



UNITED STATES ARMY AEROMEDICAL RESEARCH LABORATORY

Mechanical Surrogates for Behind Armor Blunt Trauma

Cameron R. 'Dale' Bass

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14. ABSTRACT Across modern conflicts, unprotected fatal wounds occur principally in the torso because this body region has a larger cross-sectional area and contains more vital organs than other body region. The largest threats for Warfighters and law enforcement personnel are from shrapnel and projectiles of higher energy and velocity than anticipated 53 years ago when the National Institute of Justice worked to standardize body armor. Modern body armor can defeat incoming pistol and rifle rounds by trading energy and momentum deposition into the armor for armor deformation. This deformation includes direct body armor deformation in soft body armor and deformation with fracture in hard body armor. This deformation in soft and hard body armor has the potential to create injuries behind the armor in the thorax that may be generally characterized as blunt trauma. These injuries are often termed behind armor blunt trauma (BABT). Backface deformation of the body armor over the thorax is sufficient to cause local and distant fractures, contusions, and hemorrhages; therefore, thoracic biofidelity is crucial when evaluating body armor. Many experiments have been completed to evaluate body armor protection, forecast realistic injury prediction, and examine the effects of BABT on the wearer.						
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14. Abstract (continued)

The surrogate thorax must respond like a real thorax, or the data collected is meaningless. Some aspects of biofidelity may include rib fractures, lung contusions, and internal organ damage. Biofidelity allows engineers to understand how injuries happen. Over the last 25 years, advanced biofidelic surrogates have started to incorporate innovative materials (e.g., viscoelastic materials, fluid filled bladders, rubber) and technologies (e.g., finite element analysis, 3D printing, pneumatics, embedded sensors). In addition, different chest sizes and stiffnesses have been incorporated to represent the wide range of human bodies. This paper reviews the animal, cadaver, and human surrogates used in the experiments that have contributed to this body of research. The paper focuses of a review of past and present human surrogates, reviews a selection of experiments conducted using biofidelic surrogates, and discusses the resulting data. This knowledge is essential for designing better protective systems and assessing the performance of newly developed materials and designs.

Summary

Modern body armor can defeat incoming pistol and rifle rounds by trading energy and momentum deposition into the armor through backface deformation. While the round is defeated the resulting impact from the armor's rapid deforming into the body has the potential to cause injuries to the thorax that may be generally characterized as blunt trauma. Backface deformation of the body armor over the thorax may be sufficient to cause local and distant fractures of skeletal structures, as well as contusions and hemorrhages to underlying soft tissues and organs. This injury mechanism is commonly referred to as behind armor blunt trauma (BABT). Thoracic response and the resulting injuries caused by the backface deformation of body armor have been studied to assess injury risk and to develop surrogate models that predict injury. The current BABT assessment methodology involves live fire testing of armor systems that are supported by a clay substrate. The residual clay deformation is measured for assessing the armor's performance for BABT protection. However, the clay's deformation response does not represent well the human compressive biofidelity in the thoracic region. To improve BABT injury risk assessments, the thoracic response of the surrogate needs to mimic the human thoracic response in essential ways to be considered "biofidelic."

Over the last 25 years, advanced injury surrogate models have started to incorporate innovative materials (e.g., viscoelastic materials, fluid-filled bladders, rubber) and technologies (e.g., finite element analysis, 3-dimensional printing, pneumatics, embedded sensors) to improve injury risk assessment. In addition, models with different chest sizes and stiffnesses have been developed to represent the wide range of human bodies. This report focuses on a review of past and present human surrogates, reviews a selection of experiments conducted using biofidelic surrogates, and discusses the resulting data. The appendix of this report reviews the animal, cadaver, and other human surrogate models used in the experiments that have contributed to this body of research. This knowledge is essential for designing better protective armor systems and improving the test methodology for assessing the BABT performance of newly developed materiel and armor designs. This report updates information presented in Bass (2017).

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Introduction - Assessment of Available Models for Behind Armor Blunt Trauma (BABT)

The evolution of ballistic body armor in the United States dates from a series of inventions in 1861 when thin steel plates were enclosed in military jacket materials to protect against saber attacks and bullets (Peterson, 1950). Whether or not to use protective armor was a personal choice and depended on cost (\$5 to \$7), weight (2 kilograms [kg]), and the appearance of “unmanliness.” The efficacy of the armor’s protection is unknown. The use of armored vests largely ceased in the U.S. after the American Civil War until the late 1890s when ballistic armor that was protective against handgun rounds appeared (Prat et al., 2010; Bellis, 2021; Oleksiak, 2020). In 1897, Casimir Zeglen publicly demonstrated a newly constructed silk body armor for low-velocity handgun ballistic protection. It is notable that the first test of this armor was completed by firing bullets into Zeglen’s torso (Figure 1). With increases in round velocity and size, personal ballistic protective armor did not reappear in earnest until approximately 60 years later when the U.S. government began to supply law enforcement and public officials with vests made from advanced fiber materials (e.g., Kevlar®) to protect from handgun bullets. The military vests offered increased performance and lower weight than previous designs (Franklyn & Lee, 2017).



Figure 1. This photograph from circa 1897 depicts low-velocity bullets being fired into Casimir Zeglen’s torso during a test of his newly invented silk ballistic protective body armor (Oleksiak, 2020).

Across modern conflicts, unprotected fatal wounds occur principally in the torso due to its larger cross-sectional area compared to other body regions. Other vulnerable body regions, such as the head or extremity arteries, are smaller targets relative to the torso (Holmes, 1952). Since ergonomic constraints (i.e., height, weight, mobility) limit coverage, torso coverage is focused on the spine and mediastinum, the principal targets for ballistic protection. Two major types of personal body armor exist for this ballistic protection, soft and hard. Soft armor is generally designed to protect against shrapnel resulting from explosions and low-velocity, low-energy bullets (e.g., 9-millimeter [mm] or .38 caliber). Typical soft deformation profiles may include substantial areas of local deformation, often called “penciling” (Bass et al., 2006; Carr & Lewis, 2014). Hard armor or bulletproof vests contain an additional hard plate made of polyethylene or ceramic material that is used to defeat high-velocity threats such as 7.62 mm (.30 caliber) and 12.7 mm (.50 caliber) rifle bullets. For this class of threat, a low radius of curvature generally causes penetration in hard armor systems (Bass et al., 2006). The original work to standardize body armor focused on soft armor (National Institute of Justice [NIJ], 1972). Currently, the threats for Warfighters and law enforcement personnel are from shrapnel and projectiles of higher energy and velocity than anticipated 54 years ago.

Modern body armor can defeat incoming pistol and rifle rounds by trading energy and momentum deposition into the armor for armor deformation. This deformation includes direct body armor deformation in soft body armor and deformation with fracture in hard body armor. Regardless of armor type, this deformation has the potential to create injuries behind the armor in the thorax that may be characterized as blunt trauma. These injuries are termed behind armor blunt trauma (BABT).

Backface deformation of the body armor over the thorax is sufficient to cause local and distant fractures, contusions, and hemorrhages. These injuries have been demonstrated in numerous animal studies (Prather et al., 1977; Clare et al., 1975; Cooper et al., 1982; Suneson et al., 1987; Lidén et al., 1988; Knudsen & Gøtze, 1997; Sarron et al., 2000; Mayorga & North Atlantic Treaty Organization (NATO), 2010). The injuries result from transferring a stress wave through the thorax and the physical backface deformation of the armor. One key unknown about BABT is the extent to which there may be significant injury to organs more distant from the point of impact, such as the brain, heart, spinal cord, and gut, due to significant pressure waves that occur when the deforming armor’s backface impacts the body.

The injury risk for BABT generally depends on the type and configuration of armor, the round, and the energy of the round delivered, which results in an impact displacement and profile. This impact displacement and profile also depend on the physical characteristics of the person wearing the body armor. For both the body armor and the thorax, the impact location is important, and for the thorax, the effect of the sensitivity of the impact rate may be large.

The details of BABT arise from bullet impingement on body armor. A bullet can be seen in engineering terms as a localized energy source that can cause high local compression and shear forces, penetrating protective layers. The most effective bullets deposit energy/shear/momentum rapidly in the target. One general strategy for protection is to blunt the penetration of the incoming round, picking up as much mass as possible in the body armor while depositing the round’s energy and increasing its contact area. Consequently, the protective effect of any ballistic protective vest is provided by increasing the area of impact, thus transferring

energy and momentum to the vest and spreading the impact energy over a longer time. However, the effective transfer of large amounts of energy and momentum from the incoming round into the body armor generally causes some deformation of the rear or backface of the body armor.

The BABT deformation is generally larger under soft body armor than hard body armor for a given incoming round. An interesting comparison of energy and momentum scales may be seen by comparing the characteristics of various rounds as shown in Table 1. A high degree of variability exists between the muzzle velocity (measured in meters per second [m/s]), mass (measured in grams [g]), muzzle energy (measured in kilojoules [kJ]), and muzzle momentum (measured in kilogram-meters per second [kg·m/s]). The 5.56 by 45 M193 ball has the highest muzzle velocity at 991 m/s, but the .50 caliber round has a much higher mass, muzzle energy, and muzzle momentum than the other rounds. Energy varies by a factor of over 30 between the relatively slow 9 mm full metal jacket (FMJ) handgun round and the .50 caliber M2 rifle round (National Academies of Sciences, Engineering, and Medicine, 2012).

Table 1. Typical Muzzle Parameters – Various Rifle and Handgun Rounds

Round	Muzzle Velocity (m/s)	Mass (g)	Muzzle Energy (kJ)	Muzzle Momentum (kg·m/s)
9 mm FMJ	358	8	0.5	2.86
5.56 x 45 M193 ball	991	3.6	1.7	3.57
7.62 x 51 NATO ball	838	9.6	3.4	8.13
.50 caliber	890	42	16.6	37.4

Modified from Ness (2011) with permission from The National Academies Press.

A further elucidative comparison may be made between the impact energy and momentum scales of low-rate blunt trauma events such as automobile impacts and high-rate ballistic impact events. The energy and momentum for various potential blunt trauma situations are shown in Table 2 and are plotted in Figure 2. Nonpenetrating ballistic impact involves much lower total momentum transfer than typical low-rate blunt impact. However, energy transfer is comparable, depending on the action and impact velocity. This implies an increased localization of energy transfer, a shorter interaction time, and a likely increased localization of injury in ballistic threats. Given an increased localization of the input energy, more energy/momentum may be deposited locally in the body producing BABT.

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Table 2. Energy/Momentum – Various Typical Thoracic Trauma Situations

Action	Impact Velocity (m/s)	Mass (g)	Energy (kJ)	Momentum (kg·m/s)
U.S. football block	5	100,000	2.5	500
Automobile thoracic dash impact	5	50,000	0.6	250
Automobile head impact	5	5,000	0.06	25
Blast	~300	N/A	0.0004*	0.0013
Ultrasound damage	~1,500	N/A	0.00001**	6.7×10^{-6}

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(N/A – Not Applicable).

*Based on assumed total lung volume of 3,000 milliliters (mL)

**Based on applied lung volume of 300 mL

Note 1. Velocities for blast and ultrasound damage are approximated (~).

Note 2. There is no mass related to blast or ultrasound.

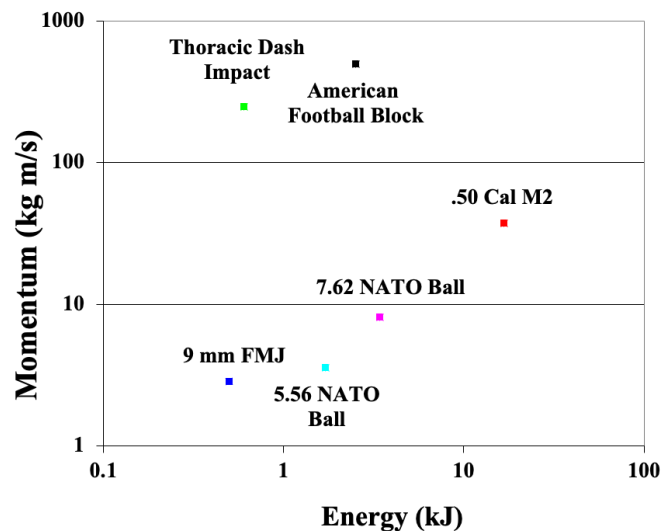


Figure 2. This graph shows that nonpenetrating ballistic impact involves much lower total momentum transfer than typical low-rate blunt impacts. Reproduced with permission from The National Academies Press (2012).

Figure 3 shows an overlay of flash x-ray images that feature a rifle round as it approaches the armor, is defeated, and the resulting deformation to the hard body armor during impact. The chest deformation shown here may lead to trauma to ribs, lungs, heart, liver, and other organs. Data are needed to determine the optimum armor system design that protects the body, potentially including the protection of organs remote from the site of impact while minimizing the weight the Soldier must carry.

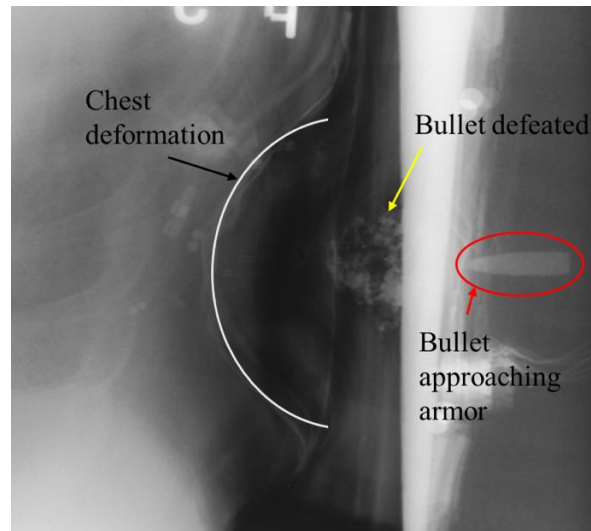


Figure 3. This flash x-ray illustrates a rifle round approaching body armor, projectile defeat, and the resulting thoracic deformation during a 7.62 mm projectile live fire test on a pig protected by hard body armor. Reproduced from Mayorga and North Atlantic Treaty Organization (2010) with permission from The National Academies Press.

Ergonomics of Body Armor

Until the 18th century, combat infantry Soldiers carried about 15 to 30 kg (33 to 66 pounds [lb]) of supplies and equipment. Their additional supplies and equipment were transported in a baggage train (Knapik et al., 2004; Whipp & Ward, 1998). Recently, this load carriage has substantially increased to 60% or more of a Soldier's lean body mass (Birrell et al., 2007). For the U.S. 50th percentile male of approximately (~) 80 kg (~175 lb), this implies load carriage of ~48 kg (~105 lb). Negative consequences of substantial load carriage include potential heat stress (Barwood et al., 2009; Sawka et al., 2001), decrements in psychomotor performance (Bensel & Lockhart, 1975), and ergonomic factors that may limit mobility (Harman et al., 1999). Beekley et al. (2007) found significant increases in oxygen consumption, ventilation, and heart rate for loads of up to 70% of lean body mass in male U.S. Army personnel.

The basic body armor system used by the U.S. Army can weigh up to 7.7 kg (17 lb), which represents about 15% of maximum load carriage for the 50th percentile male. Reductions in body armor mass are a potential method of reducing total load carriage and increasing mobility on the battlefield.

Injury Criteria and Experimentation

There are several potential sources of injury for BABT. These include the initial contact shock and the subsequent displacement of the thoracic wall. The initial shock may occur at a high frequency with a relatively low resulting displacement. A shock pressure peak occurs because of an impedance mismatch between the rear of the body armor and the thoracic wall. Later, bulk displacement may occur following significant local momentum transfer between the back of the body armor and the body. There has been extensive investigation into the relative

effect of the initial shock and resulting displacements. Animal experiments at Oksboel, Denmark were designed to investigate this (Sarron et al., 2000). This issue is not completely resolved.

Pressure profiles have been measured in tissue simulants for blunt impacts behind body armor. As shown in Figure 4, the pressure peaks may be large (higher than 6 megapascals [MPa]) with short duration (less than 1 millisecond [ms]). In addition, the stress wave propagation and concentration of reflected and refracted waves may exacerbate injury (Liu et al., 1996). This is discussed further below.

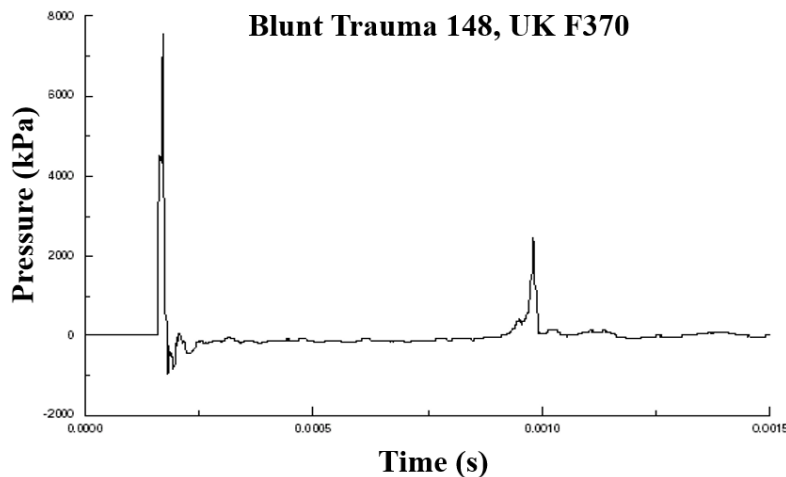


Figure 4. Pressure changes measured in gelatin simulant behind 6.4 mm ceramic (24 kg/m² areal density) with Aramid Composite (10 kg/m² areal density) and Fragment Protective Vest. Reproduced with permission from van Bree and Gotts (2000).

The experimental basis for high-rate impact is not well established. Variables that may significantly affect injury potential include delivered energy, thoracic wall displacement, contact area or contact profile, loading rate, and impact location. The more localized the energy, the greater the potential will be for deformation into and through the body armor. Large local displacements may cause destructive local shearing or compression of tissue. Distributed thoracic loading has a different injury pattern than localized loading (Crandall et al., 1998). Relatively sharp indentation profiles may be assumed by penetrations behind soft body armor (E. Lewis, personal communication, 2001) or behind full penetrations of ceramic armor captured in the soft backing material (DeMaio, 2001). The effect of the rate sensitivity of human tissue may be large, and the impact location is important. Additional factors may include sex, age, body mass, stature, and other anthropometric parameters. Experimental programs designed to develop standard injury test methodologies usually focus first on a single relevant subject population. This may imply a focus on mid-sized males as appropriate for a military population. However, it is perhaps necessary to consider sex-related size and anthropometric differences for general applications.

BABT Injury Mechanisms

Thoracic anatomical features such as the heart, major blood vessels, lungs, and other major organ systems essential to life highlight the importance of the thoracic region for the study of BABT. Ballistic protective measures have been designed to protect this region specifically. The mediastinal region is a key focus area for body armor protection. Notable structures in the mediastinum include major blood vessels (aorta, pulmonary artery, and vein), branch points of the lungs (trachea), entry into the gastrointestinal system (esophagus), and the heart. In addition, the thorax includes the lungs, offering a large surface area, and the liver, not completely protected by the rib cage. On the posterior region of the thorax, the spine presents an additional impact location where a potentially debilitating or life-threatening injury could occur.

Several potential injury mechanisms have been seen in animal, cadaver, and human epidemiological studies. These include physiological mechanisms such as cardiac and pulmonary disruptions such as commotio cordis (Link et al., 1999) and acute respiratory distress syndrome (ARDS) (Miller et al., 2002). However, commotio cordis is thought to occur in a small proportion of the cardiac cycle and is quite rare in blunt impacts, so the risk of such electrical disruptions may be small.

Several types of injuries may be attributed to displacement. These include large displacements that may cause shear or crushing. These injury mechanisms may consist of punctures caused by bony fractures. An example of this is a fractured rib penetrating a lung and disrupting the pleural cavity which may result in a pneumothorax or hemothorax. Fung et al. (1988) suggested that lung injuries may be related to compression of the alveoli under mechanical stress.

