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Wound ballistic simulation:

Assessment of the legitimacy of law enforcement firearms ammunition by means of wound ballistic simulation

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Academic dissertation

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“ Just as a horse must have endurance and no defects, so it is with weapons. Horses should walk strongly, and swords and companion swords should cut strongly. Spears and halberds must stand up to heavy use: bows and guns must be sturdy. Weapons should be hardy rather than decorative.”

Miyamoto Musashi (1584 – 1645)

ABSTRACT

Use of force to protect and defend a nation from external aggression, internal disorder and unlawful activity is considered necessary and morally acceptable. Even though ultimate, lethal force is sometimes unavoidable the force should always be in proportion with the prevailing threat. No more force should be used than is necessary to avert it and stop the aggression. The means of force allowed for a legitimate military or law enforcement organisation are by no means unlimited. International organisations have long attempted to define what can be considered acceptable technology and behaviour in a conflict. A firearm is a common means of force. Yet the available definitions of its acceptable effects and means to verify them have been somewhat lacking.

This dissertation looks into the International Law to find an interpretation of current weapons technology and a legal basis for verification of the injury potential of penetrating firearms projectiles. The result emphasizes the fact that all parties of a dangerous confrontation have the same right to be protected from superfluous and unwarranted injury - not only the offender, but also and primarily the non-involved bystander and the law enforcement official.

The literature is reviewed for wound ballistic research, proposals for injury scoring and wound ballistic simulation methods. Ballistic gelatine has long been used as soft tissue simulant to study the behaviour of a bullet and its injurious effects. The validation of gelatine has so far been somewhat dubious. Several different methods of preparing it have been published with very little information on how various preparation parameters affect the end result. Laboratory experiments conducted during this research correct some of these problems and establish a more solid basis for wound ballistic simulation by recommending the use of standard gelatine and validating it with the results obtained from published tests with anesthetized pigs and defining a function describing the relationship between dissipated kinetic energy and amount of devitalised tissue. Various methods of measuring the kinetic energy dissipated by the bullet into gelatine are compared and the method giving the highest correlation recommended.

Skin simulant is defined to complement the gelatine in studying the residual injury potential to bystanders induced by bullets that already penetrated the primary target or ricocheted from a hard surface.

Based on above, a method for verifying the injury potential of a bullet is proposed. This method will allow for a meaningful comparison of bullet effects to establish their suitability and acceptability for law enforcement use. Furthermore, it allows the results to be connected to the Red Cross Wound Classification. The research also shows that standardized injury and ballistic data should be collected and stored in a database. An outline of standard information is proposed. This would allow verification of experimental research, further refinement of wound ballistic simulation and follow-up control of the weapons already accepted for use.

Although there is no legal obligation for mandatory review for assessment of the injury potential of the firearms used by law enforcement in Finland, the fact that the society has authorized the use of force against its own members makes the moral obligation compelling.

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List of tables:

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The drawings have been done by the author using CorelDraw 8 vector graphics. Photographs have been taken by the author using Nikon Coolpix 900 digital camera and prepared using Corel Photo-Paint 8 software.

1 LIST OF ORIGINAL PUBLICATIONS

I
Jorma Jussila, MSc and Pertti Normia, legal counsellor,
INTERNATIONAL LAW AND LAW ENFORCEMENT FIREARMS, Medicine Conflict and Survival, Vol. 20, 55-69 (2004)

II
Jorma Jussila, MSc
PREPARING BALLISTIC GELATINE – REVIEW AND PROPOSAL FOR A STANDARD METHOD, Forensic Science International 2004 May 10;141(2-3):91-8

III
Jorma Jussila, MSc, B.Thomas Kjellström, MD, PhD and Ari Leppäniemi, MD
BALLISTIC VARIABLES AND TISSUE DEVITALISATION IN PENETRATING INJURY – ESTABLISHING RELATIONSHIP THROUGH META-ANALYSIS OF A NUMBER OF PIG TESTS, submitted to Injury 7/2004 and approved for publication 9/2004.

IV
Jorma Jussila MSc, Ari Leppäniemi MD, Mikael Paronen PhD and Erkki Kulomäki, senior researcher
BALLISTIC SKIN SIMULANT. Submitted to Forensic Science International 3/2004. Approved for publication 6/2004.

V
Jorma Jussila, MSc
MEASUREMENT OF KINETIC ENERGY DISSIPATION WITH GELATINE FISSURE FORMATION WITH SPECIAL REFERENCE TO GELATINE VALIDATION. Submitted to Forensic Science International 4/2004. Approved for publication 6/2004.

2 ABBREVIATIONS AND DEFINITIONS

The literature often uses miscellaneous symbols including special fonts, Greek alphabet and subscripts for various purposes. The notation below is intended for clarifying the issue. It uses the International System of Units as a guideline with some exceptions. For clarity and ease of writing subscripts are reserved for indexes and superscripts for powers only. As the notation evolved together with this dissertation some of the original papers may use it only partially.

Notation: SI-symbol concatenated with a qualifier both in italics as follows:

Table 1: SI-symbols and special names for ballistics

ά	angle	*N*	number (of observations etc.)
a	acceleration	*o*	
A	surface area	*p*	pressure
C	coefficient	*q*	
d	diameter	*r*	radius
Δ	difference	*R*	rate
e	base of natural logarithm (2.718..)	*S*	sectional density = *m/A*
E	kinetic energy	*SD*	standard deviation
f		*t*	time
F	factor		
g	gravity	*u*	
h		*v*	velocity
i,j,k		*V*	volume
K	calibre	*x*	
l	length, distance	*y*	
m	mass	*z*	
n		*T*	temperature

Reserved words for qualifiers:

an	(*άan)* Angle of attack from surface normal
b	ballistic
be	ballistic event
cr	crusher
d	dissipation (*Ed*)

deb	debrided
def	deformation
dev	deviation
form	form (of the projectile)
fr	fragmentation
i	impact
pz	piezo
r	residual, retained
rt	rifling twist
sp	specific (*msp*- specific weight)
st	stability
th	threshold
w	wound
x	exit

Naming:

Name	**Unit**	**Definition**
ádevi	degree	Angle of deflection (deviation) from the flight path
áan	degree	Angle of attack from the surface normal of the target
CbM		ballistic coefficient - Metro
CbI		ballistic coefficient – ICAO
Cd		drag coefficient
dwi	mm	maximum diameter of permanent entry wound (j = 0)
dpc_j	mm	maximum diameter of permanent cavity at measurement depth (j) e.g. dpc_{50}
dtcmax	mm	maximum diameter of temporary cavity
dtc_j	mm	diameter of temporary cavity at measurement depth (j) e.g. dtc_{50}
dwx	mm	maximum diameter of permanent exit wound
Ei	J	Kinetic energy of the projectile on impact
Er	J	Residual kinetic energy of the projectile main after penetration
Ed	J	Amount of kinetic energy dissipated into target
Edef	J	Amount of kinetic energy used by projectile deformation
Efr	J	Amount of kinetic energy dissipated into target by bullet fragments
Ki	mm	Initial projectile calibre (diameter)
Kr	mm	Largest diameter of the projectile main after penetration (Residual calibre)
li	m	Distance between the muzzle of the weapon and the first obstacle (Impact distance)
lrt	mm	rate of twist of barrel rifling (length of one complete turn)
lw	mm	Length of wound channel of projectile main

lwr	mm	Length of residual wound channel i.e. the depth of penetration of the farthest penetrating fragment of the projectile
mi	g	Projectile weight
mr	g	Retained weight of the projectile or its recovered fragments excluding those left in the simulant
mdeb	g	mass of debrided (devitalised) tissue
msp	g/cm^3	specific weight
pcr	Pa	chamber or port pressure measured with crusher method
ppz	Pa	chamber or port pressure measured with piezo method
Rfr	-	rate of fragmentation $Rfr =(mi – mr)/mi$
S	g/cm^2	sectional density of a bullet = projectile weight (*mi* or *mr*)divided by its cross-sectional area.
tbe	ms	duration of terminal ballistic event (e.g. penetration)
v_n	m/s	Velocity as measured at (n) metres from the muzzle of the weapon eg. $v_{2.5}$
vi	m/s	Impact velocity
vr	m/s	Residual velocity of the projectile main after penetration
vth	m/s	Threshold velocity

NOTE. The European calibre notation uses projectile diameter times length of casing in millimetres e.g. 9x19 mm [C.I.P. 1990] and occasionally the name of the inventor e.g. 7.62 mm Tokarev or 9 mm Luger. The latter is the same calibre as 9x19 mm. The American notation uses projectile diameter in decimal fractions of an inch. Likewise the respective units of bullet mass are in grammes (g) and grains (gr).

3 INTRODUCTION

Firearms injuries caused in military conflicts, law enforcement and civilian environment are numerous and of great social and humanitarian concern. Weapons designers produce new types of of ammunition. Yet firearms are needed for protection of the society and enforcement of law, order and peace. All this makes it ever more important to gain profound understanding on the wound ballistic processes in order to minimise injuries and suffering and to maximise the prospects of recovery.

The Rome Statute of the International Criminal Court [1999] defines the International Law as consisting of:

a) international conventions also called covenants, protocols and charters.
b) international custom as evidence of a general practice accepted as law.
c) the general principles of law recognized by civilised nations.
d) authoritative interpretations of above.

Item a, also called the "Law of Treaties" is legally binding [de Rover 1998]. Most of its statutes relevant to weaponry deal with armed international or domestic military conflicts [UN 1977 and 1980] and do not apply to law enforcement. The statutes covering law enforcement [UN 1990] have only the status of authoritative recommendation [de Rover 1998]. It can, however, be said that the 1907 Geneva Convention requirement to abstain from the use of weapons causing superfluous injury and unnecessary suffering (*maux superflus*) is an accepted international custom and generally binding. Unfortunately it is not clear what *maux superflus* means in weapons technical terms. Evaluation process is required [UN 1977] to ascertain that any new military weapon is in compliance with the International Law. This, however, does not technically bind law enforcement although morally it does.

As technology evolves, it is necessary to establish a formal evaluation process and look at the weapons and their effect *ratio legis*, from the perspective of the intent of the law, instead of declaring prophylactic prohibitions on certain technical solutions. Otherwise the statutes may rapidly become obsolete as they can be circumvented using alternative solutions complying with the letter of the law.

The evaluation process should recognize that in an armed conflict there are not only the combating parties but also bystanders and that all of them have the right to be protected from unwarranted and superfluous injury. Law enforcement does not speak of combating parties but legal authorities, bystanders and offenders. The concept is still the same. The borderline between war, peace enforcement, peace keeping and traditional law enforcement has become unclear making the need for unified use of force statutes and legal evaluation process ever more urgent.

Assessment of injury potential is central for determining the legitimacy of a weapon and its ammunition. It is essential to make a distinctive difference between assessment of injury potential and assessment of effectiveness i.e. incapacitation potential. Although greater injury usually also means greater incapacitation potential the relationship is not at all clear. As injury deals with the physiological result, the incapacitation includes also the psychological and more difficult to measure processes whose outcome is affected by determination, beliefs and even previous experiences. The term “stopping power” is often used as a synonym and incorrectly as if incapacitation potential would be the result of a physiological systems failure.

The problem in assessing the injury potential and the legitimacy of a means of lethal force stems from the fact that if injury potential to bystanders and law enforcement officials is to be minimised the injury potential to an offender often increases. The impacting bullet must have sufficient energy to reliably do its job and expend its kinetic energy in the target not to create a hazard to bystanders. This will cause an increase in injury to the offender. Unless a bullet does effectively what it is expected to do, the conflict may be prolonged. More shots may be fired and the danger for both bystanders and the law enforcement officials is increased.

Defining accurately what constitutes an unwarranted and superfluous injury is difficult out of the context of the incident. The legitimacy of the use of force by the law enforcement official depends on and must be proportional to the graveness and imminence of the threat imposed by the offender. It cannot be precisely determined before an event has taken place. Certain general measurable weapons technical definitions are still possible.

The research done for this dissertation lays the foundation for a valid wound ballistic assessment of injury potential. It takes into account not only the offender but also the bystanders and the law enforcement officials. As a result a standard test set is proposed for producing the necessary exact comparison figures and in adherence to the Red Cross Wound Classification method [Coupland 1993]. The decision on legitimacy can then be done by competent authorities by weighing these figures against the legal principle of proportionality between the threat and the force and the restrictions imposed by the International Law considering also the moral principles of the society.

4 REVIEW OF THE LITERATURE

4.1 Firearms and ballistics

4.1.1 The firearm

is the launching system for projectiles (bullets). A projectile of a modern firearm is mounted on an open end of a casing with a primer in the opposite closed end containing propellant called powder. When the firing pin of the gun is released by pressing the trigger it strikes the primer which detonates igniting the powder. The burning powder generates a large amount of hot gases. As the pressure behind the bullet mounts up it pushes the bullet along the barrel of the weapon. This “ballistic cycle” is illustrated in figure 1. The combination of the amount of powder, its burning velocity, size of combustion space, barrel length and projectile weight are the major factors determining the velocity v_0 (muzzle velocity) of the projectile (bullet) when it exits the muzzle of the barrel.

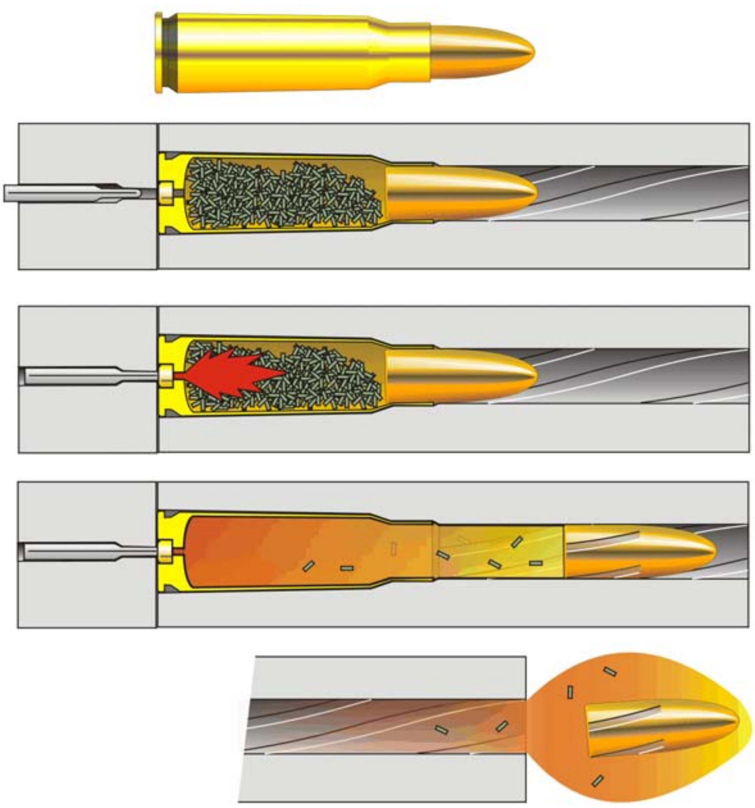

Figure 1: The ballistic cycle of firing a cartridge. From the top: A cartridge, loaded in the cartridge chamber, firing pin strikes the primer which ignites the powder, hot powder gases push the bullet down the barrel, bullet exits the barrel with pressurised gas, unburned powder and a typical yaw of some degrees.

Firearms have traditionally been divided into the categories of handguns, rifles and shotguns and their bullets respectively into low and high energy projectiles. Even if this division could decades ago be somehow justified it today has little to do with reality. The division between handguns and rifles and their separate ammunition types has long been obscure. Originally handgun calibres like .357 Magnum and .44 Magnum have been used in rifles not to speak about the legendary .44-40 of the "Old West". The German Mauser M1898 [Smith 1994], the Russian Stechkin [Zhuk 1992, Bolotin 1995] and the Chinese Type 80 [Hogg 1995] pistols can be seen as paving the way for the new PDW (Personal Defence Weapon) class. The recent advent of PDW weapons like FN P70 submachine gun and its handgun counterpart the FN "FiveSeven" shooting the same 5.7x28 mm cartridge [Celens et al. 1996, Sanow 2001] and their competitor Heckler & Koch PDW in calibre 4.5x30 mm [Crane 2004] has made the categorisation totally obsolete. Their bullets have muzzle velocities ranging from about 500 to over 700 m/s depending on the weapon.

A shotgun is not any longer a device for launching a handful of round pellets. Especially from law enforcement perspective it is a multi-purpose launcher [Jussila 2003]. It is capable of firing not only pellets but solid projectiles ("slugs"), sabotted bullets, tear gas, kinetic impact projectiles that act as remote batons, breaching ammunition for forcing an entry and so forth.

Figure 2 shows some principal bullet types. A bullet may be made of a single material like lead or copper alloy. They could also have a lead or steel core completely or partially enclosed by a jacket typically made of copper alloy called tombak. A bullet's design depends on its purpose. A bullet can be constructed for maximum penetration (armour piercing), expansion or even maximum injury. A bullet can be made to expand by using a cavity in the tip (hollow point). It can also be designed to fragment through the use of structural weakness. The injury potential of a bullet cannot, however, be determined by its looks. Even if a bullet has an exposed lead tip it may not expand in soft tissue. According to the laws of physics its behaviour is the function of its mass, velocity and structural strength and depends on the resistance it encounters.

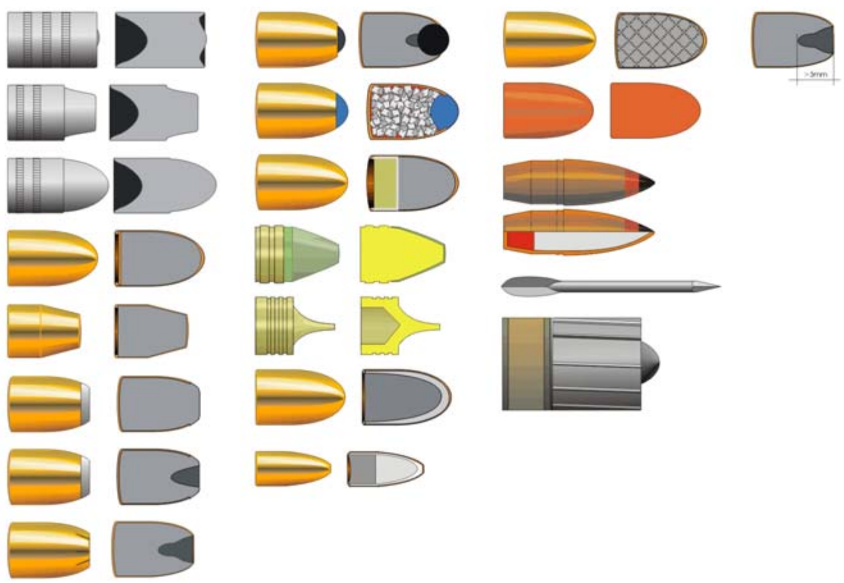

Figure 2 Bullets have been designed for both handguns, rifles and shotguns in all imaginable solid lead, jacketed, hollow point, armour piercing, tracer, prefragmented and incendiary configurations.

The calibre (diameter) of the weapon barrel sets only the upper limit to the diameter of the projectile. Virtually any smaller diameter bullet can be shot if a plastic sabot is used. With a similar powder charge the sabot method may give a light sub calibre projectile a far higher velocity than the heavier nominal calibre bullet would have.

One cartridge may also contain several independent projectiles. The most common type is a shotshell. Other examples are multibullet and flechette cartridges. See figure 3. The same general ballistic principles apply to single and multi projectile ammunition.

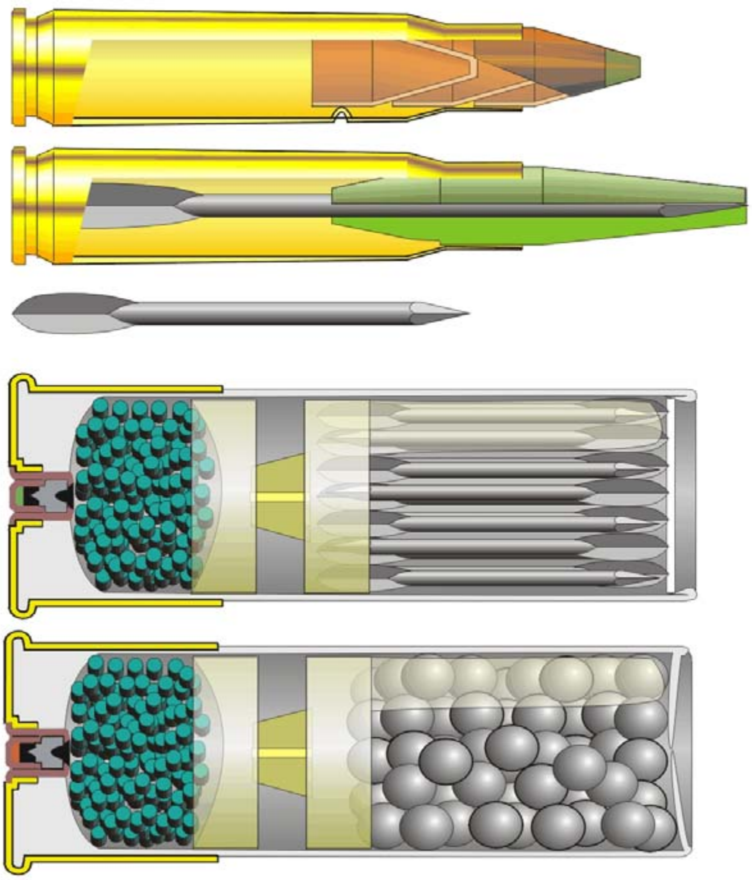

Figure 3: Multibullet, rifle flechette, shotgun flechette and shotshell cartridges

Since almost any bullet can be made to perform in a variety of ways and be launched from a variety of weapons it is even more important that a surgeon treating the wound concentrates on the wound and does not speculate on the weapon. Even in civilian environment, information on the weapon and ammunition used may not be readily available.

Bullets are often categorised with descriptive attributes like military, civilian, police, high velocity and low velocity. Seen from the perspective of ballistics these categories mean very little and can lead to false conclusions and generalisations. There are only mechanical attributes of the bullet interacting with those of the atmosphere and the target. Certain attributes make a certain ammunition type acceptable for police use but conclusions and generalisations about the properties of ammunition because they are in police or military use would be utterly false.

Ballistics is the study of the motion, behaviour and effects of projectiles. It can be divided [Moss et al. 1995] into internal, intermediate, external and terminal ballistics. Terminal ballistics can be further divided into material and wound ballistics dealing with projectile interaction with inanimate (material) and animate targets respectively.

4.1.2 Internal ballistics

Internal ballistics studies the events inside the weapon when the primer is detonated igniting the propellant. From the wound ballistic aspect it is relevant to know the internal ballistic factors affecting the bullet velocity.

Every powder type has its characteristic burning velocity. Burning is actually controlled explosion since no external oxygen is required. It obeys Piobert's law [Moss et al. 1995], which states that the surface of a powder granule is burned away before the layer beneath it is ignited. This allows the control of the burning velocity and pressure build-up by using either decreasing, constant or increasing surface area of the powder granule (degressive, neutral and progressive powders [Moss et al. 1995, Vihtavuori 2000]. In addition, special coating of granules may be used [Vihtavuori 2000]. The burning velocity is often reduced in subzero temperatures [Jussila 2001b and c, Vihtavuori 2000].

From the wound ballistic and tactical point of view it is important that the powder and primer are as insensitive to external temperature as possible and thus contribute to consistent performance.

A combination of the amount of powder, its burning velocity, burning volume and bullet resistance in the barrel give a pressure curve depicting how fast and how high the pressure builds up and how fast it subsides. An ideal powder charge burns almost completely before the bullet exits the muzzle. Shortening the barrel will reduce the v_0 when the same cartridge is used. Reducing the powder charge will naturally do that too. Figure 4 shows an example of the relationship between pressure, barrel length and bullet velocity.

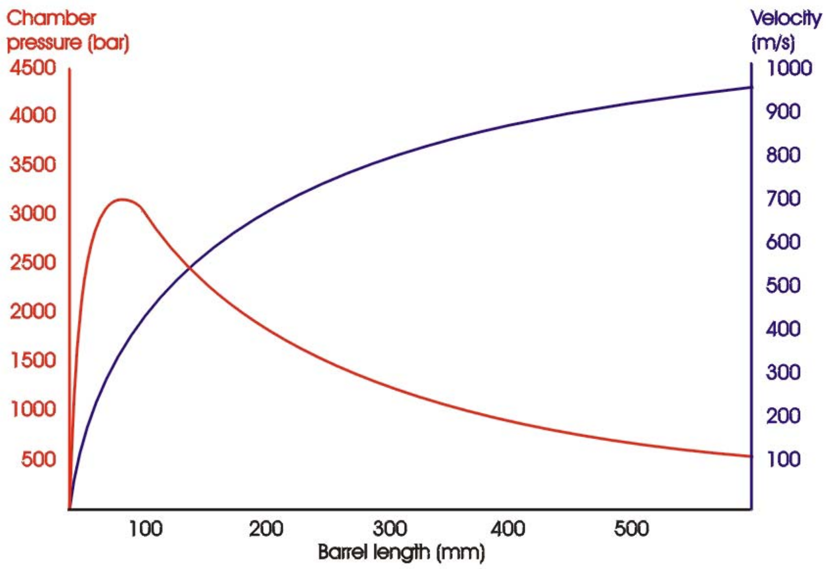

Figure 4: An example of the relationship between chamber pressure, barrel length and bullet velocity of a 5.56x45 mm cartridge calculated using Broemel QuickLoad software.

