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Kinetic Energy Less Lethal Weapons And Their Associated Blunt Trauma Injuries

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Abstract

A widely used class of Less Lethal Weapon is the kinetic energy projectile. This can cause blunt trauma to the targeted person and, under certain circumstances, its use can result in permanent injury or death. The low velocity at which Less Lethal projectiles are launched results in inaccuracy of use thus increasing the possibility that non targeted areas of the body susceptible to injury by blunt trauma will be hit. This research has been focused to investigate the impact characteristics of kinetic energy Less Lethal projectiles using different masses, materials, geometries and impact velocities and how they affect the criteria for injury to the head and the thorax.

Computer based models for simulating impacts and possible injuries were investigated. Hydro codes were used to predict the effect of a range of projectile masses and impact velocities for a simplified human target. Physical models were built and tested to compare with the computer predictions. A correlation between projectile mass, velocity and skin penetration was found.

Research was carried out on the impact process using an instrumented projectile to measure the acceleration experienced by the projectile and the duration of acceleration for a range of target materials. A simulated head model with a displacement transducer was used to investigate the impact properties of a range of projectile geometries with the objective of identifying the probable effect on blunt trauma and the level of injury that may be sustained. The introduction of air cavities into the projectile reduced the recorded displacement as well as its acceleration whilst extending the duration of the impact.

High-speed video was used to investigate the impact process between the projectile and the target using a simulated thorax. The target used was a Behind Armour Blunt Trauma (BABT) test rig originally developed to investigate behind armour blunt trauma associated with combat body armour impacted by high velocity projectiles. A wide range of projectile geometries, materials and masses were investigated to examine the probable effect on blunt trauma and the level of injury that may be sustained. The introduction of air cavities and reduction of projectile mass was found to slightly reduce the rate of displacement in the BABT rig; however the maximum displacement remained similar because of the similar masses and velocities involved.

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Chapter 1 Introduction

1.1 Definition of a "Less Lethal Weapon"

A Less Lethal Weapon (LLW) also known as non lethal or less than lethal is a weapon that has been designed to have a greatly reduced probability of causing serious injury or death; this is a general definition because a number of different users use different definitions and their requirements differ in a number of ways. NATO documentation refer to these weapons as Non Lethal and define them as "Weapons which are explicitly designed to incapacitate or repel personnel, with a low probability of fatality and permanent injury, or to disable equipment, with minimal undesired damage or impact on the environment." It should be noted that in this definition anti-materiel weapons as well as anti-personnel weapons are included.

1.2 Types of Less Lethal Weapon

The different types of Less Lethal Weapons are wide and varied and are generally considered to fall into the following areas:

- Electro-Magnetic Weapons
  - Lasers – used to dazzle
  - 95GHz - Causes surface heating of skin
  - Electro Magnetic Pulse (Explosively or electrically driven) - used to destroy or degrade electrical circuits.
- Electrical Weapons
  - Electric barriers
  - Electric batons
  - Electric guns
  - Electric water cannons
- Chemicals
  - Obscurants - smokes
  - Reactants – defoliants, corrosives and combustibles
  - Riot Control Agents – CS, CR and pepper sprays
  - Malodorants – foul smelling
  - Incapacitants – sedatives, relaxants, Anti-psychotics, anti-depressants and drugs of abuse
  - Anti Traction Materials
- Audio
  - Audible (20Hz – 20KHz)
  - Infrasound <20Hz
  - Ultrasound >20KHz
- Mechanical/Kinetic Energy
  - Barriers
  - Entanglement
  - Cloggers
  - Projectiles

It is clear that there are many types of Less / Non Lethal Weapon both currently available and in development but for the purposes of this research only kinetic energy projectiles were looked at in depth. The chosen terminology for referring to these weapons in this research is "Less Lethal Weapon" using the definition as "a weapon that has a greatly reduced probability of causing serious injury or death."

1.3 Kinetic Energy Non-Penetrating Projectiles

There are a number of kinetic energy non-penetrating projectiles fired from Less Lethal Weapons and they all have the common characteristics of being launched with very low muzzle velocities compared to lethal weapons, typically between 70 and $120ms^{-1}$. Thus the time of flight of the projectile from the muzzle of the weapon to the target is significantly greater than that for lethal projectiles. Low velocity projectiles are accurate and consistent but they have a very looped trajectory because gravity acts to pull them vertically downwards and the longer the time of flight then the greater the vertical downward movement on the way to the target. For a projectile fired horizontally the vertical distance downwards that the projectile will fall is given by Equation 1:

$$d = \frac{1}{2}at^2$$

Equation 1

Where d = vertical fall of the projectile

a = acceleration due to gravity

t = time of flight from muzzle to target.

Accurate range estimation for correct placement of the projectile on the target is essential for low velocity projectiles such as these. However, range estimation is notoriously difficult **[1]** so that although the weapons are inherently accurate they are very difficult to use accurately. Different parts of the body have different susceptibility to injury by non-penetrating blunt trauma (see Chapter 2) and the projectiles must not strike those parts of the body where they may cause serious injury or death. Projectiles that are launched with higher velocities will make range estimation less critical and will be less susceptible to the effect of cross winds on the horizontal accuracy so that they would ensure greater accuracy in the use of these weapons. However, higher velocities alone would increase the potential for serious injury to the target. This research investigates kinetic energy projectiles used as, or with, Less Lethal Weapons and how the probability of serious and permanent injury can be reduced through the use of projectiles with higher velocities to increase their accurate use thus reducing potential injuries by avoiding strikes to vulnerable parts of the body.

A Less Lethal Weapon that has proved to be very effective is the TASER © **[2]**. This uses an electrical discharge to temporarily incapacitate a suspect. Two small darts with barbs are fired at the suspect. To each dart is attached a fine wire which is also linked to the weapon. A very high voltage is fed down the wires to disable a suspect by causing the muscles of the body to seize involuntarily. This Less Lethal Weapon has proved to be very effective because it causes incapacitation with only a low risk of serious injury to the suspect. However it has a very limited range set by the two small darts and trailing wires. To overcome this lack of range a free flying TASER© has been developed **[3]** that consists of a projectile of similar weight and size as a conventional baton round, fired at similar velocities and has its own power supply so that it has all of the limitations of a baton round i.e., difficult to use accurately at anything other than short ranges and has potential to cause unacceptable levels of blunt trauma to vulnerable parts of the body. This type of projectile would benefit from being able to be launched at higher velocities to extend its useable range without any increase in serious or permanent injury by the projectile.

Another related area where non-penetrating projectiles are used is that of the tranquilliser dart used for tranquilising animals for conservation purposes. These are darts in the form of a syringe. They have a long cylindrical body with the front half occupied by the drug and the rear half has a piston and impact detonator to pressurise the cylinder to inject the drug into the animal via a needle in the nose of the dart. These projectiles are also currently limited to use over only short ranges for the same reason as kinetic energy Less Lethal Weapons. Getting sufficiently close to wild animals to use tranquilliser darts is difficult and potentially hazardous when used against dangerous game. Helicopters are therefore used which have their own form of hazard and are very expensive. Ways of increasing the range of these systems would greatly contribute to the conservation efforts of the workers involved in the conservation of the world's endangered animals.

The drugs currently using in tranquilliser darts are based on opiates and have several drawbacks, especially if they were to be used for the apprehension of human beings. The most serious problem is that these drugs are extremely toxic and it is essential that the correct and exact dosage is administered. The exact dosage is dependent on the body weight of the individual and on the individual's susceptibility to the effects of the drug. If the dose is too low it will be ineffective but if it is too high then it will cause death **[4]**. Another major drawback is that it can take up to seven minutes for the drug to become effective which means a suspect could continue to be a threat so that lethal force may be required or the suspect takes flight and cannot be found to reverse the action of the drug. These are major reasons why tranquilliser darts are not used against human beings. However, research **[5]** has resulted in a new drug that is considerably less toxic, with a much wider tolerance band and is effective in only fifteen seconds after injection. This has resulted in considerable interest in tranquilliser darts for use as a Less Lethal Weapon and overcomes many of the problems identified **[6]** with using them against personnel.

Chapter 2 Literature Review

2.1 History of Kinetic Less Lethal Weapons

Kinetic energy projectiles of vast variety have been used for centuries, in both times of war and peace, from the stone and slingshot for hunting animals to the bullet and rifle for use against ones enemies. Until very recently an important property of these projectiles was considered to be that they produced a lethal effect. It is only in recent years that attempts have been made to use projectiles for the same purposes, but that a desirable feature should be that they are less than lethal. This has resulted in the development of the tranquilliser dart for use against animals and the baton round against man. Whilst there has been centuries of development of traditional firearms to increase their effectiveness, i.e. make them more lethal, very little work has been carried out to optimise the design of non lethal projectiles in terms of accuracy and range without increasing target damage, because what was created initially was deemed capable but not necessarily good.

The first baton rounds were used by the riot police in Hong Kong **[7]** and were constructed from wood. The rounds were aimed at the ground in front of the rioters so that they would ricochet upwards into the rioter's legs. However, tests showed that they would often cause serious injury and would sometimes splinter on impact with hard ground **[8].** These wooden dowels were replaced later by the rubber bullet which eliminated the risk of shattering. The apparently "harmless" name was also used to reduce any worries the media may have, and therefore those of the public, and to help them consider it less of a danger, because rubber was considered as a soft material.

The rubber bullet also had some built in flexibility because of the elasticity of the material so that some of the impact energy from the collision was used to deform the bullet and therefore reduce the rate of energy being transferred into the target. The operational procedures of the rubber bullets were left unchanged compared to those of the wooden baton rounds mentioned above, this lead to the rise of a problem in that the rubber bullets would bounce much higher than the older wooden projectiles and significantly increased the chance of a head strike and therefore the chance of serious injury. One of the first systems based upon the rubber bullet was the 37mm diameter L2A2 that comprised a 150mm long projectile weighing 140g and was housed in an aluminium case. It was fired from a 37mm launcher at an average velocity of $70ms^{-1}$ to an effective range of 30m but, because it was fired from a smooth bored barrel, it was unstable with a tumbling movement in flight and had a high aerodynamic drag so lost velocity very rapidly. The projectile was also a loose fit in the barrel of the launcher which added further instability to its flight, resulting in a variable and unpredictable injury pattern.

The rubber bullet was later replaced with the plastic bullet that had increased accuracy. However although the plastic bullet **[9]** may have been more accurate as a weapon system it was still difficult to use accurately because of its low launch velocity, which made accurate range estimation critical.

The L5A7 plastic bullet is a blunt-ended cylindrical projectile made of polyvinylchloride. It measures 37mm diameter x 100mm long and weighs 135g. It is discharged from a specially designed riot-control gun. The weapon had a rifled barrel to gyroscopically stabilize the projectile. It was more accurate than the rubber bullet, and being more stable in flight, would strike the target end on rather than tumbling **[10]**. This was later replaced with the similarly dimensioned but lighter (98.4g) L21A1 projectile in 2001.

In the US the beanbag round is used more commonly than the plastic bullet because it can be fired from any standard shotgun rather than requiring a specific launcher. The typical beanbag round is a 55mm square of Kevlar filled with lead shot weighing 40g and is housed in a 70mm long cartridge. It is fired from a 12-bore shotgun at a velocity of approximately 75-95ms^{-1} with an effective range up to approximately 15m.

Israel use rubber coated bullets that are fired from a cup fitted to the muzzle of the M16 assault rifle. A blank round is used to propel the projectiles. There are two different types of round. The RCC-95 is a blunt cylindrical projectile composed of three metal cores covered with a hard rubber shell 2mm thick with a diameter of 18mm. It weighs 48g and has a muzzle velocity of 130ms^{-1}. The projectile dissociates into three components after firing. The recommended target engagement range is between 40m and 70m. Dispersion of the projectiles is 2.5m at 70m.

The MA/RA bullet is composed of 15 rubber balls with a metal core, each weighing 17g with a diameter of 17mm. Muzzle velocity is 78ms^{-1} and the recommended target engagement range is between 30m and 80m. At 50m the dispersion of the projectiles is 7m.

2.2 Injuries associated with Kinetic Less Lethal Weapons

Skin penetration is unlikely at the velocities used (50-60ms^{-1}) **[11]**. Bir **[12]** measured the penetration of the skin of 18.5mm projectiles for different parts of the body using human cadavers. The results are given in terms of energy density (impact energy per unit area). However, skin penetration is only one possible injury mechanism associated with these types of weapons and is usually the least serious. Blunt trauma is of major concern that can result in serious and permanent injury and in rare cases can also lead to death.

The plastic bullet underwent comprehensive testing during its early stages of development and experiments were carried out on anaesthetised sheep **[13]**. These tests were focused on examining thoracic injuries and showed that if less than 55 grains of the standard propellant were used to launch the plastic bullet then even at close range the worst damage caused was surface bruising and that the velocity of the bullet dropped away significantly with distance. It was noted that the plastic bullets were still somewhat unstable in flight and tumbled through the air so that they often hit sideways on resulting in a larger surface area at impact. Where the projectile struck squarely end-on the injury caused was generally more severe. However, no tests were done to assess the possible injury caused by a head strike. It should be noted that the velocity of the projectile is not given only the propellant weight. Miller et al **[9]** reviewed the injuries caused by the plastic bullet (and its predecessors) since they were brought into operation in Northern Ireland in 1969. During this period 33,000 plastic bullets were fired resulting in 2 deaths and 17 people left with permanent disabilities. Rocke **[14]** produced a similar study from April to August 1981 where 29,000 plastic bullets were fired. 7 deaths occurred and 31 people were left with moderate to severe head injuries. To many people, this is an unacceptably high injury rate for a supposedly less lethal weapon.

Suyama et al **[15]** also investigated the typical injuries caused by the plastic bullets and beanbag rounds when they have been deployed in the field during periods of civil unrest in Los Angeles. They confirmed the findings of Miller et al **[9]**, which give the plastic bullets predictable injury patterns but showed that whilst the beanbag tended to produce bruising rather than the lacerations associated with plastic bullets; there was insufficient medical data available to produce a reliable model for injury pattern. Some of the injuries caused by the beanbag round are described by Sehgal and Challoner **[16]**. A specific incident is described when the round was fired at a suspect and the Kevlar bag split open on impact causing several of the lead "beans" contained within it to penetrate his arm. They concluded that this would become more common as this type of less lethal weapon came into greater use by police departments around the world.

Sutter **[17]** undertook research into eye injuries caused by plastic bullets. Over a five-month period five cases were reported of serious eye injury from the use of plastic bullets. In two cases the victims fully recovered their sight in the injured eye, in two cases the vision of the victims was restored to half of what it had been previously and in one case the victim was left legally blind.

These injuries were in part due to the design of one of the plastic bullets used in Switzerland where the research took place. The "bullet" is constructed from 35 hexagonal polyvinylchloride rods weighing approximately 11g each, held together in a thin foil. On launch the foil is discarded as the projectile leaves the barrel and rods separate out and impact over the target area as traditional shotgun pellets would. This results in a large area of effect and reduced damage caused by the impacts, but there is a much higher risk of the projectiles hitting sensitive parts of the head and other vital organ areas.

Warren **[18]** notes that there is a link between projectile mass, velocity and impact area and the level of injuries that are caused. His findings were that there is a relationship between the impulse per unit area and the level of injury caused and proposed the following injury criterion:

$$\frac{(mv)}{A} \approx C$$

Equation 2

Where:
m = projectile mass
v = impact velocity
A = impact area
C = Impulse per unit area

From these trials and those conducted by other workers the injury threshold was found to be approximately 5000 kgs^{-1}. Above this value serious injury is highly likely to occur.

Impact energy has also been related to impact injury. O'Driscoll **[19]** suggests that the injury threshold is 200J for the torso and 70J for the head.

A review of all baton round discharges in 2002-2004 was conducted in 2006 by the Home Office scientific development branch (HOSDB) **[20]**. The report analysed when baton rounds were used and what the injuries and tactical results of the discharge were. The report also noted that the introduction of the L18A1 optical sight helped to reduce serious injury by helping the officers to aim at their targets more accurately but also admitted the L21A1 was also more dangerous than its predecessor the L5A7.

Rubber bullets were used by Israeli police to control riots by Israeli-Arabs in October 2000. There were 595 casualties admitted to hospital with injuries related to the riots and 201 were identified as having injuries from rubber bullets. The severity of their injuries was assessed **[21]** and established using the Abbreviated Injury Scale (AIS) **[22]**. It was found that 61% of the patients had blunt trauma injuries and the remaining 39% had penetrating injuries. 13% of patients had more than one injury and one patient was noted to having 13 rubber bullet injuries as shown in Figure 1. Injuries to the 201 patients were randomly distributed all over the body with 73 to limbs, 61 to the head, neck and face, 39 to the chest, 16 to the back and 12 to the abdomen. Three people died of their injuries, two being a result of severe ocular injury and a third as a result of postoperative aspiration after knee surgery for a severe rubber bullet injury. Type of rubber bullet (MA/RA or RCC-95) could not be identified for mildly injured patients from history or the marks left on the skin by the impact. For most patients with moderately severe injuries and all with severe injuries, the RCC-95 bullet was recovered.

Figure 1: Patient with 13 rubber bullet injuries that were clearly caused by a MA/RA round (comprised of 15 rubber balls) fired at very close range

Figure 2: Beretta LTL 7000

The gun manufacturers Beretta have also developed a new kinetic LLW. The projectile is a small hemispherical nosed rubber cylinder fired from a modified 12 bore shotgun, whilst the projectile itself is unremarkable, the sighting and launch system is far more unique.

Figure 3: Adjustable Aim point sight on Beretta LTL 7000

The weapon is equipped with a custom “Aim Point” adjustable scope. When looking through the sight, as in Figure 3 above, three dots are projected over the users view which indicate where the shot will impact (centre dot) when the upper and lower sighting dots have been positioned over the targets head and feet respectively to set the range, a switch on the grip of the weapon can then be used to adjust the spacing of the outer two dots dependant on the distance of the target and therefore their size in the scope. When the spacing of the sighting dots is adjusted an electric motor simultaneously rotates part of the chamber containing a gas port so that if the target is closer (upper and lower sighting dots further apart) more of the gas from the chamber is bled off reducing the velocity of the projectile and therefore its kinetic energy. When the target is further away (sighting dots closer together) the port is closed and the maximum chamber pressure and projectile velocity can be achieved.

By design the weapon should always impact the same quantity of Kinetic energy on the target because of the adjustable chamber linked directly into the sight system simultaneously removing the problem of range estimation. However the system is slow to adjust and heavily reliant on batteries to power the sight and mechanical chamber adjustment, without power the weapon becomes useless. Aside from this there is still the possibility to abuse the weapon by adjusting the sighting for a distant target and then discharging it at one much close the Kinetic energy of the projectile will be greatly increased along with the likelihood of serious injury.

2.3 Car Accident and Sport Injury Data

A high proportion of injuries caused in car accidents and sports injuries are blunt trauma. Over the years the design of cars and their safety equipment and protective helmets for motor cyclists and sportsmen have been developed to mitigate these types of injuries so that there is a lot of data on the causes of blunt trauma and how this can be reduced. Care must be exercised when using this data because the blunt trauma caused by car crashes and from sporting events is caused by high masses and relatively low velocities, whereas ballistic blunt trauma is caused by low masses and relatively high velocities. To classify the severity of the injuries the Abbreviated Injury Scale (AIS) **[22]** was developed and is shown in Table 1. Only blunt injuries were included in the original.

Injury severity	AIS Score
Minor	1
Moderate	2
Serious	3
Severe	4
Critical	5
Unsurvivable	6

Table 1: Level of injury related to the Abbreviated Injury Scale (AIS) score.

Head injuries can be incurred from impacting objects that cause skin lacerations, skull fractures and brain damage. The majority of head injuries from the use of baton rounds are to the skin and to the brain. An impact to the head may deform the skull and there will be a combination of linear and angular acceleration. Injuries to the brain are caused by skull deformation and head acceleration. For small amounts of skull deformation the movement of the head can be described by the usual laws of rigid body motion. Acceleration contributes to the distortion that occurs within the cranial cavity. Almost all head injury criteria are based on the Wayne State Concussion Tolerance Curve **[23]** that was developed using animals and human cadavers by way of a Unique high speed biplane x-ray system and neutral density technology used to measure brain deformation. Tests were conducted by impacting the skull with a moving weight and impacting a moving skull onto a stationary block. It relates head injury to the head acceleration and the duration of the acceleration. From this the Head Injury Criteria (HIC) model was developed, which is expressed as:

$$HIC = \left\{ (t_2 - t_1) \left[\frac{1}{t_2 - t_1} \int_{t_1}^{t_2} a(t) \right]^{2.6} \right\}$$

Equation 3

Where t_1 and t_2 are the initial and final times in seconds of the interval during which HIC allows a maximum value and a(t) is the resultant acceleration in G measured at the Centre of Gravity of the skull.

This can be simplified to:

$$\bar{a}^{2.5} T = 1000$$

Equation 4

Where $\bar{a}$ = "effective" linear acceleration of the head

T = duration of the acceleration

2.5 = constant

For head injury not to occur the numerical value of the expression should not exceed a value of 1000. For time durations greater than 7ms a better fit to the original Wayne State University data is given by:

$$\bar{a}^{3.2} T = 9580$$

Equation 5

The above expressions were developed for linear acceleration of the head. For car accidents and many sports injuries the head is subjected to high angular accelerations and they can be the most dominant cause of brain injuries. However, for baton round the angular acceleration is usually small and can be ignored.

Injuries to the thorax and abdomen are related to the amount of deformation that occurs. The structure of the thorax is such that the skeletal structure or ribs protects the vital organs lying beneath. The ribs deflect under external load to dissipate energy imparted to the body. However, if the deflection is too great this can lead to damage to the underlying organs and possibly rib fracture. Rib fractures from less lethal weapons have been reported **[14]**. Rib fractures can be minor or serious depending on where they occur in the body.

Kroell **[24]** investigated the effect of blunt trauma to the thorax related to car crashes with tests on pigs to establish levels of injury with chest compression and deformation velocity. This work was for low velocity impacts with high mass impactors, as experienced in car crashes. Bir **[25]** extended this work, using similar methodology, to encompass the velocities and impact masses of typical baton rounds. The injury criteria is referred is to as the Viscous Criteria (VC) and is a function of maximum value of chest wall velocity multiplied by the chest wall deformation.

$$ViscousCriteria = (V(t)C(t))$$

Equation 6

Where V is the chest wall velocity and C is the chest wall displacement

A number of un-embalmed cadavers were used in this study. The sudden high rate of loading doesn't allow for muscular response in a living person so the lack of muscle tone is not so relevant when conducting tests on cadavers. The force and displacement responses were measured for various impacts, normalised and plotted against time to show the response and allow comparison to numerical models. They discovered that each impact condition gave distinct responses which differed from those previously reported from lower speed automotive accident investigation. Sturdivan **[26]** has also reviewed this work and extended it to include the impact of baton rounds with the human body.

2.4 Modelling Target Impacts

A number of numerical models exist for parts of the human body although these tend to have been created for use by the automotive industry to investigate crash worthiness for cars and their occupants **[27]** in which there are low velocity high mass impacts occurring over relatively long periods of time when compared to a typical ballistic impact. Other models have been produced; these include the human jaw **[28]** the human head **[29]**, **[30]**, **[31]** and the human thorax. Grimal et al **[32]** investigated numerical modelling a simple three-layer structure to represent human muscle, bone and lung for looking at Behind Armour Blunt Trauma (BABT). Although the work was concerned with armour most of the work is still applicable for non-penetrating impacts because the damage mechanism is similar. Grimal et al found the initial impact of the baton round produces a very short duration stress wave, which propagates through the body also called the "First wave". This is followed by the round causing compression in the thoracic wall (or wherever the round may strike) called the "secondary wave." In BABT, lung damage is usually the most threatening to life **[33]**, **[34].** This research supported the idea that the lung could easily be damaged under high frequency loading mainly caused by the "First wave" effect whereas most other work using numerical modelling dealt with only the "secondary wave" as the source of damage to the lungs. Grimal et al **[35]** determined that any numerical model needs to assess both wave effects to be accurate. They also encountered a common problem when creating the numerical model. The choice of material models for biological tissues is very difficult because the mechanical behaviours of biological tissues are non-linear and extremely rate dependant **[36]** and their properties are capable of being very different in tension and compression.

Methods for reducing BABT are constantly being investigated some of which use Finite Element Modelling (FEM) to assist them. Ouellet et al **[37]** investigated the modelling of Anti-Trauma (polymeric) foam lining in body armour to reduce the rate at which the impact energy is transferred, something that could be applied in the construction of new less lethal projectiles to reduce injury probability.

Farrar **[11]** carried out a theoretical study into the mechanics of force transmission from a moving body to a stationary body (baton round to the target). He concluded that the magnitude of the force was dependent upon the speed of sound through impact surface of the projectile and that it was the physical properties of the material making up the first few millimetres of the projectile that influenced the level of force transmission. Thus an air gap in the front of a baton round would significantly reduce the force transmitted to the target at impact. This the basis of the design of a new baton round by DSTL referred to as the Attenuating Energy Projectile (AEP). With the AEP, DSTL have corrected some of the design flaws with the L21A1. **[38]** By introducing an air space inside the nose of the projectile, the force transmitted to the target is said to have been reduced. The AEP was specifically created to reduce serious brain and head injuries caused by the projectile striking the head. The energy used to collapse the nose section of the projectile into the airspace behind it reduces the energy transfer rate. The AEP was designed so that it only deforms when hitting a hard surface such as the head or areas with large bone mass such as the hips. On impact with soft areas such as the abdomen the projectile does not deform.

The creation of any numerical model requires some form of validation. Usually this can be achieved by creating a simple real life model of the simulated target, however in the case of a biomechanical system this is somewhat more difficult because of the problems of modelling tissue as described above. It is generally accepted that ballistic gelatine, ballistic soap and Plastilina are reasonable materials for modelling human muscle tissue. Hole **[39]** investigated the use of ballistic gelatine in testing with clothing and its various impacts to model un-armoured humans. He also dealt with the practicalities and difficulties of modelling skin and concluded that the use of full scale simulants are a great asset in assessing the possible damage caused but the simulants themselves are some way from giving a fully realistic damage model. A number of alternatives have been investigated to replace ballistic gelatine as a human damage model **[40]** because it is difficult to work with. However, all had some problem that made them unsuitable replacements varying from cost to incompatibility with high-speed photography. Jones **[41]** compares the computer-modelled gelatine with the actual practical simulants results. The concluded results are promising but the computer modelling was suspended before a full comparison could be drawn. Woodhouse **[42]** whilst looking at explosive charges close to the human body, also created both an anatomical and a computer model to match physical blast effects that would be seen in a real body and she further highlighted the need for more research into the physical properties of the human body and possible anatomical substitutes.

2.5 Tranquilliser Darts

These projectiles share a number of common properties with them baton rounds (i.e. that they are low velocity, non penetrating, the target is animal tissue and there is a need to minimise injury). Vets, who wish to capture wild animals for conservation purposes, have undertaken the majority of the research. Their basic design has not changed since they first appeared in the 1950's and consists of a syringe with flights added to it to aid aerodynamic stability **[43]**. An impact detonator injects an immobilising drug upon impact with the animal. Maximum impact velocity is in the region of 50-60ms^{-1}, depending on the animal that is being darted and its distance from the shooter. Velocities higher than this will result in the dart penetrating the hide of the animal. Great care must be taken to dart the animal where it is heavily muscled, typically the haunch, otherwise penetration will occur even at these modest velocities and could easily result in the death of the animal. Clearly, the more accurate the system then the lower is the probability of this occurring.

Rees **[44]** investigated the advantages of redesigning the traditional 13mm fin stabilised darts to a 12-bore (18.5mm) spin stabilised dart. Tests showed that a spin stabilised dart of low mass gave lower dispersion than the traditional drag stabilised dart but the accuracy levels were still not sufficient to enable usage at ranges significantly greater than traditional dart designs. He also concluded that varying the twist rate had little effect on the dispersion of the dart and the effects of fluid payload were negligible. Andrews **[45]** built on the findings of Rees' report and found that putting a boat tail on the darts to try to improve accuracy further was unnecessary when using spin stabilisation, it in fact made the projectile more unstable. It is known **[46]** that a flat face to a projectile, for a length to diameter ratio of 3:1, will stabilise projectiles with yaw angles up to 10^{o} without the aid of gyroscopic stability. Using this approach yielded a significantly reduced projectile dispersion value.

Chapter 3 Experimental Investigation: Tranquilliser Darts

3.1 Introduction

Currently used tranquilliser darts are used exclusively for use against domestic and wild animals. They have short ranges because of their very looped trajectories and their very poor dispersion. The currently used drugs are opiate based and their effectiveness is very sensitive to animal species and body mass. If the drug dose is too low it will not be effective but if it is too high it will be fatal for the animal. Thus it is necessary to load each dart with the drug payload for each target. These drugs are highly toxic and human beings are particularly sensitive to them so they have to be handled with great care. All of these factors weigh against tranquilliser darts being used as Less Lethal Weapons against human beings and there is the additional problem of human rights issues. If the accuracy issues could be addressed and the drug toxicity problems could be overcome there is a possible use for these systems to be deployed as Less Lethal Weapons. By their very nature such use would always be very limited and could only ever be used against a targeted individual under very limited conditions.

3.2 Currently used systems

The most widely used current systems are shown in Figures 4, 5 and 6 below.

Figure 4: Daninject darting system

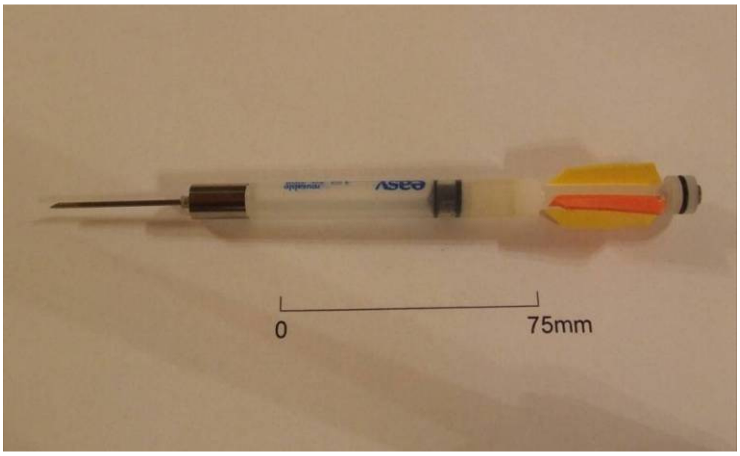


Figure 5: Disinject darting system

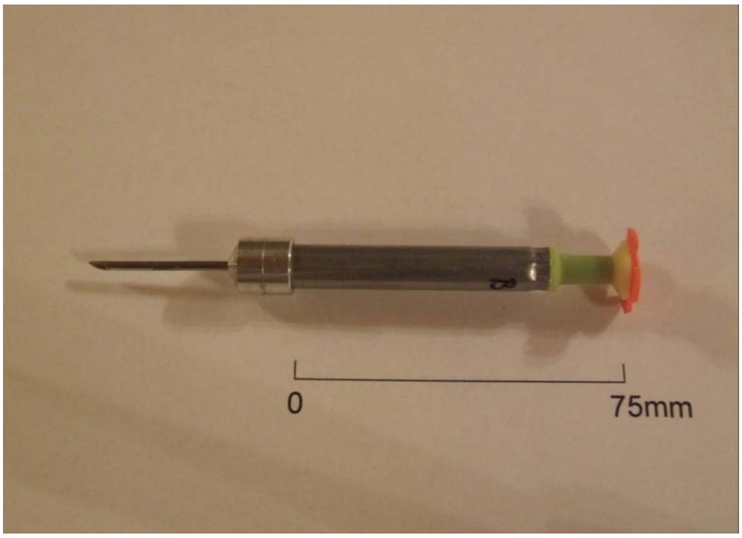


Figure 6: Pnuedart darting system

The weapons for firing these darts are usually pre-charged air weapons or CO_2 gas powered weapons. The manufacturers of these darts claim that they can be used out to 80m and beyond although users of them rarely use them beyond 35m. Tables of the charge pressure of the weapon for use at different ranges are used to ensure that the impact velocity remained similar with range and also flattened the trajectory for longer range shots by using the maximum launch velocity without penetrating the target. Trials **[47]** were completed to measure the performance of the three types of tranquilliser darts. A Daystate pre-charged air rifle with different calibre barrels 11mm and 13mm smooth bore) was used for the Pneudart and Disinject dart firings. Daninject manufacture a CO_2 gas powered weapon with rifled barrel for firing their dart and was used for these trials. For all three darts the maximum pressure setting, as advised by the manufacturer was used. Details of the different tranquilliser darts weights, payload, impact diameters and launch velocities are shown in Table 2 below.

Dart	Weight (g)	Payload (g)	Body Diameter (mm)	Impact Velocity (ms^{-1})	Launch Velocity (ms^{-1})
Pnuedart	7.85	2	13	57	135
Disinject	6.8	3	11	100	124
Daninject	7.1	2	11	47	115

Table 2: Details of dart weights, payloads and body diameter

The calculated trajectories for the three darts are shown in Figures 7 to 9 below.

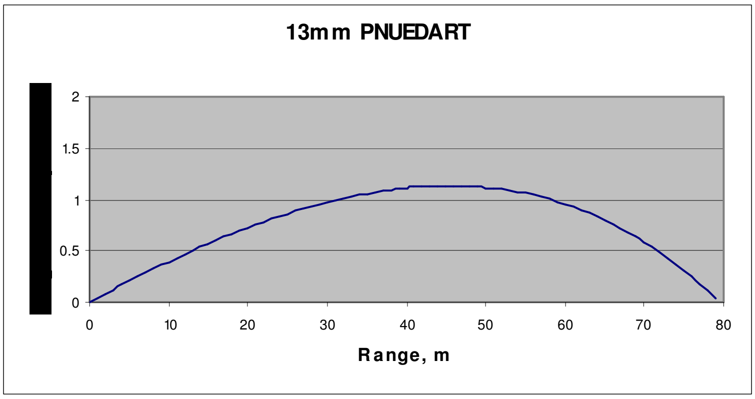


Figure 7: Calculated trajectory over 80m for the PNUEDART tranquilliser dart

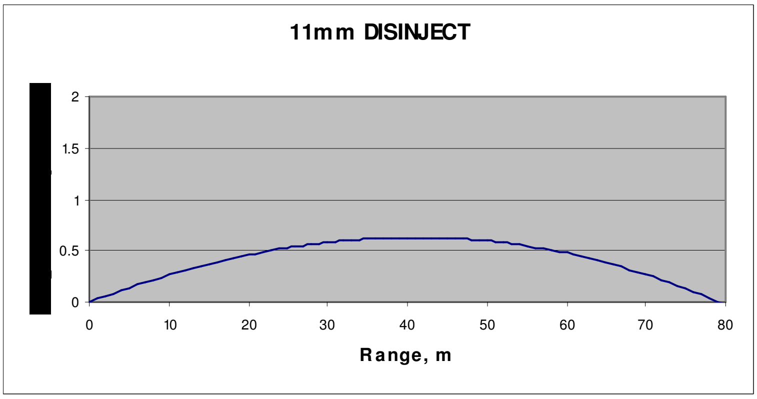


Figure 8: Calculated trajectory over 80m for the DISINJECT tranquilliser dart.

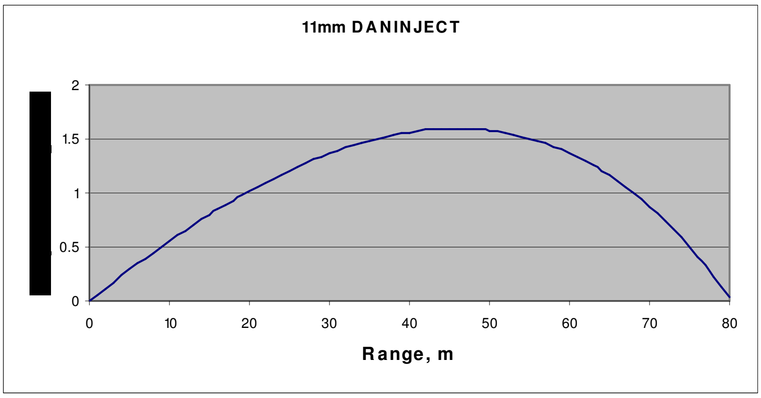


Figure 9: Calculated trajectory over 80m for the DANINJECT tranquilliser dart

The dispersion of the three different darts was measured at a range of 80m in the x and y coordinates and the standard deviation calculated. From these results the hit probability was then calculated for a target that measured 200mm x 200mm. These are shown in Table 3 below.

Dart Type	Greatest Spread (mm)		Std Dev (mm)		Probability of hitting a 200mm x 200mm target @ 80m
	x	y	x	y	
Pnuedart	570	1442	184.2	430.0	2.7%
Disinject	314	516	92.3	164.7	33.8%
Daninject	479	987	157.7	274.1	13.4%

Table 3: Dispersion and hit probability values for the three tested darts at a range of 80m

Tranquilliser darts by their very nature must be accurate to ensure that not only the target is hit but a specific part of the area, which is the heavily muscled part of the target to ensure that injuries are not incurred. Clearly the dispersion for all of these projectiles was too great for use at 80m. Indeed, the dispersion is too great for use at anything other than the range of 35m for which they are normally used in practice. The reason for such large dispersions is due to the stabilising method adopted for these projectiles. Drag stabilisation is used by all currently used tranquilliser darts. Very high levels of accuracy are achievable using this method but it is essential that the components are made to a very high tolerance. This is possible for tranquilliser darts but the financial costs would be high. Spin stabilisation is a possible solution but it would require a change in the dart geometry because projectiles with a length to diameter ratio greater than 5:1 cannot be stabilised by spinning. Thus the dart would need to be shorter and wider.

3.3 Discussion

Previous work **[45] [46]** has been undertaken to flatten the trajectory by increasing the dart impact diameter, and thus its impact area, allowing higher launch and impact velocities. The literature survey indicates that this is a sound proposal but it is unclear what the relationship between penetration velocity, projectile mass and impact area is. The impact process was therefore modelled using hydro codes and is included in Appendix 1. This showed that for a simple model the approximate relationship is that the penetrating velocity ∞ impact velocity$^{1.4}$ x projectile mass / impact area. Thus by making the dart body a larger diameter and the mass as low as possible the launch velocity would be able to be significantly increased.

The largest practical commercial calibre is that of a 12-bore (18.5mm diameter) shotgun, which is significantly larger than currently used tranquilliser darts. Firing tests were conducted using a projectile that was similar to the 18mm diameter projectile that the hydro code model was based on. These tests were conducted against a cow carcass held in a standing position. The darts were fired from a range of twenty metres using a rifled shotgun. Doppler radar was used to measure their velocity to the target. It was found that the darts would begin to penetrate the skin with an impact velocity of 170ms^{-1}. At velocities over 100ms^{-1} the skin was lacerated in what was described as "apple coring" where a circular area of skin around the impact was cut away. At velocities below 100ms^{-1} the projectile rebounded with no noticeable damage to the carcass.

The calculated trajectory for a flat face dart of 18.5mm diameter and weighing 15 grams launched with a velocity of 155ms^{-1} is shown in Figure 10. Calculated impact velocity is 109ms^{-1}.

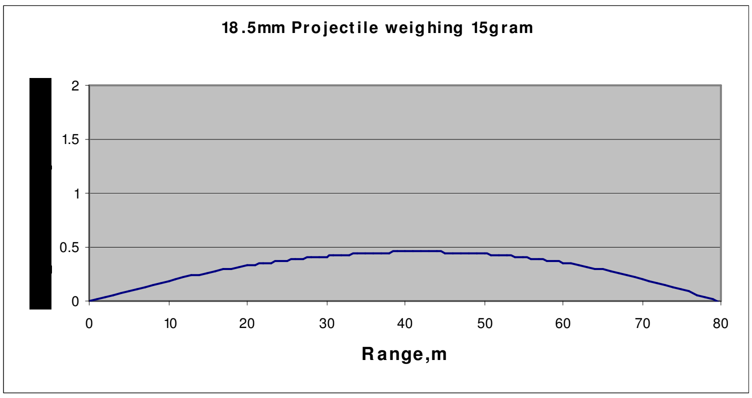


Figure 10: Calculated trajectory for a flat face dart of 18.5mm diameter and weighing 15grams launched with a velocity of 155ms^{-1}

This work was passed to a commercial company who wished to develop this concept into a commercial product. It was suggested that a soft deforming covering to the front face of the dart or by using a small radius would mitigate the “apple coring” effect but may affect dart stability. Figure 11 shows the prototype dart that was developed by the company **[47]**

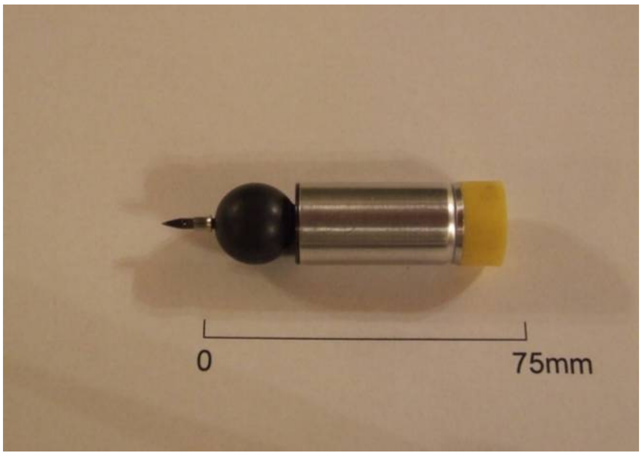


Figure 11: Prototype spin stabilised tranquilliser dart.

The dispersion of this dart, whilst considerably better than the other tranquilliser darts described above, was greater than experience suggested it should have been. More seriously, upon firing, the darts yawed very badly with recorded yaw angles at greater than 30^o so that the needle was cutting unacceptably into the target. This was cured **[48]** by the use of a lightweight frangible cap with a square edge that fitted over needle and rubber ball. The rubber ball expanded to 22mm diameter on impact.

Tests against cow carcases were very successful and live tests at 110m resulted in a total of five shots launched at an average velocity of 170ms^{-1} hitting the target within 100mm of the aim point. **[49]**

Chapter 4 Experimental Investigation: Instrumented Projectile and Target

4.1 Introduction

The criteria for potential injury to the thorax, by blunt trauma, are normally assessed by means of the Viscous Criteria, which is the product of the maximum deformation of the thorax and the mean velocity of deformation. The criteria for potential injury to the head, by blunt trauma, are normally assessed by means of the average maximum lateral head acceleration and the duration of the lateral acceleration. The extent of deformation, speed of deformation, acceleration and duration of acceleration of the target material are dependent upon the impact characteristics of the projectile. To study the potential injury caused by blunt trauma by the impact of a projectile it is necessary to either predict or measure the effect of the impact between projectile and target. It is useful to be able to separate the variables of the target and the variables of the projectile otherwise the total number of variables becomes large and the analysis of the results becomes complex. This part of the investigation used electronic instrumentation to investigate actual levels of acceleration transmitted by projectiles with different characteristics.

4.2 Impact forces and Accelerations

To investigate the forces and accelerations involved during the impact between the projectile and a target it is possible to measure them during an actual impact using sensors fitted to either the projectile or the target. Another approach is to use a deformable target with a calibrated level of deformation such as in the Trauzlblock test for explosives **[50]**. The two different approaches used were those of instruments fitted to the projectile and a second series of tests with instruments fitted to the target. The tests undertaken and their results are described below.

4.3 Instrumented Projectile

An instrumented projectile was originally developed at Cranfield University to study the forces and accelerations involved in stab tests against body armour. The actual projectile is an aluminium cylinder 50mm in diameter and 175mm in length. Inside the cylinder is mounted a circuit board, battery and accelerometers. The circuit board has a non volatile memory chip attached to record the data which is down loaded to a computer for analysis. The impact end of the projectile has a slot to allow the mounting of different types of head (from knife blades for stab testing to hemispheres for blunt trauma.) The interchangeable head also allowed the cross sectional area of the projectile to be easily changed. In addition to the accelerometers the head also has a number of strain gauges mounted on its stem to measure the impact force. The projectile can be manually triggered to record data whilst connected to the data recorder or remotely using an IR trigger. Figure 12 below shows the assembled instrumented projectile and the internal circuit board with battery and accelerometers.

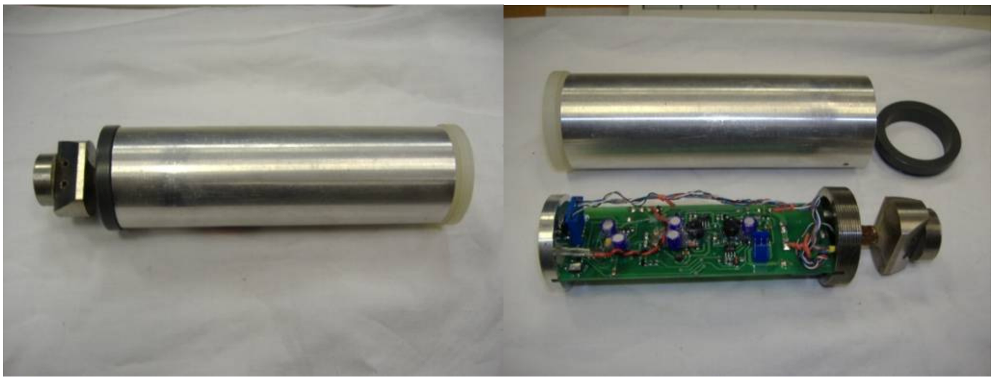


Figure 12: Instrumented Projectile and components

Initial tests were carried out by hand, triggering the projectile whilst it was connected to the data recorder and striking it repeatedly on a number of types of surface to investigate the force response and accelerations. The instrumented projectile was then used in combination with a simple drop tube to ensure fully repeatable tests under known impact conditions. The projectile was dropped from a height of 2 metres and triggered using the IR remote trigger positioned along side the drop tube. Thus the recording process began immediately before impact. It should be noted that the instrumented projectile, when triggered by hand (i.e. with the projectile connected via a wire to the power supply and data recorder) the acceleration records a large negative value which then reduces to zero over time whilst recording any accelerations experienced by the projectile. This is caused by a capacitor being charged by the power supply on triggering. This effect does not occur when using the remote trigger.

Figure 13 and 14 show a comparison between impacting a soft compressible material using two different diameter aluminium heads (with no covering). It can be seen from the graphs that the acceleration occurring with the larger diameter head is approximately 50% greater than for the smaller diameter head because the impact occurs over a greater area, thus providing a greater resistance to movement. There is a significant amount of noise being recorded by the strain gauges used to measure the force of the impact this is clearly visible between each of the 10 impacts.

