Im[\boldsymbol{H}(\boldsymbol{v}_n)] = Re[\boldsymbol{F}_{m,n}]Im[\boldsymbol{F}_{t,n}] + Re[\boldsymbol{F}_{t,n}]Im[\boldsymbol{F}_{m,n}]$$
(33)

The convolution of f_t and f_m is equal to the inverse of H_n . This can be found at any value of t by using equation (12). Where Δt_d is any regular sampling interval the convolution at $k\Delta t_d$ is given by

$$h(k\Delta t_d) = \frac{\Delta t_m \Delta t_t}{\Delta t_c} \frac{1}{N_c} \sum_{n=0}^{N_c-1} \boldsymbol{H}(f_n) \exp\left(2\pi i v_n k\Delta t_d\right)$$
(34)

A5 Convolution Of Microstripes TLM Model Output With A TASER Waveform

The output from the Microstripes TLM solver consists of the electric field response of each output cell to a Dirac delta function input. The model also outputs the wire current that has driven the model. To find the response of an output cell to a TASER waveform the electric field response needs to be convolved with the TASER waveform and scaled for the wire current. The convolution in the frequency domain is then defined as

$$\frac{DFT_{\text{mod }el} xDFT_{taser}}{DFT_{wirecurrent}}$$
(35)

This is then inverse transformed and divided by the sampling interval of the model, Δt_{model} , to give the convolution of the model output with the TASER waveform scaled with the wire current. Note that using this definition convolving the TASER waveform with the wire current will give back the TASER waveform.

A6 Examples

A square wave starting at t = 0 and extending to $t = \alpha$ with an amplitude of A is defined as

$$f(t) = \begin{cases} A & 0 < t < \alpha \\ 0 & \text{otherwise} \end{cases}$$
(36)

The Fourier transform of this function can be found as

$$F[\nu] = \int_{-\infty}^{\infty} f(t) \exp(-i2\pi\nu t) dt$$

$$= A \int_{0}^{\alpha} \exp(-i2\pi\nu t) dt$$

$$= \frac{-A}{i2\pi\nu} [\exp(-i2\pi\nu t)]_{0}^{\alpha}$$
(37)

$$= \frac{-A}{i2\pi\nu} [\exp(-i2\pi\nu\alpha) - 1]$$

$$= \frac{-A}{i2\pi\nu} [\exp(-i\pi\nu\alpha) - \exp(i\pi\nu\alpha)] \exp(-i\pi\nu\alpha)$$

$$= \frac{A}{\pi\nu} \sin(\pi\nu\alpha) \exp(-i\pi\nu\alpha)$$

Therefore the magnitude at each frequency is given by

$$\left| \boldsymbol{F} \left[\boldsymbol{\nu} \right] \right| = \frac{A}{\pi \nu} \sin\left(\pi \nu \alpha\right) = \alpha A \frac{\sin\left(\pi \nu \alpha\right)}{\pi \nu \alpha}$$
(38)

The convolution of a square wave, f(t), and a sin wave, g(t), defined by

$$f(t) = \begin{cases} A & 0 \le t \le \pi \\ 0 & \text{otherwise} \end{cases}$$

$$g(t) = \begin{cases} Bsin(t) & 0 \le t \le \pi \\ 0 & \text{otherwise} \end{cases}$$
(39)

can be found using equation (33). The result is

.

$$f * g = \begin{cases} AB(1 - \cos(t)) & 0 \le t \le 2\pi \\ 0 & \text{otherwise} \end{cases}$$
(40)

The convolution of two square waves of equal length defined as,

$$f(t) = \begin{cases} A & 0 \le t \le \alpha \\ 0 & \text{otherwise} \end{cases}$$

$$g(t) = \begin{cases} B & 0 \le t \le \alpha \\ 0 & \text{otherwise} \end{cases}$$
(41)

can be found using the convolution definition in equation (33)

$$f * g = \begin{cases} ABt & 0 < t < \alpha \\ AB(2\alpha - t) & \alpha \le t \le 2\alpha \\ 0 & \text{otherwise} \end{cases}$$
(42)

Annex B Electric Current Passing Through Surface of the Heart

B.1 Calculating Electric Field Response from Model

The output from the TLM simulation convolved with the TASER stimulus consists of the electric field components in the x, y and z directions for each output cell at each time step. This appendix describes how the electric field components are converted to current densities and integrated to provide overall current flow.

B.2 Response from TASER Waveform

The relationship between electric field strength, E (V/m), and current density, J (Amps/m²), is:

$$\boldsymbol{J} = \boldsymbol{\sigma} \boldsymbol{E} \tag{43}$$

where σ (S/m) is the electrical conductivity of the heart muscle.

Applying this in each direction, the current density components are:

$$J_{x} = \sigma E_{x}$$

$$J_{y} = \sigma E_{y}$$

$$J_{z} = \sigma E_{z}$$
(44)

B.3 Calculation of Electric Current

To convert from current densities to electric current requires the area of each cell face. Dimensions of the cells in each direction vary across the system and can be found from the block definitions in the .tlm file. Given the dimensions of the cell, the areas of the faces in each direction are:

$$A_{x} = dy dz$$

$$A_{y} = dx dz$$

$$A_{z} = dx dy$$
(45)

where dx, dy, dz, are the lengths of the cells in the x, y and z directions.

Also, the current component flowing through each cell face is the product of the current density component and cell face area:

$$I_{x} = J_{x}A_{x}$$

$$I_{y} = J_{y}A_{y}$$

$$I_{z} = J_{z}A_{z}$$
(46)

To enable automated calculation of the current passing through the heart, a convention was defined that denotes cell faces with the lower applicable co-ordinate value as "-" and the face with the higher applicable co-ordinate value as "+", as illustrated in the following diagram:



and assigns each face a value depending on whether it is exposed on the surface or not and whether a positive current component passing through that face would enter or leave the heart. The values assigned are:

$$X^{-} = \begin{cases} 1 & \text{if exposed} \\ 0 & \text{if not exposed} \end{cases}$$

$$X^{+} = \begin{cases} -1 & \text{if exposed} \\ 0 & \text{if not exposed} \end{cases}$$

$$Y^{-} = \begin{cases} 1 & \text{if exposed} \\ 0 & \text{if not exposed} \end{cases}$$

$$Y^{+} = \begin{cases} -1 & \text{if exposed} \\ 0 & \text{if not exposed} \end{cases}$$

$$Z^{-} = \begin{cases} 1 & \text{if exposed} \\ 0 & \text{if not exposed} \end{cases}$$

$$Z^{+} = \begin{cases} -1 & \text{if exposed} \\ 0 & \text{if not exposed} \end{cases}$$

Thus, the net current entering the heart through a cell is:

$$I_{\text{net}} = I_x X^{+} + I_x X^{+} + I_y Y^{-} + I_y Y^{+} + I_z Z^{-} + I_z Z^{+}$$
(48)

which can be split into currents entering and leaving the heart through that cell:

$$I_{net} = I_{in} + I_{out} \tag{49}$$

where the current entering the heart through that cell is:

$$I_{in} = I_{x}X^{-} \text{ if } > 0 + I_{x}X^{+} \text{ if } > 0 + I_{y}Y^{-} \text{ if } > 0 + I_{y}Y^{+} \text{ if } > 0 + I_{z}Z^{-} \text{ if } > 0 + I_{z}Z^{+} \text{ if } > 0$$
(50)

and the current leaving the heart through that cell is:

$$I_{out} = I_x X^{-} \text{ if } < 0 + I_x X^{+} \text{ if } < 0 + I_y Y^{-} \text{ if } < 0 + I_y Y^{+} \text{ if } < 0 + I_z Z^{-} \text{ if } < 0 + I_z Z^{+} \text{ if } < 0$$
(51)

B4 Calculation of Current Densities

Defining an effective area for each cell as:

$$A_{eff} = A_{x} (|X^{-}| + |X^{+}|) + A_{y} (|Y^{-}| + |Y^{+}|) + A_{z} (|Z^{-}| + |Z^{+}|)$$
(52)

Gives a total area for that cell over which current is entering or leaving the heart surface. Consequently the net current density for a cell is:

$$J_{\rm net} = \frac{I_{\rm net}}{A_{\rm eff}}$$
(53)

The effective area for the current entering the heart through a cell is defined as the area of those faces which are exposed and which have a current in component:

$$A_{in} = A_x \text{ if } (I_x X^{-} > 0 \text{ or } I_x X^{+} > 0) + A_y \text{ if } (I_y Y^{-} > 0 \text{ or } I_y Y^{+} > 0) + A_z \text{ if } (I_z Z^{-} > 0 \text{ or } I_z Z^{+} > 0)$$
(54)

Note that $I_x X^-$ and $I_x X^+$ cannot both be positive at the same time.

The current density entering the heart through a cell is then:

$$J_{\rm in} = \frac{I_{\rm in}}{A_{\rm in}} \tag{55}$$

Similarly the effective area for the current leaving the heart through a cell is defined as

$$A_{\text{out}} = A_x \quad \text{if} \quad I_x X^- < 0 \text{ or } I_x X^+ < 0 + A_y \quad \text{if} \quad I_y Y^- < 0 \text{ or } I_y Y^+ < 0 + A_z \quad \text{if} \quad I_z Z^- < 0 \text{ or } I_z Z^+ < 0$$
(56)

and the current density leaving the heart through a cell is defined as

$$J_{\text{out}} = \frac{I_{\text{out}}}{A_{\text{out}}}$$
(57)

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Appendix F – "Effects of simulated M26 and X26 Taser waveforms on the guinea-pig isolated heart."

DSTL/PUB20754 15 March 2005

Executive summary

Background

In a review of the medical implications of M26 Taser use⁶⁸, the heart was identified as the principal organ at risk of being adversely influenced by the M26 Taser current and a two-fold cardiac risk assessment strategy was proposed. The first part of the assessment, which was based on the U.S. observation that drug intoxication (particularly with PCP) was common amongst those in whom a serious adverse response occurred in association with Taser deployment, focused on the effects of several drugs of abuse on the cardiac action potential in sheep Purkinje fibres. This study found that PCP and Ecstasy induced prolongation of the action potential, an effect which may predict QT prolongation in man and subsequent development of a possibly lethal form of ventricular arrhythmia⁶⁹. Although this study did not address the cardiac effects of the Taser discharge, it helped to provide insight into the toxicological context in which the Taser may be deployed.

The present report describes the findings from the second part of the assessment of the potential cardiac risks associated with the M26 and X26 Taser electrical incapacitation devices⁷⁰. In this part of the risk assessment, simulated M26 and X26 waveforms have been applied directly to the ventricular epicardial surface of spontaneously beating guinea-pig isolated, perfused hearts. In this way it was hoped to establish the threshold currents required to elicit two types of myocardial responses: ventricular ectopic beats (premature ventricular contractions) and ventricular fibrillation.

Requirement and Scope of Work

The M26 Taser has been used for several years in the US and has recently been adopted by several police forces in the UK as a less lethal alternative to firearms. In May 2003, Taser International introduced the X26 Taser, the output of which differs in shape and magnitude from the M26. In use, the safety profiles of these devices appear to be extremely good. However, it is recognised that there is at least a theoretical risk that the electrical discharge could adversely influence cardiac rhythm by a direct interaction of the Taser current with the heart. Assessment of this hypothetical risk has been approached experimentally as follows:

- Computational electromagnetic modelling of M26 and X26 Taser currents flowing into the heart using a digital mannequin (*Dstl Boolean Man*) in which the material properties (conductivity and relative permittivity) of the human body are represented.
- Application of the modelled currents to the isolated, spontaneously beating, guinea-pig heart to establish the threshold for any effects on cardiac rhythm.

⁶⁸ Report reference DSTL/PUB20749.

⁶⁹ Report reference DSTL/PUB20751 and Sheridan, RD et al. (2005) Eur J Pharmacol, paper in press.

⁷⁰ The M26 and X26 Tasers are products of TASER International (http://www.taser.com).

The computational electromagnetic modelling work is described in a separate report⁷¹.

Main Findings

Simulated Taser waveforms were applied to the ventricular epicardial surface of spontaneously beating guinea-pig isolated hearts using a silver contact electrode (surface area: 18 mm²).

When applied during the T-wave of the electrocardiogram at current densities predicted by the computational electromagnetic modelling to appear at the human heart during Taser discharge, neither the simulated M26 nor X26 waveforms evoked ventricular ectopic beats. However, ectopic beats could be elicited by both Taser waveforms by increasing the peak current density of the applied waveforms:

	M26	X26	
Modelled peak current density at heart (mA/mm ²)	0.66 ^a	-0.11 ^b	
Threshold peak current density for ectopic beat (mA/mm ²)	$40.1 \pm 5.6^{\circ}$	-7.3 ± 1.1^{d}	
^a Measured at peak of first half cycle ^b Measured at peak of second half cycle			
^c Mean \pm s.e. mean for 4 hearts (a fifth heart failed to generate an ectopic in response to the M26 waveform). ^d Mean \pm s.e. mean for 5 hearts.			

 Table 23: Peak current density measurements for M26 and X26

The threshold current density for generation of ventricular ectopic beats for both the M26 and X26 Taser waveforms was greater than 60-fold the modelled current density predicted to occur at the heart.

In an attempt to evoke ventricular fibrillation, trains of simulated M26 or X26 Taser waveforms (5 s, 38 Hz trains for the M26 waveform; 5 s, 19 Hz trains for the X26 the waveform) were applied to the ventricular myocardium. (The train characteristics mimicked the typical discharge characteristics of the Taser devices.) When the simulated waveforms were applied in this way neither the M26 nor X26 waveforms elicited ventricular fibrillation at peak current densities up to the maximum output available from the electrical stimulation system:

	M26	X26
Threshold for eliciting VF (mA/mm ²)	$> 51.8 \pm 0.5^{a}$	$> -27.1 \pm 3.8^{a,b}$
^a Mean \pm s.e. mean for 5 hearts ^b More negative than -27 .	$.1 \text{ mA/mm}^2$	

Table 24: Threshold current densities for eliciting VF

The threshold peak current density for generation of ventricular fibrillation for the simulated M26 Taser waveform was greater than 70-fold the modelled current density predicted to occur at the heart during Taser discharge. In the case of the simulated X26 waveform the threshold peak current density was greater than 240-fold the modelled current density. (That this failure of the simulated M26 and X26 Taser waveforms to induce ventricular fibrillation was not a function of the biological test system was demonstrated in each experiment by the generation of fibrillation using 'conventional' 100 μ s rectangular stimulation pulses.)

⁷¹ Report reference DSTL/PUB20755, Modelling current flow in the human body from the M26 and X26 TASER devices

Conclusions

The results indicate that the simulated M26 and X26 waveforms, <u>when suitably amplified</u>, are capable of eliciting ventricular ectopic beats, but not ventricular fibrillation, when applied to the ventricular myocardium of spontaneously beating guinea-pig isolated hearts.

The threshold peak current intensity for both M26 and X26 waveforms for induction of ventricular ectopic beats was greater than 60-fold the peak current intensity predicted from the computational electromagnetic modelling to arise in the human heart during Taser discharge, implying a wide safety margin for this particular type of potentially pro-arrhythmic response.

Given that the guinea-pig heart is more susceptible than hearts of larger animals (e.g. dog, calf and pig) to ventricular fibrillation induced by extrinsic electrical stimulation⁷², the present findings provide indirect evidence for a wide margin of safety in relation to induction of this type of lethal arrhythmia. A broadly similar conclusion was reached in a study in which trains of simulated X26 waveforms of varying intensity, applied across the thorax of anaesthetised pigs, induced ventricular fibrillation only at intensities 15- to 42-fold that of the standard X26 waveform⁷³.

On the basis of the present study, it is considered unlikely that the discharge from the M26 and X26 Taser devices will influence cardiac rhythmicity by a direct action on the heart. The possibility that other factors (e.g. illicit drug intoxication, alcohol abuse, pre-existing heart disease and cardioactive therapeutic drugs) may modify the threshold for generation of cardiac arrhythmias cannot be excluded. Similarly, other responses to Taser deployment (e.g. arrhythmias precipitated by stress- or exercise-induced catecholamine release) may, in themselves, predispose to an adverse cardiac outcome independent of the primary (electrical) action of the Taser devices.

Recommendations

A database of all instances of Taser deployment to be maintained (to include aiming, 'red dot' and actual firings).

The database should include details of any adverse health outcomes occurring concomitantly with, and up to several days after, Taser deployment.

The database should include details of any events (e.g. epileptic seizure, chest pain, head trauma) or actions (e.g. pursuit, restraint) that may be relevant to determining the causation of any adverse outcome associated with Taser deployment.

Suspicion of intoxication with drugs (illicit or pharmaceutical), volatile substances or alcohol should be noted in the database and, if considered appropriate, samples should be taken by the Forensic Medical Examiner for subsequent analysis.

 ⁷² Ferris et al. (1936). Effect of electric shock on the heart. *Electrical Engineering* 55:498-515
 ⁷³ McDaniel *et al.* (2005). Cardiac safety of neuromuscular incapacitating defensive devices. *Pacing Clin Electrophysiol* 28(S1):S284-S287

1 Introduction

1.1 Background to the study

- 1.1.1 In a review of the medical implications of M26 Taser use (report reference DSTL/PUB20749), the heart was identified as the principal organ at risk of being adversely influenced by the Taser current and a two-fold cardiac risk assessment strategy was proposed.
- 1.1.2 The first part of the risk assessment, which was based on the observation made in the U.S. that drug intoxication (notably with PCP) was common amongst those in whom a serious adverse response occurred in association with Taser deployment, focused on the effects of several drugs of abuse on the cardiac action potential in sheep isolated Purkinje fibres. This study found that PCP and Ecstasy induced prolongation of the action potential, an effect which may be predictive of QT prolongation in man and subsequent development of a possibly lethal form of ventricular arrhythmia (report reference DSTL/PUB20751). Although this initial study was not designed to address the cardiac effects of the Taser discharge, it helped to provide insight into the toxicological context in which the Taser may be deployed (Sheridan *et al.*, 2005).
- 1.1.3 In the second part of the risk assessment, which is the subject of the present report, the direct effects of simulated M26 and X26 Taser⁷⁴ waveforms on the isolated, spontaneously beating guinea-pig heart have been examined.

1.2 The M26 and X26 Tasers

- 1.2.1 The M26 Taser has been in use for several years in the U.S. and is currently being used by several constabularies in the U.K. In May 2003, TASER International introduced the X26 Taser. Amongst other things, the X26 is smaller and lighter than the M26 and, according to Taser International⁷⁵, has "greater stopping power". It is seems likely that the X26 will eventually replace the M26 as the less lethal weapon of choice in circumstances where a firearm may previously have been the only alternative.
- 1.2.2 The outputs of the M26 and X26 Tasers differ markedly in terms of waveform amplitude and duration (Figure 1). The pulse repetition frequency (p.r.f.) of the M26 is typically 38 Hz while the p.r.f. of the X26 is typically 19 Hz. Both devices are designed to discharge continuously for a maximum of 5 s following a single activation of the trigger. Note that peak-to-peak amplitude of the M26 output is several times greater than that of the X26, but that the duration of each output pulse from the X26 is considerably longer than that of the M26 (Figure 1).

⁷⁴ The M26 and X26 Tasers are products of TASER International, Scottsdale, Arizona (http://www.taser.com).

⁷⁵ http://www.taser.com/law/product_info/index.htm



Figure 77: Comparison of the outputs of the M26 and X26 when the currents are injected into loads approximating that of the human torso.

1.3 M26 and X26 Taser currents and the heart

- 1.3.1 The objective of the present study was to establish whether the currents discharged by the M26 and X26 devices had the potential to influence cardiac rhythm. One way of achieving this aim is to apply Taser discharges directly to the torso of living animals. This latter method was adopted in a recently published study by McDaniel *et al.* (2005). These authors examined the effects on blood pressure and heart rate of simulated X26 discharges applied to the thorax of anaesthetised pigs (see Discussion).
- 1.3.2 A complementary approach, and the one that was adopted by Dstl, involved a combination of computational electromagnetic modelling (to estimate the shape and magnitude of the Taser currents reaching the heart), followed by experimental studies in which the modelled currents were applied directly to the ventricular myocardium of spontaneously beating hearts isolated from guinea-pigs.
- 1.3.3 Each approach has its advantages and disadvantages. In the case of the *in vivo* experiments of McDaniel *et al.* (2005) the presence of anaesthetic may have influenced the response of the heart to the Taser current. In the case of the computational modelling approach, interpretation of the results is dependent upon the validity of the modelling and the transitioning of the modelling output from the *in silico* environment to the *in vitro* biological test system. A drawback shared by both approaches is that neither uses human tissue (pig in the case of McDaniel *et al.*, guinea-pig in the case of the present study). A distinct advantage of the modelling approach is that any number of scenarios (i.e. Taser barb positions) may, in principal, be computed. These issues are further addressed in the Discussion to the present report.

1.4 Computational electromagnetic modelling

- 1.4.1 A full report of the computational modelling is given elsewhere⁷¹ and this section provides a summary. Briefly, a digital mannequin (*Dstl Boolean Man*), was used in a transmission line matrix (TLM) model to evaluate current flows in the heart induced by M26 and X26 Taser discharges applied to the anterior aspect of the mannequin's torso. The material properties (conductivity and relative permittivity) of the mannequin's various tissues and organs were incorporated into the TLM.
- 1.4.2 Barb contact points were applied in several orientations, the worst case position being a barb separation of 225 mm (one dart positioned on the torso

surface overlying the ventricles, the other dart 225 mm vertically below the first dart). In this worst case situation, the Taser currents appearing at the ventricular epicardial surface of the mannequin were as illustrated in Fig. 2. The peak current densities of the waveforms were 0.66 mA/mm² for the M26 (measured at peak of first half-cycle) and -0.11 mA/mm² for the X26 (measured at the nadir of the second half-cycle).



Figure 78: M26 and X26 waveform current densities arising at heart

1.4.3 An alternative way of visualising the currents at the heart is by way of current density contour maps corresponding to the time point at which the peak current arises. These are shown for both waveforms in Fig. 3.



Figure 79: Current contour maps for M26 (*middle*) and X26 (*right*) at a time corresponding to the point of peak current (3.7 µs into the waveform for the M26 and 7.4 µs into the waveform for the X26). The human heart (*left*) shows the approximate orientation of the digital mannequin's heart.

1.5 The in vitro test system: isolated heart preparation

1.5.1 The isolated perfused heart preparation (Langendorff preparation) was used to evaluate the potential pro-arrhythmic effects of the simulated Taser pulses. This preparation is commonly used to evaluate the physiology, pharmacology and biochemistry of hearts from small mammals (e.g. rats, guinea-pigs and rabbits) (Sutherland and Hearse, 2000). 1.5.2 The decision to use the guinea-pig heart in the present work was partly based on the similarity of the electrocardiographic P, QRS and T wave configurations in this species to those generated by the human heart. This lies in contrast to the rat heart, where the ECG is much shorter and has an unusual shape (which is mainly due to differences in the contribution of certain types of potassium channel to the electrical activity of rat heart muscle cells). Although hearts from larger animals have been used in Langendorff type experiments, the requirement for extremely large volumes of physiological salt solution to maintain the hearts for any length of time *in vitro* make this approach impractical. As an example, pig hearts require a flow of about 200 ml/min (i.e. a total of 25 litres over the typical time-course of the experiments performed in the present study). In contrast, guinea-pig hearts can be maintained *in vitro* with a perfusate flow of about 10 ml/min.

1.6 Transitioning the modelling output into the in vitro test system

- 1.6.1 The current density contour maps for the M26 and X26 (Fig. 3) indicate that the peak current density is highest on the ventricular surface under the region of the torso where the upper Taser barb is located. The current density then progressively falls off with increasing distance from the barb contact point.
- 1.6.2 Fig. 4 illustrates a section of the M26 and X26 current density contour maps superimposed upon a graphic of a human heart orientated in approximately the same position as the heart in the contour maps. The contour map for the M26 (Fig. 4, *left*) encloses current densities ranging from 0.45 to 0.66 mA/mm², while that for the X26 (Fig. 4, *right*) encloses current densities ranging from -0.07 to -0.11 mA/mm². It can be seen that the bulk of the current appears to be distributed over a sizeable area of the surface of the right ventricle (RV in Fig. 4).