When the pressure increases sufficiently high, it pushes the bullet into the barrel. The forces involved cause radial expansion and torsional twist of the barrel as the bullet is forced into the helical rifling. This and the advancing pressure wave in the barrel metal will make the barrel oscillate [Rinker 1998].

4.1.3 Intermediate ballistics

Intermediate ballistics examines the events that take place when the bullet exits the muzzle in transition from internal to external ballistics [Moss et al. 1995]. The high pressure gases behind the bullet cause turbulence which will to an extent disturb the stability of the bullet [Moss et al. 1995]. Due to small differences in the powder charge and its burning a bullet may exit the barrel at different phases of the oscillation. This will have a deteriorating effect on the accuracy of the bullet the amount of which depends on the oscillation characteristics [Rinker 1998]. Barrel oscillation may also increase the initial yaw of the bullet.

The angle between the longitudinal axis of the bullet and the trajectory, the yaw, can be up to 6 degrees or with a 7.62 x 39 mm assault rifle bullet about 4 degrees during the first few metres of flight [Tikka 1996]. The stability is regained in most cases due to the stabilisation mechanism described later. A good treatise on the statistical properties of yawing has been presented by Sebourn and Peters [1996]. According to their mathematical model and experimental data on a 5.56x45 mm M193 bullet shot with a barrel of 12 inch twist of rifling, the initial yaw of about 4 degrees is reduced to about 1.5 degrees at 25 m and starts increasing at about 400 m being 17 degrees at 800 m.

4.1.4 External ballistics

External ballistics studies the phenomena of the bullet in flight. The bullet is subjected to aerodynamic forces that combined with its construction, internal ballistics and intermediate ballistics may cause yawing, tumbling, precession and nutation of the bullet [Tikka 1989, Sellier and Kneubuehl 1994, Rinker 1998].

A bullet will not fly accurately and straight unless it is stabilised because of minor symmetric flaws in the bullet material [Rinker 1998] or centre of gravity being behind the centre of pressure as is usually the case with aerodynamically efficient forms. There are two principal stabilisation mechanisms: drag and spin. Drag stabilisation is done by means of a tail cone, tail fins or a drag tail causing increased drag in the rear and thus keeping the projectile straight [Moss et al. 1995]. Spin stabilisation means giving the projectile rapid rotation around its longitudinal axis [Greener 1910, Moss et al. 1995]. This is done either by using a rifled barrel or angled tail fins on the projectile. Spin makes even a tail heavy projectile fly straight provided that the rotation speed is high enough. With too little spin the projectile will start tumbling in mid air and may hit the target at any angle with unpredictable wound ballistic results. To estimate the minimum rifling twist required to stabilise a given projectile the Greenhill equation [Rinker 1998, Hatcher 1966, Kolbe 2000 refers to "Textbook of Small Arms", The Holland Press, 1929] is often used because it gives reasonable approximations of the required twist and is very simple to use.

[1] T = 150 / L

, where T is the length of full twist in calibres and L is the length of the projectile in calibres. Eq. 1 when expressed in SI-units transforms into:

[1a] $\boldsymbol{lrt = 150 * K^2 / l}$

, where *lrt* is the length of one full twist of rifling (mm), *K* is calibre (mm) and *l* length of the projectile (mm).

As said, Eq. 1 is only convenient to be used as an approximation. The gyroscopic stability of a bullet depends on its shape and weight distribution, density of the penetrated substance (usually air) and spin rate induced by the bullet velocity and rifling twist. The stability coefficient is expressed [Moss et al. 1995, Moss 1997] as

[2]
$$s_g = \frac{8A^2 p^2}{B\,\rho\, V^2 \pi\, d^2\, C_{m\alpha}}$$

, where ρ is the density of air and A the axial (longitudinal) moment of inertia, p the spin rate, B the transversal moment of inertia, V the velocity, d the diameter and $C_{m\acute{\alpha}}$ the coefficient of yawing moment of the bullet. Eq. 2 is used in the design of bullets [de Veth 1982]. A bullet is stable if $s_g \geq 1$. Actual design values are, however, closer to $s_g = 2$ [Rinker 1998, Kolbe 2000].

According to ICAO-defined standard atmosphere [Kolbe 2000, Moss et al. 1995] air density at sea level is 1.225 kg/m^3 (0.001225 g/cm^3) and density of muscle tissue 1060 g/cm^3 [Sellier and Kneubuehl 1994], Eq. 2 reveals that the spin rate required to maintain stability in muscle tissue would have to be some 860 000 times faster than in the flight through air. As this is not possible the bullets will in most cases rapidly lose their stability after entering the tissue and start tumbling [Janzon 1997].

Eq. 2 is problematic to use since the axial and transversal moments are ordinarily not published by ammunition manufacturers and would have to be measured using for example a torsional pendulum [Kolbe 2000].

Too much spin will result in an overstabilised projectile. It will resist any change in the trajectory and fly eventually at a marked yaw angle since the longitudinal axis of the bullet will not follow the trajectory but will maintain its original angle of elevation. This will result in increased drag and shorter range. The effects of stabilisation are illustrated in figures 5 and 6 [Moss et al. 1995].

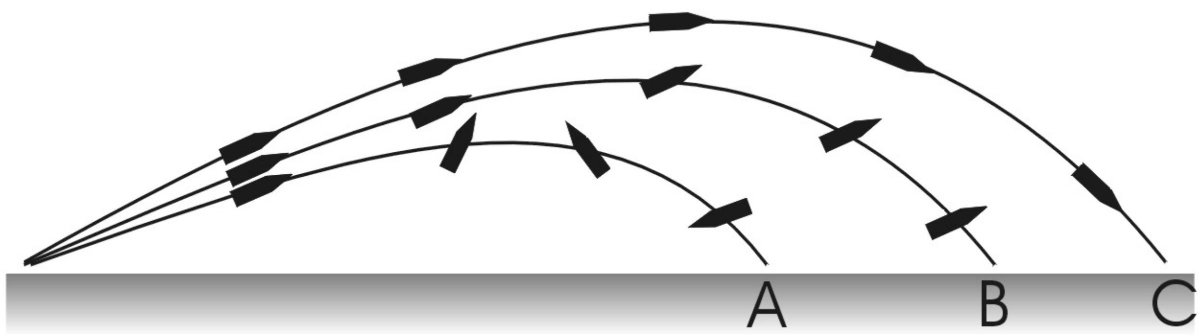

Figure 5: The bullet behaves in different ways depending on the degree of stability. A – unstable, B – overstable, C –neutral.

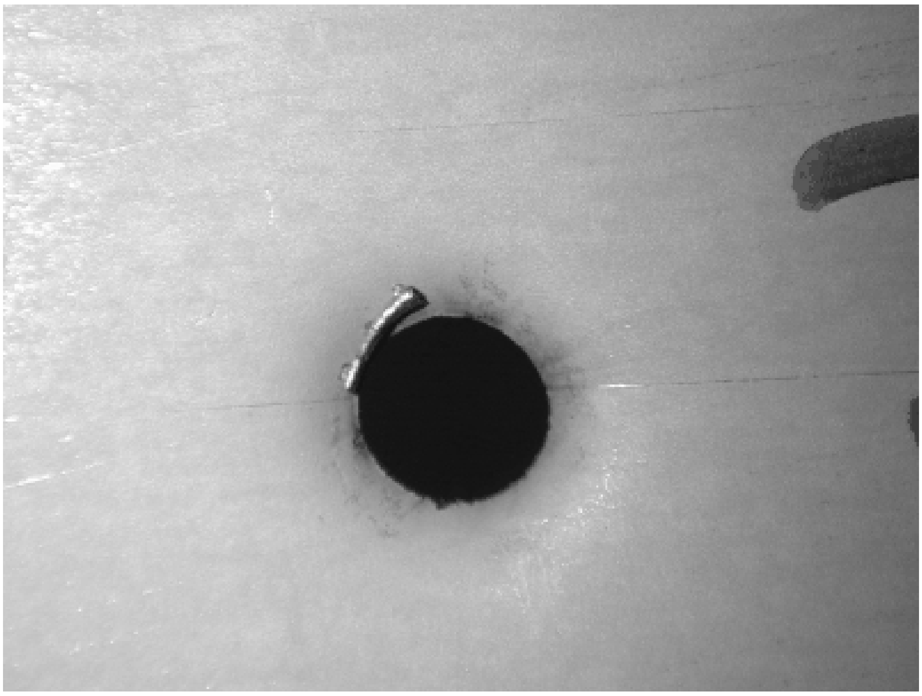

Figure 6: A 3.6 g 5.56 mm bullet shot with a Colt M4 Commando at 10 m into a 0.5 mm steel plate. The rifle had a 290 mm barrel and 7 inch rifling twist. Very little bullet yaw could be measured.

At the very moment when the bullet leaves the barrel gravity starts to pull it downwards. The faster the bullet and the better it retains its velocity the farther it will fly before hitting the ground. The trajectory of the bullet will therefore be curved and depends on the angle of the weapon, bullet mass, velocity, diameter, length and form. A form factor number (*Fform*) is used to describe the bullet form [Hatcher 1966, Rinker 1998, Kneubuehl 1999]. The trajectory also depends on the prevailing external atmospheric conditions of temperature, air pressure, humidity and the velocity and direction of the wind [Rinker 1998, Hatcher 1966, Kolbe 2000]. The bullet's aerodynamic efficiency i.e. capability to overcome the air resistance and retain its velocity is usually described with ballistic coefficient *Cb*. The higher the *Cb*, the better the velocity is retained [Rinker 1998].

Increasing the elevation (angle) of the weapon will increase the maximum range of a bullet up to a point. Calculation with Broemel QuickTARGET exterior ballistic software gives a 7.62x51 mm calibre rifle bullet fired at an optimum angle a maximum range of 3 to 4 kilometres depending on bullet whereas the usual shooting distances in law enforcement are 100-200 metres. It is difficult even for an experienced shooter to estimate the trajectory at very long distances. A critical situation with heightened stress and maybe fear of life makes this task much more difficult [Jussila 1997].

Tactical range has been defined [Jussila 2001c] as the maximum range within which the bullet's trajectory deviates no more than an arbitrary distance of ±2.5 mm from the line of sight when the weapon has been optimally zeroed to give the maximum tactical range i.e. to describe the range a shooter can expect a bullet to hit at or very close to the point of aim. The tactical range of a 9x19 mm calibre service pistol is not defined by the external ballistic characteristics of the bullet but the shooter's ability to accurately hit under stress. A pistol is a difficult weapon to master [Bruchey and Frank 1983] and its tactical range can therefore be considered to be limited to 10 – 15 m. The above Broemel-software gives tactical ranges for a 9x19 mm submachine gun and a 5.56x45 mm rifle as 65 and 120 m respectively. Beyond those ranges the shooter must aim higher to compensate for the trajectory curvature, which could be very difficult.

A "flat shooting" bullet is therefore desirable. As it means increase in velocity and increase in kinetic energy of the bullet, it often also means increased potential for injury. Finding an appropriate balance is one of the tasks when evaluating law enforcement service ammunition candidates.

Crosswind pushes the bullet aside and either up or down depending on the direction of the wind and the spin of the bullet [Rinker 1998]. Crosswind increases the difficulty of accurate shooting. It pushes the bullet aside and either up or down depending on the direction of the wind and the spin of the bullet [Rinker 1998]. Moreover the wind is rarely constant and may vary throughout the trajectory making the estimation of its effects on the bullet rather difficult in an actual situation. The susceptibility of a bullet to crosswind can, for comparison purposes, be estimated using an arbitrary of, for example, 3 m/s transversally to the bullet trajectory.

A weapon and its ammunition form a system. The combination of weapon properties, internal ballistics, intermediate ballistics and external ballistics will determine the inherent accuracy of this system. It depends on the shooter how fully he or she can utilize the accuracy potential. The inherent accuracy is an important part of injury potential. Inherent accuracy only does not describe the tactical accuracy. The effect of crosswind must be taken into account [Huffman 2000]. Huffman proposes calculating a resultant of wind drift and inherent accuracy for any given range as

[3] $$rta = \sqrt{rwind^2 + ria^2}$$

, where *rta* is resultant of tactical accuracy, *rwind* is the amount of wind drift and *ria* the radius of inherent accuracy. The *ria* can be defined as the mean dispersion radius of shots.

It is not immediately obvious that the bullet with the best inherent accuracy will also have the best tactical accuracy. Poor accuracy increases the danger of injury to bystanders and the police official through increased possibility of bullets completely missing the target and thus prolonging the dangerous situation.

4.1.5 Terminal ballistics

Terminal ballistics is the science of projectile behaviour in the target and **wound ballistics** the part of terminal ballistics dealing with what happens when a bullet strikes a living being. It is characterised by very rapid events, high pressures and great deformation rates [Tikka 1989]. A bullet must have a significant amount of kinetic energy to reach the target, penetrate into it and perform its task. The task for law enforcement is not to kill or even to injure but to stop an offender from continuing to pose an imminent grave danger to the health and life of others. Unfortunately, however, the outcome will often be a serious injury or death of the offender. This fact, however, must not stop us from trying to avoid superfluous and unnecessary injury in the spirit of the International Law and Human Rights.

A bullet impacting the target has an impact mass of *mi* (g) and velocity *vi* (m/s). Its kinetic energy *Ei* (J) is defined as

[4] $$Ei = 0.5 * mi * vi^2 / 1000$$

Impact energy *Ei* is partially dissipated into the target and performs work upon it. From Eq. 4 we can see that both the bullet mass but more significantly its velocity determines the amount of kinetic energy. If the energy is not dissipated into the target, it is used somewhere else. The wound ballistic energy equation can be expressed as:

[5] $$Er = Ei - Edef - Ed$$

, where *Er* is the residual kinetic energy, *Ei* the impact energy, *Edef* the energy used by bullet deformation and *Ed* the energy dissipated into the target tissue. Since *Ei* has to be significant, *Edef* and *Ed* must be maximised in order to minimise *Er*. The residual energy is a significant factor describing the danger to bystanders when the bullet completely penetrates and exits the primary target continuing its flight. The factor of *Edef* has often been overlooked in the literature [Tikka 1989, Pirlot et al. 2001]. Pirlot also uses the term deformation energy in conjunction with deformation of tissue simulant.

Kinetic energy dissipation (*Ed*) can be increased by bullet instability, deformation and fragmentation. When a rigid tail-heavy bullet hits the target it tends to start tumbling because the rate of spin is insufficient to maintain stability in dense medium like tissue. This increases the cross-sectional area in the direction of penetration which increases the dissipation of kinetic energy. The process is, however, somewhat out of control. The precise depth at which tumbling occurs is difficult to predict as it depends on the yaw angle on impact, properties of the tissue encountered and internal instabilities of the bullet [Peters et al. 1996].

Controlled deformation can in principle be achieved by a cavity in the tip of the bullet. Figure 7 shows some typical expanding bullet constructions. Changing the tip of the bullet changes its aerodynamic form factor [Rinker 1998, Hatcher 1966], possibly reducing the ballistic coefficient *Cb* and shortening the tactical range. Upon impact these bullets start expanding at the tip. This makes the cross-sectional area larger and increases *Ed*. It will also shift the centre of gravity of the penetrating bullet closer to the tip making a long bullet in theory more stable in penetration. The dimensions and surface angles of the cavity together with the bullet materials and construction determine the rate and type of expansion.

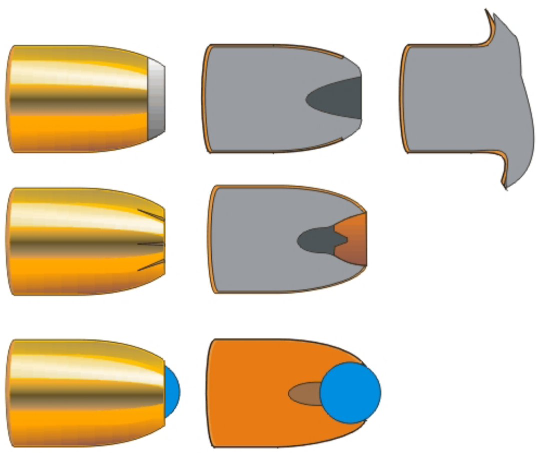

Figure 7: Constructions of controllably deforming bullets. From top: conventional hollow point, hollow point with jacket chemically or mechanically bonded to core to prevent separation, expansion valve with a wedge or ball forcing the bullet to expand on impact. The valve construction is used especially with solid copper alloy monobloc bullets.

Bullet fragmentation can be controlled by jacket thickness, making prefragmentation incisions in the jacket and by varying the strength of bonding between the bullet core and jacket.

4.2 The International Law

Restrictions on the use of force by the state officials are not new. The ancient Hindu customary law, the "Gentoo Code", translated in 1776 into English states:
"*The magistrate shall not make war with any deceitful machine, or with poisoned weapons, or with cannons or guns, or any kind of fire-arms, nor shall he slay in war any person born an eunuch, nor any person who, putting his arms together, supplicates for quarter, nor any person who has no means of escape.*" [Greener 1910]

A number of attempts have been made in the past 150 years to define what is considered acceptable for firearms and their effects. The documents can be divided into the military (war) and law enforcement (policing) regimes, usually without universal applicability.

> *The St. Petersburg declaration* (1868) renounced all projectiles under 400 g for infantry rifles filled with explosive or incendiary compounds.
>
> *The Conference of Brussels (*1874): article 13 prohibited 'the employment of arms, projectiles or material calculated to cause unnecessary suffering…'

The Hague Convention (1899) stated that: ‘The contracting parties agree to abstain from the use of bullets which expand or flatten easily in the human body, such as bullets with a hard envelope which does not entirely cover the core or is pierced with incisions’.

The Hague Convention Respecting Laws and Customs of War on Land (1907) prohibited employment ‘of arms, projectiles or materials calculated to cause unnecessary suffering’ (article 23). This wording was a translation from the original French text and was later corrected to ‘..of a nature to cause..’ (Geneva Protocol I, 1977, article 35, paragraph 2, see below).

United Nations Universal Declaration of Human Rights 1948 declares that ‘everyone has the right to life, liberty and security of person’ (article 3), and that ‘no one shall be subjected to torture or to cruel, inhuman or degrading treatment or punishment’ (article 5).

The same principles are repeated in articles 2 and 3 of the *Council of Europe Convention for the Protection of Human Rights and Fundamental Freedoms* (Rome 1950).

The Protocol Additional to the UN Conventions of 12 August 1949, relating to T*he Protection of Victims of International Armed Conflicts (Protocol I), 8 June 1977, (Article 36)* obliges nations to arrange for a method to determine whether any new weapon, means or method of warfare would be prohibited by international law.

The UN Code of Conduct for Law Enforcement Officials (*1979*) defines standards for law enforcement practice that are consistent with basic human rights (p.273). Article 3 states that: ‘the use of firearms is considered an extreme measure. Every effort should be made to exclude the use of firearms, especially against children. In general, firearms should not be used except when a suspected offender offers armed resistance or otherwise jeopardises the lives of others and less extreme measures are not sufficient to restrain or apprehend the suspected offender’.

The UN Resolution on Small-Calibre Weapon Systems (Geneva, 1979) recognises that bullet expansion is not the only factor increasing the extent of injury and that rapid advance in weapons technology requires further research and standardised assessment methodology.

The UN Convention on Prohibitions or Restrictions on the Use of Certain Conventional Weapons Which May Be Deemed to be Excessively Injurious or to Have Indiscriminate Effects (The Inhumane Weapons Convention, [IWC] Geneva 1980, prohibits the use of weapons and ammunition ‘of a nature to cause superfluous injury or unnecessary suffering’.

Paragraph 2 of the UN *Basic Principles on the Use of Force and Firearms by Law Enforcement Official* (Geneva 1990) states that:

> Governments and law enforcement agencies should develop a range of means as broad as possible and equip law enforcement officials with various types of weapons and ammunition that would allow for a differentiated use of force and firearms. These should include the development of non-lethal incapacitating weapons for use in appropriate situations, with a view to increasingly restraining the application of means capable of causing death or injury to persons. For the same purpose, it should also be possible for law enforcement officials to be equipped with self-defensive equipment such as shields, helmets, bullet-proof vests and bullet-proof means of transportation, in order to decrease the need to use weapons of any kind.
>
> Article 8 (paragraph 2(b) subsection xix) of the *Rome Statute of the International Criminal Court* (1999), repeats the by now 100-year old statement of the 1899 Hague Convention (above) declaring the use of expanding bullets as a war crime.

As explained in the introduction the problem with the International Law, as to law enforcement weaponry, is that most of the relevant "hard law" applies to military conflicts and military weapons. The second major problem is that there is no international agreement on what can be considered as superfluous injury and how it should be measured.

The Swiss delegation to the *Expert Meeting of the International Committee of the Red Cross* presented a *Draft Protocol on Small Calibre Weapon Systems* (1994*)*. Recognising that not only bullet expansion but also other factors cause tissue injury, it proposes a limit for the amount of kinetic energy that is released. It suggests prohibiting the use of 'arms and ammunition with a calibre of less than 12.7 millimetres which from a firing distance of at least 25 meters release more than 20 joules of energy per centimetre during the first 15 centimetres of their trajectory within the human body'.

4.3 Penetrating projectile induced injury

4.3.1 Soft tissue injury

Significant amount of work has been done in the military domain to better understand the wound ballistic phenomena associated with a bullet penetrating a human body. The rapid progress in electronics and in measurement accuracy of instrumentation has, however, cast a shadow over the validity of some old research results [Wilson 1921, Callender and French 1935, Callender 1943, deMuth 1966, deMuth and Smith 1966, deMuth 1974].

As a projectile begins to penetrate tissue the retarding force of the tissue causes it to decelerate and lose kinetic energy [Peters 1990]. A penetrating bullet causes crushing, laceration, stretching and contusion of the tissue in the front and around it. The entrance wound is not necessarily very large as the impacting bullet is still undeformed and stable. Once entering the subcutaneous tissue the bullet induced pressure creates a temporary cavity first discovered by Woodruff [1898]. It was also found to pulsate [Berlin et al. 1976]. The pressure will rapidly accelerate and stretch tissues radially up to and beyond their breaking point until arrested by the elastic strength of the tissue. Having reached its maximum dimensions the temporary cavity collapses due to tissue elasticity and re-expands in gradually subsiding pulsations [Janzon 1983, Tikka 1989]. The maximum expansion of the cavity has been reported [Yoganandan and Pintar 1997] to occur in tissue simulant after the exit of the projectile.

The cavitation resembles that of supercavitation [Savchenko 2001]. A blunt bullet nose detaches the target tissue from the projectile sides reducing both drag and friction that slow down the bullet spin. Supercavitation can be expected to both maintain bullet stability and increase its soft tissue penetration [Jones et al. 1998]. This was experimentally observed when the former Swedish police 9x19 mm flat nosed full metal jacketed Norma service bullet weighing 8 g was compared with a conventional round nosed full metal jacketed 9 mm bullet also weighing 8 g. The gelatine penetrations were over 120 cm and approximately 90 cm, respectively [Jussila 2001, unpublished data].

The powerful suction caused by cavitation draws fragments of skin and clothing and also dirt and other foreign matter through the entry and exit wounds into the wound channel making it vulnerable to bacterial infection [Dziemian and Herget 1950, Dahlgren et al. 1979, Bowyer et al. 1996]. When the pulsations of the temporary cavity subside the tissue is left with a permanent cavity.

During penetration the bullet may lose its stability and start tumbling. It may also deform or be designed to expand controllably. Peters developed a mathematical model [Peters 1990] to predict the tumbling of a non-deforming bullet. A deforming bullet, however, will change its form and thus its centre of gravity during penetration making the model non-applicable as such. The forces acting upon the bullet may also tear it apart into fragments of various sizes. The penetration behaviour depends on the bullet's construction and on the retardation force it encounters. All these events make the bullet to present an increased cross-sectional area towards the penetration axis and thus transfer more of its kinetic energy into the tissue. The portion of the total kinetic energy that is transferred into tissue depends not on impact velocity or mass of the bullet *per se*, but on how the bullet behaves during penetration, whether it tumbles, deforms or fragments and what the tissue induced retardation force is. These phenomena make the bullet present a larger cross-sectional area in the direction of penetration thus increasing the drag and dissipation of kinetic energy [Sellier and Kneubuehl 1994, Tikka 1996].