For ultrasonic forcing at high rate, the influence of local cavitation has been suggested. Indeed, negative pressure has been observed in ballistic animal experiments (Sarron et al., 2001). Therefore, pulsation mechanisms such as those seen in ultrasound tissue damage may cause BABT tissue damage. Typical ultrasound thermal damage is unlikely for BABT, but for short-duration ultrasound stress wave propagation, direct tissue damage and cavitation mechanisms have been proposed that may be BABT injury mechanisms. Ultrasound impulses involve low displacement with relatively high frequency (50 kilohertz [kHz] to 1 megahertz [MHz]). The effect of exposure duration on the threshold injury pressure is important, as shown by Carstensen et al. (1990) and Bass and Marriott (2009). Thresholds for damage in lung tissue in the murine model are significantly lower than in other tissues. The threshold is frequency-dependent (1 to 4 MHz) with a threshold (Equation 1) of

$$P = 0.63f^{0.54} \text{ MHz} \quad (1)$$

Unfortunately, no ‘single pulse’ thresholds are currently known; current thresholds involve five cyclic pulses. Among the nonthermal mechanisms, such as cavitation from repeated cycling and spalling from an interfacial impedance mismatch, cyclic cavitation is unlikely to be a BABT injury mechanism. However, spalling may be a BABT injury mechanism. Spalling may occur at alveolar surfaces resulting in local hemorrhage.

For high-rate BABT, there is a potential for abrasion injuries caused by the friction of the impacting surface on the body. This has been seen in epidemiological studies by Mirzeabassov et al. (2000), and cadaver experiments by DeMaio (2001) and Bass et al. (2002). These ablation injuries may be quite severe. DeMaio (2001) saw large, deep, bilateral chest wounds under certain circumstances, and Bass et al. (2002) saw injury from ablation behind helmets with relatively low-velocity incoming projectiles.

A final class of BABT injuries includes the potential for injuries that are remote from direct backface contact. The earliest observations on the effects of penetrating injuries to the nervous system that were remote from the site of penetration were case studies from the Civil War. The results of the injuries were temporary and sometimes long-term motor and sensory paralysis (Mitchell et al., 1864; Akimov et al., 1993). The occurrence of damage from the transmission of kinetic energy from the point of impact on the torso to remote body organs in humans has been observed in many cases (Ackley, 1966; Carroll & Soderstrom, 1978; Sperry, 1993; Cannon, 2001; Krajsa, 2009), and these corroborate Civil War case studies (Mitchell et al., 1864). A report on human trauma from BABT in law enforcement personnel emphasized the fact that protection from penetration does not protect from significant thoracic trauma (Wilhelm & Bir, 2008).

Mechanical Correlates with Injury

An injury criterion must be evaluated with some measured mechanical correlate with injury and a surrogate test device. The earliest criteria were based on global acceleration. These criteria may not be appropriate for injuries with sufficient localization. Beyond the correlates used for the blunt criterion (Sturdivan, 1976), several mechanical correlates that have been investigated are discussed below.

Human Epidemiology for Battlefield BABT

There is a strong need to investigate the epidemiology appropriate for behind armor effects. The limited epidemiology of high-rate events restricts the evaluation of current and future ballistic protection performance. The value of epidemiology is seen in many fields. The use of epidemiological studies in the field of anesthesia substantially lowered the incidence of death from adverse events over the previous 20 years (Hawkins et al., 1997). Epidemiological and retrospective studies are used in aircraft accidents and automobile crashes worldwide. Such investigations have been useful in designing countermeasures for injury.

Injury scales.

An organized and robust injury scale using a common basis is necessary for evaluating injuries from animal experiments, cadaveric experiments, and epidemiology. There are several extant injury scores, but none are completely appropriate for scoring BABT injuries. The Abbreviated Injury Scale (AIS), created by the Association for the Advancement of Automotive Medicine (AAAM), is an accepted standard for thoracic injury assessment (most recent version AAAM, 2015). The numerical scoring system ranges from 1 (minor injury) to 6 (maximum, survivability not probable). The most serious thoracic injury is aortic laceration which is ranked

from AIS 4 to 6 (Nahum & Melvin, 1993). However, this criterion is generally not sufficiently discriminative for research BABT work.

The Injury Severity Score (ISS) is an overall score for multiple injuries (Baker et al., 1974). To calculate the ISS, each body region is assigned an AIS score for six body regions (head/neck, face, chest, abdomen, extremities, general). The highest AIS score for each region is selected, and the three highest of these are squared to produce the ISS score in Equation 2.

$$ISS = AIS_{\max 1}^2 + AIS_{\max 2}^2 + AIS_{\max 3}^2 \quad (2)$$

The scale specifies that the maximum squared value by body region is 25. The ISS score ranges from 0 to 75. This score has been correlated with outcomes for thoracic trauma, abdominal trauma, and extremity injuries. A major limitation in the use of ISS is that when multiple injuries are sustained in a single body region, the score fails to capture the increased combined severity.

Injury criteria from other fields.

The most widely used criteria for thoracic injury in automobile thoracic injury contexts are the Thoracic Compression Criterion and the Viscous Criterion (VC) for frontal impacts, and the Thoracic Trauma Index (TTI) for side impacts. The Compression Criterion relates the relative chest deformation of the chest's depth to the injury level. According to Kroell et al. (1971; 1974), chest compressions of 30% and 40% cause AIS 2 and AIS 4 injuries, respectively. When using the VC, the rate dependency of soft tissue injury is accounted for and the maximum product of deformation velocity and relative compression, called the $VC_{\max}$, is proposed as an effective predictor of injury risk. In an analysis of 39 sternal impacts to unembalmed cadavers, a $VC_{\max}$ of 1.3 m/s was associated with a 50% probability of receiving an AIS score of 3 or higher (Viano & Lau, 1985). Eppinger et al. (1984) analyzed many side impact test results. They proposed that the TTI is proportional to age, mass, and the average of the peak values of the fourth struck-side rib and twelfth thoracic vertebra accelerations. Limitations of these criteria for BABT include development at lower strain rates than are typical of BABT and development for widely distributed thoracic deformations instead of local deformations typical of BABT.

Soviet experience in Afghanistan.

Mirzeabassov et al. (2000) reviewed combat injury data sustained during the Soviet Union military occupation of Afghanistan in the 1970s and 1980s and developed a scale for combat-specific BABT trauma. This trauma severity scale (Table 3) and the associated scale for loss of fighting efficiency (Table 4) are based on BABT injuries. As the armor used was light plates of titanium, the Soviet experience may be valuable for lighter body armor injury assessments.

This study is the most complete BABT epidemiology study available. Data were collected from 17 subjects who received impacts in the thoracic region while wearing body armor with either 1.25 mm titanium (6B2) or 6.5 mm titanium (6B3TM) plates. The data were acquired during the Soviet experience in Afghanistan. Injury data collected included the impact location, injury, long-term impact consequences, and subjects' ages. The ballistics data collected included the type of weapon fired (reportedly either a 7.71 mm Enfield or 7.62 Kalashnikov's

modernized automatic rifle [AKM] in all cases), firing distance, and impact kinetic energy.

Table 3. Description of Thoracic Trauma Levels Modified From Mirzeabassov et al. (2000) With Permission From The National Academies Press

Level of Trauma	Nature of Injuries
I Slight	Scratches on the skin, ecchymoses, and restricted subcutaneous hematomas. Isolated focal subpleural hemorrhages.
II Medium	Contused cutaneous wounds. Focal intramuscular hemorrhages. Pleural focal subpleural hemorrhages. Isolated focal hemorrhages into the intestinal mesentery.
III Grievous	Closed and open rib fractures. Lacerations of the pleura, hemorrhages into the pulmonary parenchyma. Subepi- or subendocardial hemorrhages. Subcapsular hematomas of parenchymal organs of the abdominal cavity and retroperitoneal space. Subserous hemorrhages into the intestines, ruptures of the mesentery. Restricted hemopneumothorax, hemoperitoneum. Vertebral fractures without injury to the spinal cord.
IV Extremely grievous, lethal	Ruptures and crushing of internals. Closed trauma of the vertebral column followed by an injury to the spinal cord.

Table 4. Combat Effectiveness Versus Thoracic Trauma Levels Modified From Mirzeabassov et al. (2000) With Permission From The National Academies Press

Gravity Level of the Trauma	Characteristic of the Loss of Fighting Efficiency	Probability of Rehabilitation	Class of Losses
I Slight	Loss of fighting efficiency for 1 to 3 minutes Limited fighting efficiency during 15 minutes Complete restoration within 24 hours	99%	Left in action
II Medium	Loss of fighting efficiency for 3 to 5 minutes Limited fighting efficiency up to 10 days Complete restoration within 15 to 20 days	85%	Combat sanitary (recoverable) losses
III High	Complete loss of fighting efficiency Limited fighting efficiency within 15 to 20 days Complete restoration within 30 to 60 days Possible fatal outcome	25%	Combat sanitary (recoverable) losses
IV Extremely high	Immediate death Death caused by complications Invalidism and complete loss of fighting efficiency in surviving persons	0%	Unrecoverable losses

Bullet kinetic energy plotted against injury severity was derived from human epidemiology and animal experiments (Figure 5). The lighter body armor (6B2) had a significantly lower threshold for the onset of severe injuries. The most serious injuries reported were hemopneumothoraces in two patients that progressed to abscesses. In addition, an impact in the left rib developed a large ecchymosis that extended from the groin to the knee.

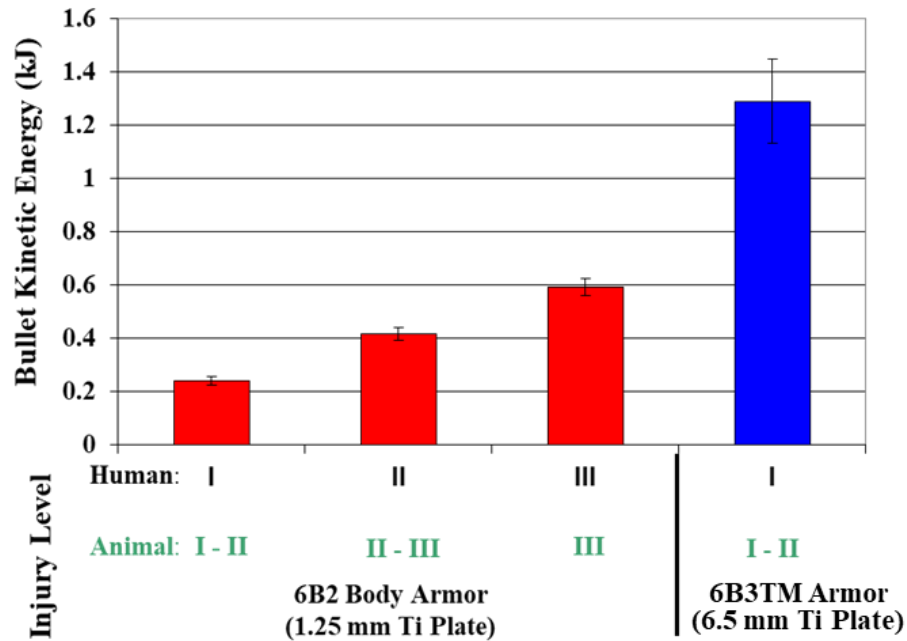


Figure 5. The initial bullet kinetic energy is shown in comparison with the injury severity from human epidemiology and animal experiments. Modified from Mirzeabassov et al. (2000) with permission from The National Academies Press.

Coverage of the plates was not reported; however, substantial injuries occurred to the subjects' backs from relatively low energy impacts implying that the impacts occurred in an area without plates. The researchers developed a scale that relates the initial kinetic energy of the bullet with the injury severity in their human epidemiology and animal experiments (Figure 5).

To understand the Russian epidemiology data, it is important to consider details of the Soviet military medical service. Extensive data analysis is available for mine trauma victims from the Soviet experience in Afghanistan (Nechaev et al., 1995). Over 90% of patients were evacuated by air, but only 4% were delivered to the Central Military Hospital (CMH) within six hours of injury and over 50% were delivered after 24 hours or more (Figure 6A). This was the initial treatment received for more than 80% of the wounded (Nechaev et al., 1995). Further, the severity of the wounds was distributed as shown in Figure 6B. It is likely that the distribution of the severity of injuries may have changed with the delivery time. Increased delivery times would exacerbate the severity of the injuries and tend to decrease the number of severe injuries owing to fatalities. This may be seen in the types of injuries reported in the epidemiology study.

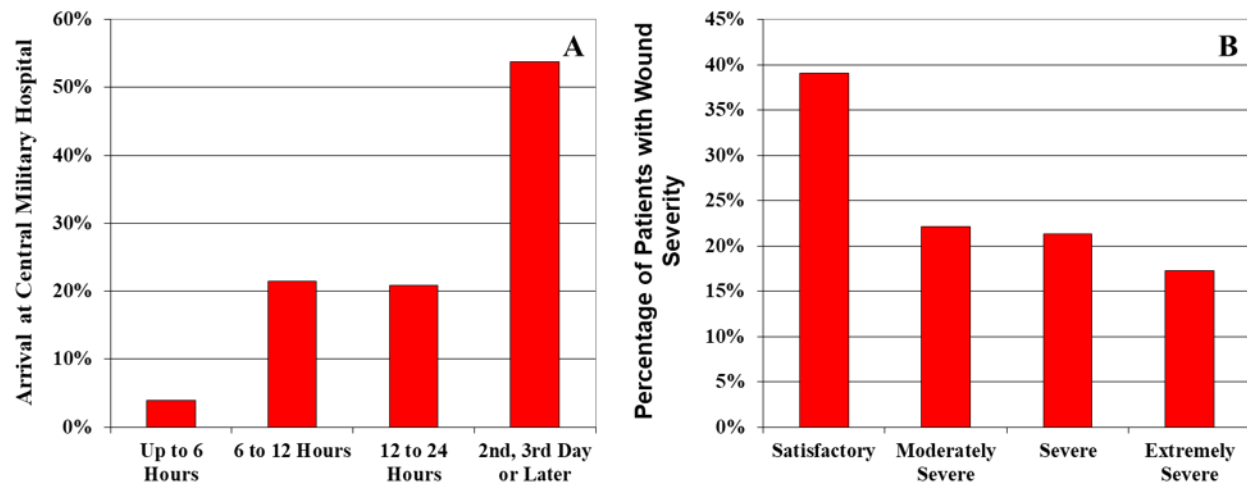


Figure 6. Shown in these graphs are (A) the time necessary to deliver wounded personnel to the CMH and (B) the severity of wounds as described by the authors (average percentages of wound severity in 1983 and 1984). Note there is an inconsistency between injury severity terms reported from Mirzeabassov in Figure 6B and Tables 3 and 4. The four terms are understood to coincide among the tables and figures. Reproduced from Nechaev et al. (1995) with permission from The National Academies Press.

Many of the initial injuries would not have been considered grave if they occurred in an automobile collision in the United States. One may speculate that there may have been grave injuries that became fatal with delayed treatment. However, the development of infection in the two pneumothoraxes increased the severity substantially. One may further speculate that Soldiers with more severe BABT injuries would have a high risk of death before reaching the CMH. This work is almost the singular instance of publicly released comprehensive epidemiology for BABT trauma correlated with well-described body armor. However, there were study limitations. The shot ranges were estimated, and battlefield trauma care may have been significantly different than the care received by Western militaries. The difference in medical care received and the prolonged duration between time of injury and administration of definitive medical care may have fundamentally changed the injury outcome and reported distribution of injuries.

U.S. experience for battlefield/law enforcement.

The National Academies of Sciences, Engineering, and Medicine (2012, p. 191) report emphasized, “there have been no known U.S. Soldier deaths due to small arms and shrapnel that were attributable to a failure of the issued ceramic body armor for threats for which the armor was designed” (J. Rickey, personal communication, 2010). Based on this, the U.S. military has fielded hard body armor with adequate survivability characteristics for Soldiers in combat. Further, since the NIJ undertook the responsibility to standardize body armor for law enforcement personnel in 1973, over 2900 lives were saved (National Academies of Sciences, Engineering, and Medicine, 2012). The tragic failure of zylon body armors in a small number of well-publicized cases in law enforcement (e.g., Rice, 2000) further emphasizes the rarity of armor failures and the success of the testing programs based on clay. “What is unknown, however, is the link to human injury for the existing hard armor assessment methodology. It is necessary to determine whether the standard is overly conservative and how to assess tradeoffs

of weight and mobility against protection from ballistic threats” (National Academies of Sciences, Engineering, and Medicine, 2012, p. 191).

BABT Test Methodologies

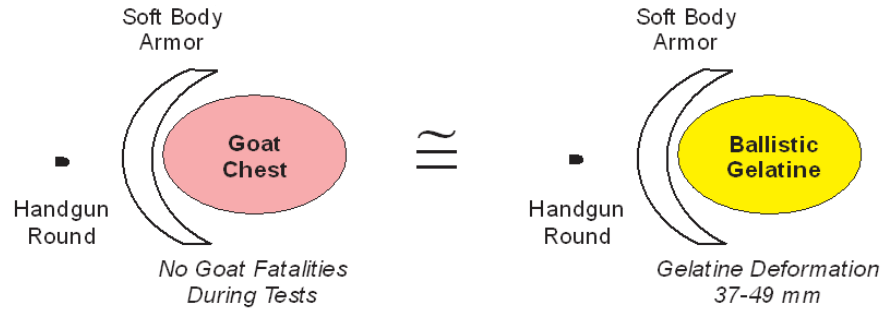
Development of Current BABT Assessment Methodology

The current BABT assessment methodology is codified in the National Institute of Justice standard number 0101.07 (NIJ 0101.07) “*Ballistic Resistance of Body Armor*” and used by many nations for the assessment of blunt trauma risk from backface deformation for both soft and hard body armors. Much of the early work performed by Prather et al. (1977) (hereafter called the Prather study) formed the foundational basis for this assessment methodology. This work was derived from two principal foundations. First, assassinations and assassination attempts on politicians and other very important people in the 1960s and 1970s led to the desire to provide unobtrusive ballistic protection to counter threats. Second, advances in fiber technology provided a basis for protection against low-velocity handgun rounds using layers of woven fibers. Injury biomechanics investigations leading to the Prather study focused on protection from low-velocity handgun threats with soft body armor. The Prather study included an injury assessment methodology developed using simulant materials correlated with live animal chest deformation responses for handgun rounds at typical muzzle velocities. A diagram of this process is shown in Figure 7.

The dynamic deformation of the body armor backface is assessed by measurement of the residual displacement of Roma Plastilina No.1 (RP1) (oil-based modeling clay) which is used as a standard for evaluating the performance of body armor. The principal advantages of this material are the potential for rapid and inexpensive tests and the large historical database of body armor tests using the clay simulant. The principal disadvantages are the limitations of the clay as a human thorax simulant, the very limited validation against human injury response (especially against hard body armors), and the inability to consider more complex BABT scenarios. For instance, the methodology was validated using goat experiments with a single velocity regime; the test is not likely appropriate over wide deformation ranges. Further, the standard does not account for the effect of local penetrations (pencil effect). This pencil effect is frequently seen in soft body armor backing (E. Lewis, personal communication, 2001).

To provide human injury risk, the Prather study used two essential methods outlined in Figure 7. The first method asserts a similarity between deformation behind armor in paired tests using soft body armor and handgun bullets with live goats and ballistic gelatin surrogates. During this phase, no goats died from backface trauma. Penetration depths were derived using only gelatin. The second method uses the first gelatin study to develop a hard cylindrical impactor used with live goats. Tests at similar impact velocities were conducted with gelatin and clay behind body armor to correlate gelatin and clay penetration depths. The development of this process is discussed below.