Figure 80: The current density contour maps for the M26 (*left*) and X26 (*right*), corresponding to time of peak current flow, are shown superimposed upon a graphic of the human heart. These contour maps represent the bulk of the current arising at the ventricular surface and illustrate that the current distribution covers a large area of the right ventricle (RV).

- 1.6.3 The question that then arises is: What is the most appropriate way in which to apply these current profiles in an animal heart preparation *in vitro*? Clearly, the closest approximation to the output from the modelling work would involve using an electrical stimulation system that enabled exact replication of the current density contours indicated in Fig. 4. However, this would be extremely difficult technically to achieve in practice.
- 1.6.4 An initial series of experiments looking at the simulated M26 Taser waveform used a commercially available circular electrode having a small surface area (1.9 mm²). However, it was considered that the area of this electrode was too small, and that stimulation of a larger area of the ventricular surface would be more representative of the current distribution predicted by the modelling. For this reason, subsequent experimentation used a custom-made rectangular electrode having a ventricular contact area of approximately 18 mm². Fig. 5 shows a photograph of a guinea-pig heart with the area of contact of the small and large electrodes indicated. These electrodes represent the upper barb (see 1.4.2).



- Figure 81: Guinea-pig heart showing the relative contact areas of the small (1.9 mm²; *left*) and large (18 mm²; *right*) stimulation electrodes. LV left ventricle;
 RV right ventricle; LAD left anterior descending coronary artery; RA right atrium. The graduations on the ruler are millimetres. This heart was previously used in an experiment, hence the left atrium has been excised.
- 1.6.5 A limitation, then, of the *in vitro* electrical stimulation system is that electrode representing the upper Taser barb in contact with the ventricles presents a homogeneous current to the ventricular surface, while the modelled current at the heart is graduated (Fig. 4).
- 1.6.6 Another consideration in the transition from modelling to the isolated heart is the direction of current flow. In the modelling the Taser barbs were located in a vertical plane (see 1.4.2). In an effort to simulate this *in vitro*, the apex of the heart was submerged in physiological salt solution into which the 'lower barb' electrode was also immersed (Fig. 6).



Figure 82: The guinea-pig isolated heart preparation. The heart is attached via the aorta to the perfusion system (not visible in picture). The 'upper barb' stimulation electrode is placed in contact with the ventricles while the 'lower barb' electrode is immersed in the physiological salt solution bathing the apex of the ventricles (see inset).

1.7 Generation of the simulated M26 and X26 Taser waveforms

1.7.1 The simulated Taser waveforms were produced by amplification of the output of a programmable waveform generator. The output of the amplifier was then fed directly to the 'upper barb' and 'lower barb' electrodes (Fig. 6). The waveform generation system is described in detail in the Methods section of this report.

1.8 Ventricular ectopic beats (VEBs) and ventricular fibrillation (VF)

- 1.8.1 The normal heartbeat is initiated in a specialised region of the heart known as the primary pacemaker (the sino-atrial node) which is located in the wall of the right atrium.
- 1.8.2 VEBs (also known as premature ventricular contractions or extrasystoles) can occur in the human heart when an ectopic pacemaker arises in the ventricles. Isolated VEBs, when they occur in individuals in whom there is no underlying heart disease, usually have no clinical significance and do not require treatment (Huszar, 1994a). When VEBs occur in the presence of heart disease (e.g. acute myocardial infarction) or intoxication with certain drugs (e.g. digitalis), they can degenerate into life-threatening arrhythmias such as ventricular tachycardia and VF (Huszar, 1994a).
- 1.8.3 VF is a potentially lethal arrhythmia that originates in multiple ectopic pacemakers in the ventricles. It is one of the most common causes of cardiac arrest (Huszar, 1994b). Although VF usually arises in the context of significant cardiac disease, it can also be precipitated by electric shock (Reilly, 1998). VF results initially in faintness, followed within seconds by loss of consciousness, seizures, respiratory arrest and, unless it is reversed by defibrillatory shocks, death (Huszar, 1994b).

1.9 VEBs and VF in the guinea-pig isolated heart

- 1.9.1 VEBs and VF can be readily elicited in the guinea-pig isolated heart preparation by application of appropriate forms of extrinsic electrical stimulation to the ventricular myocardium.
- 1.9.2 VEBs can be elicited in the guinea-pig isolated heart by applying single shocks to the ventricle. To evoke a VEB, the shock is timed to arrive during the T wave of the electrocardiogram (the so-called vulnerable period of the cardiac cycle).
- 1.9.3 The amplitude and duration of the shock are the two key parameters which determine whether a VEB will occur: short duration shocks (e.g. 10 µs) will require much higher currents to evoke a VEB than longer duration shocks (e.g. 2 ms). This relationship between the amplitude and duration required to evoke a VEB is termed a strength-duration curve which, traditionally, is constructed using rectangular shaped pulses of varying pulse width.
- 1.9.4 The guinea-pig heart can also be made to fibrillate by application of trains of shocks. Unlike the stimulation protocol used for inducing VEBs, the shocks do not have to be synchronised to any particular part of the cardiac cycle.

1.10 Can the simulated M26 and X26 waveforms induce VEBs or VF in the guinea-pig isolated heart?

- 1.10.1 The aim of the present study was to establish whether simulated M26 and X26 Taser waveforms, applied to the epicardial ventricular myocardium of spontaneously beating hearts isolated from guinea-pigs, had the ability to induce VEBs or VF and, if so, at what amplitude these responses occurred (relative to the amplitude predicted by the computational electromagnetic modelling to prevail at the ventricular surface of the human heart).
- 1.10.2 By extrapolation of the guinea-pig data to the human heart, it was hoped to estimate a margin of safety for these devices in field use and to answer the question of whether the heart was likely to be affected by the electrical currents generated between two Taser barbs sited close to the heart.

2 Materials and methods

2.1 Isolated heart preparation

- 2.1.1 Male Dunkin-Hartley guinea-pigs (Harlan-Olac, UK) weighing 280-410 g were killed by cervical dislocation and their hearts rapidly removed. The excised hearts were placed briefly in Tyrode's solution at room temperature (about 21°C) to promote expulsion of residual blood.
- 2.1.2 The hearts were then transferred to Langendorff apparatus (AD Instruments, Chalgrove, UK) where they were retrogradely perfused (in constant flow mode) through the aorta with Tyrode's solution at approximately 37°C. The flow rate was adjusted to maintain a coronary artery perfusion pressure of about 70 mmHg (typically requiring a flow rate of approximately 10 ml/min).
- 2.1.3 The left atrium was removed to facilitate placement of a balloon catheter in the left ventricle for monitoring of left ventricular contractility. A small cut was made in the pulmonary artery to facilitate drainage of Tyrode's solution from the heart. The apex of the ventricles was immersed in Tyrode's solution (Fig. 6).
- 2.1.4 The electrocardiogram was monitored across two electrodes, one positioned on the metal aortic cannula and one immersed in the Tyrode solution bathing the ventricular apex (see Fig. 6).
- 2.1.5 All experiments were conducted on spontaneously beating (unpaced) hearts. Isolated hearts typically had heart rates of 190-200 bpm after equilibration.
- 2.1.6 The composition of the Tyrodes solution was (in mM): NaCl 130, KCl 4.7, CaCl₂ 1.25, MgSO₄ 1.2, NaHCO₃ 25, D(+)-glucose 10 (gassed with 95% O₂, 5% CO₂).

2.2 Application of the simulated waveforms to the guinea-pig heart

- 2.2.1 In the initial experiments on the simulated M26 waveform, the waveform was applied using a commercial coaxial electrode (AH 73-0219; Harvard Apparatus, Kent, UK). This electrode was configured so that only the central electrode was active, the outer electrode being unused. The central electrode had a nominal diameter of 1.2 mm (surface area of approximately 1.9 mm²). This electrode is shown in Fig. 6, and the size of the central electrode in relation to the size of the guinea-pig heart is illustrated in Fig. 5 (*left*).
- 2.2.2 Given the profile of the current density contour map predicted at the human heart (see Fig. 4), it was decided to apply the simulated M26 waveform, and subsequently the simulated X26 waveform, with a custom made rectangular electrode the approximate dimensions of which were 6 mm x 3 mm (18 mm² surface area). The size of this rectangular electrode in relation to the size of the guinea-pig heart is illustrated in Fig. 5 (*right*).
- 2.2.3 The stimulation electrodes were positioned such that they were in close apposition to the ventricular epicardial surface (over the left anterior descending artery below its bifurcation with the diagonal coronary artery).

2.3 Arrangement for generation and application of simulated Taser waveforms

- 2.3.1 The predicted cardiac M26 and X26 Taser waveforms were programmed into a waveform generator (HP 33120A Arbitrary Waveform Generator, Hewlett Packard, US) using HP 34811A Benchlink software.
- 2.3.2 The output of the HP 33120A was fed into a custom designed push-pull amplifier (Poynting High Voltage Ltd, Didcot, UK) which provided additional gain of approximately 150. The output signal from the push-pull amplifier was fed directly to the stimulation electrode.
- 2.3.3 The signal return path for the stimulation current was made via a silver wire immersed in the Tyrode solution bathing the ventricular apex (Fig. 6) and connected to the signal ground of the push-pull amplifier.
- 2.3.4 Current in the stimulation circuit was derived from the voltage generated across a 100 Ohm resistor in the signal return path to the push-pull amplifier.
- 2.3.5 The arrangement for application of the simulated Taser waveforms is shown schematically in Fig. 7.



Figure 83: Arrangement used to establish threshold for generation of ventricular ectopic beats by the simulated Taser waveforms. The arbitrary waveform generator was triggered by a single pulse timed at a user-determined delay after the QRS complex of the electrocardiogram (ECG). This delay was adjusted so that the pulse arrived during the T-wave of the ECG. For the ventricular fibrillation (VF) experiments the waveform generator was also triggered by the S88 stimulator, but the trains of pulses were free-running (i.e. not synchronised to any part of the ECG).

2.4 Arrangement for application of rectangular pulses to the heart

- 2.4.1 In order to assess the response of hearts to conventional stimulus waveforms, rectangular pulses were generated using a commercial biological stimulator (Grass S88, Astro-Med Inc, US). These pulses were applied to the heart through the same electrodes as the simulated Taser waveforms.
- 2.4.2 Current in the stimulation circuit was derived from the voltage generated across a 100 Ohm resistor in the signal return path to the S88 stimulator.
- 2.4.3 Rectangular pulses were used to determine the baseline response characteristics for each heart in terms of strength-duration curves for the
generation of ventricular ectopic beats (VEBs). These curves were obtained in each experiment before application of the simulated Taser waveforms (see Section 2.5).

- 2.4.4 Trains of rectangular pulses were also used to evoke ventricular fibrillation (VF) in experiments in which the simulated Taser waveforms failed to evoke VF. In this way, the rectangular pulses acted as a positive control, thereby demonstrating that hearts were capable of generating VF.
- 2.4.5 The arrangement for application of the rectangular waveforms is shown schematically in Fig. 8.



Figure 84: Arrangement used to establish threshold for generation of ventricular ectopic beats by rectangular waveforms. The S88 stimulator generates a single rectangular pulse at a user-determined delay after the QRS complex of the electrocardiogram (ECG). This delay was adjusted so that the pulse arrived during the T-wave of the ECG. For the ventricular fibrillation (VF) experiments the S88 was set to deliver trains of rectangular pulses. These trains were not synchronised to any part of the ECG.

2.5 Experimental design

2.5.1 After isolation, initiation of *in vitro* perfusion and instrumentation (see Section 2.1), hearts were allowed to equilibrate for a minimum of 30 min. After this time, any hearts displaying spontaneous arrhythmias were excluded from further experimentation. A schematic of the experimental design is illustrated in Fig. 9.



Figure 85: Experimental design (horizontal arrow signifies time). See text for details.

- 2.5.2 Following equilibration, a strength-duration curve for the induction of VEBs in response to monophasic rectangular pulses (10 to 200 μs) was generated prior to application of the simulated Taser waveforms.
- 2.5.3 The threshold current required for generation of VEBs using single pulses of either the simulated M26 or X26 waveforms was then determined.
- 2.5.4 An attempt was then made to induce ventricular fibrillation using 5 s trains of simulated M26 waveforms (38 Hz) or X26 waveforms (19 Hz).
- 2.5.5 If VF was not induced by the simulated Taser waveforms, VF was subsequently induced using 5 s trains of rectangular pulses (100 µs duration, 38 Hz or 19 Hz) to confirm that the test system was able to generate this form of arrhythmia.
- 2.5.6 The experiments described in this report were conducted on a total of 15 hearts: 5 hearts with the M26 waveform applied using the 1.9 mm² electrode, 5 hearts with the M26 waveform applied using the 18 mm² electrode, and 5 hearts with the X26 waveform applied using the 18 mm² electrode (see Section 2.2).

2.6 Data acquisition

2.6.1 Data were digitised at 2 kHz using the PowerLab 8SP analogue-to-digital converter in conjunction with Chart 5.0 software (AD Instruments, UK). These comprised part of a proprietary Langendorff system (see http://www.adinstruments.com/). The Chart software recorded the following data: electrocardiogram, left ventricular pressure, flow rate and perfusate temperature (monitored by a thermistor located approximately 5 mm upstream of the tip of the aortic cannula).

2.7 Data analysis and presentation

2.7.1 Strength-duration curves for the generation of VEBs by rectangular pulses were constructed by taking an average of the current densities required to evoke a VEB at each of the pulse durations (which ranged from 10-200 μ s). These averages (mean \pm s.e. mean) were then plotted in a graphics programme (GraphPad Prism v3.0; GraphPad Software Inc, US).

- 2.7.2 The current density thresholds for generation of VEBs by the simulated M26 and X26 waveforms were averaged (mean \pm s.e. mean) and plotted on the strength-duration curves for rectangular pulses to allow visual comparisons to be made. The location on the *x* (duration) axis of the thresholds for the Taser waveforms is semi-arbitrary as, although the M26 and X26 waveforms have total durations of about 50 µs and 150 µs, respectively, a substantial amount of the charge (and, therefore, the biological stimulus) is contained within the early part of the waveform. This is particularly true of the M26 waveform (see Fig. 2). For ease of presentation, therefore, the VEB thesholds for both Taser waveforms have been plotted close to the zero point on the *x* axis.
- 2.7.3 Current densities were calculated by dividing the current generated in the stimulation circuit (Sections 2.3.4 and 2.4.2) by the surface area of the stimulating electrode (Sections 2.2.1 and 2.2.2).

3 Results

3.1 Induction of ventricular ectopic beats (VEBs) by rectangular pulses and by the simulated M26 Taser waveform

3.1.1 VEBs could be induced by conventional rectangular pulses and by the M26 waveform, suitably amplified, when these were applied to the ventricles using either the small surface area (1.9 mm²) or large surface area (18 mm²) stimulation electrodes. Examples of VEBs generated using the small electrode are shown in Fig 10.



- Figure 86: Example of VEBs induced in a single heart by a 100 µs rectangular pulse (left traces) or simulated M26 waveform (right traces) applied to the ventricular epicardial surface during the T-wave of the electrocardiogram (ECG in lower traces). The effect of the VEB on contractility is clearly seen in the left ventricular pressure (LVP) signal (upper traces). The VEB appears as a premature contraction followed by a compensatory pause. In these examples, the VEBs were induced using the 1.9 mm² electrode. The current densities required to evoke the VEBs were 3.45 mA/mm² for the rectangular pulse and 31.8 mA/mm² (M26 waveform). The horizontal scale indicates time from start of experiment (h:mm:ss).
- 3.1.2 The averaged strength-duration curves for induction of VEBs using rectangular pulses of various durations (applied with the small or large surface area electrode) are shown in Fig 11. These curves demonstrate the typical response characteristics of excitable biological systems (e.g. muscle and nerve) to electrical stimulation: (a) shorter duration pulses necessitate higher currents to evoke responses; (b) as the stimulation pulse becomes progressively longer, the current required to evoke a response approaches a plateau.
- 3.1.3 Also plotted on the strength-duration curves in Fig. 11 are the threshold peak current densities (mean \pm s.e. mean) required for the M26 Taser waveform to elicit VEBs using either the small or large surface area stimulation electrode. (The peak current density of the M26 waveform is defined here as the current density at the peak of the first half-cycle of the waveform see Section 1.4.2.)
- 3.1.4 The threshold peak current density for induction of VEBs with the simulated M26 waveform was (mean \pm s.e. mean) 18.8 \pm 4.7 mA/mm² for the small electrode (5 hearts) and 40.1 \pm 5.6 mA/mm² for the large electrode (4 hearts). A fifth heart in the large electrode group failed to generate a VEB in response to the M26 waveform.



Figure 87: Comparison of threshold current densities required to evoke VEBs with conventional rectangular pulses or the simulated M26 Taser waveform using either the small (*left*) or large (*right*) surface area stimulation electrode. The symbols represent the mean (\pm s.e. mean) threshold current density from 5 hearts, with the exception of the data point representing the threshold current density for the M26 using the 18 mm² electrode (the fifth heart in this group failed to generate a VEB). The x-axis location of the symbol representing the M26 waveform is semi-arbitrary (see Section 2.7.2).

3.1.5 The M26 peak current density predicted by the computational electromagnetic modelling to arise at the ventricles in the human heart is 0.66 mA/mm² (see Section 1.4). This would suggest that a safety factor for the induction of VEBs of about 30 (i.e. 18.8/0.66) for the small surface area electrode and a safety factor of about 60 (i.e. 40.1/0.66) for the large electrode. As discussed in Section 1.6, it seems likely that the findings with the larger surface area electrode area electrode area electrode area of current predicted by the modelling (see Figs. 4 and 5).

3.2 Induction of ventricular ectopic beats (VEBs) by the simulated X26 Taser waveform

- 3.2.1 The threshold peak current density for induction of VEBs by the simulated X26 waveform was examined in a further 5 hearts. For these experiments, only the large surface area (18 mm²) electrode was used (see Section 1.6).
- 3.2.2 An example of a VEB induced by application of an X26 waveform pulse to the ventricles of a single heart is illustrated in Fig. 12.



- Figure 88: Example of a VEB induced by a single simulated X26 waveform applied to the ventricular epicardial surface during the T-wave of the electrocardiogram (ECG in lower traces). In this example, the VEB was induced using the 18 mm² electrode. In this example, the peak current density (measured at the nadir of the second half-cycle of the waveform) required to evoke the VEB was -7.0 mA/mm². The horizontal scale indicates time from start of experiment (h:mm:ss).
- 3.2.3 The averaged strength-duration curve for induction of VEBs using rectangular pulses is shown in Fig. 13.
- 3.2.4 The threshold peak current density for induction of VEBs with the simulated X26 waveform was $-7.3 \pm 5.6 \text{ mA/mm}^2$ (mean \pm s.e. mean; 5 hearts).
- 3.2.5 The X26 peak current density predicted by the modelling to arise at the ventricles in the human heart is -0.11 mA/mm^2 (see Section 1.4), implying a safety factor for the induction of VEBs of about 65 (i.e. -7.3/-0.11).

18 mm² electrode



Figure 89: Comparison of threshold current densities required to evoke VEBs with conventional rectangular pulses or the simulated X26 Taser waveform using the 18 mm² stimulation electrode. The symbols represent the mean (\pm s.e. mean) threshold current density from 5 hearts. The x-axis location of the symbol representing the X26 waveform is semi-arbitrary (see Section 2.7.2).

3.3 Induction of ventricular fibrillation (VF)

- 3.3.1 Attempts were made to induce VF by application of trains of simulated M26 and X26 waveforms to the ventricular epicardial surface.
- 3.3.2 In an effort to mimic the discharge characteristics of the Taser devices, the M26 waveforms were delivered in a 5s train at a pulse repetition frequency (p.r.f.) of 38 Hz, while the X26 waveforms were delivered in a 5 s train at a p.r.f. of 19 Hz.
- 3.3.3 Despite driving the stimulation circuit to its maximum output, VF was not generated with trains of either waveform. Examples of this failure to precipitate VF are illustrated in Fig. 14 (*left-hand traces*).



- Figure 90: Neither the M26 waveform train (5 s, 38 Hz, 51.6 mA/mm²; *upper left*) nor the X26 train (5 s, 19 Hz, 30.2 mA/mm²; *lower left*) induced VF. In the same two hearts, VF was subsequently induced by application of 5 s trains of 100 µs rectangular pulses at 38 Hz (2.8 mA/mm²; *upper right*) or 19 Hz (15.8 mA/mm²; *lower right*). The 18 mm² electrode was used throughout.
- 3.3.4 The maximum current density achieved during application of the M26 trains was $51.8 \pm 0.5 \text{ mA/mm}^2$ (mean \pm s.e. mean; 5 hearts), while that achieved during the X26 trains was $-27.1 \pm 3.8 \text{ mA/mm}^2$ (5 hearts). That these currents failed to induce VF implies a safety factor for induction of this arrhythmia of greater than about 75 (i.e. 51.8/0.66) for the M26 waveform and a safety factor of greater than about 240 (i.e. -27.1/-0.11) for the X26 waveform.
- 3.3.5 That the failure of the simulated M26 and X26 waveforms to induce VF was not a function of the experimental test system was demonstrated for each heart by the development of VF in response to subsequent application of trains of rectangular pulses. Induction of VF by this 'conventional' means is illustrated in Fig. 14 (right-hand traces) in two hearts that had previously failed to fibrillate after application of trains of Taser waveforms.

- 3.3.6 The average current densities required to induce VF with 100 μ s rectangular using the 5 s, 38 Hz train protocol were 24.8 ± 8.6 mA/mm² with the 1.9 mm² electrode and 4.2 ± 1.3 mA/mm² with the 18 mm² electrode (5 hearts for each electrode size). The lower threshold for VF generation with larger stimulation electrodes is well-established (see Figs. 5.20 and 6.21 in Reilly, 1998).
- 3.3.7 The average current density required to induce VF with 100 μ s rectangular pulses using the 5 s, 19 Hz train protocol was $16.0 \pm 0.6 \text{ mA/mm}^2$ with the 18 mm² electrode (5 hearts).
- 3.3.8 Comparison of the VF thresholds for the 19 Hz (X26) and 38 Hz (M26) protocols using the 18 mm² electrode indicates that the higher p.r.f. is more efficient at inducing this form of arrhythmia.

4 Discussion

4.1 Induction of ventricular ectopic beats (VEBs) in the guinea-pig heart by simulated M26 and X26 waveforms

- 4.1.1 VEBs could be elicited by both types of Taser waveform applied during the T wave of the electrocardiogram. However, these VEBs could be induced only at peak current densities of about 60-fold (M26 and X26 applied with the large surface area stimulation electrode) or 30-fold (M26 applied with the small surface area electrode) the current density predicted by the computational modelling to arise in the human heart during 'worst case scenario' Taser discharge (see Section 1.4).
- 4.1.2 As discussed in Section 1.3, there appear to be reasonable grounds for assuming that the data obtained with the larger stimulation electrode are more applicable given the wide spread of current in the ventricular mass predicted by the modelling (see Figs. 4 and 5).
- 4.1.3 That VEBs were more readily obtained with the small surface area electrode is consistent with the well-established observation that the threshold for stimulation of the heart (i.e. generation of a VEB) is lower with smaller electrodes (see Fig. 5.20 in Reilly, 1998). Nevertheless, the findings in the guinea-pig heart would suggest that there is a wide margin of cardiac safety for induction of VEBs *irrespective of the electrode size* used in the present study.
- 4.1.4 Whether the margin of safety for VEB induction by the Taser waveforms indicated by the present guinea-pig experiments can be translated across to the human heart is discussed in Section 4.3.
- 4.1.5 Notwithstanding the finding that the threshold current densities for generation of VEBs by the simulated Taser waveforms was greater than an order of magnitude higher than the current densities predicted by the modelling to appear in the human heart during Taser discharge, VEBs in themselves are relatively benign arrhythmias when they occur in healthy hearts (see Section 1.8). However, the possibility that the threshold for VEB induction may be modified in hearts impaired by disease or by the action of cardioactive drugs cannot be excluded.
- 4.1.6 Even if the threshold for VEB induction remains unmodified in the functionally compromised heart, a VEB (occurring for whatever reason) in this setting may have a less favourable outcome (Huszar, 1994a). In humans, VEBs may be precipitated by stress (increased sympathetic tone and circulating catecholamines as is likely to occur in a confrontation involving the use of Tasers); alcohol and acidosis are also predisposing factors (Huszar, 1994a). If VEBs were to occur under these circumstances and in the context of a functionally impaired heart, it is conceivable that they might herald the appearance of such life-threatening arrhythmias as VF or ventricular tachycardia (Huszar, 1994a). The latter arrhythmia can degenerate into VF (see Fig. 3.19 in Houghton and Gray, 1998).
- 4.1.7 Although speculative, the progression of VEBs into ventricular tachycardia or VF (in the context of a stressed and functionally compromised heart) could constitute a mechanism whereby death may occur *after* Taser deployment and be *unrelated* to the primary electrical action of the device. Such a scenario, however, would likely not be restricted exclusively to Taser deployment and

would presumably apply to other forms of emotionally charged confrontation with law enforcement personnel.