The theory of Martel [Kneubuehl 1999] says

[6] $$Ed = Cv*V$$

, where Cv is a constant depending on the properties of the target material and V the volume of the ensuing hole. Therefore the size of the inflicted area is directly proportional to the dissipated energy Ed. Based on an analysis of a number of experiments with live pigs a significant correlation between the amount of devitalised tissue and dissipated kinetic energy (Ed) has been proved [Berlin et al. 1976 and 1979, Janzon and Seeman 1985, Janzon 1988, Tikka 1989, Janzon 2004]. Ed has also been called "down-track" energy [Coupland 2000].

No regression function has, however, been proposed. Tissue devitalisation also seems to depend on the size of the target being smaller in limbs of smaller size [Janzon et al. 1988 and 1997] resulting in scale dependence. A comprehensive scaling analysis of the wounding process was done by Janzon [1983].

The most critical opponent of the “kinetic energy deposit” proportionality to tissue devitalisation is Martin Fackler [Fackler 1987]. The core of Fackler’s reasoning is that too much tissue is excised by the surgeons. This line of thinking does not seem to have gained undivided acceptance and is countered by saying that unless devitalised tissue is removed a severe anaerobic infection will result with heightened probability of *perfringens* (gas gangrene) jeopardising the life of the patient [Janzon personal communication 2004].

The relationship between temporary cavity size and tissue devitalisation (cell death) has not been established [Coupland 2000]. The severity of the effects is largely dependent on the location of the wound [Fackler et al. 1988]. Cavitation is caused by pressure setting the tissue into motion. The peak internal pressure [Eisler et al. 1996] does not seem to correlate with the amount of devitalised tissue. This suggests that the devitalisation of soft tissue not in direct contact with the penetrating bullet is caused by the pressure wave induced rapid acceleration and compression that crush the cell structures [Sondén et al 2000]. Temporary cavitation could rupture blood vessels, intestines or air filled cavities [Janzon 1997]. It can be compared to blunt trauma and its effects could be quantified [EuroNCAP 2001, Bir and Viano 1999, Bir 2000]. A mathematical model for predicting tissue damage has been presented [Peters 1990], however, without a definition of what is meant by “damage”.

Different organs show different tolerance to penetrating wounds. Lungs have a low specific weight, 0.4-0.5, and are very flexible. They provide little resistance to the bullet which as a result dissipates little energy. Temporary cavitation and the resulting injury are limited (Janzon 1997, Ryan et al. 1997). DeMuth (1966) reports that there is a marked difference between penetrating and tangential hits with the latter causing greater lung injury. Temporary cavitation in liver causes serious tearing as the organ is rather fragile. The breaking stresses of swine heart, spleen and liver have been measured as 14.1, 8.1 and 4.6 kp/cm^2 [Seki and Iwamoto 1998].

The exiting bullet makes an exit wound which is usually larger than the entry wound as the bullet has already deformed or may be in an unstable state exiting base or side first. The result will in many cases be a star like rupture [Janzon 1983, Janzon 1997]. Although the size of the exit wound is included in the Red Cross wound classification [Coupland 1993 and 2000] and a large exit wound should be considered a warning sign of extensive internal tissue destruction [Janzon 1997] its effects are not totally negative. First of all the existence of an exit wound allows access to the wound channel from both ends and signifies that at least most of the projectile has exited from the wound. In uncomplicated muscle wounds it also increases wound drainage which assists in healing [Hampton 1961, Dziemian et al. 1961, Fackler et al. 1989, Hollerman et al. 1990].

4.3.2 Fragmentation

Disintegration of the bullet during penetration leaves metallic and depending on bullet construction also non-metallic fragments in the wound. An illustration of fragmentation is shown in figure 8. An example of 5.56 mm bullet fragments recovered from a block of gelatine is shown in figure 9.

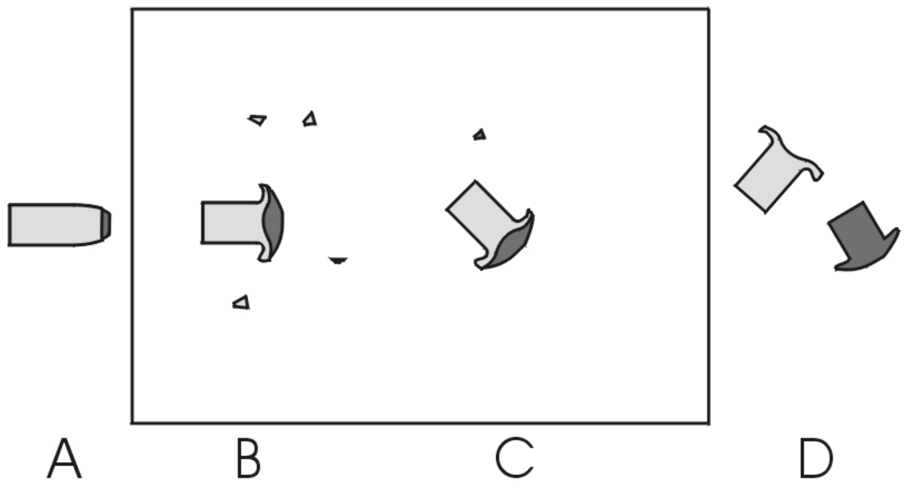

Figure 8: Fragmentation nomenclature. A – bullet before impact, B – deformation after impact with varying degree of fragmentation. C – bullet main continues penetration and starts tumbling. D – Bullet main exits with core and jacket possibly separating. Core-jacket separation could also take place inside the simulant.

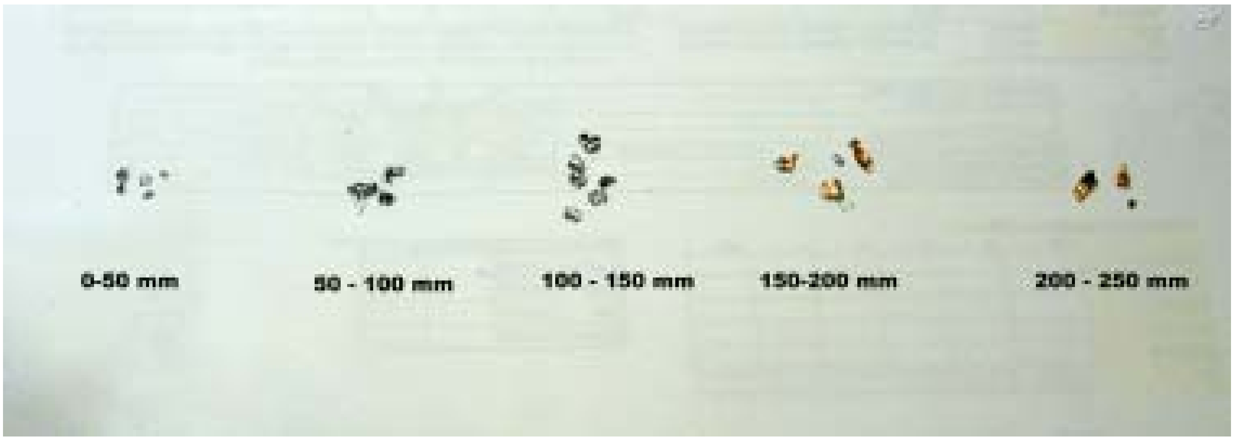

Figure 9: An example of bullet fragment dispersion at different depths in gelatine

Fragments could also be located relatively far from the permanent wound channel (Figure 10). These fragments increase the injury in several ways [Fackler et al. 1984, Bowyer et al. 1997, Leppäniemi personal communication 2004].

- they act as a nidus for infection. A fragment which penetrated the colon may cause severe infection in or outside the peritoneal cavity
- they may erode into blood circulation and cause embolism [Mattox et al. 1979,Braun 2003, Corbett et al. 2003]
- they may release metallic ions causing systemic upset. If the bullet contains lead, fragmentation increases blood lead concentration [McQuirter et al. 2004].
- they increase the surface area of the wound
- they may be located in such a place that they cannot be removed although the danger of longer term damage is possible (brain, spinal cord, heart etc.)

Figure 10: An example of the wound channel of an expanding 5.56 mm bullet in 10% gelatine as seen from the direction of the gun. A fragment has penetrated transversally about 50 mm from the bullet path.

A ricochet fragment can also cause serious injuries. These fragments can be compared to artillery fragments. If the impact velocity of a 5.56x45 mm bullet is 900 m/s and the velocity of a 0.1 g ricochet fragment is 600 m/s (arbitrary estimate), its velocity at 10 m distance may still be about 300 m/s according to the fragment deceleration table [Vähäkangas 1996].

4.3.3 Skin injury

Skin is very resistant to ballistic injury. It may tear, but usually very little devitalised skin needs to be removed [Janzon 1997]. In order to establish the threshold velocity required for penetrating the human skin quite a lot of research has been done. Some researchers have removed the skin from human cadavers and tested it in isolation [Grundfest et al. 1945, Sperrazza and Kokinakis 1968]. Considering the importance of skin as a part of an energy absorbing system these studies can hardly be used. Furthermore, the penetration process of skin pinned against a solid background is based primarily on crushing. Thus tests performed with skin samples alone leave room for doubt as the penetration may be too much based on the effect of either crushing or tensile stress caused by stretching instead of their combination.

The first one to investigate the penetrability of human skin was Journée in 1907 (in [DiMaio 1981] and [Sellier and Kneubuehl 1994]). Journée reported that a lead sphere, 11.25 mm in diameter and weighing 8,5 g at vi = 60 m/s produced superficial skin damage without penetration and that at 70 m/s perforated the skin and penetrated several centimetres into the underlying tissue. There is, however, no record on the location of the test shots on the cadaver and the precision of measured vi values could also be speculated.

Mattoo [1984] reported shooting lead spheres of 9,14 mm diameter (000 buckshot) weighing 4,5 g into the thigh section of human cadavers. The threshold velocity, vth, required for penetration was 65 m/s.

Tausch et al. [1978] conducted extensive experiments shooting 4 mm, 9 mm and .45 lead spheres and bullets into upper thighs of human cadavers to find out *vth*. A total of 212 test shots were fired. Tausch reported incorrect weights for lead spheres. Calculating for example 9 mm sphere volume and multiplying it with the density of ”lead” bullet alloy of 11,2 g/cm^3 gives 4.28 g instead of reported 5.3 g. It should also be noted that so called lead bullet is not pure lead (density 11.3 g/cm^3) but typically contains for example 2% tin and 6% antimony. The threshold velocities for the 4 mm, 9 mm and .45 lead spheres were 68.7, 68.7 and 56.7 m/s, respectively.

DiMaio et al. [1982] shot 4,5 mm and .22 calibre air gun diabolo pellets and .38 calibre round nose lead bullets into lower extremities of human cadavers. DiMaio gives the following *vth* values: *vth* (*k* = 4,5 mm) = 101 m/s, *vth* (*k* =.22 inches) = 75 m/s and *vth* (*k* =.38 inches) = 58 m/s.

Missliwetz [1987] made an extensive (2514 shots) and thorough study on the subject. He shot various 4 and 4,5 mm air gun pellets into thigh and back of human cadavers consisting of 40 adults and 10 children. Recognising the problem of what can be considered as penetration he defined *vst* for bullets that got stuck in the skin and *vth* for those that completely penetrated the skin. The average *vst* for a 4,5 mm projectile in adult human thigh skin was 99 to 130 m/s depending on projectile type whereas average *vth* was 109 to 136 m/s.

Several researchers have deduced that skin penetrability is dependent primarily on the sectional density *S* of the projectile (*S* = mass divided by cross sectional area of the bullet in g / cm^2) and given their proposal for threshold velocity equation:

[7] $\boldsymbol{vth} = \mathbf{14.1}/\sqrt{S}$ [Sellier and Kneubuehl 1994, Jauhari and Bandyopadhyay 1976, Jauhari and Mahanta 1978]. The proposed equation uses *S* in g / mm^2. Making it commensurate with the other equations for g / cm^2 gives:

[7a] $\boldsymbol{vth} = \mathbf{14.1}/\sqrt{(S/100)}$

[8] $\boldsymbol{vth} = K\frac{A}{M} + \mathbf{b}$ [Sperrazza and Kokinakis 1968] , where K for human skin is 125, A is cross-sectional area in cm^2, M bullet mass (g) and b a constant of 22.

[9] $\boldsymbol{vth} = \sqrt{334/S}\ \mathbf{*\ 10}$ [Mattoo 1984]

[10] $\boldsymbol{vth} = \mathbf{277.7 * e}^{\mathbf{-0.482}\sqrt{S}}$ [Tausch et al. 1978]

Several publications report the tensile strength and elongation at break of human skin [Holzmann et al. 1971, Daly 1982, Bader and Bowker 1983, Vogel 1987, Bartell and Mustoe 1989, Sugihara et al. 1991, Edwards and Marks 1995,]. The stretch velocities obtained with mechanical devices are, however, very low compared with those caused by bullets. Despite the fact that skin exhibits a rate dependent resistance when stretched [Edwards and Marks 1995] these reports must be looked into because no reports on high speed stretch have been found. They also give a good estimate on how skin properties vary with location and age. Standard low velocity tests are also useful for estimating materials behaviour in general.

Holzmann et al. [1971] made *in vitro* measurements on skin samples taken from above the sternum. The reported mean thickness was 1.9 mm, tensile strength 1938 g/mm2 = 19.38 MPa and elongation at break 60,6%. At the age of 35 the values seem to be either at or very close to maximum.

Bartell and Mustoe [1989] compared the properties of rat, guinea pig, pig and dog with that of human skin obtained from abdominoplasty surgical specimens and verified its extensibility with *in vivo* extensometer. They found out that the average human skin thickness (dermis and epidermis) ranges from approximately 1 to 4 mm. The modulus of elasticity was 0.136 ± 0.038 psi/%strain, stress / relaxation 66.6 ± 1.8 % and elasticity in vivo 37.2 ± 4.1 %. The precise locations of test samples were not given. The interesting thing, however, is that when measured with above parameters human skin is very close to that of a dog. The skins of rat, guinea pig and pig are not even close. The pig is generally considered as the best experimental animal [Schanz 1979].

Sugihara et al. [1991] has conducted *in vivo* uniaxial tension experiments to find out how skin extensibility varies according to location and age. According to Sugihara the extensibility slightly decreases with age on chest and anterior thigh whereas abdomen skin extensibility does not seem to change significantly. At the defined target person’s age of 30 the chest and thigh skin seem to have similar elongation.

Vogel [1987] conducted an extensive *in vitro* research involving 348 autopsy specimens. Samples were taken from the skin above the sternum. Dumbbell shaped specimens were cut along the same axis. The specimens were 50 mm long and the narrow section was 4 mm wide. At the age of 30 the skin thickness was approximately 1.75 mm, tensile strength 20 MPa and elongation at break 72%.

4.3.4 Bone injury

Bone has greater density, with specific weight of 1.11, and strength than the surrounding tissue. It is also non-elastic. Both a direct hit and cavitation pressure can cause bone injuries [Janzon 1983]. In a direct hit the bullet starts creating temporary cavity upon entering the soft tissue in front of the bone. The cavity extends along the bone with the suction carrying debris and infectious material between the soft tissue and the bone. The bullet will shatter the bone and the pressure will push the bone parts axially outwards. This is probably what Amato et al. [1989] mean when talking about temporary cavity of the bone. The cavitation force will cause a bone like femur to strike hard against the joints. This may cause immediate or delayed injury but no references on the subject have been found.

The shattered bone will start moving radially outwards together with the temporary cavity formed in the surrounding soft tissue [Amato et al. 1989, Ragsdale and Josselson 1988] with some of the fragments returning back nearly to their original position when the cavitation subsides. Some of the fragments will also follow the direction of the bullet, possibly because of suction, because the forward movement has been noticed to take place after the initial expansion of the temporary cavity [Amato et al. 1989].

There has been a debate whether the bone fragments will become secondary projectiles with destructive capability of their own [Amato et al. 1974, Amato et al. 1989, DeMuth and Smith 1966]. Becoming secondary projectiles would require a significant “push” by the pressure caused by the bullet. This might, however, break the bone fragments that would then rapidly lose their injury potential. It therefore seems more likely that the bone fragments are moved into the wound channel by suction and do therefore usually not have any significant destructive force of their own. There are, however, some unreported accounts on bone fragments from the thigh bone having penetrated into the abdomen and even to the thorax and lungs [Janzon personal communication 2004].

Figures 11 and 12 show a synthetic bone tube imbedded in gelatine and penetrated by a 9 mm pistol bullet [Jussila 2000, unpublished data]. Most of the bone fragments are close to the parent bone with some of them drawn into the wound channel. None of the fragments have formed a wound channel of their own. Kneubuehl and Thali [2003] obtained similar results shooting 7.62 mm rifle bullets through gelatine embedded swine bones and synthetic bone tubes.

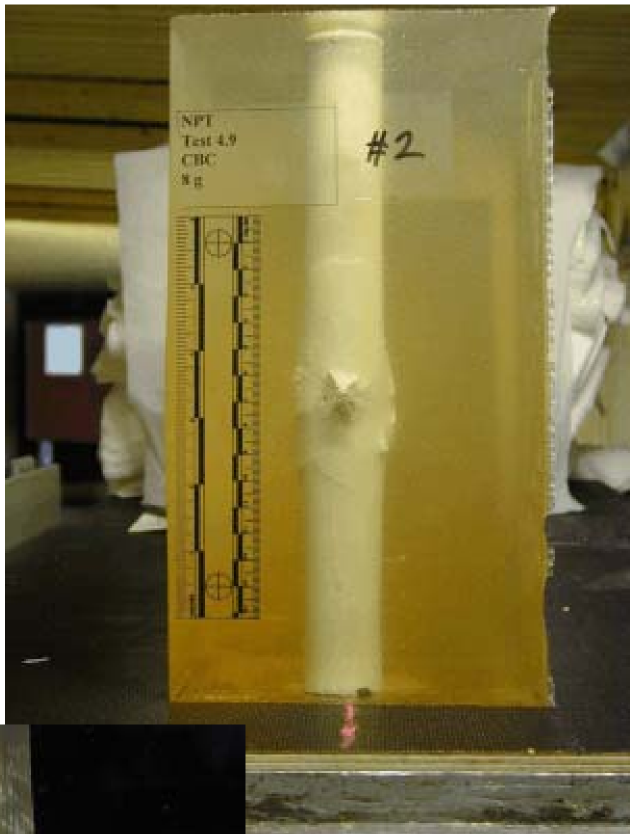

Figure 11 : An example of a 9x19 mm jacketed pistol bullet penetration of gelatine imbedded synthetic bone

Figure 12 Synthetic generic bone tube imbedded in 10% gelatine and penetrated by a 9 mm FMJ bullet. The silicone "periosteum" has been removed to more clearly show the fracture. Note the lack of longitudinal fractures in the bone tube.

Bone injury classification by three fracture zones has been proposed [Robens and Küsswetter 1982] based on experimental shootings of cadaver tibiae. The central injury and primary fracture zone consists of completely missing or disorganised bone fragments. The secondary zone consists of fragments detached from the parent bone but still approximately in their original position. The tertiary zone consists of area with linear cracks and fractures.

Huelke et al. (1968) shot human cadaver long bones with 6.3 to 10 mm steel spheres and obtained penetration threshold velocities of 200 m/s and 120 m/s for cortical and cancellous bone, respectively. It seems that cancellous bone will experience less damage than the dense cortical bone [Belkin 1978, Huelke and Darling 1964]. A rifle bullet hitting a femur at vi = 800 m/s may lose only 30 m/s in penetration [Kneubuehl 1994] but may lose its stability.

4.3.5 Skull and vertebral injury

The skull consists of 22 bones joined together into a structural unit which contains the brain and protects it. The brain consists of the cerebrum, the cerebellum and brainstem including medulla oblongata. Although the retardation properties of the brain seem to be similar to those of muscle tissue the strength is much lower [Janzon 1997]. Primary head injuries are categorised into skull fractures, focal injuries and diffuse brain injuries. Direct bullet hits always cause a serious injury. A tangential hit may also cause serious brain injuries through shock, pressure and cavitation [Watkins et al. 1988 referenced by Janzon 1997]. A tangential hit also causes a torsion motion of the head which can cause serious injuries [Aare 2003] even when a helmet is worn. Penetrating spinal injuries are serious and difficult to treat [Kleider 1969, Heiden et al. 1975, Fine et al. 1976, Gellad et al. 1988, Doll and Baum 1989].

4.3.6 Remote and delayed effects

The fast acoustic shock wave and a slower pressure wave created by the motion of cavitating tissues may cause both temporally delayed and remote to the wound channel injurious effects. A good discussion on the subject can be found in Sellier and Kneubuehl (1994) and Janzon (1997). The shock wave produces mechanical irritation which generates electrical activity in the nerve [Wehner and Sellier 1982]. It stimulates the nerves and theories exist on possible injury mechanisms. If both sympatic and parasympatic nerves controlling the heart are stimulated with different intensity a heart failure could occur [Sellier and Kneubuehl 1994]. Ordog et al. (1994) have studied the effects of the acoustic shock wave. It still remains a somewhat controversial issue [Fackler et al. 1989 and 1990, Fackler 1996] with Fackler claiming that Ordog has confused the acoustic wave with the pressure wave of temporary cavitation.

The pressure of the acoustic wave could be as high as 900 psi (34 MPa) and velocity approximately 1550 m/s [Peters 1990]. Its duration, however, is a couple of microseconds [Hollerman 1990 referring to Bowen and Bellamy 1988]. It does not move tissues and is thus claimed not to cause injuries [Harvey 1946, Fackler 1985]. Fackler uses the lithotriptor as an example of the harmlessness of acoustic waves. There is, however, evidence on vascular and kidney tissue injury [Sonden et al. 2000, Shao et al. 2003, Zhu et al. 2004].

A pressure wave compresses tissues and has some injurious effects on nerves and vascular system. It extends quite far in the body [Tikka 1982] and could compress blood vessels creating a pressure wave travelling through the veins at the speed determined by the elasticity and radius of the vessel. This or direct pressure on carotid sinus could cause anomalies in blood pressure. It could also cause rupture of a blood vessel or loosen endothelial cells that could later cause a thrombosis. Spherical steel pellet shot into the hind leg of a pig dissipated 728 J of kinetic energy and caused mean peak pressure of 150 kPa in the brain [Suneson et al. 1988]. As a result minor blood-barrier damage in the form of small vein and capillary leakage could be observed. The pressure wave was also found to cause remote damage to the myelin sheaths of nerve axons. Similar results were obtained also by Lai et al. [1996]. One can, however, criticise the "remoteness" as the bullets passed at 1 to 3 cm distance from the sciatic nerve of the dog. The nerve was certainly within the range of temporary cavitation.

Janzon (1997) refers to Liu et al. (1990) saying that after thigh injury of anaesthetised pigs blood extravasation and haemorrhage could be observed in small blood vessels and capillaries of the brain, heart and other organs.

A bullet containing lead and its fragments may cause delayed systemic reactions if left in the tissue. The blood lead levels increase for up to 3 months [McQuirter et al. 2004]. The effects of multiple hits may cause delayed multiple organ failure [Saadia and Schein 1999] because of reactivation of the inflammatory response caused by subsequent hits.

Bullets and their fragments have been observed to be relocated by the circulatory system [Ordog et al. 1988, Bartlett 2003, Braun 2003, Corbett et al. 2003, Rich et al. 1978, Mattox et al. 1979 Rich and Mattox referred to by Corbett]. This embolism could later cause significant complications.

4.3.7 Injury assessment

Several attempts have been made to correlate bullet properties with induced incapacitation. These attempts have not looked at the level of injury from the legal viewpoint of *maux superflus*, but more as a quest for increasing the probability of instant incapacitation.

As the objective of the police is to stop life endangering activity of an offender quickly and effectively the incapacitation or "stopping power" approach has certain validity. General J.S. Hatcher presented the concept of stopping power in his book "Pistols and Revolvers and their use" in 1927 and later "relative stopping power" (*RSP*) [Hatcher 1935]. According to Hatcher the incapacitation potential of a projectile was proportional to impact momentum times the bullet's cross-sectional area [Sellier and Kneubuehl 1994 pp. 242-245, Kneubuehl 1999].

[11] $$RSP = 17.9 * mi * vi * A * Fform$$

where A is the cross-sectional area of the bullet and Fform the form factor (see 4.1.4.)

U.S. Army expanded Hatcher's theory by hypothesizing that incapacitation "stopping power" (*StP*) was a function of kinetic energy deposited in 15 cm of gelatine tissue simulant [Sturdivan 1969 referred to in Bruchey and Frank 1983a]. DiMaio expanded the theory in 1974 on handgun effectiveness [DiMaio 1974 referred to in Bruchey and Frank 1983a and Sellier and Kneubuehl 1994 , Kneubuehl 1999].