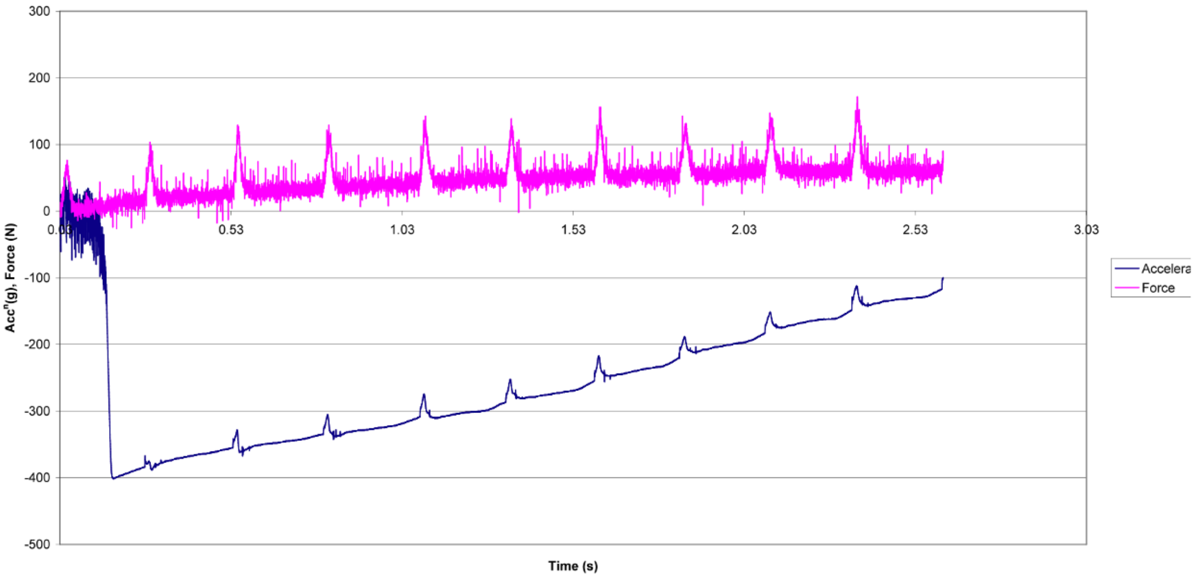


Figure 13: Instrumented Projectile fitted with the Small head impacting a compressible fabric

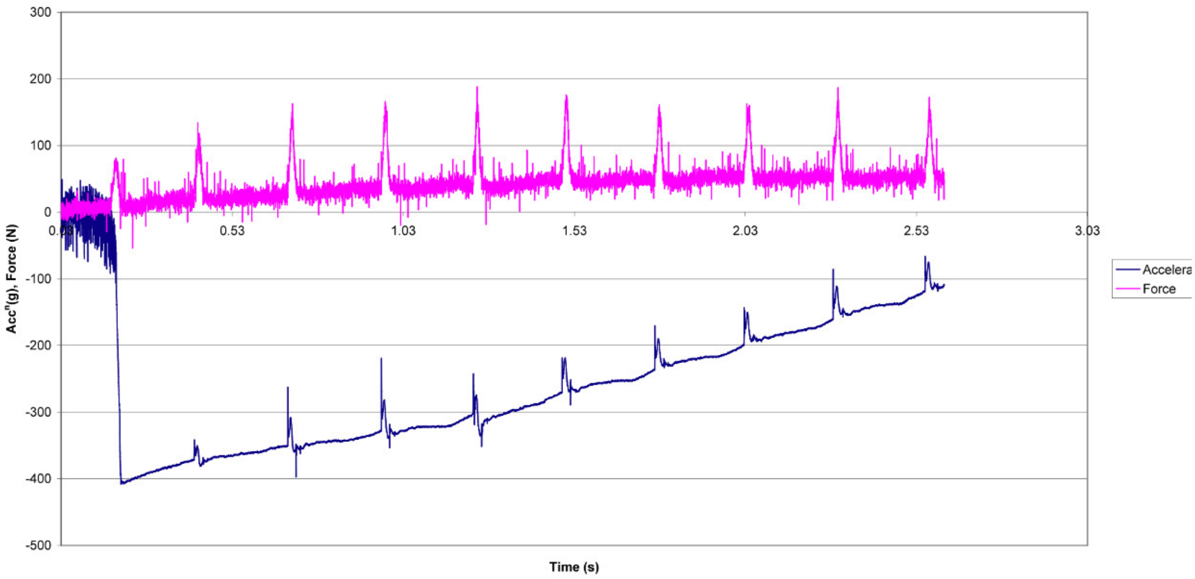


Figure 14: Instrumented Projectile fitted with the Large head impacting a compressible fabric

Figure 15 shows the response of the instrumented projectile impacting a rigid surface followed by a number of impacts on the author's leg. It can be clearly seen that the instrumented projectile experiences a much higher deceleration when impacting a rigid surface compared to the deceleration against a much softer material, such as the leg muscle, which is representative of the impacting surface of interest in this investigation.

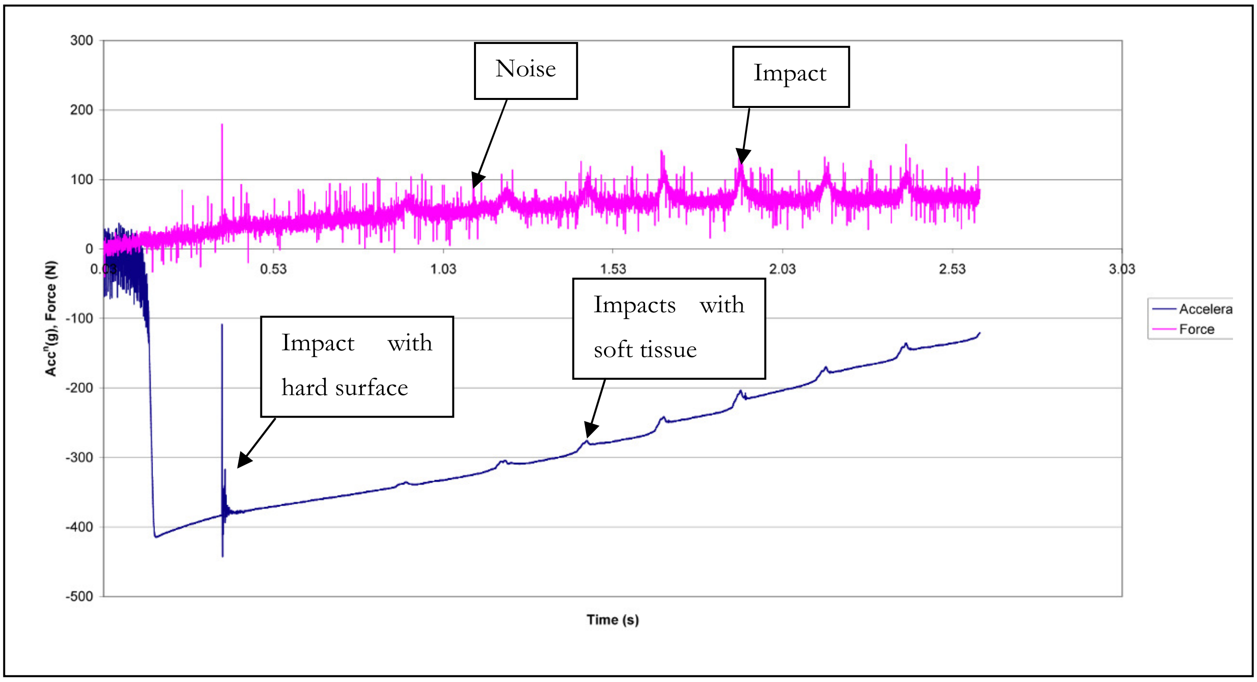


Figure 15: Instrumented Projectile Small head impacting a rigid surface followed by a number of impacts on human muscle tissue to demonstrate the response between hard and soft surfaces

Further tests were carried out to show how the impacted material significantly affects projectile deceleration and the subsequent force transmitted by the projectile to the impacted surface. The peak force transmitted into the target is much greater when a more rigid target material is used. This would imply that the kinetic energy is also being transferred at a greater rate.

The data recorded by the strain gauges is very noisy. Also, the traces for force and acceleration should be of a similar shape but if the traces during the impacts are expanded it can be seen that there is a slight delay in the response of the strain gauges and the trace displays none of the detail seen on the acceleration traces indicating that their response times are insufficient for the very fast events occurring during the impacts. Thus the force data was been discarded in the following analysis. The following graphs show expanded sections of data around single impacts for large and small heads on compressible material, large impactor head against human tissue and large impactor head against rigid material. In each case the graphs scale is retained the same to allow direct comparison. A 0.1 second interval is used for the x axis.

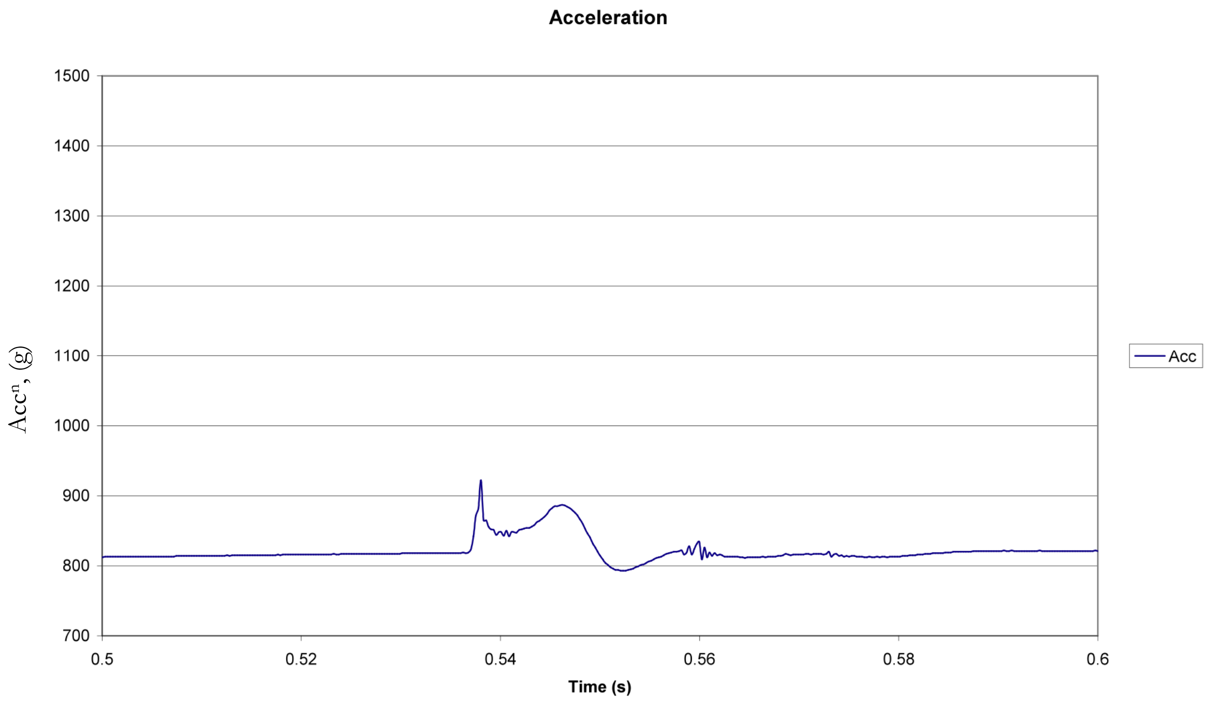


Figure 16: Expanded acceleration trace over one impact of the Large Instrumented Projectile head on compressible material

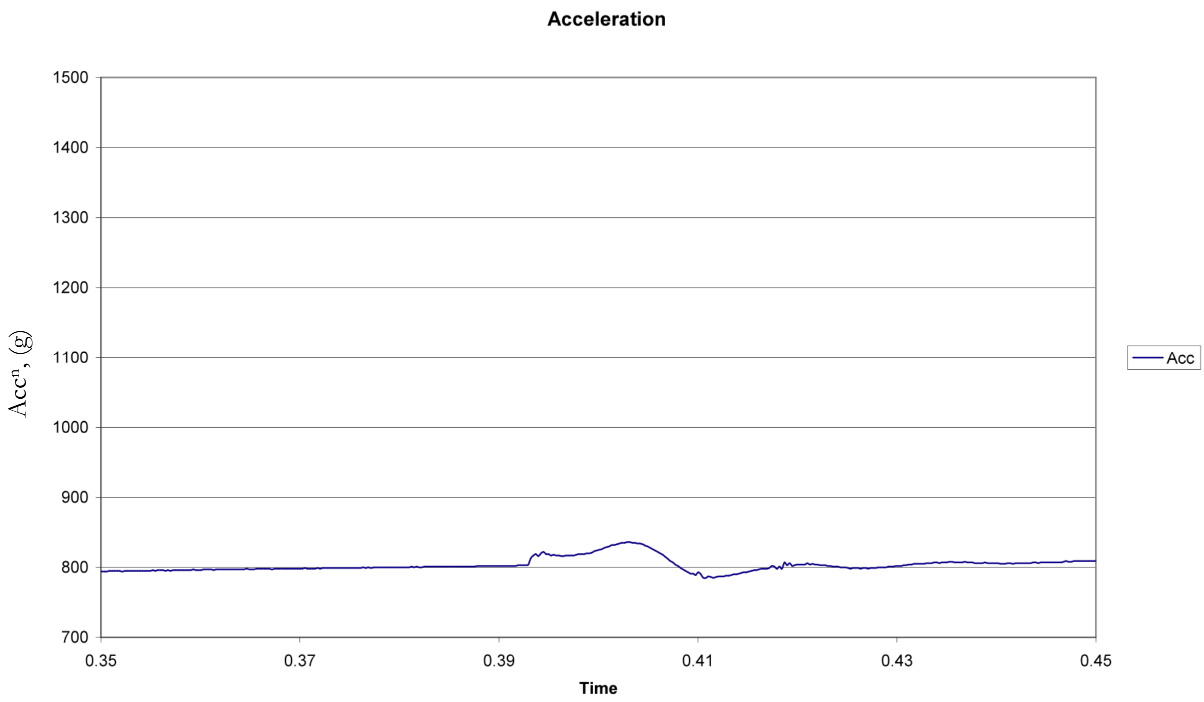


Figure 17: Expanded acceleration trace over one impact of the Small Instrumented Projectile head on compressible material

The Large Instrumented Projectile head gives a greater acceleration and therefore exerts a greater force. When replaced with the small head the acceleration recorded is of a lower magnitude but occurs over an increased length of time. When impacting human muscle tissue the total time of acceleration is considerably increased whilst the peak acceleration is considerably reduced.

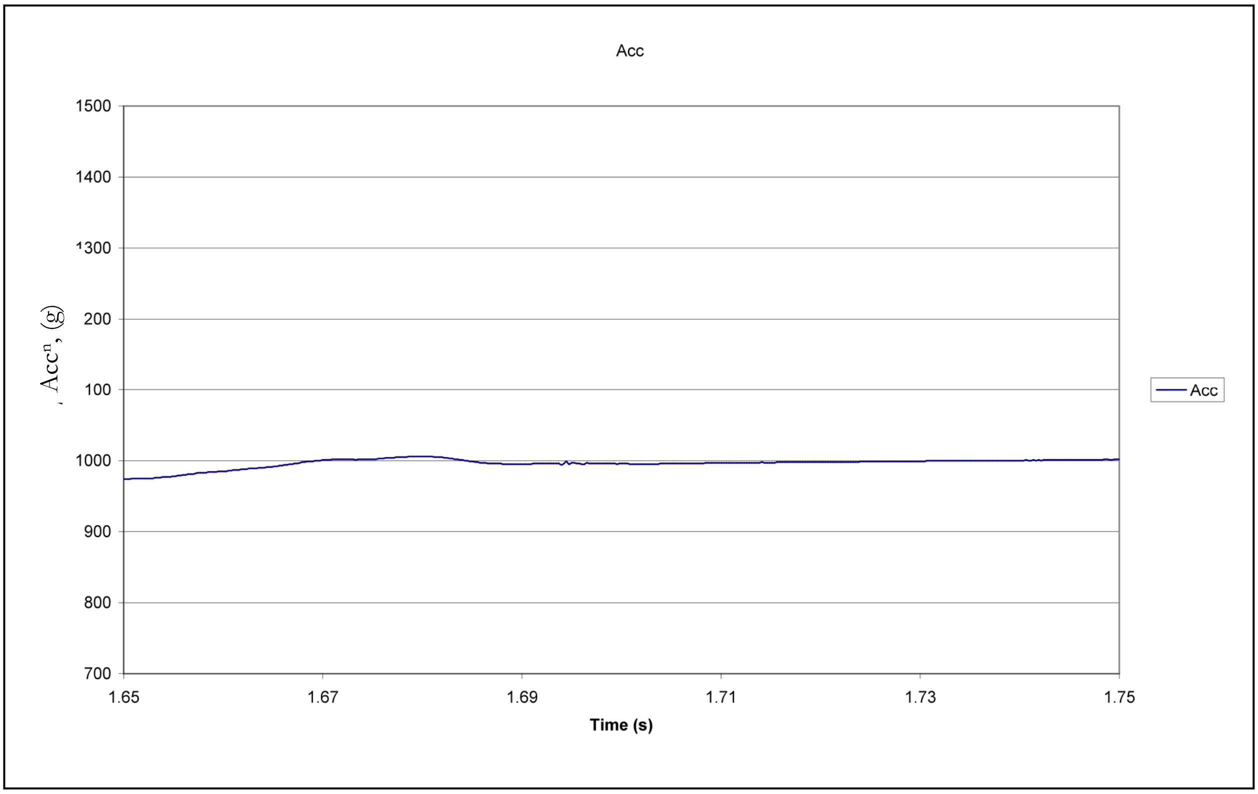


Figure 18: Expanded acceleration trace over one impact of the Large Instrumented Projectile head impact on human muscle tissue

Comparing these three impacts with those against a rigid surface shown below, demonstrates significant differences in the interaction between the projectile and the target. The peak acceleration is three times greater than that experienced impacting the compressible material but occurs in a fraction of the time.

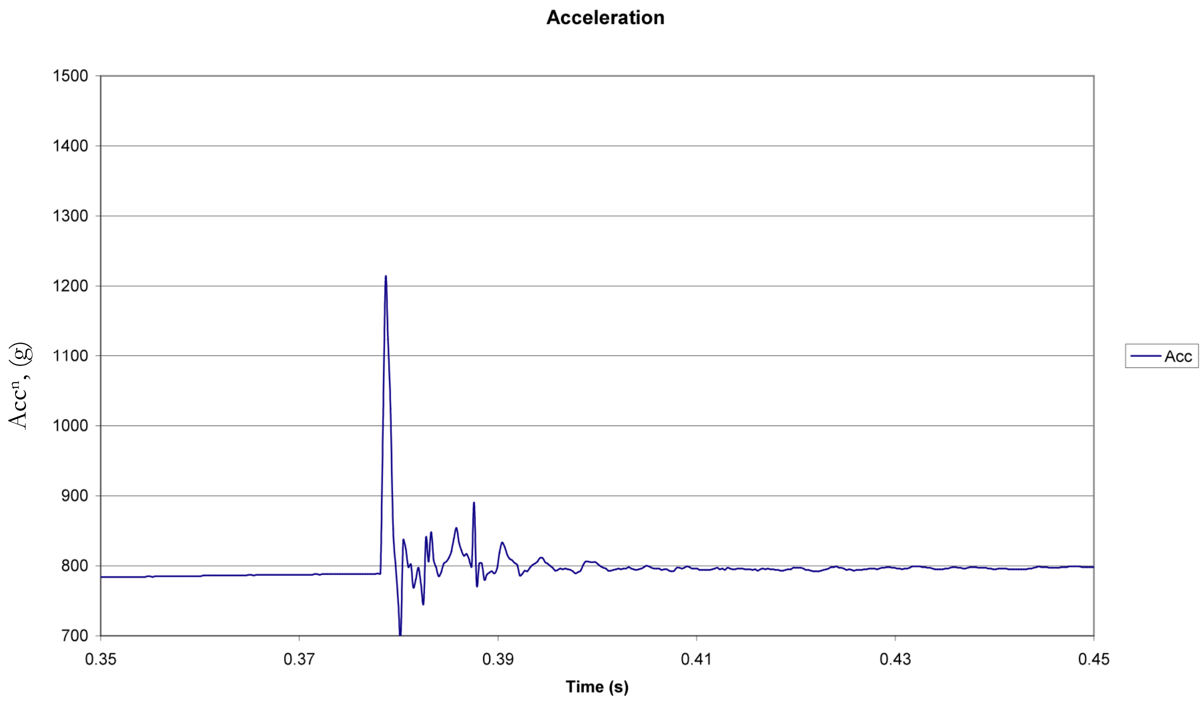


Figure 19: Expanded acceleration trace over one impact of the Instrumented Large head impact on rigid material

4.3 Discussion

The results generated by the instrumented projectile show that even the comparatively low deceleration of the projectile against the muscle tissue were enough to cause significant discomfort in the subject. Increasing the area of the impact simultaneously increases the deceleration of the projectile which could increase the chance of serious injury due to the increased Force being applied unless the projectiles mass was reduced significantly.

4.4 Instrumented Target

A major cause for concern with kinetic energy less lethal projectiles is their potential for causing serious head injuries because the head is one of the most vulnerable parts of the body with regard to blunt trauma and the effects can be the most devastating, ranging from brain damage to death. Reducing this risk, by increasing system accuracy and by reducing the potential for head injury whilst retaining weapon effectiveness, is a major aim of this research. It was established in Chapter 2 that the potential for head injuries from blunt trauma increases with increasing linear acceleration of the head and with increasing duration of linear acceleration. To be able to research into those factors that affect the linear acceleration imparted to the head, and its duration, it is necessary to be able to measure their levels imparted by projectiles with different impact characteristics. To do this a simple head model was constructed based on a simulated skull developed by Thali **[51] [52] [53]** to investigate both penetrating injuries and non penetrating injuries to the head. This simulated skull is spherical in shape and made from a composite plastic in three different layers of different density to simulate the structure of the skull. To simulate the brain the skull is filled with either gelatine or plasticine of the appropriate weight (gelatine has the disadvantage of being composed of biological material that degrades and becomes unusable after only a few days so plasticine is often used). The skull is covered with a layer of silicone rubber to simulate the scalp. These simulated skulls are commercially available from a company called "Symbone".

A light weigh displacement transducer was manufactured in the from of a 1mm thick x 5mm wide x 150mm long beam fitted with strain gauges. Deflection of the beam was detected by strain gauges so that the displacement of the skull with respect to time could be measured when impacted by projectiles with different impact characteristics. The arrangement used is shown in Figure 20 below. An additional cap of 1mm thick silicone rubber was used to protect the easily damaged silicone rubber covering applied by the manufacturers.

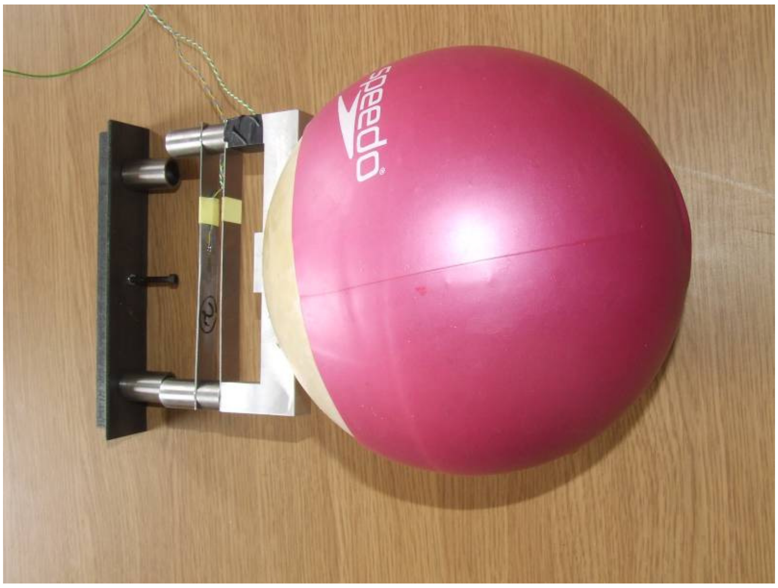


Figure 20: Head model used for investigating the impact characteristics of different projectiles

The head model was impacted using a 2m high drop tube to guide the projectiles prior to impact. Five different projectiles were tested and are shown in Figure 21 below. The standard projectile was the L21A1. Three modified versions of this were tested. One modification was the drilling of two 8mm cross holes at right angles to one another and with their centres 6mm back from the impact face. Another modification was the same but with another two 8mm diameter through holes at 6mm centres behind the first row. Another version was produced by machining away part of the centre section to produce a light weight version. An Energy Attenuating Round projectile was also tested.

Figure 21: The different projectiles used to investigate impact characteristics with the instrument simulated skull

The usually stated cause of brain damage is that the skull is struck and results in linear acceleration. However, because of the structure of the skull/brain interface the skull is accelerated at a greater rate than the brain and this results in the inner surface of the skull impacting the brain and is the result of blunt trauma and the head injuries associated with baton round strikes. Therefore two series of tests were carried, the first with any empty skull and the first with the skull filled with plasticine to simulate the brain. The empty skull set up had a mass of 0.55kg. For the second series of tests the mass was increased by 1.3kg, the average mass of an adult male brain.

The projectiles were all of different masses and are given in Table 4 below.

Projectile	Projectile Mass
Standard L21A1	98.6 grams
Energy Attenuating Round	97.4 grams
L21A1 – Single Row of Holes	95.8 grams
L21A1 – Double Row of Holes	91.6 grams
Light Weight L21A1	57.8 grams

Table 4: Masses of the five projectiles used with the instrumented head model

The impact of the projectiles was recorded on a Nicolet Digital Recording Oscilloscope. The time interval was 0.5μs. The results for the five projectiles impacting the empty simulated skull are shown below. The trace for each impact is given for the start of the displacement to the point at which the rate of increase of displacement ended. The results were transferred in to an Excel spread sheet and a polynomial trend line added.

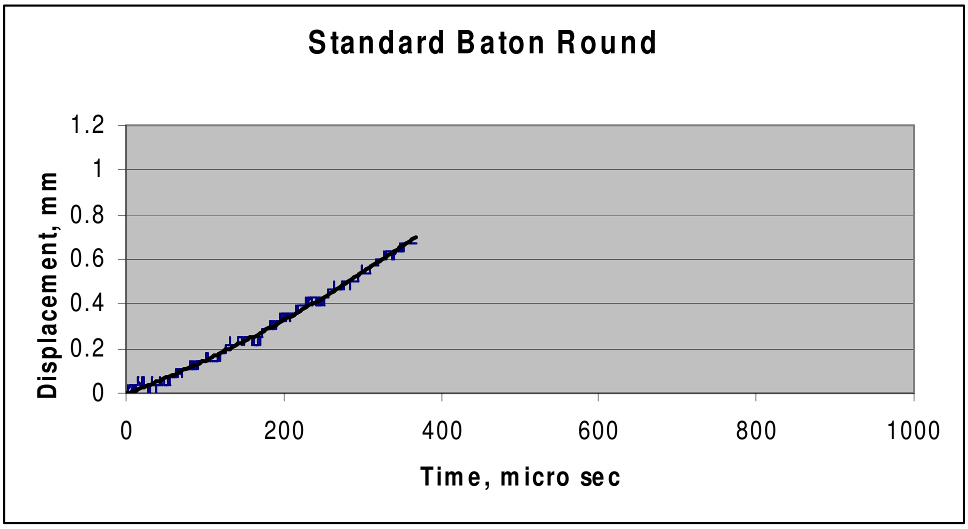


Figure 22: Results for the impact of a standard L21A1 baton round with the empty simulated skull

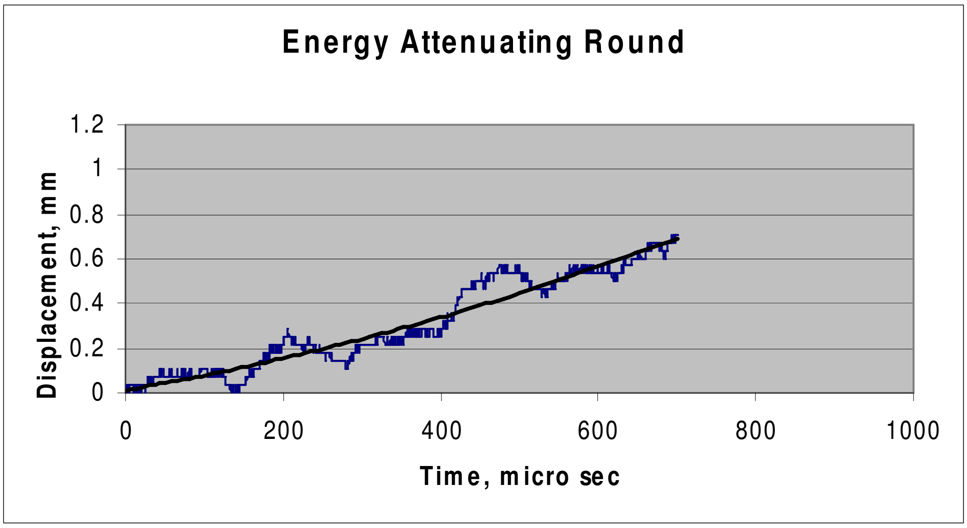


Figure 23: Results for the impact of an Energy Attenuating Round baton with the empty simulated skull

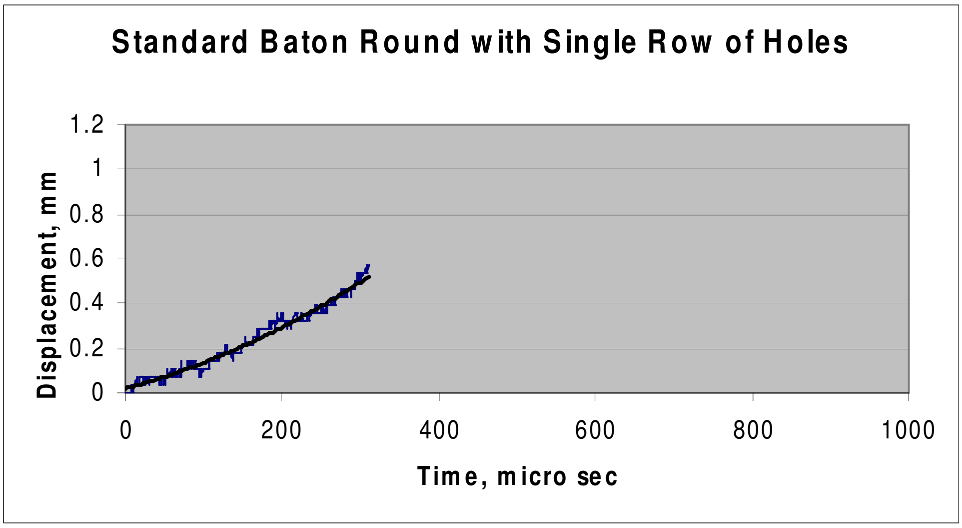


Figure 24: Results for the impact of a standard L21A1 baton round, modified by drilling two 8mm diameter through holes with their centres 6mm back from the front face, with the empty simulated skull

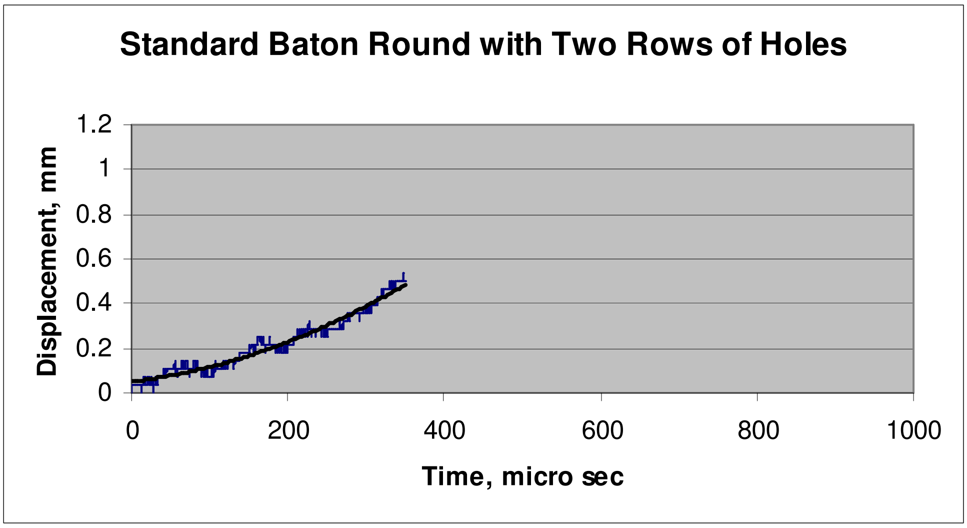


Figure 25: Results for the impact of a standard L21A1 baton round, modified by drilling two 8mm diameter through holes with their centres 6mm back from the front face and another row of 8mm diameter through hole with their centres 6mm behind the first row, with the empty simulated skull

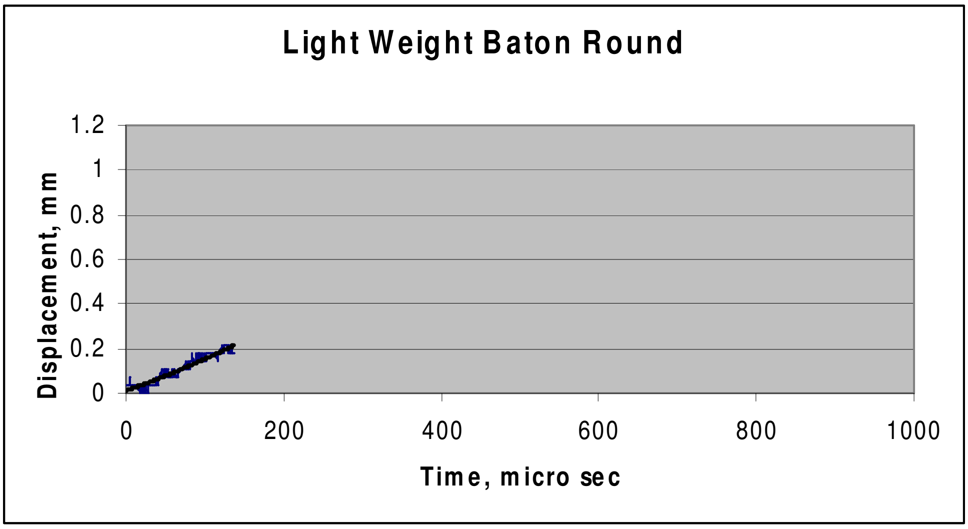


Figure 26: Results for the impact of a standard L21A1 baton round, modified by machining away 44% of the mass, with the empty simulated skull

The results for the five projectiles impacting the empty simulated skull filled with pasticine, giving it an increased mass of 1.3 kg, are shown below.

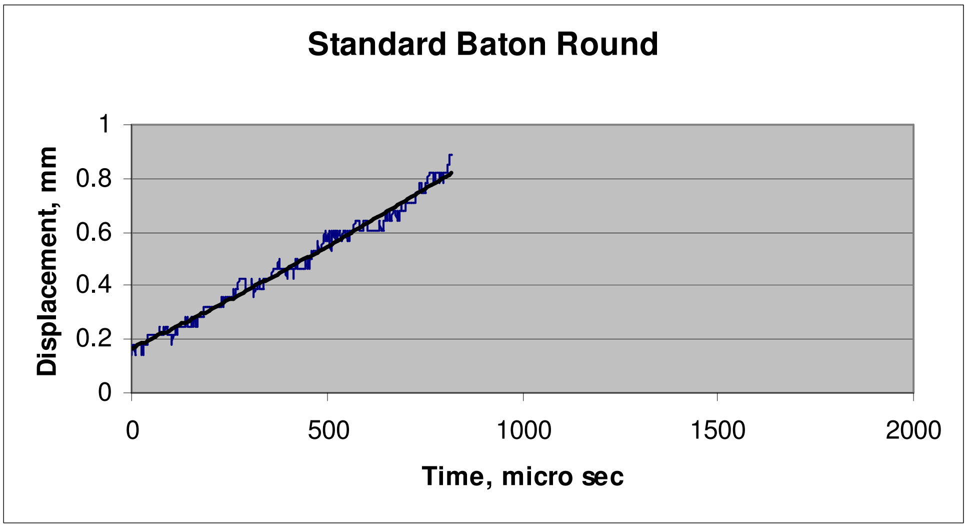


Figure 27: Results for the impact of a standard L21A1 baton round with the empty simulated skull filled with 1.3kg of plasticine

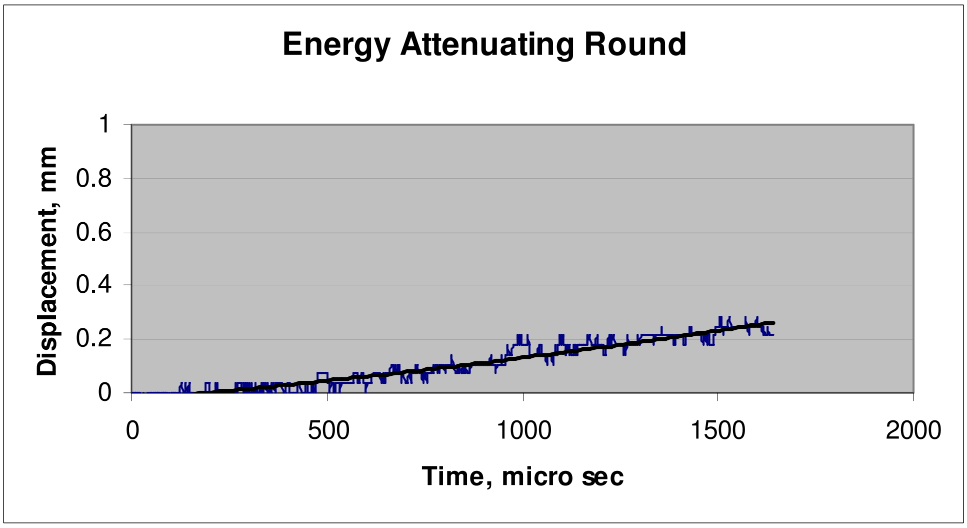


Figure 28: Results for the impact of an Energy Attenuating Round baton with the empty simulated skull filled with 1.3 kg of plasticine

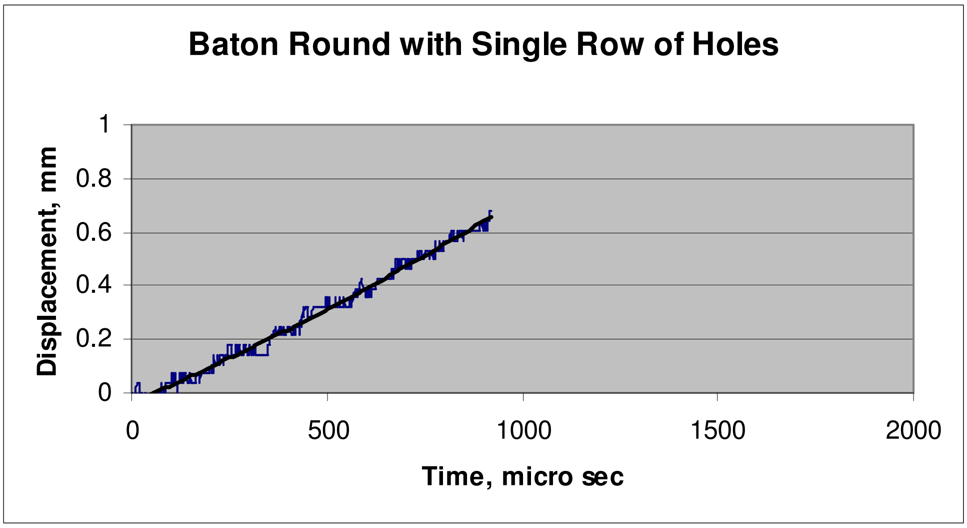


Figure 29: Results for the impact of a standard L21A1 baton round, modified by drilling two 8mm diameter through holes with their centres 6mm back from the front face, with the empty simulated skull filled with 1.3 kg of plasticine

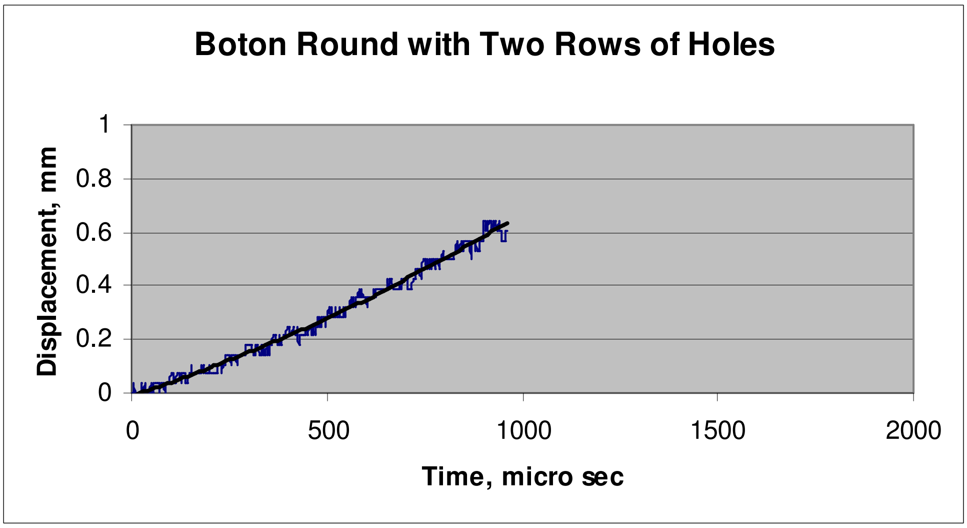


Figure 30: Results for the impact of a standard L21A1 baton round, modified by drilling two 8mm diameter through holes with their centres 6mm back from the front face and another row of 8mm diameter through hole with their centres 6mm behind the first row, with the empty simulated skull filled with 1.3 kg of plasticine

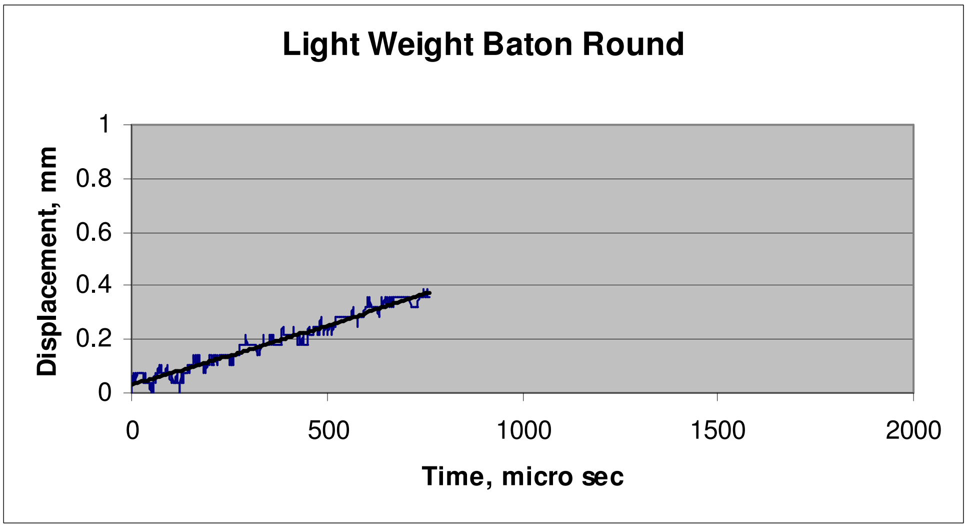


Figure 31: Results for the impact of a standard L21A1 baton round, modified by machining away 44% of the mass, with the empty simulated skull filled with 1.3 kg of plasticine

By tabulating the data for each of the projectiles used with the filled skull it is possible to compare the values calculated using the HIC.

Projectile	Displacement (mm)	Time (μs)	Acceleration (G)	H.I.C
Standard	0.708	812	218	569
AEP	0.284	1440	284	6
Single Row Holes	0.675	860	186	406
Double Row Holes	0.64	880	170	332
Light	0.3545	696	149	181

Table 5: Displacement, Time, Acceleration and Head Injury Criteria Values

4.5 Discussion

Comparing the impacts with the empty skull by the L21A1 baton rounds (unmodified and modified) it can be seen that there is a major similarity between them in that the displacement with respect to time is similar for all four projectiles. However, there are differences in the duration of the impacts. The L21A1 baton round with a single row of 8mm holes has a shorter impact duration than the unmodified L21A1 baton round. There is very little difference between the duration of impact for the L21A1 baton round modified with one row of holes and the projectile modified with two rows of holes. Farrar **[11]** postulates that an air cavity in the nose of the projectile would reduce the impact force and thus the impact acceleration and the displacement with respect to time. He also postulates that a greater depth than 10mm from the impact surface would not reduce the impact force any further. These findings show however that this is not the case and that it is the duration of the impact and not the impact force that has been reduced, although the second row of holes has not had any significant effect. (It should be noted that both projectiles are lighter than the standard L21A baton round so a small difference in the impact characteristics would have been expected because of this). The light weight projectile has a considerably reduction in the duration of the impact.

The results for the impact of the L21A1 baton rounds (unmodified and modified), with the simulated skull filled with plasticine, are not as expected. It would have been expected that a similar force would have been applied by the different projectiles and that because of the increased mass of the skull the acceleration would have been increased and therefore the displacement with respect to time would have been reduced. However, it can be seen that the opposite as occurred with the exception of the AEP projectile, which had a significantly lower rate of displacement with respect to time. The duration of the impact has also been increased slightly with the exception of the light weight projectile where the duration of the impact has doubled.

The Energy Attenuating Round baton has a significantly lower displacement with respect to time compared to the L21A1 baton rounds The results for the skull filled with plasticine are very different to those of the L21A1 baton rounds as the displacement of the skull with respect to time and the displacement have both significantly reduced compared to the impacts with the empty skull.

These impact results are highly significant with regard to the potential for baton rounds to cause blunt trauma injury to the head. The results show that the impact characteristics can be significantly altered by the geometry and mass of the projectile. It is important therefore that these studies are extended to gain a better understanding of the impact process to allow the design of baton rounds with reduced probability of causing serious injuries if they impact the head.

By comparing the HIC results for each projectile it is possible to see that all of the projectiles are below the suspected injury threshold. All of the modified projectiles have a lower value than the standard baton round, with the AEP giving the greatest reduction in possible injury. The lightweight projectile also has a large reduction in value for the HIC.

Chapter 5 Experimental Investigation: Baton Rounds

5.1 Introduction

Baton rounds are extensively used by both the military and by the police. In the UK the calibre is 37mm utilising the Heckler and Koch L104A1 launcher shown below in Figure 32. Fitted with the L18A1 optical sight, it fires the L21A1 baton.

Figure 32: Heckler and Koch L104A1 grenade launcher, with optical sight L18A1

The Heckler and Koch L104A1 is a single shot break action baton gun which has rifling to spin stabilise the projectile, an extendible locking stock and flip up ladder sights (although these have more recently been replaced with the L18A1 optical sight in order to increase accuracy and speed of aiming). It is primarily designed to fire the L21A1 Plastic bullet currently in service with the British police force as well as the newly introduced AEP round.

The potential for injury caused by baton round impacts to the chest has been shown to be linked to the level of deflection and the rate of compression of the thorax by the impacting projectile. The geometry, mass, design, materials and impact velocity all play a part in the level of potential injury that baton rounds may inflict but no work, other than the theoretical study by Farrar **[11]**, has been carried out to investigate the true significance of these variables. This section tested a wide range of different, carefully selected projectile geometries and masses by modifying standard baton rounds and firing them at a simulated human thorax. Different materials for mitigating injury were also tested by attaching them to modified baton rounds and firing them against a simulated human thorax.

Figure 33: L21A1 Baton, Casing and .357" blank for launching

The L21A1 Baton is shown above in Figure 33 and is made from a solid piece of Polyurethane polymer, it is held in an aluminium casing with a slightly crimped end. A .357" magnum crimped cartridge case filled with fast burning nitrocellulose propellant is used to propel the baton round. Below is a table that shows the average kinetic energy in Joules of the L21A1 baton round from a clamped L104A1 gun, as well as for the L5A7 baton round that it replaced.