Method 1



Method 2

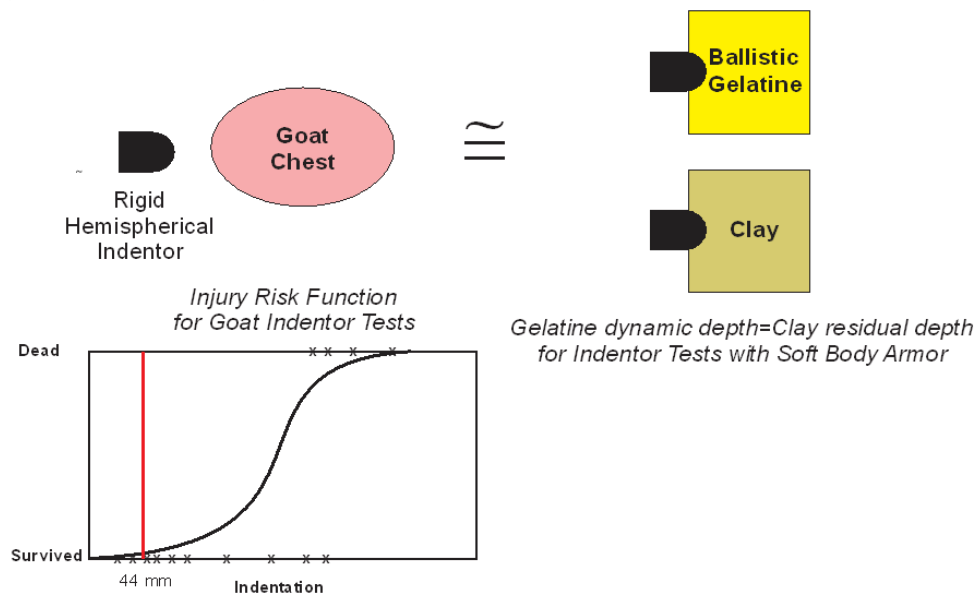


Figure 7. From the Prather clay ballistic test methodology, Method 1 correlates deformation behind soft body armor in goats with deformation in gelatin. Method 2 correlates a fatality risk assessment using goats impacted by to tests of rigid impactors impacting gelatin causing dynamic deformations and impacting clay causing residual deformation. Reproduced from National Academies of Sciences, Engineering, and Medicine (2012) with permission from The National Academies Press.

In response to armed attacks on public officials in the United States before 1973, the Law Enforcement Assistance Administration (LEAA) asked the U.S. Army Land Warfare Laboratory at Aberdeen Proving Ground, MD to develop lightweight, inconspicuous protective garments for public officials, eventually extended to law enforcement personnel (cf. Montanareli, 1973) in collaboration with other agencies including U.S. Army Natick Laboratories and the Aerospace Corporation. During that time, threats from civilian handguns were predominantly .38 caliber handgun rounds and below. Principal rounds chosen for this effort included the .38 caliber lead round nose (LRN) bullet (158 grain) with a muzzle velocity of 244 m/s and the .22 caliber, 40 grain long rifle high-velocity bullet (40 grain) with a muzzle velocity of 305 m/s. Design criteria

for these ballistic protective vests included that they must be lightweight, inconspicuous, and not interfere with body movement. Additional specifications included prevention of bullet penetration, limiting the risk of fatality to less than 10%, and allowing adult males to survive any ballistic attack. The last two requirements are not necessarily contradictory when viewed in the context of the assumption that victims would receive medical treatment for potential hemorrhage or other sequelae within an hour of the attack.

For such non-penetrating impact, the kinetic energy and velocity must be dissipated by the armor through armor deformation, momentum transfer from the bullet to the material, bullet deformation or fragmentation, and, finally, the deformation of the body in contact with the armor. The momentum/energy transfer to the body can cause serious injury or death, even without penetrating the skin.

Numerous materials were assessed to determine the optimum weight-to-strength ratio, flexibility, cost, availability, ballistic qualities (ballistic limit and behind armor deformation), and tailor-ability. Materials investigated included hi-tenacity nylon, nylon felts, hi-tenacity rayon, graphite yarns, XP (an experimental plastic developed by Philips Petroleum), Monsanto fibers, and DuPont Kevlar® 29 (K29) and 49 (K49). These materials were ranked, and a thickness of 7 plies of 400/2 denier K29 was selected for further investigation.

The injury basis for this methodology was provided by a live animal model for BABT, an adult 40-50 kg angora goat, was used to represent a 70 kg adult male. Goldfarb et al. (1975) studied the mechanical response of the lung, liver, kidney, and spleen from both the goat and human cadavers under impact with a water jet. Based on a qualitatively similar response of the goat and human collapsed lung and the determination that goat livers and kidneys were more robust for mechanical trauma than human organs, they concluded that the goat was a conservative BABT model. Paired injury tests in the goat model and deformation response tests in 20% gelatin were performed with armor samples against the .38 caliber LRN bullet at 244 m/s. The lung, liver, heart, spine, gut, and spleen were specifically targeted during these tests. Matched tests with the same round and body armor into a 20% gelatin backing material were used to develop a profile of the behind armor deformation (Figure 9). Since gelatin is transparent, high-speed film was used to determine the deformation rate, depth, volume, and area. These were correlated with the trauma in the liver, lung, spleen, and heart in the goat model. The gelatin profiles for this condition had an average dynamic deformation of 44 mm. This value was chosen for the BABT standard injury tolerance. There were no deaths from backface trauma in the paired tests with the .22 or .38 caliber rounds corresponding with this 44 mm deformation in gelatin (e.g., Goldfarb et al., 1975).

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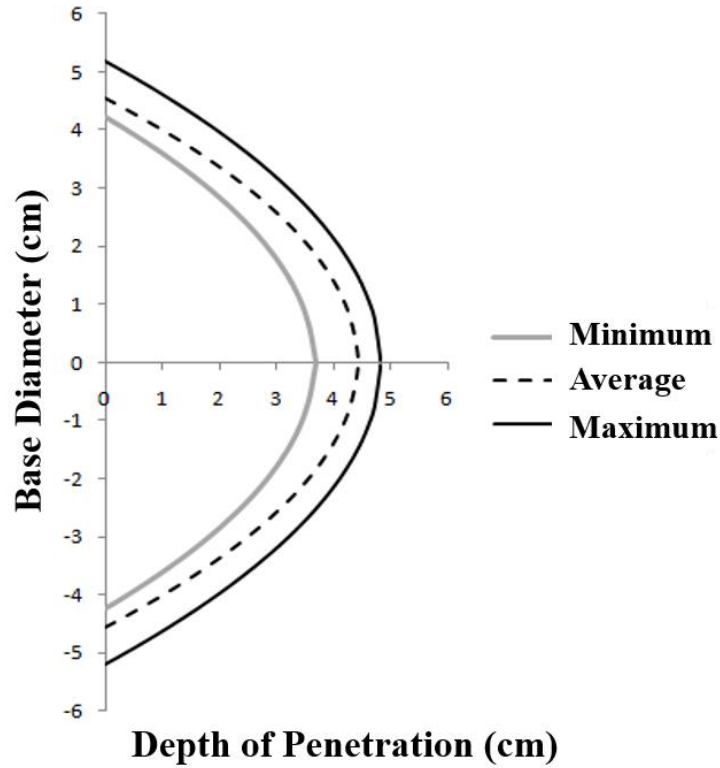


Figure 8. Blunt deformation profiles from a .38 caliber round traveling at 213 m/s were measured. The round was shot through seven-ply K29 armor into ballistic gelatin using the same test parameters as in the goat model, which was protected with the same armor. Adapted from National Academies of Sciences, Engineering, and Medicine (2012) and reproduced with permission from The National Academies Press.

At the same time, Clare et al. (1975) developed analytical blunt trauma models formulated using tests in animal models not protected by body armor. They used tests for which the projectile impacts were like the assumed backface profile, slower velocity, and larger impact mass (typically 50 to 200 grams) than handgun rounds. One model used projectile mass (M) in grams, projectile impact velocity (V) in m/s, projectile diameter (D) in centimeters (cm), and experimental animal weight (W) in kg with two discriminants defined as Equation 3.

$$x1 = \ln [MV^2] \quad x2 = \ln [WD] \quad (3)$$

Three zones of lethality (low, medium, and high) were established with increasing impact ‘dose.’

At the time of the Prather study, 20% ballistic gelatin was used as the human surrogate/backface target for armor deformation testing (R. Prather, personal communication, 2010); the use of ballistic gelatin required a dynamic deformation measurement to assess backface deformations, often high-speed photography owing to gel elasticity. The ballistic gelatin returned to its original state after the dynamic event ended.

Since high-speed photography was expensive, a material with a permanent deformation following a backface event was sought. Material selection criteria for a new backing material from LEAA included a response similar to gelatin, low cost, reusable, and minimal post-event recovery. The intent was for the material to be easy to use so that individual law enforcement agencies could conduct their tests at their facilities. The response was compared with hemispherical impact data on the goat thorax, intended to replicate behind armor response for soft armor rounds. These goat tests used an impact velocity of 55 m/s with a solid 200-gram, 80 mm hemispherical impactor. Response to several materials was compared for similar impact conditions (Figure 9).

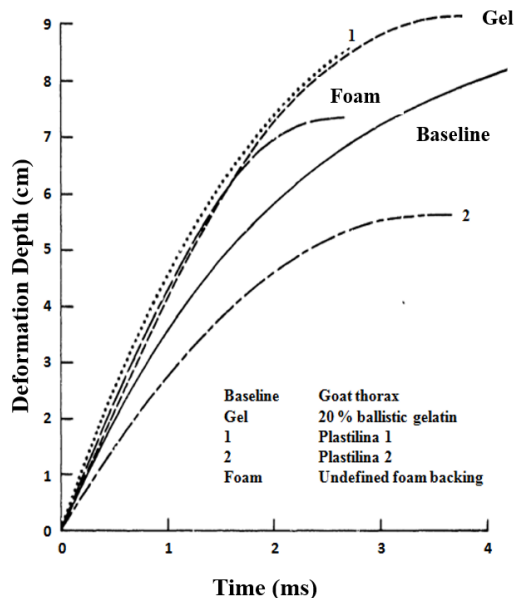


Figure 9. This graph compares candidate backing material responses to the thoracic deformation of a goat subjected to a blunt impactor at 55 m/s. Modified from Prather et al. (1977) and reproduced with permission from The National Academies Press.

Though no materials duplicated the animal thoracic response, the modeling clay, RP1, had a similar deformation time history to gelatin and was selected as the new candidate material. The material was inexpensive, did not require high-speed photography, and tests using it were repeatable. However, clay and gelatin response at this velocity for this impactor (55 m/s) is generally softer than for the goat thorax.

This deformation response was linked with fatality using blunt impactor data on live goats (e.g., Clare et al., 1975). The relationship was modeled using a logistic regression model between deformation and the probability of lethality (Figure 10). Using the model, 44 mm indenter impact deformation in the goats is associated with ~10% risk of death, like the initial program requirement of less than or equal to 10% mortality. This deformation level did not produce any deaths in the goats. So, this depth was selected as a conservative injury reference value for the clay.

An important note is that this lethality risk assessment is indirect, not based on actual body armor testing. Noncompliant blunt impactor tests were used to model the deformation and injuries from backface deformation are likely conservative for this impact velocity range. Outside this typical handgun/soft body armor velocity range, however, the injury risk function in terms of deformation response in the clay is uncertain. Prather's original study comments on the injury regression stated, "Attempts have been made using the original blunt impact data to correlate deformation depth with the probability of lethality. A depth of penetration greater than 50 mm is associated with a probability of lethality of approximately 15%. However, the available data is limited and hence no solid conclusions can be drawn yet regarding the effect of deformation depth." (Prather et al., 1977, p. 10).

This emphasizes the quite limited validation of the original injury correlation, even for soft body armor with handgun rounds. For a given impact, gelatin and clay penetration depth were generally greater than the deformation in the goat. So, gelatin can be used to determine the goat deformation compared to the clay. In the range of deformations 3 to 60 mm in the goats, the ratio of clay to goat deformation is approximately constant as Equation 4.

$$D_{\text{clay}}/D_{\text{goat}} = 1.28 \quad (4)$$

In this deformation range, the ratio varies by less than 0.3%. This has implications for the current level of 44 mm in clay. The 44 mm deformation in the clay is similar to a 34 mm deformation in the goat (4% fatality risk in the model). Alternatively, 44 mm deformation in the goat (10% fatality risk in the model) is similar to 56 mm deformation in the clay as shown in Figure 10.

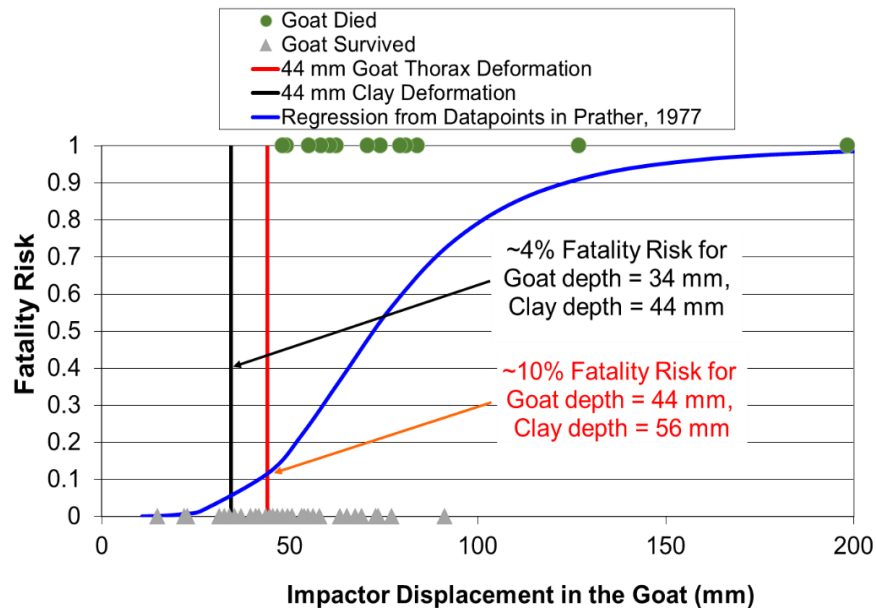


Figure 10. A logistic regression model correlates the probability of fatality against blunt impactor deformation in goat chests. Fatality cases are shown at a risk level of 1, and nonfatality cases are shown at a risk level of 0. Both 4% and 10% fatality risks are indicated on the graph. Adapted from National Academies of Sciences, Engineering, and Medicine (2012) and reproduced with permission from The National Academies Press.

Soft body armor – High energy handgun threats.

In the late 1970s, as civilian handgun threats evolved to use more powerful rounds (e.g., .357 semi-wad cutter at 396 m/s [158 grain] and the 9 mm FMJ at 350 m/s [124 grain]), more protective soft body armors were studied. These investigations showed that 16 plies of K29 sufficiently prevented penetration and that the backface deformation profiles into gelatin were similar to those from the earlier soft armor studies with lower velocity rounds. Limited goat model studies showed injuries like those seen in the original seven-ply Kevlar® tests with handgun rounds. The program was terminated before sufficient tests could be conducted to verify these preliminary conclusions. There are no formal reports on this work; however, the participants recalled that these studies did not produce deaths with the more powerful round in the animal model behind the enhanced soft armor (R. Prather, personal communication, 2010).

Hard body armor – Rifle threats and clay response.

Prather's (2010) study did not include systematic investigations of rifle threats with hard body armor. Ad hoc investigations included an assessment of .50 caliber antipersonnel (AP) threats to helicopter pilots in animal models (R. Prather, personal communication, 2010). These limited studies, however, produced no hard armor BABT risk methodology.

For rifle round velocities, the correlation of structural BABT in human cadavers was compared with clay deformation behind an ultra-high molecular weight polyethylene (UHMWPE) hard body armor system (Bass et al., 2006). The clay tests were based on NIJ standard 101.04 (NIJ, 2001) at a commercial test laboratory with a 7.62 by 54 mm M80 ball projectile. Test velocities ranged from ~670 m/s to ~800 m/s. Clay backface deformations over this range of velocities (Figure 11) were very poorly correlated with peak deformation (Figure 12). In contrast, human cadavers demonstrated a wide range of traumatic outcomes ranging from mild to very severe injuries over the same velocity range with the same round and body armor. The severity of these BABT injuries in the human cadavers generally scaled well with measured impact force and velocity. When the volume of the indentation or the cross-sectional area was used, the correlation improved, but coefficient of determination (R^2) was still 0.6 (Figure 13). Since the clay depth poorly correlates with cadaveric injury rifle round threats with this body armor type, this emphasizes concerns that the clay methodology may be inappropriate for hard armor with a low areal density that may produce a large velocity backface response.

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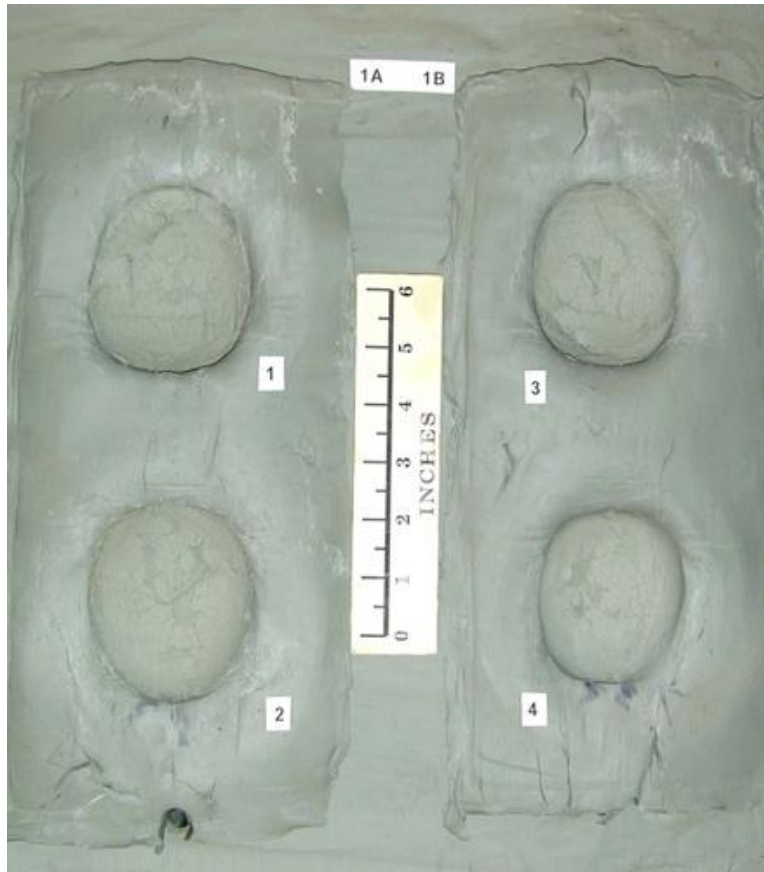


Figure 11. The clay deformation behind hard armor after shots with rifle round threats were very poorly correlated with peak deformation. Reproduced from Bass et al. (2006) with permission from The National Academies Press.

Further, the NIJ 0101 (version 06) evaluation measures static residual penetration depth into the clay. Bir (2000) analyzed dynamic clay deformation for non-lethal baton rounds finding that there was up to 20% greater dynamic deformation than residual quasistatic deformation. Also, this dynamic deformation may be rate-sensitive and contact-area sensitive. Both studies, Bir (2000) and Bass et al. (2006), raise concerns about using clay at the current depth for assessing rifle rounds in hard body armor. Depending on the characteristics of both the body armor and the clay response, it is uncertain whether a clay-based methodology for body armor based on the Prather methodology is overly conservative for injury assessment.

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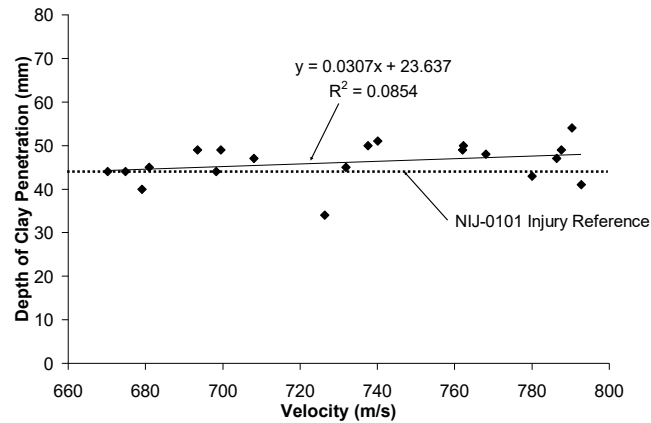


Figure 12. Variation of clay penetration depth was compared to velocity for behind body armor deformation (7.62 mm NATO round, UHMWPE body armor). This indicates that the depth of clay penetration into the torso behind armor is insensitive to the impact velocity of the incoming round. At the low end of the velocity range, there are limited injuries to the cadaveric specimens. At the high end, the injuries are severe. This makes the use of clay ineffective as an injury assessment for the conditions tested. Reproduced from Bass et al. (2006) with permission from The National Academies Press.