[12] $$StP = 0.114 * Ed * A * Fform$$

J. Taylor, a british big-game hunter developed a "Knockout value" (*KO*) in 1948 to describe the effectiveness of hunting ammunition [Kneubuehl 1999].

[13] $$KO = 0.000285*mi*vi*Ki$$

Weigel [in Sellier and Kneubuehl 1994 pp. 246-247] assumed (1975) that the effectiveness (W_H) was proportional to the volume of the shooting channel in wood.

[14] $$W_H = V = 0.00024*mi*vi^{1.5}$$

, where V is the volume of the bullet channel produced in wood.

In 1983 the American National Institute of Justice published an extensive study [Bruchey and Frank 1983a and 1983b] proposing Relative Incapacitation Index, (*RII)*. The *RII* was calculated as a function of shape and diameter of the temporary cavity and probability of injuring a vital organ, but cannot be determined without a great number of experiments and was found impractical. Subsequently a "Power Index Rating" (*PIR*) was published [Matunas 1984].

[15] $$PIR = 27.4*Ei*ET*D$$

, where *ET* is an "energy transfer factor" and *D* a "diameter value". Both values can be considered to contain a significant subjective element and introduce some doubt as to the validity of the equation [Kneubuehl 1999].

A German professor of forensic medicine, K.G. Sellier assumed that the wounding potential of a bullet would be proportional to the released energy.

[16] $$\frac{\Delta E}{\Delta S} = C*\frac{Ei*A}{mi}$$

, where C is a constant [Kneubuehl 1999].

Occasional attempts to describe "stopping power" by analysing statistics on real shooting incidents have been made [Marshall and Sanow 1992]. Marshall and Sanow attempted to find the handgun bullet with the best "one shot stopping power". The statistical analysis contains serious flaws and has been widely discredited [Roberts and Wolberg 1992, Kotzar 2004].

Some debate can be found in literature on whether and how well the kinetic energy dissipated into tissue correlates with the amount of devitalised tissue [Fackler 1986]. One argument is that since subjective assessment is involved in estimating the amount of devitalised tissue, the previous knowledge on presumed kinetic energy of the bullet may affect the surgeon's judgment.

Detailed analysis of incapacitation theories can be found in Sellier and Kneubuehl [1994] and also in Kneubuehl [1999]. Based on actual shootings [Geller and Scott 1992] it, however, seems that in about half of the shootings in USA more than one hit was needed to stop an offender and that the only certain way to stop somebody instantly is a shot through the central nervous system (CNS). This view is also shared by the Swedish research group of Janzon, Rybeck, Schanz et al.. The effect of a shot elsewhere on the body can justifiably be hypothesised to depend on more than purely physiological factors. Medication, narcotics or alcohol may affect the sense of pain and the way a person reacts to injury. Psychological and emotional factors like the will to fight, determination, conviction, beliefs and maybe even previous experiences and cultural background make the outcome less certain [Kneubuehl 1999, Janzon personal communication 2004]. In addition the incapacitation theories do not consider the factors of fragmentation or excessive penetration and are therefore not suitable for comprehensive analysis of injury potential from legal and law enforcement perspective.

The concepts of incapacitation and wounding potential have occasionally been used as synonyms in the literature. Incapacitation is the result of both physiological and psychological reactions whereas wounding potential is a measure for morphological and physiological damage. These two concepts should not be mixed.

The Swiss delegation to the *Expert Meeting of the International Committee of the Red Cross* presented a *Draft Protocol on Small Calibre Weapon Systems* (1994) [Prokosch 1995]. Recognising that not only bullet expansion but also other factors cause tissue injury, it proposes a limit for the amount of kinetic energy that is released. It suggests prohibiting the use of 'arms and ammunition with a calibre of less than 12.7 millimetres which from a firing distance of at least 25 meters release more than 20 joules of energy per centimetre during the first 15 centimetres of their trajectory within the human body'.

The Swiss proposal says nothing about what should happen after the first 15cm. However, considering the results of forensic investigations in the Balkans [Rainio et al. 2001], it should not be ignored. It does not seem to have received a very enthusiastic reception [Parks 2001], since the Second Review Conference of the Inhumane Weapons Convention in December 2001 still calls for adoption of a new protocol limiting the amount of energy deposited [Maresca 2002], saying that its military, technical, medical, legal and financial implications should be discussed. Nothing is said about law enforcement.

Of the clinical assessment methods the Mangled Extremity Severity Score (MESS) method [Farquharson-Roberts et al. 1997] of wounds in the extremities may be valid, but tries to make guesses about the weapon, ammunition and kinetic energy involved. Considering what was previously stated about weapon and ammunition performance and that the information on them is not readily available to a surgeon even in civilian setting the MESS method can hardly be considered realistic.

The Red Cross Wound Classification (RCWC) [Coupland 1993 and 2000, Bowyer et al. 1997] is simple to use and can also be to some extent used for simulated gunshot wounds. More importantly it makes no references to the weapons and ammunition used. The method takes into account the entry and exit wound sizes, permanent cavity size, possible bone fractures, injury to vital structures and the number of metallic bodies in the wound i.e. fragmentation. Table 1 shows the scoring method in detail. The method has been criticised for not taking the neurological injury into account [Bowyer et al. 1997].

Table 2: The Red Cross Wound Classification [Coupland, 1993]

Variable	Value
E = entry	Maximum diameter (cm)
X = exit	Maximum diameter (cm), 0 if no exit
C = cavity	C = 0 or 1 Can the cavity take 2 fingers? Yes = 1
F = fracture	F = 0 (no), 1 (simple fracture, hole or insignificant comminution) or 2 (clinically significant comminution)
V = vital structure (note 1)	Are brain, viscera (breach of dura, pleura or peritoneum) or major vessels injured? V=0 (no), V=1 (yes)
M = metallic body	Bullet or fragments visible on X-ray. None: M=0, One metallic body: M=1, Multiple metallic bodies: M=2

Neither RCWC nor MESS consider the amount of devitalised tissue which does not recover and provides for an excellent growth surface for bacteria unless removed. As it is permanently lost it should not only be included in injury assessment but be one of the central items. The rule of four C's is ordinarily used for identifying the devitalised tissue:

- lack of Contractility
- altered Consistency
- altered Colour
- lack of Capillary bleeding

The rule of four C's is not unanimously accepted and more conservative approach of excising only the obviously detached tissue has been presented [Fackler 1989, Santucci and Chang 2004]. As stated previously, this view may lead to severe anaerobic infection and possible gas gangrene [Janzon personal communication 2004].

4.4 Simulating bullet interaction using live and natural tissues

Wound ballistic simulation can be defined as the means to examine the injurious effects of a firearm launched projectile and to use the results for optimising its terminal performance. It is obvious that the effects of ammunition on human beings cannot be tested *in vivo* and credible simulations must be used. Even when extensive computer simulations [Ogunyemi et al. 2002, Peters et al. 1996] are available and allow the shooting mathematical models of bullets into mathematical models of targets real bullets must eventually be used with real guns. Considering the requirements of the International Law the effects caused by a certain ammunition type fired from a certain weapon must be examined to assess their legitimacy prior to deployment and later for quality assurance and to improve the validation of simulation.

4.4.1 Live, anaesthetised animals

of all kinds have been used for wound ballistic research. An animal model enables the study of physiological parameters and responses to the trauma [Janzon 1997]. Of all animals the pig is the most widely used [Schantz 1979]. If a standard assessment method is to be established animal tests can be used for validation of the method but not to produce repeatable and comparable results. The non-homogeneity of living tissue causes dispersion of the results. A large number of repetitions may be required to gain sufficient statistical confidence. The animals are far too difficult to handle and involve too many variables. If systemic responses are not to be studied and only the energy dissipation and wounding potential of a bullet are to be assessed, animal testing can be considered unnecessary because good simulants are available.

4.4.2 Humans

Military armed conflicts and civilian shooting incidents provide a wealth of information on firearms injuries. There are some 13 databases full of injury data in U.S.A only [Mercy et al. 1998, Annest and Mercy, 1998]. Relevant ballistic facts are, however, not recorded rendering it impossible to correlate injury data with theoretical wound ballistic research. Human patients and cadavers could provide useful data for the development and validation of simulation methods [Vogel 1987, Missliwetz 1987, Tausch et al. 1978]. The physical properties of soft tissue and internal organs of cadavers may change by time [Seki and Iwamoto 1998 referring to Yamada 1970]. The cadavers are necessarily stored in cold temperature which also changes the physical properties. These facts should be taken into account when interpreting the results.

4.4.3 Natural vital organs

of both humans and animals have been used for ballistic studies when cast into gelatine [Lewis et al. 1982, Missliwetz and Wieser 1986]. These organs will provide useful information. Due to their structural complexity it is difficult to see how they could be replaced with synthetic simulants. Coudane et al. [1982] shot cadaveric human legs with various types of hunting weapons. Ragsdale and Josselson [1988] shot cadaveric human distal femurs and proximal tibiae embedded in 20% gelatine. Unfortunately the bone placement in gelatine was inaccurate and the results were not analysed using any systematic scale, which had already been published [Robens and Küsswetter 1982].

4.5 Synthetic simulants

Simulants can be divided into soft tissue, skin, bone and skull simulants. Literature tends to concentrate on soft tissue simulants [Sellier and Kneubuehl 1994, Janzon 1997, Berlin et al. 1983, Fackler 1988a and 1988b, Pirlot et al. 2001].

4.5.1 Soft tissue simulants

Principally two types of tissue simulants have been used. The Swedish researchers started using specially prepared glycerine soap in the 1970's [Berlin et al. 1976 and 1977]. Ballistic gelatine has been used longer. There are also other attempts to use water, wet phone books, wet paper, clay, duct seal, transparent gel candle [Uzar et al. 2003] and even metallic lead [Missliwetz and Wieser 1986]. Special manufactured glycerine soap and hydrogels prepared from water solutions containing 10-20 mass-% gelatine have long been used to simulate muscle tissue [Harvey et al. 1962, Thompson 1993, and others].

Ballistic gelatine is usually used in 10 or 20% nominal concentrations. The actual concentration should be adjusted i.e. calibrated for every batch of gelatine powder to give precisely the desired penetration and to compensate for possible manufacturing variances. Gelatine blocks are prepared by dissolving the calibrated amount of usually 250A bloom gelatine powder into warm water, adding possibly preservative and pouring the solution into moulds where it first cools off and then solidifies. To avoid dehydration and unnecessary contamination by airborne microbes the moulds should be covered with plastic foil. The gelatine blocks are then taken to refrigerator for storage and cooling into prescribed usage temperature. Before use the gelatine block properties are verified by shooting 4.5 mm steel pellets into them and measuring both impact velocity (*vi*) and penetration depth (*lw*). An accepted de facto standard [Fackler and. Malinowski 1988] is that at *vi* = 180 m/s the *lw* should be 85 ± 5 mm. The terms calibration and verification are often used inaccurately in various reports.

The first one to use gelatine as ballistic simulant was Harvey [Harvey et al. 1962] in the 1940's. He used 20% concentration at +24 ^{o}C. Lewis [Lewis et al. 1982] poured 6 litres of 90-95 ^{o}C water over 1200 g of 250A gelatine, stirred at low speed for 3 minutes before adding 3 ml of cinnamon oil as microbial growth inhibitor (MGI). The solution was allowed to stand still in room temperature for 1 hour and was then poured into moulds that were allowed to cool in room temperature overnight. The blocks were then stored at 5 – 8 ^{o}C tightly wrapped in plastic.

The classic and often referred recipe for gelatine is that of Fackler and Malinowski [1985]. They recommend using 10% solution i.e. for example 1000 g of gelatine with 9 litres of water. The gelatine powder is poured into cold (7 – 10 ^{o}C) water, mixed and let stand in refrigerator for 2 hours. The mix is then slowly heated in water bath to +40 ^{o}C and slowly stirred until all gelatine has dissolved. 5 ml per litre of propionic acid is added to inhibit microbial activity. The solution is poured into moulds and set into a refrigerator (7 – 10 ^{o}C) for overnight. The blocks are then removed from moulds, wrapped tightly in plastic bags and stored in refrigerator at +4 ^{o}C for at least 36 hours before use. This recipe is followed also by Sellier and Kneubuehl [1994] and Thompson [1993].

As the method is rather tedious several modifications have appeared. Berlin [Berlin et al. 1983] mixed 20% of gelatine straight into distilled water at 85 – 90 ^{o}C, used no MGI and let the solution stand in refrigerator at +4 ^{o}C for a minimum of 72 hours. The gelatine was conditioned to +20 ^{o}C before use.

Firearms Tactical Institute [2000] recommend dissolving 1000 g of gelatine into 6 litres of hot tap water (49 – 60 ^{o}C) and mixing well, adding 5 ml of propionic acid and then 3 more litres of water (49 – 60 ^{o}C). The filled moulds are allowed to stand in room temperature for 4 hours before placing them in refrigerator (+4 ^{o}C) for at least 48 hours.

Federal Bureau of Investigation [Vyse 2003] is claimed to use 10% solution into water at + 60 ^{o}C. "Foam Eater" is added to prevent foaming and instead of propionic acid cinnamon oil is used. The filled moulds are allowed to stand in room temperature for 4 hours before placing them in refrigerator (+ 4 ^{o}C) for at least 36 hours.

H.P. White Laboratories [1998] follow the Fackler and Malinowski recipe for 10% gelatine with the exception that the gelatine is not conditioned to +4 but also used in 7-10 ^{o}C for at least 20 hours. Yoganandan and Pintar [1997] use the same recipe but use distilled water.

The preparation of gelatine has long been considered difficult and requiring extreme care [Fackler and Malinowski 1988, Post and Johnson 1995]. The first attempt to quantify the effects of different preparation parameters was done by Post and Johnson [1995]. The results were somewhat inconclusive due to lack of statistical confidence. Many sources quote Fackler who warns about detrimental effects of excessive heat [1988]. The gelatine manufacturer, Gelita, however, indicates [Gelita 2003] that gelling power does not significantly decrease after several hours in 60 to 80 ^{o}C temperature.

There is some debate on whether a 10% or 20% gelatine is a better soft tissue simulant. One of the arguments against 10% gelatine is that its specific weight is only 1.03 whereas that of the 20% gelatine is 1.06 being closer to muscle tissue [Janzon 1997]. The latter figure is, however, an approximation of the thigh muscle tissue of a living swine [Peters 1990a], whereas an estimate for a human thigh is 1.02-1.04 [DeMuth 1966 see table 3].

Table 3: Specific gravity of human tissues [DeMuth 1966]

Tissue	Specific gravity
Fat	0.8
Liver	1.01 – 1.02
Skin	1.09
Muscle	1.02 – 1.04
Lung	0.4 – 0.5
Bone	1.11

Usage temperature is important because it has a significant effect on retardation that the simulant induces into the projectile. 10% gelatine at +4 ^{o}C will give approximately similar bullet deceleration as muscle tissue of a 60-100 kg landrace pig [Fackler et al. 1984, Yoganandan and Pintar 1997]. The benefits and drawbacks of both simulant types have been extensively debated and even exaggerated. Some claims like that dissipated “down-track” energy cannot be measured in gelatine [Coupland et al. 2000] are clearly unfounded. There are 3 known methods for doing it. The “Crack Length Procedure” according to Knappworst [Sellier and Kneubuehl 1994], the “Total Crack Length Method” [Ragsdale and Josselson 1988] and the “Wound Profile Method” [Fackler and Malinowski 1988]. The Knappworst method is based on measuring the surface areas of the fissures and a better name for it would be “Fissure Surface Area” –method. No information is available on how Knappworst validated the method. [Knappworst personal communication 2003]. Deriving the kinetic energy directly from the gelatine cracks can, however, be an unreliable method [Ragsdale and Josselson 1988]. Ragsdale used 20% gelatine cooled to 4 ^{o}C. This kind of high concentration together with low usage temperature will, however, make the gelatine behave in a significantly different manner from 10% gelatine at the same temperature [Peters 1990]. The results and conclusions can therefore be debated.

Several points speak strongly for the use of gelatine as a general purpose soft tissue simulant.

1) gelatine is translucent and the behaviour of the projectile or the exact placement of bullet fragments are easily measured (see figure 10). With soap X-ray imaging is needed.
2) soap is plastic and does not reproduce the pulsations of temporary cavity. The cavity left in soap reflects temporary cavitation. Permanent cavity cannot be measured. In principle, gelatine allows both, although this claim has been contested [Ragsdale and Josselson 1988]. Ragsdale's conclusions can also be contested because he used 20% gelatine at the temperature of +4 ^{o}C, which makes the simulant far too hard and insensitive as a measurement tool. If one looks at a photograph of a wound channel in figure 10 one can see that it is not very easy to define the diameter of the permanent cavity in gelatine either.
3) By varying the gelatine concentration and possibly utilizing air bubble entrapment one can change the mechanical properties of the gelatine and thus, in theory, simulate virtually any kind of soft tissue for wound ballistic research or forensic reconstruction. This includes casting a brain simulant inside a synthetic skull [Thali et al. 2002]. It is difficult, however not impossible [Thali et al. 2001] to use soap as supporting tissue to examine injury of bones and vital organs, but gelatine is preferred [Lewis et al. 1982, Amato et al. 1989, Missliwetz and Wieser 1986]. Soap is factory made and cannot be prepared by the researcher to simulate different types of tissues. Table 2 shows an example of the specific gravities of human tissues.

It should, however, be noted that isotropic materials like gelatine and soap fail to take into account the heterogeneous nature of tissues and their different densities [Bartlett 2003]. Karger [1998] also found out that gelatine may not be the best simulant for testing the effects of arrows.

4.5.2 Skin simulant

Skin simulant has not been widely used. Its significance seems to have been too easily overlooked. Skin, however, increases the fidelity of measuring the effect of low or reduced velocity projectiles like ricochets and is needed for forensic reconstruction of actual shootings.

Schyma and Placidi (1977) used pig skin of unknown thickness and quality when investigating the injury potential of ricocheting bullets. Thali et al. (2002) used a silicon cap with synthetic fibers on a synthetic skull to simulate the collagen and fat of the scalp. Pigskin was also used by MacPherson (1994) in an attempt to show that it is not needed in wound ballistic research. Kneubuehl (2004) reported using lambhide when assessing the injury potential of the FN 303 less lethal launcher.

4.5.3 Bone simulant

is available from at least one source, Synbone AG in Switzerland. It is available in various forms. Kneubuehl and Thali [2003] report identical results as to loss of bullet velocity, retained kinetic energy, bone fragmentation and wound channel compared to results with swine bones. In the tests performed at Police Technical Centre in Helsinki, Finland the generic bone tubes give good, consistent results but leave some doubt about similarity with human femur as it does not seem to produce quite similar longitudinal fractures [Jussila 2003, unpublished data]. Therefore the bone injury classification [Robens and Küsswetter 1982] might not be applicable. When casting synthetic bone tubes in gelatine care should be taken to fill the medullar cavity as well to simulate the bone marrow.

Kneubuehl and Thali used only sharp pointed full jacket bullets of relatively high velocity (710 – 830 m/s). Therefore the effect of different bullet shapes and velocities remains to be investigated. Axial weight simulating the torso weight [Robens and Küsswetter 1982] was not used. Therefore the study leaves some room for doubt as to the general applicability of the results. Validation of synthetic bone with cadaveric human bones like femur is mandatory for credibility.

4.5.4 Synthetic skulls

Dried Asiatic skulls filled with 20% gelatine were used by Watkins et al. [1985] to study penetrating head wounds. The experiment setup included a pressure transducer to record the internal pressure inside the skull.

Synthetic skulls and skull spheres are also available from Synbone. Very interesting wound ballistic tests have been conducted by Thali [Thali et al. 2002]. These tests used a 10% gelatine filled synthetic skull sphere with skin attached on its surface.

Similar tests were also conducted earlier at the Police Technical Centre in Helsinki, Finland in an attempt to find a better simulation model for helmet testing. In these tests the skull was mounted on a flexible “neck” with adjustable tension of the atlas vertebra (Figure 13). The arrangement would allow the use of accelerometers and in the skull pressure sensor that would give more information on ballistic impacts. Unfortunately this line of research was not continued due to limited resources and more pressing work assignments.

Figure 13 : Police technical centre artificial flexible atlas vertebra for mounting a skull for helmet testing.

5 OBJECTIVES OF THE STUDY

Injury potential of a weapon in a broad sense encompasses not only the effects on a target individual but also danger of injury for innocent bystanders and the police officer using force. International Law demands that no unnecessary danger and unwarranted or superfluous injury shall be caused to any counterpart of a firearm incident. Injury potential can therefore be considered as a central issue when law enforcement firearms and ammunition are selected. The general objective is to propose and justify a standard wound ballistic testing method which could be used for assessing bulleted law enforcement firearms ammunition in order to ascertain their legitimacy from the International Law perspective.

The general objective is further elaborated with in-depth research on wound ballistic simulation with the following specific aims:

1. To review the international laws and agreements and interpret them into weapons technical terms to establish a basis for injury potential assessment.
2. To propose a standard method for preparing ballistic tissue simulant of 10% hydrogel solution of gelatine.
3. To establish a correlation between the amount of devitalised tissue and dissipated kinetic energy
4. To complement the gelatine based tissue simulant with skin simulant to allow simulation and assessment of bullet exit wounds and assessment of the injury potential of fragments and ricochets.
5. To validate methods used for calculating the amount of dissipated kinetic energy from the fissures formed into tissue simulant by the penetrating bullet.
6. To validate 10% gelatine as tissue simulant against wound ballistic test results obtained with live pigs.
7. To present a mathematical model of describing a bullet’s injury potential in numerical comparison figures.

6 MATERIALS AND METHODS

6.1 Paper I - International law and law enforcement firearms

The key documents of International Law, agreements, declarations and recommendations were analysed from relevant weapons technical and law enforcement tactical perspective. These documents were:

- *The St. Petersburg declaration* (1868)
- *The Conference of Brussels* (1874)
- *The Hague Convention* (1899)
- *The Hague Convention Respecting Laws and Customs of War on Land* (1907)
- United Nations Universal Declaration of Human Rights (1948)
- *The Council of Europe Convention for the Protection of Human Rights and Fundamental Freedoms* (Rome 1950).
- *The Protocol Additional to the UN Conventions of 12 August 1949,* relating to T*he Protection of Victims of International Armed Conflicts (Protocol I), 8 June 1977, (Article 36)*
- *The UN Code of Conduct for Law Enforcement Officials* (*1979*)
- *The UN Resolution on Small-Calibre Weapon Systems (Geneva, 1979)*
- *The UN Convention on Prohibitions or Restrictions on the Use of Certain Conventional Weapons Which May Be Deemed to be Excessively Injurious or to Have Indiscriminate Effects (The Inhumane Weapons Convention, [IWC] Geneva 1980*
- The *UN Basic Principles on the Use of Force and Firearms by Law Enforcement Officials*
- *The Expert Meeting of the International Committee of the Red Cross* presented a *Draft Protocol on Small Calibre Weapon Systems* (1994*)*.
- Article 8 (paragraph 2(b) subsection xix) of the *Rome Statute of the International Criminal Court* (1999)

The legal division into documents concerning armed conflicts and law enforcement was recognised. Since the borderline between the two realms is becoming ever more vague, technical conclusions of weapons common to both were drawn. These conclusions lay the legal basis for the assessment methodology proposed in this dissertation.

6.2 Paper II – Preparing Ballistic Gelatine – Review and Proposal for a Standard method

There is no internationally agreed standard ballistic soft tissue stimulant although a number of simulants are being used. Standardisation is necessary in order to be able to compare wound ballistic test results. This study reviewed the known gelatine preparation methods. Preparation parameters like water temperature, water acidity within EC directive (pH 6.5 – 9.5) [European Council 1998] for tap water and cooling time were varied to find out their effect on 10% hydrogel solution of 250A bloom gelatine. The preparation process repeatability and the resulting block homogeneity were measured by shooting 4.5 mm steel spheres and measuring impact velocity and penetration depth with the gelatine at the temperature of +4 ^{o}C. The test setup is shown in figure 14. The penetration results were used for estimating a regression function which can be used for verifying the gelatine block characteristics prior to use. For individual methods, please refer to the original publication (paper II).