4.2 Failure to induce ventricular fibrillation (VF) with simulated M26 and X26 waveforms

- 4.2.1 VF could not be induced by either the M26 or X26 waveform applied at the maximum current density achievable with the electrical stimulation system used in the study. This suggests that the current density required for induction of this form of lethal arrhythmia exceeds that predicted by the modelling by more than 75-fold for the M26 waveform and more than 240-fold for the X26 waveform.
- 4.2.2 That the failure of the simulated Taser waveforms was not a function of the biological test system was demonstrated by the ability of the hearts to generate VF in response to conventional (rectangular pulse) stimulation.
- 4.2.3 Although the M26 and X26 waveforms failed to induce VF, there was clearly some degree of entrainment of the cardiac rhythm (see, for example, the left-hand traces in Fig. 14). This is not surprising given that the maximum current densities achieved in the VF studies exceeded those required to induce VEBs (see Section 4.1.1).
- 4.2.4 Experimentally, electrically-induced VF can be achieved by stimulating the heart with repetitive trains of pulses. For example, in guinea-pig isolated hearts Choi et al. (2001) induced fibrillation using 1 s trains of rectangular pulses each of 2 ms duration applied at a p.r.f. of 20-33 Hz, while Laurita et al. (1998) applied short (about 100 ms) trains of rectangular pulses at 100 Hz (pulse duration unspecified) delivered over a period encompassing the T wave of the electrocardiogram.
- 4.2.5 To induce VF by extrinsic electrical stimulation, the stimulus must be of sufficient amplitude <u>and</u> duration to excite the ventricular muscle and involve a sufficiently large mass of muscle and specialised conduction tissue such that multiple sites of re-entry (localised regions of self-sustaining excitability) are generated (Reilly, 1998). The requirement to involve a large mass of ventricular tissue explains why electrical stimuli delivered through large electrodes are more efficient (i.e. require a smaller current density) than small electrodes at precipitating VF (see Figs. 5.20 and 6.21 in Reilly, 1998).
- 4.2.6 The current density contour maps for the M26 and X26 generated from the modelling studies (Fig. 4; Section 1.6) imply that a large area of the ventricular mass experiences current flow when the Taser barbs are in the 'worst case scenario' orientation (Section 1.4.2). This would seem to meet the 'electrode' size criterion for efficient induction of VF (Section 4.2.5).
- 4.2.7 However, it is clear from the present study that the amplitude and/or duration of both Taser waveforms were insufficient to induce VF in the guinea-pig heart. The potential implications of this finding for the human heart are discussed in Section 4.3.
- 4.2.8 In contrast to the theoretical latent implications of VEBs on cardiac rhythmicity (see Section 4.1.7), it might be expected that if Taser devices were capable of eliciting VF, then this action would occur coincidentally with Taser deployment. This would result in deaths that were manifestly causally related to Taser deployment. That this is not the case would seem to be supported by the absence of fatalities occurring *simultaneously* with Taser use. Even if a

death were to occur at the same time as a Taser was being discharged into an individual, the possibility that the death resulted from a mechanism unrelated to an electrical action of the device on the heart would be difficult to exclude.

4.3 **Polarity of the applied waveforms**

For determination of the excitation thresholds for induction of VEBs and VF. 4.3.1 the M26 and X26 waveforms were applied to the ventricular epicardial surface in the polarities indicated in Fig. 2), with the peak current densities being defined as those arising at the part of the waveforms with the greatest amplitude (the first half-cycle in the case of the M26 and the second half-cycle in the case of the X26). The influence of inverting these waveforms on the excitation thresholds was not explored. With complicated waveforms such as these, it is difficult to know which part of the waveform is responsible for driving the ensemble of myocardial cells underlying the stimulating electrode towards depolarisation, although in the case of the M26 waveform it may be reasonably assumed that it is either the first or second half-cycle that induces the greatest biological effect. In the case of the X26 waveform the sinusoidal component is mostly superimposed upon a negative component (Fig. 2). As an extracellularly applied cathodal stimulus would be expected to exert a more efficient depolarising effect, it could be argued that the X26 waveform may present a more efficient depolarising stimulus to the myocardium than the M26 waveform. That this was the case appears to be borne out by the finding that the excitation threshold for the induction of VEBs was about 40 mA/mm² for the M26 and about -7 mA/mm^2 for the X26 (approximately a 6-fold difference in potency). However, the differential VEB-inducing potency of the M26 and X26 waveforms is more or less completely offset when it is interpreted in terms of the peak current densities predicted by the computational electromagnetic modelling to arise at the heart (the modelled peak current density for the M26 is 6-fold that of the X26).

4.4 Scaling the guinea-pig results to the human heart

- 4.4.1 Apart from the obvious difference in the size of the guinea-pig heart relative to the human heart, differences in anatomy and physiology also serve to complicate any comparison between results obtained in the two species.
- 4.4.2 Nevertheless, one correlation that seems to hold across the species tested is that of VF threshold against body weight (Fig. 15).



Figure 91: Dependence of VF threshold on body weight for seven species. VF was induced by a 3 s, 60 Hz shock (electrodes on right foreleg and left hindleg). The large symbols represent mean values. (From Ferris et al., 1936.)

- 4.4.3 Fig. 15 (see also discussion on body-size scaling in Reilly, 1998) demonstrates that the guinea-pig is an extremely conservative model when it comes to extrapolating VF data to larger animal species. Additionally, since the dog has demonstrably lower VF thresholds than human (Reilly, 1998), the data presented in Fig. 15 provide indirect evidence that the guinea-pig is also an extremely conservative model for VF induction in human.
- 4.4.4 Although the modelled human ventricular current contours (Fig. 4) could not, for technical reasons, be reproduced in the guinea-pig heart, an attempt has been made to keep the electrode size relative to heart size in similar proportion to the area of current spread predicted by the modelling to arise in the human heart (see Section 1.6). Despite this compromise, the overwhelming difference in sensitivity to VF induction between guinea-pig and human suggests that the safety factors for VF induction estimated in the present study err comfortably on the side of caution when extrapolated to humans.

5 Conclusions

5.1 On the basis of the present study it is considered unlikely that the discharge from the M26 and X26 Taser devices will influence cardiac rhythmicity by a direct action on the heart.

6 Recommendations

- 6.1 A database of all instances of Taser deployment to be maintained (to include aiming, 'red dot' and actual firings).
- 6.2 The database should include details of any adverse health outcomes occurring concomitantly with, and up to several days after, Taser deployment.
- 6.3 The database should include details of any events (e.g. epileptic seizure, chest pain, head trauma) or actions (e.g. pursuit, restraint) that may be relevant to determining the causation of any adverse outcome associated with Taser deployment.
- 6.4 Suspicion of intoxication with drugs (illicit or pharmaceutical), volatile substances or alcohol should be noted in the database and, if considered appropriate, samples should be taken by the Forensic Medical Examiner for subsequent analysis.

7 Additional references

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Appendix G – "The X26 Taser – a review of the experimental and operational data related to an assessment of the medical implications of use."

DSTL/PUB20752 20 January 2005

Background

- 1. A report by PricewaterhouseCoopers on the first 12 months of the operational trial of the M26 Advanced Taser in five police forces, concluded that the Taser "*helped secure a positive outcome to an incident, minimising the potential need for officers to deploy other, possibly more lethal technologies*"⁷⁶. ACPO proposed that, subject to a review of the medical assessment and the decision of Ministers, the capability to employ Tasers should be extended to all forces for use by existing firearms officers, in situations where an authority for firearms would be granted in accordance with criteria presently laid down within the ACPO Manual of Guidance on the Police Use of Firearms. DOMILL produced a second medical statement encompassing operational data and experimental work available since the first statement produced in December 2002. On the basis of this second statement and other evidence, the Home Secretary agreed to ACPO's proposal and the PUS for the Home Department (Caroline Flint MP) announced the decision to Parliament in a Written Answer on 15 September 2004. The Home Secretary's decision applies only to the M26 Advanced Taser.
- 2. In May 2003, the manufacturers of the M26 Taser (Taser International Inc.) introduced another Taser weapon the X26. The X26 has a number of improvements that will potentially enhance operational use (such as an increased battery life), and it also has a different current output (magnitude and pulse shape) and repetition rate. These changes to the output are alleged by the manufacturer to improve the effectiveness against subjects (discussed below).
- 3. ACPO has expressed the view that the X26 may have operational benefits over the M26, and has asked the Police Scientific Development Branch (PSDB) to conduct a user handling trial on the X26, similar to the trial undertaken on the M26 before its introduction. The X26 handling trial has been completed. It employed 38 officers from 12 police forces; 39% were trained firearms officers. The draft report of the experimental trial⁷⁷ concluded that:
 - The M26 and X26 were very similar with regard to accuracy. In the test conditions employed, both weapons had a 91% success rate of both barbs hitting a target.
 - The X26 was marginally faster to discharge than the M26, following a command to do so;

⁷⁶ Association of Chief Police Officers: Independent evaluation of the operational trial of taser. Final Report. May 04. PricewaterhouseCoopers LLP.

⁷⁷ Wilkinson DI. PSDB Further evaluation of Taser devices. Draft 3.0. The final report is due to be published in Jan 05.

- Seventy nine percent of officers preferred the X26 to the M26, however, some of those expressing a more positive view of the X26 were also content to use the M26.
- 4. PSDB approached the Official Member of DOMILL for guidance on the information that DOMILL would require to produce a statement on the medical implications of the use of the X26 Taser. PSDB was advised that the information required initially would be:
 - A comparison of the currents predicted in the heart from the M26 and X26 Tasers; this would require use of the electromagnetic model developed by Dstl to support the studies being undertaken on the interaction of cardiac currents from the M26 on the cardiac rhythm. These studies are also addressing the effects of drugs of abuse such as cocaine and PCP (phencyclidine) on the cardiac thresholds for adverse cardiac effects.
 - A review of : (a) experimental work undertaken by, or on behalf of Taser International to support the introduction of the X26; (b) operational and training data compiled by Taser International and global police forces; (c) medical assessments undertaken by organisations and individuals unconnected with the manufacturers.
 - Verification by PSDB and Dstl of the electrical output of the X26 claimed by the manufacturer.
- 5. At a meeting on 22 September 2004 with the ACPO Conflict Management working group managing the operational deployment of the M26, it was reiterated by the Home Office that the M26 Taser was the only approved electrical incapacitation device. However, police forces were now making decisions on the procurement of Tasers, and implementing training programmes. If the X26 did indeed offer operational advantages, ACPO may wish to make representations to the Home Secretary for use of the X26, and if granted, would enable police forces to purchase the X26, rather than the M26. A medical statement by DOMILL would be an essential requisite and in view of the procurement action being contemplated by forces, a reasonably rapid review by DOMILL would be beneficial. The Official Member of DOMILL undertook to discuss the medical issues associated with use of the X26 at the scheduled meeting of the MASSG on 13 December 2004, and if the data available enabled a view to be taken, DOMILL would draft an interim statement. This paper has been prepared to inform the discussions by DOMILL on 13 December 2004.

Aims

- 6. The aims of this paper are to:
 - summarise the available evidence on the characteristics, operational performance and medical assessments worldwide of the X26 Taser specifically;
 - contrast these with the M26 Advanced Taser, thereby provide evidence to enable DOMILL to draft a statement on the medical implications of use of the X26 according to extant ACPO policy and guidance for the M26.

Comparison of M26 and X26 Tasers

- 7. The X26 Operating Manual⁷⁸ describes the X26 key feature the "Shaped Pulse Generator". The manufacturers claim that the M26 and previous generations of electrical incapacitation devices used a "blunt" electric pulse to penetrate the skin and clothing barriers; over 90% of the available energy was expended in breaching these barriers. Thus, high power was required for effectiveness (26 W for the M26), necessitating large, heavy batteries. The X26 has a shaped pulse comprising two features:
 - The "Arc Phase" a short current pulse of high voltage to penetrate the barrier.
 - The "Stim Phase", in which the substantial proportion of the total energy held in reserve flows through the low impedance path created in the "Arc Phase". This current is available to incapacitate the target and the incapacitating effect is claimed to be 5% greater than the M26⁷⁹, in a weapon that is 60% smaller, 60% lighter and consumes one fifth of the power.
- 8. The M26 generates a high voltage waveform with a peak current of about 10-12 amps. The waveform is essentially a damped cosinusoidal waveform (50 kHz fundamental) of approximately 40 μs duration (yellow line in Figure 92). The peak voltage is about 800 Volts into ~50 Ohms (the high frequency spikes are considered by Dstl to be measurement artifacts).



Figure 92: X26 and M26 waveform into a nominal 48 Ohm resistor.

9. The X26 waveform (black line in Figure 92) is a fast damped cosinusoidal signal of frequency approximately 120 kHz. At the start of the pulse waveform, it is superimposed on a unipolar double exponential pulse. The X26 pulse is of lower peak amplitude (about 300-400 Volts into ~50 Ohms) and of longer duration (about 120 µs). This is significant, as the quoted power is 6 W in comparison to 26 W of the M26. On their web-site, Taser International claim the X26 delivers 0.33 J/pulse, compared to 1.76 J/pulse for the M26 pulse. Notwithstanding the manufacturer's data, Dstl and an independent contractor experienced in high-voltage electromagnetics, have determined

⁷⁸ X26 Operating Manual. Video Training and Information Disk Version 10.0.

⁷⁹ Taser International use a rating scale entitled "Muscular Disruption Units". The M26 is used as the baseline of 100 units. The X26 has 105 units. The rationale and method for determining these values is not stated, but is believed to have been based upon the Taser-induced contractile force in the muscles of a pig limb.

the energy, charge and action integral⁸⁰ of each pulse from the two devices, using the data shown in Figure 92 (Table 25).

Device	Charge (A.s, Coulombs)	Action integral (A ² .s)	Energy (J)
M26	2.14 x 10 ⁻⁴	17.4 x 10 ⁻⁴	83.5 x 10 ⁻³
X26	1.25 x 10 ⁻⁴	1.6 x 10 ⁻⁴	7.5 x 10 ⁻³

 Table 25: A comparison of the calculated output in each pulse of the X26 and M26 Tasers, into a nominal 48 Ohm resistor.

10. The data show that the X26 has about half the charge per pulse as the M26, one order of magnitude lower action integral, and about one tenth of the energy in each pulse.

Experimental work on the X26

- 11. Dstl has acquired two reports of experimental studies on animals to assess the ventricular fibrillation (VF) risk from the X26: Stratbucker *et al*⁸¹ and McDaniel, Stratbucker *et al*⁸². Dr Stratbucker is the medical adviser to Taser International; the work was funded (in part) by the US Office of Naval Research. The latter paper has recently (January 2005) been published in a peer-reviewed journal⁸³.
- 12. In Stratbucker *et al*, 13 pigs were subjected to a total of 71 discharge sequences (c. 6745 individual pulses) directly to the chest using a bi-polar "Taser-like" skin electrode. The shocks were applied to the site on the chest exhibiting the maximum mechanical impulse, stated by the authors to be associated with the maximum likelihood of cardiac interactions. The pulse output of the stimulation system was adjusted to 100% of the electrical output of the standard X26. The authors assumed that the pulse waveform characteristics were much more critical for fibrillation events than whether the pulses fell within the "vulnerable period" for electrical shock identified for the heart (associated with the T wave).
- 13. A single recording of blood pressure is presented showing some small disturbance of pressure but a "*completely unchanged*" rhythm during X26-like application⁸⁴. This "*proves that the stimulation intensity is below the ventricular fibrillation threshold*." To determine the VF threshold, the stimulation intensity (parameter not declared) was increased in steps up to 2000% (i.e. 20 fold) until fibrillation was induced. Below a 16-fold increase in intensity, there were no cases of VF out of 43 "*episodes*"⁸⁵. With a 20-fold increase in intensity above the output declared to be similar to the X26, 50% of 12 episodes resulted in VF. On the basis of these data, the safety margin is stated to be 20:1, and because the electrodes were placed at the site of maximum potential interaction, in field use the margin is likely to be greater. The number of animals used

⁸⁰ The action integral is the integration of the square of the current. It is used in high current research as being indicative of the charge, energy and potency of an electrical pulse to cause damage. With lightning for example, it determines all heating and electrodynamic effects along the conducting path.

⁸¹ Stracbucker [sic] RA, Roeder R, Nerheim M. Cardiac safety of high voltage Taser X26 waveform. IEEE Eng Med Biol Conference 2003; 3261-3262.

⁸² McDaniel WC, Stratbucker RA, Nerheim M, Brewer JE. Assessing cardiac safety of Taser defensive devices. Unreferenced, undated report labelled as "Appendix B", partially funded by the US Office of Naval Research. Postdates Stratbucker's paper.

⁸³ McDaniel WC, Stratbucker RA, Nerheim M, Brewer JE. (2005). Cardiac safety of neuromuscular incapacitating defensive systems. Pacing and Clinical Electrophysiology, <u>28</u>, Supplement 1. S284-S287. The paper has a header stating: "This study did not address the safety index as it relates to individuals with arrhythmias, pacemakers, or implantable cardiac defibrillators."

⁸⁴ The presented waveform is not strictly "*completely unchanged*" during the application, but the disturbances are minor.

 $^{^{85}}$ Believed to be a 5 s burst at 19 Hz – the output of the X26.

in this phase of the programme is not stated but it is implied that 30% of the total of 13 pigs used in the whole programme was used, i.e. four.

- 14. The technical and statistical information presented in the short report is limited, but on the basis of the data evident, Dstl has no fundamental concerns regarding the conduct and interpretation of the study.
- 15. McDaniel, Stratbucker *et al* undertook what appears to be a more refined study to determine the fibrillation threshold, and the effects of body weight on the safety index the ratio of the VF threshold determined using the experimental current injection equipment, to the output of the commercial X26 Taser. Nine anaesthetised pigs were declared to have been used⁸⁶, ranging in weight from 30-117 kg. The approach is similar to that employed by Stratbucker, indeed it is not clear whether these experiments were distinct from those reported by Stratbucker *et al*, or whether there is common data. The current was applied to the chest of the animal in increments of increasing stored charge (from the X-26 output) until VF was induced. The animal was defibrillated. Once VF had occurred, the charge was reduced until five discharges of equal charge failed to induce VF. The highest charge that was applied five times without VF ("*maximum safe level*"), and the minimum level of charge that induced VF at least once ("*minimum fibrillating discharge*") were noted. The "*VF threshold*" was the average of the two.
- 16. The average discharges per animal were 26±12; there were no significant haemodynamic events reported (data not presented, but the blood pressure trace from Stratbucker *et al* is reproduced). The safety index ranged from 15x to 42x as the weight increased from 30 kg to 117 kg. The charge multiple at VF threshold was 28±10 compared to the X26 output; the maximum safe charge multiple was 26±9, and the minimum VF discharge charge multiple was 30±11.
- 17. The authors use these data to predict by logistic regression, the 50% probability of VF induction. It is stated to be 24 ± 13 charge multiples. Curiously, this is not related to body weight in their model. A Dstl statistician has reviewed the data. The induction of VF is significantly related to charge and the weight of the animal, and both parameters should be included in the logistic regression model. Using Dstl's analysis (and making some assumptions about the data and experimental design), the relationship between charge multiple (safety index) and probability of fibrillation is shown in Table 26 for a 60 kg pig.

Multiples of X26 charge	Probability of VF induction		
1	<0.001		
2	0.001		
10	0.005		
26	0.1		
37	0.5		
48	0.9		

Table 26: Probability of VF induction related to multiples of X26 charge, for a 60 kg pig (based on McDaniel et al [82]).

18. The authors' conclusions from the study were that:

⁸⁶ Pig 3 (of 10) is missing from the table of results, but in the graphical presentation of the change in Safety Index with age, ten data-points are shown.

- the safety index for the X26 Taser is >20 for human adults of greater than 45 kg body weight;
- the minimum discharge that would cause fibrillation was approximately 15 times the charge of the standard X26 pulse when used on the smallest pig (30 kg).

Modelling of the current flow, and outcome of *in vitro* studies.

Current flow

- 19. Mathematical modelling of the current flow through the heart arising from the M26 and X26 Tasers has recently been completed by Dstl and its contractor. The study concluded that:
 - In the most severe scenario, about 20% of the applied current from the M26 passes through the heart, with a peak current density of about 0.66 mA/mm², during the M26's 2¹/₂ cycle, 50 μs pulse.
 - Initially, about 10% of the applied current from the X26 passes through the heart, rising to about 20%; the peak current predicted is about 0.06 mA/mm², during the X26's 4 cycle 160 μ s pulse i.e. about one tenth of the peak current magnitude of the M26. The current duration of the X26 is about 3-4x that of the M26.
 - The most current passes through the heart when one of the Taser contact points is close to the lower frontal aspect of the heart.
 - The current leaving the heart almost matches the current entering the heart at any one time, indicating that there is little net deposition of charge.
- 20. Although the X26 appears to have less risk to the heart based on a lower peak current, the extended duration of that current could reduce the threshold for stimulation of excitable tissue.

In vitro studies – Langendorff preparation

- 21. The work recommended by DOMILL to assess the interaction of the currents predicted by the modelling on the isolated beating heart is nearing completion. The *in vitro* model being used is the isolated Guinea Pig heart (Langendorff preparation). This model is more sensitive to externally applied electrical stimuli than the hearts of larger animals⁸⁷. The preparation was used to determine if a single predicted <u>M26</u> Taser current pulse could produce a premature ventricular contraction (PVC), or if VF could be induced by a train of pulses (38 Hz, for 5 s).
- 22. PVCs could only be induced by predicted M26 current waveforms when their magnitude was on average greater than 30-fold that predicted to occur in the human body 0.66 mA/mm² (Figure 93). Repetitive M26 pulses failed to induce VF at intensities greater than 70-fold that of the modelled intensity. PVCs and VF could be induced readily using rectangular stimulation pulses, i.e. the model was capable of responding to conventional applied electrical stimulation.

⁸⁷ Reilly JP. Applied Bioelectricity: From Electrical Stimulation to Electropathology. Springer - Verlag, 1998, ISBN 0-387-98407-0. Chapter 6 – Cardiac sensitivity to electrical stimulation. Pages 220-225.



Figure 93: Thresholds for generation of premature ventricular contractions (PVC) by conventional and <u>M26</u> Taser waveforms. Each point is the mean from 5 guinea-pig hearts. The mean peak current density of the M26 Taser waveform was $18.8 \pm 4.7 \text{ mA/mm}^2$. A 1.885 mm² stimulation electrode was used for both the rectangular pulses and the simulated Taser waveform.

23. With regard to peak predicted currents, the X26 is predicted to apply about one tenth of the current of the M26, and thus on this basis, the risks of a PVC or VF may be lower for the X26. However, the X26 is a composite of a damped cosine pulse superimposed on a unipolar waveform (Figure 94), rather than a straight damped cosine pulse as in the M26. The pulse duration is longer with the X26 – it has a DC offset.



Figure 94: The current from the X26 computed to flow through the heart. The solid line is the cardiac current (left hand scale) and the dotted line is the current applied to the body surface (right hand scale).

24. Figure 94 shows that peaks subsequent to the initial peak are of greater magnitude (and negative). Applying the same criteria used for the M26 (i.e. the predominant initial current peak is used to model the PVC and VF risk) with the X26 would indicate that

the waveform would be shorter and of lower amplitude of than the M26 and therefore likely to be below the stimulation threshold. However, the second cycle of the X26 is larger than the initial, and the waveform has an overall longer duration; the approach used with the M26 would be inappropriate with the X26.