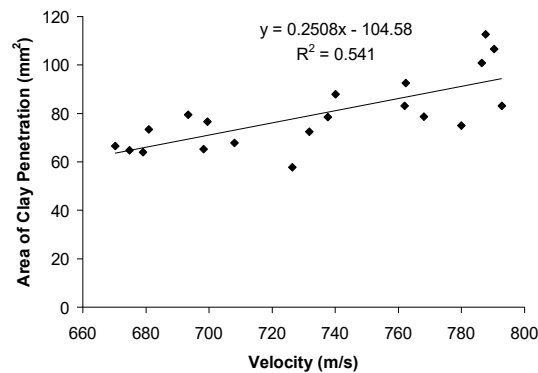


Figure 13. Variation of clay penetration area was compared to velocity for behind body armor deformation (7.62 mm NATO round, UHMWPE body armor). Clay depth generally increases with velocity, but there is substantial scatter in the clay response in these test conditions. Reproduced from Bass et al. (2006) with permission from The National Academies Press.

Clay rebound.

Prather's initial development of clay as a test surrogate includes the implicit assumption that clay plastic deformation represents the peak deformation in clay. Bir (2000) found that clay rebound was substantial but did not investigate the behavior of rifle round insults. A recent study in calibrated Roma Plastilina clay (circa 2017) demonstrated that clay has a strong rebound effect for typical rifle round backface deformation profiles in contrast to the assumed plastic behavior (Op 't Eynde et al., 2023) (For a range of backface velocities typical of rifle round insults around muzzle velocity, this effect reduces the final deformation by 5 to 25% depending on the velocity

of the impact, obscuring the actual peak dynamic deformation in the clay by a significant unknown fraction of the residual plastic deformation.

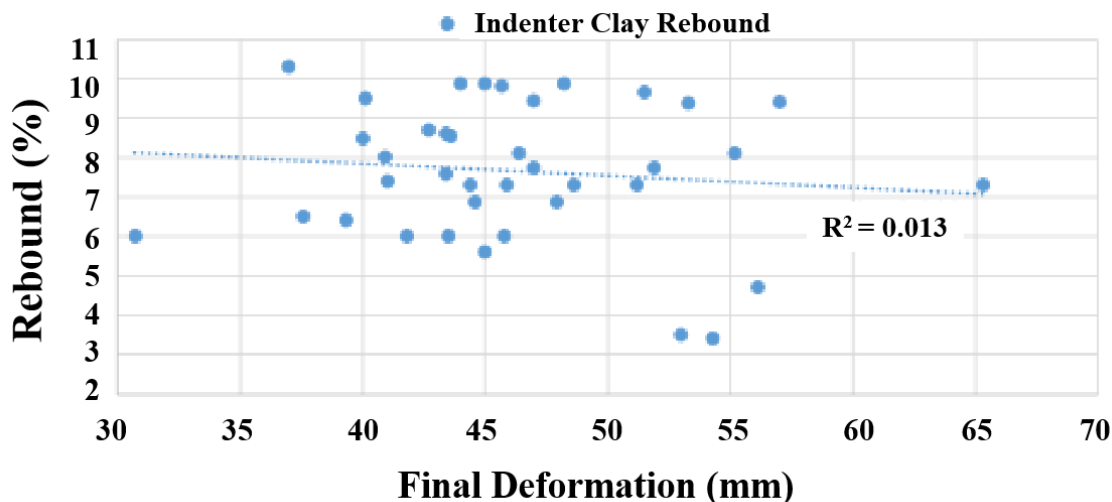


Figure 14. Clay indentation rebound versus measured final indentation deformation. Indenter rebound increased as a variable percentage of the final deformation making prediction of dynamic deformation difficult (Op ‘t Eynde et al., 2023). Reproduced with permission from Joost Op ‘t Eynde, Ph.D.

The percentage of “rebound” between the peak deformation depth and residual deformation depth was measured consistently around ~15 to 20% with respect to deformation depth. This percentage indicated that larger kinetic energies would see a corresponding increase in the magnitude of the “rebound” effect in clay. However, the rebound percentage decreased relative to the indenter kinetic energy. This decrease indicated a limit to this mechanism: While greater indenter kinetic energy creates greater “rebound,” the rebound amount would be less as a fraction of the total residual deformation depth. This deformation confounds the use of displacement depth as an injury metric, increasing the variance of these assessments by 20% or more in addition to the intrinsic variance in any injury model assessment. Similar effects were found in modeling by the U.S. Army (Zhang et al., 2022).

Prather study methodology summary.

The current clay methodologies for soft and hard body armor (e.g., NIJ0101.07) are fundamentally based on the Prather et al. (1977) study. However, the Prather study was intended as a rapid expedient to field a test methodology for soft body armor against handgun rounds. Key limitations include

1. Using an impactor with a single profile at a single velocity to simulate ballistic deformation rather than ballistic behind armor deformation.
2. The lack of fatalities in the live goat tests at the levels used for the assessments.
3. Materials used (clay and gelatin) were softer than the goat thoraces.

4. Owing to changes in material response, (National Academies of Sciences, Engineering, and Medicine, 2012) the sculpting clay known as RP1 has stiffened considerably since the early 1970s. This dramatic qualitative change requires that the clay is preheated to the vicinity of 100 ° Fahrenheit (F) to sufficiently soften the wax components so the clay will have a qualitatively similar response to the clay used by Prather et al. There is no guarantee that changes will not continue to occur in the constituents of this clay, though initial efforts have been made to standardize a variant of this clay for military use.
5. The Prather methodology for BABT assessments discussed above have been shown to provide either over-conservative or over-liberal risk assessments depending on the armor system design (National Academies of Sciences, Engineering, and Medicine, 2012; Gryth et al., 2007). Risks of overconservative and over-liberal injury risk methodologies should not be minimized in armor development and assessments where competing tradeoffs, such as Soldier-borne mass are important.

The Prather methodology provides no direct injury criterion for backface velocities typical of hard body armor though it continues to be used by militaries to date. The strengths and weaknesses of the current Prather methodology are listed in Table 5. In view of these limitations, it is uncertain how conservative or liberal the current hard armor criteria are for human response.

Table 5. Strengths and Weaknesses of the Prather Clay Methodology and Similar Test Methods

Strengths	Weaknesses
1. Ease of use	1. Clay variability (handling, thixotropy, temperature effects, etc.)
2. Immediate results	2. Clay constituents have changed considerably since the original study
3. Relatively low cost	3. Current methodology requires elevated clay temperatures
4. Large historical database of results	4. Method has limited validation for soft body armor
5. Apparent success in the field of soft body armor	5. Method has no validation for hard body armor
6. Apparent success in the field for hard body armor	6. Pass/fail criterion

Reproduced with permission from National Academies of Sciences, Engineering, and Medicine (2012).

Alternative BABT Surrogates

The fundamental methodology to assess BABT requires a live fire round to strike the armor under test, and to measure the behind armor response. The insult parameters of the live fire round (threat definition, impact velocities, and obliquity angles) will vary depending on armor type and its penetration resistance requirements. However, based on numerous efforts to improve the BABT test surrogate and its response measurements, the armor development and procurement communities appear to have low confidence in the ability of the current RP1 clay surrogate and its displacement measures to accurately assess the injury risk that the test is intended to inform. Many of these efforts are presented and discussed below and in the appendix.

Generally, when developing a test methodology for the purpose of injury risk assessments, there are important tradeoffs that must be considered before adopting a particular technique, test method, or test surrogate into a test standard. Generally, increased test surrogate complexities are associated with increased costs, but the complexity may be critical to provide increased surrogate biofidelity (similarity to the human condition) and improved injury risk assessments. In contrast, simpler models may provide inexpensive and efficient test conduct, but may miss essential elements needed for injury assessments making them unreliable for system design.

Desirable characteristics of a test surrogate for use in conducting injury risk assessments include (cf. Bass et al., 2005)

Surrogate biofidelity – the test surrogate should be robust with repeatable physical response and provide demonstrable human-like response to the extent necessary. For example, very simple instrumented beam elements have represented human arms for automobile air bag upper extremity injury assessments (e.g., Bass et al., 1997). One important caveat for test method biofidelity is that a more complex surrogate does not necessarily imply a more biofidelic surrogate. Often the increase in complexity can reduced biofidelity. Parameters for biofidelity of a human surrogate include representative anthropometry, mass, mass distribution, and localized force-deformation characteristics in the regions of interest.

Engineering measurement – a physical response parameter such as displacement, acceleration, or force, are often used to characterize the physical response of the test methodology or test surrogate device. These response measurements may be used as input metrics for injury criteria assessments.

Injury risk evaluation – the injury basis for a methodology is often an association between an engineering measurement and some injury model (either cadaver, live animal, or epidemiology). Often, this injury risk metric must be scaled from the injury model, particularly in live animals, to be applicable for use with a test methodology predicting risk in humans.

Validation by injury model – the validation of the injury risk evaluation is a particularly important part of the test methodology development. As noted by Bass et al. (2005), “*An injury risk model is without value without successful validation using 1) epidemiology or physical reconstruction of an actual injury event, 2) an animal injury model, or 3) a cadaveric human injury model. Development of a relationship between a robust surrogate for injury and a validated injury model is crucial in the success of this approach*” (p. 347-361).

Injury epidemiology is often helpful in informing test surrogate design, development and its instrumentation as well as in defining test conditions for a test methodology (cf. Bass et al., 2005). It is important to note, however, that epidemiology studies are retrospective and have limitations in predicting real world outcomes for future changing conditions.

For the BABT test methodology, test surrogate selection is critical as its design will limit the potential engineering measurements, and both the surrogate and its measurement capabilities are needed to establish the injury risk function and its validation. The surrogate structure needs to possess sufficient biofidelity characteristics such that its influence on the armor's performance is representative of the human torso. Yet, the surrogate's design must accommodate the needed instrumentation for confident injury assessments. Note that human cadavers, animal cadavers, and live animals are often used as surrogates for living humans. Though these are useful for research, they would not generally be used to assess production armor systems.

BABT Test Surrogate Classifications

Existing nonbiological surrogate ballistic impact simulators may be divided into three classes as shown in Figure 15. The first class may be characterized as bulk tissue simulants; they are comprised of a single layer of material and are characterized by deformation response (e.g., post-test residual clay penetration depth or dynamic gelatin penetration depth). The second class, or instrumented response elements, generally includes a simplified thoracic wall that simulates the motion of the surface and may incorporate multiple layers. The third class is instrumented detailed anatomical surrogates. These generally include some form of thoracic viscera and are designed to investigate a wide range of forcing conditions. It is defined henceforth as a research device if it includes internal thoracic organs. A subset of the third class includes biological surrogates such as human cadavers, live animals, or animal cadavers. Use of these generally trades more expense and complexity for greater potential biofidelity.

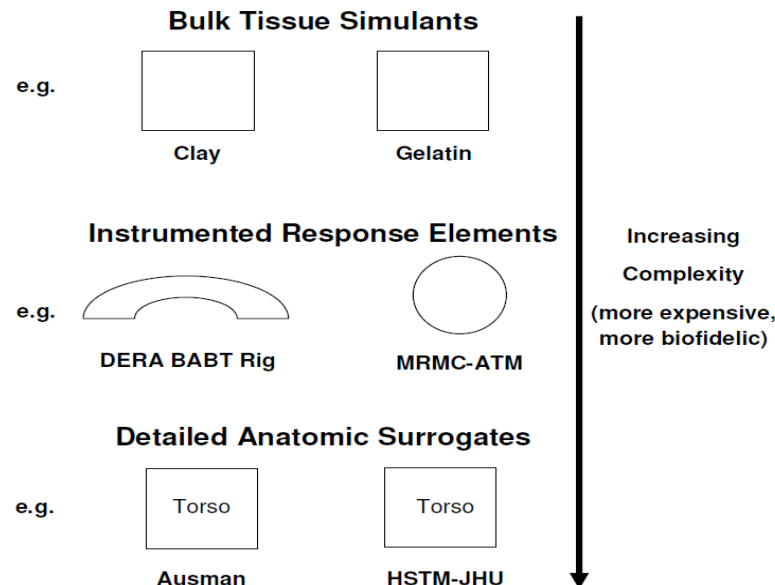


Figure 15. Several BABT assessment devices and methodologies exist. There is a hierarchy of potential models that generally trade biofidelity, expense, and complexity. Reproduced from National Academies of Sciences, Engineering, and Medicine (2012) with permission from The National Academies Press.

All three classes of BABT test surrogates possess attributes that provide benefit and useful information. However, there are tradeoffs as devices run from simpler to more complex; this usually implies less expensive to more expensive, but devices with higher complexity generally have the potential to assess more detailed injury criteria. For instance, it is difficult to evaluate complex BABT interactions, especially for very lightweight body armor systems, without detailed anatomical surrogates. It is advisable to use a relatively inexpensive bulk tissue simulant or instrumented response element for production testing to avoid the potential for penetrating events that would destroy an expensive test device. Each class of devices may have an advantage for a given test condition. The three classes of devices are discussed below.

Bulk Tissue Simulants

Bulk tissue simulants are characterized by a single, ideally isotropic and homogeneous layer. This surrogate type is generally the simplest but may have substantial limitations in representing thoracic biomechanics, especially across varying loading rates and different thoracic regions. Though many bulk tissue simulants have been considered, including those investigated in the original Prather study discussed above, this report only briefly touches on clay, synthetic clay, and ballistic gelatin. While the use of an alternative response element may alleviate some of the undesirable aspects of clay (e.g., temperature sensitivity), tradeoffs may be introduced relative to human regional thoracic response and injury assessment values. All bulk tissue simulants must be validated using matched-pair testing with a combination of epidemiological reconstruction of actual live fire events in humans, human cadaveric torso response in an appropriate demographic cadaver, or biofidelic simulation using advanced numerical models that include validation with living and cadaveric torso models.

Clay.

The current BABT test surrogate material is a commercial clay material, RP1 (NIJ 0101.07 and ASTM E3004) is the current simulant used to measure body armor backface deformation distance. Its selection for use and its limitations were described above.

Ballistic gelatin.

Hydrated gelatin (Kind & Knox, Sioux City, IA) is a commonly used test device for evaluating ballistic penetration in tissues. Introduced by Harvey et al. (1962), gelatin at 20% by mass at 24 degrees Celsius (°C) was used to investigate ballistic penetration. Fackler and Malinowski (1985) introduced a test methodology using 10% ballistic gelatin by mass at 4 °C. For this formulation, the ballistic temporary cavity, permanent cavity, and penetration were like that seen in living tissue.

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Figure 16. A 9 mm bullet was photographed while traversing ballistic gelatin. The image shows a bullet traversing the gelatine block, entering on the left and exiting on the right. There is a large temporary cavity seen in the block for the entire bullet path and material is exuded on the right following the bullet shear (Groover & Boor, 2014).

The 10% and 20% gelatin are linear materials with little viscoelastic response (Bass et al., 1998). However, human tissue has a strong viscoelastic character. The high shear rate response from penetrating impacts is similar to living tissues; however, the lower rate blunt impact properties of ballistic gelatin are unlikely to be similar to human tissue.

As a practical test device, gelatin is difficult to handle and degrades over time though it is still used regularly as a test device by the Army Research Lab (Kinsler, 2008). Further, the properties may vary with production technique. Gelatin blocks are not generally reusable, and the local properties change with large deformation impacts. This may limit the usefulness of the gelatin for repeated testing.

However, gelatin may be useful for simulating viscera, though work is necessary on skin or membrane encapsulation. In tests with non-lethal munitions, Bir found difficulties with round penetration (Bir, 2000). Further issues include the fact that local ballistic tissue failures seen for blunt tests are unlikely to be representative of human tissue if the penetrating properties are similar.

Ballistic gelatin at 20% by weight has been used in cooperative testing with Natick Soldier Center and Defense Evaluation and Research Agency (DERA). The tests include body armor with a ceramic plate and a UHMWPE laminate. The test round was a 7.62 mm M80 ball round at 838 m/s nominal velocity. These tests are matched with tests performed with the DERA BABT Simulator to assist with the validation of the physical models.

Recent plastic deformation and plastic simulants.

Army Research Laboratory (ARL) Reusable Temperature Insensitive Clay (ARTIC).

The ARL has developed a clay substitute material called the ARTIC. This material development effort originated from recommendations by the National Academy of Sciences Committee on Body Armor Testing (2012). The intent of this material development effort was to provide an alternative to RP1 that provides deformation responses at room temperature similar to the initial RP1 of 1976. Gardner et al. (2023) reported a clay-like simulant with a similar

response to the current calibrated Roma Plastilina clay at elevated temperatures. Based on the BFD data presented by Gardner et al. (2023), the ARTIC clay simulant response appears to have a +/-7 mm variability for the conditions tested. Evaluation of rebound using this simulant was not reported. Efforts are ongoing to make this material available commercially and to phase in ARTIC as an acceptable substrate for BABT assessments during armor system acquisitions. However, use of ARTIC as a BABT bulk tissue simulant retains the same injury assessment limitations of RP1.

Styrene-Ethylene-Butylene-Styrene (SEBS).

SEBS is a thermoplastic elastomer with the general structure polystyrene-b-poly(ethylene-co-butylene)-b-polystyrene. A 25% concentration of SEBS was developed for both ballistic trauma (Mrozek et al., 2015) and blunt trauma (Bracq et al., 2021) as a substitute for ballistic gelatin for deformation depth studies. Since it is generally opaque, direct video assessments are difficult. This material has generally been assessed against soft body armor with reportedly similar response to RP1 clay, gelatin, and porcine thorax (James & Keirl, 2023). However, since RP1, for example, has substantial limitations in reproducing armor backface thoracic human response, the fidelity of this response should be further investigated. Anecdotally, SEBS construction is sensitive to method and manufacturer. So, further investigation is needed for repeatability and robustness in time and by construction technique.

Instrumented Response Elements for BABT Testing

The instrumented response element is designed to simulate the average behavior of the thoracic wall including surface tissue (skin, subcutaneous tissue, bone, mediastinal contents or lung, etc.). The characteristics of several existing devices are reported below, including the parameters measured and injury validation used. The tradeoffs involved in constructing such a device involve simplicity and ease of use versus biofidelity. Laboratory instrumentation measures time histories or responses, including deformation, acceleration, or other physical parameters that are correlated with injury response developed for this model.

DERA BABT simulator.

The United Kingdom (UK) DERA has developed a test device intended to evaluate the injury effect of behind armor blunt trauma, the DERA BABT rig (Tam et al., 2000). A half-cylinder silicone rubber chest wall (GE Silicones RTV 428) was developed by Cooper et al. (1996) that provided rotation and vertical positioning. This rig provided adjustments for response elements with varying thicknesses if desired. The primary physical model was derived from a finite element model that included high-rate blast and blunt response of the thorax.

The assumed BABT injury mechanism for this physical model is that injuries are a function of chest wall motion, including displacement, velocity, acceleration, and deformation profile. This may be postulated based on porcine organ damage being caused by impact pressure waves and subsequent displacement.

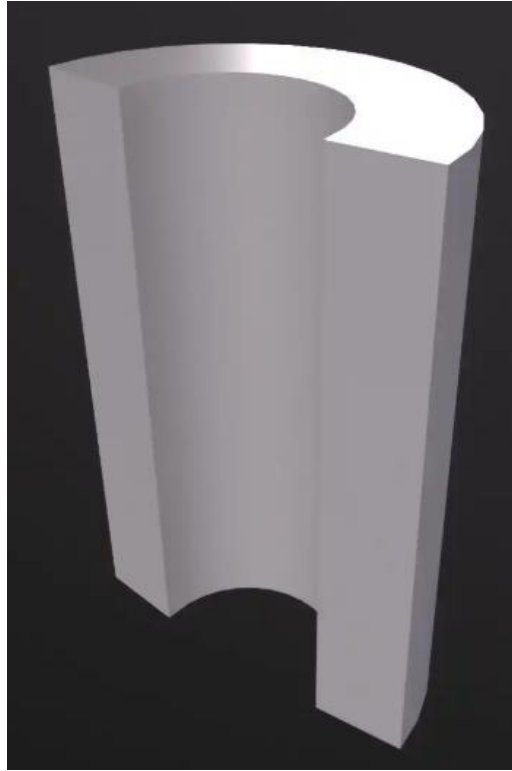


Figure 17. The DERA BABT response element was intended to evaluate the injury effect of behind armor blunt trauma.

The test device uses a novel laser deformation sensor array system to measure the time history of displacement of the back wall surface of the response element. The deformation sensor is kept outside the bullet trajectory and may provide velocity and acceleration response of the backface of the test device.