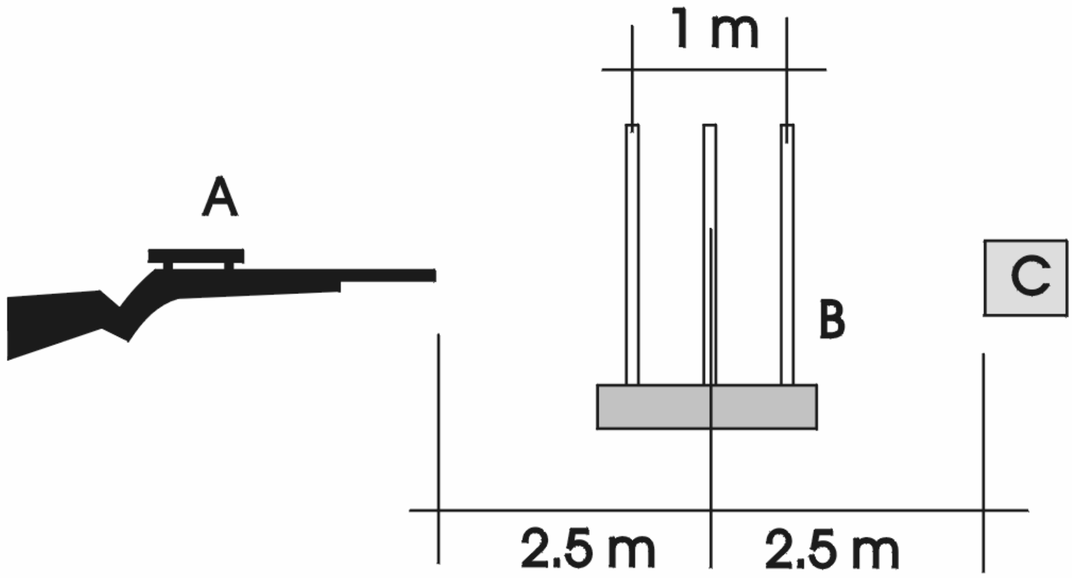

Figure 14: Schematic of the testing setup. A – weapon, B – chronograph screens, C – gelatine.

6.3 Paper III - Ballistic variables and tissue devitalisation in penetrating injury – Establishing Relationship Through Meta-analysis of a Number of Pig Tests

Ballistic soft tissue stimulant can be used for measurement of kinetic energy that a penetrating bullet dissipates. In order to find out the correlation of various ballistic variables of the bullet with the amount of injury caused, a number of tests [Berlin et al. 1977, Albreht et al. 1979, Tikka et al. 1982, Tikka et al. 1987, Kjellström et al. 2002] with live anesthetised pigs were statistically analysed. The tests were either published in scientific literature or in official reports and included a total of 38 calibre 5.56x45 mm, 5 calibre 7.92x57 mm, 24 calibre 7.62x51 mm, 48 calibre 7.62x39 mm, 16 calibre 9x19 mm bullets and 18 6 mm steel spheres with 25, 1, 2, 2, 11 and 0 of them deforming during penetration. Of the bullets only the 9x19 mm bullets that deformed were constructed for controlled deformation. The total number of individual shots was 140 consisting of rifle and pistol calibres. A summary of the primary data is presented in table 4.

Table 4: A summary of the pig test primary data used for analysis.

Reference	weapon	cal	bullet	*mi*	pig m	*N*	*vi*	*Ei*	*Ed*	*tdeb*	*lw*	*mdeb*	*mdeb/Ed*
Albreht et al. [1]	Yugoslav M48	7,92x57	FMJ	12,85	61,4	4	687,8	3039,5	642,0	6	205,0	123,8	0,19
Albreht et al. [1]	Yugoslav M70	7,62x39	FMJ	8	61,7	8	663,2	1759,8	695,6	6	210,0	214,4	0,31
Albreht et al. [1]	Colt M16A1	5,56x45	M193 **										
Albreht et al. [1]	FN FAL	7,62x51	NATO FMJBT	9,56	71,2	4	810,5	3139,8	1719,0	6	222,5	527,5	0,31
Berlin et al. [3]	Colt M16A1	5,56x45	M193 FMJ	3,6	67-93	3	824,7	1220,3	212,3	1	107,7	103,3	0,49
Berlin et al. [3]	Colt M16 mod 613	5,56x45	SS92 FMJ	3,6	67-93	10	855,4	1312,2	287,4	1	106,6	187,5	0,65
Berlin et al. [3]	Husqvarna AK4 (FN FAL)	7,62x51	Norma	9,5	67-93	9	731,8	2533,6	293,6	1	118,0	134,1	0,46
Berlin et al. [3]	Valmet M62	7,62x39	Russian FMJ	8	67-93	14	631,4	1575,5	292,9	1	127,2	228,3	0,78
Kjellström et al. [15]	Sig Sauer	9x19	Norma SP FMJTC	8	52,4	5	368,8	544,5	128,1	1	79,8	24,5	0,19
Kjellström et al. [15]	Sig Sauer	9x19	MEN QD * MBHP	5,9	50,7	6	401,5	475,6	317,1	1	79,5	42,6	0,13
Kjellström et al. [15]	Sig Sauer	9x19	Speer GD * JHP	8	48,6	5	355,0	504,2	330,1	1	80,6	49,9	0,15
Tikka et al. [24]	Valmet M62	7,62x39	LapuaS309 FMJ	8	20-30	11	663,3	1766,1	142,3	6	95,6	35,2	0,25
Tikka et al. [24]	AKM 47	7,62x39	tsDpvth FMJ	8	20-30	13	661,0	1750,4	133,4	6	86,6	21,7	0,16
Tikka et al. [24]	Colt M16A1	5,56x45	M193 ** FMJ										
Tikka and Seeman [25]		6mm	steel ball	0,86	23-39	18	1078,1	500,6	397,7	1	129,8	112,0	0,28
						110							

* controlled deformation bullet

** rejected due to fragmentation

Legend:

FMJ – full metal jacket

BT – boat tail

TC – truncated cone

MBHP – monoblock hollow point (expanding)

JHP – jacketed hollow point (expanding

As controllably deforming bullets are often used by the police, an attempt to include assessment of deformation energy was included. The current literature often incorrectly refers to dissipated energy *Ed* being the difference of impact energy *Ei* and residual energy *Er* ignoring the energy *Edef* used by the bullet for deformation.

The mass of devitalised tissue excised during debridement, *mdeb* was first made commensurate taking into account the delay between wounding and surgical operation. In some of the cases the pig hind legs had been deliberately contaminated with bacteria to study the effect of delay. These infectious effects had also to be made commensurable to 1 h delay level used in analysis. The amounts of excised tissue are based on subjective assessment of the surgeon. This fact was considered to be part of the process and no commensuration was attempted. The corrected *mdeb* values were correlated with Ed and a regression function was derived.

Quantification of the kinetic energy *Edef* used by bullet deformation was attempted for controllably deforming 9x19 mm Speer Gold Dot bullet by measuring the energy required to compress it to the same residual length as when it is shot into 10% ballistic gelatine. For the basic data sets please refer to the original publication (paper III).

6.4 Paper IV - Ballistic Skin Simulant

A simulated skin adds to the fidelity of forensic reconstructions of firearms injuries. As the mechanical properties are different from those of muscle tissue it has a different threshold velocity required for penetration. This is significant especially when assessing the injury potential of projectiles that have already lost most of their kinetic energy in penetration or on impact with a hard surface. Meaningful injury potential assessment of overpenetrating or ricocheting bullets requires the use of validated stimulant for human skin.

The study reviewed literature on previous tests with human cadavers in order to establish target mechanical properties for skin simulant. A number of reported attempts to establish threshold velocity *vth* required for the penetration of human skin were reviewed. See table 5.

Table 5: Reviewed studies on penetration threshold velocity of human skin.

Reported results					**Calculated results**					
Source	*Bullet*	*d (mm)*	*vth (m/s)*	*mi (g)*	*vol (mm3)*	*a (mm2)*	*mic (g)*	*S (g/cm2)*	*Eth (J)*	*Eth/a*
Journee in [7]	.44 lead sphere	11,25	70	8,50	745,51	99,40	**8,35**	8,40	20,46	0,21
DiMaio et al. [7]	diabolo pellet	4,40	101	0,53		15,21	0,53	3,52	2,73	0,18
DiMaio et al. [7]	.22 diabolo pellet	5,46	75	1,07		23,41	1,07	4,57	3,01	0,13
DiMaio et al. [7]	38 LRN	9,12	58	7,32		65,33	7,32	11,21	12,32	0,19
Mattoo [9]	000 Buckshot	**9,14**	65	4,50	399,79	65,61	4,48	6,82	9,46	0,14
Missliwetz [4]	4,5 mm lead sphere	4,50	110,4	0,54	47,71	15,90	0,53	3,36	3,26	0,20
Missliwetz [4]	4,5 mm diabolo	4,50	135,6	0,49		15,90	0,49	3,08	4,50	0,28
Missliwetz [4]	4,5 mm spire point	4,50	109	0,56		15,90	0,56	3,52	3,33	0,21
Missliwetz [4]	4,5 mm hollow point	4,50	133,2	0,44		15,90	0,44	2,77	3,90	0,25
Missliwetz [4]	4 mm brass sphere	4,00	120,6	0,31	0,03	12,57	0,31	2,47	2,25	0,18
Missliwetz [4]	4 mm steel sphere	4,00	126,1	0,26	33,51	12,57	0,26	2,11	2,10	0,17
Tausch et al. [10]	lead sphere	9,00	68,7	5,30	381,70	63,62	**4,28**	6,72	10,09	0,16
Tausch et al. [10]	Lead round nose	9,00	66,2	6,20		63,62	6,20	9,75	13,59	0,21
Tausch et al. [10]	Lead round nose	9,00	41,8	10,60		63,62	10,60	16,66	9,26	0,15
Tausch et al. [10]	Truncated cone	9,00	54,5	7,90		63,62	7,90	12,42	11,73	0,18
Tausch et al. [10]	Spire point	9,00	57,9	7,90		63,62	7,90	12,42	13,24	0,21
Tausch et al. [10]	.45 lead sphere	11,46	56,7	9,00	788,05	103,15	**8,83**	8,56	14,19	0,14
Tausch et al. [10]	.45 lead round nose	11,46	37	11,70		103,15	11,70	11,34	8,01	0,08
Tausch et al. [10]	4 mm lead sphere	4,00	68,7	0,47	33,51	12,57	**0,38**	2,99	0,89	0,07

Legend: *d* = bullet diameter, *vth* = reported threshold velocity, *mi* = reported bullet mass, *vol* = spherical bullet volume, *a* = cross-sectional area, *mic* = corrected bullet mass, *S* = sectional density, *Eth* = threshold energy

Note: Figures in bold have been corrected from the original publication. The reference bullet used in this article is inside a frame. Bullet "lead" alloy density = 11,2 g/cm^3 . Steel density = 7,9 g/cm^3. The number after the researcher is the literature reference used in the original paper.

Four synthetic materials and eight natural leathers were subjected to tensile and shooting tests. They are listed in table 6 below. The candidate S8b was excluded because the humidity could not be maintained during the tensile tests.

Table 6: Skin simulant candidates

No.	Simulant candidate	Thickness (mm)
R1	Trelleborg SBR2533 nitrile rubber.	2
R2	Trelleborg NR2645 natural rubber	2
R21	Trelleborg NR2645 natural rubber	1
R3	Teknikum 662830 chlorosulfonated rubber	2
S1	Moose hide, chrome tanned and through dyed. Light pigmentation finish	1.3-1.5
S2	Moose hide, chrome tanned and through dyed aniline leather	2.0-2.2
S3	cowhide, chrome tanned and through dyed. Light pigmentation finish	1.2-1.4
S4	cowhide, semi-finished upholstery “crust”, chrome tanned and through dyed. Surface ground	0.9-1.1
S5	cowhide, semi-finished upholstery “crust”, chrome tanned and through dyed. Surface not ground	0.9-1.1
S6	cowhide, finished upholstery leather, chrome tanned and through dyed aniline leather.	0.9-1.1
S7	cowhide, semi-finished chrome tanned upholstery ”crust”. Not treated to final softness	0.9-1.1
S8	chrome tanned pig hide	1.41
S8b	as S8, but conditioned in climate chamber to Rh 70%	

The material candidate thicknesses were measured using a Mitutoyo No. 293-805 digital micrometer with 5-10 N measuring force. Skin samples S1 - S8 were subjected to separate tensile testing. Five test specimens were cut using a dumbbell shaped specimen cutter. The resulting specimens were 75 mm long with 4 mm wide and 25 mm long thin section. Two of the five specimens were cut at 90^{o} angle to the remaining three to compensate for the possible effect of directional orientation of collagen fibers and Langer lines [Edwards and Marks 1995, Bader and Bowker 1983]. The testing temperature was +23 ^{o}C and relative humidity 28 %. The tensile test was done using an Instron 4204 material tester with 1 kN load cell. The crosshead speed was 50 mm/min and the initial distance 50 mm. Data acquisition rate was 6.667 points per second. The testing method designed to be as close to that of Vogel (1987) as feasible [Vogel 2004 personal communication].

The shooting test was a partial repetition of an earlier test with human cadavers [Missliwetz 1987] using 4.5 mm lead spheres shot with an air rifle from the distance of 5 m. The simulant candidates were attached on the surface of a 10% gelatine block using PVC-LMF film (kitchen wrap) of 11 µm thickness and 1.25 g/cm^3 density. The projectile velocity was measured at 2.5 m and adjusted with deceleration to obtain the impact velocity. The purpose of the test was to find a regression function to indicate the theoretical threshold velocity *vth* required for penetration.

6.5 Paper V - Measurement of Kinetic Energy Dissipation with Gelatine Fissure Formation with Special Reference to Gelatine Validation

There are three distinctive methods for calculating the dissipated kinetic energy *Ed* from the fissures formed in ballistic gelatine.

The Fissure Surface Area (FSA) method by Knappworst [Sellier and Kneubuehl 1994 pp 192-194] suggests that

[17] $$\Sigma r_i = c * (E'_{tr})_i$$

, where Σr_i represents the sum of all crack lengths at a certain cross-section of the gelatine block. C is a constant and E'_{tr} is the kinetic energy the projectile dissipated into the section *i* of the block. Thus, the sum of all lengths of all cracks in section *i* is claimed to be proportional to the energy dissipated into that section.

For a bullet channel of length *lw* the energy ratio number RE_{FSA} can thus be estimated as:

[18] $$RE_{FSA} = \Sigma RE_i$$

, where *REi* is the ratio number for a section *i* and

[19] $$RE_i = \Sigma r1_i * lw_i + (|\Sigma r1_i - \Sigma r2_i| * lw_i/2)$$

,where r1and r2 are the Σr for impact and exit sides of the section respectively.

The Total Crack Length Method (TCLM) [Ragsdale and Josselson 1988] estimates temporary cavity size from the fissures assuming that the fissures have been formed as sections of the circumference of the maximum expansion, i.e. temporary cavity of the bullet channel. Therefore the radius of the temporary cavity is:

[20] $$r_{tc} = \Sigma r / (2 * \pi)$$

and RE_{TCLM} can be expressed as the sum (Eq. 18) of all volumes of temporary cavity of the section:

[21] $$RE_i = \pi * lw * (r1_{tc}^2 + r1_{tc} * r2_{tc} + r2_{tc}^2) / 3$$

The Wound Profile Method (WPM) [Fackler and Malinowski 1985] takes two largest cracks and adds their lengths r_{max1} and r_{max2} together to produce an estimate of the temporary cavity diameter. We thus obtain:

[22] $$r_{tc} = (r_{max1} + r_{max2}) / 2$$

and the RE_{WPM} as in Eq. 21 above.

The primary purpose of the study was to find out which method would give the best correlation with the actual measured *Ed*. Non-deforming bullets in calibres 9x19 mm and 7.62x39 mm were shot into ballistic gelatine measuring impact and residual velocities. In order not to waste energy on the possible impact caused motion of a gelatine block the block was tied to place using a “shroud” made of elastic cloth. The shroud also simulated the cavitation suppressing effect of surrounding tissue. After shooting the gelatine blocks were cut into 50 mm sections and the fissures measured using all three methods. The obtained comparison figures were correlated with the measured values of *Ed*.

The secondary purpose of the study was to validate the velocity retardations with the corresponding values from the pig tests in paper III. Previous validations of ballistic gelatine found in literature are of somewhat dubious nature due to the fact that the gelatine preparation and verification process is inadequately described and most of the validations were done using steel spheres at very narrow velocity distribution.

The test setup is shown in figure 15.

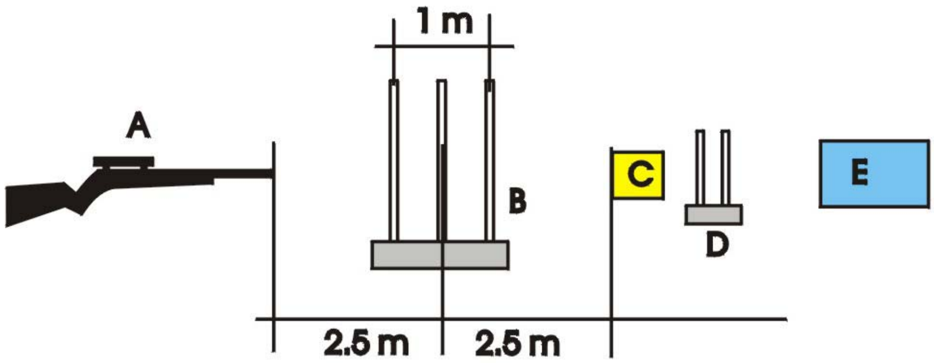

Figure 15 Testing arrangement. A – weapon, B – impact velocity measurement, C – gelatine, D – residual velocity measurement and E – backstop of cellulose wadding

6.6 Statistical methods

6.6.1 Paper II

Variable *Lp/Vi* (penetration in mm divided by impact velocity in m/s) was calculated for every shot.
Significance of difference of means was tested with Mann-Whitney test for independent samples with 95% confidence level using SPSS statistical analysis software.

In addition the process reproducibility was analysed as follows:

- difference between impact directions (homogeneity of block) with Kruskal-Wallis test
- normalised regression function for pellet penetration Lp and correlation coefficient were estimated using the least square method
- standard error was calculated
- estimate for minimum and maximum acceptable Lp was established

Note: As the naming convention has evolved during the research, there are slight differences between the original papers and the naming convention presented in chapter 2. For example *Lp/Vi*
is the same as *lw/vi* in chapter 2.

6.6.2 Paper III

Microsoft Excel 2000 version 9.0.3821 SR-1 was used for statistical analysis. Mean values and standard deviations were calculated. Mean values were compared with two-tailed t-test using 95% level of confidence.

Frequency distributions were formed by grouping the observations of debrided tissue (*mdebc*) into classes according to both energy dissipated per unit length of wound channel (*Ed/lw*) and energy dissipated per unit penetration time (ballistic event) (*Ed/tbe*). The latter was considered important in order to see the effect the event speed i.e. projectile velocity has on tissue devitalisation. The class widths were arbitrarily chosen in order to obtain classes having at least 4 observations. True mean and standard deviation were calculated for each class.

Pearson correlations between *mdeb* and various ballistic variables were calculated.

Regression functions were estimated for all observations included in the analysis using the least square method. The functions were not adjusted to intersect with (0,0) since even in the theoretical case of a bullet not expending any energy into tissue it still crushes a hole (permanent cavity) thereby destroying tissue. Function type was selected by maximising correlation coefficient with the assumption that the curve must be rising. The functions are shown in figures 1 and 2.

In order to determine the energy expended on deformation regression functions on *mdebc* per total dissipated energy *Ed* were estimated for both non-deformed and deformed bullets.

6.6.3 Paper IV

Microsoft Excel 2000 version 9.0.3821 SR-1 was used for statistical analysis. Mean values and standard deviations were calculated. Regression functions were estimated for all skin samples included in the analysis using the least square method. The Pearson correlations for various proposed skin penetration functions were calculated. The goodness of fit was compared calculating the X^2 (Chi-square) –values.

6.6.4 Paper V

Microsoft Excel 2000 version 9.0.3821 SR-1 was used for statistical analysis. Mean values and standard deviations were calculated. Pearson correlations were calculated for the comparison of kinetic energy estimation methods. The z-test at 95% level of confidence was used to verify the significance of difference between impact velocity normalized bullet decelerations.

7 RESULTS

7.1 Paper I – International law and law enforcement firearms

If the international Law is interpreted from the human rights perspective and *ratio legis*, it needs no changes although the weapons technical wording may be obsolete. This is especially important as technical restrictions on weapons may be easily circumvented using another technical solution.

The need to protect bystanders and the police officer in addition to the offender from unwarranted danger and injury requires *ratio legis* interpretation and sanctions the use of expanding controlled penetration bullets.

A number of technical interpretations of the International Law and recommendations are presented as the basis for assessing the legitimacy of firearm and ammunition types from the injury potential point of view:

- *To avoid superfluous injury and unnecessary suffering to the offender*
  - There must be a maximum for acceptable kinetic energy dissipation for the first 250 mm of penetration in defined tests with accepted synthetic material, for example, gelatine validated to simulate muscle tissue.
  - There must be a maximum for an acceptable viscous criterion of non-penetrating kinetic impact projectiles (baton projectiles) in defined tests.
  - There must be a maximum value for acceptable fragmentation in defined tests (including kinetic impact projectiles).
  - There must be a maximum for acceptable 'crookedness' of the permanent wound channel in defined tests.
  - No fragmentation bullets shall be used directly against persons.
  - No explosive bullets shall be used directly against persons.
  - No incendiary bullets shall be used directly against persons.
  - Projectiles used directly against persons shall not contain X-ray-undetectable components.

- *To avoid unwarranted risk and injury to uninvolved persons and other officials.*
  - Both the weapon and the ammunition must function reliably as a combination in defined conditions.
  - Ammunition performance must be consistent; in particular, penetration, permanent and temporary cavity formation must be consistent in defined tests.
  - Accuracy and selectivity of weapon and ammunition must provide for a sufficient tactical range and accuracy in various defined conditions.
  - Penetration ability of the standard issue projectile must be controlled with minimum and maximum tissue simulant

penetration in defined tests with a defined maximum for acceptable residual kinetic energy after penetration of 250mm of simulated tissue.
   - A personal side-arm standard issue projectile should not penetrate the body armour worn by the official.
   - Special circumstances may warrant the use of bullets with higher penetration ability.
   - There must be a maximum for acceptable ricochet deflection angle from standardised surfaces and a maximum for acceptable kinetic energy of the heaviest fragment.
   - Functional safety of the weapon must be proven by a) standard test set and b) any necessary weapon specific tests.
   - Visual and tactile markings shall be provided to assist in identification of various types of ammunition under adverse light and weather conditions.
   - For ease of use under stress, the weapon should not require the performance of any fine motor functions in a tactical situation except for loading the magazine and pressing the trigger.

- *To increase availability, multi-purpose systems should be available.*
- *To increase proficiency, the weapon systems should handle with reasonable similarity.*
- *To increase accountability*, it should be possible to trace the bullet back to the weapon that fired it and as a matter of principle, all firearms should be assigned to named officials.
- *Exceptional and grave circumstances may justify deviation from the above recommendations.*

7.2 Paper II – Preparing Ballistic Gelatine – Review and Proposal for a Standard method

The study indicated that homogenous consistent quality ballistic gelatine is easy to prepare. Water temperature had far smaller significance than previously thought. Water acidity variation within the European Council directive recommended limits did not have any measurable effect.

A regression function for the penetration of a 4.5 mm steel sphere was established:

[23] $$lw = 0.594 * vi - 21.92 \pm 5$$

, where *lw* is penetration (mm) and *vi* impact velocity (m/s). This function is presented also in figure 16 below. A standard preparation method of 10% ballistic gelatine was proposed. For more detailed results, please refer to the original publication (paper II).