- 25. The evidence from the electro-physiological literature is that the threshold for stimulation of excitable tissues reduces as pulse duration is extended, and as the number of cycles is increased⁸⁷. Although the reduction in peak cardiac current predicted for the X26 would suggest lower risk, the extended duration may offset some of that benefit. Because of the complex shape of the Taser currents, the overall effect of this trade-off cannot be quantified from the literature, which has been developed using square waves, biphasic waves (single cycle sinusoid), monophasic waves (half cycle sinusoid), and alternating current.
- 26. Another aspect of the extended duration of the X26 is that it could conceivably alter the specificity of the activation i.e. different calibre nerve fibres could be excited by the X26, or muscle fibres could be more effectively stimulated by the longer duration pulse. Indeed, Taser International state that the X26 is designed to "*overpower the normal electrical signals within the body's nerve fibres*"^{78,} and is contrasted with the M26 which relies on direct stimulation of the muscles.
- 27. There are currently no plans to expose isolated Guinea Pig hearts to predicted X26 cardiac currents. DOMILL may wish to take a view on this.

Operational use – Taser International database

- 28. On the Taser International website, police officers are given the opportunity to contribute to a database of operational use of the M26 and X26 Tasers. Plainly, this is a self selected database that may not reflect either the numbers or outcomes of the history of M26 and X26 use⁸⁸. In September 2004, Taser International provided Dstl with the database containing 526 records of operational use of the X26. The records were dated 29 April 2003 to 25 September 2004 (28 records were undated). Discharge of the darts occurred on 295 occasions; the device was used in "drive-stun" mode in 133. The injuries to subjects (offered and assessed by the officers) are classed as "Minor" or "Moderate". Some of the injuries did not arise directly from X26 use.
- 29. Sixty one injuries were classed as "Minor", the most common being abrasions and cuts to hands, knees and head arising either from the altercation with the officer, or the fall of the subject during application of the Taser. Eleven of the "Minor" records showed evidence of the contact of the head with the ground or objects. Nine injuries were classed as "Moderate" but only four were likely to have arisen directly from X26 use:
 - "Subject had lacerations on the bottom, top, and side of right foot. Also lacerations on hands";
 - "Scrape on forehead, puncture wound from probes, complaining of sore left ankle";
 - "Suspect fell flat on his face causing two teeth to puncture through the upper lip. Suspect broke his nose and chipped a couple of teeth.";
 - "Suspect fell and struck back of head on pavement."

⁸⁸ Taser International estimates that only one in ten of field uses are reported in the database.

Operational use and technical review by other agencies

Office of the Police Complaint Commissioner, British Columbia, Canada

- Battershill et al have recently completed an interim review⁸⁹ of the Taser (M26 and 30. X26) for the Office of the Police Complaint Commissioner in British Columbia, Canada. The report was prompted by the death of a suspect; the report was to "review the present use of force protocol, and make such recommendations as he [Battershill] deems appropriate for the use of the Taser by police officers....pending the results of emerging studies presently underway". The interim review encompassed assessment of published medical literature (undertaken by the police authors, but to be reviewed subsequently in the final report by a medical panel), analysis of Taser field-use data acquired from Taser International (4599 reports)⁹⁰ and from the Edmonton and Victoria Police Services, and a review of excited delirium and restraint-associated deaths in British Columbia⁹¹. Dstl has provided information to the review team.
- Unfortunately, the analysis of the Taser International database did not differentiate M26 31. and X26 Tasers (other than identifying that 15% of the reports involved the X26). Forty nine of the 4599 reports contained information indicating that use of the Taser had resulted in medical complications, and eight of these were deaths. However, some of these deaths were plainly not directly associated with Taser use (four cases of death by firearm); four deaths were classed as "Death Other (respiratory/circulatory)"92. The largest category of medical complications were identified as "Various [respiratory/circulatory]" and numbered 23. The remainder were incontinence (presumably acute with no long-term implications) and use on two pregnant women (with no complications to the mother or foetus).
- 32. Battershill reviews a report produced in 2004 by a Dr Charles Butler for the Kalamazoo County Sheriff's Department. The report discusses the scientific and medical data evaluating the safety and efficacy of Taser (M26); Dstl has not been able to acquire the report, but Battershill quotes liberally from it. Butler states that blunt trauma from falls after Taser use may have been underestimated in many safety reviews. He recounts two case reports of two police officers (presumably being trained) who suffered serious head injuries that required hospitalisation, and that the Las Vegas police department trained 500 police officers to use the Taser; eight of the officers were injured and were off work⁹³. Injuries to police officers arising from exposure to the M26 are discussed in a police forum on the web⁹⁴; there is a statement from one officer that he suffered a spinal injury directly from the Taser (not a fall) during training.
- 33. With regard to the medical risks directly associated with Taser use, Battershill's interim report concludes that "Although there is no evidence to suggest that the output of the M26 Taser exceeds acceptable levels, the X26 provides a greater margin of safety as documented in the Alfred studies [discussed below].". The authors recommend that the X26 be purchased by agencies, due to enhanced data collection capabilities and lower electrical output.

http://www.reviewjournal.com/lvrj_home/2004/Jan-20-Tue-2004/news/22960979.html for a news article on the Las Vegas training injuries.

⁸⁹ Laur D et al. Taser technology review & interim recommendations. Office of the Police Complaint Commissioner, British Columbia, Canada. OPCC File No 2474. Sep 04.

⁹⁰ The data supplied to Dstl was in the form of an Excel spreadsheet; the review team from British Columbia were provided with the individual reports.

⁹¹ The focus on excited delirium and restraint associated deaths may stem from the circumstances of death of the ⁹² Taser International maintain that there have been no deaths directly caused by use of a Taser.

⁹³ It is common practice in North America for officers undergoing Taser training to be exposed to the Taser. ACPO in the UK prohibit use on officers for training purposes, because of the risks identified in the DOMILL statement. See

⁹⁴ http://www.policemag.com/forum/topic.asp?TOPIC_ID=715.

The Human Effects Center of Excellence, US Air Force Research Laboratory

- 34. The Human Effects Center of Excellence (HECOE), established by the Air Force Research Laboratory and the Joint Non-Lethal Weapons Program, have conducted a "Human Effectiveness and Risk Characterization" (HERC) for electrical incapacitation devices. The devices evaluated were M26 (primarily) and X26 (to a lesser extent). The Executive Summary of the report is publicly available and is presented in Appendix B. The study concluded that: "...*despite the dramatic nature of the neuromuscular response, application of this conducted energy weapon for temporary incapacitation does not appear to pose significant risk to the recipients. The Panel added that future research will be useful in increasing confidence in extrapolating the risk assessment findings to a more heterogeneous population with uniquely sensitive members.*"
- 35. The full report has a restricted release caveat; Dstl is currently seeking release within the terms of an existing information exchange agreement with the US DoD on non-lethal weapons.

The Alfred Hospital Australia

- 36. The Biomedical Engineering department of The Alfred Hospital, Melbourne was commissioned by the Victoria Police Department to perform an assessment of the output and risks associated with the M26 and X26 Tasers. The report on the M26 was published in September 2003, and the X26 assessment was made available in June 2004⁹⁵. The review of the X26 comprised measurement of the output of the X26, application of these data to Australian Standards on the vulnerability of the body to electric currents, and a comparison with the output of electro-surgical and electro-convulsive therapy units, and electric fencing units. A comprehensive review of the literature was also undertaken.
- 37. The author compares the Taser to:
 - Electrosurgery units: for example, a 500 kHz damped sine, with a pulse repetition frequency (PRF) of 31 kHz;
 - Electro-convulsive therapy devices (ECT): square waves (1 ms), PRF of 70 Hz, 0.76 A output into a 500 Ohm load;
 - Electric fences: a PRF of about 1 Hz.
- 38. These devices are either alternating current (AC) or have different current level outputs, pulse shape or pulse repetition frequencies than the Taser. Use of the Australian Standard is inadvisable the Standard addresses low frequency (below 1 kHz) AC current.
- 39. Some aspects of the document are confusing. For example, the report states that theoretical power calculations were not undertaken on the X26 due to "insufficient technical data", but a later section provides data on the X26, but curiously under a title "Measurement on supplied Taser <u>M26</u> unit". Dstl also has some concerns regarding technical aspects of the assessment. For example the "Single Pulse Power" of the X26 is shown as only 0.7% of that of the M26; the basis of this calculation is not evident from the report, and Dstl electromagnetic engineers cannot verify these figures from the data presented. The "Single Pulse Power" units are declared as Joules, however, the Joule is not a unit of power.

⁹⁵ Taser X-26 Safety Analysis. Biomedical Engineering, The Alfred, Commercial Road, Melbourne, Victoria 3004, Australia. 29 Jun 2004.

40. The report concludes that: "the current output of the X26 is significantly below the fibrillation threshold set out in the Standard [Australian Standard AS 3859-1991 – Effects of current flowing through the human body]....[The X26] provides greater electrical safety and better performance than the M-26. From an electrical safety viewpoint, the device presents an acceptable risk when used by trained law enforcement officers in accordance with the manufacturer's directions for use."

Recently published research on the M26 Taser

- 41. McManus *et al* have recently published a retrospective analysis of the medical consequences of use of the M26 Taser in Multnomah County, Oregon⁹⁶. The M26 Taser was adopted by the Portland Bureau of Police in May of 2002. The retrospective chart review encompassed Multnomah County police reports and corresponding emergency medical services (EMS) care reports from June 2002 to July 2003, on all incidents involving the use of the M26. "Adverse events" encompassed death, dysrhythmia, cardiac complaints, or serious injury. The Multnomah County death registry was also reviewed.
- 42. Of the 227 successful M26 deployments, 96 (42%) of the incidents had EMS reports. Median patient age was 36 years; 92% were male. Thirty one (32%) patients received "drive stun" application, and the remainder had dart applications. There were no documented deaths, dysrhythmias, or cardiac complaints. Sixty (63%) of the patients had no documented injury, 27 (28%) sustained minor secondary injuries (haematomas, lacerations, and contusions) and 9 (9%) sustained self-inflicted or unrelated injuries. The authors concluded that in this case series, the M26 appears to be a "safe and effective" weapon. However, a higher incidence of minor injury was noted than that declared in previous manufacturer's reports. They recommended that a prospective trial would better define the risk–benefit relationship.

Amnesty International review of police use of Taser

- 43. On 30 November 2004, Amnesty International (AI) published a review of the police use of Taser in the US (predominantly) and Canada⁹⁷. This report has been sent to DOMILL members. Although recognising the importance of developing less lethal force options to decrease the risk of death and serious injury from police firearms (and impact weapons), AI are critical of the use of the Taser at a relatively low level on the "force scale" in the US, and state that they are rarely used as alternatives to firearms. This needs to be contrasted with current use in the UK, where the Taser is only used by firearms officers in situations where authority for firearms use would normally be granted. The different purported use in UK and US is highlighted in the report. DOMILL's statements on the medical implications of use of the M26 are quoted in the AI report. There are no overt criticisms of the UK policy, practice and medical assessment.
- 44. The "headline" information in the report is the presentation of a synopsis of 74 Taserrelated deaths since June 2001; autopsy reports were reviewed for 21 cases. There have been no deaths directly and exclusively attributed to the use of the Taser. In the Appendix to the report, of the 72 cases reviewed, there were 5 cases in which the Coroner/Medical Examiner or jury considered that the Taser contributed to death of the subject. Sixteen autopsy reports available to AI were reviewed by a Dr Sidsel Rogde,

⁹⁶ McManus JG, Forsyth T, Hawks RW, Jui J (2004). A retropsective case series describing the injury pattern of the Advanced M26 Taser in Multnomah County, Oregon. Acad Emerg Med, Vol 11, No 5, 587.

⁹⁷ United States of America. Excessive and lethal force? Amnesty International's concerns about deaths and illtreatment involving police use of Tasers. AI Index 51/139/2004. November 2004.

Professor of Forensic Medicine, University of Oslo. Dstl has contacted AI and requested release of her report to DOMILL.

XP cartridges

45. ACPO wish to use XP cartridges with the M26 or X26. The XP is an "eXtra-Penetration" barb cartridge designed for deeper penetration into clothing. It may also be used against bare skin.

	21 ft. Regular	25 ft. XP
Needle dimensions	9.4 mm long; 0.8 mm wide	13.4 mm long; 0.9 mm wide
Mass	1.6 g	2.6 g
Mean Velocity (Energy) - 0.2 m	48 m/s (1.8 J)	43 m/s (2.4 J)
- 4 m	25 m/s (0.5 J)	26 m/s (0.88 J)

Table 27: Comparison	of Regular and XP	cartridges for	the M26/X26 Tasers
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- 46. Table 27 compares the two cartridges. The principal increased risk from the use of the XP is the length of the needle: the XP is 4 mm longer than the Regular, having a total length of 13.4 mm. In a study to advise on the appropriate standards for stab-resistant armours⁹⁸, Bleetman undertook two surveys of the skin to organ distances^{99,100}, on the assumption that no serious injury to the victim of a knife attack would occur if the internal organs are not breached by the assailant's weapon. In Bleetman's first study (1998), a retrospective review of Axial Computer Tomography scans of 71 patients (age range: 20-40 y; 44 males & 27 females). The patients were scanned in a supine posture with their hands above their heads. The three shortest distances to a each of a variety of intrathoracic and intra-abdominal organs were determined in each patient. The stomach, bowel, and the blood vessels of the neck were not included. No organ was within 9 mm of the skin. The *minimum* of the range of distances determined from the skin to the spleen, liver, femoral artery and pleura were all less than the needle length for the XP (13.4 mm). The *median* distances for these organs were: spleen – 22 mm, liver – 18 mm, femoral artery – 17 mm, pleura – 21 mm.
- 47. In Bleetman's subsequent study in 2000, the minimum skin to organ distances were determined using ultrasound in 25 healthy volunteers (age range: 18-50 y; 15 males & 10 females). The effects of posture and changes in the exposure of the organs below the lower costal margin during respiration were assessed. For an erect posture, the minimum distances observed in any individual for the left kidney, spleen, anterior and posterior liver, pericardium, anterior and lateral pleura were all less than the XP cartridge needle length. The average depth for these organs ranged from 17 mm (anterior pleura) to 31 mm (left kidney).
- 48. There is plainly a risk that if an 13.4 mm XP needle is used against exposed skin or a lightly clothed individual, and that the needle penetrates to its full depth, that a breach (perforation) of the torso wall could occur in a small proportion of the population, and some of the more superficial organs could be penetrated by the needle.

⁹⁸ In 1999, the US National Institute of Justice proposed a standard of 20 mm knife penetration for armours (test blade delivering 42 J), and PSDB had proposed a 5 mm standard.

⁹⁹ Connor SEJ, Bleetman A, Duddy MJ J (1998). Safety standards for stab-resistant armour: a computer tomographic assessment of organ to skin distances. Injury, <u>29</u>, 297-299.

¹⁰⁰ Bleetman A, Dyer J (2000). Ultrasound assessment of the vulnerability of the internal organs to stabbing: determining safety standards for stab-resistant body armour. Injury, <u>31</u>, 609-612.

Annex A: The second statement produced in March 2004 by DOMILL on the medical implications of use of the M26 Advanced Taser.

The first statement is an Annex to this second statement.

Background

- 1. The role of the DSAC¹⁰¹ Sub-committee on the Medical Implications of Less-lethal Weapons (DOMILL) is to provide the Secretary of State for the Home Department and the Secretary of State for Northern Ireland with:
 - a. Advice on the medical implications of generic classes of less-lethal weapon systems (which includes biophysical, pathological and clinical aspects);
 - b. Independent statements on the medical implications of use of specific lesslethal systems, when used according to the formal guidance provided to users;
 - c. Advice on the risk of injury from identified less-lethal systems striking specific areas of the body, in a format that would assist users in making tactical decisions, and developing guidance to users to minimise the risk of injury.
- 2. On 30 Jan 03, the Home Secretary gave authority to proceed with an operational trial of the M26 Taser as a less-lethal option in incidents at which authority to use firearms had been granted. The M26 Taser would be used by police officers already trained in the use of firearms. The operational trial commenced on 21 Apr 03 for a duration of 12 months. Five police forces are taking part in the trial, employing a joint policy, operational guidance and training strategy developed by the Association of Chief Police Officers (ACPO). The police forces funded an independent evaluation of the trial, undertaken by PricewaterhouseCoopers.
- 3. Prior to the commencement of the trial, DOMILL provided an independent statement on the medical implications of the use of the M26 Taser within the ACPO Policy and the ACPO Operational Guidance¹⁰². The statement was based primarily on an assessment of the medical risks undertaken on behalf of DOMILL by the Defence Science and Technology Laboratory (Dstl). The statement is an Annex to this document. DOMILL also produced medical advice notes for the subjects on whom the M26 had been used, hospital staff, and General Practitioners. The DOMILL statement concluded that: *"From the available evidence on the use of the device, the risk of life-threatening or serious injuries from the M26 Advanced Taser appears to be very low."*
- 4. DOMILL recommended that research should be undertaken to clarify the cardiac hazards associated with use of the M26 Taser on individuals who could be considered to have a greater risk of adverse effects. The principal investigations should address the possible cardiac hypersusceptibility to M26 Taser currents arising from drugs commonly used illegally in the UK, acidosis and pre-existing disease, and a more thorough review of the vulnerability of pacemakers and other implanted devices. DOMILL did not consider it *essential* from a medical perspective that the studies be completed before approval was considered for the initial trial of the M26 Taser under the terms of the ACPO Policy and Guidance. DOMILL also requested that the output of the sighting laser of the M26 Taser should be measured and classified according to British Standards.

¹⁰¹ Defence Scientific Advisory Council.

¹⁰² DSAC Sub-committee on the Medical Implications of Less-lethal Weapons (DOMILL). Statement on the medical implications of the use of the M26 Advanced Taser. DSTL/CBS/BTP/PAT-ACPO/MAN/REP/4/ dated 9 Dec 02.

Extension of the operational trial of the M26 Taser

- 5. An interim report on the first five months of the operational trial has been produced by PricewaterhouseCoopers. The interim report concluded that use¹⁰³ of the M26 Taser "helped secure a positive outcome to an incident, minimising the potential need for officers to deploy other, possibly more lethal technologies"¹⁰⁴. ACPO has proposed that, subject to a review of the medical assessment and Ministerial support, the trial should be extended thus:
 - With Chief Officer agreement, the trial should be extended to all forces for use by existing firearms officers, in situations where an authority for firearms would be granted in accordance with criteria presently laid down within the ACPO Manual of Guidance on the Police Use of Firearms;
 - The five forces within the current trial should commence a further trial for 12 months where the deployment of the M26 Taser is extended for use by specialist units at incidents where there is presently no remit to authorise firearms, but where officers are facing violence or threats of violence of such severity that it is likely that they will need to use force to protect themselves or a member of the public.
- 6. ACPO and the Home Office have requested that DOMILL review the extant medical statement and offer a second statement on the medical implications of use, consequential to:
 - Revised and reviewed ACPO policy, operational guidance and training;
 - The outcome of the research to date addressing their recommendations in the extant statement;
 - The data presented to them by ACPO on the outcome (to date) of the initial trial currently proceeding.

This statement is the outcome of that review.

Review of the research undertaken

Effect of M26 Taser cardiac currents

- 7. The research requested by DOMILL was undertaken by Biomedical Sciences department of Dstl. Dstl adopted a two-fold experimental approach to clarifying the risks of adverse cardiac effects arising from use of the M26 Taser:
 - a. **Effect of drugs of abuse on cardiac function.** This approach was predicated on empirical observations made in the United States that many of those involved in confrontations in which Taser was used were under the influence of drugs. The hypothesis tested was that the drugs *per se* could predispose an individual to an adverse cardiac event, irrespective of Taser use. Seven drugs

¹⁰³ "Use" by ACPO's definition is the: (i) drawing of a device in circumstances where any person perceives the action as a use of force or a threat of use of force; (ii) discharging the barbs at a subject; (iii) application and discharge in "touch stun" mode.

¹⁰⁴ Association of Chief Police Officers: Independent evaluation of the operational trial of taser. Interim report dated September 2003.PricewaterhouseCoopers LLP.

of abuse were tested for their ability to modify the electrical properties of cardiac ventricular conduction tissue *in vitro*¹⁰⁵.

- b. **Direct application of electrical pulses to isolated beating hearts.** The pulses represent the current predicted to flow in the heart during discharge of the M26 Taser. The assessment is designed to investigate the effect of the pulses on heart rhythm, the threshold for any effects observed and the effects of selected drugs of abuse upon this threshold. These studies necessitated the development of novel, complex computer models of the interaction of M26 Taser pulses with the human body, in order to predict the shape and magnitude of current flowing in the heart.
- 8. Effect of drugs of abuse on cardiac function. Seven recreational drugs, or their active metabolites, were examined in the sheep isolated cardiac Purkinje fibre preparation. MDMA (Ecstasy) and phencyclidine (PCP) produced effects on the action potential suggestive of an increased risk of development of *torsades de pointes* arrhythmia. Although cocaine, cocaethylene (a psychoactive metabolite formed when cocaine and alcohol are concurrently abused) and (+)-methamphetamine did not induce action potential prolongation, a critical review of the scientific and clinical literature revealed that these drugs still have the potential to compromise cardiovascular function in a way that could precipitate a life-threatening cardiac event. The clinical literature suggested that morphine (the principal metabolite of heroin) and Δ 9-tetrahydrocannabinol (the principal psychoactive component of cannabis) are likely to be relatively benign in terms of cardiovascular toxicity at doses likely to be employed by abusers.
- 9. The results from the study, together with evidence gleaned from the literature, suggest that some frequently abused drugs have the potential to contribute to any cardiac-related morbidity or mortality that may arise in the context of Taser use. Furthermore, it seems reasonable to assume that this conclusion could be generalised to other emotionally charged and possibly violent confrontations with law enforcement personnel.
- 10. The adverse cardiac effects produced by any individual drug are likely to be dependent on several risk factors, including dose consumed, co-use with other drugs (including pharmaceutical drugs and ethanol) and pre-existing heart disease. This complex interplay of multiple risk factors could conceivably contribute to any cardiac-related morbidity or mortality associated with Taser use against drug-intoxicated persons. Officers should be aware that the risk of any adverse response in the aftermath of Taser deployment may be higher in drug-impaired individuals and, accordingly, they should be vigilant of any unusual behaviour displayed by the apprehended person that may signal the need for early medical intervention.
- 11. DOMILL has reviewed the paragraph in its first statement that discussed proarrhythmic factors (paragraph 28) and concludes that it does not require modification on the basis of the current work. The current work provides experimental evidence to support the original statement.
- 12. **Direct application of electrical pulses to isolated beating hearts.** The complex mathematical modelling underpinning the second experimental approach has never been undertaken before and has challenged the limits of current knowledge. Early setbacks with the modelling have been overcome and the quantitative modelling of the M26

¹⁰⁵ The assay looked at the effect of drugs on the cardiac action potential (the electrical basis for cardiac conduction, contraction and relaxation) in sheep isolated Purkinje fibres. Prolongation of the action potential duration is thought to be a possible marker for a potentially lethal type of ventricular arrhythmia known as *torsades de pointes*.

Taser current flow in the heart will be completed shortly. This will enable the studies on the isolated beating heart to commence.

Vulnerability of pacemakers and other implantable electronic devices

- 13. The implanted devices examined in the review included cardiac pacemakers, cardioverter defibrillators, cochlear implants and other implantable neurostimulatory devices, such as phrenic and vagal nerve stimulators. Published material on the construction of the devices was consulted to assess the likely consequences of Taser barb impact on the device. An assessment of available published information on the observed interaction of external electromagnetic fields with active implantable devices was also undertaken. The review also addressed the probability of a person wearing an active implantable device being present in a situation where a Taser may be deployed and used; this drew upon a comparison of the age profiles of the frequency of use of pacemaker and implantable cardioverter defibrillator wearers in the UK, and data on the age profile of persons arrested by the police.
- 14. It was concluded that the probability of direct impact and physical damage to implanted electronic devices was very low. The effects of M26 Taser electrical fields on the function of cardiac pacemakers are unlikely to be permanent. The limited number of studies that have been reported on devices similar to Tasers indicate that effects are likely to be limited to reversion to asynchronous pacing mode, and that these effects are temporary. The effects of Taser output on implantable cardioverter defibrillators are likely to be similar to those on cardiac pacemakers. The nature of the cardiac rhythm sampling process indicates that application of a Taser for a period of 5 seconds is unlikely to result in inappropriate therapy delivery. The effect of Taser outputs on other active implantable devices, such as cochlear implants and nerve stimulators, has not been reported. The interaction with nerve stimulators could produce deleterious effects but the risk of such interaction occurring is low, and it is unlikely that the effects will be long-term or life-threatening.
- 15. The age profile of cardiac pacemaker recipients is significantly different from the overall population and that of persons arrested in situations where a Taser may be deployed. The probability of an individual wearing a pacemaker being present in such a situation is therefore likely to be considerably lower than the overall incidence of pacemakers in the population.
- 16. It is concluded that there is no requirement to undertake experimental studies on the vulnerability of active implantable medical devices to the output of the M26 Taser.