The body armor was tuned to lateral eviscerated pig baton data and tested against a 12.7 mm AP round against the UK Enhanced Body Armor and a 7.62 NATO ball against Improved Northern Ireland Body Armour (INIBA). Validation studies included both lateral and anterior shots. Peak accelerations were comparable between the BABT rig and lateral pig shots. These accelerations were approximately 20,000 G for the 7.62 mm test round and INIBA armor. However, the response of the anterior porcine chest wall varied somewhat from the rig behavior. As the rig was developed using lateral impacts, this is not surprising.

Details of eviscerated pig data 7.62 rounds at 3 kilojoules (kJ) behind commercial ceramic body armor with six eviscerated and six intact pigs are reported by Cannon et al. (2000). The velocities of the physical and eviscerated models were similar at 15.2 m/s and 9.6 m/s, respectively. Peak displacement of 12.6 mm was seen in the eviscerated pigs, and a peak displacement of 7.8 mm was seen in the intact pigs. Local peak acceleration was approximately 13,000 G. The mean time to peak displacement was found to be approximately 2.7 ms. The viscous criterion of 0.29 m/s was seen for both. The DERA BABT device has been used in cooperative testing with Natick Soldier Center (now named the U.S. Army Combat Capabilities Development Command Soldier Center [DEVCOM SC]). The tests include body armor with a

ceramic plate and a UHMWPE laminate. The test round was a 7.62 mm M80 ball round at 838 m/s nominal velocity. There are two significant drawbacks to this system. First, the system has been tuned to a specific thoracic wall velocity. Outside this regime, it is unlikely to respond appropriately to the rear face impact. Second, the simulator is shaped like a cylinder, and the laser system relies on this cylindrical shape to operate properly. As the human body is not cylindrical, it is difficult to use for the evaluation of actual body armor. To enhance the system, a different displacement measuring system could be developed using multiple instances of a diffuse laser time of flight system.

DREV Torso Injury Assessment Rig (Bourget et al., 2002).

Defense Research Establishment Valcartier (DREV) has developed a thoracic injury assessment rig that is similar to the DERA BABT simulator as shown in Figure 18. However, both the material of the simulator and the geometry have been altered and tuned to the material response of Bir for nonlethal baton impacts (2000). It has similar characteristics and performance to the DERA BABT rig. Testing has been performed to optimize the mechanical properties to the material response of Bir. This rig has been further developed into the Blunt Trauma Torso Rig (BTTR) and a flat version the flat BTTR (fBTTR). All incorporate laser measurement technology (Bolduc & Anctil, 2010, Shewchenko et al., 2020).

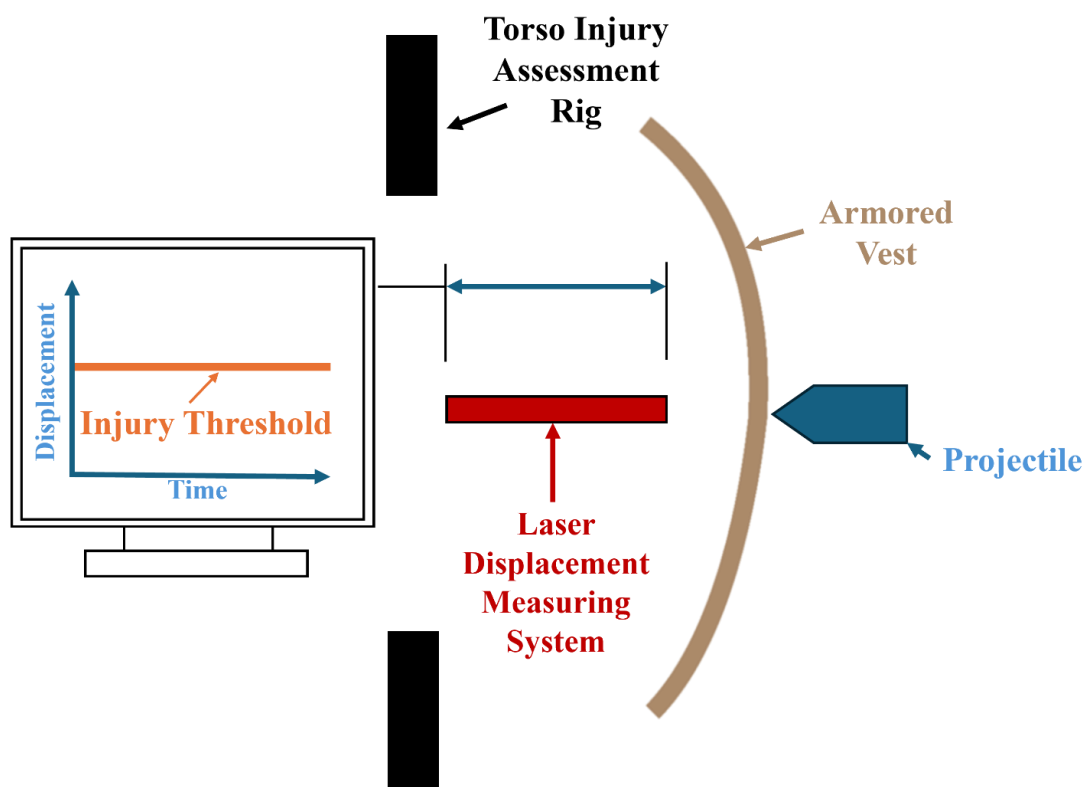


Figure 18. The DREV BABT simulator displacement sensor system is similar to the DERA BABT simulator.

Anter Company (Mirzeabassov et al., 2000).

A private company in St. Petersburg, Russia patented a more complicated response element comprised of a multi-layer thorax simulator (Figure 19). This simulator was also covered under U.S. Patent 5850033. The simulator was proposed for penetrating and blunt injuries. It included an outside skin layer, a layer of muscle-simulating material, and a layer of bone-simulating material. The muscle layer was comprised of several additional layers. These include a layer of muscle-simulating tissue (4), a layer of carbon paper or other indicating paper (5), a layer of cellular material such as nylon-6 net (6), and two layers of paper (7) separating the muscle simulant from the other layers. The paper was used as a brittle strain-sensitive material to indicate the strain level inside the simulant and approximate the temporary cavity during penetrating injury and determine the extent of local deformation for blunt trauma.

The skin simulant was composed of vulcanized rubber with mechanical properties that approximate those of skin tissue. The muscle layer was comprised of non-vulcanized rubber. The properties of the layers were selected to match the low-rate physical properties of human tissues. The frontal area of the target was a 40 cm by 40 cm square, with a muscle layer thickness of approximately 10 to 12 cm, and the target weight was approximately 20 kg.

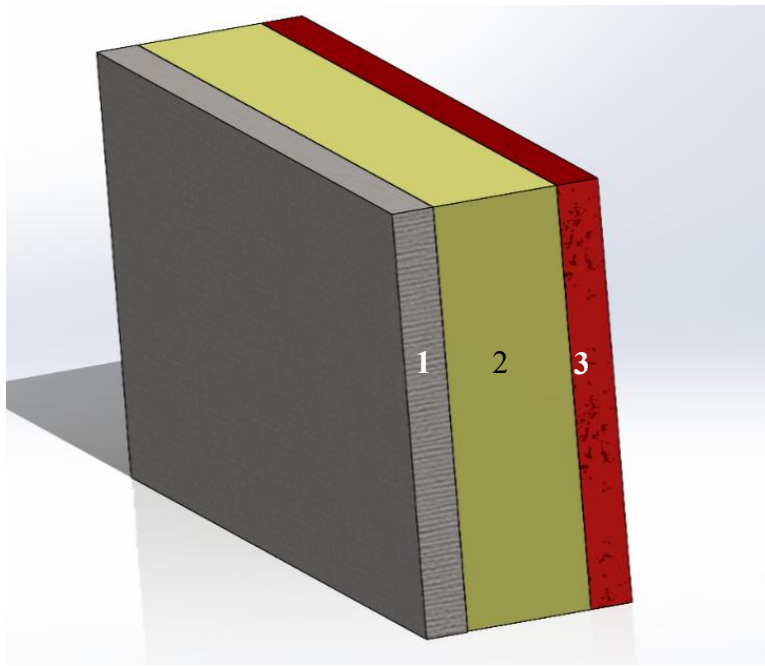


Figure 19. The layers of the Anter thorax simulator include the skin simulant (1), muscle simulant (2), and bone simulant (3).

There is no electronic instrumentation for this simulator; penetration or injury is indicated by paper between layers. The construction is reusable; the paper indicator layers may be replaced. Additionally, these layers could be augmented with Fuji pressure-sensitive film. The basis for this injury model is experimentation using small dog subjects. Validation rounds include 7.62 mm with two impact energies, a 5.56 M16 rifle (M16A1) and a 5.45 mm assault rifle (AK74). The validation included local thoracic deformation evaluated using flash x-ray.

These assessments are generally penetration assessments, though some assessments were conducted using thoracic body armor, generally of light titanium construction.

ATLAS torso.

A recent response element was developed by the Johns Hopkins University Applied Physics Laboratory (Perrino & Johns Hopkins University Applied Physics Laboratory, 2022) under contract with the U.S. Army DEVCOM SC. The original approach consisted of rigid support and connected load cell overlaid by a response element to simulate thoracic response (Figure 20). It is intended to provide a repeatable surrogate to replace the Prather methodology for some body armor testing. Some essential design requirements were affordability, repeatability, reliability, and association with some injury risk for BABT. The intent was to also provide support for computational modeling of BABT testing of armor materials.

There are no published injury assessments or correlations using this system, and no data on repeatability or reliability. However, principal limitations of such systems include the following:

1. *The response of the load cells.* Since load cells respond with a timescale that is characteristic of their construction, one potential issue is mechanical ringing that is not representative of soft viscoelastic human thoracic response. Additional details of load cell range and frequency response often present issues at ballistic rates.
2. *The response of the simulated torso element.* Since both the armor behavior and the injury response depend on biofidelity of the armor backing response element, the response element must have biofidelic displacement/velocity/acceleration response for the typical backface behavior of the armor. Off axis hits will also increase the likelihood that the axial load cell response of a deformable material is not the load cell response if the load cell were under the material at that location.
3. *Insufficient localization of the response.* Given that the task of the body armor is to rapidly expand the engagement of the armor material under the load of the bullet, a “perfect body armor” would immediately transfer all the momentum of the bullet into the body armor. Such an instantaneous force transmitted to the load cell would likely be larger than that of a more localized impact more slowly and incompletely transferring momentum. However, the latter type of impact has a much greater risk of BABT owing to localization of the armor displacement.

Based on these issues, care must be taken in ensuring a biofidelic response surface for humans (likely needing > 50 mm thickness characteristic of other response elements) and likely a need to increase the number of independent load cells to avoid load cell bending crosstalk and other effects.

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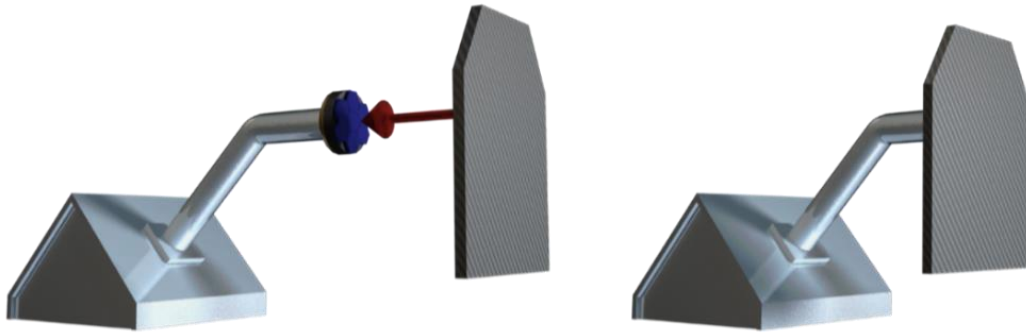


Figure 20. The JHU ATLAS Torso consists of a load cell with a response surface offset from a rigid support (left) and the complete assembly of the plate and support (right) (reproduced with permission from Michael Maffeo, U.S. Army DEVCOM SC).

Based on concerns expressed by the Army, this initial load cell approach was abandoned and an alternate approach pursued. This second approach consists of rigidly supporting the armor edges and optically recording the armor's dynamic backface deformation response with a high-speed video camera. Analysis of the high-speed video with a digital image correlation technique provides the ability to calculate surface displacement kinematics. To better represent the "as worn" armor system configuration, various methods to include a standard shoot pack behind the armor plate are being considered along with attempts to improve visual image quality. This alternate ATLAS BABT concept is illustrated in Figure 20. An advantage of this test methodology is the dynamic response of the armor's backface surface is recorded, which may prove beneficial for production lot acceptance purposes. However, a disadvantage is the lack of a backing material with deformation properties that are representative of the human, which could influence the armor system's ballistic and BFD performance and pertinent injury assessments.

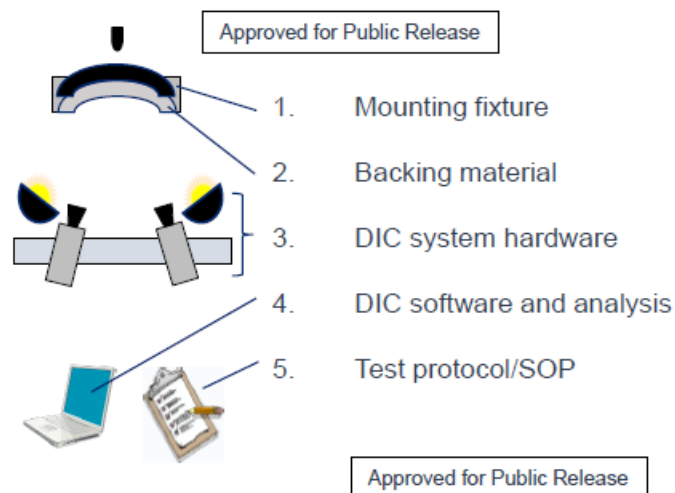


Figure 21. The alternate JHU ATLAS BABT concept uses digital image correlation to record dynamic armor backface deformation reproduced with permission from Michael Maffeo, U.S. Army DEVCOM SC.

Instrumented Detailed Anatomical Surrogates

The final class of instrumented surrogates is detailed anatomical surrogates. These surrogates include anatomical features similar to humans, generally including internal organs. In principle, when validated, these may be appropriate for the investigation of more complex behind armor phenomena. Owing to the complexities of design and instrumentation, use of these devices may be best suited for research and armor system development efforts, to potentially include first article tests, but it is unlikely these devices will directly form the basis for large-scale testing efforts such as for production lot acceptance of body armor components and systems.

3-Rib Chest Structure (3RCS).

Bir (2000) developed a physical model with a response element, as shown in Figure 21, for the purpose of assessing the lethality of non-lethal munitions. This surrogate design leveraged components from a Biofidelic Side Impact Dummy (BioSID) rib structure, augmented with a high rate (up to 10 m/s) linear displacement transducer. The three ribs are mounted to an 18.1 kg spine box opposite the impact side, and viscoelastic damping material is incorporated into the ribs to provide bending resistance and energy dissipation. Nylon supports are mounted between the ribs to provide additional lateral support and to prevent large transverse rib motions. The impact surface was a urethane plate with a vertical dimension of 15.5 cm and a horizontal dimension of 23 cm. A nitrile shock damping padding covered the urethane bib for preliminary tests (Bir, 2000).

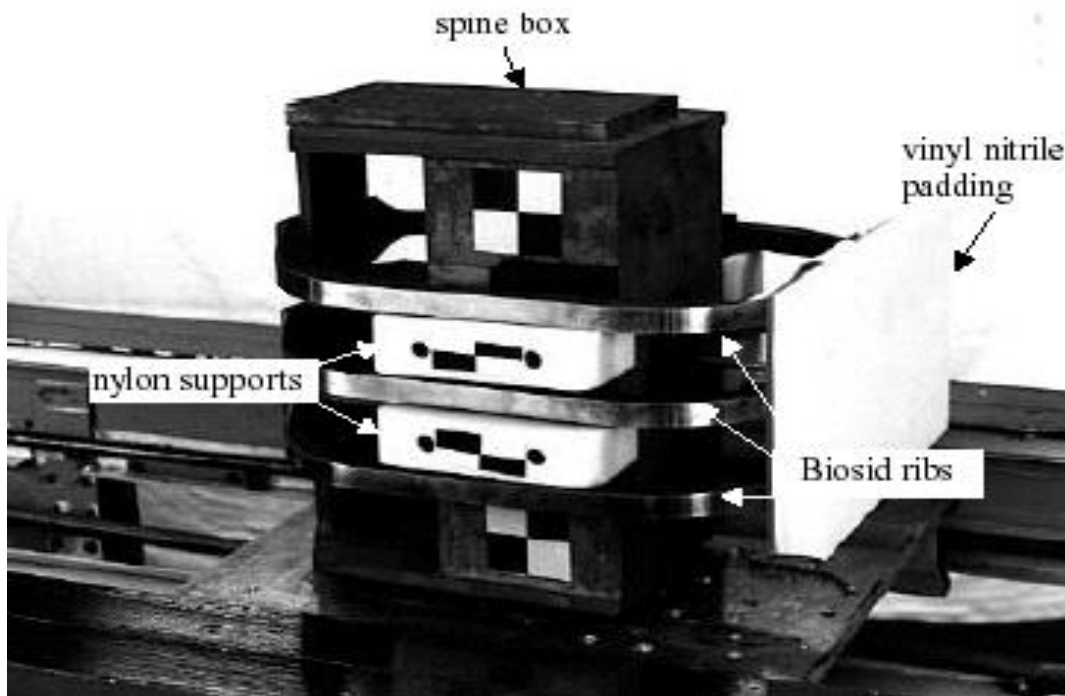


Figure 22. The 3-Rib Chest Structure (3-RCS) developed by Bir (2000) combined the advantages of the Hybrid III dummy loading surface and the BioSID dummy's continuous rib structure. Reproduced with permission from Cynthia Bir, Ph.D.

The model was validated against the UK baton round (instrumented baton – 140 grams) at 20 m/s, 40 m/s, and a reduced scale 30-40 grams at 60 m/s impact velocity with corresponding initial impact energies of 28 Joules (J), 112 J, 72 J, and initial impact momentum of 2.8 kilogram meters per second (kg m/s), 5.6 kg m/s, and 2.4 kg m/s. The impact location was sternal directly on the thorax.

Thirteen cadaveric specimens were used, with approximately 15th percentile male anthropometry. The data were normalized by standard techniques often used as a source of validation data for relatively low energy, high momentum impacts. The scaling is based on geometric similarity (Eppinger et al., 1984) and chest depth was used as the scaling factor λ in Equation 5, where

$$\lambda = 50^{\text{th}} \% \text{ Male Chest Depth} / \text{Subject Chest Depth} \quad (5)$$

All dynamic quantities may be scaled using this factor. For instance, displacements are scaled as Normalized Displacement = $\lambda \times$ Measured Displacement. Bir developed response corridors (force vs. deflection) for each velocity impact; they are significantly different. Three thoracic ribs are used. This assumes localization of impact with limited effect outside the area. The model was originally developed for use with baseball impacts in evaluating commotio cordis injuries.

The model has sensor limitations at higher kinetic energy. The measured displacement and video displacement were not always the same, and differences in the displacements were exacerbated at higher kinetic energies. As the energy delivered to the thorax was relatively low and dispersed, this effect was expected to increase with increasing kinetic energy. In addition, the materials used were tuned for impacts with a specific energy and momentum. It is unlikely that they will be appropriate for use outside the specified range.

Hybrid III (HIII) crash test dummy.

The standard automobile frontal crash test dummy, the Hybrid III, has been used by several investigators for high-rate impact. In addition to the use discussed above by Bir (2000), the HIII has been used by Chichester et al. (2001) for mine blasts and high-rate impacts from blasts in structures (Bass, 2001a; Chichester et al., 2001; Bass, 2001b). The rib structure of the HIII consists of six ribs constructed of steel overlaying a viscoelastic damping material. The ribs are connected in the front to a sternal bib, and a single displacement sensor located at the sternum is standard instrumentation. This single displacement sensor has significant limitations (Shaw et al., 2000). Enhanced instrumentation is available with an array of string potentiometers. The use of the HIII has several advantages. The dummy is widely used and is manufactured in several different sizes, representative of various standard anthropometries.

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There are several substantial drawbacks to using the HIII as a ballistic BABT test device. The dummy is validated for low-velocity impacts. Further, the local response of the HIII is likely not biofidelic, even for these low-rate impacts (cf. Kent et al., 2006).