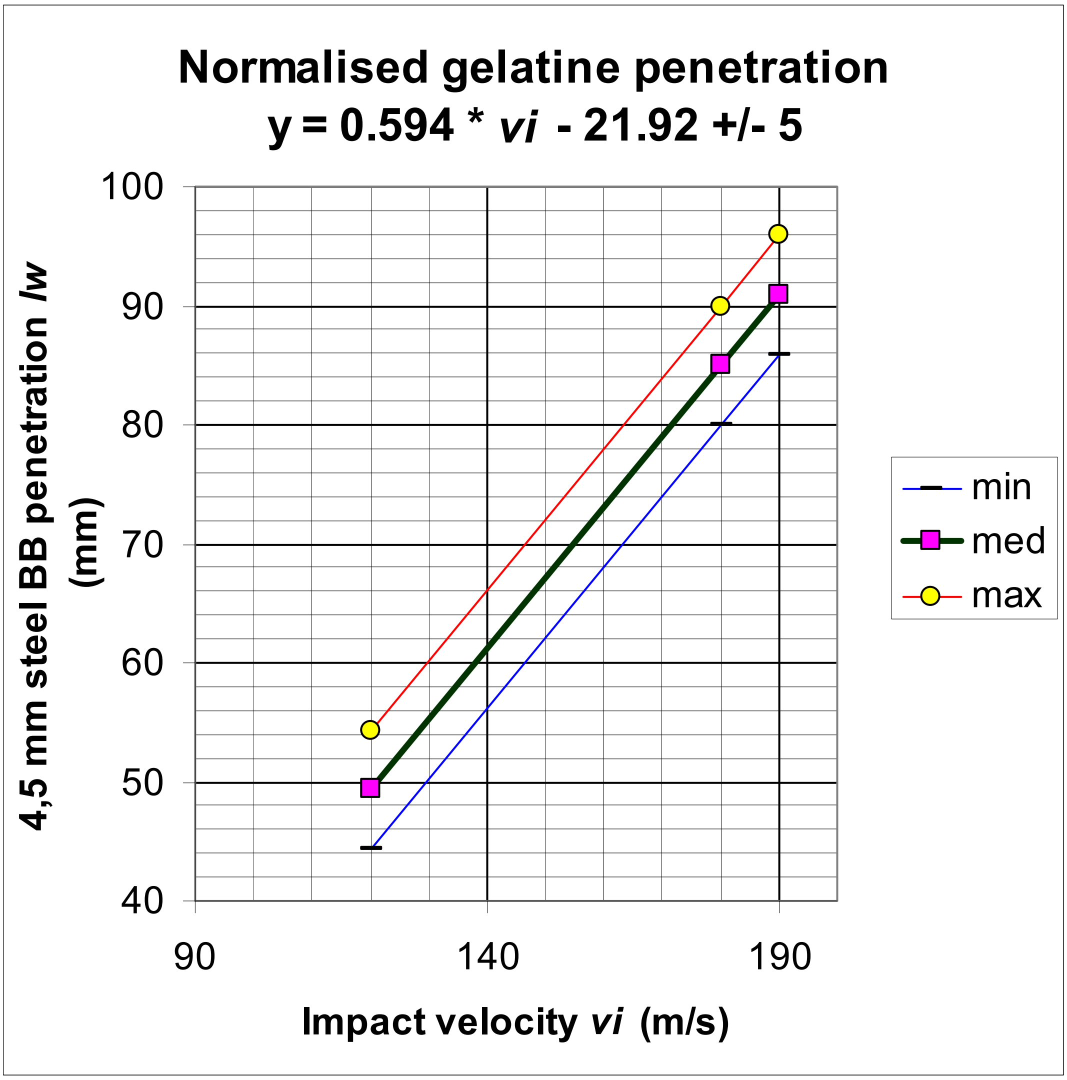

Figure 16: Graphic representation of the gelatine penetration function

This regression function can be used to verify that the gelatine block meets the set requirements for penetration resistance.

7.3 Paper III - Ballistic variables and tissue devitalisation in penetrating injury – Establishing Relationship Through Meta-analysis of a Number of Pig Tests

The primary data from the experiments was made commensurate. The result is shown in table 7.

Table 7: Commensurate amounts of devitalised (debrided) tissue and their correlations with kinetic energy dissipations.

calculated mean values										***mdebc* correlations …**		
Reference	**cal**	**bullet**	***N***	***vr***	***mdebc***	***mdebc/Ed***	***tbe***	***Ed/tbe***	***Ed/lw***	**with *Ed***	**with *Ed/tbe***	**with *Ed/lw***
Albreht et al. [1]	7,92x57	FMJ	4	610,5	87,9	0,14	6,3	100,7	3,1	0,74	0,66	0,67
Albreht et al. [1]	7,62x39	FMJ	8	514,2	152,2	0,22	7,1	99,7	3,4	0,25	-0,32	-0,27
Albreht et al. [1]	7,62x51	NATO	4	520,5	374,5	0,22	6,9	239,6	7,5	0,05	-0,09	-0,12
Berlin et al. [3]	5,56x45	M193	3	747,9	103,3	0,49	2,7	75,6	1,9	1,00	1,00	1,00
Berlin et al. [3]	5,56x45	SS92	10	751,4	187,5	0,65	2,7	101,9	2,6	0,61	0,49	0,47
Berlin et al. [3]	7,62x51	Norma	9	686,4	134,1	0,46	3,3	88,6	2,5	-0,25	-0,54	-0,53
Berlin et al. [3]	7,62x39	Russian	14	555,0	228,3	0,78	4,5	52,4	1,9	0,88	0,85	0,84
Kjellström et al. [15]	9x19	Norma SP	5	322,6	24,5	0,19	4,6	27,7	1,6	0,91	0,89	0,86
Kjellström et al. [15]	9x19	MEN QD *	6	231,2	42,6	0,13	5,0	63,6	4,0	0,67	-0,05	0,11
Kjellström et al. [15]	9x19	Speer GD *	5	208,4	49,9	0,15	5,7	58,6	4,2	0,10	0,10	0,12
Tikka et al. [24]	7,62x39	LapuaS309	11	636,0	25,0	0,18	3,0	50,3	1,5	0,18	-0,43	-0,33
Tikka et al. [24]	7,62x39	tsDpvth	13	635,3	15,4	0,12	2,7	51,7	1,6	-0,16	-0,63	-0,64
Tikka and Seeman [25]	6mm	steel ball	18	485,5	112,0	0,28	3,3	121,5	3,1	0,45	0,38	0,37

Legend: *N – number of observations, vr – residual velocity (m/s), mdebc – commensurate mass of devitalised tissue (g), Ed – dissipated kinetic energy (J), tbe – duration of penetration (ms), lw – length of wound channel (mm)*

The relationship between dissipated energy Ed for unit length of wound channel and devitalised tissue *mdeb* was presented as a regression function:

$$\text{[24]} \qquad \boldsymbol{mdeb = 44.575 * Ed + 10.319 \text{ with } R^2 = 0.293\ (R = 0.54)}$$

The relationship is presented also in figure 17.

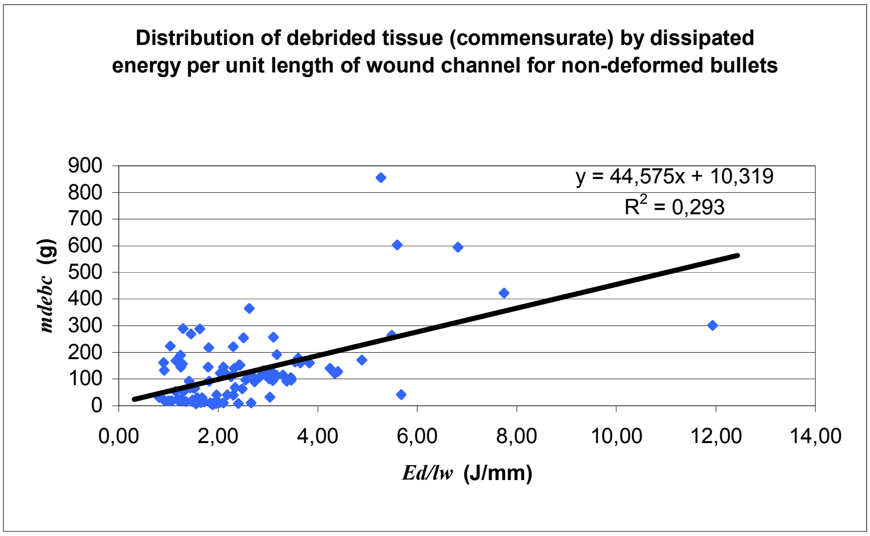

Figure 17: Equation 24 presented in graphic form

The regression function for excised tissue normalised with the speed of energy dissipation gave a lower correlation than Eq. 24 above.

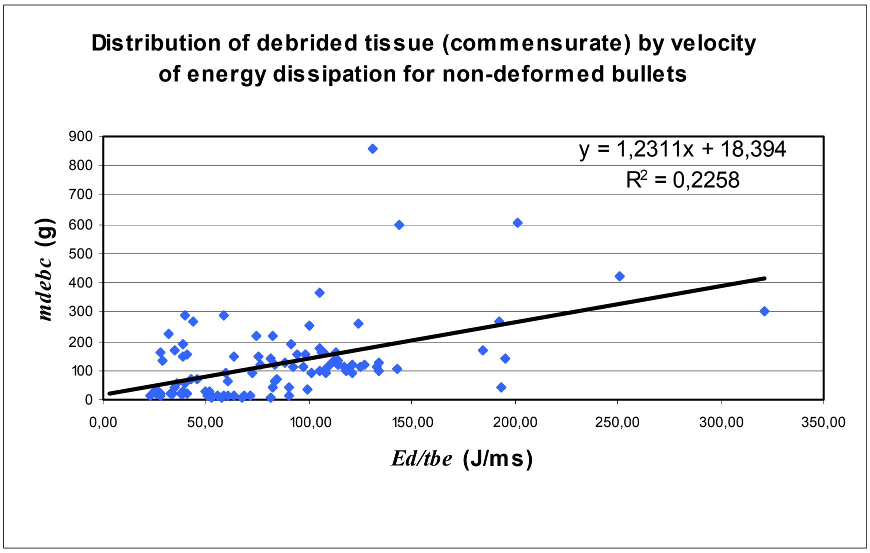

Figure 18: Distribution of the amount of excised tissue by the kinetic energy dissipation normalised with the duration of the event

It was also found out that if very small pigs are used the correlation coefficient is almost 0. This leads to the conclusion that animal tests should use over 50 kg pigs if the ballistic effects are to be studied.

The attempt to quantify deformation energy *Edef* did not lead into any conclusive results. The method of quantification by measuring the energy required to compress the bullets to the same residual length as after shooting into ballistic gelatine remains as the only available and logical one for the time being.

The correlation between *Ed* and *mdeb* was proved. Table 8 presents calculated correlations with various ballistic variables and shows that no other ballistic variable correlates very well with tissue destruction. Some debate can be found in literature on whether and how well the kinetic energy dissipated into tissue correlates with the amount of devitalised tissue [Fackler 1986]. One argument is that since subjective assessment is involved the previous knowledge on presumed kinetic energy of the bullet may affect the surgeon's judgment. Paper III, however, indicates that kinetic energy dissipation per millimetre of wound channel is the best indicator.

Table 8: Correlations of devitalised tissue (*mdeb*) with various ballistic variables.

Ballistic variable	R
impact velocity vi	0,11
impact momentum = $mi*vi$	0,09
impact kinetic energy = $0.5*mi*vi^2$	0,16
impact power = $mi*vi^3$	0,23
dissipated kinetic energy per mm of wound channel	0,54
as above but per ms of penetration	0,48

7.4 Paper IV - Ballistic Skin Simulant

The analysis of threshold velocity equations and experimental data showed that the equation of Mattoo, Eq. 9, gives the best fit with experimental data with Chi-square value of 47.21. This is also shown in figure 19.

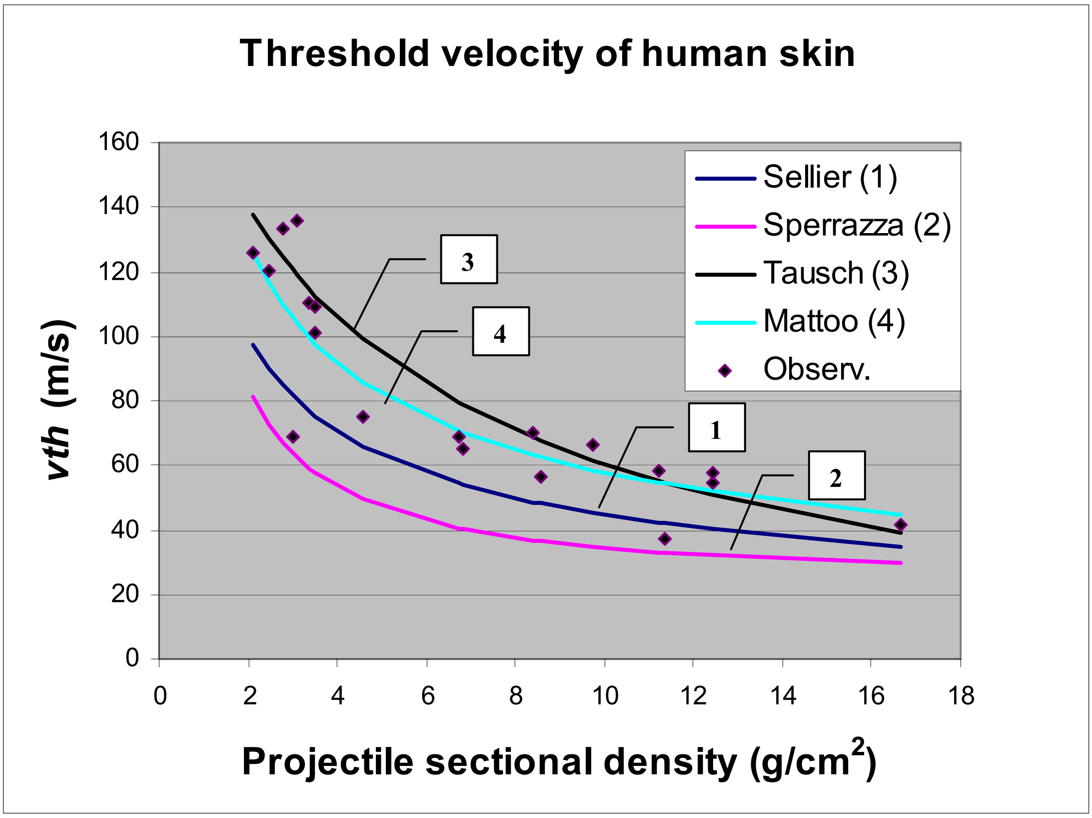

Figure 19: Comparison of various proposed equations for threshold velocity with the observations in table 4.

The tests showed that the simulant with mechanical properties closest to those of frontal chest skin of a 30 year old male was sample no. 7, the semi-finished chrome tanned upholstery “crust” cowhide of 0.9-1.1 mm thickness. Its threshold velocity *vth* = 90.7 m/s, tensile strength 20.89 ± 4.11 MPa and elongation at break 61 ± 9 %. The corresponding values for the target human were estimated to be *vth* = 94 ± 4 m/s with a 4.5 mm lead sphere, tensile strength 18 ± 2 MPa and elongation at break 65 ± 5 %. The individual test results are shown in table 9.

Table 9: Skin simulant candidates and test results

Sample no.	Material	Nominal Thickness (mm)	Measured thickness (mm)	Density (g/cm3)	Hardness (ShA)	Threshold velocity *vth* (m/s)	Tensile strength (Mpa)	Maximum elongation (%)
R1	Trelleborg SBR2533 nitrile rubber.	2	1,94 ± 0.01	1,25	50+/-5 *	92.4	5,0 *	350 *
R2	Trelleborg NR2645 natural rubber	2	1,88 ± 0.04	1,02	40+/-5 *	98.4	17 *	600 *
R21	Trelleborg NR2645 natural rubber	1	1,0 ± 0,02	1,04	40+/-5 *	82.9	17 *	600 *
R3	Teknikum 662830 chlorosulfonated rubber	2	2,10 ± 0.03	1,77	51 *	137.3	10.9 ± 0.11 *	723 ± 6 *
S1	Moose hide, chrome tanned and through dyed. Light pigmentation finish	1.3-1.5	1.2 ± 0.09	0,59		48.8	26.39 ± 9.28	82 ± 8
S2	Moose hide, chrome tanned and through dyed aniline leather	2.0-2.2	1,72 ± 0,05	0,60		test aborted	11.92 ± 1.54	84 ± 11
S3	cowhide, chrome tanned and through dyed. Light pigmentation finish	1.2-1.4	1.23 ± 0.11	0,64		103.4	15.47 ± 3.06	50 ± 3
S4	cowhide, semi-finished upholstery “crust”, chrome tanned and through dyed. Surface ground	0.9-1.1	0.85 ± 0.07	0,60		90.3	14.75 ± 4.59	50 ± 13
S5	cowhide, semi-finished upholstery “crust”, chrome tanned and through dyed. Surface not ground	0.9-1.1	0.97 ± 0.12	0,56		78.2	14.16 ± 2.62	61 ± 12
S6	cowhide, finished upholstery leather, chrome tanned and through dyed aniline leather.	0.9-1.1	0.98 ± 0.03	0,65		96.0	14.18 ± 5.64	65 ± 7
S7	cowhide, semi-finished chrome tanned upholstery ”crust”. Not treated to final softness	0.9-1.1	0.92 ± 0.03	0,56		90.7	20.89 ± 4.11	61 ± 9
S8	chrome tanned pig hide	1.41	1.25 ± 0.07	0,62		116.1	14.27 ± 3.62	51 ± 11
S8b	as S8, but conditioned in climate chamber to Rh 70%					135.4	†	†

* values announced by the manufacturer
† not measured. Conditioning could not be maintained for tensile testing

The fact that the chosen simulant is a natural product will introduce some error which can be considered acceptable. No synthetic material matching the mechanical properties of human skin was found.

Sample R21, the 1 mm thick natural rubber showed similar threshold velocity, but leaves some doubt since the elongation at break and tensile strength values differ greatly from those of human skin.

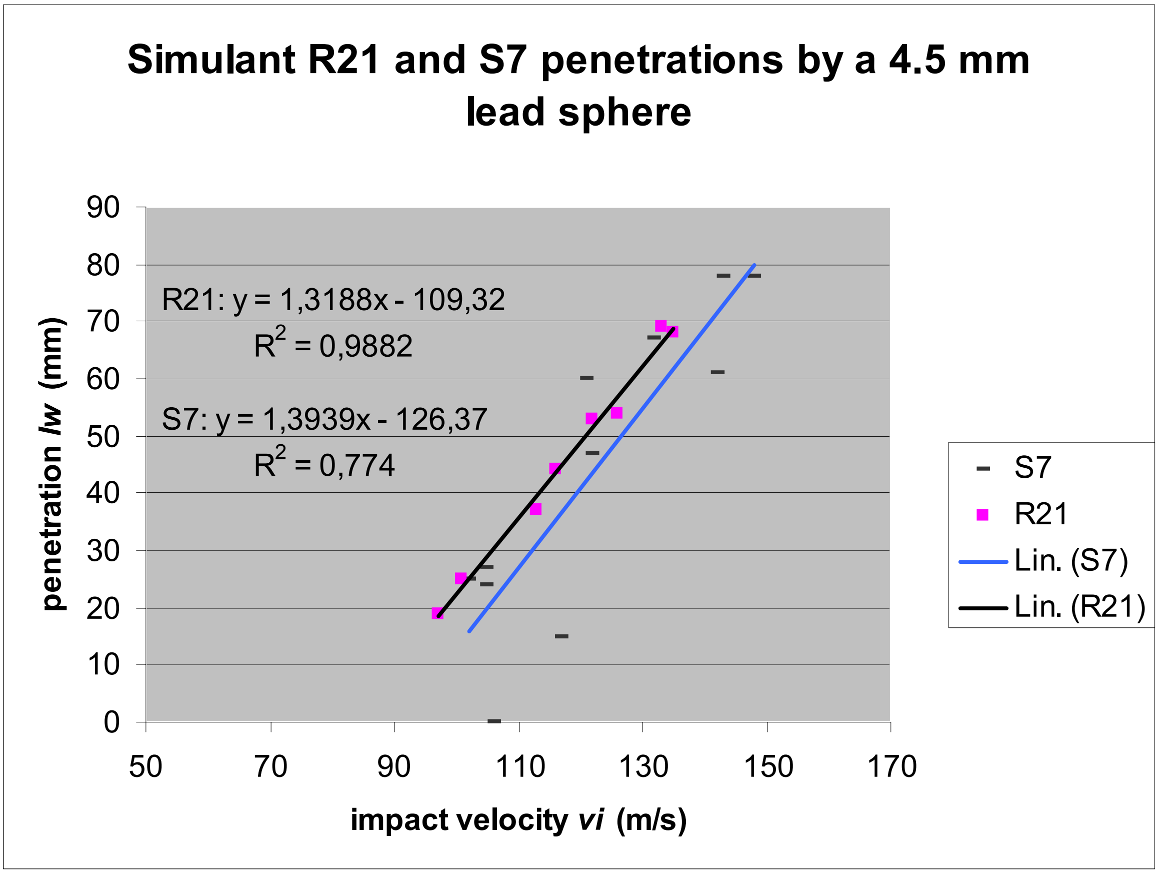

Figure 20: Regression functions for human skin simulant threshold velocity

7.5 Paper V - Measurement of Kinetic Energy Dissipation with Gelatine Fissure Formation with Special Reference to Gelatine Validation

The Wound Profile Method (WPM) [Fackler and Malinowski 1985] measuring only the two longest fissures per a cross section of gelatine was found to give the best correlation of 0.89 with the measured amounts of dissipated kinetic energy. The Fissure Surface Area (FSA) (Knappworst-method) [Sellier and Kneubuehl 1994] and Total Crack Length methods (TCLM) [Ragsdale and Josselson 1988] gained 0.51 and 0.52 respectively.

The experimental results were also compared with those from pig tests with the same 9x19 mm Norma and 7.62x39 mm full jacket bullet types. This comparison is shown in figures 21and 22 below.

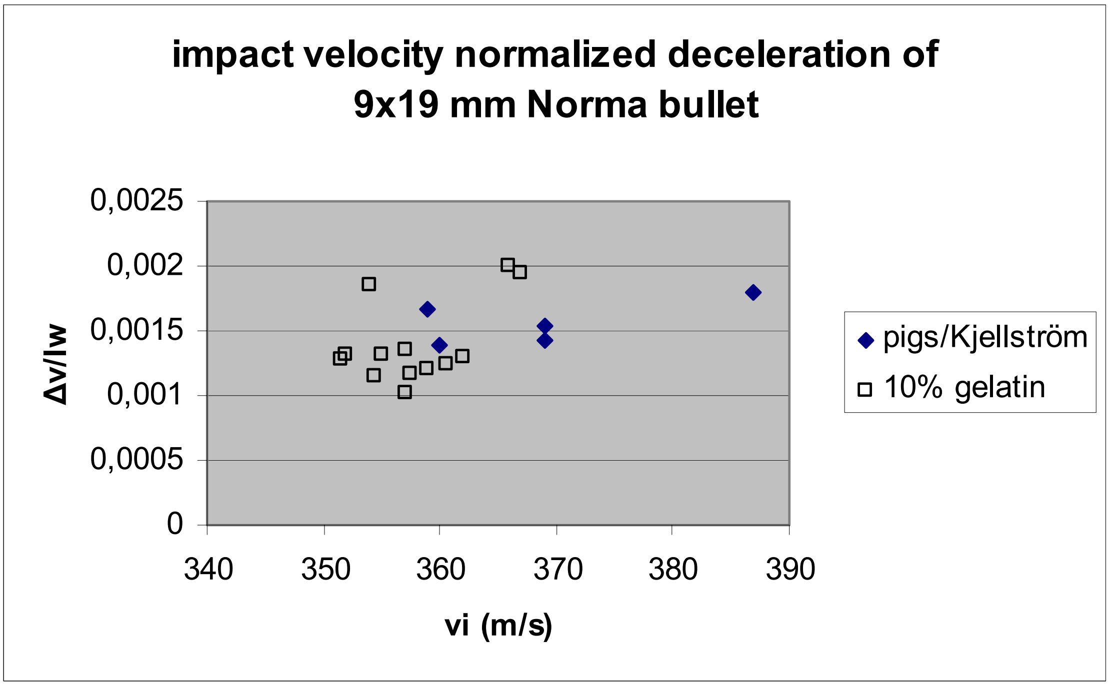

Figure 21: Deceleration comparison of the 9x19 mm Norma bullet

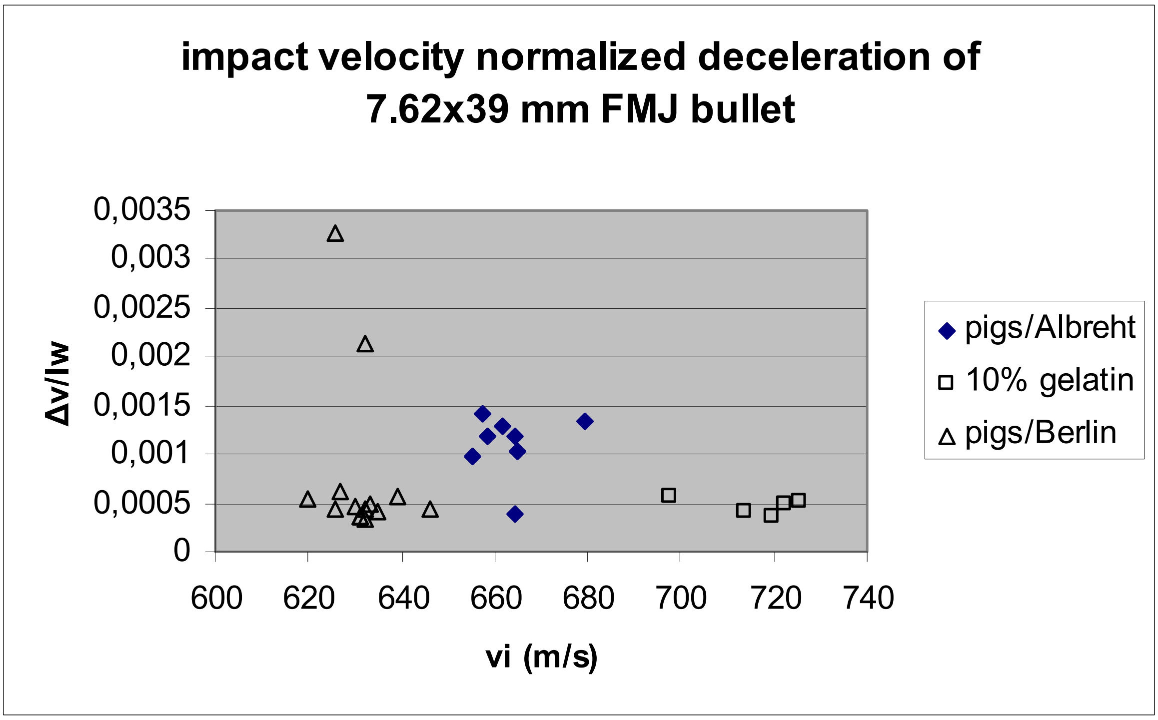

Figure 22: Deceleration comparison of the 7.62x39 mm FMJ bullet

Using the z-test at 95% level of confidence no difference between impact velocity normalized bullet decelerations could be determined for the 9 mm bullet used. The same test showed significant difference for 7.62 mm bullets. That, however, can be hypothesized to be the result of the bullet's tendency to tumble in non-homogenous living tissue causing significant dispersion of observed deceleration values. The results add further evidence supporting the validity of 10% gelatine at +4 °C as wound ballistic tissue simulant and validate the use of the elastic shroud.