Ocular hazard of the laser sight

17. The output of the sighting laser has been tested and is a Class 3R according to the British Standard BS EN 60825-1. Class 3R exceeds the internationally agreed maximum permissible exposure values, but due to the safety factors in these values, devices of this Class are unlikely to cause ocular injuries for accidental exposures. Intentional viewing or deliberate exposure of the eyes of a subject must be avoided.

Overall conclusion

18. The risk of life-threatening or serious injuries from the M26 Taser is very low.

Recommendations

- 19. DOMILL reaffirms its view that it does not consider it essential from a medical perspective that the experimental studies are completed before approval is considered for the extension of the M26 Taser trial under the terms of the ACPO Guidance. This DOMILL statement will be reviewed when the results of the study on the isolated beating heart are available.
- 20. The studies by Dstl on the effects of drugs on isolated Purkinje fibres should be published in the medical press.
- 21. Six months after the commencement of the extended operational trial, the Home Office should provide DOMILL with a report outlining the circumstances of every use of the M26 Taser, the post-incident medical assessments undertaken by the FME, and the clinical consequences noted by the FME or clinical staff. DOMILL should be advised as soon as practical of any primary or secondary injury that could be classed as life-threatening, unexpected, or potentially leading to disability.
- 22. DOMILL should be advised of any changes in:
 - a. the specification or performance of the M26 Taser;
 - b. the guidance to users, and training practices;
 - c. the policy and practice of deployment, use and audit.

Chairman, DSAC Sub-committee on the Medical Implications of Less-lethal Weapons.

<u>Sub-Annex: First DOMILL statement on the medical implications of the use of the M26 Advanced Taser (December 2002)</u>

Background

- A1. The role of the DSAC¹⁰⁶ Sub-committee on the Medical Implications of Less-lethal Weapons (DOMILL) is to provide the Secretary of State for the Home Department and the Secretary of State for Northern Ireland with:
 - c. Advice on the medical implications of generic classes of less-lethal (LL) weapon systems (which includes biophysical, pathological and clinical aspects);
 - d. Independent statements on the medical implications of use of specific LL systems, when used according to the formal guidance provided to users;
 - e. Advice on the risk of injury from identified LL systems striking specific areas of the body, in a format that would assist users in making tactical decisions, and developing guidance to users to minimise the risk of injury.
- A2. This advice is in support of the UK Government's requirements arising from:
 - f. Recommendations 69 and 70 of the Patten report into policing in Northern Ireland¹⁰⁷: (i) a research programme to find an acceptable, effective and less potentially lethal alternative to the Baton Round, (ii) provision of a broader range of public-order equipment to the police;
 - g. The desire of the Association of Chief Police Officers (ACPO) to have a wider range of options in conflict management scenarios, including those most commonly associated with self-defence and restraint, and the police use of firearms.

In summer 2000, the Secretary of State for Northern Ireland set up a UK-wide interdepartmental Steering Group to co-ordinate a programme to address both requirements.

A3. The report of the Steering Group on Phase 2 of the programme described the various classes of LL weapon systems being evaluated to address the requirements¹⁰⁸. The report categorises the technologies according to the requirement for research and evaluation. Within Category A (devices which may be subject to research and evaluation immediately) are electrical incapacitation devices, specifically Tasers.

Evaluation of Tasers

A4. Tasers are hand-held devices that propel two barbs at an individual. The barbs are intended to attach to the skin or clothing on the torso and/or lower limbs. A sequence of very short duration high voltage current pulses passes through wires connecting the device to the barbs. The current flows into the body and results in a loss of muscular control and in pain. Some models also enable direct contact of the Taser hand-set to the surface of an individual; two closely spaced fixed electrodes pass the current pulses into

¹⁰⁶ Defence Scientific Advisory Council.

¹⁰⁷ Report of the Independent Commission on Policing in Northern Ireland; September 1999.

¹⁰⁸ Patten Report Recommendation 69 and 70 Relating to Public-Order Equipment – A research programme into alternative policing approaches towards the management of conflict. Second Report of the Steering Group; November 2001. www.nio.gov.uk/policing.htm.

the subject. This manner of application is usually classed as use in "stun" or "probe" mode; pain is the principal local physiological effect.

- A5. The Police Scientific Development Branch of the Home Office has undertaken an evaluation of a number of commercially available Taser devices¹⁰⁹. The evaluation addressed barb accuracy and dispersion, the measurement of electrical output and reliability, a review of manufacturers' claims and handling characteristics in a number of test scenarios. DOMILL also undertook a general review of the medical implications of the use of Tasers^{110,111}.
- A6. On the basis of the objective technical and medical evaluations, and the policy underpinning the development of a broader range of options for conflict management in the UK, ACPO has proposed that an operational trial of the M26 Advanced Taser should take place. DOMILL was invited to provide this current statement for Ministers on the medical implications of the use of the M26 Advanced Taser in an operational trial.

Guidance on use by police of the M26 Advanced Taser

- A7. The policy and practice defining the training for use, deployment and operational use of a weapon system is central to an assessment of the medical implications of that use. The ACPO Guidance¹¹² states that an operational trial would be limited to firearms officers in selected police forces. The M26 Advanced Taser would provide firearms officers with additional means of dealing with threats of violence in which conventional firearms and other less-lethal tactical options may be deployed. Such options include batons, sprays of sensory incapacitant, and "empty hand" physical restraint.
- A8. Deployment and use of the Taser would conform to the principles of guidance already laid down in the ACPO Manual of Guidance on Police Use of Firearms. The trial would be subjected to critical and independent review.

Technical approach for the assessment of medical implications of use

- A9. The milestones placed upon DOMILL by the Steering Group dictated the nature of the technical approach: a wide-ranging review of literature and preliminary analytical studies on the biophysical interaction of Taser current pulses with the body. On behalf of DOMILL, the Defence Science and Technology Laboratory (Dstl) undertook a comprehensive review of information publicly available, and provided by manufacturers and police forces in North America. Over 800 references were acquired and reviewed. The review encompassed:
 - a. basic neurophysiological science to consider the mechanism of the interaction with excitable tissues;
 - b. peer-reviewed scientific and medical papers specifically addressing laboratory and operational use of Tasers and stun weapons: electrical output, risks to personnel, analyses of medical issues observed in hospital facilities in

¹⁰⁹ PSDB Evaluation of Taser Devices. Publication Number 9/02, September 2002.

¹¹⁰ The Medical Implications of the Use of Electrical Incapacitation Devices (Tasers). Prepared for DOMILL by the Defence Science and Technology Laboratory. DSTL/PUB20749. April 2002.

¹¹¹ An Update on the Review of the Medical Implications of the Use of Electrical Incapacitation Devices. Prepared for DOMILL by the Defence Science and Technology Laboratory. DSTL/PUB20750. 30 September 2002.

¹¹² The M26 Taser. Operational Trials involving Firearms Officers in Selected Forces. Notes for Guidance on Police Use. ACPO. 4 September 2002.

individuals subjected to Tasers, and the circumstances surrounding the deaths of personnel subjected to Tasers in the course of their arrest;

- c. evidence on the risks provided by manufacturers: scientific, medical, use on volunteers and records of operational use;
- d. the basis of the application of electrical safety standards and criteria to Taser outputs;
- e. newspaper reports of Taser use and complications arising from use;
- f. surveys of effectiveness and injuries observed and recorded by law enforcement agencies in the United States and Canada;
- g. peer-reviewed papers on the hazardous effects of electric fields on physiology.

The review by Dstl was conducted by cardiac and nerve electrophysiologists, physicists and engineers specialising in the interaction of electrical energy with the body, and trauma specialists.

- A10. Dstl also undertook computer-based modelling of the interaction of Taser pulses with the body. The primary purpose was to assess qualitatively the distribution of currents from Tasers in the body, and to determine semi-quantitatively the changes in current magnitude and distribution for different barb separations and Taser outputs.
- A11. DOMILL endorsed Dstl's approach and reviewed the substantial body of information compiled by Dstl. This statement is based on these data.

Classification of Taser outputs

A12. Tasers have been classed by users as "low-power" (5-7 Watt) or "high-power" (14-26 Watt). Tasers have been in use for over 20 years, principally in the US. Over most of this period, only low-power Tasers were available, deployed and used. High-power Tasers have been available and in use on volunteers and operationally for about two years; the M26 Advanced Taser is classed as high-power. Assessments undertaken by the PSDB showed that the principal differences in measured output between low- and high-power Tasers were the pulse repetition rate and pulse duration; differences in peak current and voltage between devices were also noted. Dstl modelling studies showed that the magnetic field strength in the body (an index of current) was greater with the high-power Tasers.

The evidence of hazard and risk from the M26 Advanced Taser

A13. The body of manufacturers' experimental evidence from biological models of the hazardous and intended effects of Taser on excitable tissues is not substantial, particularly with regard to the M26; the peer-reviewed evidence is even more limited. The epidemiological evidence to assess the hazards associated with use of the M26 Advanced Taser is not as robust as that for the low-power models. However, the manufacturer's database of over 1600 operational uses of the M26 and reports from law enforcement agencies in North America did offer some insight into the risks and nature of injuries.

Classification of injuries

A14. Unintended adverse effects from the use of Tasers may be classed thus:

- Primary: immediate or delayed consequences of electrophysiological phenomena resulting directly from the current flow in the body; it is surmised from the known effects of electric fields and currents on the body (for example, lightning, electric fence controllers) that the organ of principal concern is the heart;
- Secondary: physical trauma directly associated with Taser use, principally injuries from the barbs and falls; the head is the principal area at risk;
- Coincidental: injuries received in the incident not directly related to Taser use e.g. baton use, self-inflicted wounds, gun-shot wounds.

It is notable that in two surveys from law-enforcement agencies in North America, more than half of the number of people confronted with the M26 Advanced Taser were impaired by alcohol, drugs or mental illness. Some drugs and metabolic consequences of muscular activity are believed to increase the susceptibility of the heart to potentially life-threatening disturbances of rhythm (arrhythmias).

Conclusions

- A15. On the basis of the evidence, the following conclusions are offered on the medical implications of the use of the M26 Advanced Taser in an operational trial that may be undertaken within the terms of the ACPO Guidance provided to DOMILL.
- A16. **Deaths:** Over the period of use of low-power Tasers, there have been a small number of deaths associated with a large number of operational uses. One paper discusses 16 deaths over a 4 year period in Los Angeles¹¹³. Other factors such as pre-existing heart disease and drug use were implicated in these reported deaths. On the available evidence, DOMILL considers it extremely unlikely that a death from primary injuries has been caused by a low-power Taser.
- A17. With regard to the high-power M26 Advanced Taser, the risk of death from primary injury is low and in common with low-power Tasers, is certainly very much lower than that from conventional firearms. Deaths have been reported to be associated with (but not necessarily caused directly by) use of the M26. DOMILL is not aware of any deaths from primary injuries with this weapon, in both operational and volunteer use in North America.
- A18. The confidence of the opinion of a very low risk of death from future use of the M26 is not as high as that for the low-power devices. This uncertainty arises from the smaller numbers of historical operational uses, and the dearth of information on the potentially adverse electrophysiological effects of the higher current flow in the body, particularly in subjects who may have a predisposition to cardiac arrhythmias arising from drug use, pre-existing heart disease or genetic factors.
- A19. DOMILL is not aware of any deaths arising from the secondary consequences of Taser use.
- A20. **Life-threatening and serious injuries:** The risk of life-threatening injuries and of other serious injuries such as the loss of an eye, is considered to be very low. The intuitive high risk of serious head injury from an uncontrolled collapse is not manifested in practice; most subjects apparently collapse in a semi-controlled manner.

¹¹³ Kornblum RH, Reedy SK (1991). Effects of the Taser in fatalities involving police confrontation. J Forensic Sci. Vol 36, 434-448. For a rebuttal of some of the conclusions of this paper, see Allen TB (1992). Discussion of "Effects of the Taser in fatalities involving police confrontation". Letter to Editor. J Forensic Sci. Vol 37, 956-958.

- A21. The probability of impact of a barb on the surface of the eye is considered to be low. The impact of barbs on the head has occurred operationally; non-operational evaluation trials on targets have also resulted in head impacts. On the basis of trial data, it is probable that by employing the ACPO Guidance, fewer than 1% of upper barb impacts will hit the head. In the worst case of frontal application, the eyes are a small proportion of the presented area of the head.
- A22. The PSDB has shown in trials that the Taser may cause combustion of flammable solvents on the subject's clothing. This may result in serious burns to the torso and head; the Guidance to Users must highlight and control the risk from flammable liquids such as petrol on the subject.
- A23. **Other effects:** Falls may result in abrasions, scratches, minor lacerations, swellings and areas of redness on the skin. Minor secondary trauma from the penetration of the skin by the barbs will occur; there is sufficient experience from North America to effect simple removal by UK medical professionals.
- A24. Some of the barb penetrations will exhibit small circular burns; areas of skin where current has entered the body from barbs retained in clothing may also exhibit burns. These burns are likely to resolve within a few days, without complications and the need for medical intervention.
- A25. DOMILL is not aware of any evidence that the Taser would induce an epileptic seizure.
- A26. The M26 Taser has a US laser classification that indicates that it is potentially hazardous for *intrabeam* viewing of its sighting laser. The classification according to British Standards and the potential to cause injury must be determined.
- A27. Use on drug and cardiac-impaired individuals: It is believed that drugs such as cocaine and pre-existing heart disease may lower the threshold for cardiac arrhythmias. Many of the 16 fatalities associated with use of the low-power Tasers in the Los Angeles survey had also taken PCP (phencyclidine) prior to the incident. PCP is also thought to be pro-arrhythmogenic but is infrequently encountered as a substance of abuse in the UK.
- A28. There is no experimental evidence that the aforementioned pro-arrhythmic factors increase the susceptibility of the heart to low- or high-power Tasers specifically, sufficient to cause an arrhythmic event. Nevertheless, there is sufficient indication from the forensic data and the known electrophysiological characteristics of the heart (and the effects of certain drugs on this) to express a view that excited, intoxicated individuals or those with pre-existing heart disease could be more prone to adverse effects from the M26 Taser, compared to unimpaired individuals. The ACPO Guidance to Users reflects this view.
- A29. **Overall:** From the available evidence on the use of the device, the risk of lifethreatening or serious injuries from the M26 Advanced Taser appears to be very low.

Recommendations

- A30. Research should be undertaken to clarify the cardiac hazards associated with use of the Taser on individuals who could be considered to have a greater risk of adverse effects. The principal investigations should address:
 - a. Accurate, quantitative estimates of the magnitude of the magnetic and electric field strengths from the M26 in potentially vulnerable parts of the body; this
would require enhancement of the preliminary model developed by Dstl. These data will focus the investigations in (b) and (c) below;

- b. Possible hypersusceptibility to Taser currents arising from drugs commonly abused in the UK, acidosis and pre-existing disease; *in vitro* tissue models are available that could be used to address these issues;
- c. The vulnerability of pacemakers and other implanted devices; this issue requires a more thorough review. Experimental studies to assess electromagnetic incompatibility issues are currently not warranted and should await the outcome of the review;

DOMILL does not consider it *essential* from a medical perspective that these studies are completed before approval is considered for the M26 Advanced Taser trial under the terms of the ACPO Guidance.

- A31. The output of the sighting laser of the M26 Taser should be measured, classified according to British Standards and operated to reduce the risk from the ocular hazard.
- A32. Forensic Medical Examiners (FME) and appropriate clinical staff in the principal hospitals within the areas of the police forces participating in the trial should be briefed on the nature of the M26 Advanced Taser, clinical and operational experience from North America, and the presumed and known risk factors. Additionally, it is recommended that a paper be prepared addressing these issues and the wider policy underpinning use, for submission to an appropriate clinical journal.
- A33. At the end of any operational trial (or 6 months after commencement, whichever is earlier), the Home Office should provide DOMILL with a report outlining the circumstances of every use of the M26 Advanced Taser, the post-incident medical assessments undertaken by the FME, and the clinical consequences noted by the FME or clinical staff. DOMILL should be advised as soon as practical of any primary or secondary injury that could be classed as life-threatening, unexpected, or potentially leading to disability.
- A34. DOMILL should inspect the M26 Training Programme Manual to advise on the specific medical risk factors declared in the document.
- A35. DOMILL should be advised of any changes in:
 - d. the specification or performance of the M26 Advanced Taser;
 - e. the guidance to users, and training practices;
 - f. the policy and practice of deployment, use and audit.

Chairman, DSAC Sub-committee on the Medical Implications of Less-lethal Weapons

Annex B: Human Effectiveness and Risk Characterization (HERC) for Electromuscular Incapacitation (EMI) devices – Report summary.

The Human Effects Center of Excellence (HECOE), USAir Force Research Laboratory, Brooks City Base, San Antonio, USA.

- B1. The Human Effects Center of Excellence (HECOE), established by the Air Force Research Laboratory and the Joint Non-Lethal Weapons Program (JNLWP), conducted a Human Effectiveness and Risk Characterization (HERC) for Electromuscular Incapacitation (EMI) devices.¹ Evaluated devices included the TASER® M26 (primarily) and X26 (to a lesser extent), in which electrical current is carried to the subject via two tethered darts.² Such devices are designed to induce involuntary muscle contractions causing the subject to be temporarily incapacitated. The restricted release report³ of the HERC provides safety and efficacy information, as well as identifies data gaps, on TASER M26 and X26 effects to support the JNLWP and Services in their decision-making processes regarding the employment and further development of EMI devices.
- B2. The HERC process is consistent with the National Academy of Sciences and the Society for Risk Analysis recommendations and standards. Three workshops were conducted as part of the HERC process. The first, a data-sharing workshop, identified possible sources of relevant data and determined any insufficiencies in effectively evaluating EMI devices. The second, a peer consultation workshop, outlined potential data gaps, identified additional sources of data, and provided feedback on preliminary strategies for completing doseresponse and exposure assessments. At the third workshop, an Independent External Review Panel (IERP) submitted comments and recommendations that were incorporated into the formal HERC document. A final proposed draft was then reviewed by the JNLWD, the sponsoring program manager, HECOE, and the IERP. The product of these three workshops, resultant taskings, and final draft feedback is the HERC.
- B3. The HERC process presents a characterization of the likelihood of intended and unintended effects from the use of the TASER M26 and X26. Overall, the results indicate that the use of the TASER M26 and X26, as intended, will generally be effective in inducing the desired temporarily incapacitating effect without presenting a significant risk of unintended severe effects. Although likely to be uncommon, some severe unintended effects might occur. In some cases, key data gaps and uncertainties preclude the development of effectiveness and risk probabilities. These overall conclusions regarding effectiveness and risk are consistent with current experienced use of the TASER M26 and X26 in the field, limited empirical data, as well as human effects or safety assessments developed by others. Furthermore, an additional aspect of the analysis is consideration of the comparative risk. Analyses provided by law enforcement agencies indicate that increased use of the TASER M26 or the TASER X26 has decreased the overall injury rate of both police officers and suspects in conflict situations when compared to alternatives along the use-of-force continuum.
- B4. The occurrence of in-custody deaths has been reported in conjunction with use of TASER devices. However, there are several arguments against any predominant role of EMI in arrest-related deaths. In previous epidemiological reports, deaths were often attributed to illicit drug intoxication in suspects. Although these reports address incidents involving EMI waveforms different from those of the M26 and X26, drug intoxication has been associated with in-custody deaths under a number of circumstances, regardless of how the subjects were subdued. Contemporary medical opinion supports the view that the drug intoxication itself causes or predisposes one to underlying vulnerability. Based on the documentation and research reviewed, this report concludes that EMI is likely not the primary causative factor in reported fatalities. It does recommend further research on EMI exposure in sensitive populations and EMI-drug interactions.

- B5. Information developed in the dose-response and exposure assessment was integrated to provide quantitative or qualitative estimates of effect and risk probabilities. The likelihood of various effects when used as intended can be summarized as follows:
 - Complete EMD 80% to 56% (decreasing with distance)
 - Partial EMD 6% to 4% (decreasing with distance)
 - Eye strikes -0.01% to 0.04% (possibly increasing with distance)
 - Fall injuries -0.15% to 0.10% (decreasing with distance)
 - Seizure 0.7% is the upper theoretical bound estimate based on head strike probabilities and a worst-case assumption that all head strikes in the region of the brain result in an electrical exposure that exceeds the seizure threshold. No seizure incidents have been reported.
 - Ventricular Fibrillation (VF) is not expected to occur in otherwise healthy adult populations, although data are too limited to evaluate probabilities for potentially sensitive populations or for alternative patterns of exposure. No cases of VF have been reported in training or field exposure conditions.
 - TASER exposures induce other effects of minimal severity (e.g., dart-localized burns or lacerations) when successfully employed. These effects are of minimal severity and not further analyzed.
 - Some effects of potential concern are too uncertain or lacked sufficient data to develop probability estimates.
- B6. The IERP concluded that despite the dramatic nature of the neuromuscular response, application of this conducted energy weapon for temporary incapacitation does not appear to pose significant risk to the recipients. The Panel added that future research will be useful in increasing confidence in extrapolating the risk assessment findings to a more heterogeneous population with uniquely sensitive members.

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Appendix H – "Association of Chief Police Officers: Independent Evaluation of the Operational Trial of Taser"

Pricewaterhouse Coopers LLP, on behalf of ACPO Final Report, May 2004

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Summary of key conclusions

- In general, the Taser device was viewed by the firearms officers involved in the trial as a useful and effective piece of equipment. The officers to whom we spoke in all of the pilot forces were positive about its potential benefits.
- The main operational benefits of Taser reported were that it can help to de-escalate potentially violent situations, can reduce the risk of harm to officers and can, in some circumstances, be used with more precision than alternatives such as irritant spray and baton gun.
- Officers told us that the visual impact of arcing Taser or 'red dotting' a subject was frequently sufficient to make a person posing a threat cease to do so. It was thus seen as being highly effective in terms of de-escalating potentially violent situations and therefore possibly reducing the need to introduce lethal force into incidents.
- Concerns were raised by a number of firearms officers about practical problems with Taser, notably operational reliability, design, storage and data recording. These issues were, however, raised primarily in the early months of the trial when officers were unfamiliar with the technology. By the end of the trial many of these problems appeared to have been overcome.
- It is difficult to make direct comparisons between Taser and other less lethal options because each weapon has certain benefits for specific situations. The judgement about which is best to deploy depends on the environment and nature of incident in question. That said, we concluded that Taser seems to be beneficial addition to the range of conflict management options currently available to officers.
- The trial guidelines dictated that Tasers are only deployed alongside conventional firearms and in circumstances in which it is judged appropriate for firearms officers to carry firearms. Many of those involved in the trial senior as well as operational officers considered that this restriction meant that opportunities to use Taser to resolve violent or potentially violent incidents that did not meet the criteria for firearms deployment had been missed.
- There has been little press interest in Taser, especially outside the trial areas. Public awareness of Taser is limited. But the experience of the trial forces to date is that the public appears to be supportive of Taser, particularly where forces are open and informative about the deployment of the technology.

Section 1: Introduction

- 1 In February 2003 PricewaterhouseCoopers LLP (PwC) was commissioned by the Association of Chief Police Officers (ACPO) to undertake an independent evaluation of the operational trial of the Taser device. The trial concluded on 31 March 2004. This is our draft final evaluation report.
- 2 The trial was co-ordinated by the ACPO Police use of Firearms Secretariat on behalf of ACPO. We are very grateful to Martyn Perks, the staff officer of the ACPO Working Group on Police use of Firearms, and the liaison officers in each of the five forces for their assistance throughout.

Terms of reference

3 Our brief for this assignment was:

'To evaluate how successfully Taser devices have been used as a supplementary option to other deployment methods, namely firearms, dogs, baton rounds and irritant spray.'