Figure 23. The standard automobile frontal crash test dummy, the Hybrid III, has been used by several investigators for high-rate impact. The 50th percentile male dummy is shown. Reproduced with permission from Humanetics.

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Anthropomorphic Test Module (ATM) – U.S. Army Medical Research and Development Command.

This surrogate was developed by the U.S. Army Medical Research and Development Command as an instrumented response element as a part of an injury assessment methodology for BABT as shown in Figure 23. The shoulders of the torso are not instrumented but provide an anthropometrically correct platform for mounting body armor as worn by Soldiers. The response of the ATM element was measured using a multiple accelerometer array implanted within a polymer with approximately cylindrical form. The initial peak impact response was mitigated using a rubber pad over the surface of the response element as shown in the center of Figure 23.



Figure 24. The ATM with mounted body armor (left) is shown without body armor (right) to reveal the response element within the torso. The ATM instrumented response element with padding is shown in the center. Reproduced from Leggieri (2010) with permission from The National Academies Press.

The essential elements of this methodology are:

1. The development of a detailed anatomical finite element model of the human
2. Identification of the global mechanical response and injury response in animal and cadaver tests for impact with hard projectiles
3. Development of a simple response element with a mechanical response that is correlated with animal and cadaver tests
4. Validation of the human finite element model with animal and cadaver tests
5. Correlation of the response element deformation with finite element model calculations and hence animal and cadaver injury response

The computational finite element analysis model was based on 30 moderate-rate porcine and 12 low-rate blunt impactor cadaver tests (Figure 25). Generally, test impact velocities did not reach those typical of high-rate impact behind hard body armor. Limited model validation was performed using animal and cadaver tests for the finite element model. The response included a global response of the model and surrogates for a limited number of instrumentation locations.

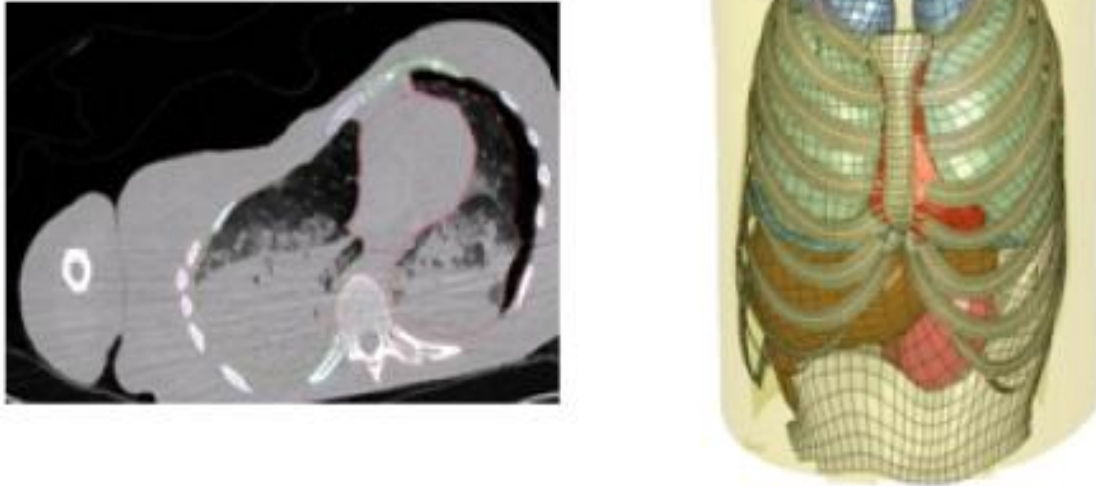


Figure 25. A human CT scan (left) was used to create a detailed anatomical finite element model (right) of the human torso with ribs and internal viscera. Reproduced from Leggieri (2010) with permission from The National Academies Press.

Though the model provides an acceptable correlation with automobile impact corridors (Kroell et al., 1971, 1974), these automotive loading conditions are quite different from the loading characteristics associated with BABT impacts. The principal limitation of the ATM surrogate is the lack of robust validation data for rates typical of impact behind hard body armor at typical rifle round velocities. Further limitations of the model involve the derivation of the ribs' beam formulation from global stiffness validation data.

The presenters raised research questions related to the ATM's response to penetration, repeatability of measurements including the potential for material properties changes in the rubber with repeated shots, and the basis of the model validation (Leggieri, 2010). These issues are the subject of ongoing research.

Owing to using the complex finite element model for injury assessments, the ATM model and associated finite element model are more complex than the typical response elements considered above and likely represent a transition device between instrumented response elements and detailed anatomical surrogates.

AUSMAN (Australian – Defence Science and Technology Office).

AUSMAN is a reusable mechanical surrogate developed by the Australian Department of Defense - Defence Science and Technology Organization. The 21 kg mass torso surrogate is shown in Figure 27 with body armor mounted to the torso. AUSMAN consists of a polymeric skeletal system enveloping a simulated cardiopulmonary system and liver; it incorporates an anthropomorphic rib structure and a realistic spine. The entire thorax is encased in polymer with gel couplant between the internal viscera and the rib structure. The lungs are based on open cell foam, and the surrogate includes simulated heart and liver. Further, the design currently includes a mount for an HIII head/neck into the dummy to provide the potential for neck injury assessment.

Mechanical response is measured by accelerometers in the sternum and mid-thoracic spine and pressure transducers in the lungs. The structure was designed so that implanted sensors could be easily replaced. AUSMAN has limited validation for blast (Bass, personal communication, 2007), though a previous version was correlated against sternal ballistic response in cadavers (Bass et al., 2006). The blast version of the dummy surrogate is currently under development.



Figure 26. The AUSMAN thorax is shown with body armor in place prior to testing. Note the protrusion from the neck is a simulated trachea. Use of this trachea and the Hybrid III neck mount would need to be coordinated with a custom neck and lower neck load cell.

National Defense Research Institute Anthropometric Dummy (Sweden).

The Swedish National Defense Research Institute (Jonsson & Shantz, 1988) developed a thorax model used for blast, ballistic blunt, and missile impacts. The thorax was enclosed by a rubber tube with a thickness of 6 mm with an elliptical shape that is 35 cm laterally and 25 mm in the anterior/posterior direction. Internal viscera were simulated by a water-filled cavity that included cylindrical foam rubber surrogate lungs. These lungs had a diameter of 10 cm and a length of approximately 20 cm. The lungs were sealed using a thin rubber shell to prevent water infiltration. The lungs were positioned in the chest using wire mesh and strings that were rigidly

mounted at each end of the thorax model. The geometric relationship between the simulated lungs and the thorax is shown in Figure 28. Each simulated lung included a pressure transducer located at the center of the lung structure.

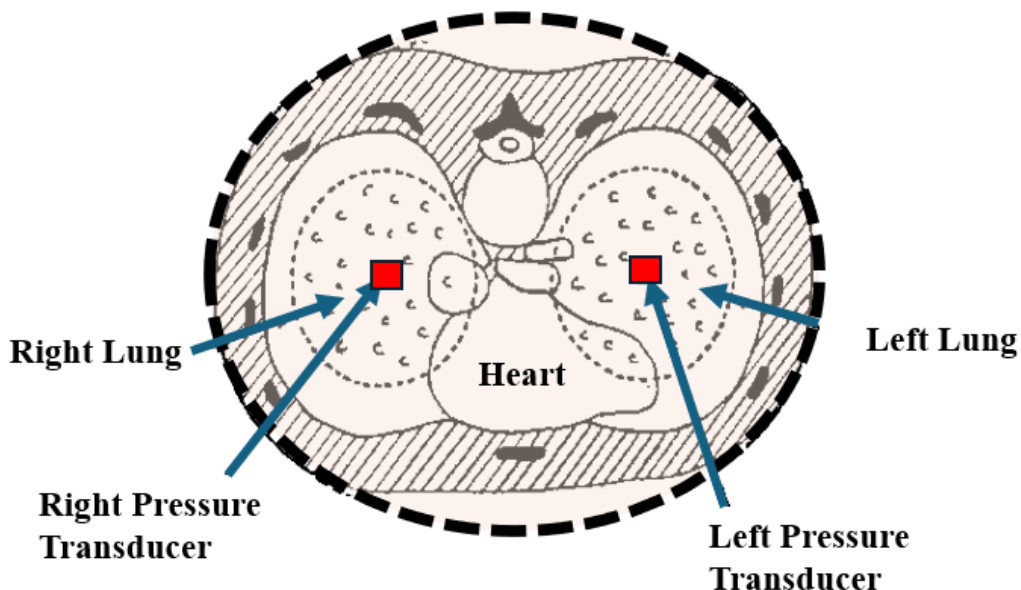


Figure 27. An internal cross section of the Swedish National Defense Research Institute Anthropomorphic Dummy is compared with a cross section of the human thorax at the level of the heart. The dummy is represented by dashed lines. Adapted from Jönsson et al., 1988.

Experiments using this model were performed using a shock tube, a pendulum device, and ballistic impact behind body armor. Test rounds included 7.62 mm at 870 m/s in both soft point and FMJ, a 9 mm submachine gun at 430 m/s, and a 37 mm anti-riot baton round at 76 m/s. Body armor for the rifle rounds was a 10 mm thick polyethylene trauma pack, 17-ply K29, and a 10 mm ceramic plate. For the 9 mm round, the body armor used a 2.3 mm steel plate instead of the 10 mm ceramic plate. For the baton round, no body armor was used. Impacts were performed at the mediastinum with energies that ranged from 0.2 kJ to 5.6 kJ.

Intrathoracic pressure was measured for impact with the various rounds tested and compared with lateral rabbit impact experiments using the pendulum impactor. An injury scale for inter-lung pressure was developed using pendulum impacts with velocities of approximately 5 m/s that were stroke-limited to 10% thoracic compression. They found that the blast pressure peaks were far larger in the blast experiments than in the impact experiments for similar levels of lung damage. So, they concluded that dummies validated for blast pressure would not be calibrated for blunt impacts using the same pressure measurements. The scale concludes that the impact of a 7.62 mm test round at 3.2 kJ behind a trauma pack, ceramic plate, and K29 body armor has a low risk of lung injury.

The researchers saw small (~10% of peak) oscillations in the pressure signal at approximately 3 kHz. They concluded that the oscillations were related to gross resonant structural response. There are significant questions regarding impact injury with mediastinal forcing using injury indices developed in a different velocity regime for lateral impacts. Further development of this surrogate is unknown.

Instrumented Model Human Torso (Johns Hopkins Applied Physics Laboratory).

Another research device for ballistic impact was developed by a team at Johns Hopkins University (JHU) Applied Physics Laboratory. At least two versions of this model were produced, one frangible and a more robust reusable model.

Frangible JHU Model.

This proof-of-concept model included rib, sternum, and spinal structures. Internal organs are represented as homogeneous viscera of urethane. The model has a fat layer and outer skin with a sensor pad between the skin and the fat layer. A concerted attempt was made to select materials with biofidelic response characteristics. There has been no reported validation at high rates. The bone material was chosen to be frangible with a failure modulus similar to human values. The design is intended to allow rapid replacement of frangible components (M. Bevan, personal communication, 2002).

Instrumentation includes a sensor pad and an array of eight piezoelectric elements. These elements are sensitive to bending, limiting the potential use as force sensors. An additional four sensor sheets were used, a resistive flexure grid twinned with the anterior pad, and additional piezoelectric and resistive flexure grids located 0.5 inches inside the rib structure. These sensors were designed to fit locations used. An additional piezoelectric pad was located internally at the location of the heart.

Data from the anterior piezoelectric sensor array was sampled at 10 MHz and the remaining arrays were sampled at 25 kHz. This lower data rate does not appear to be an intrinsic limitation in the data rates of the piezoelectric sensor arrays.

Preliminary testing was performed with soft body armor (Type II). Rounds tested included 9 mm at 330 m/s and .357 Magnum jacketed soft point bullets at 420 m/s. Analysis of only the anterior piezoelectric element was reported. The researchers draw a correlation between the measured peak voltage of the array and entering kinetic energy. There was no reported analysis of additional arrays.

The advantages of this model are that it is potentially extensible and potentially well-instrumented. However, the calibration of the sensors may be difficult. Extensive experience with the integration of bending elements across linear and planar structures (Bass et al., 1998) suggests that it is difficult to perform this integration without substantial error. In addition, the piezoelectric materials used for compressive force are generally extremely sensitive in bending. Further, the model is frangible. It is difficult to produce a cost-effective model with frangible components.

Reusable JHU Model (Human Surrogate Torso Model).

The reusable JHU model (Human Surrogate Torso Model [HSTM]) is shown in Figure 28 and was produced in two anthropometric versions (5th and the 50th percentile human anthropometry). It has a detailed anthropomorphic skeletal structure with overlying skin, internal organs, and viscera. Internal organs include the heart, lungs, stomach, and intestinal mass. The model is constructed from ribs with fracture and bending properties of bone, and organs constructed of silicone polymers. The high-rate material properties of these organs have not yet been compared with high-rate human material properties.

Sensors used in the torso included sternal and spinal accelerometers, and pressure sensors at various locations (Figure 29). Additional instrumentation may include a vertebral load cell, surface pressures and loads, strain gauges for bone simulants, and the potential for displacement sensing.

The HSTM has been used in NIJ soft body armor tests to characterize mechanical response (Roberts et al., 2007; Merkle et al., 2008). Tests include 9 mm threats at 436 m/s incoming velocity. The responses have further been correlated with clay responses. The device has no validation against an injury metric and is still in development.

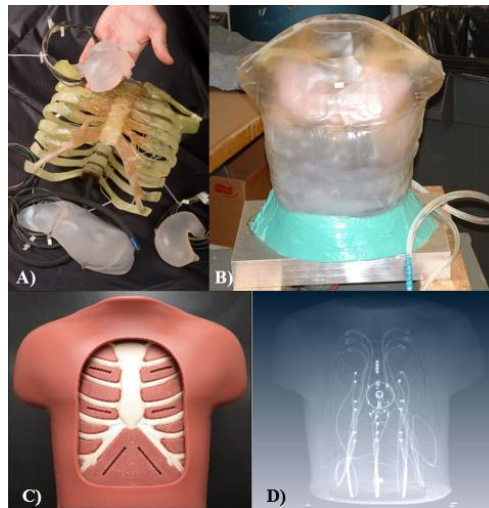


Figure 28. The skeleton and organs of the original HSTM included the ribs, sternum, cartilage, vertebral column, heart, liver, and stomach. (A). The HSTM was covered with simulated muscle and skin (B) after the pressure sensors and accelerometers were affixed. The newest version of the surrogate has a cut away and holes to access the sensors (C). A radiograph of the surrogate shows the internal wires and sensors (D). Figures reproduced with permission from Andrew C. Merkle, Ph.D.

CTS PRIMUS.

A frangible torso for use with ballistic testing (PRIMUS), particularly behind armor blunt trauma assessments, has been developed by the German manufacturer CTS. The response of this frangible torso was reported by Jenerowicz et al. (2023) using simulated backface deformation of hard armor plates of ceramic and UHMWP with impact from 7.62 mm × 51 AP8 rounds. The

simulator was a polycarbonate indenter at up to 230 m/s incoming velocity. Response results were compared with PMHS data from Bir (2000). Limitations include the frangible nature of the dummy, uncertain construction and quality control for assessments across models.

Biological surrogates.

Generally, the most complex surrogates for BABT injury assessments are biological surrogates. These have been used on a limited basis for research and development purposes. Three different types of biological surrogates can be used, each with their benefits and limitations. These types include human cadaver, deceased animal, and live animal. All require specialized training of the research staff and the research conduct must follow strict ethical and care guidelines. Human cadaver surrogates generally provide appropriate anthropometry for donning body armor systems and the tissue can receive injury similar to living humans. However, specimen availability and selection may be limited. Numerous animal types (caprine, ovine, canine, porcine) have been used to assess BABT effects. Like the human cadaver, animal models can all reveal structural and tissue damage. However, the fit of armor on the animal is generally less than optimal and results often involve mass scaling to translate results to human. A limitation of research that involves deceased tissue is its inability to provide physiological results. If physiological results are needed, then a living surrogate is needed. The use of any biological tissue for research is expensive, time consuming, and requires specialized expertise, thus it is rarely used for body armor testing programs and justifies the investment into development of BABT surrogates for the research and testing body armor systems.

Summary and Discussion – Instrumented Alternatives to Clay

Several existing test devices are potentially suitable for developing a test methodology for ballistic BABT. Each may have unique advantages for a given test condition, though none are widely used in BABT hard armor testing. All likely need further testing and validation. For such testing, two aspects must be considered. The first is the biofidelic response of the surrogate, and the second is the validation of the mechanical correlate from this model with an injury model. Each surrogate class has advantages. For example, the bulk tissue simulant like the RP1 clay as a BABT surrogate is inexpensive and easy to use, which makes it an attractive model in activities like production contracts that require frequent and repeated tests for demonstrating contract performance compliance. A significant drawback of the RP1 clay is its poor injury risk association with the backface deformation distance. Another example is the instrumented response elements; all the anatomical surrogates have anthropomorphically representative thoracic forms, reducing the risk of potentially misleading appliqué response in the clay or gelatin for body armor meant to be worn. A substantial drawback to instrumented surrogates is the potential for increased cost of surrogates and sensor replacement. However, careful design can likely minimize both handling and sensor costs.

A key element needed for most of these surrogates is the lack of well-supported rifle round BABT injury criteria beyond the limited and preliminary efforts of Prather et al. The U.S. Army Aeromedical Research Laboratory (USAARL), in collaboration with the Medical College of Wisconsin (MCW), the University of Virginia (UVA), and Wayne State University (WSU) is This effort focuses on typical regions and organs expected to be at risk for BABT, including the ribs, lungs, liver, spine, and kidneys with a human cadaveric and physiological models at

assessment time points of 1 hour, 6 hours, and 24 hours post impact. This multi-year comprehensive study is a generational effort to provide future rounds of BABT surrogate designers with knowledge of the most efficient response metrics to be associated with BABT injury risk assessments including typical physical response parameters suitable for BABT assessments.

Conclusions

In the modern era of effective personal protection from many small arms threats, BABT becomes an important tradeoff for injuries and mortality on both the battlefield and for general personal protection. Substantial work has been conducted on experimental animal models, with fewer experimental studies utilizing human cadavers, but the current work does not allow the development of a thoracic BABT injury criterion from existing studies. Additional animal and/or cadaveric experimentation is necessary to develop a BABT injury criterion. Further, there is a strong need for a robust and widely used ballistic trauma injury classification scale. Though there are several existing injury scales, including a widely used scale for automobile injuries promulgated by AAAM, called the AIS, none are well-suited to ballistic trauma. To provide data for this injury scale, there is a strong need to collect military epidemiological data on a large scale.

The preeminent methodology used for BABT testing, especially for hard body armor threats, is based on the Prather methodology. Unfortunately, the biomechanical and pathophysiological bases for this methodology are weak. An improved criterion would likely help optimize personal protection of personal protection threats. The development of a method with a repeatable material component is important. The clay used in the Prather methodology has changed dramatically and qualitatively since its development in the 1970s, requiring testing the clay at temperatures approximately 15 °C higher than originally required to soften the response. The dynamic effect of this elevated temperature is still unclear.

Finally, there is a strong need for test methodologies with more anatomical fidelity than the current single response elements such as clay or gelatin to investigate the effect of backface deformation on various organ systems. Though substantial work to develop anatomical, physical, and mathematical finite element models has been completed in simulating the human thorax, heart, lungs, liver, and kidneys, the fidelity of these models is limited. Thus, the prediction of damage from transmitted pressures associated with blunt trauma to organs such as the intestines, spinal cord, brain, and vascular system cannot be made yet.

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Recommendations

Based on historical precedents of physical human injury modeling over the last six decades, there are two fundamental prerequisites for developing sufficiently biofidelic human physical surrogates for injury prediction, which must be verified and validated against performance in the desired test condition and threat profile. These are:

1. Sufficient biofidelic dynamic response of the surrogate

Biofidelic response is especially important to produce an effective evolution of injuries in any surrogate model. This response is generally different for different conditions and must be appropriate across all conditions simulated. For example, the Prather methodology was intended for soft armor with low-velocity rounds and had limited validation for the soft armor case. The Prather methodology is now used well outside the initial validation range in hard armor with high-velocity rounds with their attendant difficulties and important limitations. In addition, dynamic response is often important to achieve realistic backface response and armor defeat mechanisms.