8 DISCUSSION

The significance of this study is in laying a justified basis for valid comparison of law enforcement ammunition injury potential. What is needed and accomplished is a weapons technical interpretation of the international law to set a yardstick for wound ballistic assessment, a standard preparation and validation method of a standard soft tissue simulant, a validated skin simulant and a standard method for measuring and estimating the amount of devitalised tissue. None of these have been available so far.

In a review of the scientific literature, there is very little coherence and coordination between theoretical and medical research of wound ballistics. The results of one field are very rarely cross-verified.

8.1 Firearms and ballistics

The firearms are continuously being made more sophisticated although very few really new inventions have been made during the past decades. Internal, intermediate and external ballistics are very well covered by established laws of physics.

One area of development in the realm of intermediate ballistics, however, requires some attention. When the bullet exits the barrel an ear damaging loud bang can be heard and the high-pressure gases cause the bullet to yaw [Moss et al. 1995]. Considering that the distances in law enforcement operations may be rather short and that an unstable bullet may be more prone to disintegrate and cause unnecessary injuries and perform in an inconsistent manner, the bullet should be reasonably stable at already a few metres away from the muzzle of the gun. It can be hypothesised, that controlling the exit gases would be the means towards greater bullet stability. The mechanisms that may be used are a muzzle brake, muzzle flash extinguisher and a sound suppressor [Moss et al. 1995]. The latter is beneficial also from the occupational health point of view as it reduces the loud bang [Kyttälä and Pääkkönen 1996, Toivonen 2004] which is harmful to ears especially in an operational situation where no hearing protection can be used.

As an effective sound suppressor tends to be rather long and heavy [Kyttälä and Pääkkönen 1996, Toivonen 2004] and therefore rather awkward in police operations more research is required in order to find better technical solutions that stabilise the bullet and reduce the muzzle bang to a more tolerable level.

From the wound ballistician's point of view the information offered by ammunition manufacturers is sadly lacking [Nennstiel 1996 and 2004]. Even ballistic coefficients are sometimes difficult to get and some doubt is unavoidable as to the reliability of the figures given. Axial and transversal moments would be required to analyse the bullet's stability in various conditions, but are even more rarely available. The international organisations doing evaluation of the ammunition should insist on availability of a detailed ammunition data sheet with verified design parameters.

Most of the current military bullets have been designed to fly stably. Little attention seems to have been paid upon wound ballistic stability. Yet both design objectives can be achieved and are in no conflict. Using the heavier metals in the front and lighter metals to fill the rear end of the bullet, the centre of gravity can be moved ahead of the point of pressure creating a penetration stable bullet. Combining this construction with expansion would also make the bullet to have the controlled penetration desirable for law enforcement operations. Law enforcement bullet design, especially in rifle calibres, requires more research.

8.2 The International Law

Although the International Law [UN 1977] requires establishment of a review system to ensure the compliance of only a new military weapon with the law, it would be slightly extreme to say that the same does not apply to law enforcement. This view is strongly supported also by the United Nations Basic Principles of Use of Force and Firearms by Law Enforcement Officials [UN 1990]. Although legally only a recommendation [de Rover 1998], it repeats the prohibition to use firearms and ammunition that cause superfluous injury. Furthermore, it recommends that the law enforcement officials be trained on the effects of the weapons they use.

The essential principles of use of force are those of legality, necessity and proportionality [de Rover 1998]. The proportionality to the prevailing threat binds the assessment of legitimacy partially with the incident and means that legitimacy of a weapon cannot entirely be determined beforehand and out of the context of the incident. Grave and exceptional circumstances may also necessitate the use of exceptional means that in the particular case can be considered to be in acceptable proportion to the prevailing threat.

Looking at the injury potential from the perspective of the primary target person and ignoring the bystanders and the law enforcement official would reveal only a part of the picture. Looking only at wound ballistics would in the same way address only a part of the problem. If unwarranted injuries are to be avoided the accident susceptibility of both the firearm and the ammunition designs has also to be assessed [Jussila 2003].

In view of the continuous development of weapons technology the only sensible way to interpret the International Law is by *ratio legis* i.e. not by what the law says but by what it means. Considering the need to protect non-involved bystanders from harm the law seems to accept the use of controllably expanding bullets in law enforcement operations [Paper I]. This, however, introduces another problem and many new questions. What can be considered law enforcement? Where can the borderline between law enforcement and military operations be drawn? Is the safety of the non-involved less important in military operations? Should expanding controlled penetration bullets be sanctioned also for certain military operations? Considering that no accepted, comprehensive and validated standard exist for the assessment of the injury potential, is there any proof of substantial power of evidence that the current accepted military bullets really are less injurious even to the primary target than well designed expanding bullets? This is a case not proven and requires more research.

8.3 Penetrating projectile induced injury

The wounding effect of a penetrating bullet depends on the location of the hit and the track of the bullet in a human body. The wounding potential should not be confused with incapacitation potential and depends on the bullet's capability to penetrate and transfer energy to the tissues. To bring the concept of wounding to a measurable level it might be better to speak about unrecoverable injury and non-viable tissue.

There seems to be little doubt about the relationship between dissipated kinetic energy and tissue devitalisation [Berlin et al. 1976 and 1979, Janzon and Seeman 1985, Janzon 1988, Tikka 1989, Janzon 2004, paper III]. There is, however, little information about the effect of an acoustic wave on the nervous system. A well planned research effort should be done to measure the properties of acoustic waves produced by different types of bullets and to verify their immediate and delayed effects on the nervous system. This could maybe lead to complementing the simulant system with acoustic sensors and pressure transducers.

A unanimous view exists on the increased injury caused by bullet fragmentation (see 4.3.2). The surgeon must weigh the possibilities of removing a fragment against the hazards of leaving it in place. The problems may also appear many years later if a fragment is carried by blood circulation into a vital organ [Mattox et al. 1979, Fackler et al. 1984, Braun 2003, Corbett et al. 2003]. There is, however, no proposed method of quantifying the injury increase. Even though the animal tests analysed in paper III stated that a number of the bullets deformed and fragmented during penetration, no information on the degree of fragmentation and deformation was recorded. Therefore, it was impossible to draw any conclusions in this respect. As many bullets will fragment during penetration of tissues quantification is necessary if injury potential is to be assessed. As the mass of the fragments can be measured as the difference of impact and retained masses of the bullet and the impact velocity is known the kinetic energy possessed by the fragments E_{fr} can be calculated to some degree of accuracy. Considering the added injury induced a coefficient of fragmentation c_{fr} is used to multiply E_{fr}. An arbitrary value of $c_{fr} = 2$ is proposed. Further research is needed to reach a better estimate of increased injury induced by bullet fragmentation.

Fragmentation can also be designed into the bullet to reduce the amount of residual energy. If part of the bullet remains in the target and the rest exits in several fragments the danger to bystanders is reduced because deformed fragments have less mass, high drag and lose their velocity and energy fairly rapidly. This design principle can, however, be interpreted as a violation of the *maux superflus* –principle and is not easily acceptable [Leppäniemi 2004 personal communication, Janzon 2004 personal communication]. As use of firearm by a law enforcement official may require shooting through an intermediate barrier like a window, a bullet prone to fragment will introduce the possibility of inconsistent performance and unexpected results. Considering the injury mechanism and the hazards involved it may, however, be recommended that law enforcement bullets should not show any significant fragmentation [Paper I].

The exiting bullet makes an exit wound which is usually larger than the entry wound as the bullet has already deformed or may be in an unstable state exiting base or side first. The result will in many cases be a star like rupture [Janzon 1983, Janzon 1997]. The difference between entry and exit wounds can also be hypothesized with different penetration mechanism. In an entry wound the projectile presses the skin against subcutaneous tissue thus reducing the stretch whereas on exit the skin is stretched outwards from the supporting tissue thus increasing the stretch. As the wound must anyway be opened (debrided) for tissue excision and the skin injuries can relatively easily be corrected [Leppäniemi 2004 personal communication], the entry and exit wound sizes as markers for wound severity cannot be held very significant. A large exit wound should, however, be treated as a warning sign for possible extensive internal injury [Janzon 1997].

In order to cause only the justified injuries the bullet must be inherently accurate and have a satisfactory tactical range. Inherent accuracy means that when the service weapon is mounted on a machine rest, the bullets of the ammunition being evaluated must hit very close to each other at a given range. When mounting a weapon on a machine rest for measurement of the inherent accuracy, care should be taken not to distort the barrel oscillation (see 4.1.2). Tactical range is defined as the range where the bullet flies within ± 2.5 cm of the line of sight (line of aim) in defined weather conditions [Jussila 2001c]. This allows the shooter to concentrate on the task at hand and expect the bullet to hit at the point of aim within that range without the need to waste intellectual resources on pondering about the trajectory of the bullet.

A police officer using a firearm must know what it will do and what not [UN 1990]. As a corollary the bullet must perform consistently in various foreseeable circumstances. A law enforcement bullet must therefore have sufficient tactical range and kinetic energy, yet avoid excessive injuries and especially danger to bystanders.

Increasing bullet velocity gives a longer tactical range. It will also increase kinetic energy. If most of the energy is not dissipated into the target or deformation of the bullet, the result is increased danger of injury to bystanders due to excessive penetration and high residual velocity and energy of the exiting bullet. If most of the energy is dissipated into the target person the result will very often be increased injury [paper III]. If the bullet velocity is reduced the tactical range shortens and the bullet may not perform consistently. This may in turn prolong the gunfight and significantly increase the danger to both bystanders and law enforcement officials.

A bullet that completely penetrates or misses the target will eventually hit something and possibly deflect from the impact surface becoming a ricochet. An indirect danger of injury to bystanders is induced by a ricochet. Assessment of the danger must take into account the fact that a ricochet is usually deformed by the impact and in a ballistically unstable state flying into an unexpected direction. A police officer firing a weapon is psycho-physiologically able to control a certain limited sector of vision [Solomon 1989] due to what is called tunnel vision caused by the stressful situation. Before shooting he or she can to some extent ascertain of the safety of this control sector. The steeper the angle of deflection a ricochet has the more probably it exits the sector and increases the danger to bystanders. Schyma and Placidi [1997] made experiments on the subject. Ricochet assessment was also a part of the Police Technical Centre test series [Jussila 2001c]. An ideal law enforcement bullet should not fragment during glass or other light barricade and subsequent soft tissue penetration. It should, however, lose most of its kinetic energy into deformation or disintegration on impact with a hard substance like street surface or brick wall in order to minimise the danger from ricochets.

A bullet must do every time what is expected of it in a surgically accurate manner, nothing less, nothing more. This is the optimisation problem faced when ammunition are evaluated to find the suitable ones for law enforcement use [Jussila 2001c].

Tissue devitalisation also seems to depend on the size of the target being smaller in limbs of smaller size [Janzon et al. 1988 and 1997] resulting in scale dependence. Based on the conclusions in paper IV the combination of too small test animals, high energy projectiles and measurement inaccuracy [Tikka et al. 1982] could lead to unreliable results that cannot be scaled.

A standard test set producing wound ballistic data for legitimacy assessment of law enforcement firearms ammunition is needed. It should comprise of repeatable and relatively easy to use tests that give realistic figures for comparison of different types of ammunition. The variables examined should form a bridge between simulation experiments and real life surgical operations in such a way that the figures are meaningful for the surgeon who can give feedback for further improvement of the test set and its biofidelity.

None of the injury scoring systems used today seem to suit to this purpose. The Red Cross Wound Classification does not consider the amount of devitalised tissue. The significance of entry and exit wound sizes can also be debated as far as injury severity especially from the irreversibility point of view is concerned. Therefore it can be used as a starting point but not as a basis for injury classification. The envisioned possibilities for simulating the classification are presented in table 10.

Table 10: Simulation possibilities of RCWC

Variable	Method
E = entry	Skin simulant on soft tissue simulant
X = exit	Skin simulant on soft tissue simulant
C = cavity	Gelatine as soft tissue simulant. Soap does not register permanent cavity.
F = fracture	Gelatine imbedded bone. Soap not suitable
V = vital structure	Gelatine imbedded vital organs. Soap not suitable
M = metallic body	Gelatine as soft tissue simulant. Soap not very suitable

None of the medical databases in use today contain ballistic information relevant for developing and validating a comprehensive simulation system. An Interface Firearms Injury Scoring System – IFISS is therefore proposed. It is an interface definition standardising the data collected both after simulation and during surgical operation. The data should consist of:

Weapon type (if known)
Calibre (if known)
Ammunition type (if known)
Shooting distance (if known)
Impact type (direct/ricochet/through barrier)
Barrier type
Ballistic protection worn
Projectile type (if known)
Projectile retained weight
Projectile degree of deformation
Wound channel length and proximity to vital organs
Entry and exit wound locations
Maximum diameters of entry and exit wounds
Mass of excised tissue
Bone injury classification

The above interface when applied in medical operations, simulant testing and computer simulation would provide for a common bridge between these three worlds. It would establish a system allowing consistent prospective and retrospective analysis that is called for [Yoganandan and Pintar 1997]. The proposed IFISS-scoring could be used as the basis for a common research database serving all areas of research. A conceptual drawing is presented in figure 23. No such system combining the results of all branches of firearms injury research exists today.

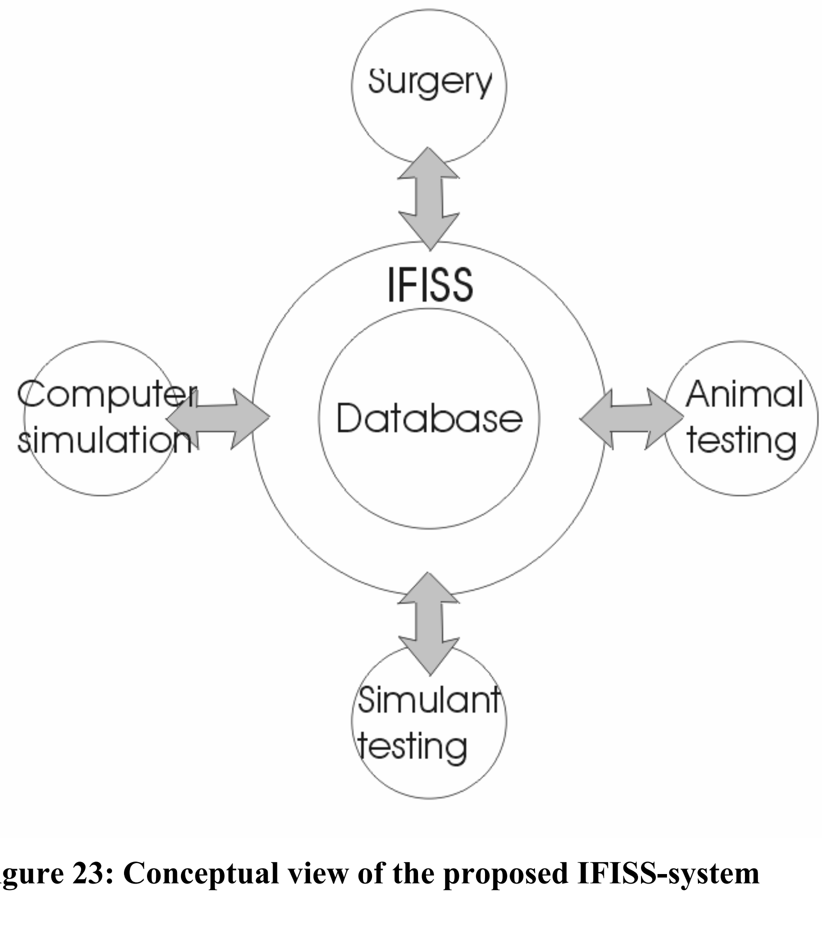

Figure 23: Conceptual view of the proposed IFISS-system

8.4 Simulating bullet interaction using live and natural tissues

Living beings are different and they need to be anesthetised before wounding. The individual differences would mean increasing the number of repetitions in order to achieve statistical confidence. Anaesthesia introduces a source of doubt. Are the physiological reactions unchanged? Is the retardation force of a totally relaxed muscle the same as with full muscle tonus? Using cadavers or organs harvested from cadavers is also problematic. If a person has been dead for some time what changes to the biophysical properties of the organs have taken place? Achieving sufficient power of evidence might be difficult.

8.5 Synthetic simulants

The tissue simulants and their preparation methods have not been standardized making comparison of the reported results somewhat difficult and reducing their power of evidence. To reach the goal of comprehensive and surgery compatible wound ballistic simulation a lot needs to be done. Validation of simulation materials is still at an embryonic stage with only muscle and skin tissue simulants having been validated. Bone simulants have not been validated with human bones. As the purpose is not to simulate wound ballistic events on a pig the simulant system must be brought as close to a human being as possible. It has too often been taken for granted that a pig resembles a human being. An example of this is the specific gravity of muscle tissue quoted to be 1.06. It actually is that of a 100 kg landrace pig. Human muscle tissue specific gravity is 1.02-1.04. A comprehensive study on the viscoelastic properties of human tissues needs to be done in order to develop and validate corresponding simulants.

Wound ballistic testing with tissue simulants cannot be replaced with computer simulation. Power of evidence and needs of quality assurance require that real bullets must be fired upon simulated targets. Computer simulation and modelling are, however, important for learning more about the complex interaction between a projectile and a target. The mathematical possibilities can far faster help to find better protection and bullet designs than experimental research only.

Steel spheres have often been used to achieve precise dosage of kinetic energy dissipation without the unpredictability and added variables of bullet tumbling, deformation and fragmentation. Too far reaching conclusions from the obtained results should be avoided. Without the effect of tumbling, deformation and fragmentation the spheres show a significant correlation between the impact energy and tissue destruction [Fackler 1987]. This may have been occasionally misunderstood as a general law applying to tumbling and deforming bullets as well.

Tissue simulants can be divided into soft tissue, skin, bone and skull simulants. Several requirements for soft tissue simulants have been presented. [Sellier and Kneubuehl 1994, Janzon 1997, Berlin et al. 1983, Fackler 1988a and 1988b, Pirlot et al. 2001]. Some requirements may, however, be in contradiction to the use of a simulant as a measurement tool and the requirements should maybe be modified and complemented as follows:

A good tissue simulant must possess the following qualities:
- similarity in the deceleration of the projectile between the simulant and the living tissue the simulant has been validated for
- similarity in the deformation behaviour of the projectile
- similarity in the kinetic energy dissipation
- kinetic energy dissipation measurability with reasonable accuracy
- extrapolation of temporary cavity diameter
- elastic behaviour similar to living tissue for observation and measurement of temporary cavity formation and tissue compression
- extrapolation of permanent cavity diameter
- reproducibility

The above list of requirements means that the simulant does not need to possess exactly the same biomechanical properties as living tissue as long as the results can be measured and appropriately extrapolated or scaled [Janzon et al. 1988] to reflect what happens in living tissue. In fact a simulant with lower tensile strength than that of muscle tissue might allow for more accurate measurement of the cavities and kinetic energy dissipation; hence the requirement for extrapolation instead of similarity.

Even if soap makes a reasonably good muscle tissue simulant its possibilities in wound ballistic research and especially forensic reconstruction are rather limited. Measuring the degree of bullet fragmentation is an essential part of injury potential estimation. The total weight of the fragments can be found as the difference between impact and retained weights. It, however, neither describes the degree of fragmentation nor the distribution of the fragments in the simulant. Both facts can easily be found when translucent gelatine is used whereas with opaque soap this is not possible without x-ray equipment. If the bullet cannot be found, as not so frequently happens, the retained weight of the bullet can be estimated from the fragments recovered from gelatine.

A deforming bullet uses some amount of kinetic energy for deformation. Paper III presents a method of estimating this energy *Edef* by crushing the bullet into the same length as when shot into gelatine. The method leaves something to be desired as it simply crushes the bullet axially. On impact with soft tissue simulant the open cavity in the tip of a hollow point bullet forces the sides of the cavity outwards. Thus the actual value of *Edef* may be different. Kinetic energy (*Ed*) dissipated into a plastic material like soap will produce a cavity the size of which indicates the distribution of energy along the bullet channel. The *Ed* can be directly calculated by measuring the size of the cavity [Berlin et al. 1982] A similar method could also be applied to the fissures created by *Ed* into gelatine [Sellier and Kneubuehl 1994]. This could render unnecessary the estimation of *Edef* provided that the correlation between the fissure lengths and temporary cavity size reflecting the *Ed* can be proved to be sufficiently high. One attempt has been done to prove it [Ragsdale and Josselson 1988] resulting in fairly low correlations. Although the gelatine used was somewhat dubious (see 4.5.1) the test arrangement was good and should be repeated using well controlled 10% gelatine proposed in paper II and non-tumbling, non-deforming steel spheres as projectiles.

Gelatine seems to be the best basis for producing ballistic simulants for all kinds of human tissue types. Contrary to common belief good quality gelatine can be prepared quite easily [paper III]. Polymer technology could be used to produce synthetic skin tissue. Simulation of remote effects on blood vessels and nerves could be done, but suitable simulant materials must first be found and then agreed upon.

Although gelatine seems to be the best soft tissue simulant for research on bullets this may not be the case with arrows [Karger et al. 1998]. This is probably due to the difference in cavitations. A relatively slow arrow does not cause significant cavitation. Therefore friction against the long shaft of the arrow becomes a significant factor. A faster and shorter bullet causes the simulant to cavitate away from its sides. It should also be noted that isotropic materials like gelatine and soap fail to take into account the heterogeneous nature of tissues and their different densities [Bartlett 2003]. Compound simulants consisting of layers of different mechanical properties can be made of gelatine. It is also probably possible to develop gelatine based tissue simulants that are suitable for all kinds of penetrations and also microscopically and of pathological reactions resemble soft tissues. No such substances are, however available at present and more research is required.

Gelatine, as it is today, is a measurement tool which acts upon the bullet in the same way as soft tissue and records the kinetic energy dissipation profile. That can then be used for estimating tissue devitalisation. Considering the prevailing controversy on the significance of temporary cavity size, this can to some extent be debated. If a consensus on standard tissue simulants is reached, cavitation, pressure transfer and biomechanical properties can easily be measured and standardised as well.

Wound ballistic research with muscle tissue simulant produces information on what happens when a bullet penetrates muscle tissue. A human being is very complicated organism. Simulating penetration of a human being and effects on various tissue types is undoubtedly possible but very difficult. Until more complex simulant combinations have been validated skin, muscle tissue and bone simulants are all we have.

8.6 Considerations on the design of a simulation scenario

When injury potential is to be assessed the test method should have a strong relationship with some foreseeable tactical situation. On the other hand all possible scenarios cannot possibly be tested before any ammunition can be accepted for service use. We have to concentrate on the essentials.

The shooting distance is one of the important issues of test design. In principle it should be the same as the foreseeable minimum distance of tactical use. For example a 9x19 mm pistol and submachine gun should be shot at 5 to 10 m, a 5.56x45 mm assault rifle at 10 m and a 7.62 mm sniper rifle at 50 to 100 m. Only the last one presents a problem for testing. Long distance makes accurate bullet placement increasingly difficult and walking to the simulant setup and back to the gun very laborious. The solution is to shoot the bullets at shorter range using an impact velocity that is the same as when shot with a sniper rifle at 100 m.