Range (m)	Kinetic Energy of L21A1 (J)	Kinetic Energy of L5A7 (J)
2	257	274
20	244	246
35	230	216
50	215	200

Table 6: Comparing kinetic energy of the current and previously used police baton rounds used by UK police forces

From the table it is possible to see that whilst the newer L21A1 baton has a lower kinetic energy as it leaves the muzzle of the launcher it also maintains this energy slightly better at an increased range. Whilst the kinetic energy of the L21A1 is still dropping off quite rapidly at range it is following a gentler gradient that should make it more predictable when used in a real life scenario, since it will have a similar level of kinetic energy at maximum range as it does at the minimum range. A review of the L104A1 between 2002 and 2004 has been carried out for the Association of Chief Police

Officers (ACPO) Working Group on Firearms **[54]**. In the two years the study was undertaken there were 37 incidents where the L104A1 was used, there were 50 rounds fired across all 37 incidents. In 32 of the 37 instances the L104A1 was fired at less than 15 meters and in eight cases were fired at less than three metres. There were no serious injuries caused as a result of these firings, the most common injury was significant bruising to the strike area. Some of the reported injuries are shown below in

Table 7.

Perforation of the skin in the area around the strike to the abdomen (3 incidents)
Small cut to knuckle of ring finger (direct strike to the hand)
Fracture (1 incident) in which a single chest strike resulted in a fracture to the sternum and adjoining rib
Groin injury resulting in a decision being made to surgically remove one testicle

Table 7: Sample injuries caused by L21A1 baton from the ACPO report

28 of the incidents were concluded immediately after the discharge of one of more L21A1 batons, of these seven impacts "neutralised" the threat, the remaining 21 stopped the threat long enough for officers to advance and overpower the suspect.

The remaining nine incidents continued after the discharge of the L21A1 baton(s) and were resolved using other less lethal technologies (Taser and CS gas). None of the 50 batons fired struck the head of the suspect, the area most likely to cause significant injury if hit.

The use of the L21A1 baton is likely to increase the probability of injuries that are not considered life-threatening including injuries such as: bruises, cuts and minor bone fractures in limbs. It is also likely to reduce the chance of more serious, potentially life-threatening head injuries that are the main cause of death and injury from any baton rounds. The consequences of an impact to the head will be more serious with the L21A1 compared to the older L5A7 because of the slightly increased kinetic energy and tougher projectile; however there is a reduced risk of striking the head, because of the increased accuracy of the L21A1 over the L5A7. This combined with a strict set of Rules of Engagement (RoE) to ensure that officers do not fire above chest height further minimises the chance of striking the head.

The guidance **[55]** for use of the L21A1 round states:

"Baton rounds should be aimed to strike directly (i.e. without bouncing) the lower part of the subject's body i.e. below the rib cage." Baton Gunners are trained to use the belt-buckle area as the point of aim, at all ranges thus militating against upper body hits.

Unless there is a serious and immediate risk to life, which cannot otherwise be countered, use at less than one metre or aiming the weapon to strike a higher part of the body is prohibited. In these circumstances the risk of serious and even fatal injuries is increased and the firer must be able to justify the increased use of force."

Knowledge of the effect of these projectiles when they strike a person is clearly very important and it is highly desirable that the possibility of a lethal effect should be minimised. Because of all the unknown variables involved when trying to model a non-penetrating blunt trauma caused by these projectiles it is necessary to carry out actual tests on simulated targets. Such tests were usually conducted using gelatine to represent the flesh covered by a synthetic skin as previously described in Chapter 2. However a realistic simulated target was developed by DSTL Porton Down, known as the Behind Armour Blunt Trauma (BABT) rig, it was originally designed to measure the blunt trauma caused by the impact of a bullet into combat body armour (CBA). It was decided to use this model because it gives more consistent results than gelatine and is reusable over a large number of shots. Figure 34 below shows details of the Behind Armour Blunt Trauma test rig with mirror and back lighting.

The BABT rig consists of a large steel superstructure onto which a hand moulded silicone half cylinder rests. The sides of this silicone cylinder are clamped rigidly into the steel superstructure. The rig then reacts when struck, similarly to that of the human chest **[58]**. In order to measure the response that the model has to the impact as well as the effect on the projectile, a high speed video camera to record the impacts and subsequent response of the test rig was used. To make this possible a number of reference points were marked down on both the surface of the model and a marker board across the top of the target.

Figure 34: Behind Armour Blunt Trauma (BABT) rig with mirror and back lighting

The high-speed video camera was positioned such that it could record both the front and back faces of the BABT model during impact. In order for the camera to be able to look at both sides of the BABT rig a mirror was positioned underneath it and angled at 45 Degrees to the lens. This provided a vertical view looking up the inside of the rig and clearly showing the back face of the silicone body simulant as well as the reference marker tape. Several other camera perspectives were used in order to get the best view of the impact process. These are described later.

This setup allows the measurement of both impact velocity using the photo chronographs and return velocity of the rebounding projectile calculated from the high-speed video. It is also then possible to calculate the impulse on the target from the time the projectile has spent in contact with it as well as the kinetic energy density, the amount of kinetic energy transferred to the target and the approximate amount of deflection in the wall of the model.

The L104A1 launcher was placed in the universal mount and secured in such a way that the barrel could be broken in order to load it without adjusting the point of aim significantly. The end of the muzzle was positioned 10m from the front of the BABT rig because this was the most common engagement range used by police officers aiming accurately (rather than indiscriminate crowd control discharges). Photo chronographs were used to measure the velocity of the projectile.

A number of different projectile types were fired in order to compare the impact energy and deflection of each type's impact. These consisted of the original rubber bullet, an L5A7, an L21A1 as well as a number of modified L21A1 batons to investigate ways of reducing target damage. Results of firing each projectile three times were collected in order to make sure that the projectiles behaved consistently.

5.2 Test Projectiles

Figure 35: The original rubber bullet

Whilst the original rubber bullet was not designed to be fired from the L104A1 it did function to a degree. It was found to tumble rather badly down range towards the BABT rig. This actually confirms police descriptions of its use, one of the main reasons why it was replaced with a more accurate system. The main cause of the inaccuracy is the size and shape of the front end, which affects the aerodynamics of the projectile. No useful impact data was recorded with this projectile.

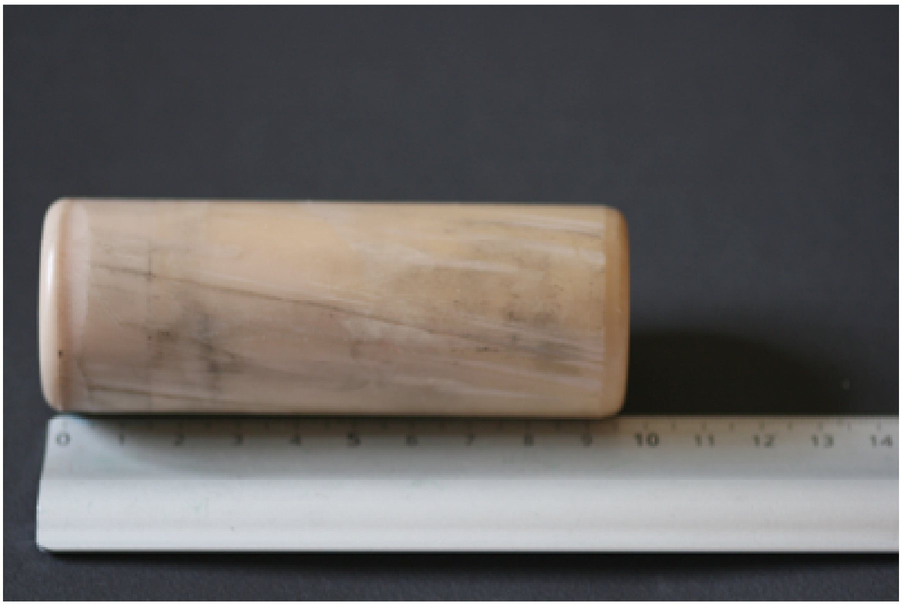


Figure 36: The Standard L5A7 Baton

The L5A7 baton shown in Figure 36, which was replaced in 2000 with the newer L21A1 because of accuracy problems i.e. head strikes and therefore serious injury were more likely.

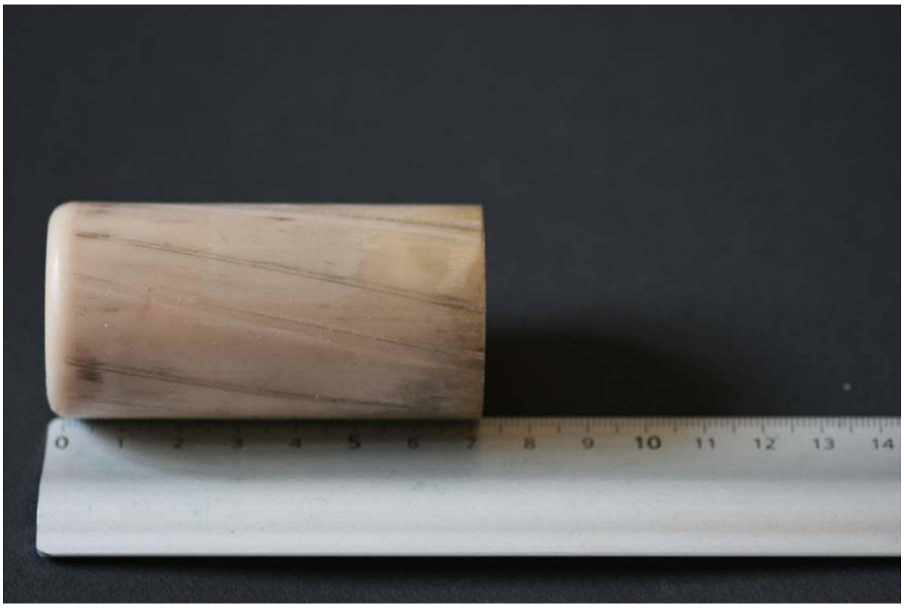


Figure 37: The L5A7 baton, shortened to reduce weight. Rifling marks from the launcher are visible

To see if some weight could be removed from the original L5A7 and how much faster it could be fired to give the same effect as the original baton round a version was fired that was made shorter by cutting a piece from the back end and is shown in Figure 37. According to theory, lighter faster projectile will have the same kinetic energy density as a heavier slower one.

Figure 38: Modified L5A5 baton with four equispaced holes in two rows

Tests were fired with a L5A7 with the front end modified to compress a great deal more when impacting with the target. Four holes were bored in the front of the baton, with two holes set slightly back from the first pair. The holes in each row are perpendicular to each other and run right through the projectile. There are two main benefits to this. Firstly, the compression occurs in the projectile that uses up part of its kinetic energy (the amount used up can be calculated by comparing it to a standard projectile accounting for the slight change in mass due to the holes). Secondly because this compression occurs it is also slowing the impact and increasing the contact time, which leads to the impact impulse being reduced. This could be a significant factor when dealing with head strikes.

Figure 39: The standard L21A1 baton (Polyurethane polymer) 37 mm calibre with a 9 mm nose edge radius and a boat-tail on the base (Cd 0.24)

The L21A1 baton (shown in Figure 39) has an increased nose radius designed to stop the projectile from cutting on impact with a person. However, it is known that by putting a radius on the front edge of a projectile makes it less stable in flight. The boat tailing on the back of the projectile was added improve accuracy. The reduced diameter mid section is to prevent the whole projectile engaging in the rifling, which would have a high friction force and slow it down as it travels down the barrel.

When modifying a projectile to cause more or less damage it is also necessary to look at the effects of the modification on the projectile's flight. One of many factors affecting the projectile's flight is the drag on the projectile. As the projectile moves through the air, the air in front of it is displaced. The energy needed to displace this air reduces the kinetic energy of the projectile continually during its flight. Because the projectile is moving below the speed of sound (approx $340ms^{-1}$ in air) the pressure wave that is formed is travelling faster than the projectile and spread out from it as it moves away. The generation of this pressure wave results in fore body drag. However the effects of fore body drag are much less significant in the case of LLWs because they travel at velocities below the speed of sound. The fore body drag for a given shape will increase in a fairly linear trend up until the speed of sound at which point it increases at a significantly faster rate. Because the standard baton round travels at less than a $1/3^{rd}$ of the speed of sound fore body drag doesn't have such a significant effect on its flight as the base drag described below.

There is also drag related to the rear section of the projectile called Base drag. Base drag occurs from the turbulent flow of air behind the projectile in its wake. Low pressure behind the projectile causes air to be pulled in to fill it, which in turn leads to a resistance of motion. In order to reduce this base drag in a baton round the rear of the projectile is boat tailed, this allows the air to flow in behind the projectile easier and therefore reduce the pressure drop and drag. There is a trade off when using a boat tail between drag and stability, the less drag due to boat tailing will decrease the stability of the projectile but allow it to travel further at a higher velocity.

Because of the projectiles comparatively large size, there is also drag associated with friction between the projectile and the air it is passing through.

The drag force is a combination of these three forces and can usually be written as below:

$$Drag\ force = \frac{1}{2}\rho V^2 A C_D$$

Equation 7

Where:

ρ = Density of air

V = Velocity of the projectile

A = Cross sectional area of the projectile

C_D = Drag Coefficient

The drag coefficient relates to the shape of the projectile and is a value between 0 and 2 with a lower number indicating a more streamlined projectile. C_D can be assumed to stay constant when the projectile is travelling below the speed of sound.

Figure 40: The standard L21A1 baton with two 8mm diameter perpendicular holes running through the nose. This allows the nose to be compressed more on impact

Tests were also fired with an L21A1 that had been modified in a similar way to the previous L5A7 projectile. Two perpendicular holes running through the projectile in its nose were added, to allow increased compression on impact. This is shown in Figure 40. There is a side effect from this, in that it can affect the projectiles stability. By removing mass from the front section the projectiles centre of gravity (CoG) will be shifted. If the centre of gravity is moved towards the nose of the projectile and in front of the centre of pressure (CoP) then, any yaw movement of the projectile will generate a yawing moment that will push the projectile back towards stable flight. If the centre of gravity moves back behind the centre of pressure then the projectile will become unstable. The centre of pressure refers to the point about which the net moment is zero and the resultant force appears to act. By placing holes in the nose of the projectile the CoG will move towards its base.

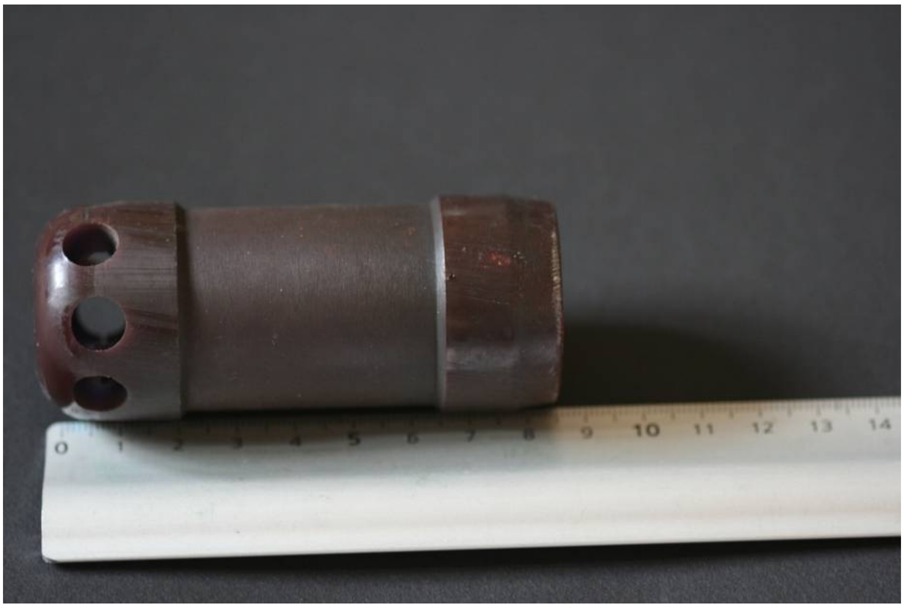


Figure 41: The standard L21A1 baton with four equispaced 8mm diameter perpendicular holes running through the nose. This allows the nose to be compressed more on impact

Trials were also fired with a L21A1 baton with four holes drilled in it in one row to allow increased compression of the version with two holes. Tests were then carried out using the L21A1 baton shown in Figure 42 that has two of the holes offset in a second row similar to the L5A7 in Figure 38.

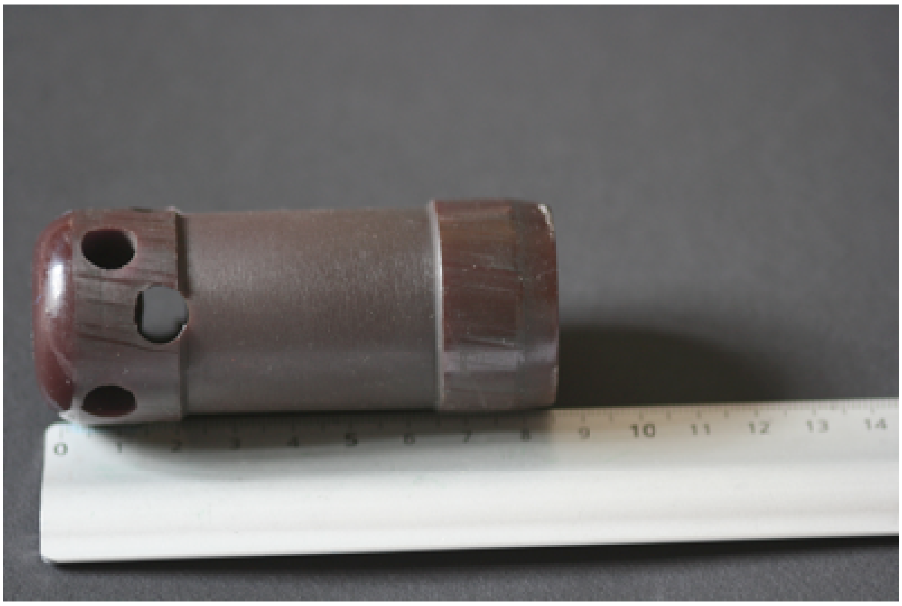


Figure 42: The standard L21A1 baton with four equispaced 8mm diameter perpendicular holes running through the nose. This allows the nose to be compressed more on impact.

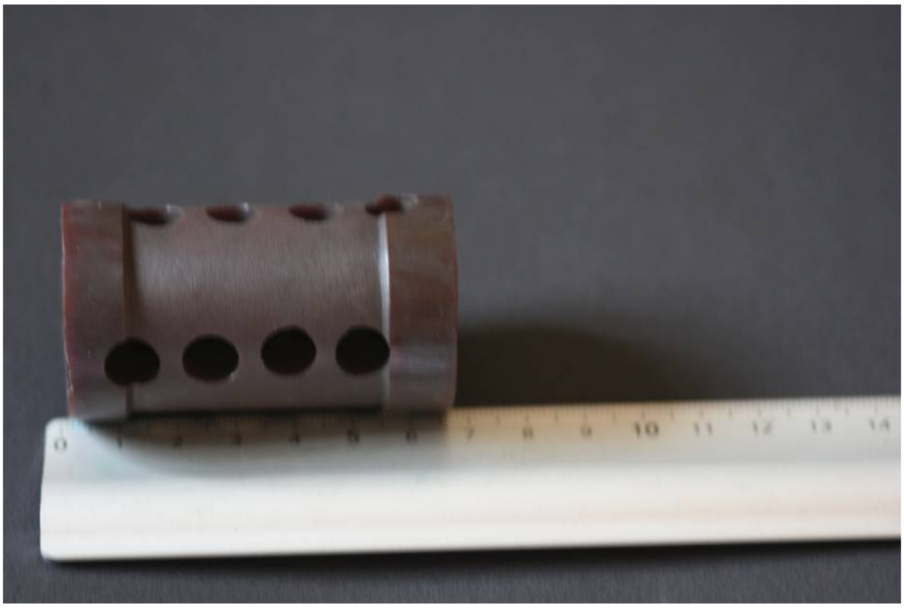


Figure 43: The standard L21A1 baton with eight 8mm diameter perpendicular holes equispaced along the length of the projectile along its quadrants. This allows the entire projectile to be compressed more on impact. Also both ends have been cut down to further reduce the mass

Trials were also fired with a baton that had both ends removed to make it more of a "flying cylinder" the most aerodynamically stable shape as well as this there are eight holes drilled along its length in two perpendicular rows. This allows the projectile to be further compressed.

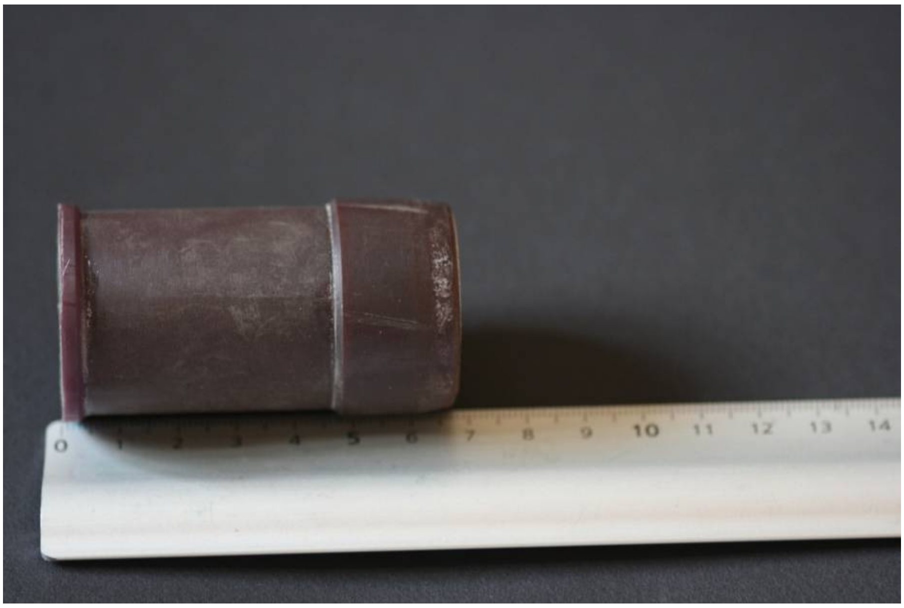


Figure 44: The standard L21A1 baton with the front nose sectioned off, this reduces weight and produces a more stable flight with a flat front face

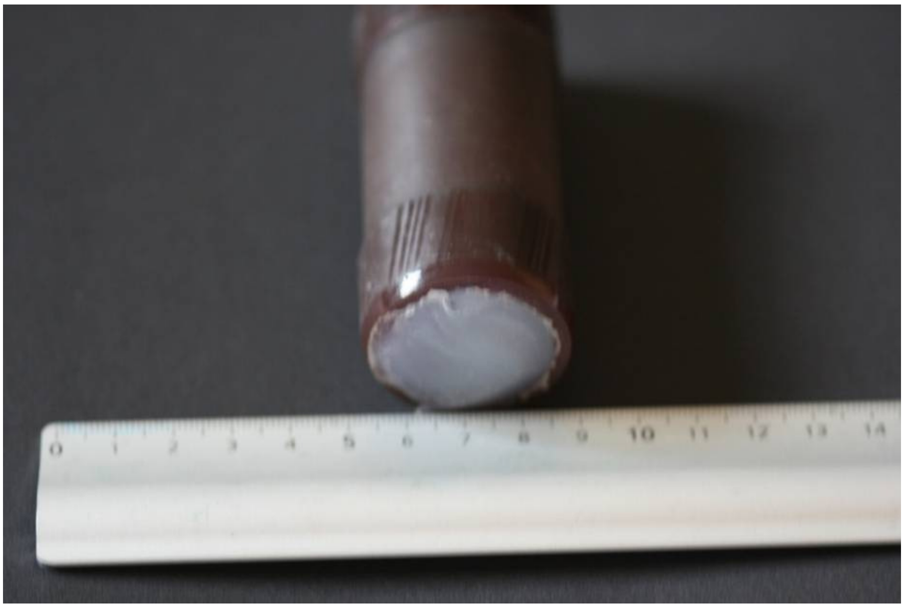


Figure 45: The standard L21A1 baton with the front face bored out

The front face is bored out to a depth of 10mm and filled with silicone sealant. This reduces the mass of the projectile slightly whilst introducing a material with a higher energy storing capacity into the nose of the project.

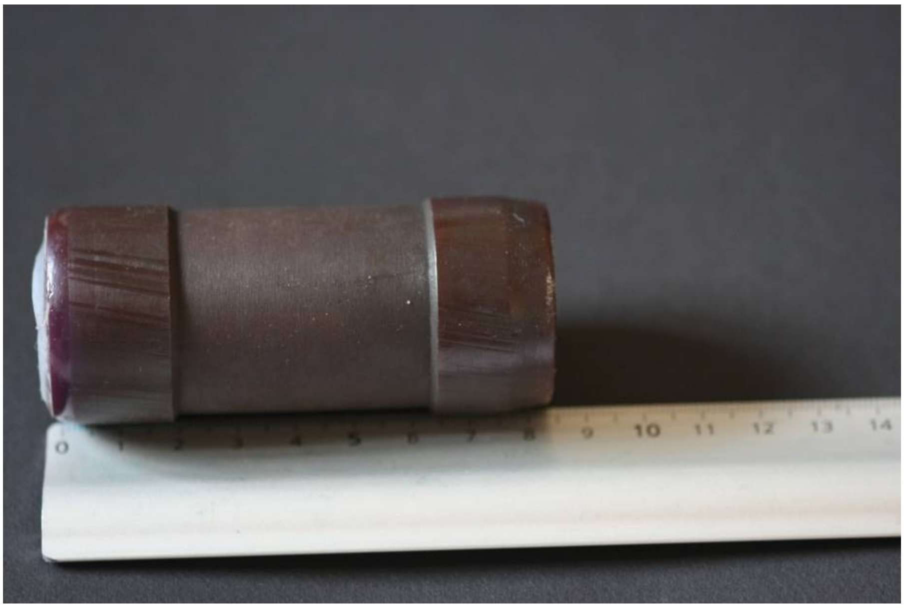


Figure 46: The side profile of the projectile remains largely unchanged with the exception of the slightly visible silicone insert

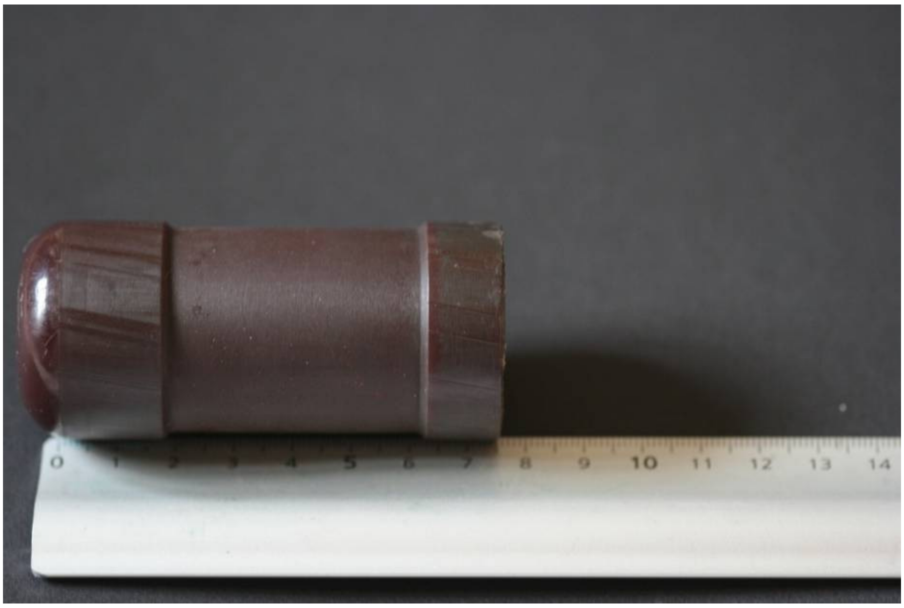


Figure 47: The standard L21A1 baton. The Rear boat tail has been sectioned off and the projectile hollowed out to an ID of 20mm

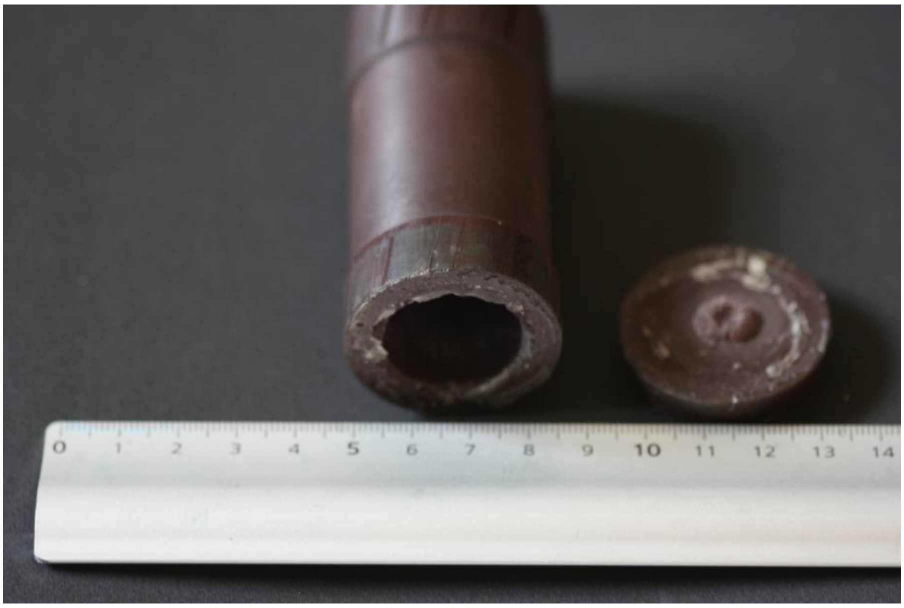


Figure 48: End view. The Rear boat tail has been sectioned off and the projectile hollowed out to an ID of 20mm

This projectile has been bored out to an internal diameter of 20mm the rear boat tail was then reattached thus making a hollow projectile with a massively reduced weight. The thinner projectile walls also mean that the projectile should be more elastic than a standard one, again so that the impact time can be increased and the energy transfer rate reduced.

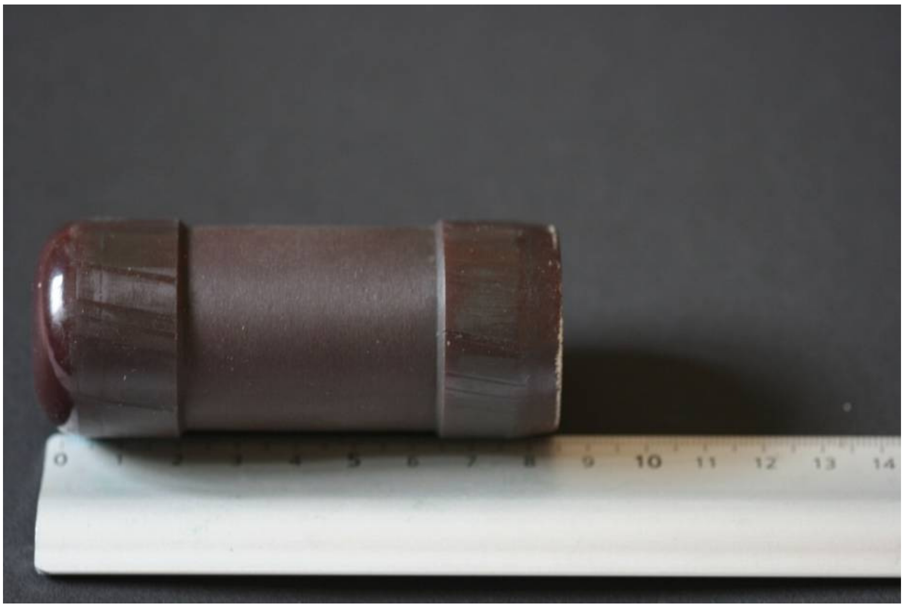


Figure 49: The standard L21A1 baton. The front face has been hollowed out to a diameter of 10mm Side view

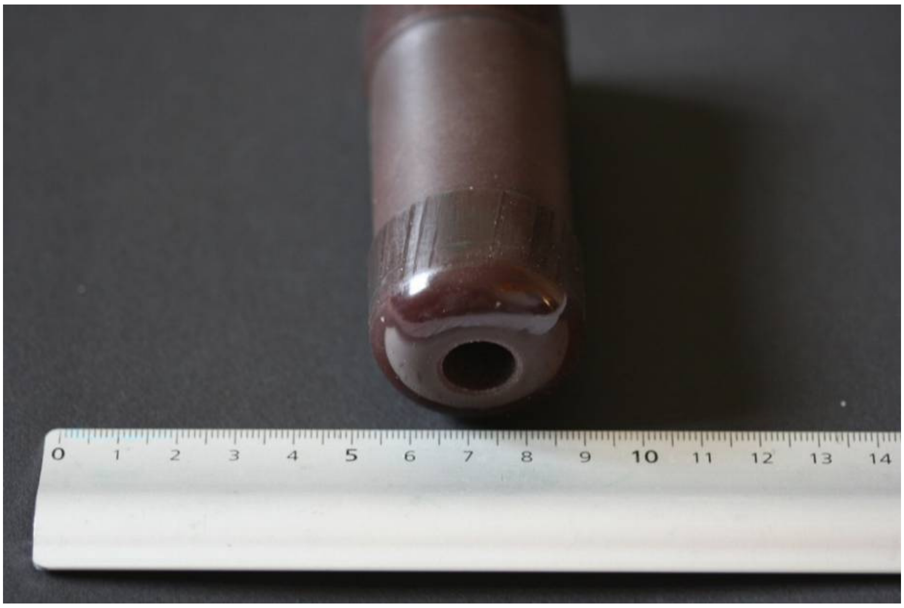


Figure 50: The standard L21A1 baton. The front face has been hollowed out to a diameter of 10mm End view

This L21A1 has had the front face bored out to a diameter of 10mm. This is to investigate stability during flight as well as a reduced impact area on the face, which should mean the kinetic energy density is greater on impact, which should make this more dangerous.

The following three projectiles all have the front 9mm rounded edge removed and have had the flat cylindrical surface covered with a compressible material (neoprene, felt and sponge). This is because whilst a flat cylinder is a good stable shape for flight, on impact the spin of the projectile caused by the rifling creates a cutting or "apple coring" motion which can easily lacerate skin and could cause serious injury. By placing a compressible material on the front of the projectile the material will negate this cutting effect both by its compression and by the fact it will spread out and cover the comparatively sharp edge of the projectile.

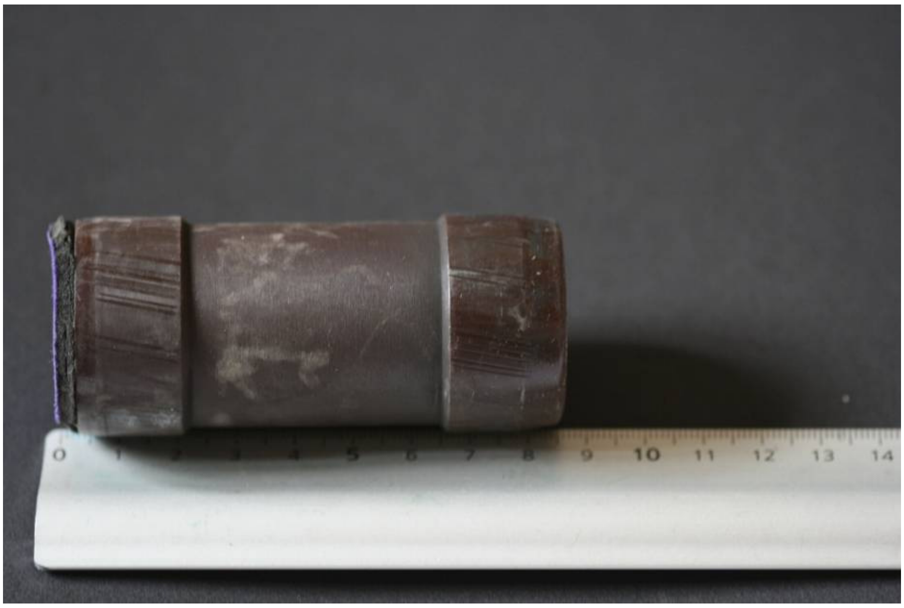


Figure 51: The standard L21A1 baton. The front face has been removed and replaced with a layer of neoprene

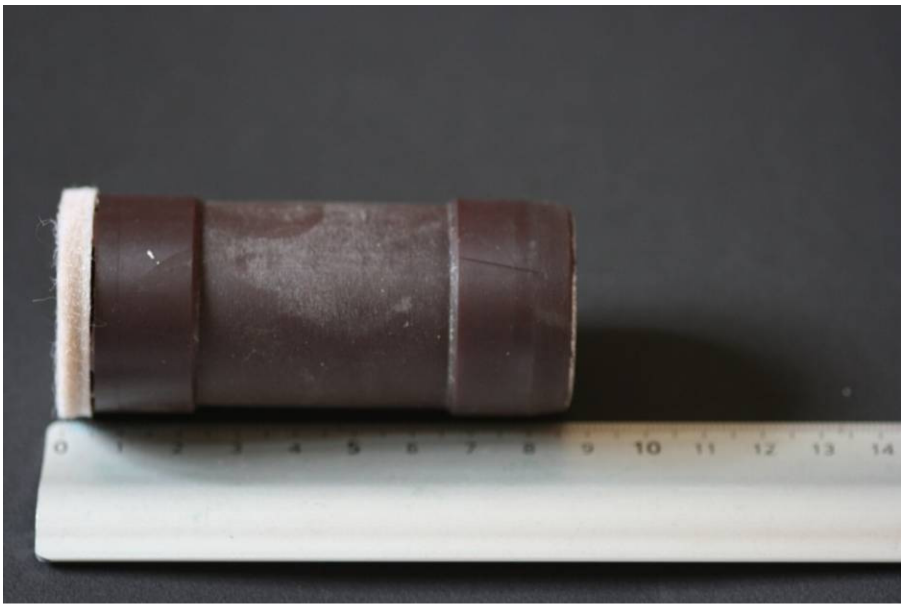


Figure 52: Standard L21A1 baton with front face removed and replaced with a felt material

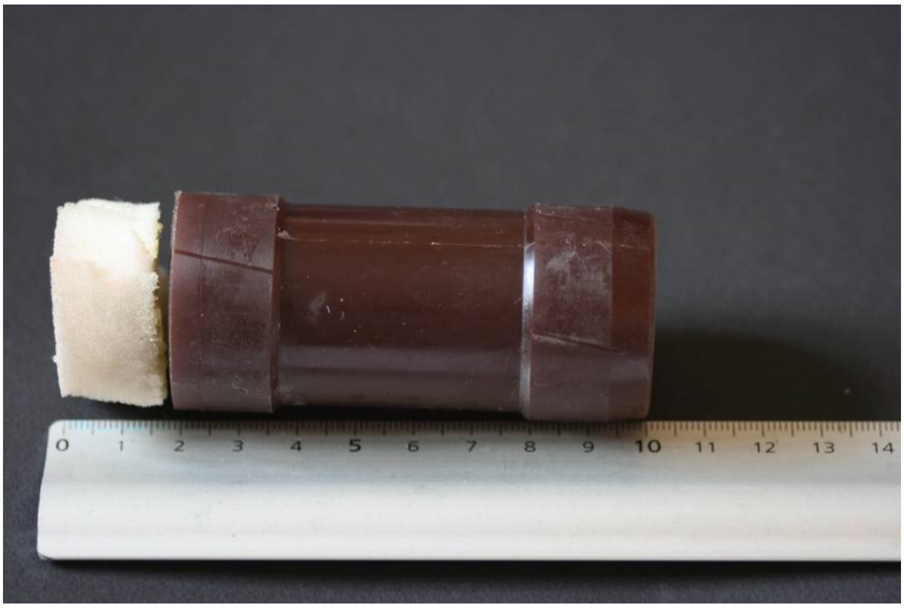


Figure 53: The L21A1 baton with front face removed and replaced with synthetic sponge

The table below is a reference list of the projectiles fired in these tests, the names used to refer to them and the Mass of each.

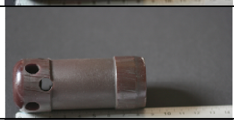
Projectile	ID	Mass (g)
	Standard	98.4
	2 Hole	92.3
	4 Hole	89.1
	2 Row	88.8
	CTD	39.9
	Silicone	96.1
	Hollow	70.3
	End Hole	94.6
	Neoprene	93.5
	Felt	93.6
	Foam	93.4

Table 8: List of Projectiles

5.3 Initial Baton Round Results

The following section presents the results gathered from the testing of the L21A1 projectile in its standard and modified forms. The results are presented as still images extracted from high-speed video (HSV).

When using the Phantom high-speed video there are a number of variables to set to accurately record results, these include the lens aperture, zoom and focus on the camera.

The laptop software is then configured to allow the correct exposure, triggering requirements and desired frame rate to capture the impact successfully. For the majority of these tests the exposure was set automatically and the frame rate locked at 3000 frames per second (FPS).

Once triggered the camera saves the previous frames to the laptop. The user can then select which frames they want saving (i.e. the ones surrounding the impact event.) These are then saved as a .cin file. In order to check consistency each projectile was fired three times, an example of the repeatability of the standard L21A1 baton is shown below in Figure 54.

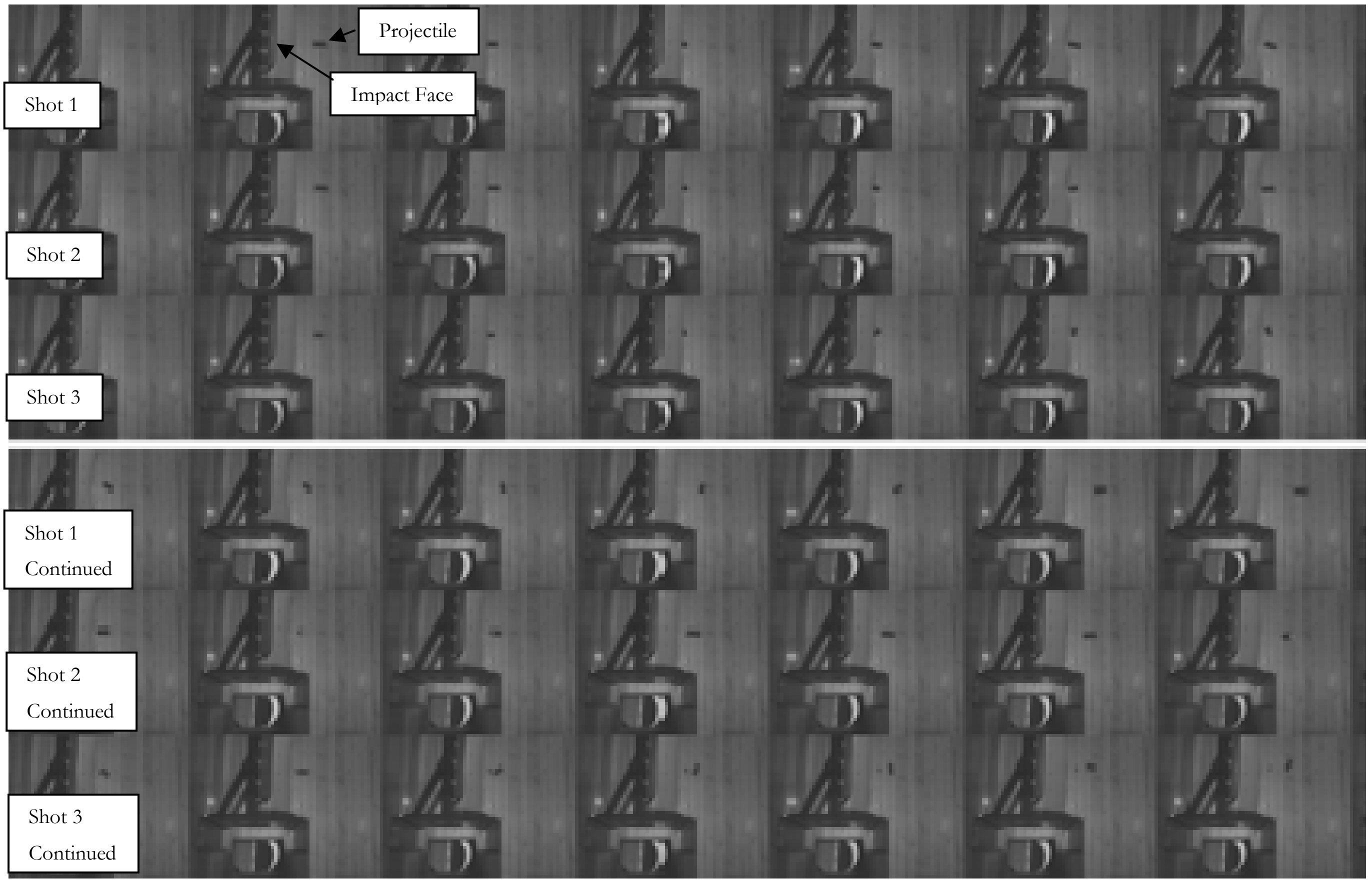


Figure 54: Stills from high speed video of three baton round strikes to compare repeatability. Each row represents one firing with columns representing a similar point in time

5.3.1 Initial baton test results:

With the initial tests, the camera was setup using a mirror at 45 degrees to the camera to look up inside the BABT rig and view the rear face deflection. T = 0 is the arbitrary point in time at which movement is seen on the BABT rig.