2. Sufficient granular injury assessment metrics based on the desired threats

Surrogate models should always be matched to realistic threats in an injury model or multiple injury models. Generally, injury model response and surrogate model response must be matched or scaled from the in vivo state for some threats.

Arguably, neither prerequisite has been adequately satisfied for any previous or current model as discussed above. Biofidelic response behind armor is largely based on either porcine or human cadaveric response but often lacks in vivo response or scaling. For injury criteria, there are no available general risk criteria for regional BABT, essential for developing effective test methodologies.

These essential aspects of physical modeling are modulated by tradeoffs necessitated by testing imperatives. For example, it is generally not desirable to have a very expensive detailed physical model that can be damaged easily by backface deformation or occasional ballistic penetrations. Often this suggests a two-stage partition by which a first-stage biofidelic response element that is inexpensively vulnerable to penetrations is used as a filter to determine initial velocity with a biofidelic backface response. Then, for further research assessments, a more detailed second-stage response element or surrogate can be used to develop advanced injury criteria, perhaps suitable for use with the first-stage surrogate or injury model. These sensitive tradeoffs should be assessed in the context of developing BABT injury criteria by multiple worldwide groups. These include the important effort by USAARL and the consortium of MCW, UVA, and WSU in developing generalizable BABT injury criteria based on injury metrics suitable for use in developing surrogates for assessing BABT injuries. These injury risk assessments and their associated physical metrics are essential for the future development of more biofidelic and accurate BABT test methodologies.

References

- Ackley, P. O. (1966). *Handbook for shooters and reloaders (Vol II)*. Plaza Publishing.
<https://cornellpubs.com/product/3136/>
- Akimov, G. A., Odinak, M. M., Zhivolupov, S. A., Glushkov, B. S., & Milovanova, T. I. (1993). The mechanisms of the injuries to the nerve trunks in gunshot wounds of the extremities (experimental research). *Voenno-Meditsinskii Zhurnal (Military Medical Journal)*, 80(9), 34–36. <https://pubmed.ncbi.nlm.nih.gov/8236897/>
- Association for the Advancement of Automotive Medicine (AAAM). (2015). *The abbreviated injury scale*. AAAM.
- Baker, S. P., O'Neill, B., Haddon, W., Jr., & Long, W. B. (1974). The injury severity score: A method for describing patients with multiple injuries and evaluating emergency care. *The Journal of Trauma*, 14(3), 187–196.
<https://www.scopus.com/pages/publications/0015962447>
- Barwood, M. J., Newton, P. S., & Tipton, M. J. (2009). Ventilated vest and tolerance for intermittent exercise in hot, dry conditions with military clothing. *Aviation, Space, & Environmental Medicine*, 80(4), 353–359. <https://doi.org/10.3357/ase.2411.2009>
- Bass, C. R., Duma, S. M., Crandall, J. R., Pilkey, W. D., Khaewpong, N., Eppinger, R. H., & Kupp, S. (1997). Interaction of air bags with cadaveric upper extremities. *SAE Transactions: Journal of Passenger Cars*, 106, 3644–3650.
- Bass, C. R., Bolduc, M., & Waclawik, S. (2002). Development of a non-penetrating, 9 mm, ballistic helmet trauma test method. In *Proceedings of the Personal Armour Systems Symposium* (Vol. 2002, pp. 18-22).
- Bass, C. R., Davis, M., Rafaels, K., Rountree, M., Harris, R. M., Sanderson, E., Andrefsky, W., DiMarco, G., & Zielinski, M. (2005). A methodology for assessing blast protection in explosive ordnance disposal bomb suits. *International Journal of Occupational Safety and Ergonomics*, 11(4), 347–361.
- Bass, C. R., Salzar, R., Lucas, S., Davis, M., Donnellan, L., Folk, B., Sanders, E., & Waclawik, S. (2006). Injury risk in behind armor blunt thoracic trauma. *International Journal of Occupational Safety and Ergonomics*, 12(4), 429–442.
<https://doi.org/10.1080/10803548.2006.11076702>
- Bass, C. J., & Marriott, P. J. (2009). Ultrasound of the ankle. *Australasian Journal of Ultrasound in Medicine*, 12(4), 10–17. <https://doi.org/10.1002/j.2205-0140.2009.tb00065.x>
- Bass, C. R., Crandall, J. R., Wang, C., Pilkey, W. D., & Chou, C. (1998). Open-loop chestbands for dynamic deformation measurements. *SAE Transactions: Journal of Passenger Cars*, 107(6), 1380–1387. <https://doi.org/10.4271/980857>

- Bass, C. R. (2017). The thorax and abdomen: Behind armour blunt trauma. In M. Franklyn & P. V. S., Lee (Eds.). *Military Injury Biomechanics: The Cause and Prevention of Impact Injuries* (1st ed., pp. 329-372). CRC Press. <https://doi.org/10.4324/9781315151731>
- Beekley, M. D., Alt, J., Buckley, C. M., Duffey, M., & Crowder, T. A. (2007). Effects of heavy load carriage during constant-speed, simulated, road marching. *Military Medicine*, 172(6), 592–595. <https://doi.org/10.7205/milmed.172.6.592>
- Bellis, M. (2021). *History of body armor and bullet proof vests*. ThoughtCo. [thoughtco.com/history-of-body-armor-and-bullet-proof-vests-1991337](https://www.thoughtco.com/history-of-body-armor-and-bullet-proof-vests-1991337).
- Bensel, C. K., & Lockhart, J. M. (1975). *The effects of body armor and load-carrying equipment on psychomotor performance* (Report No. 75-92-CEMEL). U.S. Army Natick Research and Development Labs. https://archive.org/details/DTIC_ADA014978
- Bir, C. (2000). *The evaluation of blunt ballistic impacts of the thorax* [Doctoral dissertation, Wayne State University]. ProQuest.com.
- Birrell, S. A., Hooper, R. H., & Haslam, R. A. (2007) The effect of military load carriage on ground reaction forces. *Gait & Posture*, 26(4), 611–614. <https://doi.org/10.1016/j.gaitpost.2006.12.008>
- Bolduc M & Anctil B. (2010, September 13-17). Improved test methods for better protection: a BABT protocol proposal for STANAG 2920. In *Proceedings of the Personal Armour System Symposia*, Quebec City, QC.
- Bourget, D., Anctil, B., Doman, D., & Cronin, D. (2002, November 18-22). *Development of a surrogate thorax for BABT studies* [Oral presentation]. Personal Armor Systems Symposium, The Hague, Netherlands.
- Bowen, I. G., Fletcher, E. R., Richmond, D. R., Hirsch, F. G., & White, C. S. (1966). *Biophysical mechanisms and scaling procedures applicable in assessing responses of the thorax energized by air-blast overpressures or by non-penetrating missiles* (Technical Progress Report No. DASA-1857). Lovelace Biomedical and Environmental Research Institute.
- Bracq, A., Delille, R., Maréchal, C., Bourel, B., Lauro, F., Roth, S., & Mauzac, O. (2021). On using a SEBS polymer gel block as a new ballistic target to assess blunt ballistic impacts: Application to a wide range of LLKE projectiles. *International Journal of Impact Engineering*, 153, 103874. <https://doi.org/10.1016/j.ijimpeng.2021.103874>
- Cannon, L. (2001). Behind armour blunt trauma - - an emerging problem. *Journal of the Royal Army Medical Corps*, 147, 87–96. <https://doi.org/10.1136/jramc-147-01-09>
- Cannon, L., Tam, W., Dearden, P., & Watkins, P. (2000, August 28-30). *Thoracic wall response to nonpenetrating ballistic injury: The validation of a physical model of behind armor blunt trauma* [Oral presentation]. 12th Conference of the European Society of Biomechanics, Dublin, Ireland.

- Carr, D., & Lewis, E. A. (2014). Ballistic-protective clothing and body armour. In F. Wang & C. Gao (Eds.), *Protective Clothing* (pp. 146-170). Woodhead Publishing. <https://doi.org/10.1533/9781782420408.1.146>
- Carroll, A. W., & Soderstrom, C. A. (1978). A new nonpenetrating ballistic injury. *Annals of Surgery*, 188(6), 753–757. <https://doi.org/10.1097/00000658-197812000-00007>
- Carstensen, E. L., Campbell, D. S., Hoffman, D., Child, S. Z., & Ayme-Bellegarda, E. J. (1990). Killing of *Drosophila* larvae by the fields of an electrohydraulic lithotripter. *Ultrasound in Medicine & Biology*, 16(7), 687–698. [https://doi.org/10.1016/0301-5629\(90\)90102-i](https://doi.org/10.1016/0301-5629(90)90102-i)
- Chichester, C., Bass, C., Boggess, B., Davis, M., Sanderson, E., & Di Marco, G. (2001). *A test methodology for assessing demining personal protective equipment (PPE)* (No. RM1). Army Communications Electronics Command, Night Vision and Electronic Sensors Directorate.
- Clare, V., Lewis, J., Mickiewicz, A., & Sturdivan, L. (1975). *Blunt trauma data correlation* (Report No. EB-TR-75016). Edgewood Arsenal.
- Cooper, G. J., Pearce, B. P., Stainer, M. C., & Maynard, R. L. (1982). The biomechanical response of the thorax to nonpenetrating impact with particular reference to cardiac injuries. *The Journal of Trauma and Acute Care Surgery*, 22(12), 994–1008. <https://doi.org/10.1097/00005373-198212000-00004>
- Cooper, G. J., Maynard, R. L., Pearce, B. P., Stainer, M. C., Taylor, D. E. M. (1984). Cardiovascular distortion in nonpenetrating chest impacts. *The Journal of Trauma and Acute Care Surgery*, 24(3), 188–200. <https://doi.org/10.1097/00005373-198403000-00002>
- Cooper, G. J. (1996). Protection of the lung from blast overpressure by thoracic stress wave decouplers. *Journal of Trauma*, 40(3 Suppl), S105–S110.
- Cooper, G., Pearce, B., Sedman, A., Bush, I., & Oakley C. (1996). Experimental evaluation of a rig to simulate the response of the thorax to blast loading. *The Journal of Trauma: Injury, Infection, and Critical Care*, 40(3), S38–S41. <https://doi.org/10.1097/00005373-199603001-00007>
- Crandall, J., Bass, C., Duma, S., & Kuppa, S. (1998). *Evaluation of 5th percentile female Hybrid III thoracic biofidelity during out-of-position tests with a driver air bag* (Technical Paper 980636). SAE International. <https://doi.org/10.4271/980636>
- DeMaio, M. (2001, April 24). Closed chest trauma: Evaluation of the protected chest [Presentation]. *NATO Task Group on Behind Armor Blunt Trauma*, Copenhagen, Denmark.
- Drobin, D., Gryth, D., Persson, J. K. E., Rocksen, D., Arborelius, U. P., Olssen, L. G., Bursell, J., & Kjellstrom, B. T. (2007). Electroencephalograph, circulation and lung function after high-velocity behind armor blunt trauma. *The Journal of Trauma: Injury, Infection, and Critical Care*, 63(2), 405–413. <https://doi.org/10.1097/01.ta.0000236015.68105.48>

- Eppinger, R., Marcus, J., & Morgan, R. (1984). *Development of dummy and injury index for NHTSA's thorax side impact protection research program* (SAE Paper 840885). SAE International. <https://doi.org/10.4271/840885>
- Fackler, M. & Malinowski, J. (1985). The wound profile: A visual method of quantifying gunshot wound components, *Journal of Trauma and Acute Care Surgery*, 25(6), 522–529. <https://pubmed.ncbi.nlm.nih.gov/4009751/>
- Franklyn, M., & Lee, P. V. S. (Eds.). (2017). *Military injury biomechanics: The cause and prevention of impact injuries* (1st ed.). CRC Press. <https://doi.org/10.4324/9781315151731>
- Fung, Y. C., Yen, R. T., Tao, Z. L., & Liu, S. Q. (1988). A hypothesis on the mechanism of trauma of lung tissue subjected to impact load. *Journal of Biomedical Engineering*, 110(1), 50–56. <https://doi.org/10.1115/1.3108405>
- Gardner, J., Cruz, J. C., Mrozek, R., Hopping, J., Beaudoin, E., & Lombardo, L. (2023, September 11-15). *Ballistic assessments of the ARL Reusable Temperature Insensitive Clay (ARTIC) as a ballistic backing material* [Oral presentation]. 16th Personal Armour Systems Symposium, Dresden, Germany. <https://doi.org/10.52202/080042-0038>
- Goldfarb, M., Clurej, T., Weinstein, M., & Metker, L. (1975). *A method for soft body armor evaluation: Medical assessment* (Report No. EB-TR-74073). Edgewood Arsenal. https://archive.org/details/DTIC_ADA005575
- Groover, K., & Boor, N. (2014). *Aimed research sub-microsecond photography of federal Power-Shok 100grn.243.JPG*, Wikipedia Commons. https://commons.wikimedia.org/wiki/File:Aimed_Research_Sub-Microsecond_Photography_of_Federal_Power-Shok_100grn_.243.JPG
- Gryth, D., Rocksen, D., Persson, J. K. E., Arborelius, U. P., Drobin, D., Bursell, J., Olsson, L.-G., & Kjellstrom, T. B. (2007). Severe lung contusion and death after high-velocity behind-armor blunt trauma: Relation to protection level. *Military Medicine*, 172(10), 1110–1116. <https://doi.org/10.7205/milmed.172.10.1110>
- Haley, J. L., Alem, N. M., McEntire, B. J., & Lewis, J. A. (1996). *Force transmission through chest armour during the defeat of a .50 caliber round* (Report No. 96-14). U.S. Army Aeromedical Research Laboratory.
- Harman, E., Frykman, P., Pandorf, C., Tharion, W., Mello, R., Obusek, J., & Kirk, J. (1999). *Physiological, biomechanical, and maximal performance comparisons of female Soldiers carrying loads using prototype U.S. Marine Corps modular lightweight load-carrying equipment (MOLLE) with Interceptor body armor and U.S. Army all-purpose lightweight individual carrying equipment (ALICE) with PASGT body armor* (DTIC Report No. ADA365448). U.S. Army Research Institute of Environmental Medicine and U.S. Army Soldier, Biological, and Chemical Command. <https://apps.dtic.mil/sti/tr/pdf/ADA365448.pdf>

- Harvey, E. N., McMillen, J. H., Butler, E. G., & Puckett, W. O. (1962). The mechanism of wounding. *Wound Ballistics*, 143–235. <http://resource.nlm.nih.gov/101654140>
- Hawkins, J. L., Koonin, L. M., Palmer, S. K., & Gibbs, C. P. (1997). Anesthesia-related deaths during obstetric delivery in the United States, 1979-1990. *Anesthesiology*, 86(2), 277–284. <https://doi.org/10.1097/00000542-199702000-00002>
- Holmes, R. H. (1952). Wound ballistics and body armor. *Journal of the American Medical Association*, 150(2), 73–78. <https://doi.org/10.1001/jama.1952.03680020007003>
- James, G., & Keirl, J. (2023, September 11-15). *The effect of backing methods on the measured ballistic performance of armour materials* [Oral presentation]. 16th Personal Armour Systems Symposium, Dresden, Germany. <https://doi.org/10.52202/080042-0033>
- Jenerowicz, M., Bauer, S., Thoma, O., Boljen, M., Riedel, W., & Straßburger, E. (2023). Evaluation of behind armor blunt trauma (BABT)—Numerical investigation with GHBMCM50 and dummy tests with CTS-Primus breakable thorax. In *Proceedings of the 33rd International Symposium on Ballistics*.
- Jönsson, A., Arvebo, E. & Shantz, B. (1988). Intrathoracic pressure variations in an anthropomorphic dummy exposed to air blast, blunt impact, and missiles. *The Journal of Trauma: Injury, Infection, and Critical Care*, 28(1), S125–S131. <https://doi.org/10.1097/00005373-198801001-00026>
- Kent, R., Bass, C. R., Woods, W., Salzar, R., Lee, S., & Melvin, J. (2006). The role of muscle tensing on the force-deflection response of the thorax and a reassessment of frontal impact thoracic biofidelity corridors. *Journal of Automobile Engineering*, 220(7), 853–868. <https://doi.org/10.1243/09544070JAUTO108>
- Kinsler, R. (2008, 6-10 October). *Benefits of gelatin vs. clay for analyzing behind-armor effects in body armor testing* [Oral presentation]. Personal Armour Systems Symposium, Brussels, Belgium.
- Knapik, J. J., Reynolds, K. L., & Harman, E. (2004) Soldier load carriage: Historical, physiological, biomechanical, and medical aspects. *Military Medicine*, 169(1), 45–56. <https://doi.org/10.7205/milmed.169.1.45>
- Knudsen, P., & Götze, H. (1996). *Behind armour blunt trauma* [Unpublished manuscript]. Danish Army Combat School.
- Knudsen, P. J., & Götze H. (1997). *Behind armour blunt trauma* (Trials report 02/97). Danish Army Combat School.
- Krajsa, J. (2009). *Causes of pericapillary brain hemorrhages caused by gunshot wounds* [Doctoral thesis, Masaryk University].

- Kroell, C. K., Schneider, D. C., & Nahum, A. M. (1971). Impact tolerance and response to the human thorax (SAE 710851). In *Proceedings of the 15th Stapp Car Crash Conference*. <https://doi.org/10.4271/710851>.
- Kroell, C. K., Schneider, D. C., & Nahum, A. M. (1974, December 04). Impact tolerance and response to the human thorax II (SAE 741187). In *Proceedings of the 18th Stapp Car Crash Conference*. <https://doi.org/10.4271/741187>
- Leggieri, M. (2010, August 9-11). *Blunt trauma research to support a new body armor blunt trauma performance standard and testing method* [Presentation]. Committee to Review the Testing of Body Armor Materials for Use by the U.S. Army Phase III, Aberdeen, MD.
- Lidén, E., Berlin, R., Janzon, B., Schantz, B., & Seeman, T. (1988). Some observations relating to behind body-armour blunt trauma effects caused by ballistic impact. *The Journal of Trauma and Acute Care Surgery*, 28(1), 145–148. <https://doi.org/10.1097/00005373-198801001-00029>
- Link, M. S., Wang, P. J., Maron, B. J., & Estes, N. A. (1999). What is Commotio cordis? *Cardiology in Review*, 7(5), 265–269. <https://doi.org/10.1097/00045415-199909000-00010>
- Liu, B., Wang, Z., Leng, H., Yang, Z., & Li, H. (1996). Studies on the mechanisms of stress wave propagation in the chest subjected to impact and lung injuries. *The Journal of Trauma and Acute Care Surgery*, 40(3), S53–S55. <https://doi.org/10.1097/00005373-199603001-00011>
- Mayorga, M. A., & North Atlantic Treaty Organization. (2010). *Thoracic response to undefeated body armor*. North Atlantic Treaty Organization, Research and Technology Organization. <https://books.google.com/books?id=hh9RnQAACAAJ>
- Merkle, A. C., Ward, E. E., O'Connor, J. V., & Roberts, J. C. (2008). Assessing behind armor blunt trauma (BABT) under NIJ standard-0101.04 conditions using human torso models. *The Journal of Trauma: Injury, Infection, and Critical Care*, 64(6), 1555–1561. <https://doi.org/10.1097/ta.0b013e318160ff3a>
- Miller, P. R., Croce, M. A., Kilgo, P. D., Scott, J., & Fabian, T. C. (2002). Acute respiratory distress syndrome in blunt trauma: Identification of independent risk factors. *The American Journal of Surgery*, 68(10), 845–850. <https://pubmed.ncbi.nlm.nih.gov/12412708/>
- Mirzeabassov, T., Belov, D., Tyurin, M., & Klyaus, L. (2000, September 5-8). *Further investigation of modelling for bullet-proof vests* [Oral presentation]. 5th Personal Armor Safety Symposium, Colchester, UK.
- Mitchell, S. W., Morehouse, G. R., & Keen, Jr, W. W. (1864). *Reflex paralysis* (Circular no. 6). Surgeon General's Office. <https://digirepo.nlm.nih.gov/ext/mhl/101127157/PDF/101127157.pdf>

- Montanarelli, N., Hawkins, C., Goldfarb, M., & Ciurej, T. (1973). *Protective garments for public officials* (LWL-TR-30B73). Edgewood Arsenal.
- Mrozek, R. A., Leighliter, B., Gold, C. S., Beringer, I. R., Jian, H. Y., VanLandingham, M. R., Moy, P., Foster, M. H., & Lenhart, J. L. (2015). The relationship between mechanical properties and ballistic penetration depth in a viscoelastic gel. *Journal of the Mechanical Behavior of Biomedical Materials*, 44, 109–120.
<https://doi.org/10.1016/j.jmbbm.2015.01.001>
- Nahum, A. M., & Melvin, J. W. (1993). *Accidental injury, biomechanics and prevention*. SAE International. Springer.
- Nechaev, E., Gritsanov, A., Fmoin, N., & Minnullin, I. (1995). *Mine blast trauma: Experience from the war in Afghanistan*. Vreden Research Institute of Traumatology.
<https://www.abebooks.com/first-edition/Blast-Trauma-Experience-Afghanistan-Nechaev-E.A/31413942349/bd>
- National Academies of Sciences, Engineering, and Medicine. (2012). *Testing of body armor materials: Phase III*. The National Academies Press. <https://doi.org/10.17226/13390>.
- National Institute of Justice. (1972). *Ballistic resistance of body armor* (Standard 0101.01). U.S. Department of Justice.
- National Institute of Justice. (2001). *Ballistic resistance of personal body armor* (NIJ Standard-0101.04a). U.S. Department of Justice, Office of Justice Programs.
- Ness, L. S. (2011). *Jane's ammunition handbook 2011-2012* (20th ed.) (A. G. Williams, Ed.). Jane's Information Group.
- Oleksiak, W. (2020). The monk who stopped bullets with silk: Inventing the bulletproof vest. *Culture.pl: #technology & innovation*. <https://culture.pl/en/article/the-monk-who-stopped-bullets-with-silk-inventing-the-bulletproof-vest>
- Op 't Eynde, J., Pang, D. Y., Morino, C. F., Abrams, M. Z., Kait, J. R., Salzar, R. S., Bentley, T. B., Shender, B. S., & Bass, C. R. (2023, September 11-15). *The severe limitations of clay for assessing human response for behind armor blunt trauma* [Oral presentation]. Personal Armour Systems Symposium, Dresden, Germany.
- Perrino, K., & Johns Hopkins University Applied Physics Laboratory (2022). *ATLAS Task 1 closeout meeting* [Public release presentation]. Johns Hopkins University Applied Physics Laboratory.