- 4 The evaluation did not cover any medical assessment of the use of Tasers, nor did it include making judgements on the operational decisions to deploy Taser in respect of specific incidents. The Police Complaints Authority (PCA) is tasked with overseeing post-incident investigations where Taser is discharged.
- 5 This report builds on an interim report produced for the ACPO steering group in September 2003.
- 6 The remainder of this report is structured as follows:
 - Section 2 sets out the background to the trial and its parameters;
 - Section 3 describes our evaluation methodology and evidence base;
 - Section 4 presents the key findings from our analysis of Taser deployment forms and our fieldwork visits to pilot forces;
 - Section 5 sets out our main conclusions from the research;
 - Annexes A-C contain supporting documentation.

Section 2: Background

7 In this section of the report we provide brief details about Taser. We describe the scope of the trial and set out the main elements of the policy set out by ACPO describing its operational parameters and key procedures. We then describe our evaluation methodology in terms of the approach we adopted for gathering research evidence and information.

The Taser device

8 The Taser is an item of conflict management technology that works by delivering an electrical current that interferes with the body's neuromuscular system, temporarily incapacitating a subject. The Taser is laser-sighted and uses cartridges attached to the end of the barrel. The cartridges project a pair of barbs, which attach to the skin or clothing and deliver an electrical charge. The maximum range is 21 feet. The effect of a Taser discharge is instant and only lasts as long as the charge is applied. Every time the Taser is fired, it stores the time and date when it was fired. The Taser trial police forces used the American-made M26 Advanced Taser. The power output from this version of Taser is 26 watts.

Taser trial policy and parameters

- 9 Five police forces took part in the trial:
 - Lincolnshire Police;
 - Metropolitan Police;
 - Northamptonshire Police;
 - North Wales Police; and
- 10 In February 2003, ACPO issued a policy document to the forces taking part in the Taser trial that set out how the trial should be conducted¹¹⁴.
- 11 The document notes that while Taser technology has been subject to 'rigorous assessment' by the Police Scientific Development Branch (PSDB), the Defence Scientific Advisory Council's Sub-Committee on the Medical Implications of Less Lethal Technologies (DOMILL) has a number of 'residual medical concerns' about the deployment of Taser, particularly in regard to special population groups.
- 12 The lack of certainty about the medical implications of Taser at the outset of the trial was a factor in causing ACPO to decide that the use of Taser should be 'deliberately constrained by policy for the purpose of the trial'. The policy document sets out these policy constraints as follows:
 - Taser will only be deployed in circumstances where firearms officers are authorised to carry firearms;
 - Taser will be readily available and will only be deployed alongside conventional firearms;
 - the command structure will be in accordance with current advice contained within the ACPO Manual of Guidance on Police Use of Firearms with respect to conventional weaponry; and

¹¹⁴ Operational Trial of Taser – Policy (ACPO, February 2003)

• officers will be trained in line with the above principles.

Definitions

13 There are two important definitional issues addressed in the policy document:

Deployment – is defined as where Taser is deployed to a policing operation where the use of firearms has been authorised. Officers were required to complete an evaluation questionnaire for every such deployment throughout the course of the trial period.

Usage – is defined as any of the following three actions carried out in an operational setting:

- 1. drawing of a device in circumstances where any person perceives the action as a use of force or threat of a use of force, whether or not this is accompanied by a verbal warning, sparking of the device or placing of the laser sight red dot onto a subject;
- 2. firing of a device so that the barbs are discharged at a subject; and
- 3. application and discharge of a device in 'touch stun mode' to a subject.
- 14 All uses that fall within categories 2 and 3 above are referred to the Police Complaints Authority (PCA) for further investigation.
- 15 In summary, there are three main categories of types of operational incident with which this evaluation is concerned:
 - where Taser has been deployed to the incident;
 - where Taser has been drawn; and
 - where Taser has been drawn *and* fired or applied in stun mode.

Section 3: Evaluation methodology

16 In this section of the report we described how we approached the evaluation in terms of defining research questions and the evidence base.

Research questions

- 17 As our initial brief for the evaluation was a general one 'To evaluate how successfully Taser devices have been used as a supplementary option to other deployment methods, namely firearms, dogs, baton rounds and irritant spray' – we sought during the initial, exploratory stages of the evaluation to determine a number of key research questions that would help us to focus our work. These questions were produced in discussion with senior officers in the trial forces during our first round of fieldwork and agreed with ACPO through the process of agreeing our interim report. The questions are set out below.
 - To what extent has Taser successfully reduced the need to use lethal force (ie conventional firearms) at incidents where it is deployed?
 - To what extent have firearms officers accepted that Taser is a useful supplementary option to existing conflict management technologies?
 - To what extent have commanders accepted that Taser is a less lethal option that they are content to have deployed?
 - Is there evidence of public confidence in the police's ability to deploy Taser appropriately and with restraint?
- 18 Our main findings, as reported in this document, are structured around these four key questions.

Evidence base

- 19 Our approach to data collection has been to gather evidence from two main sources:
 - the completed Taser deployment forms, passed on to us by the ACPO trial co-ordinator based in the ACPO Police use of Firearms Secretariat; and
 - semi-structured interviews and meetings with relevant officers in the five trial forces.
- 20 We supplemented these two main data sources with information provided to the ACPO Police use of Firearms Secretariat by trial forces following Taser usage incidents. We have also taken note of press reports and PCA statements published following incidents where Taser has been actually fired or applied. In this report we present the results of our analysis of the data collected.
- 21 Copies of the deployment form and the interview questionnaire are attached as annexes to this report.
- 22 The visits included interviews with an Assistant or Deputy Chief Constable, a member of the Police Authority, the chief firearms officer and a focus group with a selection of firearms officers with direct experience of using Taser in an operational setting.

- 23 The purpose of our visits was to:
 - find out about the experience of using Taser in practice, and obtain views about its operational benefits and problems;
 - compare Taser as per the terms of our brief with other forms of less lethal technology;
 - understand the local policies and procedures governing the deployment of Taser in the five forces, and listen to views about the impact of those policies and procedures on potential Taser deployment and use;
 - listen to views about the adequacy of training and guidance;
 - start to understand public attitudes about Taser; and
 - explore the pilot forces' overall experience of the trial year and reach a judgement about the success of the trial.
- 24 We consider that this provides a solid evidence basis for ACPO and the Home Office to consider the way forward for Taser.

Section 4: Key findings

- 25 In this section of the report, we present our analysis of the Taser deployment forms received between 28 February 2003 and 19 April 2004 and our research from our two rounds of fieldwork.
- 26 Our key findings section is structured as follows:
 - A. Taser deployment and usage (basic factual information about the number and nature of Taser deployment and usage over the trial period);
 - B. Evidence to answer research questions (results of the trial in each of the four key research areas outlined in the previous section).

A. Taser deployment and usage

Returned deployment forms

27 Police officers were required to complete an evaluation questionnaire each time a Taser was deployed to an incident. We received 1,530 such forms. Our expectation is that forms may not have been completed for a number of Taser deployments, but it is not possible to say how many. Unless Taser was actually used, forms were frequently not fully completed.

Taser 'uses'

- 28 In summary:
 - 71 forms were returned outlining Taser deployment;
 - 13 forms were removed as they covered the same incident;
 - the analysis of Taser deployment therefore covers 58 cases.
- 29 The table below shows the number of forms returned by each force, the number of usages and the number of usages as a percentage of total deployments.

Police force	Number of forms returned	Number of usages	% usages
Metropolitan Police	867	30	3.3%
Northamptonshire Police	96	6	6.3%
North Wales Police	118	8	6.8%
Thames Valley Police	256	1	0.4%
Lincolnshire Police	193	13	6.7%
Total	1530	58	3.8%

Subject details

30 The table below summarises the key characteristics of a 'Taser subject'. Subjects were typically male and average height and build.

Gender	Breakdown		
Male	94%		
Female	6%		
Height			
Under 5 foot	0%		
5-6 feet	70.83%		
Over 6 feet	29.17%		
Build			
Slight	20.93%		
Medium	58.14%		
Large	20.93%		

Note: Base of 50

- 31 The section of the form on officer defined ethnicity of taser subjects was completed in respect of 46 usages. The results were:
 - IC1, White 40 (87% of forms where this information was completed)
 - IC2, Dark European 1 (2.2%)
 - IC3, African Caribbean 5 (10.9%)

B. Addressing the research questions

To what extent has Taser successfully reduced the need to use lethal force (ie conventional firearms) at incidents where it is deployed?

32 Taser was typically deployed to incidents characterised by violent or threatening behaviour, in many cases involving a knife or a firearm. The graph below shows the breakdown of incident details recorded on the deployment forms.



Percentage breakdown of incident

Note: An incident can have multiple characteristics such as possession of gun and threatening police.

33 Further evidence of the serious nature of these incidents is provided by the reasons for using Taser recorded by firearms officers. The graph overleaf shows that self or public protection were key factors in decision-making. To this data, we can add the fact that decision to use Taser was spontaneous, rather than planned, in 48 of the incidents. In 19 incidents (33% of the total), officers commented that Taser was used on subjects who were under the influence of alcohol. In 13 incidents (22.5% of the total) Taser was used on subjects noted to be under the influence of drugs.



Action to warrant taser use

Outcome of incidents

34 Despite the violent nature of incidents where Taser was called into use, the suspect was successfully arrested in 95% of cases. Officers also reported that a weapon was recovered on 16 occasions (27.6% of cases) and premises searched on six occasions (10.35% of cases) following Taser use.



Outcome of incident

Details of Taser usage

- 35 In summary, Taser was drawn at 58 incidents¹¹⁵. Of these incidents (according to the information provided on the forms) Taser was:
 - aimed and the 'red dot' laser sight used 45 times (77.6% of cases);
 - aimed without the red dot being used eight times (13.8% of cases);
 - aimed and arced seven times (12.1% of cases);
 - discharged 14 times¹¹⁶ (19% of cases);
 - applied in 'drive stun' mode twice (3.4% of cases);
 - arced but malfunctioned twice (3.4% of cases).



Details of taser usage

Note: base of 58 incidents. Total adds up to more than 58 incidents because multiple actions could be taken at each incident (eg Taser could be aimed and then fired).

- 36 This high success rate in terms of incident resolution was achieved in the majority of cases without Taser actually being fired. In 26 cases (44.8% of all cases), officers needed to do no more than aim Taser and use the laser sight for the subjects to become compliant. In seven cases (12.1% of cases) aiming Taser ensured compliance. In one case compliance was achieved after Taser was arced.
- 37 Compliance was not achieved early and Taser was actually fired at 13 incidents (involving people) and was used in stun mode twice. The table in **Annex C** sets out the key features of the incidents when Taser was actually fired or applied in stun mode.

¹¹⁵ For the purposes of this analysis we have counted multiple Taser uses at a single incident as a single usage

- 38 Our fieldwork interviews with firearms officers supports the conclusion that Taser appears to have been effective in reducing the need to use lethal force at incidents where it has been deployed. It certainly appears to have had a strong 'deescalation' effect. In many incidents, the threat of Taser (rather than its actual use) had been enough to make the individual subject become compliant.
- 39 Officers told us that the visual impact of arcing Taser or 'red dotting' a subject was frequently sufficient to make a person posing a threat cease to do so. It was thus seen as being highly effective in terms of de-escalating potentially violent situations – and therefore possibly reducing the need to introduce lethal force into incidents. The feedback on this issue supported the analysis of the completed deployment forms set out above regarding the impact of the red dot.
- 40 The following quotations from firearms officers provide a flavour of the views that we found on the ground in the trial forces:

"It is less harmful than other non-lethal options such as baton and CS Gas"

"A very effective form of personal safety"

"Taser often resolves issues by being seen and is therefore personal safety equipment and not exclusively a firearm"

"It is a good tool to use against violent offenders and has good results when deployed"

"Taser protects life and prevents harm..." "... excellent equipment"

"Taser de-fuses situations more easily and quickly than calling a firearms deployment, it should be used before the need for firearms arises."

"It reduces injuries to both officers and the public"

"It was a lot quicker in resolving many situations."

"Taser de-fuses situations more easily and quickly than calling a firearms deployment"

- 41 The only cautionary comment that we received from an officer on this issue was that when in bright daylight a subject posing a threat had not realised that he had been red dotted and continued to be non-compliant.
- 42 Our overall conclusion, however, is that the evidence suggests that Taser has been effective in preventing incidents from escalating to the point where lethal force is required. In many incidents, the threat of Taser – rather than its actual use - has made the individual become compliant.

To what extent have firearms officers accepted that Taser is a useful supplementary option to existing conflict management technologies?

- 43 Taser was seen by many officers as having the potential to reduce the risk to officers called to deal with incidents concerning violent offenders. This is partly because Taser can be fired from a distance, reducing the need for officers to engage with subjects at close range – e.g. using batons and shields. But also because Taser is seen as being a pre-emptive strategic option which can help resolve an incident before the risk of harm to officers becomes heightened. While immobilised, subjects can be restrained and handcuffed quickly minimising risk of injury to officers.
- 44 Officers explained that in most firearms incidents, the situation is such that the individual being tackled is usually submissive when confronted by SO19 officers (in the Metropolitan Police) armed with conventional firearms. In these incidents, the individual is not typically violent and resolution of the situation is through negotiation and a strong, visual armed presence. Taser is suited very well to incidents where the individual is violent and is difficult to approach and restrain. Taser is suited to handling violent individuals in non-firearms situations. In these instances SO19 officers could be deployed with Taser very effectively to assist officers in situations they cannot contain.
- 45 We asked officers to compare the operational effectiveness of Taser with that of other less lethal technologies currently available to them. Officers were keen to stress that it is difficult to make such a comparison because different technologies have certain benefits for certain situations depending on specific the environment and nature of subject(s) involved. One of the senior officers whom we interviewed said that she thought it was important to find the 'niche' for Taser in the range of responses available.
- 46 Officers did, in general, suggest that Taser, whilst adding complexity to the response strategy, offered them a more flexible method of response, which was to be welcomed.

Taser compared with baton gun

- 47 The general view was that Taser is a more flexible response tool than the baton gun, despite the longer range of the latter, with officers in the Metropolitan Police expressing a clear preference for Taser over baton gun. Taser was reported to represent a viable less lethal option in stand-off situations and was considered to be a better option than the baton gun in terms of ease of use and effectiveness in making an individual compliant. It was also said to be more effective than a baton gun in terms of presenting the weapon, arcing it and red dotting an individual. Taser was seen by many as easier to use, providing a more flexible response (i.e. the aiming and red dot stage) easier to handle and more capable of being used indoors than the baton gun, which they suggested was largely restricted to outdoors operations due to the dangers of ricochet.
- 48 Baton Rounds rely solely on pain thresholds and do not always fully incapacitate someone like the Taser (when used effectively). The Baton Gun involves a greater degree of contact with the individual compared with the Taser. The Baton Gun is also is liable to ricochet if used in confined areas.
- It was suggested that Taser could be used to complement the baton gun by acting as a follow up means of immobilising the subject at relatively close range.Officers reported that on some occasions in the past the baton gun has been used with little regard for follow up tactics. When considering the use of Taser it is

important that a strategy is devised that incorporates an action plan for the next steps once Taser has been deployed. This could involve the use of a shield team or dogs to move in to neutralise the threat.

50 It should be noted that in making comparisons between Taser and Baton Gun (and indeed making any such comparative judgement) we are restricted to reporting the views expressed to us be frontline officers and their commanders. The views expressed to us are not universally held. We have received comments from Dr Graham Cooper at DSTL that challenge the inference that Taser compares favourably with Baton Rounds in certain situations¹¹⁷. More detailed evaluation data on the Baton Gun would be required to reach a definitive view on this issue.

Taser compared with other less lethal options

- 51 The Taser compares favourably with other less-lethal methods. Northamptonshire Police do not yet use the baton gun, but do use a pepper spray, which was seen to be useful but not as effective as Taser - spray being non-discriminatory and difficult to target upon an individual. Officers in this force considered the apparently minimal injuries inflicted by Taser to be an important advantage over other less lethal options open to them. It was suggested that irritant spray, dogs and batons were more likely to cause injuries to subjects and bystanders than Taser.
- 52 Officers in all forces considered the ability of Taser to isolate an individual in a way that other less lethal options cannot as a key benefit. Taser was said to provide a good alternative to baton guns and incapacitant sprays in confined areas of action such as inside buildings or vehicles where innocent bystanders might be struck by a rebounding baton or affected by dispersing spray.
- 53 Taser was reported to be of operational benefit because of the ability to transcend the pain threshold. The basic technology underpinning Taser – the use of an electric shock – means that it does not (unlike some other conflict resolution options available to the police) rely purely on the psychological impact of pain to secure compliance on the part of the recipient. Taser incapacitates the subject regardless of whether the subject is fully aware of what is happening to them. Officers in those forces dealing with problems with drug users considered this to be a particularly attractive benefit of Taser. Another benefit suggested by officers in one of the pilot forces was that once the current had been established it could be reapplied without re-firing, helping the police, if necessary, to keep a subject subdued until they could be restrained.
- 54 Taser also provides forensic evidence that other weapons do not. Its data port and downloadable functions can provide valuable forensic evidence for each incident.

Practical limitations and problems

55 A limitation of Taser compared with other less lethal options is that it requires the individual to be in full view. Taser is not reliable in instances where the individual is only partially in view. For example, if the individual is behind a low-wall and only in view above the waist then Taser is less effective than other less-lethal options. It was also suggested that in certain situations dogs could have more of a deterrent effect than Taser or a real firearm. Some officers stated that certain groups of individuals were more fearful of dogs than firearms.

¹¹⁷ Comments on draft PwC report from Dr Graham Cooper received by ACPO on 13 April 2004

- 56 We expected to find a level of concern about practical difficulties of carrying and deploying Taser alongside (i.e. at the same time as) other weapons. While a number of senior officers raised this issue, it was not reflected by the firearms officers themselves. They were clear that carrying Taser does not, given appropriate training, limit their ability to deploy conventional firearms or other less lethal technology where necessary.
- 57 Although the overall view throughout the pilot forces was that Taser was potentially an effective addition to firearms weaponry, there were concerns raised relating to some practical problems with Taser. These can be summarised in terms of:
 - reliability;
 - design attributes;
 - storage and associated equipment; and
 - serial numbers and date recording.

58 Each of these issues is addressed in turn below.

Reliability

- 59 Most of the officers to whom we spoke had only limited experience of the practical use of Taser at the time that we made our visits. In the initial round of visits, reliability appeared to be a problem area. By the time we conducted the second round of visits, reliability was not raised as a major issue. This suggests that the effect of the 'learning curve' was in operation throughout the trial period as officers became more familiar with the technology, so their ability to use it consistently and effectively increased.
- 60 We have also had reports of battery packs failing during training. Officers commented that they are not well built, that they easily crack and fracture. It was noted that the clips that hold the cartridges break easily. Officers commented that batteries often get jammed, that it is difficult to get them out, and that they need to be changed frequently. It was hoped that the new design Taser would address some of these problems.

Design attributes

- 61 Officers generally liked the design of Taser in terms of its weight and portability, although there were some criticisms of its design. Some senior firearms officers thought that the size of the gun makes it difficult to use in covert operations – although it is questionable whether it was designed with this type of use in mind, and indeed the visible impact of Taser was seen as a positive attribute by many.
- 62 Some officers reported that the overall maintenance and battery changing arrangements and downloading issues are very impractical. Officers suggested that the need to recharge the battery once a week was burdensome. There was a suggestion in one force that the battery charging should be carried out centrally and it should not be the responsibility of officers who are working long shifts.
- 63 Officers thought that improvements could be made in the manufacturing of the Taser. It was reported that currently it is made from low quality materials and can crack easily. Officers reported that the new Taser model overcomes most of these problems.

- 64 The key risk to Taser's operational benefit is the possibility that the barbs miss the intended target. The effectiveness of Taser is related to the distance of the intended target from the officer using Taser. At greater distances there is an increased risk that the officer will miss the intended target or that the probes will not penetrate the individuals clothing.
- 65 The thickness of the wire was a concern for some officers who were worried that the wire could snap. Other officers would welcome more research into Taser capability of piercing different materials. In one instance Taser was not deployed as the subject decided to hide under a thick duvet.
- 66 There were various views about the size of the gun, most considering that it was fine and relatively easy to carry; others complaining that it was too big and uncomfortable. We understand that smaller Taser models are available and could be adopted if Taser were to be rolled out more widely.
- 67 The gun was reported to be a little fragile and can sometimes break easily. It had reportedly broken more times in the UK than in USA.

Storage and associated equipment

- 68 Storage was reported to be a problem in a number of forces. Some officers reported that in the absence of a better alternative it is kept in the boot of an Armed Response Vehicle (ARV), which is viewed as far from ideal.
- 69 Currently the Tasers are reported to be awkward to carry and require eight AA batteries. There are also reports that the cartridges used can be broken easily. There was enthusiasm for the idea of Tasers being replaced with the X26 model which is 60% smaller than the M26 and has a lithium iron battery. Officers thought that the new model could overcome most if not all of the operational problems associated with the M26 but there were clear resource implications.
- 70 Officers would prefer to carry the Taser on their person rather than carry it in their cars, as they feel they should have quick and easy access to it.

Serial numbers and date recording

71 There were some problems with the Taser data recording system throughout the trial (the system for recording key information following a Taser discharge). Following an incident in Northamptonshire, the serial number downloaded from a number of Taser recording devices did not match the serial number on the Tasers. This was not, however, viewed as a major problem as the devices had individual manufacturer's numbers that were traceable to the serial numbers for each piece of equipment.

Training and guidance

72 Officers were generally content with the Taser training package they had received. Within the Metropolitan Police, SO19 officers had already received a high level of training in the use of firearms and were therefore able to adapt quickly to the use of Taser. The majority of firearms officers we spoke to felt that the training programmes were sufficient for officers with their experience of handling firearms. Officers from the Metropolitan, Lincolnshire and Northamptonshire Police did stress, however, that they would have concerns about the adequacy of the current Taser training programme if Taser were ever to be rolled out to non firearms officers. Many of the firearms officers and trainers considered that Taser should only ever be used by specially trained firearms officers who are highly skilled at making judgements under stress.

- 73 The main suggestion among firearms officers and trainers for future improvements to the training programmes related to realistic training ground scenarios. Training for firearms officers in Thames Valley incorporated simulation exercises that were well received. Here video training has provided officers with the ability to train in situations that help them to assess certain situations and make decisions about what actions to take and when to use the conventional and non lethal options they have available to them. We are not aware of this type of training being provided in other forces. Clearer communication about Taser training was called for by some officers. There was a suggestion that there could be a central, national, Taser training team.
- 74 Our overall conclusion in this area is that Taser appears to have been widely accepted by all the trial police forces as a helpful additional piece of equipment. A number of practical problems were reported at the start of the trial, but these had generally been overcome by the end of the year. Officers who were sceptical at the start of the trial tended to change their views and support the technology after they had had experience of using it.

To what extent have commanders accepted that Taser is a less lethal option that they are content to have deployed?

- 75 We noted in section 2 that the current ACPO policy is that Taser should only be deployed in situations where individuals are 'armed or otherwise so dangerous that the use of a firearm, by an officer, may be necessary'. The effect of this restriction is that Tasers are only deployed alongside conventional firearms and in circumstances in which it is judged appropriate for firearms officers to carry firearms.
- 76 At the outset of the pilot the Metropolitan Police decided to deploy Taser only in the ARV supervisors' cars. This could be described as following a policy that is more restrictive than that envisaged by ACPO. On 21 July 2003 the Metropolitan Police force decided to deploy Taser on all of its Armed Response Vehicles (ARVs) in line with the other forces.
- 77 In contrast, Lincolnshire decided to deploy Taser on the person of all their firearm officers, which could be said to be a rather more relaxed interpretation of the trial policy and guidance. The Taser was located inside officers' jackets until the moment that authorisation to deploy was granted by the relevant commander or they self authorised. In practice this has meant that Lincolnshire officers were more likely to 'self arm' with Taser than officers in the other forces and indeed did so on a number of occasions. This policy was changed part way through the trial to bring Lincolnshire into line with the other trial forces (ie Tasers in Lincolnshire are now located in ARVs and not carried by officers).