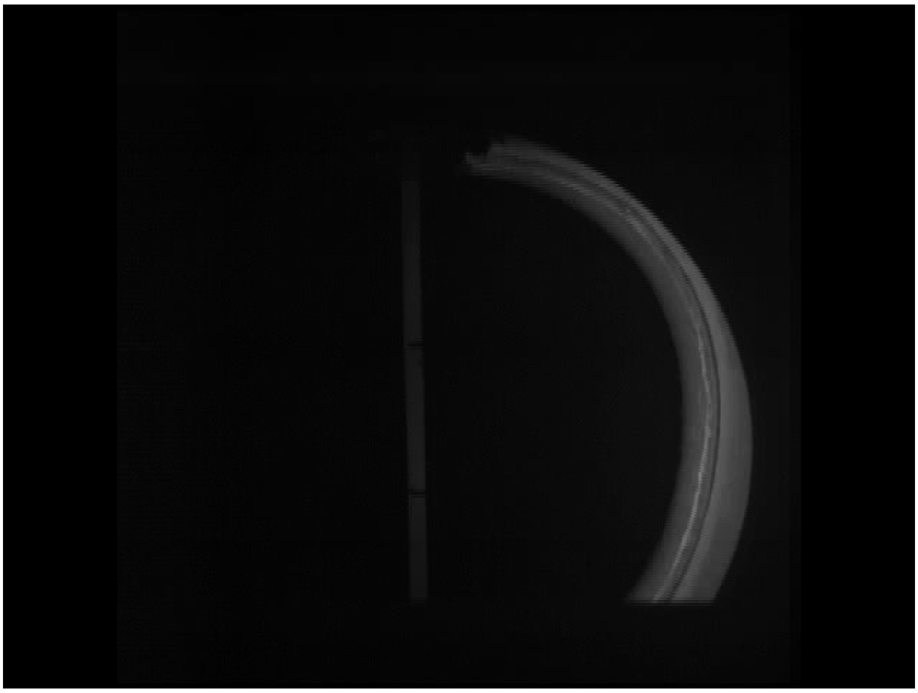


Figure 55: BABT rear face against standard L21A1 at T = 0s

Figure 56: BABT rear face against standard L21A1 at T = 3ms

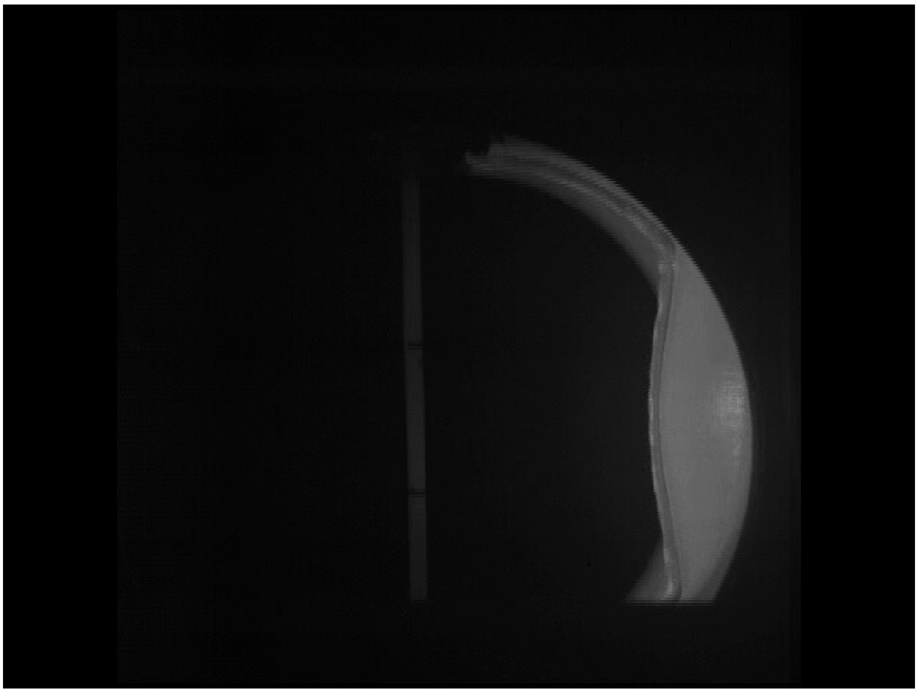


Figure 57: BABT rear face against standard L21A1 at T = 6ms

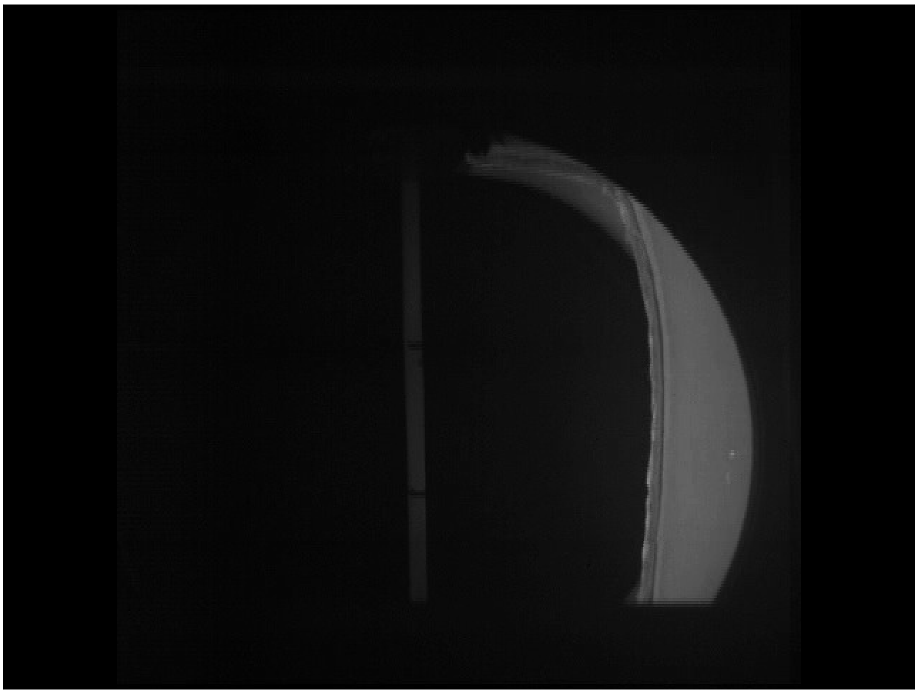


Figure 58: BABT rear face against standard L21A1 at T = 13ms

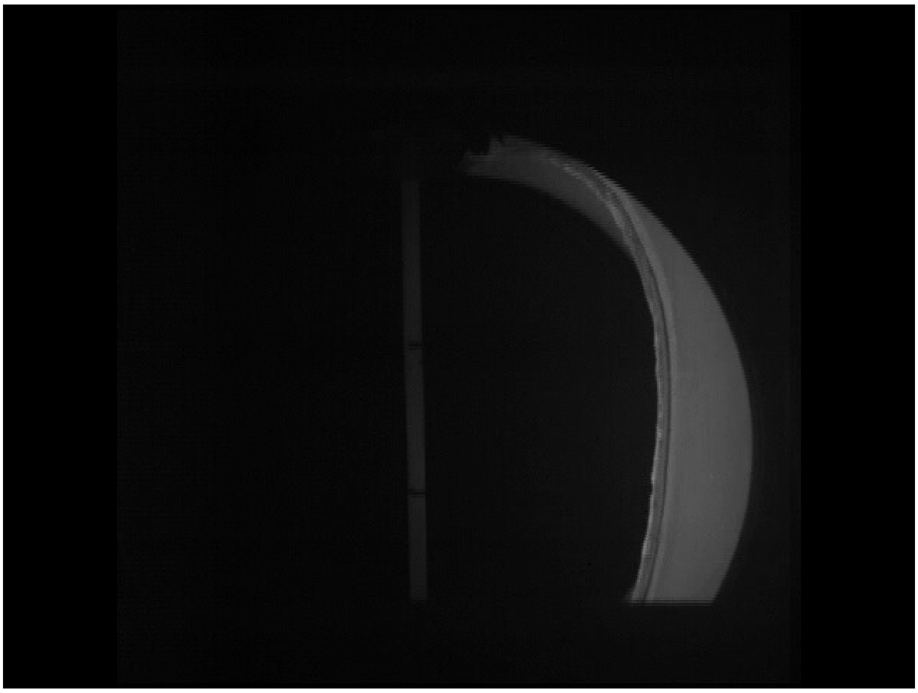


Figure 59: BABT rear face against standard L21A1 at T = 23ms

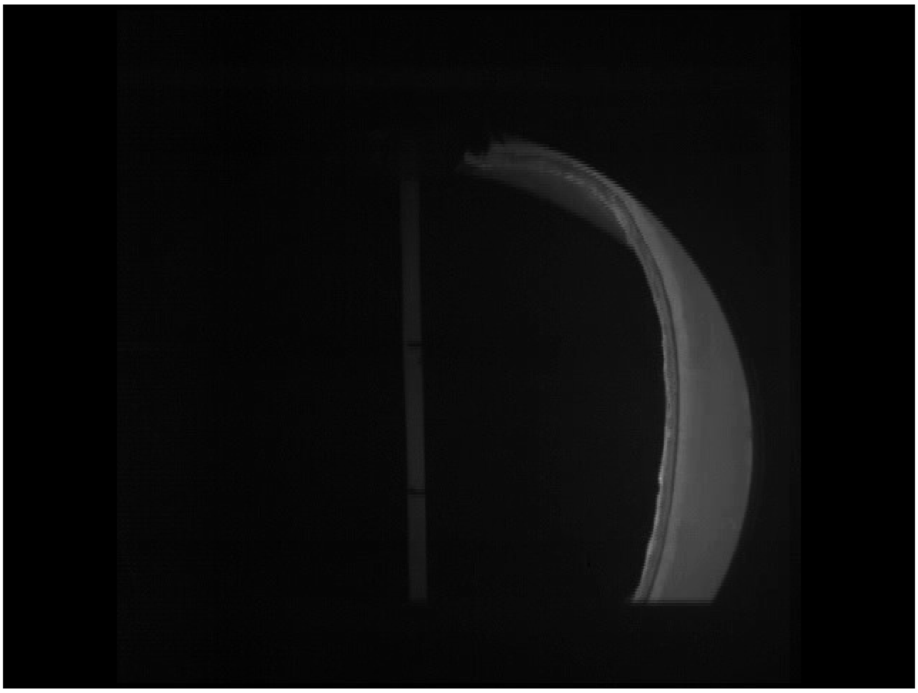


Figure 60: BABT rear face against standard L21A1 at T = 33.5ms

The ridged area marks the centre of the model vertically. On the left hand edge is a piece of tape attached to the BABT rig superstructure to give a fixed scale to the picture. The marks on the tape are 100mm apart. The physical impact itself lasts approximately 1/75th of a second, although the BABT rig continues to react for 1/15th of a second after this.

5.3.2 Compared to physical violence

People that have been hit by a baton round sometimes report it as feeling as though they had been punched very hard **[56]**. In order to make a simple comparison between a baton round strike and being punched the BABT rig was also tested against someone punching it. The following stills are taken at the same time interval as the previous sequence to directly compare the fists impact to that of a standard baton round impact.

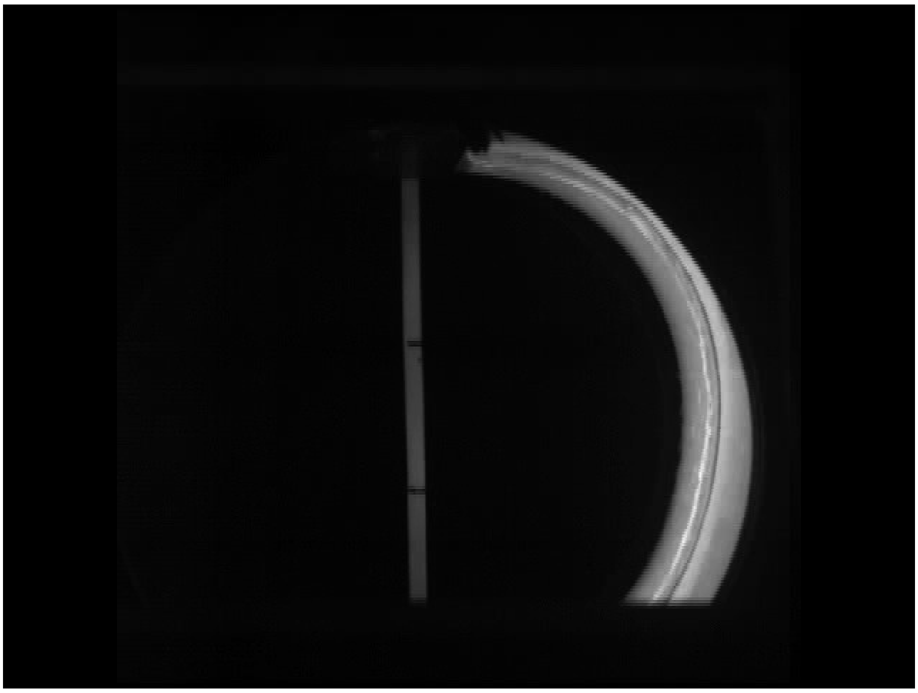


Figure 61: BABT rear face against punch T = 0s

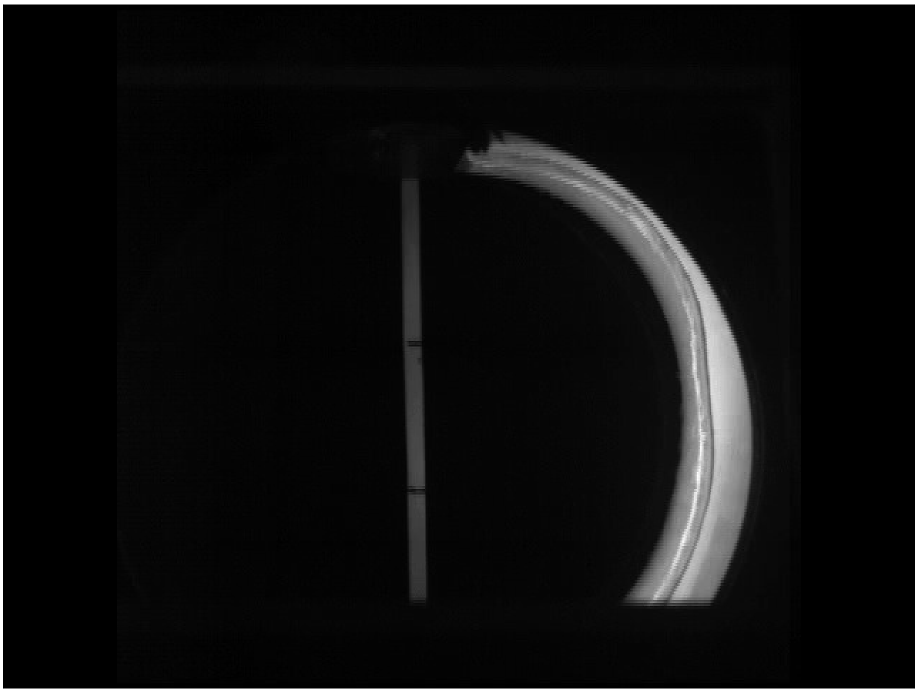


Figure 62: BABT rear face against punch T = 3ms

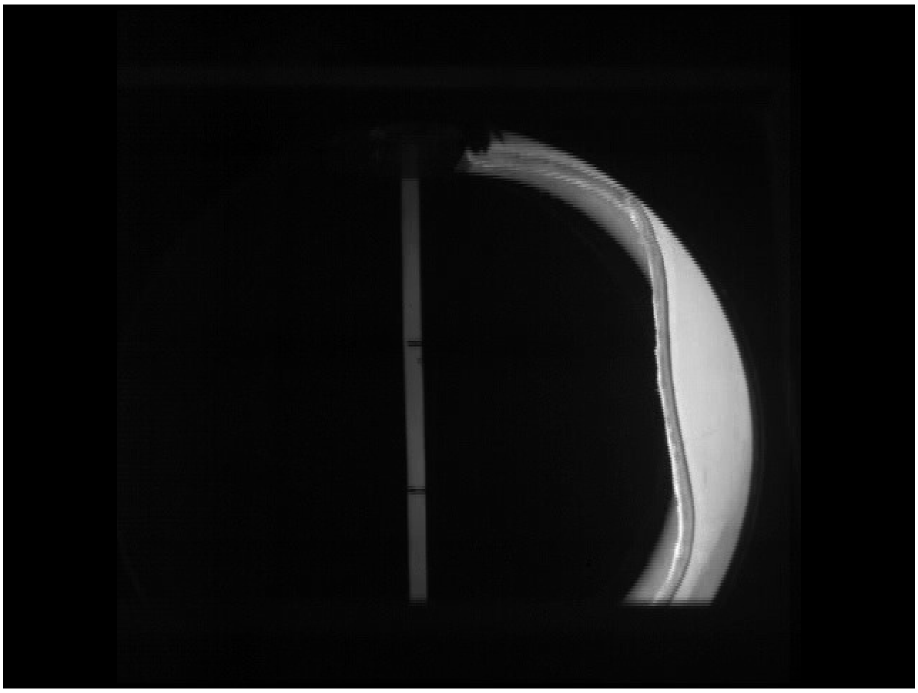


Figure 63: BABT rear face against punch T = 6ms

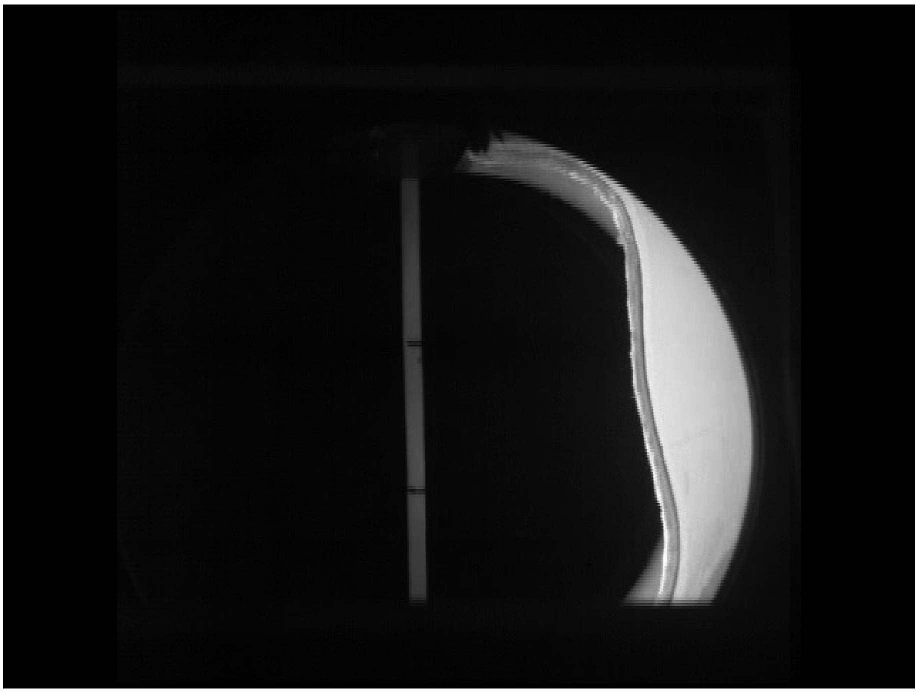


Figure 64: BABT rear face against punch T = 13ms

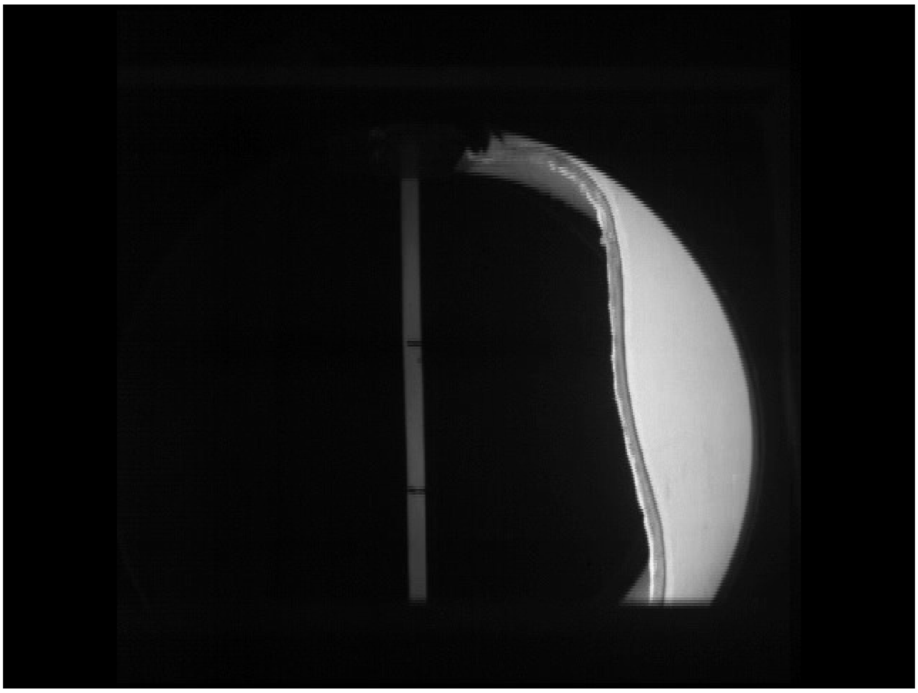


Figure 65: BABT rear face against punch T = 23ms

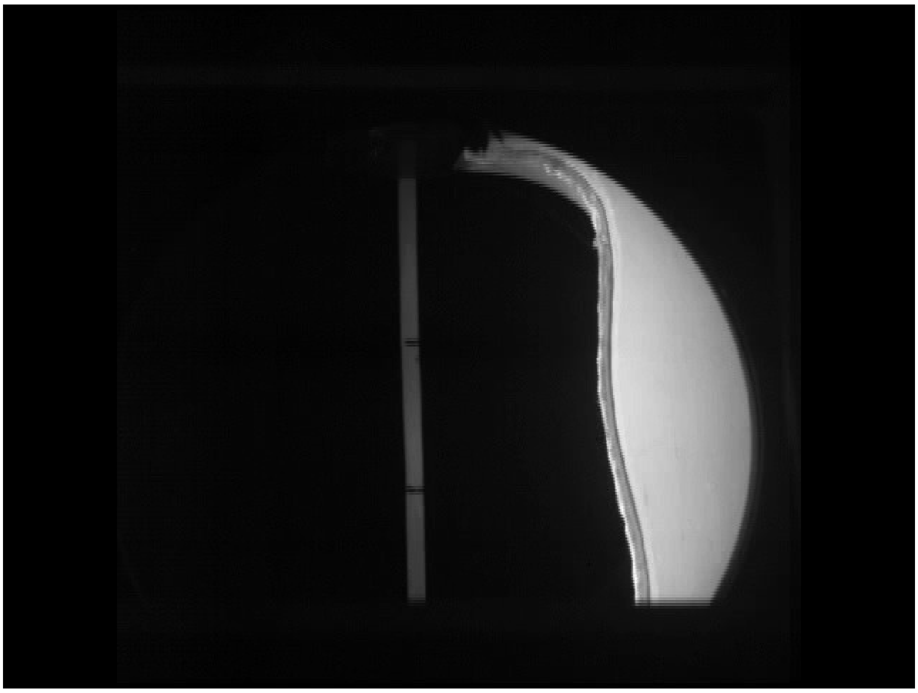


Figure 66: BABT rear face against punch T = 33.5ms

By comparing the last frame from each sequence it is possible to see that the maximum deflection (76mm) of the test rig when punched is greater than when hit by the police baton round (41mm). However, the rate at which this deflection occurs is slower and is of a greater size due to the fist being of a greater surface area than the baton round. This touches upon the fact that it is not just the projectile velocity, size or mass that is important but that the duration of impact is also a key factor when assessing the damage potential of a projectile. If the impulse of an impact can be reduced then the impact is much less likely to be dangerous.

By looking at the front of the test rig during both a baton round strike and the effects of a fist strike it is easier to see what is happening during the impact. Each pair of frames below is the same time step apart starting from the instant the projectile/fist makes contact with the BABT rig's front surface.

Figure 67 + Figure 68: Comparison of L21A1 vs. Punch on front surface of BABT rig at T = 0

Figure 69 + Figure 70: T = 9ms

Figure 71 + Figure 72: T = 14ms

Figure 73 + Figure 74: T = 20ms

Figure 75 + Figure 76: T = 23ms

Figure 77: + Figure 78: T = 31ms

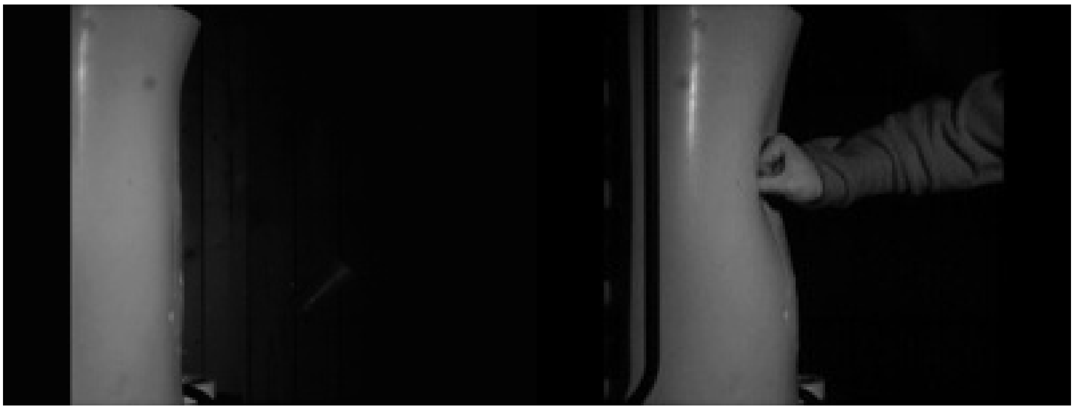


Figure 79 + Figure 80: T = 34ms

Figure 81 + Figure 82: T = 38ms

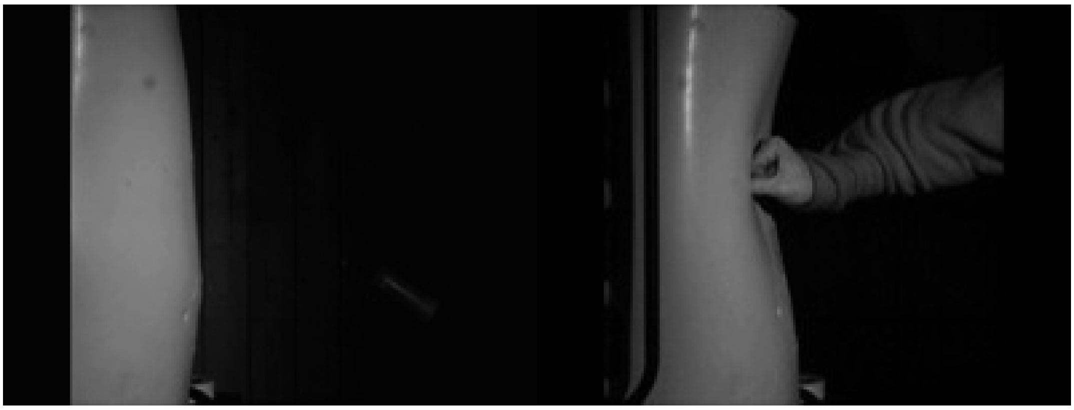


Figure 83 + Figure 84: T = 49ms

It can seen from the stills presented above, that whilst the baton round has rebounded from the front of the BABT rig after 49ms, the punch has only just caused its' maximum deflection in the test rig. The baton round has caused maximum deflection after just 14ms in contact with the BABT rig. In fact the batons impact is actually over by the third image in the series whereas the punch impact is really only just beginning, it also takes the baton just 15% of the time taken to create a similar depth deflection by a thrown punch. This difference in impact response time is likely to be one of the key factors in the level of damage sustained by a person; this is also especially true in the case of a baton strike to the head.

5.3.3 The effects of a sharp edge on impact

It is known that a simple sharp edged cylinder will be very stable at higher velocities to the extent that is not necessary to spin the projectile to stabilise it, this is important when trying to increase the range and velocity of a projectile whilst maintaining accuracy. However, the sharply angled front edge could cause a cutting motion when striking the target (as experienced in Chapter 3 with tranquilliser darts.) In order to evaluate this, the front rounded area was cut from a L21A1 baton. Whilst this reduces the weight of the projectile from 98.4g to 93.3g the change in impact velocity is negligible ($1ms^{-1}$ difference.)

Figure 85: Sharp edged projectile in stable flight

Figure 86: Sharp edged projectile Impact T = 0ms

Figure 87: Sharp edged projectile T = 1.5ms

Projectile has struck just to the left of the BABT centreline so deformation is more visible.

Figure 88: Sharp edged projectile T = 3ms

Figure 89: Sharp edged projectile T = 5ms

Figure 90: Sharp edged projectile T = 6.5ms

Figure 91: Sharp edged projectile T = 8.5ms

Figure 92: Sharp edged projectile T= 10ms

Figure 93: Sharp edged projectile T = 12ms

Figure 94: Sharp edged projectile T = 13.5ms

Figure 95: Sharp edged projectile T = 15ms

Figure 96: Sharp edged projectile T = 16.5ms

By comparing this to the front view of a standard L21A1 impact shown below it is possible to see that the projectile actually embeds less in the target when it has the sharp edge, this is caused by the increased impact area. When the standard L21A1 first hits the target the rounded nose has a smaller contact area. This contact area then increases as the projectile pushes against the target and the target effectively wraps around it causing it to slow. The net result is that the sharp edged projectile penetrates the target less but is slowed down more abruptly because of the force being spread across a constant area rather than a steadily increasing one.

Figure 97: Standard L21A1

Figure 98: Standard L21A1 Impact T = 0s

Figure 99: Standard L21A1 T = 1.5ms

Figure 100: Standard L21A1 T = 3ms

Figure 101: Standard L21A1 T = 4.5ms

Figure 102: Standard L21A1 T = 6.5ms

Figure 103: Standard L21A1 T =8ms

Figure 104: Standard L21A1 T = 9.5ms

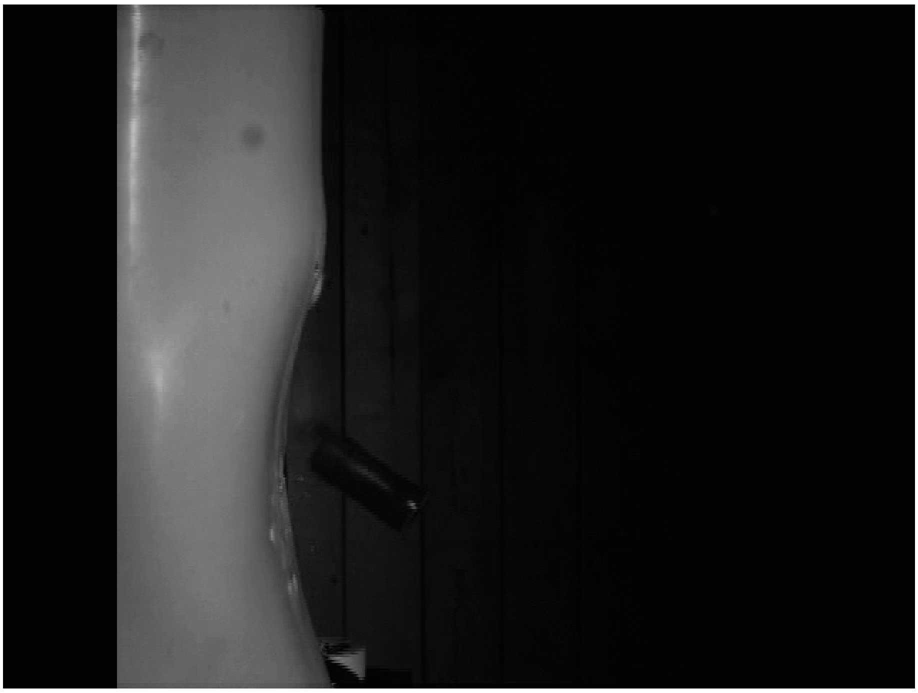


Figure 105: Standard L21A1 T = 11.5ms

Figure 106: Standard L21A1 T = 13ms

Figure 107: Standard L21A1 T = 14.5ms

By looking at T = 14.5ms on each impact the sharp edged projectile (SEP) is also rebounding away from the target slightly sooner than the standard L21A1. The SEP is also tumbling horizontally rather than vertically as in the standard L21A1 strike but this is only due to the off centre impact with the BABT rig. The cutting action that was expected didn't present itself on the target. This could be due to the increased resistance to laceration of the silicone model compared to human skin and is more likely to be a small concern because the actual spin rate of the projectile is quite low. Because of this no further tests with the SEP were carried out. Further results were analysed for deformation and impact times rather than for damage to the BABT model.

5.3.4 Modified Projectiles

For the next series of tests, the camera was moved back so that it could record both the front and back faces of the BABT rig (back face viewed using a mirror). This allows a more comprehensive analysis of each impact.

The first tests performed using this camera angle used other types of baton round to compare what happened with them on impact with the standard L21A1 baton. Figure 108-111 below shows the maximum deflection caused on the front and back faces of the BABT rig by the L21A1 impact from this angle.

Figures 108, 109, 110 and 111: Maximum Deflection of BABT rig with L21A1 impact

By testing a shortened version of the L5A7 Baton with the standard HK104 Launcher (shown below in Figure 112 and 113), the impact speed was 59.1ms^{-1}, slightly lower than that of the L21A1.

Interestingly the maximum deformation on the front face of the BABT rig occurs 4.6ms before the maximum deflection on the rear face. This is caused by the compression wave effect of projectile strike in the BABT rig material. The maximum deflection of the rear face occurs at the BABT rigs centre point (shown by the ridge in the mirror). Because of this and the fact that the projectile has struck the target about 80mm lower than the standard L21A1, there is sufficient time difference for there to be a wave of motion propagated through the BABT model. This can also be seen by comparing the front face of the model, there is little deflection of the silicone rubber surrounding the impact in the initial frame (but still significant deflection noticeable on the back face). However, in the second image there is a large deflection of the silicone rubber around the impact area but the projectile is no longer in contact and is in fact rebounding towards the launcher.

Figure 112: Max front deflection (Short L5A7)

Figure 113: Max back deflection (Short L5A7)

Even though the mass is fractionally greater the velocity of the projectile is 10ms^{-1} slower than that of the L21A1; however the deflection measured is still similar.

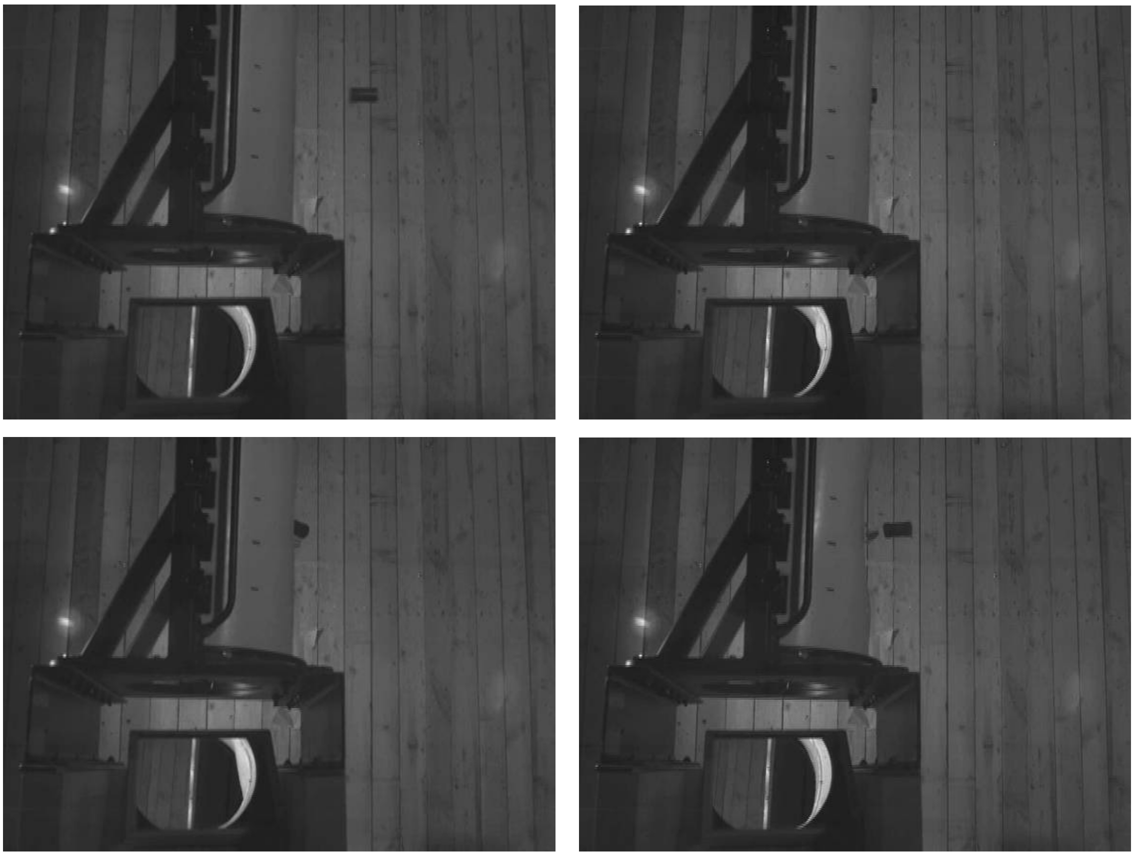
The next test involving a longer L5A7 projectile (mass 0.135kg) was propelled from the muzzle at a much lower velocity (between 35-39 ms^{-1}). This reduction in velocity was partially caused by the 30% increase in mass when keeping the quantity of propellant constant.

The increase in mass causes an approximate drop of 10ms^{-1} in velocity, leaving a further velocity drop unaccounted for. The more significant remaining 20ms^{-1} drop must therefore be caused by incomplete obturation of the baton round in the case during firing, and friction between the rifling and the baton itself. From the high-speed video it is possible to see that the projectile is still very stable in flight, however it is losing quite a significant amount of altitude (shown below in Figure 114 & 115) as it travels down range. This loss of height is approximately 25mm over the 500mm visible approach to the target. Whilst this is not a large fraction of the distance travelled over a larger range the drop will be noticeably more significant, at a standard engagement range of 20m the projectile will have dropped one metre, this will make range estimation especially important so as not to miss the target or hit where it would cause significant injury.

Figure 114 + Figure 115: Height drop of L5A7 baton

The lack of obturation here is predominately caused by use of the incorrect casing to fire the L5A7. The baton itself is of a marginally smaller diameter than the newer L21A1 baton resulting in a loose fit in the casing unlike the greater interference fit of the L21A1. Even so, the baton still engages with the rifling as it travels down the barrel as is evident by its rotation as it approaches the target.

Using a shortened L21A1 baton (of mass 67.1g) another test was performed to see the effects that it may have on the BABT rig. The impact event lasts more than double the time recorded for a standard weight L21A1. The velocity of the cut down L21A1 is approximately the same for both versions, due to the increased volume into which the gas from the .357 blank can expand when using the cut down baton held in the casings crimp.



Figures 116, 117, 118 and 119: Shortened L21A1 Impact

Again, maximum rear deflection occurs after the projectile has started to move back away from the target.

For the next test, the projectile used was one of the modified L21A1 baton rounds with a neoprene front face. The projectile had an average velocity of 69ms^{-1} across firings. The projectiles flight appears to be mainly stable but the nose is tipping up a few degrees by the time it impacts with the BABT rig. The impact event lasts for 8ms.

Figure 120: Neoprene fronted L21A1 Time = 0ms

Figure 121: Neoprene fronted L21A1 Time = 2.66ms

Figure 122: Neoprene fronted L21A1 Time = 8.66ms

Figure 123: Neoprene fronted L21A1 Time = 19.66ms

Figure 124: Neoprene fronted L21A1 Time = 46.98ms

From Figure 120 to 124 above it is possible to see the main events of the baton strike including impact, maximum penetration, end of impact event, maximum midpoint deflection of BABT rear face and maximum deflection of front face. Of interest is Figure 122, the maximum penetration of the projectile, the shape of the protrusion is much more angular than that of the standard baton strike, the impact also lasts 2ms longer than that of a standard baton. The angular protrusion is connected to the angle at which the projectile is hitting the target moments after the initial impact; because the back end of the projectile is tipping downwards the sharper front edge of the projectile is pushing further into the silicone rubber of the BABT rig.

The following images show the impact of a foam fronted projectile against the BABT rig

Figure 125: Foam fronted L21A1 Time = 0ms

Figure 126: Foam fronted L21A1 Time = 4.32ms

Figure 127: Foam fronted L21A1 Time = 10.66ms

Figure 128: Foam fronted L21A1 Time = 50.98ms

The projectile takes 4.32ms from impact to reach maximum depth; this is almost twice the time of the neoprene-fronted projectile yet the time taken to rebound is still approximately the same. This suggests that the energy is being transferred back from the BABT rig into the foam projectile to give it a greater rebound velocity.

The following images show the impact of a felt fronted projectile against the BABT rig.

Figure 129: Felt fronted L21A1 Time = 0ms

Figure 130: Felt fronted L21A1 Time = 2.33ms

Figure 131: Felt fronted L21A1 Time = 9.33ms

Figure 132: Felt fronted L21A1 Time = 49.0ms

The time taken between impact and maximum depth is less than 2.3ms, therefore shorter than the time of the foam fronted projectile but similar to the neoprene fronted one. This would suggest that there is little difference between the neoprene and felt material during the impact process.

5.4 Kinetic Energy transfer of the projectile

Whilst it is useful to compare what happens to a target model at each impact it is also beneficial to look at what is actually happening to the projectile. This is hard to do when the target is not transparent as well as deformable. In order to look at the effect on the projectiles they were fired against a solid plate. Whilst the solid plate doesn't model a human thorax this will be similar to an impact to the head because of the increased rigidity of the target compared to the BABT rig. The following section shows that during a typical baton round impact the head remains rigid. A test was also carried out against a much thinner steel plate (1mm thickness) because this would compare to the earlier testing and validation of the AutoDyn model examined in Appendix 1.

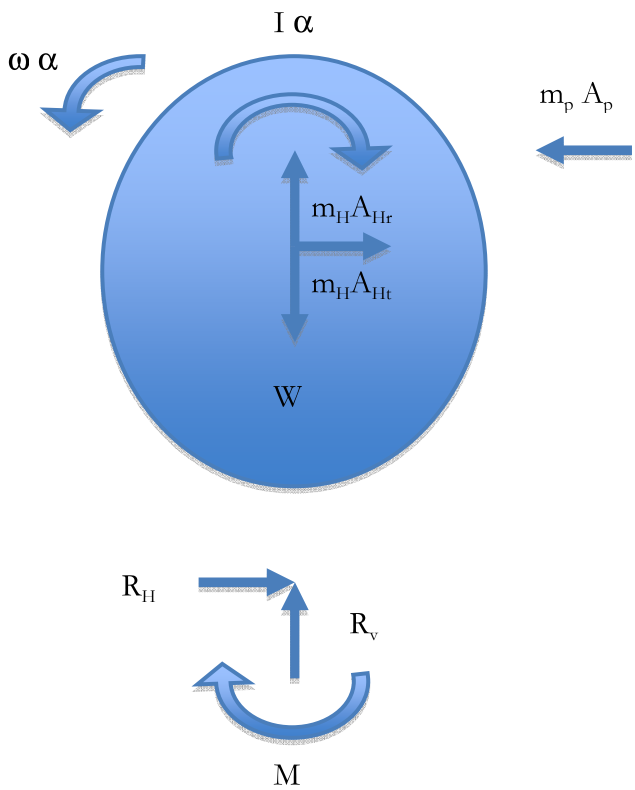
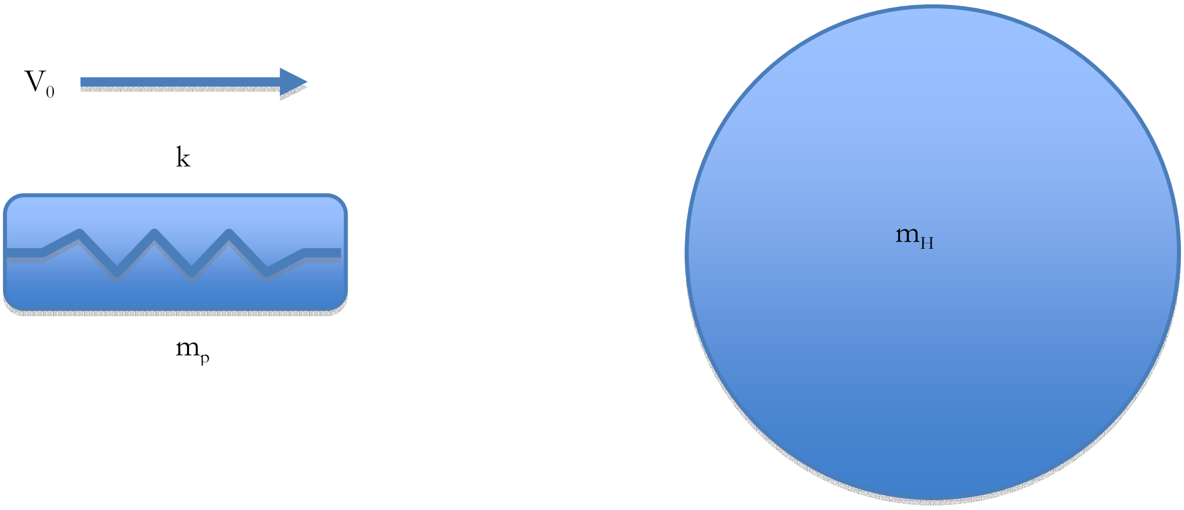
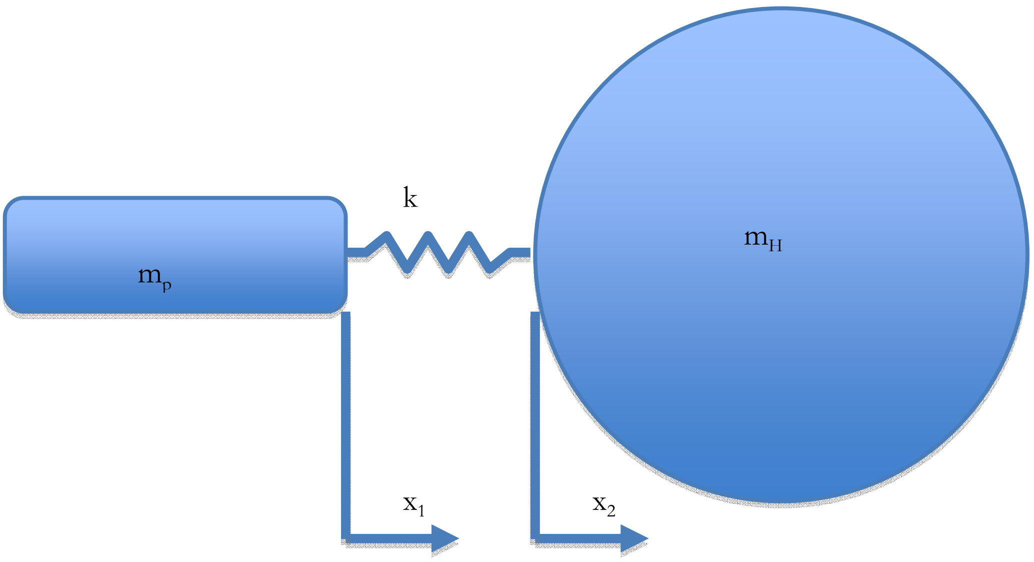


Figure 133: Dynamic Equilibrium of the head during impact

m_H = Mass Head
A_H = Acceleration Head
M = Turning Moment
R_H = Resistive Force Horizontal Component
R_V = Resistive Force Vertical Component
W = Weight of Head
M_p = Projectile Mass
A_p = Projectile Acceleration
I = Impulse
ω = Angular frequency

To simplify the projectile it is assumed to behave like an elastic spring. Where V_0 is the impact velocity, k is the spring stiffness





The equations of motion are given by:

$$m_p \ddot{x}_1 = -k(x_1 - x_2)$$
$$m_H \ddot{x}_2 = k(x_1 - x_2)$$

Equation 8

Combining equations gives:

$$m_p \ddot{x}_1 + m_p \ddot{x}_2 = 0$$
$$m_p x_1 + m_p x_2 = A + Bt$$

Equation 9

Where A and B are constants. Using the initial conditions $x_1 = x_2 = 0$ $x_1. = V_0$ at t=0

$$m_p m_h(\ddot{x}_1 - \ddot{x}_2) = -k(m_p + m_h)(x_1 - x_2)$$

Equation 10

$$\omega^2 = \frac{k(m_p + m_h)}{m_p m_h}$$

Equation 11

This shows the simple harmonic motion with angular frequency given by ω.

Also,

$$x_1 - x_2 = C\cos\omega t + D\sin\omega t$$

Equation 12

Where C and D are constants.

Using the initial conditions, C = 0 $D=V_0/\omega$.

$$x_1 = \frac{m_p V_0 t + (mH\frac{V_0}{\omega})\sin\omega t}{(m_p + m_H)}$$

$$x_2 = \frac{m_p V_0 t - (mH\frac{V_0}{\omega})\sin\omega t}{(m_p + m_H)}$$

Equation 13

Because the projectile is assumed as perfectly elastic then it will regain its initial length when $x_1 - x_2 = 0$, $\omega t = \pi$

So:

$$x_1 = x_2 = \frac{m_p V_0 \pi}{(m_p + m_H)\omega}$$

Equation 14

For a projectile of mass m_p = 0.098kg, m_H = 1.85kg, k =EA/l, V_0 = 70ms^{-1}, ω =3650rads^{-1} and the time of contact t = 0.71ms

Then $x_1 = x_2$ = 2.44mm

Therefore during the contact period the head can be assumed to be rigid, a fixed plate can therefore be used as a reasonable approximation of a head impact.