Simulation of long range shooting can technically be achieved in two ways. Reducing the amount of powder in the cartridge or using a shorter barrel will result in lower velocities. A bullet may, however, not be fully stabilized at a short range and may subsequently have an exceptionally large yaw angle upon impact, which may cause the bullet to tumble and disintegrate even if it normally would not do that. If simulation of shooting distance is used, it is recommended that the stability of the bullets is verified by shooting through a cardboard target prior to testing or by placing a cardboard witness sheet in front of the simulant. If the yaw angle seems to be unacceptably large, there may be something wrong with the barrel, the bullet and the twist of the rifling may be incompatible or the bullet simply does not stabilize sufficiently at that particular distance. In the last case the distance needs to be increased. A 5.56x45 mm assault rifle may be used at very short ranges and such distance adjustments cannot be seen necessary for the assessment of maximum injury potential.

9 CONCLUSIONS

Papers I to V of this dissertation provide an unbroken chain of evidence from the requirements of the International Law to a proposal for a standard method to assess the injury potential of penetrating firearms ammunition.

Paper I interprets the legal obligations of the International Law into weapons technical requirements. It was found that the intent, *ratio legis*, of the International Law is to prevent unwarranted and superfluous injury and suffering, not to prohibit any technical bullet designs *per se*. Technical terminology is used only to illustrate the intent. Meaningful enforcement of this intent is impossible without an agreement on a validated and realistic assessment method which does not view injury potential in isolation but also takes the relevant variables of a firearms incident into account.

Paper II proposes that 10% gelatine be used as a standard muscle tissue simulant. It also studies the effects of major preparation variables and proposes a precise method to prepare the simulant.

Paper III defines the correlation between kinetic energy dissipation of a penetrating bullet and the tissue devitalisation it causes.

Paper IV defines the mechanical properties of the human skin relevant to projectile penetration and proposes a simulant material to complement the muscle tissue simulant when testing low velocity projectiles, ricochets and post penetration dangerousness of a projectile.

Paper V compares the methods of measuring kinetic energy dissipation from the bullet channel formed into gelatine. It also proposes the use of a flexible "shroud" to hold the gelatine in place and suppress cavitation in the same way the surrounding tissue does in a human body.

Even so the simulation fidelity needs improvements that can be obtained through coordinated and systematic research. Until then the method is only the best we can do at the moment. The coordination of the research requires not only co-operation between surgeons and wound ballisticians to bring together the medical and weapons technical expertise but also a common database to store the information in. No such system exists today.

Based on papers I to V and above conclusions a proposal for a standard method of assessing the injury potential of a penetrating projectile is presented as the major conclusion of this disseration. The method takes into consideration the injury potential to all counterparts of a firearms incident, not only to the perpetrator as has been the case before.

The assessment method needs a formal process which interprets the results both from the legal and moral points of view weighing the acceptability of a weapon in the society. This is mandatory for the weapons of war. Morally it is no less compelling for the weapons of law enforcement that the society has given the authority to use force against its own members for the protection of its own members.

10 RECOMMENDATION FOR A STANDARD ASSESSMENT METHOD

The standard wound ballistic assessment method proposed is intended for providing information that can be used for assessing the legitimacy of bulleted ammunition for law enforcement purposes. The method consists of a basic reference test, a ricochet test, an entry-exit wound test and a mathematical model for injury potential assessment.

The method does not determine the legitimacy but gives comparison figures on which the decision can be based. The comparison figures are not precise forecasts on the amount of tissue destruction but relative numbers derived from it.

The model is based on interpreting injury in terms of devitalised tissue (*mdeb*). A firearms incident invariably has three parties: the law enforcement official, the offender and the non-involved bystander. The offender is the primary target of a bullet fired by a law enforcement official and the injury is caused by a penetrating bullet and increased by bullet fragmentation.

The same naturally applies to a bystander if the bullet misses the offender and hits a bystander instead. This model, however, assumes that the injury potential to a bystander is a result of residual energy after penetration of an offender and of ricocheting bullet. A ricochet is considered to be more dangerous i.e. having greater injury potential the more it is deflected from the impact surface. This is due to the fact that a steeply deflecting ricochet flies into the direction not intended or controlled by the police officer. It more probably hits a bystander and is therefore potentially more dangerous.

The simulation is based on using a 25 cm gelatine block for basic reference test (torso shot) and its half 12.5 cm block for entry/exit wound test (extremity shot). The 25 cm length has been chosen for the following reasons.

1. It is improbable that in a shooting incident the opponents stand facing each other. Police officers are taught to stand at an angle (the "L"-stance) towards a customer. In a threatening situation a person subconsciously seeks for a stable stance which means turning into an angle towards the threat. It is therefore probable that a bullet passes through a torso diagonally instead of a straight angle.
2. Shooting through 25 cm of simulant gives more complete picture of the bullet's behaviour and energy transfer characteristics in tissue. Even if vital organs are fairly close to the skin it is not insignificant if a bullet dissipates most of its kinetic energy for example 10 cm before exiting.

It is understood that the method does not directly address the proximity of vital organs. Taking this into account would also introduce the need to include hit placement probability calculus making the method excessively complex. The purpose is not to produce precise physiological forecasts on the injury but to give realistic comparison figures by using validated tissue simulants.

10.1 Materials

Soft tissue simulant: 10% ballistic gelatine in 20x20x25 cm blocks prepared, verified and used as in paper II.
Skin simulant: 1 mm upholstery “crust” cowhide defined in paper IV.
Ricochet impact surface: Concrete
PVC-LMF film (kitchen wrap) of 11 µm thickness and 1.25 g/cm^3 density

10.2 Basic reference test

The test consists of shooting through a 25 cm primary block of gelatine, measuring the residual velocity and catching the bullet with a secondary gelatine block complemented with skin simulant. The skin is held in place with one layer of PVC-LMF film. Arrangement is shown in figures 24 - 27.

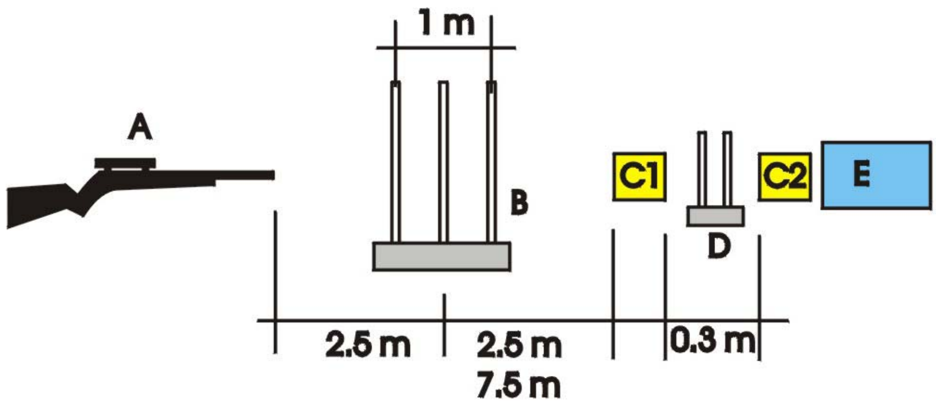

Figure 24: Schematic of the basic reference test arrangement

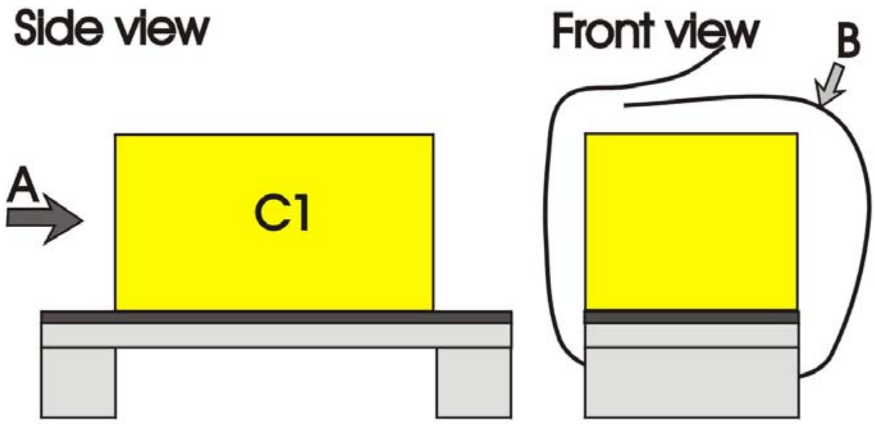

Figure 25: Schematic of primary block C1. A- impact direction, B – the shroud

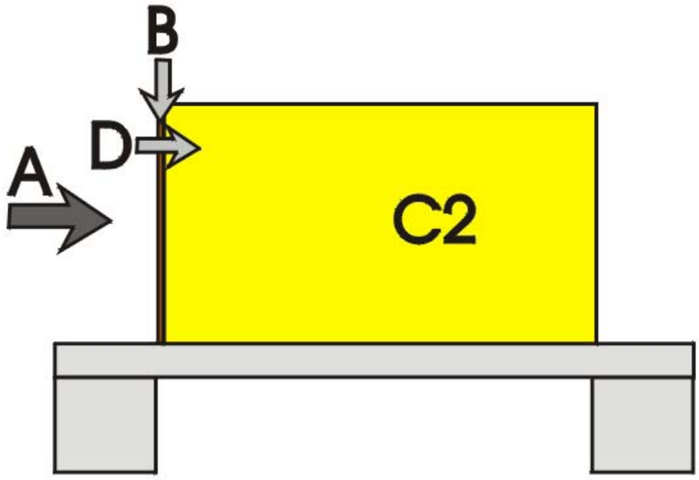

Figure 26: Schematic of secondary block C2. A – impact direction, B – skin simulant, C2 – gelatine block and D – plastic film to hold the skin simulant in place.

Figure 27: Photograph of the basic test setup at Police Technical Centre, Helsinki

The purpose of the test is

a) to measure kinetic energy dissipation *Ed* into the primary gelatine block by measuring impact energy *Ei* and residual energy *Er* and estimating deformation energy *Edef*.
b) to measure the level of fragmentation into the primary gelatine block and
c) to calculate the bullet's injury potential to a target person using items a and b and to a bystander deriving the mass of excised (devitalised) tissue from *Er*.

The secondary block depicts the bullet's ability to injure a bystander in the "worst case" scenario of the bystander being quite close.

The test is repeated at least five times. More repetitions may, however, be required to gain sufficient statistical confidence.

Measurement is done as follows. The primary gelatine block is cut into 50 mm sections. The fissure lengths of each cross section and on entry and exit are measured using the Wound Profile Method for calculating the proportion of kinetic energy dissipated into each 50 mm section of gelatine as described in paper V. The maximum diameter of the temporary cavity in gelatine is noted according to Red Cross Wound Classification variable C (cavity). Fragments found in the primary block of gelatine are counted to obtain the Red Cross Wound Classification variable M (metallic body).

10.3 Ricochet test

The test consists of shooting a bullet at a 60^o angle of attack (surface normal) into concrete brick and catching the ricochet with a block of gelatine complemented with skin simulant as depicted in figures 28 and 29.

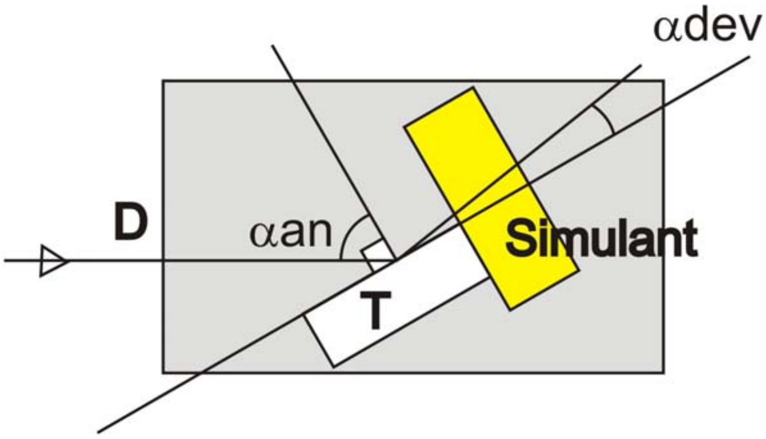

Figure 28: Schematic of the ricochet test arrangement. D – direction of shot, αan – angle of attack, T – ricochet surface, αdev – angle of deviation.

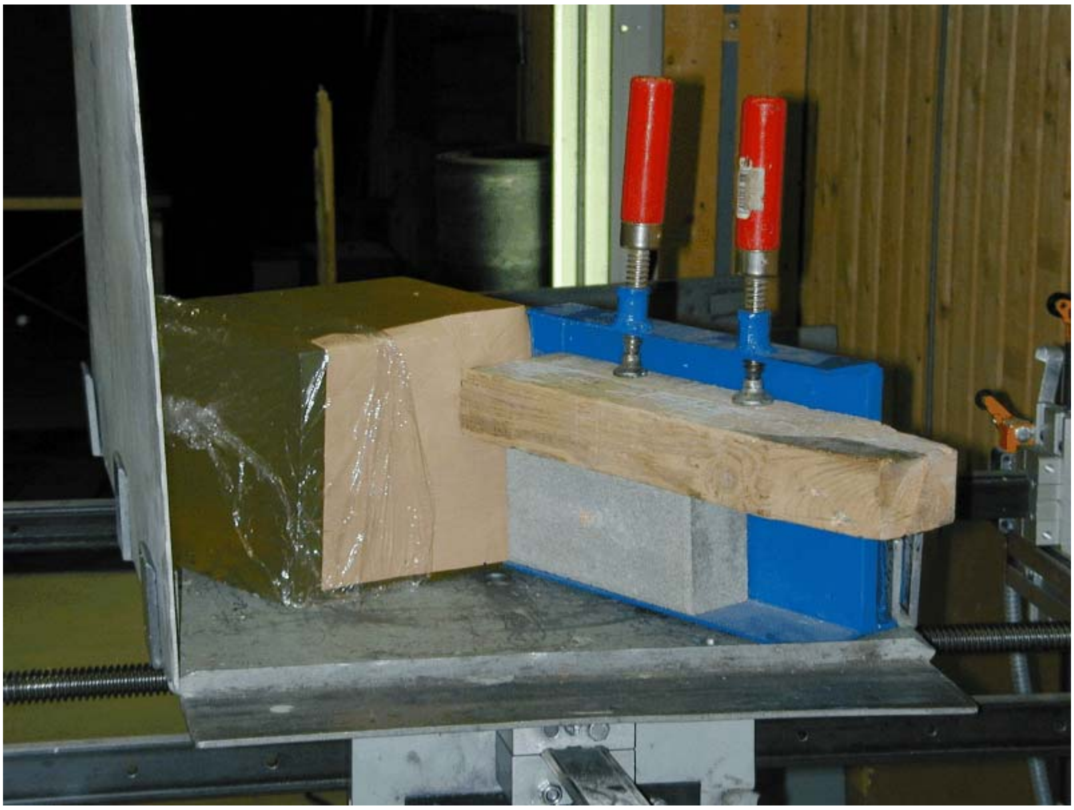

Figure 29: Photograph of the ricochet test setup.

The purpose of the test is to determine the danger of injury a ricochet will cause to a bystander by measuring the soft tissue penetration ability of the ricochet or ricocheting fragments and their deflection angle and express the injury potential in terms of the mass of excised (devitalised) tissue.

The test is repeated at least five times. More repetitions may, however, be required to gain sufficient statistical confidence.

10.4 Entry and exit wound test

The test consists of shooting through a 12,5 cm (half length) gelatine block complemented with skin simulant on both impact and exit sides. The skin is held in place on impact side with one and on exit side with two layers of PVC-LMF film. The arrangement is shown in figure 30.

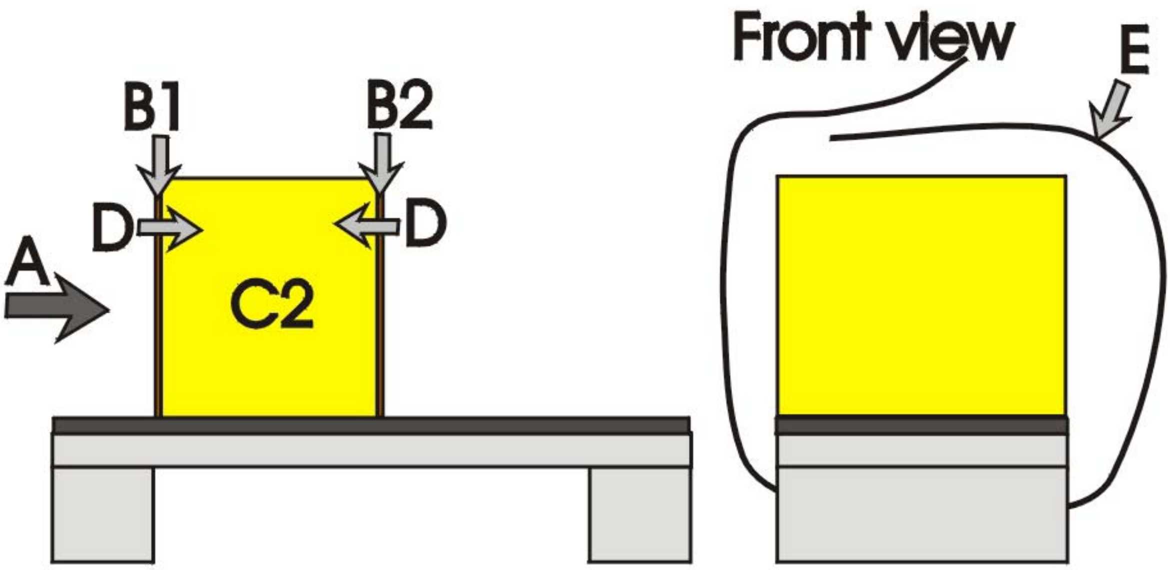

Figure 30: Schematic of entry and exit wound test arrangement. A – impact direction, B1 and B2 – skin simulants, C2 – 12.5 cm gelatine block, D – Plastic film for holding the skin, E – the shroud.

The purpose of the test is to determine the sizes of entry and exit wounds in a compatible way with the Red Cross Wound Classification. The test simulates a thigh wound without bone injury.

10.5 Mathematical model for injury potential assessment

The purpose of the mathematical model is to produce three comparison figures describing a bullet's potential for injury.

[1] $$\mathbf{IPI = IPt + IPb}$$

, where IPt is injury potential i.e. probable mass of devitalised tissue of the primary target (offender) and IPb is the same for bystander if hit by accident.

[2] $$\mathbf{IPt} = \boldsymbol{mdeb} + \boldsymbol{mdebfr}$$

, where *mdeb* is the sum of devitalised tissue according to

[3] $$\boldsymbol{mdeb} = \sum mdeb_i = 44.575 * Ed_i + 10.319$$

for all 50 mm sections *i* of the gelatine as described in papers III and V. The *mdebfr* is obtained using the same equation 3, but substituting Ed *Efr* (J) as follows:

[4] $$\boldsymbol{Efr = cfr} * [0.5 * (\boldsymbol{mi} - \boldsymbol{mr}) * \boldsymbol{vi}^2 / 1000]$$

, where *cfr* is the fragmentation coefficient, *mi* the impact mass (g), *mr* the retained mass (g) and *vi* the impact velocity (m/s) of the bullet. An arbitrary value of 2 is proposed for *cfr* based on relative increase in immediate, delayed local and remote damage caused by fragments [Ordog et al. 1988, Fackler et al. 1984].

[5] $$\mathbf{IPb} = \boldsymbol{mdebr} + \boldsymbol{mdebric}$$

, where mdebr is the sum of devitalised tissue according to Eq. 3 substituting *Ed* with *Er*. The injury potential of a ricochet, *mdebric*, is estimated as follows. The retained mass of the projectile *mr* and the specific weight *msp* of the bullet are measured. From *mr* and *msp* the radius *rric* of a sphere is calculated. The amount of devitalised tissue is estimated as the mass of muscle tissue inside a cylinder with a radius of *rric* and maximum penetration depth *lw* of any ricocheted projectile fragment.

[6] $$\boldsymbol{rric} = \sqrt[3]{3 * mr / (4 * \pi * msp)}$$

If *lw* < 5 mm, *mdebric* = 0, else

[7] $$\boldsymbol{mdebric} = [\pi * (\boldsymbol{rric}^2) * \boldsymbol{lw} * 0.00104] * (1 + \boldsymbol{Adef}/90)$$

, where 0.00104 is the density of muscle tissue in g/mm^3 [DeMuth 1966]. The value 5 mm is the safe penetration distance [Connor et al. 1998, Bleetman and Dyer 2000, Bleetman et al. 2003], where penetration does not yet reach a vital organ. *Adef* is the mean deflection angle of the ricocheting fragments.

If the ricocheting bullet has broken into less than 2 mm fragments (arbitrary value) *mdebric* is given the value of 0.

It is very difficult to measure the residual velocity *vr* of a ricochet and thus derive *mdebric* from Eq.3. Therefore a rough estimate based on the amount of crushed tissue is used. A ricocheting bullet is severely deformed and may be broken to fragments. Their ballistic coefficient and velocity decay are impossible to determine in order to say what the danger will be at certain distance. Therefore a worst case scenario of a bystander standing next to the impact surface is proposed.

The injury potential comparison figures will thus be:

- The Red Cross Wound Classification variables E, X, C and M
- Total figure for injury potential, IPI
- Injury potential for target person, IPt
- Injury potential for bystander, IPb
- Detailed wound ballistic data

11 SUMMARY

The study reviewed the International Law and established weapons technical and wound ballistic interpretations based on *ratio legis*. They show that the law can be interpreted in meaningful way without any significant need to rewrite it as technology advances. The rationale is based on the concept of triunity between the bystander, the law enforcement official and the offender and the need to protect them all from superfluous and unwarranted injury – in that order. The interpretations in paper I lay the legal basis for wound ballistic evaluation of injury potential. A formal procedure and organisation for review of service ammunition is, however, still waiting to be established.

The study revealed some deficiencies in contemporary wound ballistic research. It tends to concentrate on soft tissue ballistics. Even the soft tissue simulant and its preparation process have not been standardised and the effects of different preparation variables have not been properly researched. This has been corrected in paper II, which proposes the use of 10% ballistic gelatine as the standard muscle tissue simulant and a standard method for preparing and verifying it. A regression function for verification of valid gelatine was presented as

[23] $$lw = 0.594 * vi - 21.92 \pm 5$$

, where *vi* is the impact velocity (m/s) of a 4.5 mm steel sphere, *lw* the depth of penetration (mm) and ± 5 the value for allowed tolerance (mm).

In order to obtain meaningful measurement results with a simulant the measurements must be correlated with actual gunshot injury. This was done in paper III by analysing 140 pig tests that not only gave a reasonable correlation of 0.54 between excised (debrided, devitalised) tissue (*mdeb*) and dissipated kinetic energy (*Ed*) per millimetre of wound channel, but also showed that the use of too small test animals may result in excessive measurement error and poor correlations. The relationship was described with a regression function of

[24] $$mdeb = 44.575 * Ed + 10.319 \text{ with } R^2 = 0.293\ (R=0.54)$$

The analysis also showed that other ballistic variables such as impact energy, impact velocity, impact power and impact momentum correlate poorly with devitalised tissue with correlation coefficients of 0.16, 0.11, 0.23 and 0.09, respectively. The paper also corrected a misunderstanding that dissipated energy would be the difference between impact and retained energies. Part of the impact energy is expended in bullet deformation. A proposal for estimating this deformation energy was made.

The significance of skin simulant lays in its role as a threshold velocity (*vth*) filter when the ability to penetrate the skin and injury potential of low velocity projectiles like exiting or ricocheting bullets are to be assessed, and to assess entry and exit wounds. Paper IV investigated and presented the average properties of human skin and found the values as *vth* = 94 ± 4 m/s for a 4.5 mm lead sphere, tensile strength 18 ± 2 MPa and elongation at break 65 ± 5 %. Semi-finished chrome tanned upholstery “crust” cowhide of 0.9-1.1 mm thickness were found to have similar properties of *vth* = 90.7 m/s, tensile strength 20.89 ± 4.11 MPa and elongation at break 61 ± 9 %.

Paper V continued with validating the gelatine against swine muscle tissue and proving the Wound Profile Method to have the highest correlation of 0.89 and thus being the best method of measuring dissipated energy from the fissures of bullet channel torn in gelatine. Furthermore it presented the use of an elastic shroud to simulate the suppressive effect of surrounding tissue and validated both the method and paper II proposed gelatine using the data from paper III by shooting non deforming 9x19 mm and 7.62x39 mm bullets and measuring the dissipated energies.

It is recognised that the bridge between simulated wound ballistic research and surgery is quite weak. Data important for simulation is not stored in medical databases. Providing a common interface between the two worlds would enhance the fidelity of simulation. Outlines of an interface and a database were proposed.

Based on this research a standard wound ballistic test set together with a mathematical model is proposed. It consists of a basic reference test, a ricochet test and an entry and exit wound test. The test set will provide realistic comparison figures on injury potential to assist in making a decision on the legal acceptability of law enforcement firearms ammunition.

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