Views on Taser authorisation and deployment

78 A number of officers, both senior and frontline, considered the trial policy – ie aligning Taser authorisation with conventional firearms authorisation – to be too restrictive. The main concern was that opportunities to use Taser to resolve violent or potentially violent incidents that do not meet the criteria for firearms deployment are being missed. Domestic violence incidents were cited by some officers as being examples of situations that could be ideal for Taser deployment, but where firearms authorisation (and hence Taser authorisation) was seldom granted.

- 79 The general consensus particularly among firearms officers was that the Taser authorisation process should be de-coupled from the authorisation process for conventional firearms, thereby allowing it to be deployed at incidents where it could be used most effectively. Officers reported that under existing guidelines the deployment of Taser has been very limited and some officers expressed concern that the weapon had not been rigorously tested in terms of its operational reliability and its appropriate use.
- 80 Taser was reported by officers to be a very effective piece of equipment for police work and some argued that it should not be restricted to firearms staff. Taser could be introduced at a lower level of authorisation, possibly on a par with or slightly below spray. If the level of authorisation required for Taser deployment were lowered then it could be used in a much wider variety of scenarios.
- 81 In Lincolnshire there was some frustration that the original arrangement of officers carrying Taser on their person had been abandoned, as they considered that this had worked well.
- 82 Although the trial policy and guidance documentation explicitly states that there is not a hierarchy of force in conflict management situations, but rather a range of options from which to select the most proportionate and appropriate response, a number of officers who we interviewed did discuss their views about Taser's position on such a hierarchy or continuum. There was a widespread view that Taser is actually likely to be a less harmful conflict response tool than baton guns, incapacitant spray and dogs and could, therefore, be authorised for a wider range of incidents than those meriting an ARV response.
- 83 It was recognised, however, that this was not a straightforward issue. To ask firearms officers to attend a wider range of incidents so that Taser can be deployed effectively would be to introduce conventional firearms into a larger number of incidents. On the other hand, to allow non-firearms officers to deploy Taser would have significant training implications.
- 84 The trial rules have meant that Taser deployment is restricted. Some firearms officers considered that, even within the limitations of the guidance, commanders could have authorised more Taser deployments if they had wanted to. If true, this suggests that this criterion has been only partially met. More discussion with commanders might be required before any general extension of Taser.

Is there evidence of public confidence in the police's ability to deploy Taser appropriately and with restraint?

- 85 The trial did not include a requirement for forces to assess or inform public opinion in respect of Taser, although some of the forces did take steps to do so. We found that forces had not yet undertaken any formal evaluation of the impact of these strategies and therefore our ability to answer this research question with a high degree of certainty is limited. In this section of the report, we summarise the results of our interviews with Police Authority members, community liaison officers in order to provide some analysis in this area, but the results should be seen as illustrative and preliminary only.
- 86 PricewaterhouseCoopers has been commissioned to undertake a short analysis of public attitudes to Taser deployment and the results of this work will be available shortly.

- 87 During the trial, the Metropolitan Police established informal consultation arrangements with police and community consultation groups, local borough commanders, local authorities and the Police Complaints Authority. This informal consultation focused on explaining what Taser was, the guidelines around its use, who in the force could use it and the expected after effects on suspects. We were told that this response to this exercise had been positive and had promoted a greater public understanding of why Taser is being used - namely as a less lethal option to a firearms response and to improve officer safety.
- 88 Police Authority members in London reported that there had been 'a solid appreciation of the need for police protection' among the wider general public in the Capital. We understand that those consulted did not express concern that Taser represents an escalation of force. Rather, given its ability to resolve situations more readily, Taser was seen as a useful means of de-escalating violence in policing situations.
- 89 One London Police Authority member stated that the 'success' of Taser in the trial could be gauged by the lack of adverse local and national media coverage. Taser usages were reported in the national media on a number of occasions throughout the trial year, but such reporting did not tend to be critical of the new technology, with the exception of the coverage afforded to a critical statement from Amnesty International in October 2003.
- 90 In North Wales there was a full demonstration of Taser at the start of the trial and this received extensive coverage in the local press. All those involved in the event were reportedly in favour of the addition of a further non-lethal alternative to conventional firearms. Views have been sought from a variety of different groups within the North Wales community, including the Women's Institute, elderly residents, magistrates and other members of the general public.
- 91 We were told that feedback received by North Wales has been positive and no complaints have been received. Discussions with local councillors and community groups has similarly been positive. Indeed, we were advised that these groups favoured a roll out Taser across the country. It was felt that Taser could assist in improving the public's image of the police in the way they handle violent situations. The public may view the use of pain to get an individual to comply as unnecessary in some cases, and Taser addresses this concern.
- 92 In Northamptonshire, Taser was launched using the national press, local media and the Northamptonshire police website. This strategy seems to have been success in terms of informing the public about Taser and the representatives of the Force and Authority that we interviewed suggested that the strategy had contributed to a 'good response' to the trial from the local community.
- 93 More work is required and is in train in order to assess public attitudes to Taser. But the experience of the trial forces to date is that the public appear to be supportive of Taser, particularly where forces are open and informative about the technology. The trial experience suggests a full public demonstration of Taser has major benefits in terms of educating and informing the public. This might be factored into any extension of Taser to other forces in future.
- 94 Further research into public attitudes to Taser has been commissioned. But the trial experience in this area to date indicates that the public has not reacted negatively to Taser, particularly where forces have made efforts to consult with and inform the public at the start of the trial. This approach should be considered as part of any wider roll out of Taser.

Overall views about the trial process

- 95 The majority of those that we interviewed during the fieldwork considered the trial to have been a success.
- 96 Officers would have welcomed some feedback on their use of Taser during the trial year, and would have liked further opportunities to feed their views on Taser into the evaluation process. Some officers felt that the trial had been slow, but understood that the deployment of Taser had to be carried out in a controlled manor over a period of time.
- 97 The pilot forces stated that there had been good team working during the trial process and that the pilot forces had worked well with each other as a team. Each representative has been very receptive to other views and ideas and this has ensured that a good relationship has been established between the liaison officers. There were many positive responses to the trial process and praise for the liaison officers who had put considerable time and effort into the process.
- 98 The evaluation form was said by some to be too lengthy and as a result it was thought that some officers had not completed this form completely or accurately enough. The revised form (issued in December 2003) was said to be much more efficient and user friendly. It was suggested that an online form could make the process easier, all officers have access to a computer and this would save a lot of effort and time. This should be borne in mind if the trial is repeated or extended.

Section 5: Conclusions

- 99 We would like to highlight the following key themes and messages that have emerged from the Taser trial evaluation:
 - the number of deployment forms returned to us was lower than we expected at the outset of the trial. Our initial assumption was that around 300 forms would be completed each month; we received an average of around 100 forms. Similarly, the number of Taser usages (58) was lower than might perhaps have initially been expected;
 - the low level of Taser deployment and usage is a consequence of the policy parameters set by ACPO for the Taser trial indeed ACPO wished the trial to be 'deliberately constrained' by such restrictions. Ensuring that Taser can only be deployed to an incident where conventional firearms are deemed to be appropriate has meant that the number and nature of incidents to which Taser is deployed is limited. A number of police officers involved in the trial regretted this limitation and suggested that Taser could potentially be deployed for a wider range of incidents to good effect;
 - where Taser has been deployed it has invariably helped secure a positive outcome to an incident, minimising the potential need for officers to deploy other, possibly more lethal, technologies. On the occasions when Taser was used in respect of a human subject, they were arrested without any serious injury to the subject or the arresting officers;
 - in many cases, officers have needed to do no more than aim, or aim and use the 'red dot' laser sight, or aim and arc Taser to ensure compliance on the part of the suspect. Taser appears to have a high visual deterrent value which can enable officers to de-escalate possibly violent situations relatively quickly and easily;
 - in the early stages of the trial, there were a number of occasions when the use of Taser was not straightforward and multiple Tasers had to be fired on several occasions to bring the subject under control. Such incidents happened less frequently in the later stages of the trial, suggesting that a 'learning curve' effect was in place, with officers getting better at using Taser with more operational and training scenario practice;
 - officers both senior and operational generally regarded Taser as a useful supplementary option to their current range of technology for dealing with conflict situations. It was seen as comparing favourably with baton guns and incapacitant spray, although it was recognised that both could be more appropriate than Taser in given situations. Key Taser benefits were described as: the high deterrent value; reduced risk of harm to officers who might otherwise need to engage with suspects at close quarters; the minimal impact on bystanders in confined spaces; and the fact that Taser does not depend on the subject reacting solely to pain for compliance;
 - there were a number of minor operational problems with Taser, although officers considered these to be outweighed by the benefits. Officers consider that there is room for improvement in terms of the reliability of the technology; the size of the device; the robustness of the battery packs; and the accuracy of serial numbers and date recording.

- 100 Our overall conclusion is that the trial has, within its own terms of reference, been a success. Where used, the Taser device has, on the whole, helped officers to arrest of suspects without the need for resort to lethal force. We have seen no evidence of adverse public reaction to Taser in trial areas or elsewhere, although further research is required to validate this proposition. Firearms officers and senior officers have, in general, welcomed Taser as a useful supplementary piece of incident management technology.
- 101 Decisions about whether Taser should be extended to other forces or for use in respect of less serious incidents are for ACPO and the Home Office. The view that was most commonly expressed by officers and Police Authority members in the trial forces was that Taser use should be extended to a limited range of other (nonfirearms) incidents. This statement is accompanied by some caveats:
 - Taser deployment should continue to be the responsibility of specially trained officers. Extending usage beyond the firearms officers would need to be monitored carefully;
 - the range of incidents for which Taser could be deployed would need to be carefully defined;
 - efforts should be made to inform and educate local communities about Taser in advance of a roll out;
 - Taser should continue to be monitored and officers should receive regular feedback on good practice.

Annex A – Evaluation questionnaire

PRICEWATERHOUSE COPE	RS	Æ
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	INCIDENT DETAILS						
	a. Time of Incident						
	b. Date of Incident						
	c. Incident Number						
	d. Location (address) of incident						
	· · ·						
	Postcode (first 3 characters, or full if known)						
	e. Brief details of incident						
	f. Spontaneous Pre-planned						
	g. Visibility: Poor 🗌 Average 🗌 Good 🗌						
	h. Resources in attendance:						
	i. Number of AFOs:						
	ii. Dogs: GPD 🗌 Firearms 🗌 Other 🗌						
	iii. Baton Gunner: No 🗌 Yes 🔲						
	iv. Number of Tasers in attendance:						
	i. Was a Taser used?: No 🗌 (complete sections 2 and 3 only)						
	Yes 🗌 (complete sections 2, 3, 4, 5, 6, 7, 8 and 9)						
	j. Number of Tasers used:						
	If more than one Taser was used, then please complete an additional form for each Taser						
	OUTCOME OF INCIDENT						
	Briefly describe the result of the operation:						
	FORM COMPLETED BY						
	a. Name: Rank: Rank:						
	b. Role in incident:						
	c. Signed:						
	d. Date:						
	e. Force:						
e	e Taser was not used, only this page needs to be completed.						

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	Taser used on:								
	a. Last Name:								
	b.	First Nam	ne:						
	С.	Other Na	mes:						
	d.	Age (DOB	B):						
	e.	Address:						••••••	·
						Po	ostcode	••••••	
	f.	Male 🗌	Female]					
	g. Officer defined ethnicity (6+1) Self defined ethnicity (16+1)								
	h.	Height:	Under 5 feet]	5 – 6	feet 🗌	Ove	er 6 feet 🗌	
	i.	Build:	Slight [Me	dium 🗌		Large	
	j.	Was the s	subject under the i	influence of:					
		Alcohol :	Yes 🗌	No 🗌	Wa	is this know	n prior t	to use: Yes 🗌	No 🛄
		Drugs:	Yes 🗌	No 🗌	Wa	is this know	n prior t	o use: Yes 🗌] No 🗌
	k.	Any know	/n relevant medica	al condition:					
	Ι.	Weapon:	Firearm 🗌 Syringe 🔲	Knife 🗌 Missile 🗌	Poin] Othe	ted weapon r 🗌		Blunt weapor	י 🗖
	I. For t	Weapon: further sul	Firearm	Knife 🗌 Missile 🗌	Poin Othe	ted weapon r 🗌		Blunt weapor	
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5.	I. For the second secon	Weapon: further sul	Firearm D Syringe D Djects please com	Knife Missile plete additio	Poin] Othe	ted weapon r □ s		Blunt weapor	י <u>ר</u>
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.5.1. lf	Taser was discharged (fired) complete the following section:						
а	. Cartridge 1 number:						
b	Probe Contact:						
	Top : No 🗍 Yes 🗌 Clothing penetration 🗌 Skin penetration 🗌						
	Bottom: No 🔲 Yes 🔲 Clothing penetration 🔲 Skin penetration 🗌						
с	. Distance between subject & firer (m):						
d	. Subject Orientation						
	Standing 🗍 Kneeling 🗌 Sitting 🔲 Prone 🗌 Moving 🗌						
	If Moving, details:						
e	. Incapacitation achieved: Yes 🗌 No 🗌						
	Reason if unsuccessful:						
L							
lf	the Taser was discharged for a 2^{nd} time, please complete the following section:						
f.	Cartridge 2 number:						
a	. Probe Contact:						
	Top: No 🗌 Yes 🗍 Clothing penetration 🗍 Skin penetration 🗍						
	Bottom: No 🗌 Yes 🗍 Clothing penetration 🗍 Skin penetration						
h	Distance between subject & firer (m):						
i.	Subject Orientation						
	Standing Kneeling Sitting Prone Moving						
	If Moving, details:						
j.	Incapacitation achieved: Yes 🗌 No 🔲						
	Reason if unsuccessful:						
C	artridge reapplied: Yes 🗌 No 🗌 If yes, how many times:						
5.2. lf	stun mode was used, please complete the following section:						
a	. Subject Orientation:						
	Standing 🗌 Kneeling 🗌 Sitting 🗌 Prone 🗍 Moving 🗌						
	If Moving, details:						
b	. Incapacitation achieved: Yes No						
	Reason if unsuccessful:						
14	If the Taper was used for a 2 rd time in Stup Mode, closes complete the following postion:						
	Subject Orientation:						
	Standing Kneeling Sitting Prove Moving P						
	if Moving Intering Italing Moving						
	Incanacitation achieved: Ves 🗌 No 🏹						
	Reason if unsuccessful						



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7.	AFTER CARE
Subje	ect requested probe removal: Yes 🗌 No 🗌
	a. Probe removed by:
	Officer (Clothing attachment)
	Force Medical Examiner Hospital staff
	b. Duration between probe discharge and removal:
	Under 30 mins 🗌 30 – 60 mins 🗌 1 – 2 hours 🗌 Over 2 hours 🗍
	c. Did probe positioning delay transportation of the subject to police station?
	No 🔲 Yes 🗌 (if yes give length of delay below)
	Under 30 mins 🛄 30 60 mins 🗌 1 – 2 hours 🗌 Over 2 hours 🗌
	d Injuries Sustained
	Primary (as a result of the Taser):
	Secondary
	If Secondary injury cause:
	e Detained in Hosnital: Ves 🗌 No
	When a Force Medical Evaminer has examined a subject if possible is convide their report should be attached
	to this document
	f. Force Medical Examiners Report attached: Yes No
	• • • • • • • • • • • • • • • • • • •
3.	ADDITIONAL INFORMATION
	Please comment further if not addressed above (i.e. issues from debrief):
	·
9	OFFICER DETAILS
	Name Rank
	Role in incident:
	b Silver Commander:
	Name: Rank:
	Role in incident:

..... Rank:

.....

When completed please return this form to:

Role in incident:

Name:

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Annex B – Fieldwork interview checklists

Round 1 Visits:

Meeting with the senior (ACPO level) officer

Why did you agree to take part in the pilot of Taser?

What benefits do you think Taser can bring to your force and local community?

What do you think the success criteria should be for our evaluation exercise?

[Prompts: reduction in use of force, acceptance by officers, public acceptance]

What role do you think Taser has in relation to other deployment methods (baton rounds, dogs, guns, pepper spray etc)?

What training is available for officers in the use of Taser?

Would you consider extending the availability of Taser to non-firearms officers? Why/why not? What would be the implications of doing so?

There have been very few incidents of Taser actually being fired. Why do you think this is?

Meeting with the commander responsible for authorising Taser use

Can you describe the policies and procedures that you have in place for authorising the use of Taser?

What factors do you consider in making an authorisation decision?

How have these policies and procedures been implemented in practice? What has worked well; have there been any problems?

What are the potential benefits of Taser? How do you think officers view the technology?

What are the main operational problems?

There have been very few incidents of Taser actually being fired. Why do you think this is?

Meeting with evaluation project liaison officer

How do you feel the evaluation project is going so far? What could we do to improve it?

Are there any key issues from your point of view that you think we should be considering?

Are there other ways that you would like to communicate with us? [other than liaison group meetings]

How do you think we should run the next round of visits later in the year? Should we talk to the same or different people?

Focus group with firearms officers

Can you tell us about your own experience of using Taser? Has it been broadly positive or negative?

In what circumstances would you use Taser instead of another deployment tool (guns, dogs, pepper spray, baton rounds)?

What are the practical problems with Taser use?

[prompt: technical, battery failures, other faults, authorisation procedures and policies]

What are the good things about Taser? What benefits do you think it has?

Overall, does it help you do your job better?

What training have you had in Taser use? Was this sufficient/appropriate?

How would you improve the Taser?

[prompt: correcting faults, design, policies and procedures]

How are you finding the evaluation forms? Is it clear and straightforward?

Round 2 Visits:

Interviews to cover two main themes:

Public attitudes to Taser

Experience of the trial year

Public attitudes

Meetings with:

officer responsible for community liaison a police authority representative

Questions

What have you done as a police force/authority to gauge public attitudes to the Taser trial (eg open days, local media etc)?

What was the impact of any such activities?

How do you consider the public has reacted to the Taser trial?

How do you think the public would react to extension of Taser to 'non-firearms' incidents such as domestic violence, street disorder etc?

Has the trial been discussed with the force/authority's partners – eg through the Crime and Disorder Reduction Partnership? If so, what views were expressed?

What more do you think the force/authority could do to gauge and respond to local people on the issue of Taser?

Experience of the trial year

Meetings with:

A senior officer – authorised to speak about the trial on behalf of the force Group of firearms officers Trial liaison officer

Questions

What were your success criteria for this trial? [Prompt: in the interim report we suggested reduction in lethal force; acceptance by firearms officers; acceptance by authorising commanders; evidence of public confidence]

How well do you think the trial measures up against these criteria?

What went well? What went badly?

Based on a whole year's experience, how do think Taser compared with other deployment methods (baton rounds, dogs, guns, pepper spray etc)?

What do you think should happen next? Should Taser:

be rolled out to all forces? be deployed on a wider range of incidents (ie those that do not warrant firearms deployment)?

Are there any operational, procedural or technical problems that should be addressed before, or as part of, an extension of Taser?

How was the trial process itself? Could it be improved?

Annex C – Record of Taser uses

Date of incident and force	Key features of incident	Outcome
4 August 2003, Metropolitan Police	Subject in possession of handgun. Taser used alongside baton gun. Taser fired once.	One barb struck subject, one barb struck nearby wet grass creating a current. Subject affected, enabling officers with dog to make arrest.
12 August 2003, Northamptonshire Police	Armed robbery subject, thought to be armed. Three tasers fired in turn.	First and second tasers failed to attach properly. Third taser attached successfully and subject temporarily incapacitated, then arrested.
13 August 2003, North Wales Police	Police attempting to arrest man suspected of wounding. Non-compliant, threw object at officers. Thought to be in possession of weapon. Three tasers fired at subject simultaneously when subject approached officers.	Tasers temporarily incapacitated suspect. Subject arrested.
21 August 2003, Northamptonshire Police	Police attempting to arrest man suspected of wounding. Irritant spray ineffective. Non-compliant subject in possession of knife. Two tasers fired in turn.	First taser ineffective. Second taser effective. Subject arrested.
23 August 2003, Lincolnshire Police	Officers attempting to make arrest in football crowd. Violent resistance. Self- authorised use of taser applied in stun mode.	Taser used in stun mode. Subject became compliant and was arrested.
9 September 2003, Lincolnshire Police	Woman reported assault on her by her husband, on attending officers were faced with violent offender.	Taser fired and man arrested.
28 th November 2003, Lincolnshire Police	Male armed with knives threatened to kill his girlfriend. Officers were threatened by suspect.	Taser was fired three times in total. The suspect was arrested
1 st December 2003, Metropolitan Police	Women at risk of self-harm, holding a knife to her chest. Taser used to facilitate evacuation and control of subject.	Taser fired and women arrested
17 th December 2003, Northamptonshire Police	Subject in believed to be in possession of 9mm handgun and/or shotgun. Believed to carry knife on and had a history of violence and was a known drug addict.	Suspect was non compliant when faced other methods (firearms support dog). A taser was fired and was effective, but the suspect needed another activation of the taser to make him compliant. Suspect was arrested.
21 st December 2003, Metropolitan Police	Suspect in street carrying a hand gun.	Taser fired and suspect arrested, Suspect agreed that the firing of taser was appropriate.
23 ^{rdt} December 2003, Metropolitan Police	An officer in a police car was attacked by a male carrying a stick smashing its windows.	Suspect was fired upon by with taser, followed by a second discharge rather than a new cartridge being discharged. Suspect was arrested.
Supplement to HOSDB Evaluations of Taser Devices

16 th February 2004, Metropolitan Police	Officers arrived at the premises of a suspect to execute a warrant. Subject was located within premises and refused to comply with requests to leave the premises and became violent in the process.	Suspect refused to leave the premises. Attempts were made to use the taser in stun moded. The suspect was forcibly detained and arrested.
21 st March 2004, Metropolitan Police	Female seen by police with handgun and 2 swords	Taser fired at suspect who was arrested. 2 swords and one handgun recovered.
27 th March 2004, Metropolitan Police	Suspects concerned in armed robbery. Armed intervention took place with taser deployed to assist in detainment	Suspect's vehicle stopped and three people were arrested. 2 loaded firearms were found and a quantity of gold bullion recovered.
29 th March 2004, Metropolitan Police	Officers went to ant address to arrest three suspects for murder involving firearms and knives.	Officers were confronted by nine males who were all abusive and aggressive towards police. Police line was rushed and taser used to protect offices and subdue subjects. Three suspects were arrested on suspicion of murder.

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Appendix I – "Assessment of the M26/X26 Taser Electromagnetic Compatibility with Commercial Aircraft Systems"

Roger H Smith ERA Report 2004-0241 November 2004

ASSET MANAGEMENT SOLUTIONS

Assessment of the M26/X26 Taser Electromagnetic Compatibility with Commercial Aircraft Systems

Roger H Smith ERA Report 2004-0241 ERA Project 7V0195901 FINAL REPORT Commercial-in-Confidence

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November 04 Ref: RHS/vs/61/01959/Rep-5631

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Summary

This report considers the EMI risks associated with the use of the M26 and X26 Taser on commercial fixed wing aircraft.

Measurements of the radiated emissions from the Taser were carried out in laboratory conditions as defined for avionic equipment. This was not considered to fully represent the real application of the Taser. Some assessment of the impact of the practical configuration was made with the result that it was considered that the radiated emissions from the Taser should not affect flight critical systems and should have only a minor detrimental effect on aircraft communications. Aircraft testing confirmed that the Taser emissions presented very minor coupling to the radio communications and did not present any compromise.

Conducted discharge of the Taser barbs between earthed metalwork of an aircraft and flight deck instrumentation is considered an unlikely event in practice. Aircraft avionic equipment tests do not carry out electrostatic discharge at the Taser maximum output voltage level but at lower levels of typically 25 kV. Practical testing with the Taser showed that this was generally not a problem with the exception of one radio control panel where damage resulted in the loss of the display.

Recommendations are made for additional emission testing to be more representative of practical operating conditions in order to provide additional baseline data.

The initial work was carried out on the M26 Taser; characterisation of the X26 Taser shows it to have a significantly different waveform, with a lower output voltage and with less overshoot that should reduce the emissions compared to the M26.

Overall it is considered that use of the M26 or X26 Taser should not impact on aircraft safety.