The force on the projectile and head is given by $F=k(x_1 - x_2)$

$$F = \frac{kV_0}{\omega}\sin\omega t$$

Equation 15

Substituting ω

$$F_{\max} = V_0\sqrt{k}\sqrt{\frac{m_p m_H}{m_p + m_H}}$$

$$F_{\max} = \frac{V_0 C_0 m_p}{l}$$

$$\therefore = A_0 \rho_0 c_0 V_0$$

Equation 16

For a standard projectile travelling at $50ms^{-1}$

$F_{max} = 28{,}063N$

This is sufficient energy to cause skull fractures or serious brain injuries **[57]**. From this peak force equation it would be possible to reduce the force transferred without changing the velocity of the projectile by adjusting the density or area of impact. By using a different material the density and speed of sound could be simultaneously reduced. Reducing the area of impact would increase the chance of penetration into the target, however by introducing an air cavity into the projectile nose, the area through which stress waves can travel is reduced whilst the impact contact area is allowed to remain the same. Farrah **[11]** found the peak force could be halved from the value predicted for a standard baton.

$$F_{Max} = A_0 \rho_0 c_0 V_0$$

Equation 17

With time of contact being given by

$$T_c = 2l / c_0$$

Equation 18

With an air cavity the peak force can be represented as

$$F_{cav} = A_{eff} \rho_0 c_0 V_0$$

Equation 19

Where A_{eff} is the effective area through which the stress wave can travel (Area of projectile – Area of Cavity). Therefore any air cavity introduced into the projectile nose should reduce the maximum force occurring during impact, for this reason a number of open cavity designs were tested in this phase. Due to the testing being split across several range days, it was not possible for the camera setup to be identical for each set of tests. To counter this, every time a new camera setup was used, a standard L21A1 baton was recorded impacting the target to provide a simple reference to compare against the following impacts and allow comparison between each series of tests.

Standard L21A1 impact against 1mm steel sheet

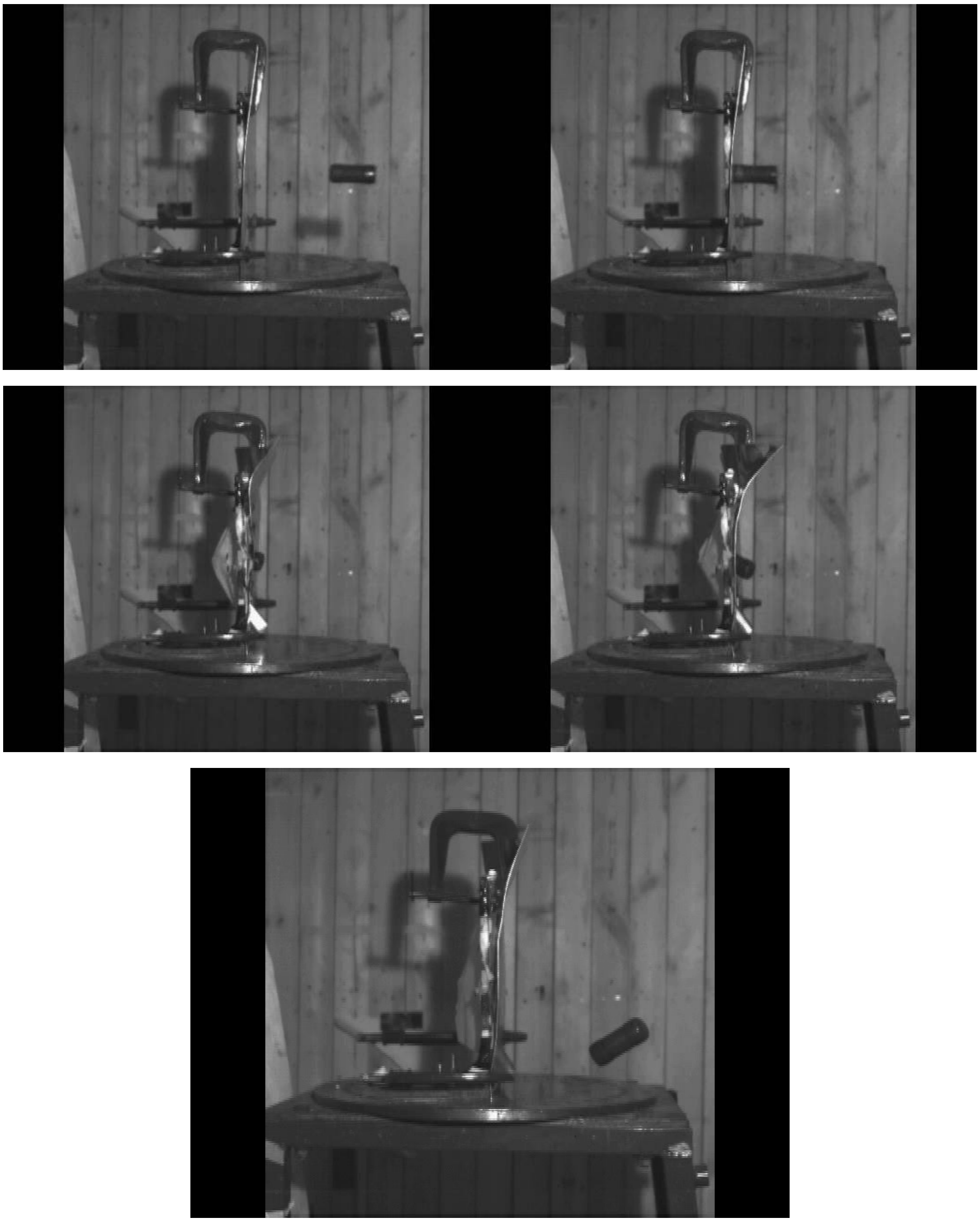


Figure 134, 135, 136, 137 & Figure 138: L21A1 Impact against 1mm Steel sheet at T = 0, 2.4, 5.2, 7.8, and 113.2ms

The impact of the L21A1 causes a massive deformation of the steel sheet that absorbs most of the projectiles kinetic energy as is evidenced by the greatly increased time that the projectile takes to rebound from the target. The deformation is much larger than that shown in the hydro code model (Appendix 1) against an unbacked 1mm steel skin although the L21A1 is much larger and heavier than the modelled hydro code projectile. The Hydro code impact does show more limited signs of deformation so it is possible that the two impacts could be comparable with further modelling. By increasing the thickness of the plate to 8mm the deformation from each projectile impact was reduced.

Standard L21A1 baton against an 8mm steel plate.

Figure 139: Standard L21A1 against plate Time = 0ms

Figure 140: Standard L21A1 against plate Time = 2.1ms

Figure 141: Standard L21A1 against plate Time = 2.6ms

Figure 142: Standard L21A1 against plate Time = 3.3ms

Figure 143: Standard L21A1 against plate Time = 9.3ms

From the above Figure 139 to Figure 143 it can be seen how much the standard L21A1 baton compresses on impact with the hard plate. It becomes just 65mm compared to its original length of 88mm, deforming elastically, before rebounding at 22ms^{-1}, less than half the inbound velocity. The kinetic energy at impact was 200.4J. The return kinetic energy equates to 26.25J. There is thus a transfer of 174J of energy during the impact. Most of the 174J is transferred directly into the target over the duration of the impact (0.5ms).

The following series of images shows a L21A1 baton with a foam front.

Figure 144: Foam fronted L21A1 against plate Time = 0ms

Figure 145: Foam fronted L21A1 against plate Time = 2.1ms

Figure 146: Foam fronted L21A1 against plate Time = 2.7ms

Figure 147: Foam fronted L21A1 against plate Time = 3.4ms

Figure 148: Foam fronted L21A1 against plate Time = 9.4ms

From Figure 144 to Figure 148 it can be seen that the strike lasts 0.6ms compared to 0.5ms for the standard round. This almost identical time suggests that the foam makes very little difference with regards to the impact duration.

The following images show the impact of a felt fronted L21A1

Figure 149: Felt fronted L21A1 against plate Time = 0ms

Figure 150: Felt fronted L21A1 against plate Time = 2.2ms

Figure 151: Felt fronted L21A1 against plate Time = 2.7ms

Figure 152: Felt fronted L21A1 against plate Time = 3.6ms

Figure 153: Felt fronted L21A1 against plate Time = 9.1ms

The strike time is 0.5ms which is longer than the standard L21A1 impact. The optical chronographs record the approximate impact velocity as 57ms^{-1}, which is approximately the same as the standard baton. The modified projectile is however 0.006kg lighter and 0.003m shorter. Again, the projectile loses approximately half its velocity impacting with the target.

The following sequence of images show the standard L21A1 baton impacting against the metal plate from the second set of tests (and camera angle). A standard 5 image sequence is used: Flight, Impact, Compression, Impact end, Rebound. Frame rate was set at 5000 frames per second.

Figure 154: Standard L21A1 against plate (2) Time = 0ms

Figure 155: Standard L21A1 against plate (2) Time = 2.4ms

Figure 156: Standard L21A1 against plate (2) Time = 2.8ms

Figure 157: Standard L21A1 against plate (2) Time = 3.6ms

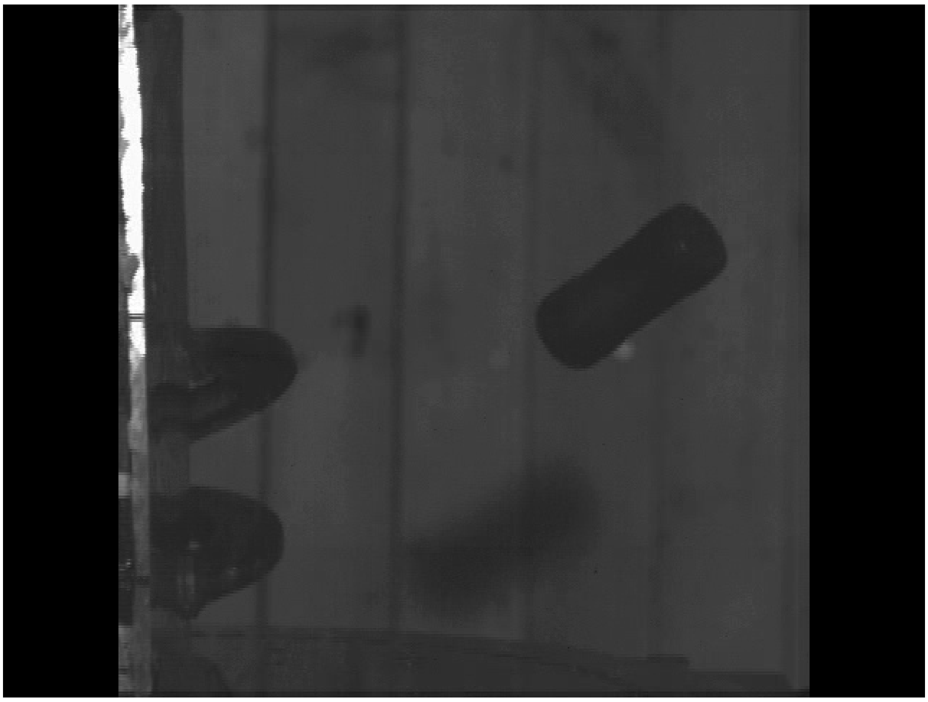


Figure 158: Standard L21A1 against plate (2) Time = 9.6ms

The total event time recorded was 9.6ms for the projectile to rebound to its position at T = 0. The projectile had an impact velocity of $65ms^{-1}$, compressed to a minimum length of 70.4mm and rebounded with a velocity of $26ms^{-1}$. From these the KE at impact was 213.4J with a residual KE of 34.29J

The following stills show the modified L21A1 with 4 holes drilled through the front of the body (equispaced and through the entire diameter).

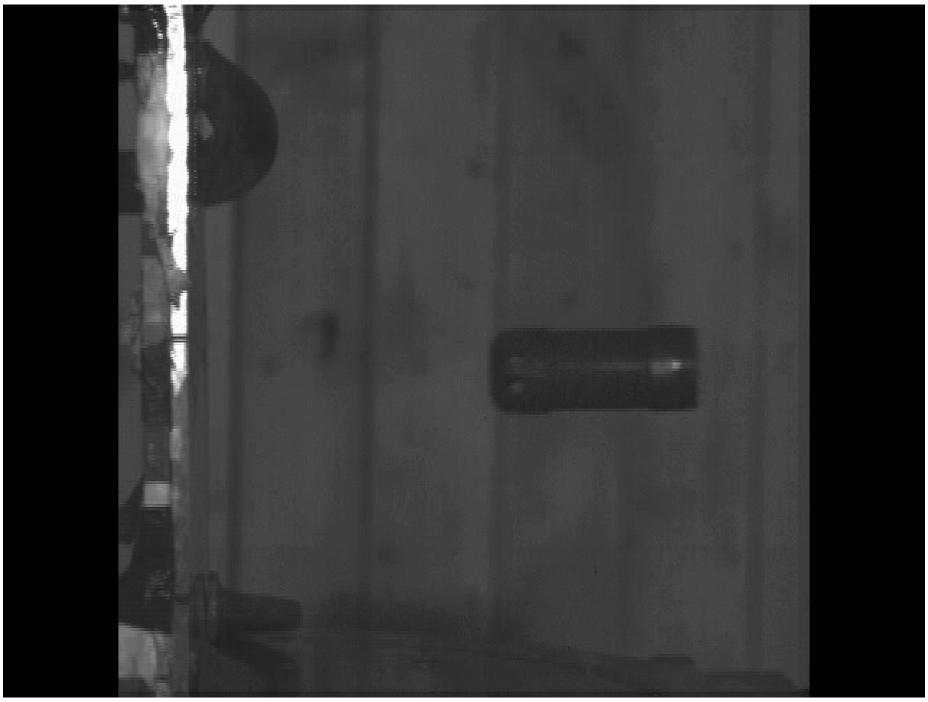


Figure 159: 4 Hole L21A1 against plate (2) Time = 0ms

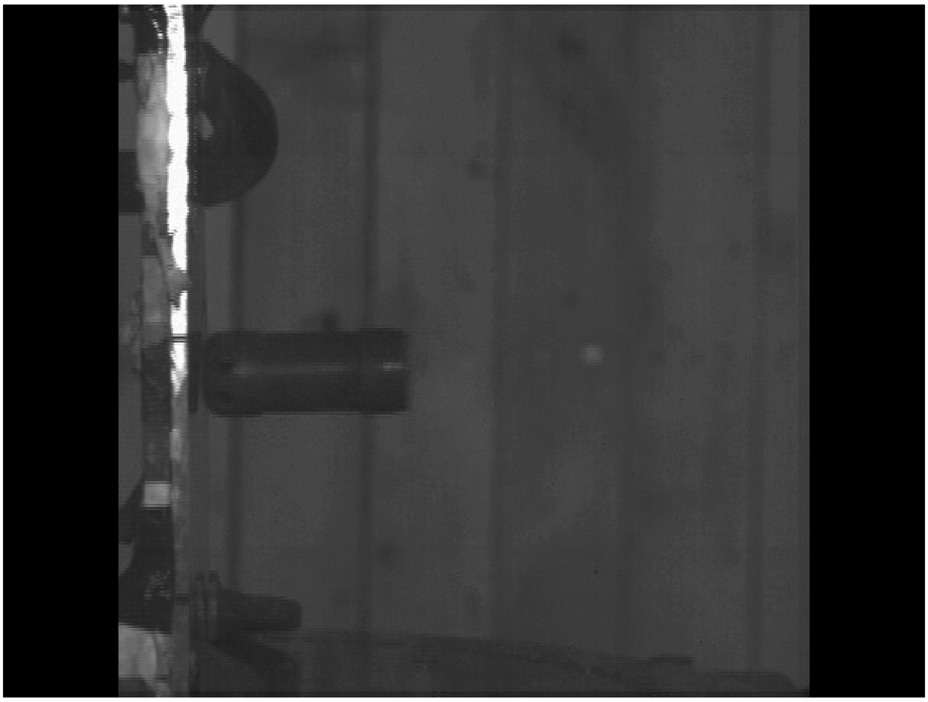


Figure 160: 4 Hole L21A1 against plate (2) Time = 2ms

Figure 161: 4 Hole L21A1 against plate (2) Time = 2.6ms

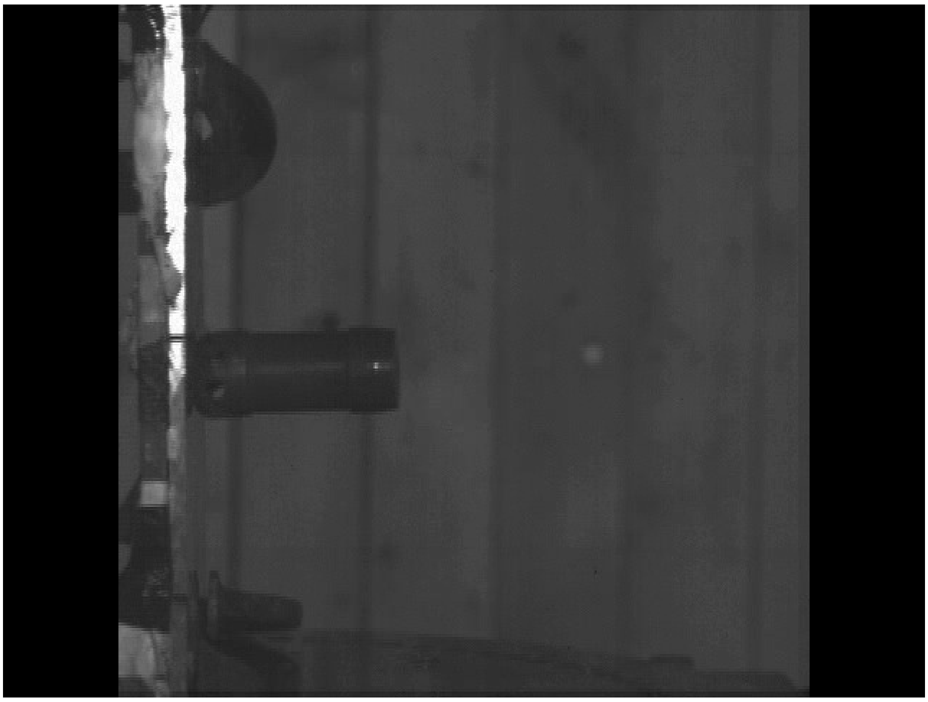


Figure 162: 4 Hole L21A1 against plate (2) Time = 3.8ms

Figure 163: 4 Hole L21A1 against plate (2) Time = 11.2ms

The total event time recorded was 11.2ms for the projectile to rebound to its position at T = 0. The projectile had an impact velocity of 61.3ms^{-1}, compressed to a minimum length of 62mm and rebounded with a velocity of 17.6ms^{-1}. The KE at impact was 167.49J with a residual KE of 13.8J giving a total of 153.69J transferred into the plate.

The following stills show the modified L21A1 with 4 holes drilled through the front of the body (equispaced, in 2 rows and through the entire diameter.)

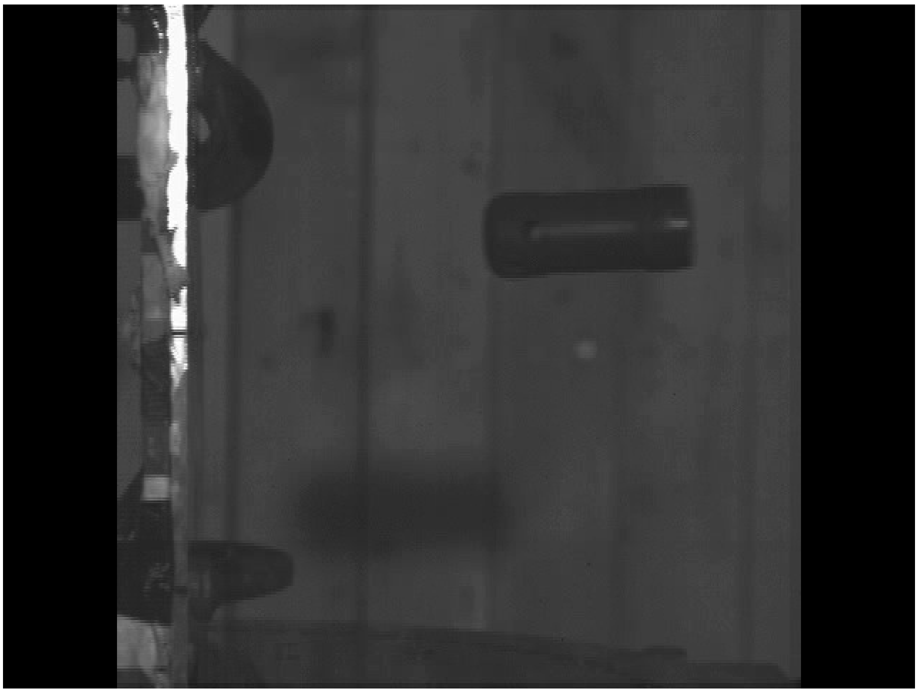


Figure 164: 4 Hole 2 Row L21A1 against plate (2) Time = 0ms

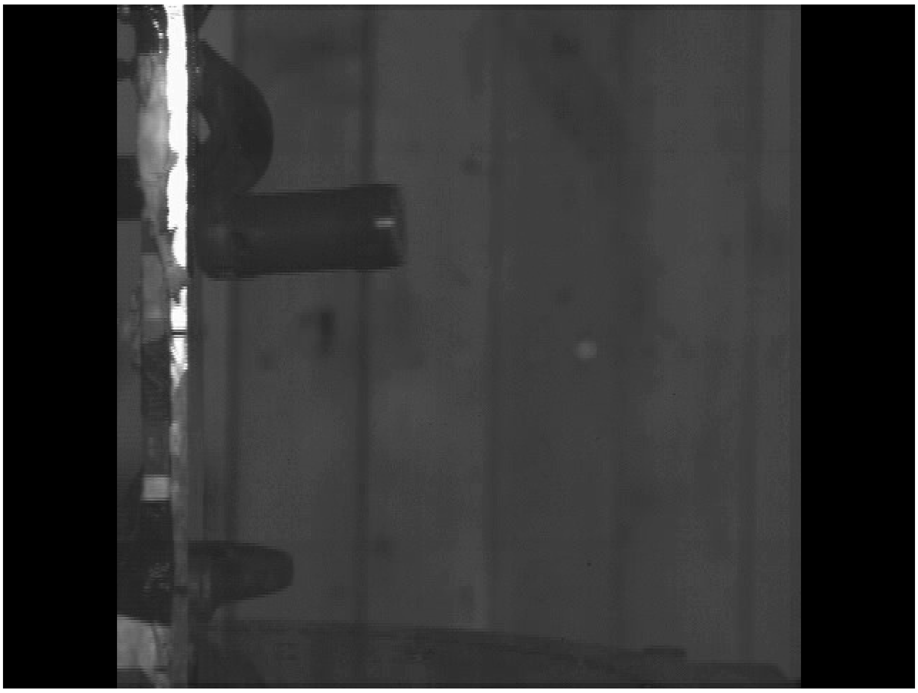


Figure 165: 4 Hole 2 Row L21A1 against plate (2) Time = 2ms

Figure 166: 4 Hole 2 Row L21A1 against plate (2) Time = 2.6ms

Figure 167: 4 Hole 2 Row L21A1 against plate (2) Time = 3.8ms

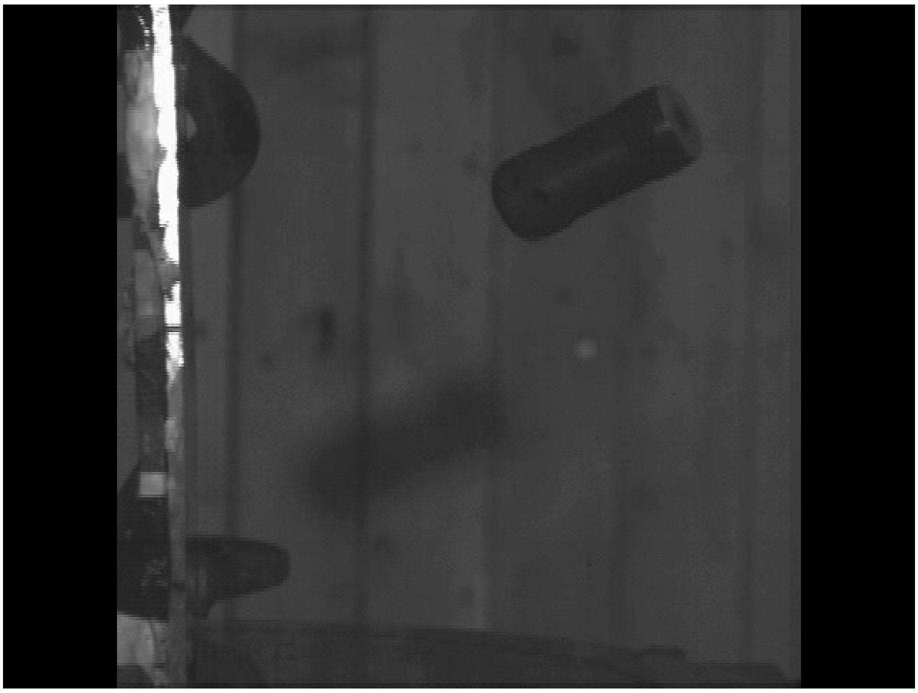


Figure 168: 4 Hole 2 Row L21A1 against plate (2) Time = 10ms

This combination of holes allows the projectiles nose to become greatly compressed on impact to 56.7mm. From the first image in the sequence it is possible to see the projectile is stable in flight but is flying with the nose dipped slightly, this is due to the shift in centre of gravity cased by drilling the holes in the nose. The impact compression event still lasts for 0.5ms i.e. the same as the standard baton; however the projectile had an increased velocity to 75ms^{-1} and rebounded with a velocity of 22.3ms^{-1}. The increased velocity gave a KE at impact of 250J and the residual KE was 21.8J indicating that 228J had been transferred from the projectile.

The following sequence shows the L21A1 with 2 holes equispaced in the nose.

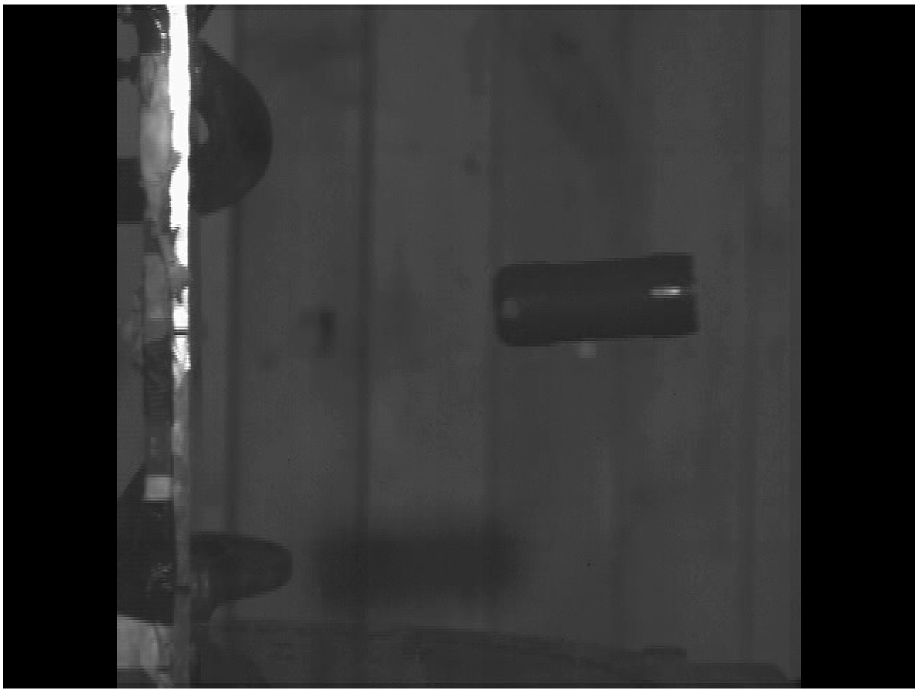


Figure 169: 2 Hole L21A1 against plate (2) Time = 0ms

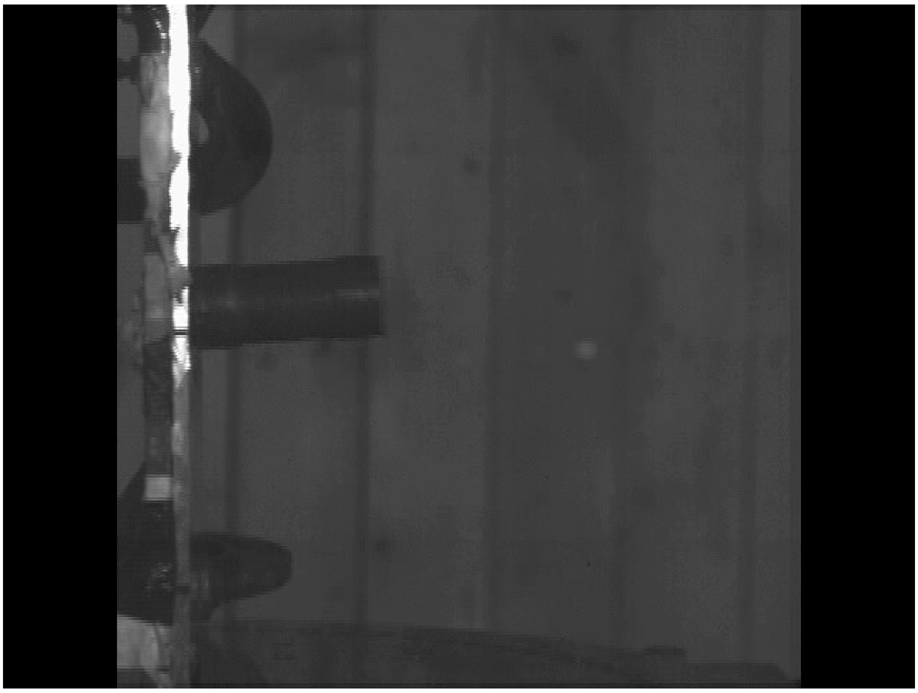


Figure 170: 2 Hole L21A1 against plate (2) Time = 2.2ms

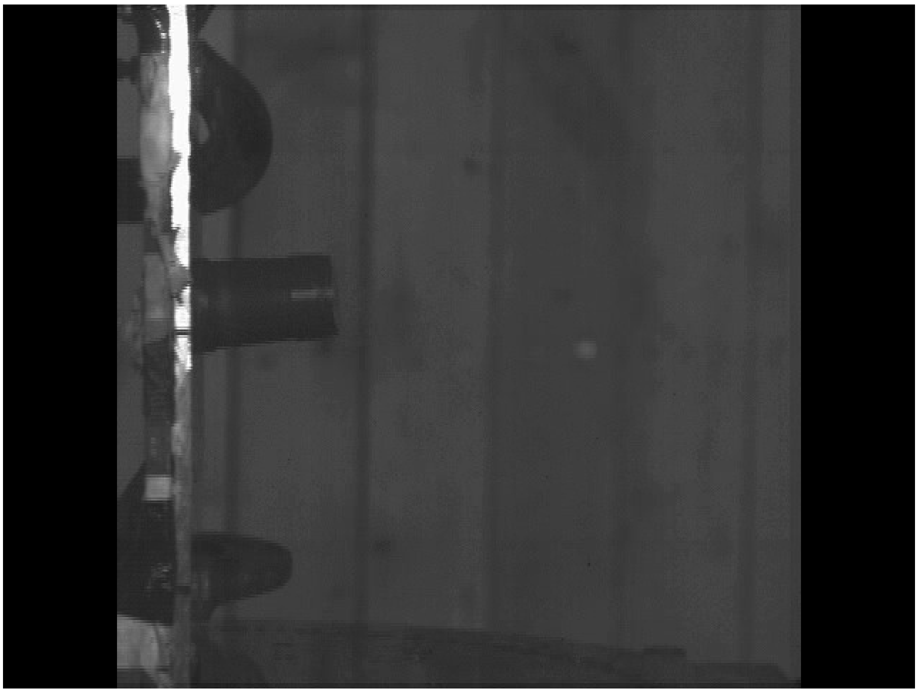


Figure 171: 2 Hole L21A1 against plate (2) Time = 2.6ms

Figure 172: 2 Hole L21A1 against plate (2) Time = 3.8ms

Figure 173: 2 Hole L21A1 against plate (2) Time = 9.6ms

Similar to the other projectiles with holes, the baton travels towards the target nose down (but slightly less so than the ones with more holes.) The smaller number of holes means more energy is spent compressing the actual nose area. Because the projectile strikes with the nose slightly down this causes the compression with the target to be slightly lopsided and sends the baton away at an angle (comparable to the nose down angle before impact.) The impact event lasted 1.6ms from projectile impact to rebound.

The total event time recorded was 9.6ms for the projectile to rebound to its position at T = 0. The projectile had an impact velocity of 62.5ms^{-1}, compressed to a minimum length of 60mm and rebounded with a velocity of 27.5ms^{-1}. From these the KE at impact was 179.99J with a residual KE of 23.2J giving a total of 156.8J transferred into the plate.

The following sequence shows the cut down L21A1 with 8 holes in 4 rows equispaced along the length of the projectile.

Figure 174: Cut down 2 L21A1 against plate (2) Time = 0ms

Figure 175: Cut down 2 L21A1 against plate (2) Time = 2.2ms

Figure 176: Cut down 2 L21A1 against plate (2) Time = 2.6ms

Figure 177: Cut down 2 L21A1 against plate (2) Time = 3.2ms

Figure 178: Cut down 2 L21A1 against plate (2) Time = 9.4ms

The cut down projectile has a greatly reduced mass compared to the standard L21A1 and the added holes allow it to compress significantly more (56mm compressed). The inbound velocity of 73.2ms^{-1} is also greater because the same quantity of propellant is being used to propel it as would be used on the normal L21A1. The impact compression event lasts just 0.4ms and the rebound velocity is 25.8ms^{-1} which is similar to that of the standard L21A1. A similar velocity will be achieved because the increased compressibility of the projectile will allow more potential energy to be stored within it. The potential energy is then released during the following elastic expansion of the projectile against the steel plate. The KE at impact was 107J. This is half the energy of the standard projectile. The residual KE is 13.02J; therefore 94J has been transferred from the projectile.

The following sequence shows a L21A1 with a hole bored into the front impact face.

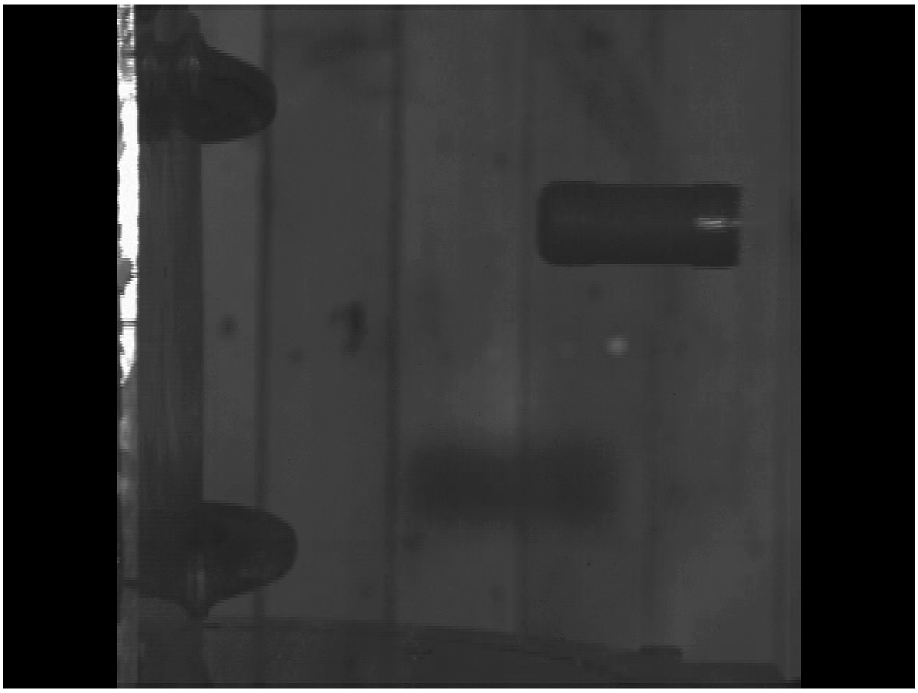


Figure 179: End hole L21A1 against plate (2) Time = 0ms

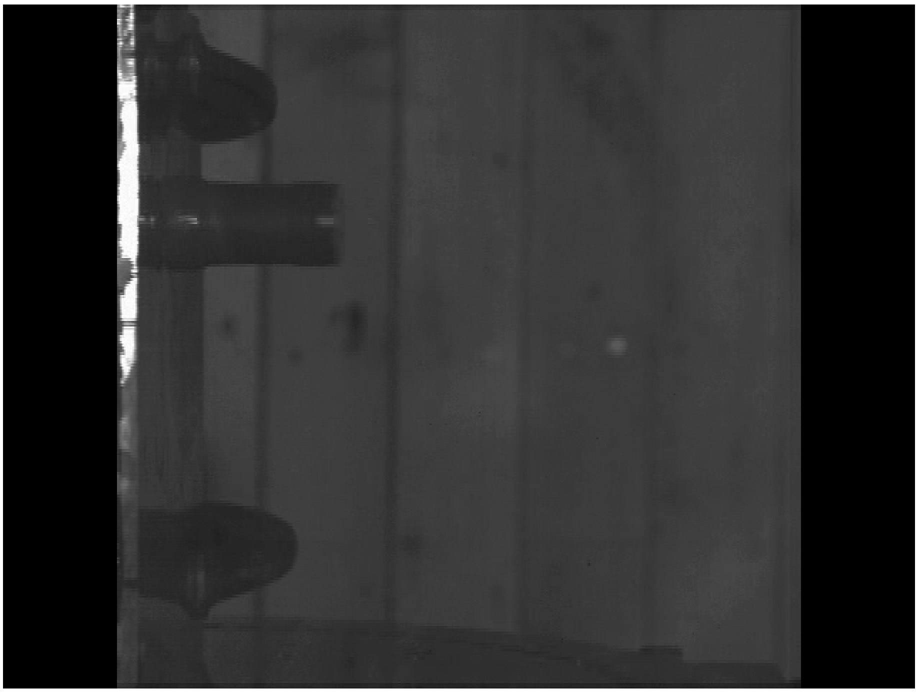


Figure 180: End hole L21A1 against plate (2) Time = 2.2ms

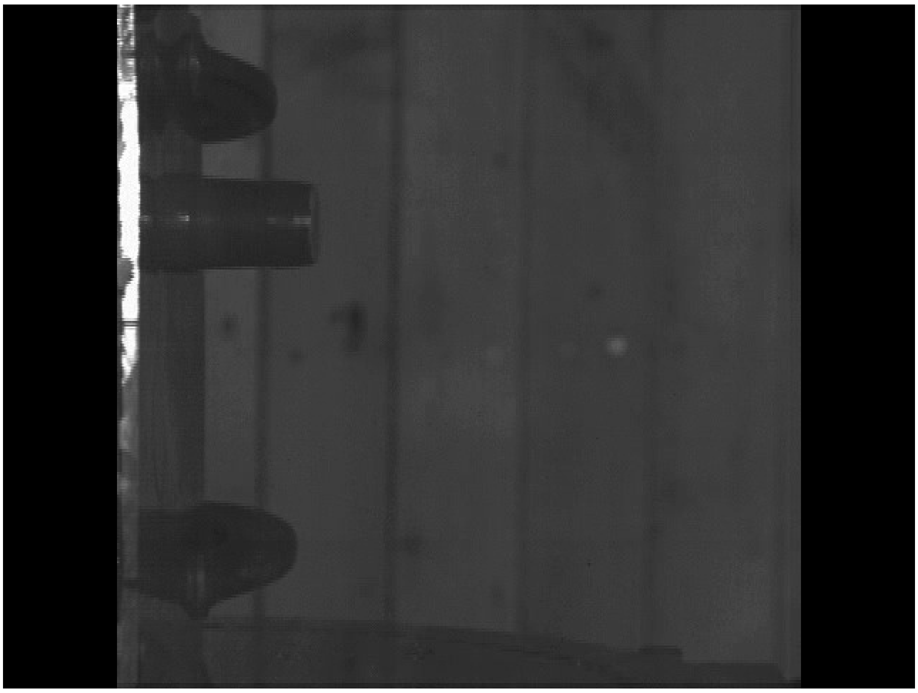


Figure 181: End hole L21A1 against plate (2) Time = 2.6ms

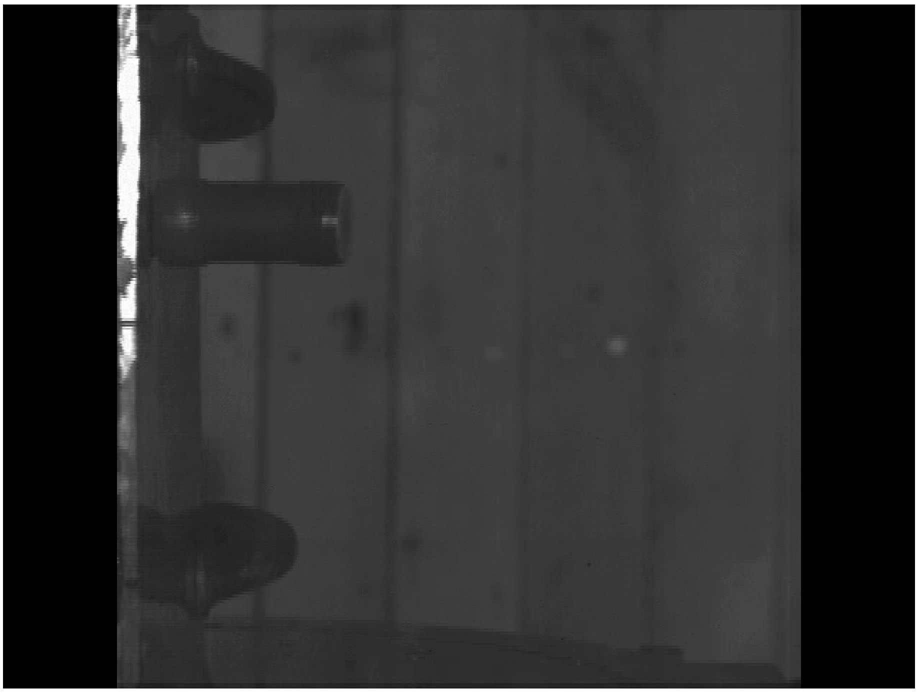


Figure 182: End hole L21A1 against plate (2) Time = 3.2ms

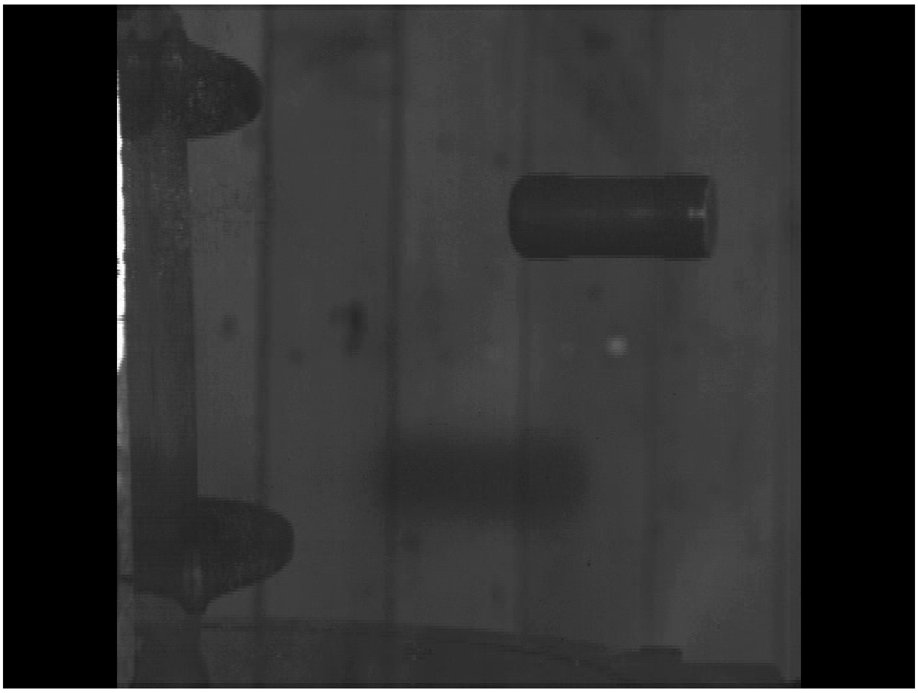


Figure 183: End hole L21A1 against plate (2) Time = 9.4ms

Looking at Figure 181 it is possible to see the projectile compresses in a slightly different manner to that of the normal projectile and the projectiles with the transverse holes. The front of the projectile splays out instead of bunching up in the middle as with the standard projectile. The total event time recorded was 9.4ms for the projectile to rebound to its position at T = 0. The projectile had an impact velocity of 72.1ms^{-1}, compressed to a minimum length of 72.1mm and rebounded with a velocity of 25.8ms^{-1}. From these the KE at impact was 245J with a residual KE of 32.26J giving a total of 212.74J transferred from the projectile.

The next series shows a hollowed out L21A1 with a rear end cap attached using contact adhesive.

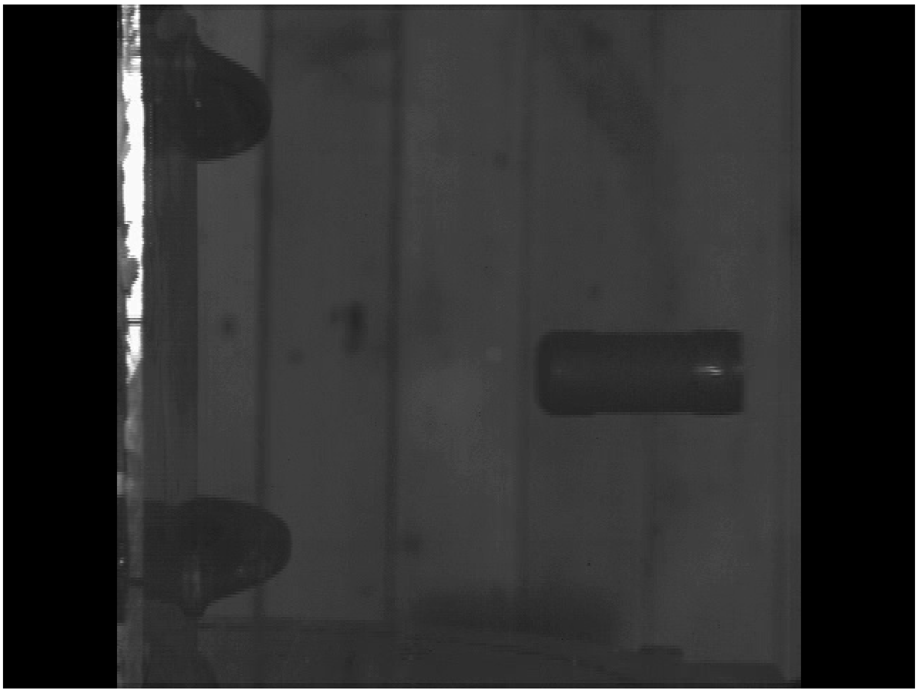


Figure 184: Hollow L21A1 against plate (2) Time = 0ms

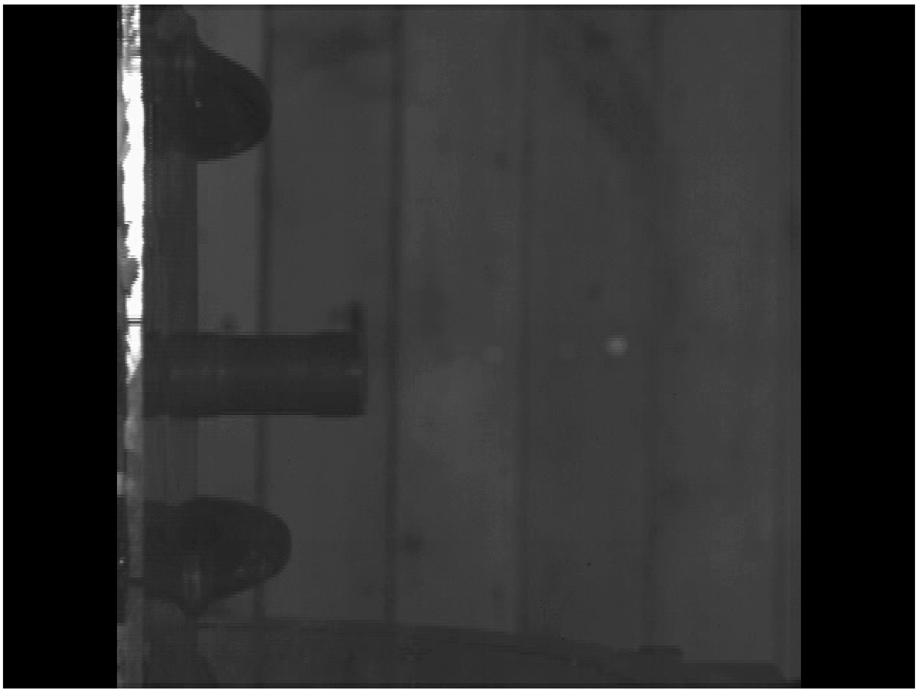


Figure 185: Hollow L21A1 against plate (2) Time = 2.4ms

Figure 186: Hollow L21A1 against plate (2) Time = 3ms

Figure 187: Hollow L21A1 against plate (2) Time = 3.6ms

Figure 188: Hollow L21A1 against plate (2) Time = 11.6ms

From Figure 186 it can be seen that the projectile deforms massively around its mid section as the momentum of the rear part continues after the front has impacted with the target. It is also worth noting that in Figure 188 the end cap is being forced off the projectile as it rebounds away from the target.

The total event time recorded was 11.6ms for the projectile to rebound to its position at T = 0. The projectile had an impact velocity of $67ms^{-1}$, compressed to a minimum length of 70mm and rebounded with a velocity of $20ms^{-1}$. From these the KE at impact was 157.6J with a residual KE of 14.68J giving a total of 142.92J transferred from the projectile.

The next series of images is for a very short projectile.

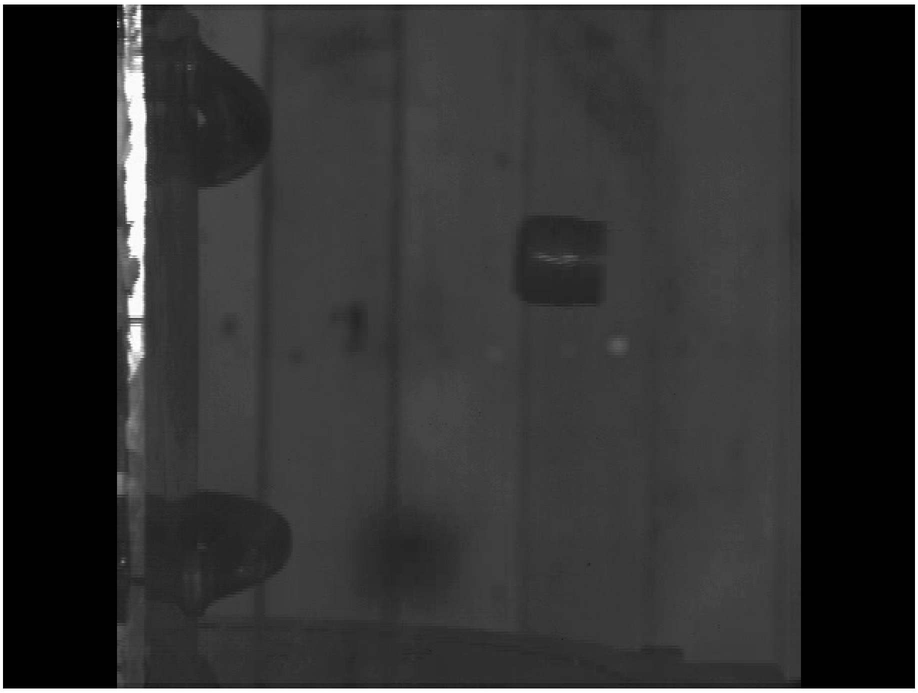


Figure 189: Front L21A1 against plate (2) Time = 0ms

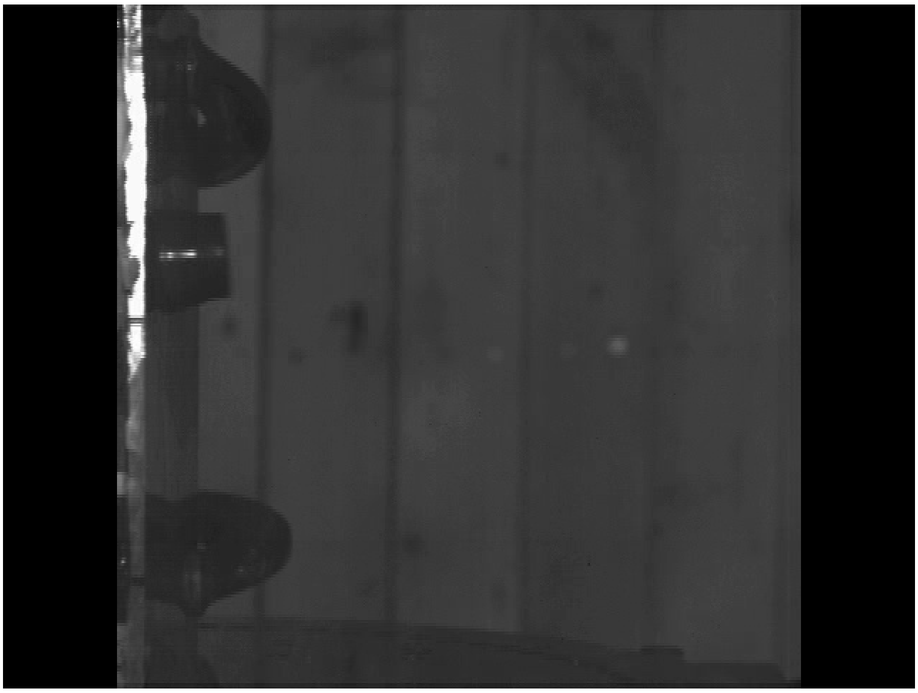


Figure 190: Front L21A1 against plate (2) Time = 1.6ms

Figure 191: Front L21A1 against plate (2) Time = 2ms

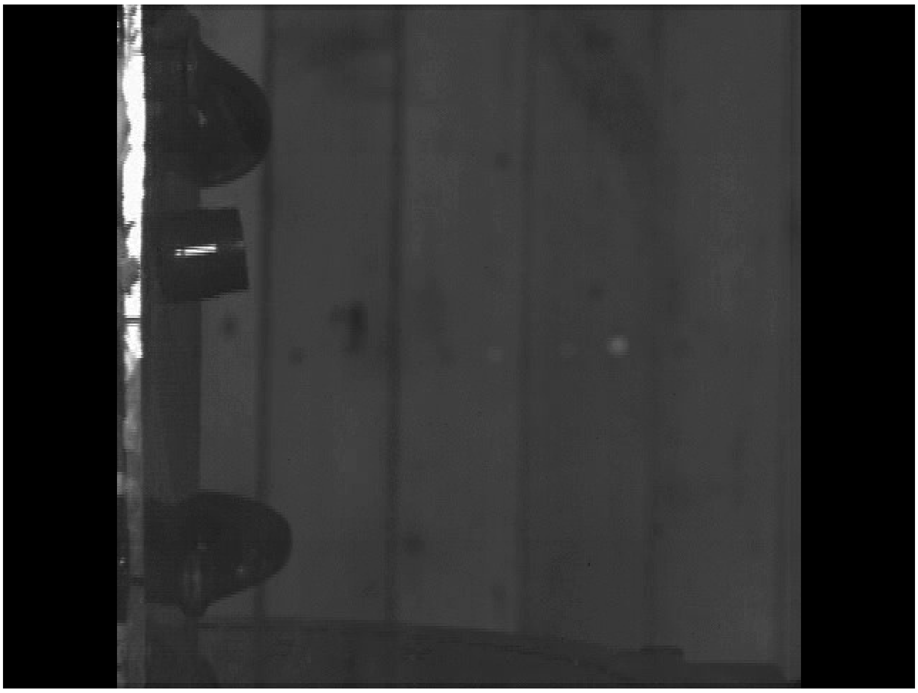


Figure 192: Front L21A1 against plate (2) Time = 2.2ms

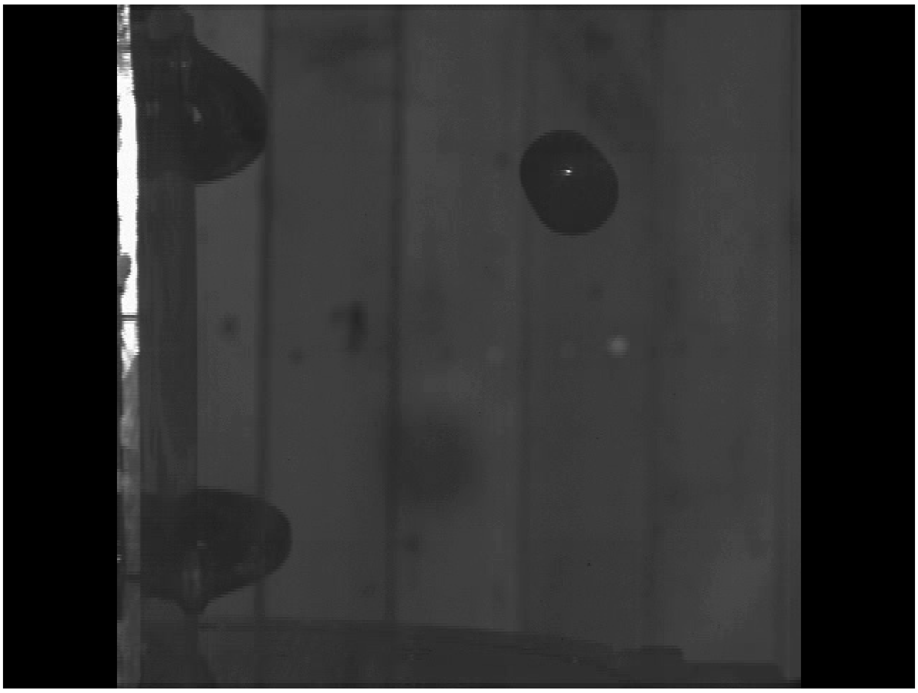


Figure 193: Front L21A1 against plate (2) Time = 10.8ms

The projectile is travelling at a slightly reduced velocity compared to a standard baton round because the same casing is used and there is a much greater volume for the gas from the .357 blank to expand into. The total event time recorded was 10.8ms for the projectile to rebound to its position at T = 0. The projectile had an impact velocity of 101.1ms^{-1}, compressed to a minimum length of 32mm and rebounded with a velocity of 18.6ms^{-1}. From these the KE at impact was 203.74J with a residual KE of 6.5J giving a total of 197.24J transferred from the projectile.

The following is using a silicone filled front L21A1

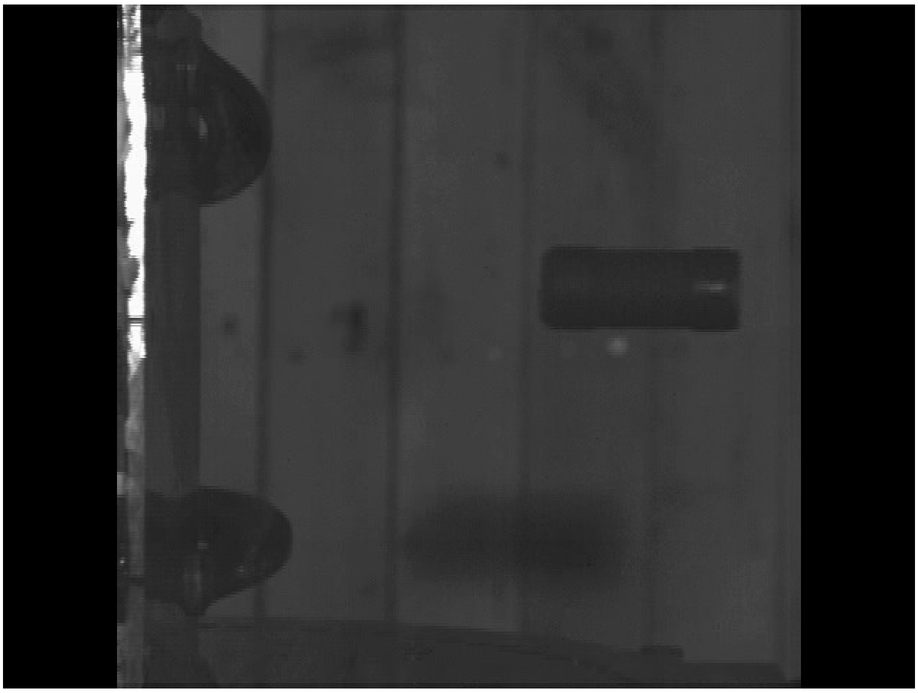


Figure 194: Silicone L21A1 against plate (2) Time = 0ms

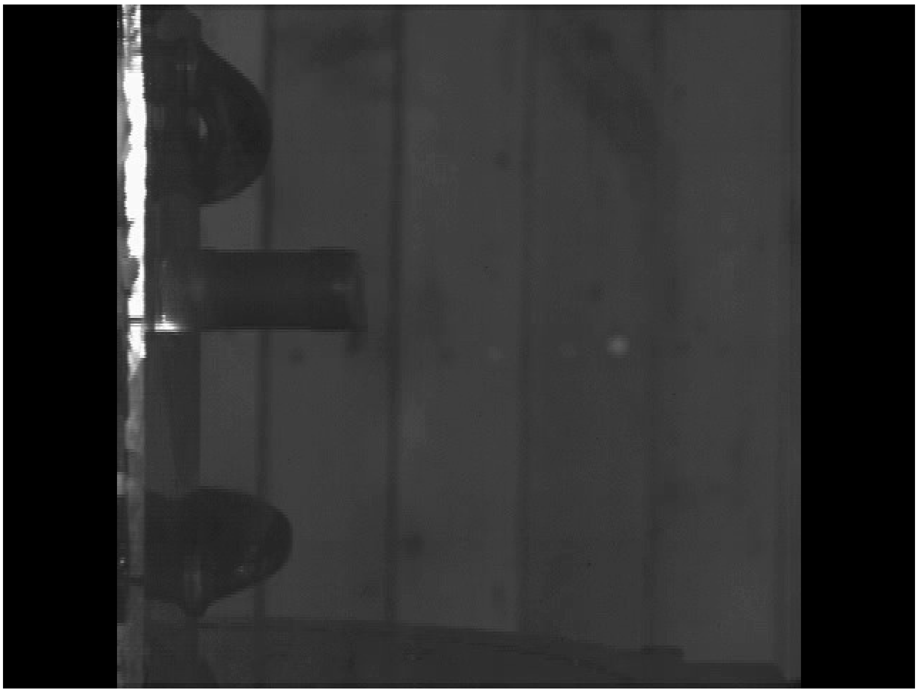


Figure 195: Silicone L21A1 against plate (2) Time = 2.6ms

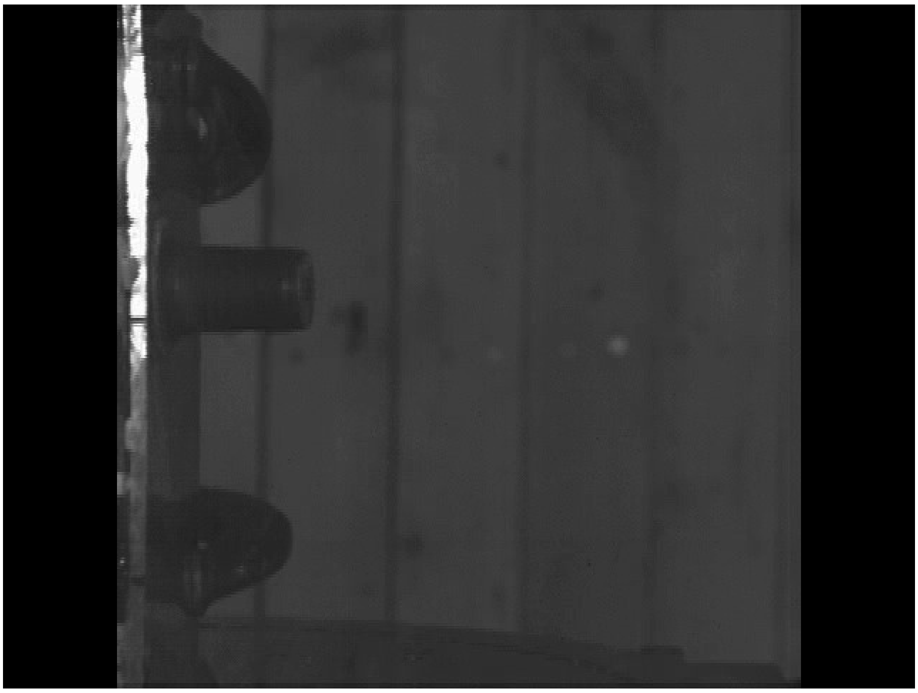


Figure 196: Silicone L21A1 against plate (2) Time = 3.2ms

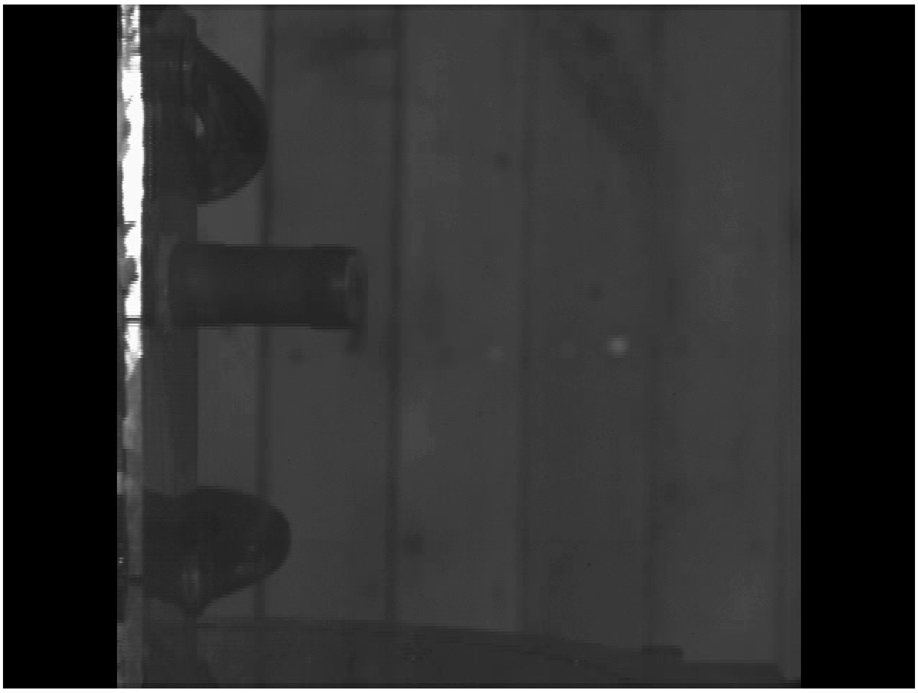


Figure 197: Silicone L21A1 against plate (2) Time = 4ms

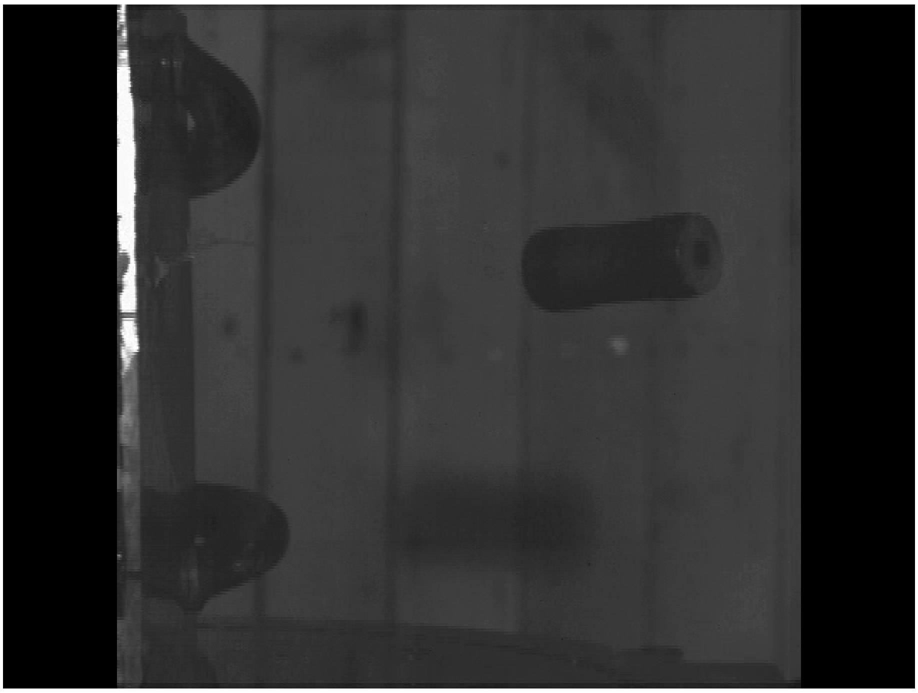


Figure 198: Silicone L21A1 against plate (2) Time = 10ms

The total event time recorded was 10ms for the projectile to rebound to its position at T = 0. The projectile had an impact velocity of $64ms^{-1}$, compressed to a minimum length of 66mm and rebounded with a velocity of $26.6ms^{-1}$. From these the KE at impact was 197.77J with a residual KE of 32J giving a total of 165.77J transferred from the projectile.

Table 9 below shows the impact and rebound velocities for each of the firings along with the maximum deflection of the projectile, its kinetic energy and KED.

Plate Tests	Proj Mass (kg)	Velocity (ms^{-1})	Rebound Velocity (ms^{-1})	Deflection (mm)	KED (J/cm2)	KE at Impact (J)	Residual KE (J)
Standard	0.098	63.80	21.67	23.10	18.63	200.27	26.25
Foam	0.094	68.20	21.67	29.70	20.25	217.68	27.41
Felt	0.093	57.20	23.64	28.60	14.21	152.79	29.89
Standard	0.098	65.86	26.67	17.60	19.85	213.39	34.29
4 Hole	0.089	61.32	21.62	25.55	15.58	167.49	13.80
4 Hole 2	0.088	75.51	25.81	31.23	23.28	250.31	21.80
2 Holes	0.092	62.45	27.59	27.82	16.74	179.99	23.21
Ctd	0.040	73.24	25.81	11.35	9.95	107.01	13.02
end hole	0.095	72.10	25.81	15.90	22.88	245.91	32.26
Hollow	0.070	66.99	20.00	17.60	14.68	157.76	14.68
Front	0.040	101.06	18.60	7.95	18.95	203.74	6.48
Silicone	0.096	64.15	26.67	22.14	18.40	197.77	32.77

Table 9: Results from firings against rigid plate

The kinetic energy of each projectile is plotted below. By comparing the impact and rebound kinetic energy it is possible to see that all of the projectiles transfer a significant portion of their energy. Of note is the very short projectile which produces the same kinetic energy as the standard baton despite being less than half of its mass. It also transfers more of this energy resulting in a lower rebound velocity.

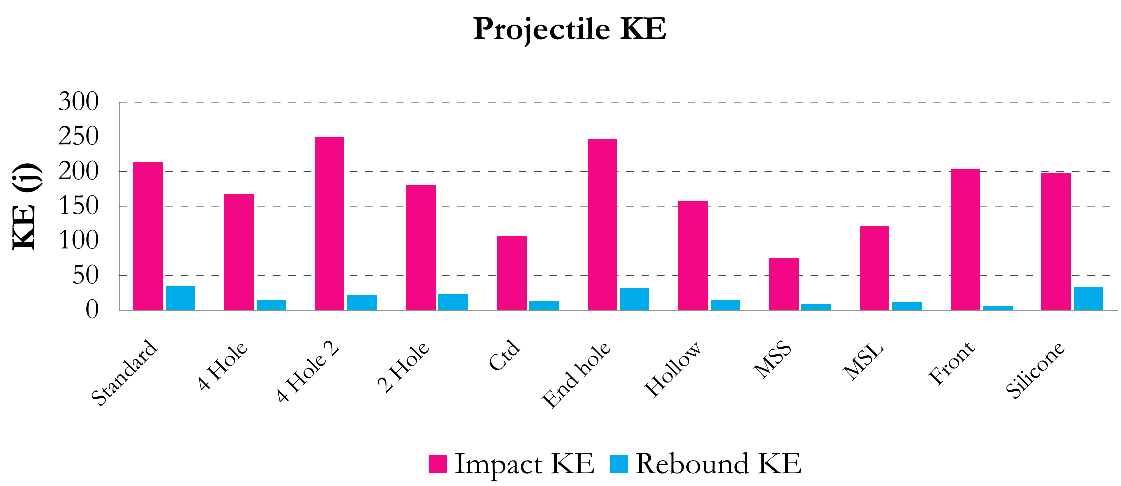


Figure 199: Projectile Kinetic energies

Of note is that the kinetic energy of some of the projectiles is above the 200J injury criteria for the body and all projectiles are above the 70J injury criteria for the head **[57]**. Farrar **[11]** used a mathematical model to examine a constant velocity impact of a PVC rod against a rigid target. He concluded that the impact was divided into two stages: Elastic compression and Viscoelastic relaxation. The elastic compression could be assumed because the loading time at impact is such that the viscous component has insufficient time to react. He found that 90% of the initial kinetic energy is dissipated during the impact, and attributed it to the opposing viscous forces acting against the longitudinal and lateral deformation. The results shown here show that more kinetic energy is retained than the mathematical model would account for, probably due to the increased compressibility of the Polyurethane L21A1 over the PVC L5A7.

By plotting a graph of the kinetic energy density for each of the projectile impacts it can be seen that the KED of the projectiles average approximately 15J/kg^3. The lower mass projectiles have much lower KED values than the standard projectile; therefore according to this injury criterion it would be possible to increase the velocity of these lighter projectiles to raise the KED to match that of the standard round which in turn would give a flatter trajectory.

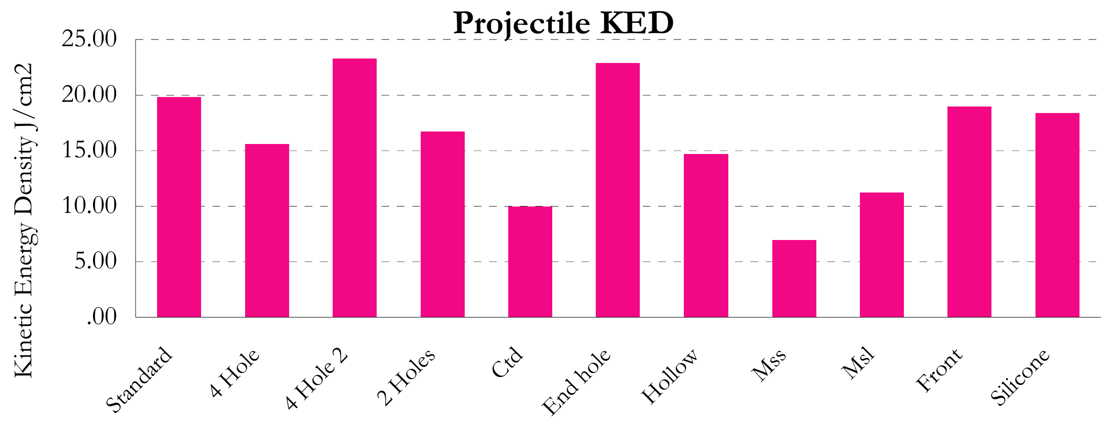


Figure 200: Projectile Kinetic Energy Densities

Lighter projectiles fired at higher velocities would provide a higher impact force compared to a Heavier projectile fired at a lower velocity due to the v^2 relationship. However the projectile momentum would be significantly lower.

4.5.1 Modified projectiles against BABT rig

The next series of tests use the modified projectiles from the previous tests on the BABT rig to compare and contrast the effects on more flexible target.

Figure 201: Standard L21A1 against BABT rig (3) Time = 0ms

Figure 202: Standard L21A1 against BABT rig (3) Time = 2.6ms

Figure 203: Standard L21A1 against BABT rig (3) Time = 5.3ms

Figure 204: Standard L21A1 against BABT rig (3) Time = 10.9ms

Figure 205: Standard L21A1 against BABT rig (3) Time = 41.6ms

From the above figures showing the standard L21A1 impact against the BABT rig, it is again possible to see the compression wave travelling through the BABT rig material and be reflected off the fixings at each end. The projectile takes 31.6ms to rebound to its start point. Its rebound velocity is 4.89ms^{-1}. The BABT maximum deflection was 35mm.

The following sequence shows the 4 holes in 1 row modified baton impact.

Figure 206: 4 Hole L21A1 against BABT rig (3) Time = 0ms

Figure 207: 4 Hole L21A1 against BABT rig (3) Time = 2.3ms

Figure 208: 4 Hole L21A1 against BABT rig (3) Time = 5.3ms

Figure 209: 4 Hole L21A1 against BABT rig (3) Time = 7.3ms

Figure 210: 4 Hole L21A1 against BABT rig (3) Time = 45.9ms

The projectile takes approximately 38 milliseconds to rebound to the start position, the impact velocity was 69.5ms^{-1} with a rebound velocity of 3.88ms^{-1}. The BABT back face deformation appears slightly larger than that of the standard baton being 37.5mm. This is due to the projectile striking higher than the standard one and the parallax effect of the mirror makes the deflection appear larger. The front face deflection is smaller than that caused by the standard projectile.

By splitting the four holes between two rows, the maximum compressible length should be increased whilst simultaneously increasing the amount of energy required to deform it compared to having the holes in one row.

Figure 211: 4 Hole 2 Row L21A1 against BABT rig (3) Time = 0ms

Figure 212: 4 Hole 2 Row L21A1 against BABT rig (3) Time = 2.3ms

Figure 213: 4 Hole 2 Row L21A1 against BABT rig (3) Time = 4.9ms

Figure 214: 4 Hole 2 Row L21A1 against BABT rig (3) Time = 7.3ms

Figure 215: 4 Hole 2 Row L21A1 against BABT rig (3) Time = 62.6ms

The total impact time is increased to 62.6ms, 15 milliseconds longer than having the projectile holes in one row. It is worth noting that this increased time is partially due to the angle the projectile is rebounding on. The projectile flight appears stable and therefore the large change of angle is caused by uneven compression of projectiles nose during the impact. The impact velocity was 62.5ms^{-1} whilst the rebound velocity was 2.7ms^{-1}. The BABT maximum deflection was 32.5mm.

By removing the second row of holes (but keeping the first row the same) the amount of compression area is reduced, but the force required to compress it is increased over the previous two layouts.

Figure 216: 2 Hole L21A1 against BABT rig (3) Time = 0ms

Figure 217: 2 Hole L21A1 against BABT rig (3) Time = 2.3ms

Figure 218: 2 Hole L21A1 against BABT rig (3) Time = 4.9ms

Figure 219: 2 Hole L21A1 against BABT rig (3) Time = 7.3ms

Figure 220: 2 Hole L21A1 against BABT rig (3) Time = 59.6ms

The total impact time of this projectile is 59.6ms. This is shorter than having two rows of holes but longer than having all the holes combined into one row. The impact velocity was 64.2ms^{-1} whilst the rebound velocity was 2.7ms^{-1}. The BABT maximum deflection was 37.5mm. Thus the rebound velocity is almost half that of the standard L21A1. The fact that the four holes in one row produces the least change in rebound velocity suggests that the strength of the material and geometry has been compromised and that the energy required to compress this airspace is greatly reduced.

The next images show the cut down projectile impacting with the BABT rig. The projectile is much lighter and, in theory much more compressible (due to the quantity of holes all along its length.)

Figure 221: Cut down L21A1 against BABT rig (3) Time = 0ms

Figure 222: Cut down L21A1 against BABT rig (3) Time = 2ms

Figure 223: Cut down L21A1 against BABT rig (3) Time = 4.3ms

Figure 224: Cut down L21A1 against BABT rig (3) Time = 6.3ms

Figure 225: Cut down L21A1 against BABT rig (3) Time = 34.3ms

There is a total impact time of 34.3ms. The impact velocity was 77.4ms^{-1} whilst the rebound velocity was 53.3ms^{-1}. The BABT maximum deflection was 30mm. Whilst this is comparable with the standard baton both the kinetic energy and the momentum will be lower, thus reducing the peak force regarded by some as the critical factor in serious injury. This is shown by the greatly reduced deflection in the BABT rig and the smaller compression wave travelling through it.

The following images show the silicone rubber fronted projectile impacting with the BABT rig.

Figure 226: Silicone L21A1 against BABT rig (3) Time = 0ms

Figure 227: Silicone L21A1 against BABT rig (3) Time = 2.6ms

Figure 228: Silicone L21A1 against BABT rig (3) Time = 5.3ms

Figure 229: Silicone L21A1 against BABT rig (3) Time = 6.9ms

Figure 230: Silicone L21A1 against BABT rig (3) Time = 59.9ms

The total impact time is 59.9ms. This is an increase of 18ms over the standard L21A1 round with the rebound velocity being half as much as the standard projectile. The slight hollowing of the front section to allow the silicone to be implanted also allows it to be spread wider during the impact process allowing the kinetic energy to be transferred across a larger area. The impact velocity was 61.6ms^{-1} whilst the rebound velocity was 2.8ms^{-1}. The BABT maximum deflection was 37.5mm.

The following images show the Hollow L21A1. It is worth noting that unlike the AEP the rear section of the projectile is hollow and the front remains the same so that the front can only compress as much as the standard L21A1 but the mass is greatly reduced.

Figure 231: Hollow L21A1 against BABT rig (3) Time = 0ms

Figure 232: Hollow L21A1 against BABT rig (3) Time = 2.3ms

Figure 233: Hollow L21A1 against BABT rig (3) Time = 5.3ms

Figure 234: Hollow L21A1 against BABT rig (3) Time = 7.3ms

Figure 235: Hollow L21A1 against BABT rig (3) Time = 35.3ms

The impact lasts for 35.3ms, which is shorter than the standard L21A1. The impact velocity was $65.1ms^{-1}$ whilst the rebound velocity was $5.3ms^{-1}$, which is greater than the standard projectile. This is interesting because the weight has been reduced to $2/3^{rd}$ of the standard projectile. The BABT maximum deflection was recorded as being 27.5mm.

By just firing the front half of the projectile (using the standard cartridge) it was possible to compare the effects of the greatly shortened projectile on the launch and impact processes.

Figure 236: Front L21A1 against BABT rig (3) Time = 0ms

Figure 237: Front L21A1 against BABT rig (3) Time = 2.3ms

Figure 238: Front L21A1 against BABT rig (3) Time = 2.9ms

Figure 239: Front L21A1 against BABT rig (3) Time = 4.3ms

Figure 240: Front L21A1 against BABT rig (3) Time = 29.9ms

The event lasts for 29.9ms with an impact velocity of 70.4ms^{-1} and a rebound velocity of 6ms^{-1}. The maximum deflection of the BABT rig was 15mm.

The table below lists the details for each firing shown in this section. Deflection refers to the rear face deflection of the BABT rig. KED and kinetic energy are also listed for each firing.

BABT Tests	Proj Mass (kg)	Velocity (ms^{-1})	Rebound Velocity (ms^{-1})	Deflection (mm)	KED (J/cm2)	KE at Impact (J)	Residual KE (J)	Rear face Velocity (ms^{-1})	Viscous Criteria (m^{2}s^{-1})
Standard	0.0984	64.20	4.89	35.00	18.86	202.78	1.61	13.5	0.4725
4 Hole	0.0891	69.52	3.88	37.50	20.03	215.31	0.86	18	0.675
4 Hole 2	0.0878	62.48	2.71	32.50	15.94	171.37	0.61	15	0.4875
2 Holes	0.0923	64.24	2.87	37.50	17.72	190.45	0.44	13.5	0.50625
Ctd	0.0399	77.44	-23.69	30.00	11.13	119.64	0.70	6	0.18
Silicone	0.0961	61.60	2.83	37.50	16.96	182.33	0.75	13.5	0.50625
Hollow	0.0703	65.12	5.36	27.50	13.87	149.06	1.06	15	0.4125
Front	0.0399	70.40	6.00	15.00	9.20	98.88	1.18	15	0.225

Table 10: Results from firings against BABT rig

The BABT rig wall deflections closely match those produced by Dstl **[58]** where an identical test rig was used and an average deflection of 32mm was obtained for both the L21A1 and the new AEP round. All modified projectiles produced a lower kinetic energy density than the standard baton.

5.5 Discussion

The graph below shows the comparison of velocities for each of the projectiles used against both the rigid plate and the BABT test rig.

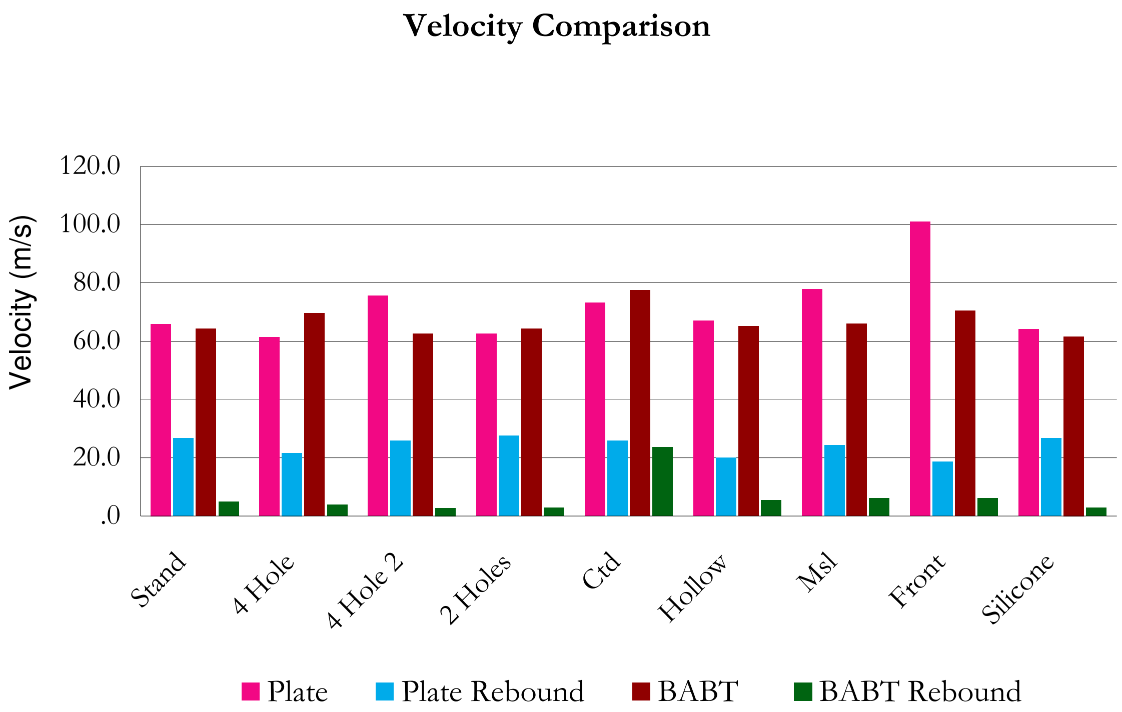


Figure 241: Graph Showing Velocity Comparison of Modified Rounds against the metal plate and the BABT rig

From the test results impacting batons at the rigid metal plate it can be seen that there is not a large difference between total impact times between the front face modified projectiles and the standard L21A1 projectile. This is counter intuitive because the modified projectile compresses more on impact than the standard L21A1 and this compression uses up part of the projectiles initial kinetic energy. However, because the projectile is striking a solid immovable target then the kinetic energy transferred to the target is likely to be transferred back into the projectile. When hitting a softer target this return kinetic energy transfer is a slower, due to the increased amount of deflection that occurs in the target. This indicates that the kinetic energy alone is not the only major factor causing impact damage but the rate at which it is transferred into the target (and/or back to the projectile.)

When striking a hard surface the kinetic energy and momentum is transferred back into the projectile faster than when striking a less rigid surface. Because the projectile is never permanently damaged or deformed visibly after impact is complete, it is possible to assume that the deformation process and initial impact is entirely elastic. Thus any compression in the projectile is also elastic and becomes stored potential energy until it starts to expand. The expansion of the projectile occurs at a slower rate indicating that this phase is not behaving entirely elastically. A viscoelastic component would explain the projectiles reduced rebound velocity. There will be some energy lost during the impact due to heat generation caused by the elastic deformation in the projectile as well, which will further reduce the rebound velocity.

Because this rate of transfer is very fast it isn't possible to measure it accurately, even with the use of the high-speed video the actual moment of transfer of kinetic energy is still occurring between the video frames.

The reduction in mass of the projectile and hence its reduction in kinetic energy could be compensated for by increasing the velocity. Higher velocities increase accuracy of use because this would result in a flatter trajectory making range estimation less critical. Projectile drop is inversely proportional to v^2. Thus a small increase in velocity will have a large effect on the trajectory.

If the mass m is reduced by a factor z (where $0 < z < 1$), then the velocity will need to be increased to reach the same KE as the original projectile:

$$\frac{V_0}{\sqrt{Z}}$$

Equation 20

In addition the momentum of the projectile is also reduced.

$$mVo/\sqrt{z}$$

Equation 21

An alternative to increasing the velocity of the projectile to match the kinetic energy of the original would be to add extra mass onto the rear of the modified projectile by simply increasing its length by L_z.

$$L_z = \frac{M - zM}{k}$$

Equation 22

Where k is a constant created by the density and cross sectional area of the original projectile.

This increase in length to bring the mass back to that of the original projectile will also increase the impact time compared to the shorter projectile with no free compressible space. The increase in impact time will therefore also reduce the peak force exerted to the target.

On a number of firings there was some unburnt propellant left in the barrel of the launcher. This is an important problem because unburnt propellant means that the total amount of energy transferred into the projectile is obviously going to be reduced. In an all burnt firing the energy is distributed as follows in Table 11. The weapon recoil and barrel rifling will account for less than 1% of the energy transferred by the propellant gases.

Motion of projectile	32%
Motion of propellant gas	3%
Frictional losses	3%
Heat loss to gun	20%
Heat retained by propellant gas	42%

Table 11: Showing approximate % distribution of energy from propellant

Because approximately only 32% of the energy is transferred into the projectiles motion any propellant lost due to an incomplete burn will have a significant effect on the projectiles launch velocity and therefore trajectory and range. The unburnt propellant was mainly noticed on the cartridges that had been hand loaded above the recommended level of propellant. Whilst it was possible to hand load the projectiles to achieve higher velocities the amount of unburnt propellant left in the chamber and barrel after multiple discharges would become an issue.

Hole **[39]** performed extensive tests on abdominal simulants and concluded that the most likely cause for damage to the internal organs in the abdomen caused by a typical baton could be shown by the following diagram.

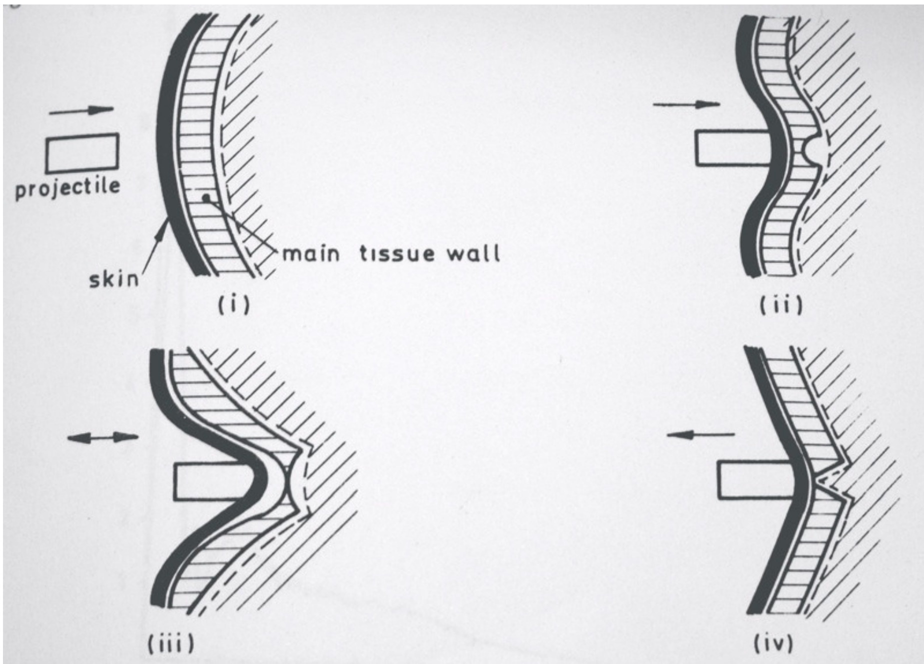


Figure 242: The typical damage mechanism from a baton round impact [10]

The diagram shows that whilst the skin maybe intact there is a significant amount of internal tearing and serious injury potential from what appears to be localised surface bruising. Hole also found that clothing would significantly reduce both skin tearing and the internal muscle tissue damage. When performing tests with the BABT rig there is not enough refinement to demonstrate the damage mechanism that Hole **[39]** describes, however in a number of impacts there is a noted difference between front and rear face deflection. This difference could be related to the internal damage and skin lacerations. There is a large trade off when developing a human model between repeated usability and the complexity of the model, the BABT rig is very much a reusable model but it cannot measure all the damage mechanisms. What is clear from all the testing is that there will also be a carefully balanced relationship between the "stopping power" of a kinetic less lethal weapon and its chance of causing serious injury. The difference between the BABT rig and the human body is that the surface of the BABT rig has a much higher resistance to ripping than human skin due to it being constructed as a single homogenous layer. As the projectile impacts the target the energy that is transferred in the target (as opposed to the energy used to compress the projectile) is directed into stretching the skin, the skin stores this as potential energy of deformation. If there is enough potential energy stored the skin may become so stretched it will actually rupture. Farrah **[11]** formulates an equation for the rupture process and energy levels needed for different age groups. The equation assumes that the entire kinetic energy of the projectile is used to stretch the skin. In reality this is not the case, as is evident from the results of this research part of the energy goes into deforming the projectile as well as being transferred into the material behind the skin.

When comparing deflections for all the projectiles against the BABT rig there is a very similar level of deformation. Because of this similar level of deformation over the range of modifications to the front of the projectile carried out during this research programme, when it strikes a soft target i.e. the stomach or abdomen, then the impacts will be similar. Figure 243 below shows the back face displacement of the BABT rig during the impact of the baton round. All of the modifications performed to the L21A1 reduce the amount of displacement caused; however the rate of displacement is unaffected.