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Abbreviations List

EMI	Electromagnetic Interference
EMC	Electromagnetic Compatibility
EMD	Electro Muscular Disruption
CE	Conformite Europenne
am	Amplitude Modulation
ATE	Automatic Test Equipment
MCDU	Multifunction Control and Display Unit
LCD	Liquid Crystal Display
VHF	Very High Frequency
PSDB	Police Scientific Development Branch
UA	United Airlines

1 Introduction

With the increase in terrorism, there is a greater level of concern with respect to civil aircraft and the acceptable protection measures that can be used on board when in flight. Safety is of major concern in the aircraft environment, and the EMC risks associated with the use of the Taser technology on aircraft must be assessed.

The Taser is a battery-operated device that generates a high voltage electrical current. A cartridge is attached to the front end of the weapon, which contains two barbs (the electrodes) each of which is attached to a coiled length of wire. When the device is fired the barbs are propelled towards the subject, pulling the wires behind them and attach themselves to the skin or clothing of the targeted individual. When the barbs strike a person, a current can be sent down the wires and through the person's body between the two barb points.

This report assesses the electromagnetic compatibility issues associated with the use of the Taser International M26 on board commercial aircraft. It also considers the differences between the M26 and the new X26 Taser. Two aspects are considered, firstly that of the emissions produced when the Taser is fired and the possible effect on aircraft avionics. The second is that of the electromagnetic environment on board the aircraft causing the Taser to malfunction. Testing evidence available has been considered, together with the manufacturer's characteristics of the Taser.

2 EMC Requirements

Within Europe, most electrical and electronic equipment has to be tested to demonstrate electromagnetic compatibility such that broadcast transmissions are not compromised and that the device operates correctly within the electromagnetic environment of the anticipated operating scenario. For commercial aircraft, there are specific EMC standards that are applicable, specifically RTCA/DO-160D [1]. European and US aircraft manufacturers have specific in house standards with additional testing requirements, but these are based on DO-160D for radiated emission and susceptibility requirements.

For aircraft applications, the primary concern is safety. For modern avionics with fly by wire control systems, it is essential that emissions from all equipment on the aircraft are controlled to minimise the possibility of flight critical systems malfunctioning due to coupling from adjacent systems and cabling. Communications to the ground by radio are also essential to safety of flight.

The susceptibility of aircraft and avionic systems is also defined, with the flight critical systems being subjected to high field strength levels at equipment level and very high field strengths for whole aircraft, to cover the combination of on board system emissions that will sum together (but not in direct proportion to the number of equipments) and the worst case high intensity radiated fields in the operational scenarios from local radio and radar transmissions.

3 Taser Characteristics

The following technical information for the two Taser International devices is provided. The manufacturer provides no information on EMC characteristics.

3.1 M26 Information

Information in the brochure on the manufacturer's web site [2] for the M26 Advanced Taser Model 44000 Electro Muscular Disruption (EMD) device states that the output voltage is 50 kV (estimated), the power is 26 Watts at 162 mA rms, the pulse energy 1.76 Joules per pulse. No pulse repetition rate is defined neither is any information on the waveshape provided.

In the PSDB Report [3], the output power is defined as 26 Watts and the pulse repetition frequency as 25 - 38 Hz.

The United Airlines Report [4], quotes the output peak parameters as 50 kV, 18 A, 324 kW, with power as 26 Watts, current 162 mA and adds the pulse repetition rate as 15 pulses per second and the waveshape as sinusoidal (damped implied) with a frequency of 38.5 kHz. Pulse energy is quoted as 1.76 Joules.

There appear to be some discrepancies between the technical descriptions provided from the different sources.

From the general technical information [2], for the lower power Air Taser; discharging a high voltage capacitor through an inductor to the output probes generates the "pulse" referred to as a "blunt pulse". This will result in a damped sinusoidal output with the damping determined by the load resistance and the energy by that stored in the discharge capacitor.

3.2 X26 Information

For the X26 Model 26000, the only information available was from [2], where the device is referred to as using "shaped pulse technology." Power output 50 kV peak, 2.1 mA average current and 152 mA rms body current. The pulse repetition rate is 15 to 19 pulses per second but the pulse power is not stated.

This device is stated to use a very high voltage initial pulse (arc phase) to provide clothing penetration of 2 inches and ionize the air path to the target permitting the higher energy from the shaped pulse to have a low impedance conduction path to the body. This technology produces a pulse event, and is claimed to be 5% more effective than the M26 in its EMD effectiveness.

Subsequent information supplied [7], provided time domain X26 pulse characteristics that confirm the initial pulse consisting of three to five half cycles with a frequency of about 100 kHz followed by a burst of high frequency voltage with no specific frequency content occurring 50 to 100 microseconds later and lasting for approximately 50 microseconds.

4 Equipment for Use on Aircraft

When assessing a new item of equipment to be operated on board an aircraft, the EMC characteristics as measured against DO-160D would be used as a baseline to determine the risks and any operational limitations. As a non-aircraft item, and not specifically defined for aircraft applications, the Taser manufacturer would not have this specific evidence available. For normal applications within Europe, CE marking would apply, where the EMC characteristics of emission and susceptibility would be controlled; this is not the case for this item of equipment.

5 Measurements

A number of different measurements have been carried out on a variety of commercially available Tasers to assess their characteristics and performance. This section reviews the results.

5.1 PSDB Measured Data

Measurements were carried out by PSDB [5] on a number of different Taser devices, the M26 being chosen as the reference device. These tests were related to the electrical characteristics of the devices and their target accuracy. For the electrical tests, the barbs were connected to a resistive load configured as a potential divider. The lower arm was set at 1 ohm and the upper arm varied to give a total resistive load between 47 ohms and 4700 ohms. A high impedance digital oscilloscope probe was connected across the one ohm resistor to enable the pulse

characteristic and amplitude to be recorded. The oscilloscope had a bandwidth in excess of 100 MHz (probably 500 MHz) recording 5 Giga-samples/second.

The output pulse was a damped sinusoid, having a characteristic frequency around 50 kHz. This is higher than that defined by UA (see 3.1). This difference may be the result of tolerance variations in the Taser inductance and capacitance values, which will define the ringing frequency. The report states that higher output voltages but with greater ring wave damping resulted as the values of the load resistance increased, as theory would predict.

In [3] observations in section 2.9.4 were made showing that the Taser did cause some effects on adjacent computer screens, caused a computer keyboard to lock and a calculator and an electronic stopwatch to switch on and off. At the start of the pulse, a high voltage, high frequency transient overshoot of around 3.5 times the amplitude of the first half cycle of the basic damped sinewave pulse resulted. The frequency content of this initial transient was estimated to be around 6 MHz by expanding the single digitized waveform available in the electronic copy of the report. This transient voltage from the additional information in [6] shows that the overshoot is typically twice the peak damped sinusoidal voltage.

5.2 United Airlines Measurements and Assessment

This report details the work carried out using the M26 Taser in the EMC laboratory to characterise its emission amplitude profile with frequency related to DO-160D aircraft equipment limits. It then details the results of testing carried out on board aircraft to ascertain any practical electromagnetic incompatibilities.

The laboratory results show radiated emission levels up to a maximum of 27 dB above the limit (22 x limit values in linear terms) over the DO-160D radiated emission frequency band.

Practical evaluation testing on the aircraft showed no unwanted interactions with flight safety or critical systems including the communications radios.

6 Analysis of Measurements with M26

This section considers the results of the various tests and assesses the validity and the implications of Taser firing in aircraft.

6.1 **PSDB Measurements**

6.1.1 Summary

The measurements [5] and [6] were related to the output characteristics of voltage and current and the associated energy calculations. Measurements were made using seven values of load resistance between 47 and 4700 ohms connected at the output of the wires in the form of a potential divider with measurements being made with an oscilloscope across the 1 ohm lower arm of the load.

The waveform was a damped sinusoid of approximately 50 kHz with a fast ringing transient overshoot at the start of the pulse. The pulse fired at approximately 15 pulses per second. The peak damped sinusoidal voltage level increased from 800 V up to 62 kV, as the load resistance increased, the peak current remained flat within the uncertainty bands. The voltage amplitude of the initial transient ring increased from typically 2.4 kV up to 146 kV with the increase in load resistance.

6.1.2 Assessment

Energy levels were calculated in two ways, both gave energy levels in excess of the manufacturers stated level of 1.76 J. The method of calculation may have been different; the

manufacturer [2] appears to use the energy available from the charged capacitor as that available to be discharged. This area may need further investigation.

In [3] it was noted that computer monitors showed lines on the screen, the computer keyboard occasionally locked up and that a calculator and electronic stopwatch switched on. There was no specific detail in the report as to the physical location of these equipments and their cables to the Taser being fired or how frequently the effects were noted. The computer should be CE marked and operate in a field strength of 3 V/m plus 80% am modulation without any significant screen degradation. The transient time domain peak field strength will be much higher than the peak field measured during the emission tests in the frequency domain and is not covered by CE marking requirements for normal environments, transient screen effects may occur and would be considered acceptable. Similarly, for transient events coupled to the wiring, then some upset may occur providing the equipment returns to normal function after the transient event.

For critical avionic equipment, the susceptibility to radiated fields will be tested to field strength levels of 200 V/m, considerably higher than the commercial computer limits where effects were noted. The peak pulse field strength level is unknown and cannot be estimated without further information on the pulse edge characteristics.

6.2 Laboratory EMC Measurements

6.2.1 Summary

Radiometrics Midwest Corporation carried out radiated emissions testing for United Airlines on the M26 Taser. The results of these tests were contained in Appendix 1 of the United Airlines report [4].

Testing was carried out to assess the radiated emissions from the M26, testing it in accordance with the requirements of DO-160D in the manner applied to normal aircraft equipment at 1 m separation. The Category M limit was defined for the testing and applies where there are significant apertures but where the equipment is not in direct view of antennas such as the passenger compartment and the cockpit.

The M26 was set up over a metal ground plane in the following configurations:

- a) Armed
- b) The Taser discharging between the fixed probes
- c) The Taser with wires extended 30 cm apart 5 cm above the ground plane connected to a 1000 ohm load at the remote end of the 11 foot long ground plane.

Ambient emissions were initially measured showing the levels well below the defined limits, with the Taser in the armed mode, emissions remained at the ambient levels. With the Taser discharging between the fixed probes, the emissions increased significantly with the worst case emission 31 dB above limit at the lowest measurement frequency of 2 MHz and with emissions over limit by up to 17 dB between 400 MHz and 1000 MHz and up to 10 dB above limit between 1 GHz and 6 GHz.

With the cables extended and operating into the 1000 ohm load, the emissions were worst case with the maximum emissions over limit at 2 MHz and 400 MHz by 26 and 27 dB respectively but with emissions in excess of the limits over the full frequency range. Table 1 shows a comparison of the peak levels above the Category M limit for the two firing modes at spot frequencies over the range.

FREQUENCY	ABOVE CAT M LIMIT (dB)			
(MHZ)	BETWEEN PROBES	THROUGH WIRES INTO LOAD		
2	31	26		
5	14	20		
10	3	17		
17	1	21		
25	**	20		
35	3	22		
50	**	12		
70	**	7		
100	**	14		
140	**	16		
280	**	14		
450	10	27		
650	16	19		
1300	10	10		
2000	4	7		
5000	**	6		

Table 28: **Comparison of Emission Levels**

** Below Specified Limit

6.2.2 Assessment

Category M limit defined for the testing is considered to be applicable to the Taser for initial assessment for use in the aircraft application. The more stringent category H limit applies where the item would be in direct line of sight to an antenna and is more stringent than category M in the communications bands. Category L is less severe than M for equipment located away from apertures (windows) and far from antennas; this has no notches for the communications frequency bands. Category B is the least stringent limit and is 20 dB less severe than category M; this applies to equipment for which emissions "should be controlled to tolerable levels."

The change in levels at 30, 400 and 1000 MHz occurs where the measuring receiver bandwidth changes. The changes in the level at these frequencies are related to the characteristics of the emissions generated. For impulsive emissions, characteristic of the Taser, the levels would be proportional to the change in bandwidth. In the two notches between 1 and 2 GHz, a narrower bandwidth is employed accounting for the apparent reduction in levels.

For the probe firing mode, the emissions are a direct result of the arc breakdown across the fixed probe air gap. The damped sinusoidal frequency generated by the discharge circuit is below the lowest frequency of measurement in DO-160D, hence the emissions are seen as impulsive transient events due to the high voltage fast ringing edges on the leading edge of the pulse giving rise to the broadband emission spectrum.

With the wires extended and loaded resistively, there is no spark discharge across the air gap but an electric field generated from the high common mode current fast rise time initial transient when the pulse is discharged through the resistive load. In this case the source of the emission is the cable and that will radiate much more efficiently over the wider frequency range than the Publication No. 64/06

spark gap. The source of emissions will be common mode from the loop produced by the wires and the stray capacitance to the ground plane. The predominant current flow in the two wires comprising the loop will be common mode at the frequencies above 2 MHz.

The Taser is unique compared to all other equipment for a number of reasons: it may be employed on the flight deck, it is not connected to any aircraft power or wiring harnesses and its use would normally maintain a separation of at least 0.5 m from any wiring harnesses or other equipment. Further, its use would be very rare and it is designed for use over a short time of a few seconds, not continuously.

The testing shows radiated emissions exceeding the category M limit, however it is considered that category B limit should be considered for the Taser given its extremely limited operational application. The methodology allows the results to be applied to any of the chosen DO-160D limits and analysis shows that emissions exceed this limit from 2 MHz to 35 MHz and between 400 MHz and 550 MHz by up to 5 dB.

The limits are concerned with the protection of radio communication and navigation equipment primarily which are the most sensitive to in-band interference to the receiving antenna, with the limits set low to allow for the addition of emissions from the multitude of other electrical and electronic equipment on board. For flight critical equipment, the coupling risk mechanism is cross coupling between co-located wiring harnesses where cables may be run directly adjacent and where the local field strength could be typically two to three orders higher than the radiated emission level at 1 m distance.

Measurements of radiated emissions were carried out on the M26 Taser in accordance with DO-160D 5 cm above a metal ground plane. This is not representative of the functional configuration for the Taser, which would normally be operated at a height of at least 1 m above a metal floor. The effect would be to increase the effective common mode radiating loop area and to decrease the capacitance to ground. Radiated emission will be related to the common mode loop area and the impedance to ground. The emissions could be up to 26 dB higher up to 10 MHz, 20dB at 30 MHz, 16 dB at 100 MHz and 6 dB at 500 MHz making worst case assumptions.

The Taser wiring loop placed 0.3 m horizontally above the ground plane provides a more balanced arrangement above the ground plane than would be achieved in practice with the loop vertical. The effective loop area is probably representative of practical conditions although not representing the maximum area, however that is unlikely to occur in practice.

The load resistance crudely represents the human body, the voltage across the contact points being related to this resistance. The Taser was loaded with 1000 ohms for both the laboratory and the aircraft emission testing; it is not known what typical impedance a body may present, (PSDB used 47 to 4700 ohms). The differential mode current through the load remains constant and is independent of the resistance value however. The common mode emission current is defined by the degree of impedance unbalance in the differential loop and may vary with the load resistance resulting in a difference in the radiated field level from that obtained with the 1000 ohm load.

The full length of the wire was not extended out along the ground plane because it was only 11 feet long and the maximum cable length is 21 feet. The length of wire extended out may have an effect on the radiated emissions.

6.2 On Aircraft Testing

6.3.1 Summary

Appendices 2, 3, 4, 6 and 7 from [4] show the results of ground tests on five aircraft (A320, B777, B747, B737 and B757) where the Taser was operated during ground EMI test procedures that checked all critical systems and communications equipment. For the first three aircraft

extensive testing was carried out and a limited test on the last two based on equipment criticality All equipment was reported to function correctly, the only comments being on the A320 that slight popping was heard on the VHF radio and a barely audible clicking on the HF radio, the effects were not considered to interfere with radio operation.

Appendix 5 [3] reports on the effect of direct contact discharge of the Taser onto the A320 MCDU fitted in a shop ATE test bench and between the first officers seat track and various flight deck systems on the B747. For the MCDU, the only effect was to trip the bench ground fault interruption circuit that would not exist on the aircraft. On the B747 flight deck, damage resulted to one LCD on the VHF Radio Control Panel but this did not affect control from the alternative VHF Radio Control Panel.

Appendix 8 [3] reports on tests carried out on an A319 aircraft during flight. Tests were carried out with manual and autopilot control and during a CAT III coupled landing approach. No abnormal system functions were observed to occur.

6.3.2 Assessment

6.3.2.1 Systems

Two types of aircraft system risks are of concern, the ability to maintain radio communications between crew and ground control and the effects on critical electronic control systems.

For the radio communications and navigation equipment, the most critical coupling path is through the antenna port directly. The antennas are normally mounted on a metallic section of the aircraft to optimise the antenna performance, which in this case will further minimise coupling of any in-band interference that occurs from within the aircraft due to the screening provided that would be at least 20 dB. The coaxial antenna feeder cable for the radio signal will provide in the order of 80 dB of attenuation (four orders) to in-band interference. Other wiring harnesses on the radio system would be less sensitive to interference and protected by screening and filtering. EMC testing would be carried out but with the receive band exempted.

Critical avionic systems are protected by screening and filtering and are tested to field strengths of typically 200 V/m to ensure integrity. These systems are usually duplex or triplex to minimise common mode failure mechanisms from occurring.

6.3.2.2 Results

Popping/clicking effects were just audible in the background on the radio systems, these were considered acceptable by United Airlines. The Taser wires were laid out on the floor extending between the flight deck and the adjacent cabin to provide maximum coupling to the radio racks positioned beneath the floor. This test approach was considered reasonable assuming common mode current flow at the HF and VHF radio frequencies and assuming a non-metal floor. If the floor is metal, then further attenuation would be provided although leakage paths due to poor bonding would allow RF current to flow on the other side of the floor and reradiate. This position represents the closest approach to antennas under the belly of the aircraft and to associated antenna coaxial cable feeders. Other positions on the flight deck would be less likely to cause interference coupling to the less sensitive radio wiring harness where distance proximity would be greater and the flight deck metal control consoles would provide further attenuation. The operation of a Taser is anticipated to be rare and the time of operation is relatively short at 5 seconds per firing and unlikely to exceed three firings at worst case. Radio communication during this short period is not anticipated to be a high priority, and the risk of damage to the radio systems is extremely remote. It must also be noted that normal firing would be at a height of approximately 1 m above the floor, increasing the common mode radiating loop area but increasing the loop capacitive impedance. This would increase the field strength on the flight deck but not affect the coupling to the antenna and feeder significantly.

For the flight critical avionic equipment, the position of the Taser wires and load may not have been adjacent to specific avionic equipment racks, control panels or cabling and hence the testing is unlikely to represent worse case conditions. Sensitivity of these systems to RF is much lower than for radio equipment. As stated above, these critical systems will have been tested to 200 V/m (166 dB μ V/m). The field strength levels from the laboratory testing were up to 80 dB μ V/m but were bandwidth dependant especially because the Taser emissions were impulsive in nature.

A worst case analysis is shown in Table 2 to estimate the field strength based on the laboratory results but increasing the measuring bandwidth to 100 kHz, increasing the Taser wire loop area, allowing for the increased common mode impedance of the loop when 1 m above the ground, assuming the Taser wires were at a distance of 0.3 m from aircraft equipment wiring and that the equipment consoles provided only 6 dB of attenuation.

Frequency	Lab	BW	Loop Area	Loop Impedance	Distance	Console Atten	Field Strength	
MHz	dBµV/	dB	dB	dB	dB	dB	dBµV/m	V/m
2 - 30	65	40	30	-4	10	-6	135	5.6
30 - 400	70	20	24	-4	10	-6	114	0.5
400 - 1000	80	0	10	-4	10	-6	90	0.3
> 1000	80	0	4	-4	10	-6	84	0.15

Table 29: Worst Case Field Strength

Making worst case assumptions, the highest field strength generated is at the lowest frequency at 5.6 V/m, well below the qualification levels of the aircraft critical systems.

Direct discharge of the barbs through flight deck equipment, damaged one LCD display on a radio control panel however a second control panel could be used. The probability of a Taser being fired and hitting the display and earth is considered very low, it is anticipated that any firing would normally be from the flight deck out towards the cabin and not into the flight deck. Most wiring on the flight deck is concealed behind metal consoles where there is no possibility of the Taser barb puncturing wiring insulation and discharging directly into equipment wiring. For any cables not behind metal panels, they would be behind plastic panels where it is considered the barb would not puncture.

7 Susceptibility

No susceptibility testing has been carried out on the M26 Taser. The manufacturer's data refers to the safety mechanism and the trigger pull as an "electronic trigger". With electronic triggers there is a risk of malfunction when subjected to RF electric fields. Malfunctions could give rise to inadvertent operation but could conversely inhibit the function. The trigger circuit to operate the Taser is digital in operation, requiring a change in the digital state to occur before it fires the gas cartridge and consequently the barbs. There are decoupling capacitors on the trigger, the circuit path lengths will be very short and as a result it is considered unlikely that RF coupling from on board transmitter sources could cause the trigger to malfunction. It is assumed that the X26 would employ the same circuitry.

8 Taser X26

Technical information is very limited, making comparisons difficult. The output voltage is the same as the M26 version with the body current being comparable. The output energy is not defined but is assumed to be comparable with the M26.

The primary difference appears to be the pulse characteristic, with an initial pulse to break down the air gap to allow the high energy damped sinusoidal part of the pulse to couple more efficiently by the claimed 5%. How this is achieved is not clear, the pulse must be similar to the M26 that has the initial fast transient characteristic. It is possible that the X26 has two high voltage sources, which are fired sequentially to achieve the defined characteristic.

References [7] and [8] supplied subsequently provide raw data from X26 characterisation and an overlay comparing the voltage output of the X26 with the M26 under 47 ohm loading conditions. The raw data was briefly assessed, and showed a significantly different waveform. The initial characteristic showed a damped sinusoidal waveform of approximately 100 kHz of between 3 and 6 half cycles with a pulse of high frequency random noise 80 to 100 microseconds after the low frequency event and lasting for typically 80 microseconds. The high frequency ringing on the low frequency component of the waveform was only 25% of that from the M26, with the later high frequency amplitude levels were similar to that of the M26.

On the basis of the comparative waveforms, then the EMC emission levels should be lower for the X26.

9 Conclusions

The radiated emission measurements carried out were not representative of the practical conditions under which the Taser would be fired but followed the specification approach applied to aircraft equipment where wiring harnesses are run adjacent to structural metalwork.

The results showed that the radiated emissions were impulsive and broadband in nature, extending over the frequency range to above 1 GHz. The source of the emissions was considered to be from the high frequency ringing on firing.

The radiated emissions were related to the Category M limit, it is considered for the infrequent operation of this device that the Category B limit could be reasonably applied where emissions are then shown as up to 5 dB above the limit.

The levels are not considered a major risk to general avionic systems based on anticipated rare use of the equipment, but could result in some degradation of communications reception. For HF the relative position of the antenna would be critical to any degradation. In the case of VHF, the antenna would be much closer below the aircraft belly with the emissions up to 16 dB above the Category M notch limit.

For avionic flight safety critical equipment, a worst case assessment taking into account the impulsive characteristics of the emissions, the bandwidth of the measurements and the effect of a larger radiating loop area, the field strengths are still considerably lower than the qualification levels applied to the avionics equipment and should not cause any problems.

Aircraft testing confirmed that only very minor audible interference could be detected on the radios and that no other systems appeared to be susceptible. Conducted discharge through avionic equipment to ground showed only one event of damage on a communications panel LCD where the display function was inhibited.

Although not an EMC issue, the measured energy output figures appear inconsistent with the manufacturer's figure.

The Taser trigger circuits should not be susceptible to the fields generated within the aircraft fuselage.

10 Recommendations

It is considered that from the evidence available and especially the aircraft tests, that the M26 Taser should not present a risk to flight critical equipment on commercial fixed wing aircraft. The characteristics of the X26 show that the emissions from this version should be lower than the M26, indicating that the risk to flight safety critical equipment will be lower.

Further limited and tailored emission measurements could be carried out to provide a representative baseline emission profile, investigating the following areas:

- a) Variations of load resistance
- b) Effect of Taser 1 m above the ground plane
- c) Orientation of the Taser wiring to a vertical loop
- d) Effect of the Taser wiring loop area
- e) Impact of wiring not being fully extended.

The X26 Taser characteristics are different from those of the M26. The pulse characteristics indicate a lower risk, however limited emission testing is recommended to provide documentary evidence to support the assessment.

11 References

- Environmental Conditions and Test Procedures for Airborne Equipment RTCA/DO-160D July 29, 1997
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