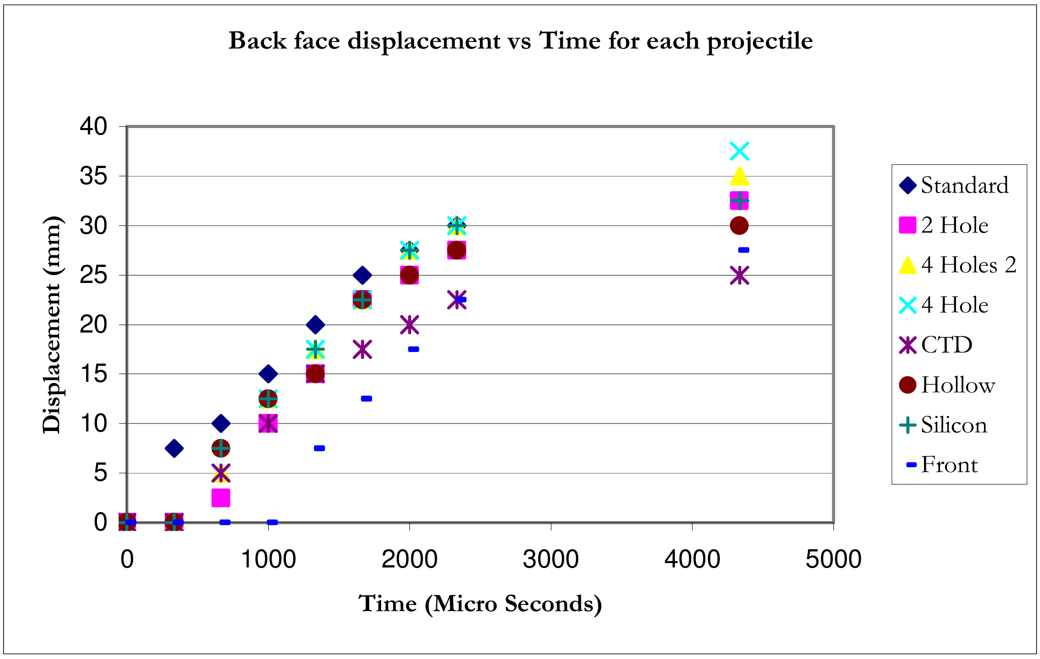


Figure 243: Initial BABT back face displacement during impact

The graph below plots the displacement of the wave travelling through the rear BABT face. The starting point for each data series is the arbitrary point at which measurement began. The projectiles with significant proportions of mass removed cause a lower rate of linear displacement in the BABT rig. The standard and 4 Hole projectile have the highest rate of linear displacement.

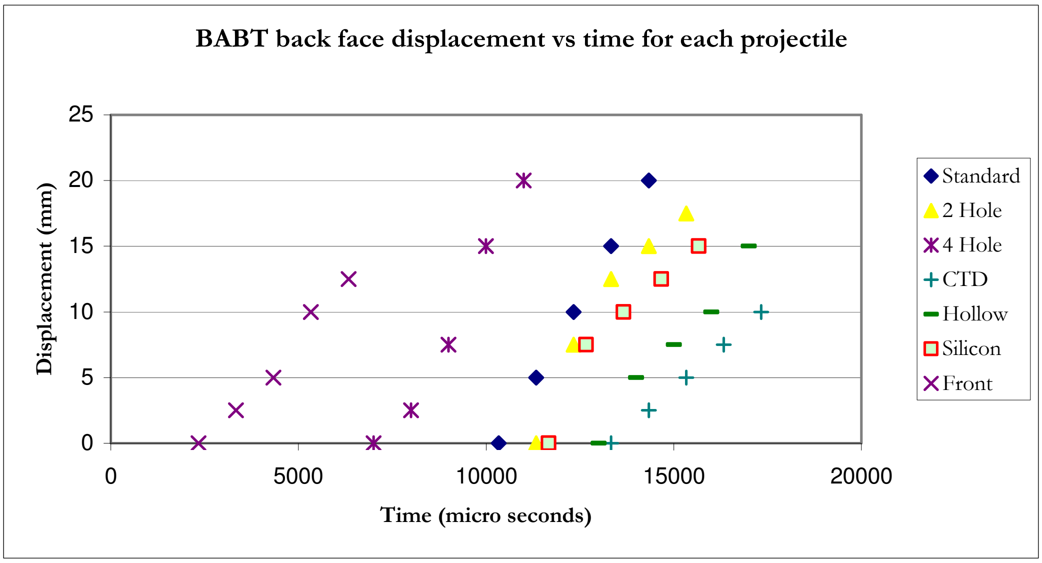


Figure 244: Secondary BABT back face displacement during impact

The tests performed as part of this research that used unsealed air cavities appear to confirm the theory developed by Farrar **[11]**. The open cavity design would however benefit from some accuracy testing because it is likely that the aerodynamics of the projectile will have changed, although the open cavity projectiles were still accurate at the ranges tested.

The effects between head strikes were more noticeably different for each modified projectile. One of the main reasons for the UK government's development of the new AEP baton round was to reduce the likelihood of serious injury caused by a strike to the head, whilst at the same time retaining the end result (i.e. temporary incapacitation of the target). Maguire **[59]** has since conducted a study on the injuries caused by the new AEP round, whilst the study was only of a small scale (14 patients), 8 of these required admission to hospital and of these 6 had injuries to the face, neck and head. The type and severity of injury was noted as being of a similar form and scale to previous studies conducted with the L21A1 baton. The results presented in this paper are misleading because it would appear that the AEP round actually increases the wounding effect. However this is because there were a high proportion of hits to the upper torso and to the head compared to previous baton round injuries. This indicates a difference in the way the weapons were being used and not the way that it was interacting with the target.

Chapter 6 Conclusions & Further Work

6.1 Conclusions

Kinetic energy less lethal weapons have been used for more than fifty years and are the most prolific of a wide range of weapons designed to impose compliance by an advisory without the deliberate resort to lethal effects, yet very little is known about how different projectile characteristics affect lethality. There is significant documentary evidence to show that these weapons can, under certain circumstances, causes high levels of permanent injury or death. Different parts of the body are susceptible to different levels of trauma and permanent injuries and death resulting from striking these vulnerable areas. The rules of engagement given for the use of these weapons specifically forbid targeting the upper torso and head but the accurate use of these weapons can be difficult resulting in unacceptable injuries. The aims of this research was to investigate ways of avoiding strikes from these weapons to those vulnerable areas of the body and to research those projectile characteristics that could reduce their damaging effect should a vulnerable area be struck.

A prominent feature of these types of weapon is that they must impact the body at low velocities to avoid excessive injury. A consequence of this is that they have a very looped trajectory. Whilst these weapons are inherently very accurate and consistent, they are very difficult to use accurately because it is very difficult judge range accurately and this has a considerable effect on the position of the vertical point of impact of the projectile. Increasing the launch velocity of these projectiles would flatten their trajectory and would improve the accurate use of these weapons that would in turn reduce the probability of striking a vulnerable part of the body. However, increasing launch velocities alone would result in an unacceptable increase in injuries wherever they stuck the body.

6.1.1 Head Injuries

Studies point to brain deformation or strain as a principle cause of brain injury. Unfortunately the measurement of strain is almost impossible during impact, particularly in vivo. Therefore input variables, such as head acceleration, are used as alternative parameters to characterise the injury mechanism.

When impacted the head is subjected to combined linear and angular acceleration: Skull fractures are often absent but severe brain injury was found in experimental animals. Rotational acceleration produces local and diffuse injuries. Linear acceleration appears to produce pressure gradients whilst angular acceleration produces shear stress and differential motion between the skull and the brain.

The mechanism causing unconsciousness following an impact is not fully understood. Considerable controversy exists with the biomechanics community regarding the validity of competing hypotheses because they do not correlate with clinical or pathological observations. Injuries to animals under similar conditions are often less severe than injuries to humans.

Using an instrumented projectile and an instrumented simulated skull the effects of target and projectile characteristics on the levels of linear acceleration, displacement with respect to time and the duration of these events were investigated. As would be expected the linear acceleration levels for the instrumented projectile was very high for rigid targets and reduced as the rigidity reduced. However, the duration of the acceleration increased so that the product of the two, and therefore the potential injury criteria, remained similar.

For the instrumented simulated empty skull different projectile geometries were investigated. Small reductions in the duration of displacement were noted for projectiles with airspaces caused by cross drilling of holes just behind the impacting face of the projectiles. The effect was not significantly altered by adding another set of holes behind the first set, indicating that it is the projectile characteristics of the first few centimetres that have the greatest effect on impact duration. Reducing the weight of the projectile had little effect on the rate of change of displacement but significantly reduced the duration of displacement.

For similar tests with the simulated skull filled with plasticine the results were not as would be expected with the displacement with respect to time being similar to that for the empty skull. The light weight projectile was the exception to this and the results were closer to as expected.

The Energy Attenuating Round had a significantly reduced displacement for the empty skull compared to the standard baton round but the duration of the displacement was significantly greater. Both duration and displacement were significantly reduced when tested against the simulated skull filled with plasticine.

6.1.2 Thorax Injuries

The second main area of the body particularly vulnerable to serious injury and death by blunt trauma is the thorax. Data from researchers investigating injuries caused in automobile accidents have identified those factors that affect the level of seriousness caused by blunt trauma to these areas of the body. They have found that the probability of serious injury to the thorax by blunt trauma is increased with increasing levels of chest deformation and the rate at which the deformation occurs. Automobile accidents are low velocity events but researchers investigating injuries caused by kinetic energy less lethal weapons confirm these relationships hold when they are applied to higher velocity events. Thus the characteristics of targets/projectiles were investigated with regard to how they affected the above blunt trauma injury criteria.

A behind armour blunt trauma (BABT) test rig was used to examine the impact of the L5A7 and L21A1 baton rounds, some minor modifications were made by changing the front of the projectile. Further tests were then conducted utilising open air cavities in the projectile noses. These tests showed that the introduction of air cavities to the projectile reduced the initial and secondary rate of displacement in the BABT rig. However if the air cavity was too large the wall of the projectile would be compromised and the effectiveness of the cavity would be voided.

Testing was also carried out firing the modified projectiles against a rigid metal plate, used to simulate a head impact. The rebound velocities of these projectiles were significantly higher. The projectiles also deformed heavily on impact, something not witnessed when testing against the BABT rig. This deformation would extend the amount of time over which the impacts force is exerted simultaneously reducing the peak force.

Studies point to the Viscous Criteria as the main injury mechanism for projectile strikes against the thorax. The results from the BABT rig tests show that Viscous Criteria for several of the modified projectiles is actually higher than that of the standard projectile. The projectiles with more significantly reduced mass however gave reduced VC values.

6.1.3 Skin Penetration

An essential feature of any kinetic energy less lethal weapon, and especially important for tranquilliser darts, is that the body of the projectile should avoid penetration of the skin. Theoretical studies during this research, followed by range testing, indicated that there is a relationship between the mass of the projectile (m), and the velocity of skin penetration at impact (v), of the form:

$$m \propto v^{1.4}$$

Equation 23

This shows the importance of minimising mass to allow projectiles to be launched at higher velocities without penetrating the skin. Based on this work a new range of tranquilliser darts have been developed by a commercial organisation that has increased the distance over which they can be used by a factor of three.

6.1.4 Deterrence

Whilst it is unacceptable to cause serious injury through the use of Kinetic Less Lethal Weapons and that there are continuing efforts to reduce the possibility of these injuries there is still a requirement for the weapon to act as a deterrent. If the projectile has no chance of causing injury then its ability to stop an offender will likely be compromised. The officers using these weapons will need confidence that the projectiles will indeed do their job. Therefore there needs to be a trade off between possible injury and effectiveness as a deterrent.

6.2 Future Research

This research has uncovered a number of highly significant findings and the following are the recommended areas for future research:

- The work on tranquilliser darts has made a major contribution to increasing their ballistic performance but of all of the kinetic energy less lethal projectiles it has the widest range of possible targets being used against a wide range of animals and possibly, human targets in the future. Avoidance of penetration of the skin is essential and research should be conducted into the terminal ballistic properties of the wide range of skin types for the targets for which this type of projectile would be used against.

- The work using the simulated head target has shown the potential for significantly reducing the probability of injury by blunt trauma to the head from kinetic energy Less Lethal Weapons. This work should be expanded to include a head form of the correct mass that uses three axis accelerometers to investigate the impact characteristics of a wide range of projectile materials, projectile geometries and impact velocities.

- The work using the simulated thorax BABT rig has shown the potential for significantly reducing the probability of injury to the thorax by blunt trauma from kinetic energy Less Lethal Weapons. This work should be expanded to use a method of measuring thorax deformation with a greater resolution to investigate the impact characteristics of a wide range of projectile materials, projectile geometries and impact velocities.

- A potential method of flattening the trajectories of low velocity projectiles is to use projectiles that generate lift. The different methods of achieving this, along with the methods of launching these projectiles, should be investigated.

- Kinetic energy Less Lethal Weapons depend, to some extent, on inflicting blunt trauma to the human body for their effectiveness as a deterrent weapon. Reducing blunt trauma may therefore reduce their deterrent effect. It is important therefore that the relationship between the deterrent effect that these weapons may have and the blunt trauma that they cause is investigated

Chapter 7 Appendix 1 The Modelling of Tranquilliser Dart Impacts

7.1 Introduction

Mathematical models have the advantage of consistency. They can make the analysis as complex or as simple as is necessary to obtain the results for the conditions being investigated. However, to mathematically model the interaction between a projectile and human tissue it is necessary to know the physical properties of the tissue and the effects of high strain rates on the tissue properties. The modelling of neurological and physiological effects is still not possible. It must be stressed that the use of any theoretical model also requires validation by experimentally obtained results.

7.2 Factors affecting the impact process

The starting point for modelling the impact between a projectile and animal tissue is to consider those factors that affect the impact response. These include:

- Projectile velocity
- Projectile mass
- Projectile cross sectional area
- Projectile spin rate
- The geometric shape of the projectile
- Target impact location

7.3 Modelling an impact

A computer model of the impact process allows the assessment of a larger number of repeatable firings. Additionally, it is possible to quickly change a large number of variables, usually one at a time, and identify those variables that have the greatest effect on the interaction between the projectile and the target. A well developed and practical way of modelling impact processes is to use hydro codes. A hydro code is a computational tool for modelling the behaviour of continuous media. Simply defined, a hydro code is a computer-based system for modelling fluid flow at high speeds. A hydro code can however be adapted to use material strength and a range of equations to create realistic behaviour of almost any material. The diagram below shows a simplified flow diagram of the hydro code process.

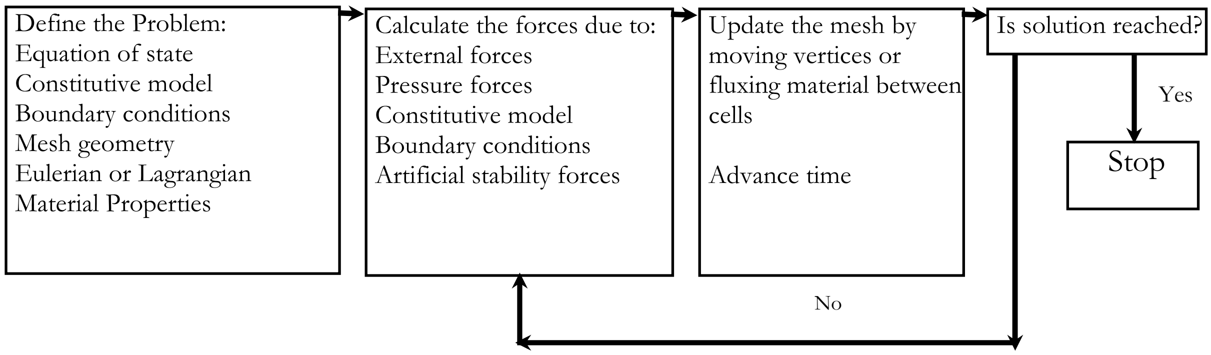


Figure 245: Hydro code flow diagram

The hydro code model considers the internal and external forces on a user-defined mesh of cells that represent the system being studied which usually include the projectile and part of the target where the impact will take place. It assumes that over a very short time span the forces exerted are constant and uses them to adjust the mesh's geometry, then the forces are recalculated and the process begins again. This is repeated until a solution is found.

The hydro code system itself is made up of three parts:

- *The Newtonian laws of Motion*: This models the incompressible inviscid fluid flow.
- *The Equation of State*: This relates the pressure to the density and internal energy accounting for the compressibility effects.
- *The Constitutive/Strength Model*: This relates stress to a combination of strain, strain rate, internal energy and damage as well as describing the effect of deformation.

The approach used with the hydro code is to define a "mesh" to approximate the geometry of interest. This mesh is then divided up into a larger number of smaller more manageable cells. Generating a mesh to represent the geometry, assigning material properties and setting up boundary conditions are the basic inputs for a hydro code model. Generally, the mesh is one of 2 types: Lagrange or Euler. There are several less common meshing systems in existence including Arbitrary Lagrange Euler (ALE), which is a combination of the features of the main two meshes.

In the Lagrangian mesh, the grid points are embedded into the material and move with it in space. It is useful for tracking material boundaries in solid impacts. However problems may arise using this method when large deformations are likely to occur because the cells can become distorted leading to a smaller time step, incorrect results and even possibly the models failure. The diagram below shows how the grid distorts with the material as time increases.

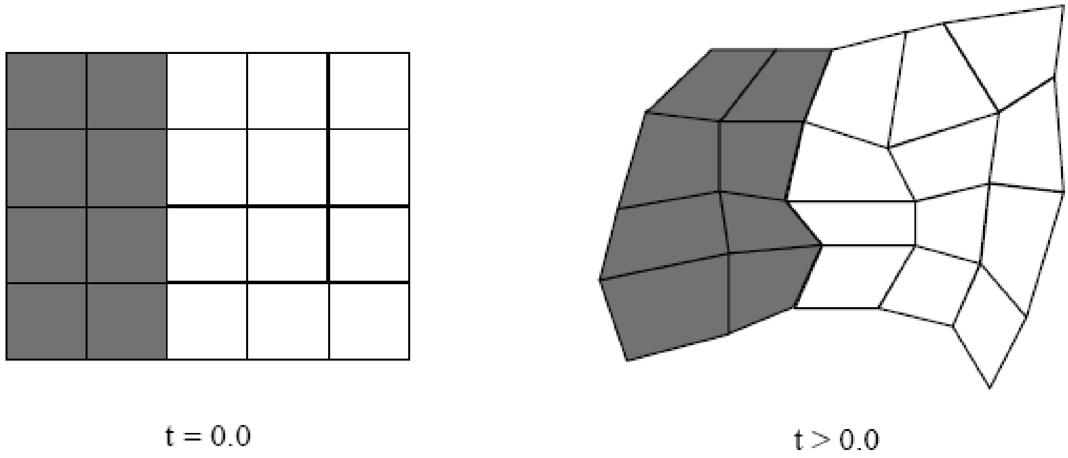


Figure 246: LaGrange meshing showing deformation of cells over a time period

In the Eulerian mesh, the grid points are fixed in space with the material moving across them. Eulerian techniques tend to be used in situations when there are large material movements across the model, such as in blast wave modelling because there are no grid distortions. A larger mesh must be defined to cover the area in which there is anticipated motion, which may extend to a larger area surrounding the physical parts of the model.

When using hydro codes to model an impact there can be a number of problems with the meshing and there are several ways to minimise their effects. Some of these problems can include large area deformations breaking cells, modelling shockwaves, hour glassing and fixing the time step.

There are a number of ways to cope with large deformations in the model. Re-zoning can be used in which a new mass, energy and momentum are remapped across the mesh. This can also be done automatically by re-zoning the mesh after each cycle. Erosion algorithms can be used and any cells with a defined level of distortion are deleted from the model. There is an option to retain the mass of the deleted cell although this can lead to unexpected results, because part of the model is unrealistically disappearing and lumping its mass onto the nearby cells. It is also possible to link a lagrangian and eulerian mesh together in order to reduce the number of cells that are distorted.

Shockwaves may be introduced as part of the initial conditions or the result of a boundary condition. To model a shock wave artificial viscosity can be used. This numerical method was devised by Von Neumann and Richtmeyer **[60]** for handling shockwaves by introducing an artificial dissipative mechanism that would result in the shock being spread out over several zones, rather than concentrated in just one.

Hydro code models generally use quadrilateral cells to define the solution in a material and because of this there is an inbuilt weakness in the definition. The expressions for strain rates and forces involve differences only in velocities of the diagonally opposite corners of the quadrilateral cell. If the cell distorts in such a way that these differences remain unchanged there will be no strain increase in the zone and therefore no resistance to this distortion. If these distortions happen in an area of several cells a pattern resembling an hourglass is created. This leads to the condition called hour glassing as shown below.

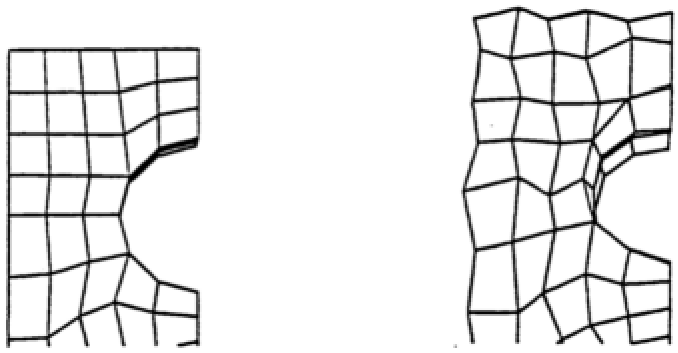


Figure 247: Hour glassing diagram

Hydro codes use an explicit scheme when solving a problem. There is a minimum time step between each cycle of integration that must be retained for the results to be accurate. The value of the time step depends on several factors of both the initial model setup and the current point in the solution so that the local time step at each cell can be calculated. The minimum value of these local factors is multiplied by a safety factor (usually 2/3) and is set as the time step for the next cycle of integration. This is especially important in a lagrangian mesh because the time step must satisfy the Courant condition shown below.

$$\Delta t \leq \frac{d}{c}$$

Equation 24:

The time step (t) must be less than the length of a zone (d) divided by the local speed of sound (c). This ensures that a disturbance does not propagate across a zone in a single time step. Therefore, impacts with larger deformations will have smaller time steps, and therefore take longer to solve. Thus if there is a large deformation the time step becomes so small that the impact effectively halts in the model and it would take a near infinite time to solve.

In addition to meshing the model it is necessary to assign boundary conditions and material properties to the various parts of the model (i.e. the projectile and target.) These boundary conditions usually include setting velocities for the projectiles mesh fixing parts of the target mesh so that it acts as if clamped along one edge. Assigning material properties is more complex. Most hydro codes have a library of materials and their associated mechanical properties, such as Young's modulus, density, specific energy, Poisson's ratio and the equation of state. These material properties can then be applied to cells in the mesh where appropriate. Some materials in the hydro code library have a number of different possible equations of state. The equation of state relates the specific volume (v) and specific energy (e) to the local hydrostatic pressure (P) in a state of thermodynamic equilibrium.

$$P = f(v, e)$$

Equation 25

This equation can take many forms depending on the situation in which it is used. When used in a hydro code it is solved at each time step simultaneously with the energy equation, having solved the mass and momentum conservation equations for velocity and density.

For an ideal gas the equation of state takes the form:

$$pv = RT$$

Equation 26

This can be converted to:

$$p = (\lambda - 1)\rho e$$

Equation 27

However in many cases, if the material is of solid or liquid form, the influences of change in entropy is small so p can be considered a function of density alone. An alternative to this is to consider the initial elastic behaviour expressed by an approximation to Hooke's Law, which can be written as

$$pK = \mu$$

Equation 28

Where $\mu = (\rho/\rho 0) - 1$, and K is the bulk modulus.

This form of the equation of state is of use only when small compressions are expected and should not be used if it is possible for large deformations to occur.

7.4 Modelling the dynamic response of biological materials

The ultimate purpose of the hydro code model is to mathematically recreate the behaviour of an actual system. Therefore, the analysis must be an accurate mathematical model of a physical prototype. This model comprises all the nodes, cells, material properties, constants, boundary conditions, and other features that are used to represent the physical system, in this case the projectile and the body biological tissue.

7.4.1 Problems with modelling

The problem exists that biological material systems have much more complicated interactions than their engineering material counterparts, and are difficult to model with any degree of accuracy. To model biological material, its mechanical properties must be known but there is very little data on the mechanical properties of this type of tissue. That data that is available indicates that the material properties are highly non-linear and very rate dependent.

Despite the difficulties of modelling biological materials and the subsequent validation of the results hydro code models can still yield very useful results by using the properties of simpler materials and investigating the effect of different variables on the impact process and validating the results experimentally. For this investigation it was chosen to use a very thin sheet of steel to represent the skin and to use gelatine for the bulk soft tissue. Gelatine has a similar density to that of human soft tissue but is homogeneous and the mechanical properties are the same in all directions. It is also a well known and often used soft tissue stimulant. Mechanical properties for steel sheet can be found in the hydro code material library but the properties for gelatine are not.

7.4.2 Modelling of an impact using the AutoDyn Hydro code package

The chosen hydro code package was AutoDyn because of its relative ease of setup and large existing material library. There are two versions of AutoDyn available a 2D version and a 3D version for more complex modelling. For this investigation, the 2D version of AutoDyn was used in order to simplify the model. A simple 2D projectile can be rotated around one axis to give a 3D shape (this applies to the target too so only perpendicular impacts can be measured.) The body of the projectile was modelled as a simple polycarbonate cylinder of 18mm diameter to match the bore of the shotgun barrel. The target was modelled as a cylinder of gelatine 100mm in diameter with the "skin" joined onto the front surface (via a boundary condition). Lagrangian meshing was used in all materials because the deformations were not thought to be significantly large. Because gelatine is not in the library of materials a new material was defined for the model, the gelatine was based on its main consistent, water. The gelatine was given a simple strength model and linear equation of state to give it some rigidity but keeping the model as simple as possible. A series of simulations were run to find out how the projectile and impact behaved using a thin sheet of steel in the skin layer so as to try to reproduce known effects that approximate those seen in biological materials as well as investigate the effects of mass and velocity on the target. The use of sheet steel as a skin was also to allow a practical validation model to be constructed.

The hydro code model allowed for easy adjustment of projectile mass to investigate the effects of momentum and kinetic energy on the target. One of the basic requirements for a tranquilliser dart is that it should not penetrate the skin. Results were therefore obtained to identify the impact velocity at which penetration of the skin occurred for different impact velocities. This required setting the model to run for a given impact velocity and a given mass. The result was then observed. If the skin was penetrated the impact velocity was reduced and the model re-run. If the skin was penetrated this was repeated until penetration did not occur. If for the first run the skin was not penetrated then the impact velocity was increased in increments until the skin was penetrated. Once the penetration velocity was identified the above was repeated for different projectile masses. The results of impact velocity against mass are shown in Figure 248.

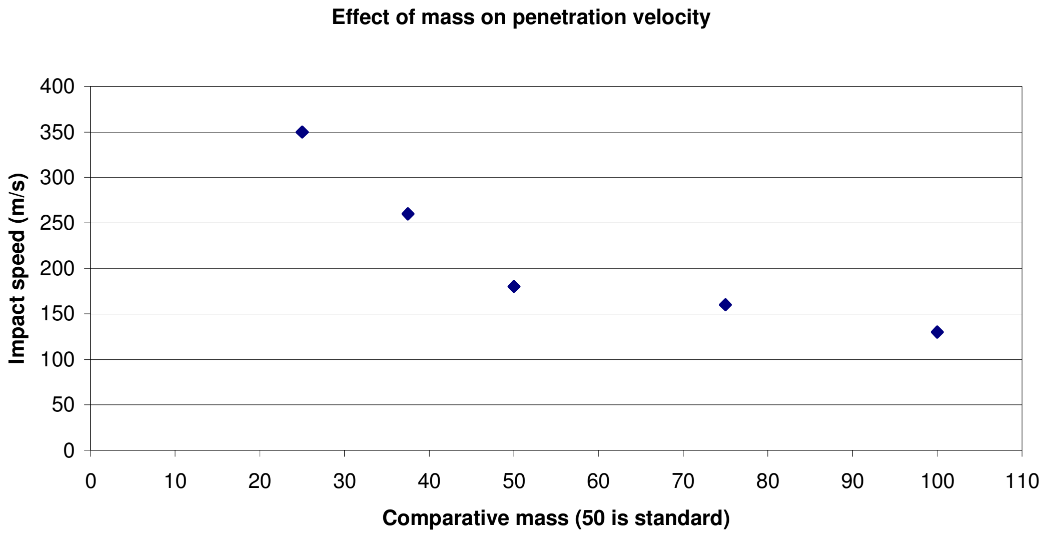


Figure 248 Graph showing the effect of mass on penetration velocity

The graph above shows that, as the mass of the projectile increases then the velocity required penetrating the skin decreases.

As was shown in Section 2 different researchers purport to have demonstrated differently that the penetration of skin occurs at a given value of impact velocity, impact momentum per unit area and impact energy per unit area. From the AutoDyn model it can be seen that for thin steel sheet the impact velocity for penetration is strongly influenced by the impact velocity and the projectile mass.

To see the relationship between impact kinetic energy per unit area and penetration impact velocity the graph shown in Fig 5 was produced.

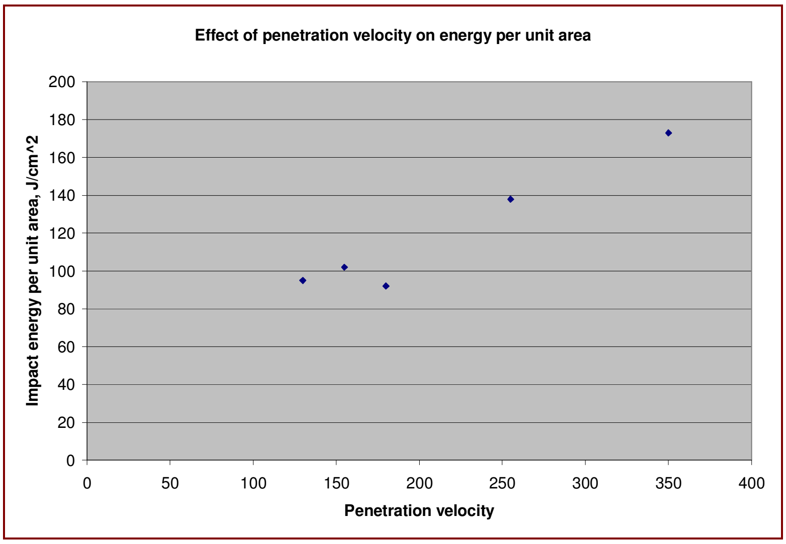


Figure 249 Graph showing the relationship between Kinetic Energy per unit area and penetration velocity

If the onset of penetration is dependent on a fixed energy per unit area as is currently thought, then graph should show all of the points on a similar horizontal value. It can be seen that the relationship holds true at the lower velocities but not at the higher velocities where the amount of energy required to penetrate the target increases.

To see the relationship between impact momentum per unit area and penetration impact velocity the graph shown below was produced.

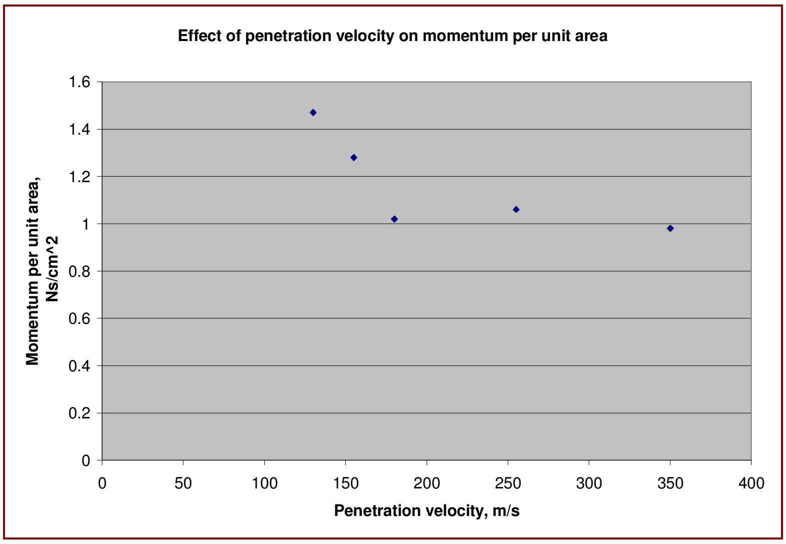


Figure 250 Graph showing the relationship between Momentum per unit area and penetration velocity

The graph shows the opposite trend. Clearly there must be a relationship lying somewhere between the impact velocity and the impact velocity squared. It was found that the best-fit relationship was that of impact velocity to the power 1.4. This is shown plotted below.

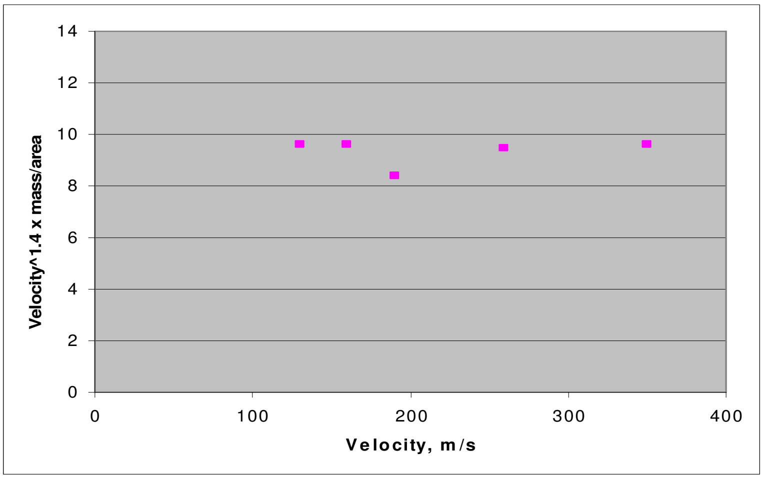
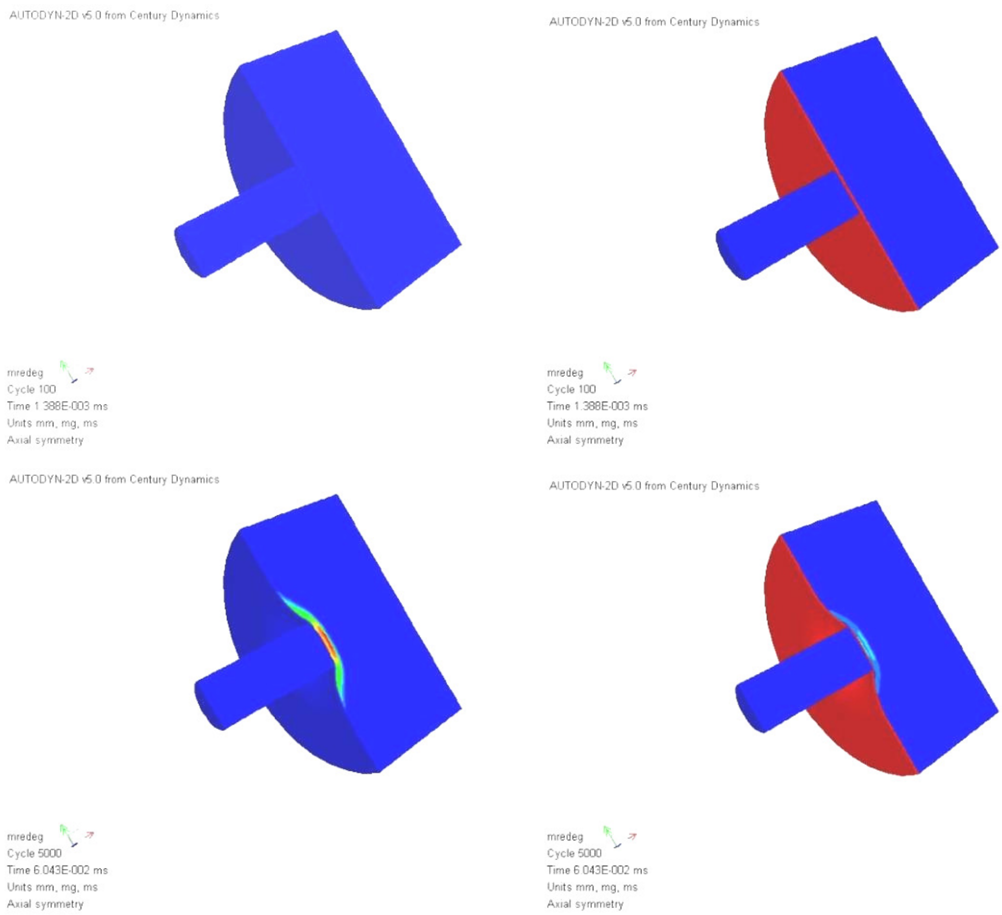
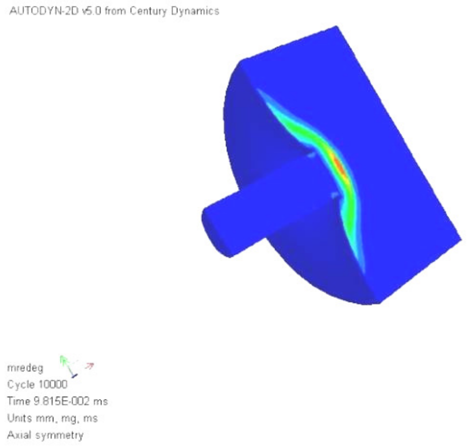


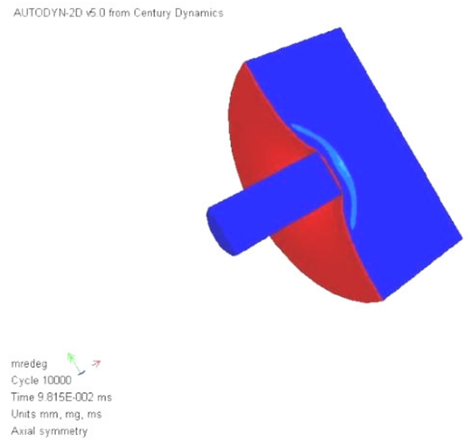
Figure 251: Graph showing the relationship between (Impact Velocity)$^{1.4}$ x mass per unit area and penetration velocity

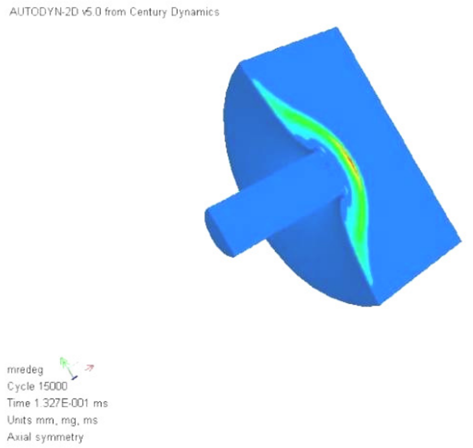
This relationship is very similar to that identified during a very large study undertaken in the USA during the 1950's and 1960's **[61]** to identify the incapacitating effect of steel fragments and flechettes. This study was based on live firings against goats and gelatine and from wounds received by servicemen in the Korean War. That relationship is proportion of incapacitation is ∞ (impact velocity)$^{1.5}$ x mass/area. This relationship has become the standard as used by NATO for the calculation of incapacitation by fragmenting munitions.

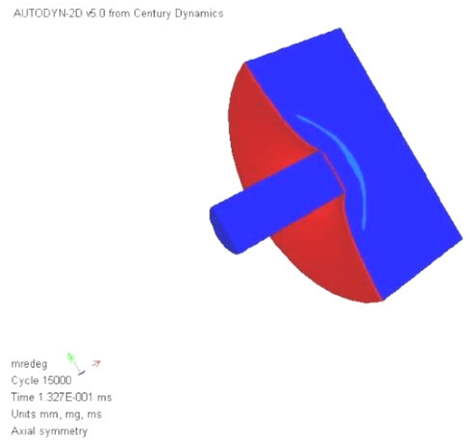
The Figures below show a sample impact that rebounds without any penetration. It is possible to see the shockwave generated by the impact in the left hand column whilst the right shows the changes in density of the target. The "skin" is significantly denser because it is made of steel in this model. It should be noted that the condition was set that the skin was attached to the gelatine.

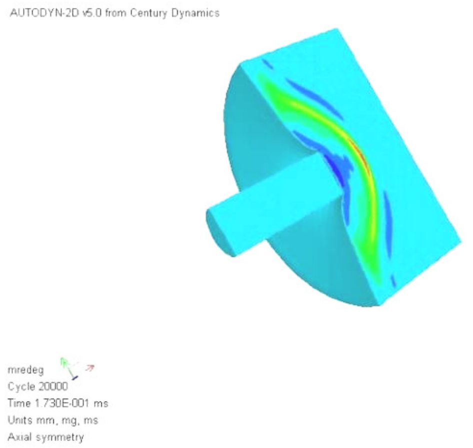



AUTODYN-2D v5.0 from Century Dynamics
mredeg
Cycle 10000
Time 9.815E-002 ms
Units mm, mg, ms
Axial symmetry


AUTODYN-2D v5.0 from Century Dynamics
mredeg
Cycle 10000
Time 9.815E-002 ms
Units mm, mg, ms
Axial symmetry


AUTODYN-2D v5.0 from Century Dynamics
mredeg
Cycle 15000
Time 1.327E-001 ms
Units mm, mg, ms
Axial symmetry


AUTODYN-2D v5.0 from Century Dynamics
mredeg
Cycle 15000
Time 1.327E-001 ms
Units mm, mg, ms
Axial symmetry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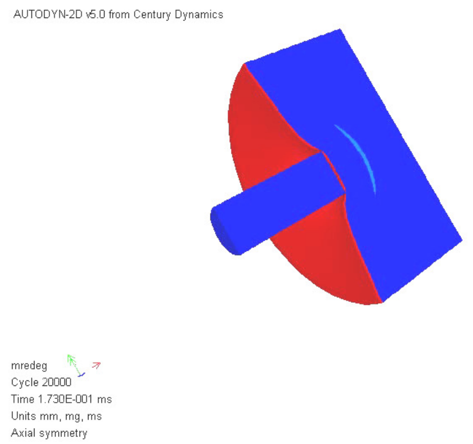
mredeg
Cycle 20000
Time 1.730E-001 ms
Units mm, mg, ms
Axial symmetry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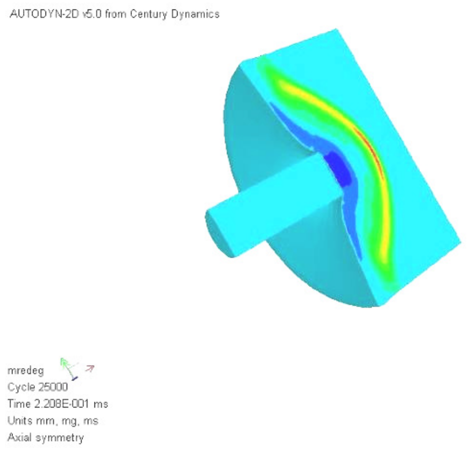
Axial symmetry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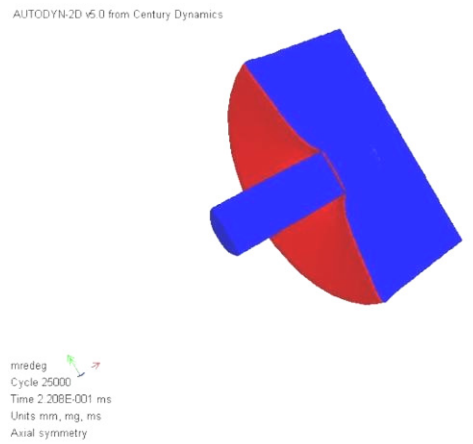
Units mm, mg, ms
Axial symmetry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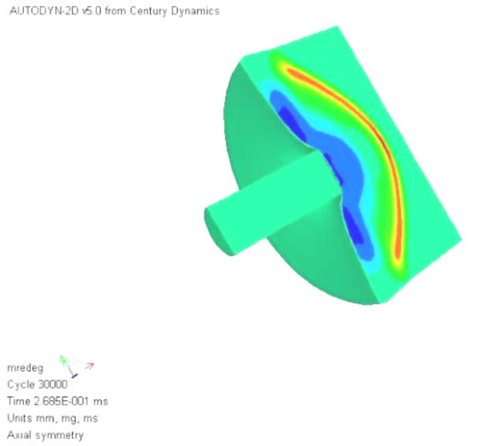
Units mm, mg, ms
Axial symmetry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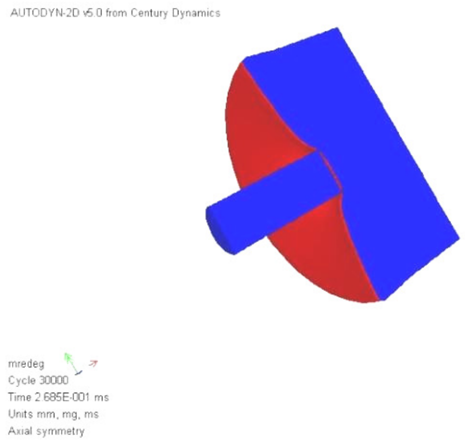
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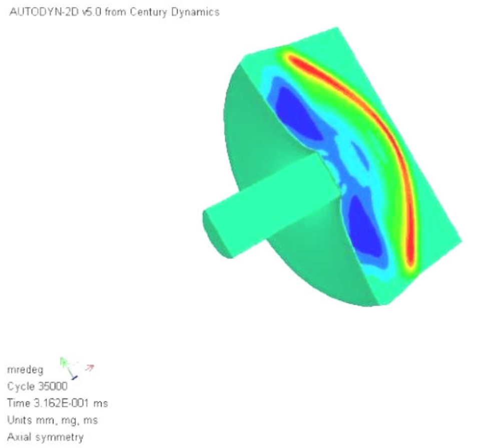
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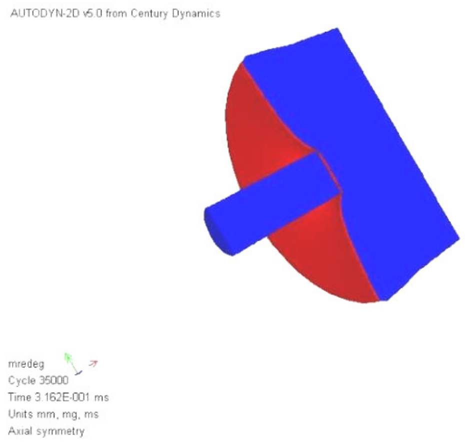
Units mm, mg, ms
Axial symmetry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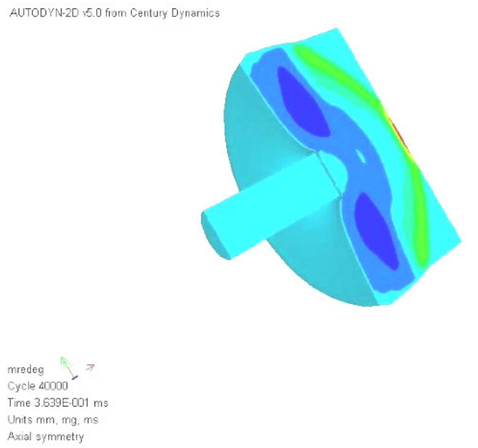
Units mm, mg, ms
Axial symmetry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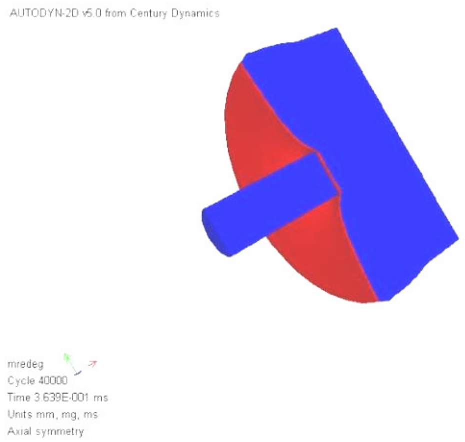
Units mm, mg, ms
Axial symmetry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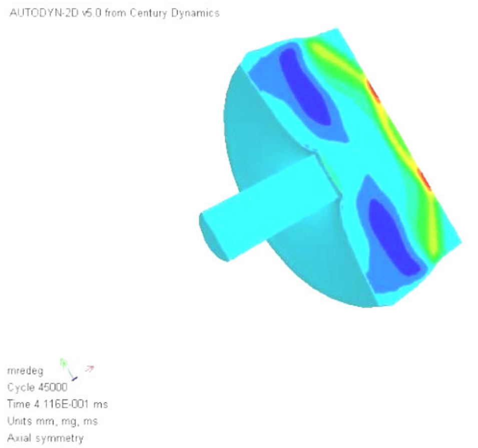
Units mm, mg, ms
Axial symmetry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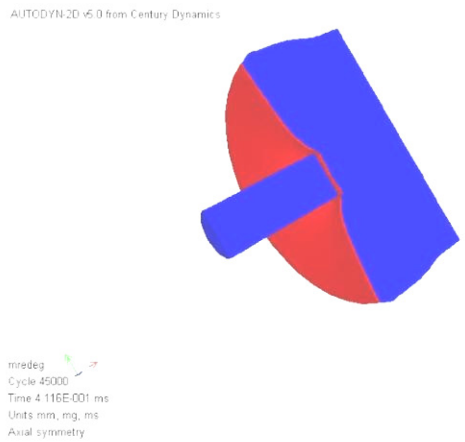
Units mm, mg, ms
Axial symmetry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Units mm, mg, ms
Axial symmetry

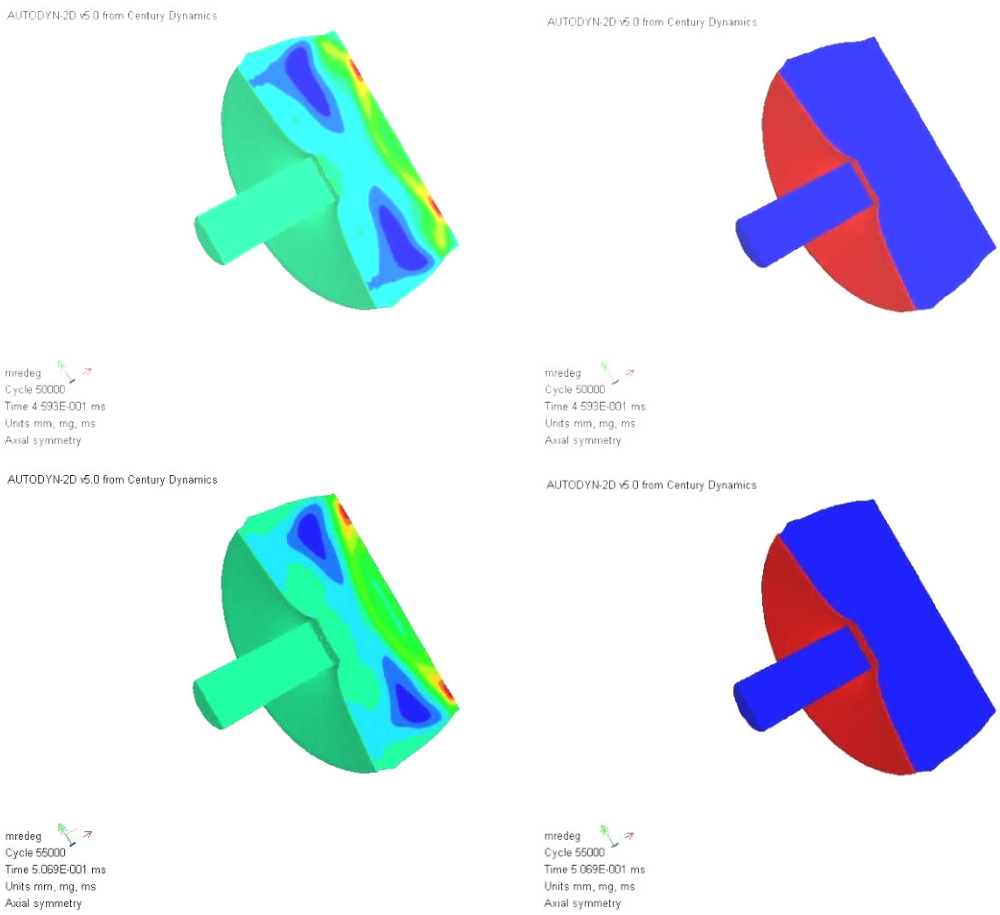


Figure 252: Hydro code impact showing the shockwave vs density change

It can be seen that the density of the target around the impact zone increases as the material is subjected to compression from the impact of the projectile. What is of interest though is that there is a large shockwave generated by the projectile that is transferred into the target as described by Grimal. This shockwave is what is thought to cause the most damage when the projectile hits the skull. If the victim is killed there will be no evidence of bruising because bruising only occurs in living tissue. If the victim survives then bruising is difficult to observe inside the skull. However, there is evidence that bruising deep into the brain does occur. A shooting incident occurred where the victim suffered a penetrating wound to the top of the skull by a high velocity projectile causing laceration of the outermost surface of the brain. This would have caused a compression wave to pass deep into the brain. The victim survived for a few hours after the incident. At the autopsy it was observed that bruising of the brain tissue had occurred and extended deep into the white matter.

Tranquilliser darts produce a small penetrating injury from the needle attached to the front of the dart. The impact of the tranquilliser dart with needle was modelled to investigate how this affected the impact process. The following images show an impact of a tranquilliser dart with modelled needle impacting the simulated target.

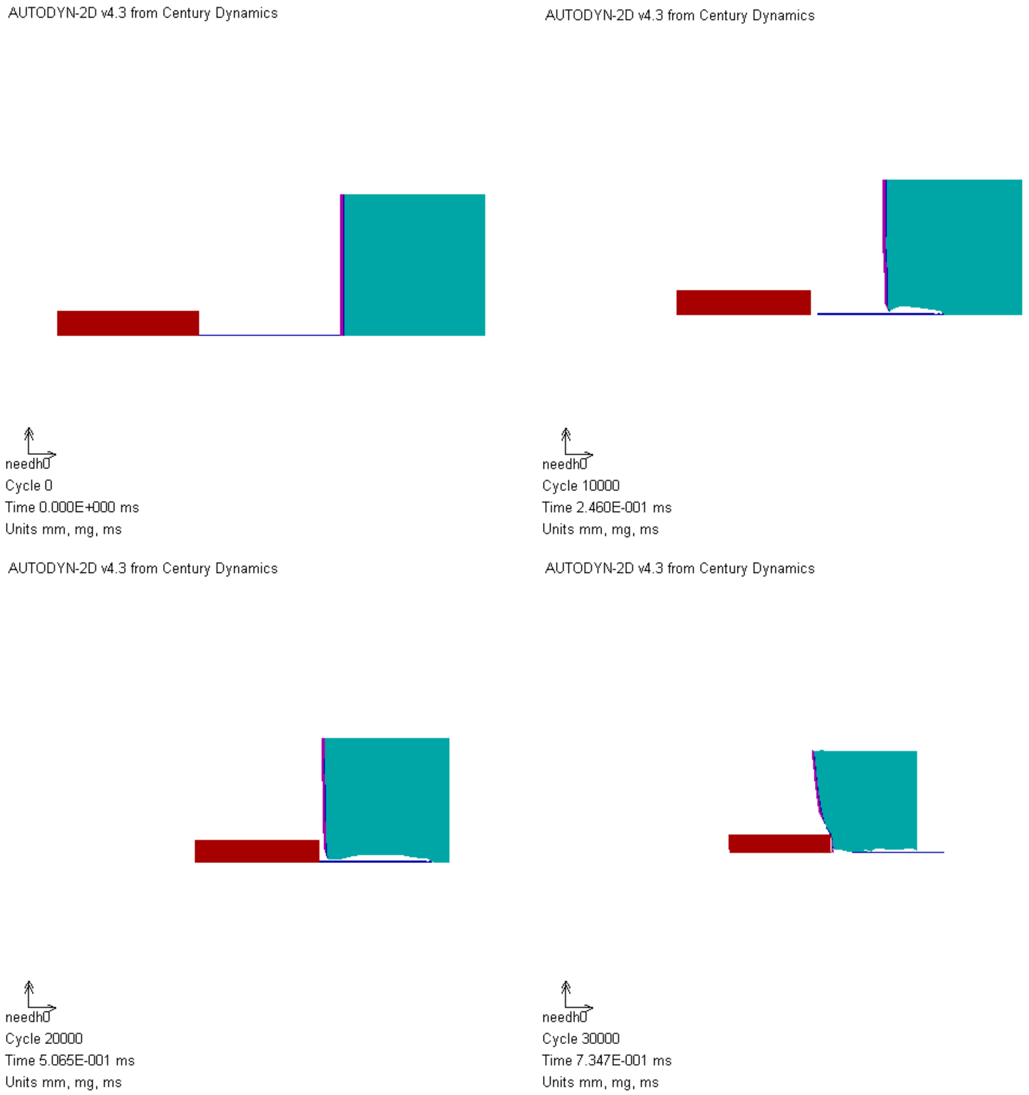


Figure 253: Hydro code impact with modelled needle

The projectile behaves realistically compared to the actual firings against a cow carcass; in these the needle would become detached from the dart body and penetrate the target whilst the dart body would rebound. From the images, it is also possible to see the temporary wound cavity being formed by the passage of the needle through the target, which has begun to close as the needle moves past.

For validation purposes it is not possible to attach the thin steel sheet to the gelatine. It was therefore necessary to model the impact with out setting the condition for the skin to be attached to the gelatine. The next images show the tested model when the front skin is not attached via boundary conditions to the actual target material.

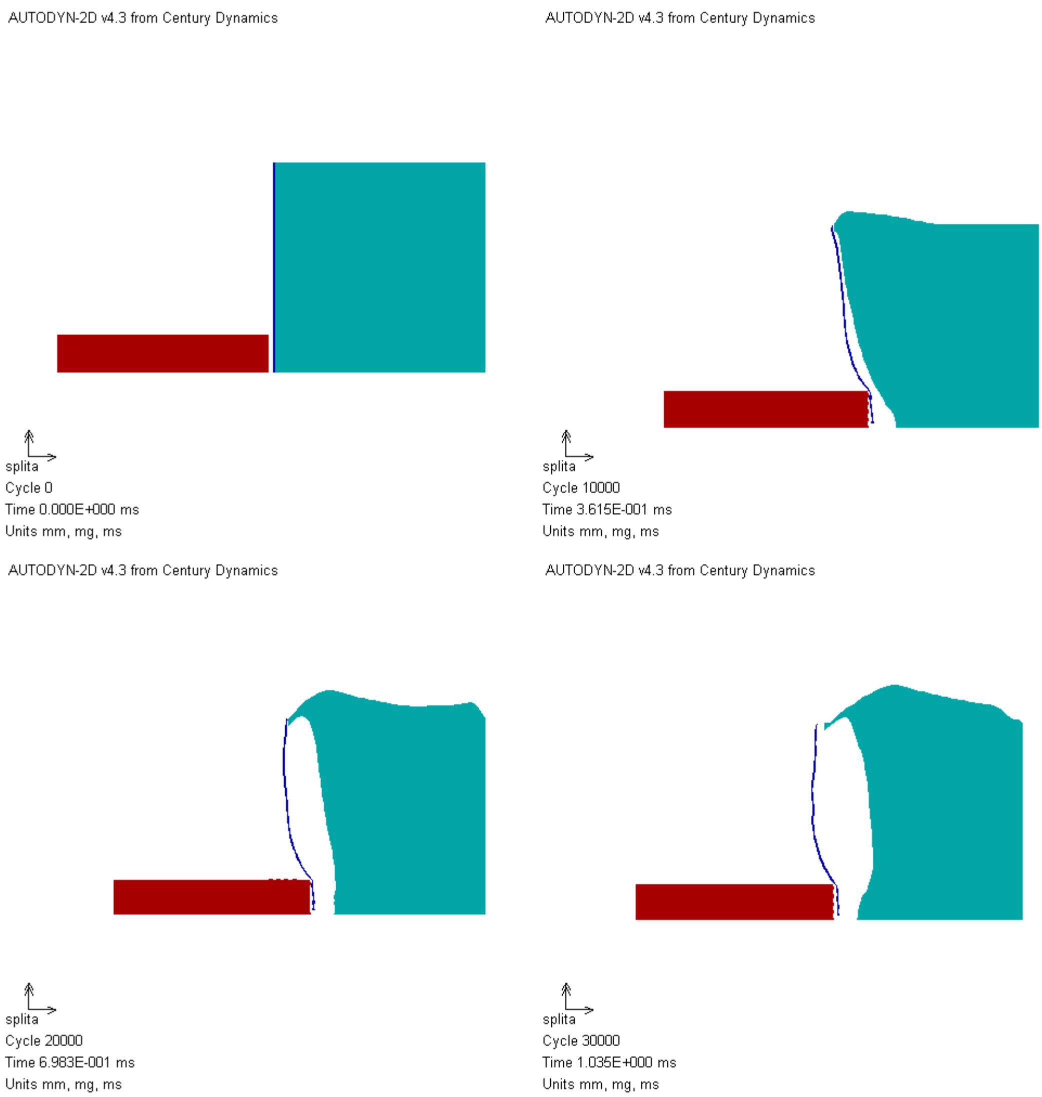


Figure 254 Hydro code impact with unfixed skin

It can be seen that the skin is forced away from the target by the impact whilst causing deformations to both it and the target backing. The skin is quite heavily deformed by the impact and the backing does eventually return to its original position.

7.5 Model Validation

To validate the hydro code model it was necessary to create an experiment model using the variables set in AutoDyn using Gelatine, thin sheet steel matching the model and a polycarbonate projectile fired at a range of velocities. The projectile was fired using a smooth bore shotgun from a range of 10 metres into the assembled and restrained target. This was then photographed and marked as penetrating or non-penetrating, no other injuries were considered at this stage.

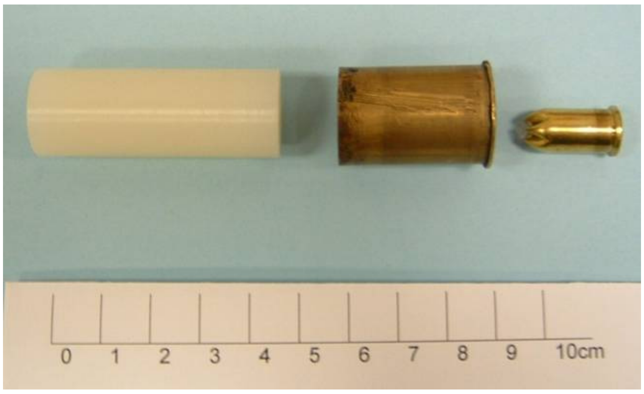


Figure 255: Projectile, Breech Adaptor and .357" blank cartridge

The projectiles were 18mm diameter and 50mm long and 25grams in weight. They were fired from a standard shotgun. An adaptor was made, shown above in Figure 255 that was machined from brass that had the same dimensions as a standard shotgun cartridge. The end was bored out to accept a .357" magnum blank cartridge that fitted into the base of the base of the brass adaptor. The other end of the brass adaptor was hollowed out slightly and lipped to accept the projectile which was gently gripped by the interference fit, tight enough to stop the projectile falling along the barrel but lose enough not to stop it from being released on firing. A full AutoCAD drawing of the adaptor can be found in the appendix. After firing, the used .357" blank can be pushed from the adaptor and a new one inserted.

7.5.1 Velocity measurement

Both Doppler radar and photo chronographs were used to measure the projectile velocity. The Doppler radar uses microwave radiation at a low power (approx 5 watts.) It projects a beam of microwaves that are reflected off of the projectile which are reflected are returned at a different frequency. The computer uses this difference in frequency to calculate the velocity of the projectile. This is displayed as a waterfall plot on a visual display unit (VDU).

Photo chronographs use a light detector to measure the light between it and a light source. There are several of these detectors along the length of the range at a set distance apart. As the projectile passes over a detector reduces the amount of light falling on it that in turn starts a timer. When the projectile passes over the next detector the timer is stopped. The average velocity of the projectile between two sensors is calculated from the time between starting and stopping the timer and the distance between the two sensors.

7.5.2 Velocity Control

The propellant used in the .357" magnum blank cartridge cases was Alliant Green Dot propellant. Different launch velocities were achieved by using different quantities of propellant. The different launch velocities that were achieved for different quantities of propellant are shown in Table 12.

Mass of Green Dot Propellant	Average Launch Velocity
0.225 g	200 ms^{-1}
0.20 g	190 ms^{-1}
0.175 g	160 ms^{-1}

Table 12: Details of the different launch velocities achieved for the Ecovet projectile for different quantities of Alliant Green Dot propellant.

Three targets were constructed to validate the AutoDyn hydro code model:

1mm steel sheet with gelatine backing
0.55mm thick Steel sheet with gelatine backing
0.25mm thick Steel shim plate with gelatine backing

The gelatine was held in a thin plastic container (not modelled in AutoDyn hydro code) to allow it to be mounted on the target stand. The Steel plate was taped to the container and a steel-mounting frame, which was bolted to the range floor ten metres from the muzzle.

The results from the AutoDyn model predicted that the 1mm thick steel plate would be penetrated at 200ms^{-1}, dented at 150ms^{-1} and suffer no serious damage at 100ms^{-1}

From the results, it was possible to see that at 170ms^{-1} the projectile passed through the 1mm thick steel plate causing it to peel back as shown in Figure 257. At 160ms^{-1} no penetration occurred. When using the thinner steel "skins" penetration occurred at all velocities from 120ms^{-1} and above which are values lower than those predicted by the hydro code model.

Figure 256 to Figure 258 below show the impact with the steel front sheet for three different velocities.

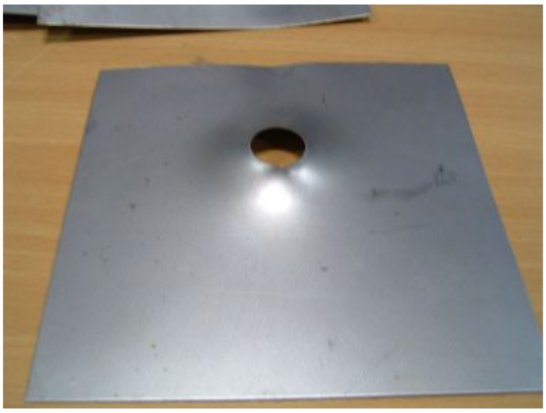


Figure 256: 200ms^{-1} impact against 1mmthick plate.

Figure 257: 170ms^{-1} impact against 1mm thick plate

Figure 258: 160ms^{-1} impacts against 1mm thick plate

7.6 Discussion

The Computer modelling has considerable potential. However, this potential is limited by the lack of data on the mechanical properties of the biological materials used. It would be possible to find more properties for gelatine through testing utilising ultrasonic's to measure the Young's Modulus. This could then be used in the hydro codes material library. Additionally more work needs to be done to investigate the mechanical properties of chamois leather as described and used by Bir et al **[12]**; which would allow their model to be fully replicated by the hydro code.

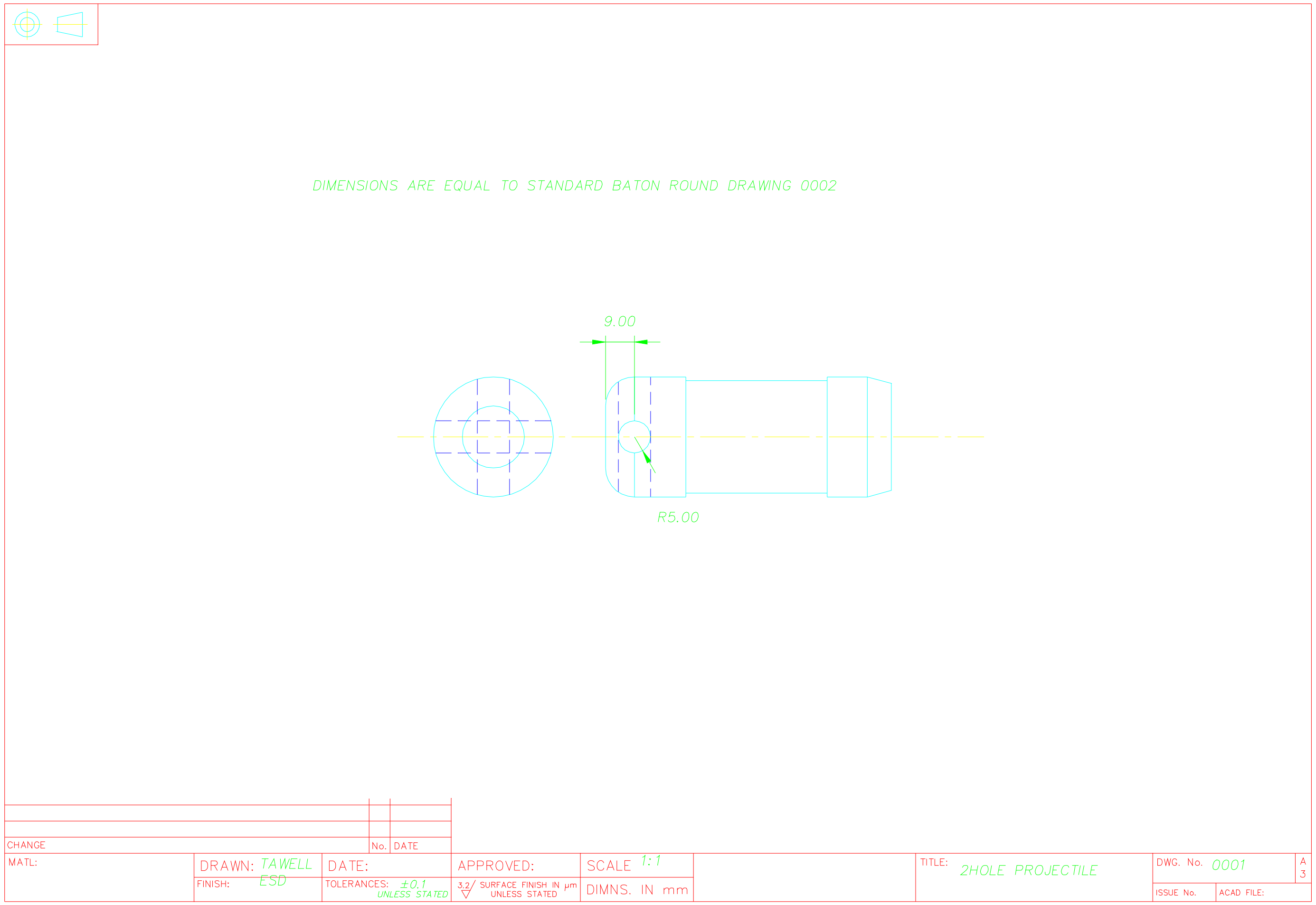
One of the main problems encountered with the hydro code modelling is that, whilst it was possible to generate accurate results for one setup (projectile mass, velocity and target configuration), if one of the variables was changed significantly then the model would produce erroneous results. This is likely linked to the incomplete mechanical properties mentioned above but also with the chosen equation of strength, whilst a number of the EoS models were suitable and produced valid results it is entirely possible that as you change certain variables the results will begin to differ wildly, it was beyond the scope of this work to fully investigate all the suitable EoS models.

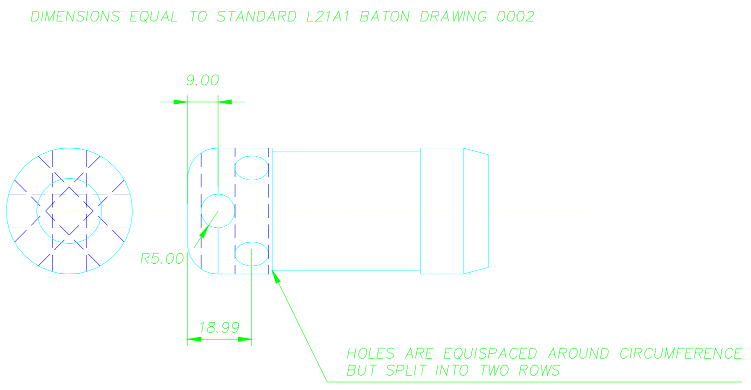
Chapter 8 Appendix 2

8.1 Notation

Sg	Stability Factor
E	Modulus of Elasticity
F	Axial Force
I	Impulse
Tc	Time of contact
KE	Kinetic Energy
KED	Kinetic Energy Density
Vo	Impact velocity
Vf	Rebound velocity
L	Length of projectile
M	Mass of projectile
SEP	Sharp Edged Projectile
BABT	Behind Armour Blunt Trauma
D	Diameter of projectiles cross section
T	Time
Um	Maximum compression
ν	Poissons ratio
$\rho 0$	Density of projectile
σ	Stress
Fc	Contact Force
Fp	Peak contact force

8.2 AutoCAD drawings





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	FINISH: ESD	TOLERANCES: ±0.1 UNLESS STATED	3.2 SURFACE FINISH IN μm UNLESS STATED	DIMNS. IN mm		ISSUE No.	ACAD FILE:

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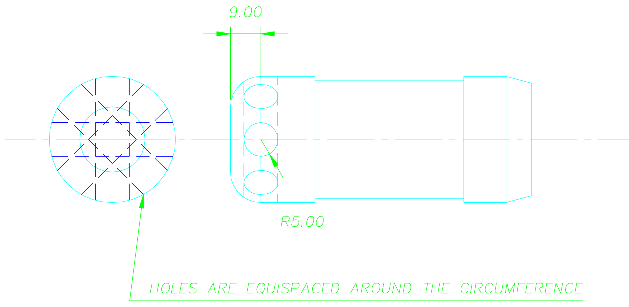

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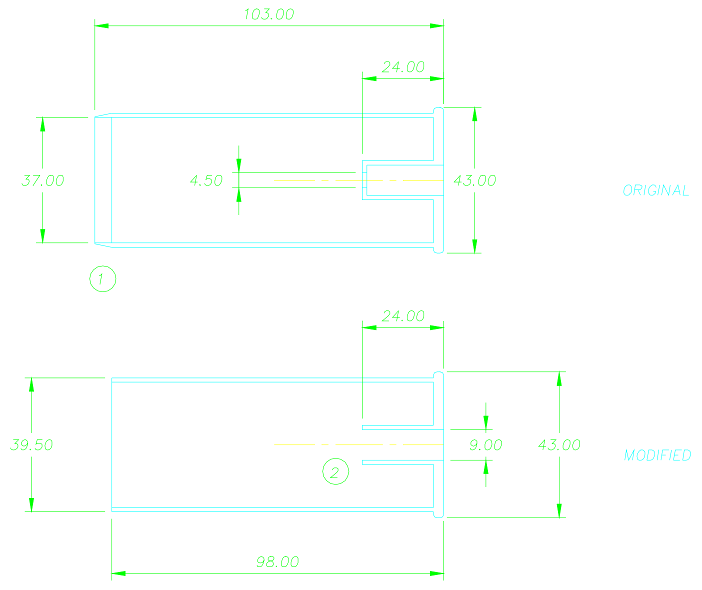
A3



CHANGE | No. | DATE

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DRAWN: TAWELL

FINISH: ESD

DATE:

TOLERANCES: ±0.1 UNLESS STATED

APPROVED:

3.2 SURFACE FINISH IN μm UNLESS STATED

SCALE 1:1

DIMNS. IN mm

TITLE: 37mm MOD

DWG. No. 0001

A3

ISSUE No.

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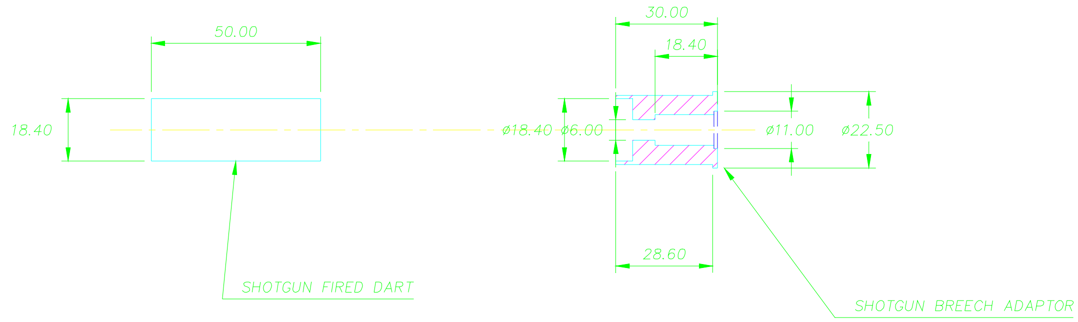

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FINISH: | TOLERANCES: ±0.1 UNLESS STATED | 3.2 SURFACE FINISH IN μm UNLESS STATED | DIMNS. IN mm

TITLE: BREECH ADAPTOR

DWG. No. 0001 | A3

ISSUE No. | ACAD FILE:

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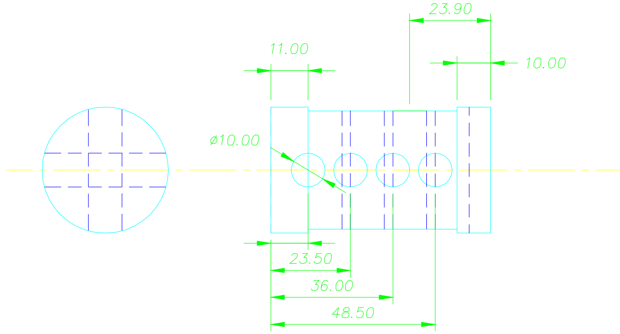

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MATL:

DRAWN: TAWELL

FINISH: ESD

DATE:

TOLERANCES: ±0.1 UNLESS STATED

APPROVED:

3.2 SURFACE FINISH IN μm UNLESS STATED

SCALE 1:1

DIMNS. IN mm

TITLE: CUTDOWN PROJECTILE

DWG. No. 0009

A3

ISSUE No.

ACAD FILE:

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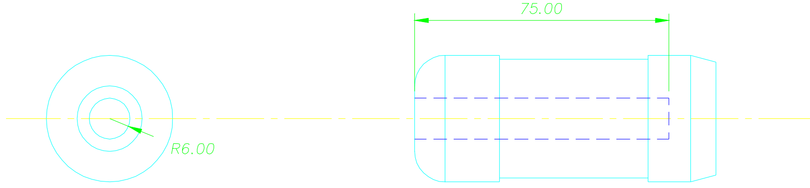

CHANGE	No.	DATE

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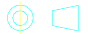

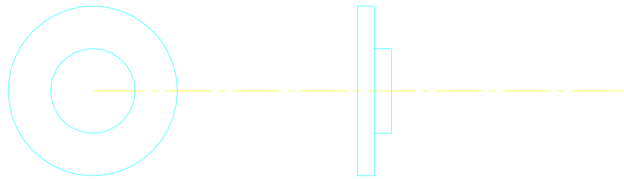

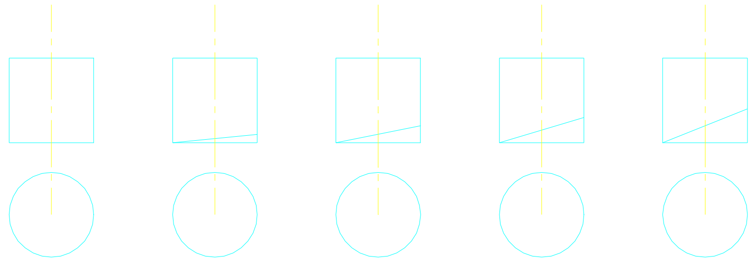

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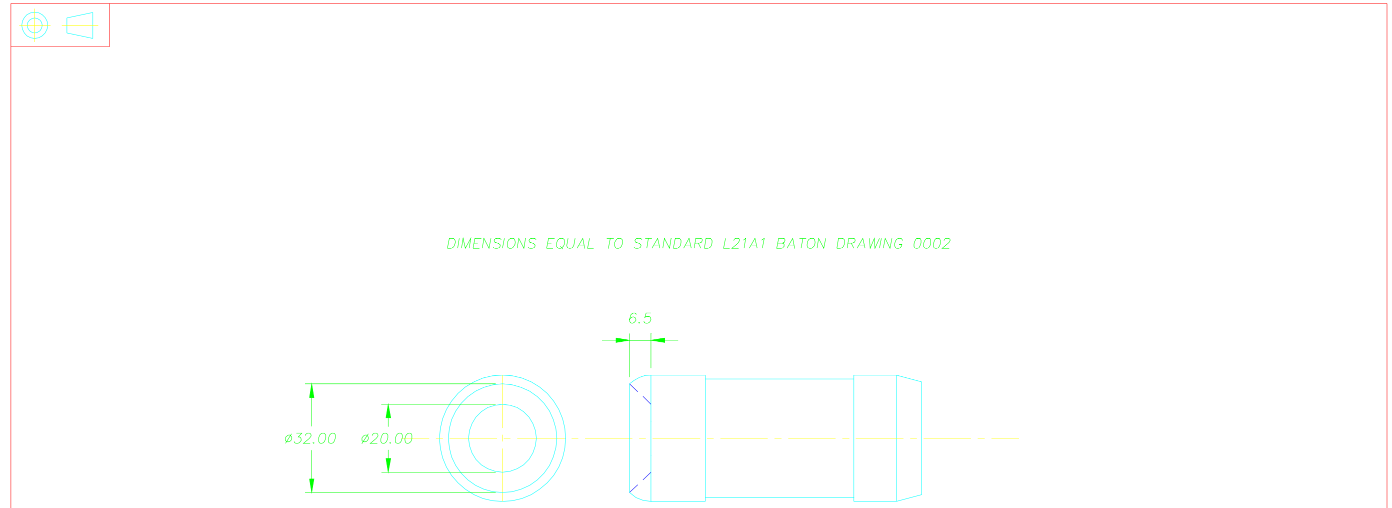

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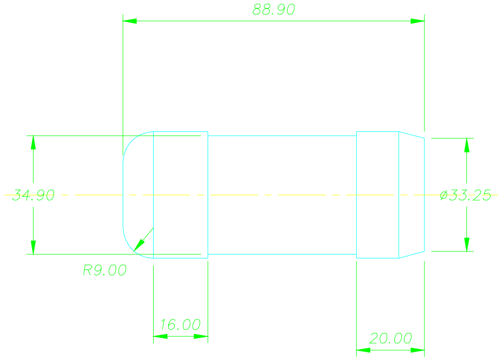
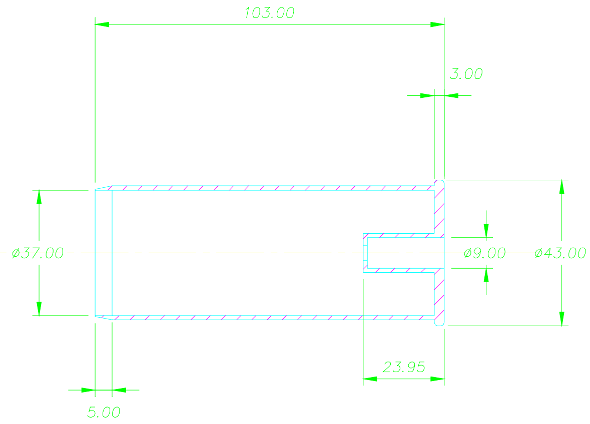


STANDARD L21A1 BATON ROUND



37MM CASING SECTION VIEW

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FINISH: ESD

DATE:
TOLERANCES: ±0.1 UNLESS STATED

APPROVED:
3.2 SURFACE FINISH IN μm UNLESS STATED

SCALE 1:1
DIMNS. IN mm

TITLE: STANDARD L21A1 BATON AND CASING

DWG. No. 0002
A3
ISSUE No.
ACAD FILE:

8.3 ACPO Guidelines for use of baton rounds

ASSOCIATION OF CHIEF POLICE OFFICERS (ACPO)

GUIDELINES ON THE USE OF BATON ROUNDS AND FIREARMS IN SITUATIONS OF SERIOUS PUBLIC DISORDER

INTRODUCTION

Responsibility for setting the policy as to weapons and equipment which may be used in any force area rests with the chief officer of police. Where this equipment includes baton rounds and/or CS munitions for use in public order situations, the chief officer may delegate authority for the deployment of this equipment to an officer of Assistant Chief Constable/Commander rank. Such delegated authority may be for a specified time period, or within a specific geographical location or for a particular operation.

Public disorder includes a wide spectrum of unlawful activity which at the upper level may include serious rioting. In these situations conventional public order policing responses may have been tried and failed; and taking account of the level of violence and risk to officers, be considered no longer appropriate. Where on the basis of risk assessment of existing intelligence it is believed that serious rioting would involve a risk of loss of life, serious injury or significant damage to property, an officer of Assistant Chief Constable/Commander rank may, with the prior agreement of the chief officer or police, deploy officers who are trained in the use of baton rounds and/or suitable CS munitions as a less than lethal contingency in dealing with serious disorder. In addition where there is reason to believe that lethal weapons may be used it will be appropriate to consider the deployment of specially trained officers armed with convention firearms. These instructions should be read in conjunction with the Police Health and Safety Manual, Volume Three Appendix A.

The use of baton rounds can cause serious injuries. Use of baton rounds in Northern Ireland between 1974 and 1989 regrettably resulted in a number of deaths. The weapon system and baton rounds currently in use are of a significantly different design. However, as with all applications of force, there remains a potential for unintended serious and even fatal injury. The design and use of baton rounds is therefore subject to strict criteria. They may only be used as part of the common weapon system approved for use by members of the police service of HM forces in the United Kingdom. These revised guidelines take account of the continuing developments in the weapon system, baton round design criteria, command, control and training, all of which is designed to reduce the potential for serious and life threatening injuries. Nothing in these guidelines should be construed so as to constrain the police serious in its fundamental responsibility to save life, protect property and maintain the peace. Police officers shall at all times fulfil the duty imposed on them by law, by serving the community and by protecting all persons against illegal acts, consistent with the high degree of responsibility required by their profession. In discharging their duties police officers will be cognisant of the provisions of the UN Code of Conduct for Law Enforcement Officers and of their obligations to uphold human rights.

This document provides guidelines in responding to these levels of threat and on the use of baton rounds.

The deployment of specialist firearms teams in situations of public disorder must be closely co-ordinated and gives rise to specific command and control issues. For this reason specialist firearms resources should not be deployed without the express authority of an officer of at least Assistant Chief Constable rank.

Baton rounds are designed to prove a less than lethal option in dealing with threats of serious violence and provide an effective means by which rioters armed with petrol bombs or other weapons can be kept at a distance, contained or dispersed. They also provide a means of keeping at a safe distance those posing a serious threat to life which would otherwise require the intervention of officers at close quarters, and thus potentially placing them at great risk.

Baton rounds should only be used:

Where other methods of policing to restore or sustain public order have been tried and failed, or must from the nature of the circumstances be unlikely to succeed if tried

And

Where their use is judged to be necessary to reduce a serious risk of:

Loss of life or serious injury; or

Substantial and serious damage to property where there is or is judged to be a sufficiently serious risk of loss of life or serious injury to justify their use.

In assessing the risk of loss of life or serious injury occurring, account should be taken of the risks to police officers and members of the emergency services as well as to members of the public and others.

Use of Force: Legal Provisions

Nothing in these guidelines affects the legal principles pertaining to the use of reasonable force as provided for under:

The common law duty to preserve the peace

The common law rules of self-defence

The Police and Criminal Evidence Act 1984 sec 117

And

The Criminal Law Act 1967 sec 3 which states:

"A person may use such force as is reasonable in the circumstances in the prevention of crime, or in effecting or assisting in the lawful arrest of offenders or suspected offenders or of persons unlawfully at large".

The reasonableness of individual action will be subject to the combined tests of necessity and proportionality; in that, the objective cannot be achieved by a lesser degree of force and threat the injury or harm to be prevented is greater than the harm which is likely to be caused by the firing of a baton round.

Conditions of Use

Only baton rounds and baton guns of a type authorised by the Home Office may be used. Details of the approved equipment is included in the ACPO police user manual.

Baton guns are not to be loaded unless their use is imminent.

Baton gun commanders, in charge of tactical formations which contain baton gunners, will be responsible for giving directions to baton gunners including instructions to load and unload, authority to fire and directions to cease firing.

Warnings

Unless circumstances do not permit, baton rounds are to be fired only after an oral warning, for example by means of a load hailer or PA system, has been given to the crowd to disperse. The warning should make clear that, unless the rioting stops or the crowd disperses, baton rounds will be used without further warning. A record is to be kept of the words used in giving the warning. The following words should be used whenever possible:-

"Attention, attention, this is a police message. Unless you stop rioting immediately, baton rounds will (again) be fired. No further warnings will be given".
Baton rounds should be fired at selected individuals and not indiscriminately at the crowd. Baton rounds should be aimed to strike directly (ie without bouncing) the lower part of the target's body ie below the rib cage.

Unless there is a serious and immediate risk to life which cannot otherwise be countered use at under 20 metres or aiming the weapon to strike a higher part of the body is prohibited. In these circumstances the risk of serious and even fatal injuries is significantly increased and the firer must be able to justify the increased use of force.

Steps are to be taken to ensure that medical attention is provided at the earliest opportunity for any casualties.

When possible, baton rounds should be recovered.

Baton gunners may be deployed on foot or in specially adapted protected vehicles from which baton rounds may be fired. Baton rounds should not be fired from moving vehicles. Tactical formations will differ dependant on the local circumstances and resources of a particular force.

Reports

Baton gunners must complete reports pertaining to the reason for firing baton rounds and information about the outcome and number of rounds fired. The record should also list any known injuries that may have occurred as a result of using baton rounds.

In England and Wales the chief officer should supply to the Home Secretary a written report on the circumstances surrounding the firing of baton rounds as soon as possible after the incident.

PRE PLANNED OPERATIONS

In situations where serious public disorder is anticipated an officer of Assistant Chief Constable/Commander rank may, with the prior agreement of the chief officer of police, give authority for the deployment of officers trained and equipped with baton guns.

Command and Control

Police and command decisions in respect of the issue, deployment and use of baton rounds should be subject to continuous critical review during the lifetime of any incident. The officer in overall command of the incident (the Gold Commander) should ensure formal review and documentation of the requirement for baton guns as the disorder enters each new phase.

Authority for use

Before a decision to use baton rounds is put into effect, a designated senior officer, will by virtue of an on the ground assessment, confirm that the situation is sufficiently serious to justify the use of baton rounds, and that the criteria for use continues to be met. Except where urgent action is necessary, in circumstances where there is an immediate risk to life, baton rounds will only be used following authorisation by the Silver Commander.

Designated senior officers (DSO's) will be drawn from the Superintending and Inspecting ranks and will be fully trained for the role by virtue of a course approved nationally by the Association of Chief Police Officers. DSO's will have a detailed understanding of public order tactics and the ACPO guidelines governing the use of baton guns. The designated senior officer, will ensure that effective processes are in place for direction and control of baton gun commanders and baton gunners who have been specifically trained in the use of the equipment and know its characteristics.

Strict criteria applicable to the selection and training of baton guns commanders and baton gunners will ensure proficiency with the weaponry, through understanding of the conditions relating to its use, the injury potential and characteristics of baton rounds.

Records

All command decisions in respect of the issue, deployment and authority to use baton rounds should be fully recorded and documented. The DSO will be responsible for documenting the assessment of the situation and rationale pertaining to the decision to recommend the use of baton rounds. In addition baton gun commanders will ensure that a record is maintained of the firing of baton guns and that baton gunners complete reports pertaining to the firing of baton rounds.

SPONTANEOUS DISORDER

Chief Constables must have contingency plans for the availability and deployment of baton rounds in emergency situations. These should provide for the availability and deployment of baton gun resources and establishment of appropriate command structures to enable an effective response to serious spontaneous disorder. As in pre-planned operations an officer of Assistant Chief Constable/Commander rank may, with the prior agreement of the chief officer of police, give authority for the deployment of officers trained and equipped with baton guns. The officer authorising deployment will ensure formal review and documentation of the requirement for baton guns as the disorder enters each new phase.

The contingency plans should provide for the introduction of formalised command and control structures with the minimum of delay however, nothing in these guidelines should be construed so as to be prevent an immediate and effective police response or the firing of baton rounds where their use if necessary. Baton rounds may only be used if the strict criteria set out at paragraph 19.7 is met.

The requirement to deploy officers with baton rounds should be formally reviewed by an officer of at least Assistant Chief Constable rank on a regular basis.

ACPO GUIDELINES

(Reproduced from original / section on training and associated appendices deleted)

GUIDELINES ON THE USE OF THE BATON GUN AS A LESS LETHAL OPTION

<u>Conditions of Use</u>

These guidelines apply to the use of the L21A1 Baton Round in policing operations. The L21A1 Baton Round may only be used in conjunction with the L104A1 Anti-riot gun using the L18A1 optical sight, hereafter referred to as the 'Baton Gun'.

The Baton Gun should be zeroed in accordance with current guidelines (see Appendix A).

The Baton Gun must only be issued to and used by officers who are fully trained in its use, currently authorised and have an understanding of firearms tactics. It is recommended that Forces employ Authorised Firearms Officers in this role.

The deployment of the Baton Gun is intended to provide a less lethal option and should be considered within the terms of the Conflict Management Model. The intention is to control and neutralise the threat without recourse to lethal use of force.

Legal restrictions with respect to the use of force apply, as they do with other tactical options.

Authority for Use

The minimum level of authority for granting the issue of the Baton Gun in situations other than public disorder should be identical with force procedures relating to the issue of conventional firearms.

Deployment

Baton Guns should be available for deployment at the earliest opportunity.

Tactical deployment must include the deployment of additional officers, in possession of conventional firearms, in support of the Baton Gun officers.

Command

The Command structure will be in accordance with current advice contained within the Manual of Guidance on Police use of Firearms with respect to conventional weaponry.

Operational Use

Baton Rounds should be aimed at the belt buckle area so that they strike directly the power part of a subject's body, i.e. below the rib cage.

Unless there is a serious and immediate risk to life, which cannot otherwise be countered, use at under one metre or aiming the weapon to strike a higher part of the body is prohibited. In these circumstances the risk of serious and even fatal injuries is increased and the firer must be able to justify the increased use of force.

Due to the nature of policing, it will never be possible to provide a definitive list of situations in which use of the Baton Gun may be appropriate. However, the Baton Gun is not intended to be a replacement for conventional firearms. It's use may be appropriate where immediate incapacitation is not imperative and the threat faced, at this time, could be controlled and neutralised without recourse to conventional firearms.

Post incident procedure should be in compliance with the current advice contained within the Manual of Guidance.

THE GUIDELINES ON THE RULES OF ENGAGEMENT FOR THE USE OF BATON ROUNDS BY THE ARMED FORCES IN NORTHERN IRELAND

GENERAL

Only to be used on the command of the designated local commander, in situations of potential violent disorder. Its use must be no more than absolutely necessary in the circumstances, and there must be no alternative other than the use of lethal force. Personnel may only use items if they have been fully trained in its use and the application of these ROE.

These ROE do not affect your general right to self-defence. **However in all situations you are to use no more force than absolutely necessary to achieve your aim.**

WARNING

A warning is to be communicated before any items are used, unless to do so would increase the risk of death or grave injury to you or any other person. The commander at the scene or his representative is to give the following warning at the earliest opportunity:

"ATTENTION. UNLESS YOU DISPERSE/STOP, BATON ROUNDS WILL BE USED AGAINST YOU."

Where possible commanders are to order a change in profile for a visible demonstration of intent.

BATON ROUNDS

L21A1 baton rounds may be fired, if authorised by the commander at the scene when absolutely necessary to protect own forces or others under their protection from physical violence. This may include dispersing a violent crowd posing a risk to life by singling out the perceived ringleaders and troublemakers.

Baton rounds are to be fired at selected individuals, not indiscriminately. They are to be aimed so that they should strike directly (i.e. without bouncing) the lower part of the body (i.e. below the ribcage). They are not to be fired at a range of less than 20 metres unless there is an immediate and serious risk of loss of life or serious injury, which cannot otherwise be countered.

MEDICAL ASSISTANCE

Medical assistance is to be provided to casualties as early as possible.

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