- Peterson, H. L. (1950). Body armor in the Civil War. *Ordnance*, 34, 432–433.
https://archive.org/download/sim_military-collector-historian_1952-06_4_2/sim_military-collector-historian_1952-06_4_2.pdf
- Prat, N., Rongieras, F., Voiglio, E., Magnan, P., Destombe, C., Debord, E., Barbillon, F., Fusai, T., & Sarron, J.-C. (2010). Intrathoracic pressure impulse predicts pulmonary contusion volume in ballistic blunt thoracic trauma. *The Journal of Trauma and Acute Care Surgery*, 69(4), 749–755. <https://doi.org/10.1097/ta.0b013e3181f2fe30>
- Prather, R. N., Swann, C. L., & Hawkins, C. E. (1977). *Backface signatures of soft body armors and the associated trauma effects* (Report No. ARCSL-TR-77055). U.S. Army Armament Research and Development Command.
- Prather, R. (2010, August 9-11). *The lightweight body armor program - A history* [Presentation]. Committee to Review the Testing of Body Armor Materials for Use by the U.S. Army, Phase III, Aberdeen, MD.
- Rice, K., & Lightsey, S. (2000). An update on US National Institute of Justice performance standards for personal body armor. In *Proceedings from the 5th Personal Armor Safety Symposium*. Colchester, UK (pp. 235-44).
- Roberts, J. C., Ward, E. E., Merkle, A. C., & O'Connor, J. V. (2007). Assessing behind armor blunt trauma in accordance with the National Institute of Justice Standard for Personal Body Armor Protection using finite element modeling. *The Journal of Trauma: Injury, Infection, and Critical Care*, 62(5), 1127–1133.
<https://doi.org/10.1097/01.ta.0000231779.99416.ee>
- Sarron, J. C., Destombe, C., Götze, H., & Mayorga, M. (2000, September 5-8). *Physiological results of NATO BABT experiments* [Presentation]. Personal Armour Systems Symposium, Colchester, UK.
- Sarron, J. C., Caillou, J. P., Destombe, C., Lonjon, T., Da Cunha, J., Vassout, P., & Allain, J. C. (2001, April 24). *Displacements of thoracic wall after 7.62 non-penetrating impact* [Presentation]. NATO BABT Task Group, Copenhagen, Denmark.
- Sawka, M. N., Latzka, W. A., Montain, S. J., Cadarette, B. S., Kolka, M. A., Kraning, K. K., & Gonzalez, R. R. (2001) Physiologic tolerance to uncompensable heat: Intermittent exercise, field vs laboratory. *Medicine & Science in Sports & Exercise*, 33(3), 422–430.
<https://doi.org/10.1097/00005768-200103000-00014>
- Sendowski, I., Martin, P., Muzellec, J., & Breteau, J. (1994). *Rear side effects of protective vests in non-perforating model*. Institute of Tropical Medicine of the Armed Forces Health Service.
<https://www.bing.com/ck/a?!&&p=ab3282067d2906447972562d714e38532e741b06d59aa445358b8089247d3524JmldtHM9MTc4NDA3MzYwMA&ptn=3&ver=2&hsh=4&fclid=2b2396fd-5808-6da4-2659-816a59046c31&u=a1aHR0cHM6Ly9wdWJtZWQubmNiaS5ubG0ubml0Lmdvdi8xOTAyNzM0Mi8&ntb=1>

- Shaw, G., Crandall, J., & Butcher, J. (2000, September). Biofidelity evaluation of the THOR advanced frontal crash test dummy. In *Proceedings of the 2000 International IRCOBI Conference on the Biomechanics of Impact*.
- Shewchenko, N., Fournier, E., Bayne, T., Magnan, S., and Bourget, D. (2020, October 11-15). The development of the f-BTTR and its use for hard armour testing. In *Proceedings of the Personal Armour Systems Symposia*. Copenhagen, Denmark.
<https://doi.org/10.52202/078352-0053>
- Sperry, Y. K. (1993). Scleral and conjunctival hemorrhages arising from a gunshot wound of the chest. *Journal of Forensic Science*, 38(1), 203–209.
<https://pubmed.ncbi.nlm.nih.gov/8426154/>
- Sondén, A., Rocksén, D., Riddez, L., Davidsson, J., Persson, J. K., Gryth, D., Bursell, J., & Arborelius, U. P. (2009). Trauma attenuating backing improves protection against behind armor blunt trauma. *The Journal of Trauma: Injury, Infection, and Critical Care*, 67(6), 1191–1199. <https://doi.org/10.1097/ta.0b013e3181a5b0e1>
- Sturdivan, L. M. (1976). Modeling in blunt trauma research. In *Proceedings of the Second Annual Soft Body Armor Symposium*, Miami Beach, FL.
- Suneson, A., Hansson, H. A., & Seeman, T. (1987). Peripheral high-energy missile hits cause pressure changes and damage to the nervous system: Experimental studies on pigs. *The Journal of Trauma and Acute Care Surgery*, 27(7), 782–789.
<https://doi.org/10.1097/00005373-198707000-00016>
- Tam, W., Dorn, M. R., & Gotts, P. (2000). A new method for quantifying behind armour blunt trauma. In *Proceedings of Personal Armour Systems Symposium (PASS2000)* (pp. 05-08).
- Van Bree, J. L. M. J., & Gotts, P. (2000, 5-8 September). *The twin peaks of BABT* [Oral presentation]. Personal Armor Systems Symposium, Colchester, UK (pp. 371–380).
<https://resolver.tno.nl/uuid:555109ed-c4be-4ee0-a012-39d9af0e538d>
- Viano, D. C., & Lau, I. V. (1985). *Thoracic impact: A viscous tolerance criterion* (SAE Technical Paper 856025). SAE International.
- Whipp, B. J., & Ward, S. A. (1998). Determinants and control of breathing during muscular exercise. *British Journal of Sports Medicine*, 32(3), 199.
<https://doi.org/10.1136/bjsm.32.3.199>
- Wilhelm, M., & Bir, C. (2008). Injuries to law enforcement officers: The backface signature injury. *Forensic Science International*, 174(1), 6–11.
<https://doi.org/10.1016/j.forsciint.2007.02.028>
- Zhang, T. G., Graham, M. J., & Satapathy, S. S. (2022). *Modeling the rebound of ballistic Roma Plastilina No. 1 Clay* (Report No. ARL-TR-9540). Army Research Laboratory.
<https://apps.dtic.mil/sti/trecms/pdf/AD1180059.pdf>

Appendix – Experimental Injury Risk in Behind Armor Blunt Trauma (BABT)

Large Animal Experiments for BABT

Animal experiments may be used to develop injury criteria for blunt trauma including BABT. However, animals used in such experiments, typically livestock, have significant differences in anatomy from humans; therefore, scaling data from animals to humans must be performed with techniques that may be uncertain or nonexistent.

Though several experiments investigated thoracic penetration and BABT with soft body armor (cf. Prather, 1977; Carroll & Soderstrom, 1978; Lidén et al., 1988) and hard body armor using animals, this report concentrates on those studies that are applicable to BABT with hard body armor. This includes several direct impact studies at high rates.

Large animal studies have been designed to assess injury resulting from non-penetrating ballistic impact on body armor. These were performed by American, Canadian, Swedish, Danish, Dutch, and French teams, mostly in anesthetized pigs and using various body armor models and threats ranging from .38 caliber to .30 caliber (7.62 mm) and .50 caliber (12.7 mm). Many of these studies were reported by the NATO Task Group on Thoracic Response to Undeclared Body Armor (Mayorga and North Atlantic Treaty Organization, 2010) and a series of international symposia called Personal Armor Systems Symposia.

Lovelace Foundation for Medical Education and Research (Bowen et al., 1966).

Bowen et al. (1966) reported experiments on dogs with the lateral thorax impacted by nonpenetrating missiles (Figure A1). Cup-shaped missiles were constructed of aluminum with variable mass. The impact occurred on a flat cylindrical end with a diameter of 7 cm. Impactor masses varied from 63 grams g to 381 g, impact velocities varied from 18.9 m/s to 91.4 m/s, and the dog mass varied from 12.2 kg to 23.1 kg. The dogs were positioned so that impacts were produced at the right lateral chest wall near the mid-thorax. Ribs fractured include the fourth through eighth ribs implying impact locations near the fifth or sixth rib. Animals that survived the immediate post-impact time were sacrificed 30 to 40 minutes from the impact time.

Scaling techniques were developed to transfer dog values to equivalent human values. These scaling relations, however, are uncertain, as the impact area of the missile was not scaled in the experiments with the dog's body mass (Bowen et al., 1966). The mass of the impacted lung was compared with the lung mass on the contralateral side. This ratio is generally correlated with injury severity; the threshold value of the ratio of the right mass to the left for fatalities in the watched period is approximately 2.3. In addition, the scaled energy of impact (scaled to a 75 kg man) is correlated well with fatality. The increased mass of the impacted lungs is plotted in Figure A1 against the scaled impact energy. The increased lung mass of the animals measured post-mortem has some limitations as an injury measure as bleeding into the lung occurs most effectively while the animal is living. However, the correlation was relatively good over the limited study time.

The impactor mass of 63 g may represent behind armor impact in some regimes. For body armor with 24 kg/m² areal density, the effective impact diameter of approximately 37 mm reported by Mirzeabassov et al. (2000) implies an additional 84 g added mass owing to the induced motion of the body armor. In addition, the time scale is similar to BABT forcing. Tam et al. (2000) reported approximately 2 ms to full displacement of approximately 4 cm with a peak acceleration of approximately 28,000 G, where G is the acceleration due to gravity.

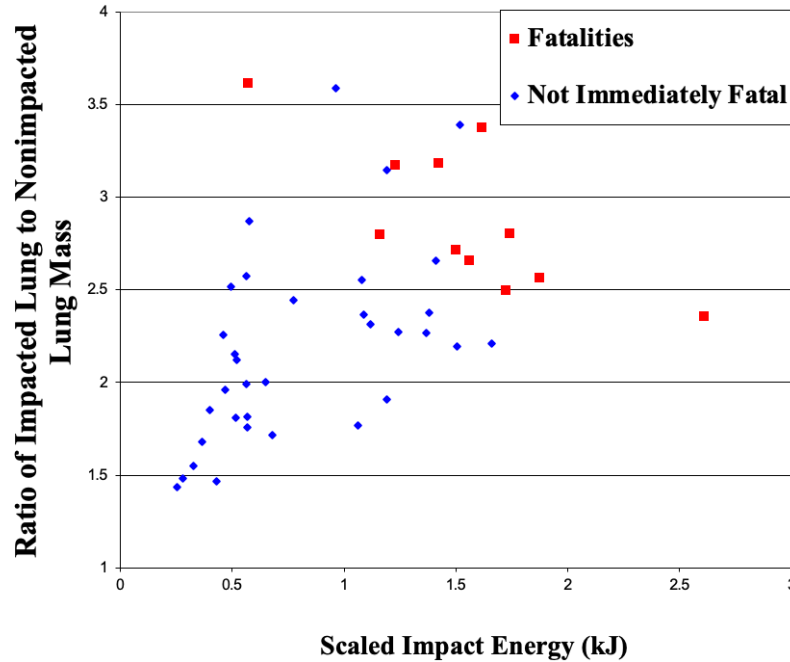


Figure A1. Mass ratio of impacted/injured lung to nonimpacted lung versus scaled impact energy is shown with fatal impacts in blue and non-fatal impacts in red. Impact energy was scaled to a 75 kg man and lung masses were compared for impacted and nonimpacted lungs. Reproduced from Bowen et al. (1966) with permission from The National Academies Press.

Danish Army Combat School (Knudsen & Götze, 1997).

Animal experiments were performed to assess the potential for thoracic injury from BABT behind undefeated ceramic body armor. Projectiles included a 5.56 mm NATO ball at 921 m/s, 7.62 mm NATO ball at 848 m/s, and 12.7 mm armor piercing rounds with reduced load at 463 to 595 m/s. Tests were performed using twenty 60 kg swine and one control. The swine were placed in a standing posture, and lateral impacts were performed at the level of the xiphoid cartilage. Physiological monitoring of electrocardiogram (ECG), spirometer, and pulse oximetry were performed for the hour-long observation period before sacrifice.

Two of the four animals with the largest recorded kinetic energy were sacrificed for ethical reasons before the end of the sixty minutes. Injuries were assigned as shown in Table A1. Minimal injuries were seen at kinetic energies below 1.7 kJ while fatal injuries were expected for tests with impact energies above 8 kJ for the body armor selected for testing. Cardiac lesions were seen in many test animals and controls suggesting this damage was an experimental

artifact. No consistent correlation was seen between skin damage and lung damage. No specific injury criterion was developed that was independent of the experimental setup.

Table A1. Bullet Specifications and Injury Outcomes Reproduced from Knudsen and Gøtze (1996) with permission from The National Academies Press.

Round	Impact Velocity (m/s)	Kinetic Energy (kJ)	Injuries
5.56 mm NATO ball	9920-922	1.693-1.700	Minimal
7.62 mm NATO ball	838-861	3.248-3.429	Minimal to moderate
12.7 mm M2	463-595	4.839-7.992	Severe to fatal

Oksboel Trials – NATO.

As a more extensive follow-up to the Danish Army Combat School tests, trials were performed using extensive instrumentation in Oksboel in 1999. The trials used porcine specimens similar to the earlier Danish Army Combat School tests. Denmark, France, the UK, and the U.S. provided the protective equipment for testing. The Danish and French developed body armor systems that defeat the 7.62 x 51 mm threat while the UK and U.S. systems defeat the more energetic 12.7 mm (.50 caliber) sniper rifle threat. The pigs were separated into three trial groups with eight animals each and one body armor design was assigned to each group. There were three control animals. The impact site was selected in the right thorax in the middle of the eighth rib. Instrumentation included pressure and acceleration measurements in the thoracic wall and physiological measurements for half an hour before euthanasia, which in retrospect was too short a time.

The data were from pressure transducers, accelerometers, ECG, blood oxygen saturation, respiratory rate observations, and post-experiment autopsy examination. The gross and microscopic studies included the lungs, liver, and in some studies, the heart and kidneys (Mayorga & North Atlantic Treaty Organization, 2010). Unfortunately, no intestine, brain, spleen, aorta, or spinal cord studies were reported. Each of the four separate experiments (i.e., Danish, UK and two French studies) followed a similar protocol concerning animal anesthesia and physiological observations. Armor selections varied widely, and an attempt was made to compare one armor type to another.

The extensive test series was designed to discern the cause of wounding, separating the effects of the initial large, short-duration pressure peak and a secondary displacement pressure peak, presumably caused by the deformation of the body wall behind the body armor. The body armor was designed as shown in Figure A2. The first type is typical body armor with a steep first pressure peak and a more extended later displacement peak (G1). The second would have a second peak only (G2), and the third would have only a first peak (G3).

The armor did not perform as expected. As shown in Figure A2, the ‘first peak only’ armor showed a decreased second peak, and the pressure at the first peak was reduced. ‘Second peak only’ armor significantly reduced the first and second peaks, but never so much that the first peak was less than the second peak. The ‘first peak only’ armor is a difficult engineering problem, implying infinite rigidity in the armor system, significantly limiting resulting backface displacement. Attaining a ‘second peak only’ condition is a very difficult problem and implies a match in impedance between the rear of the armor and the tissue. To illustrate this problem, the G2 condition clearly shows a first peak from initial impedance mismatch between armor and tissue along with the second peak (Figure A3).

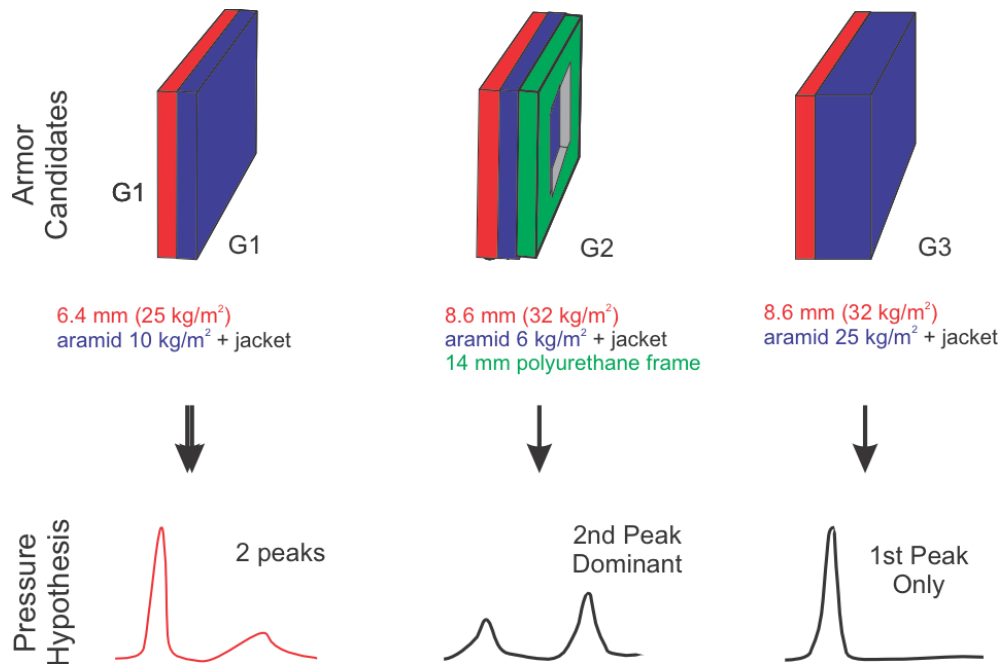


Figure A2. Body armor for the Oksboel trials produced a ‘two peak’ condition (G1), which has an initial peak caused by high frequency contact of armor and thoracic tissue followed by a displacement related second peak. The ‘second peak only’ condition (G2) also has two peaks, but the second peak is enhanced relative to the first. The first peak cannot be completely suppressed without contact matching impedance between the tissue and the backface of the armor. The ‘first peak only condition’ (G3) is created with a stiff armor, maximizing contact impedance differences between armor and thoracic tissue. Modified from Sarron et al. (2000) with permission from The National Academies Press.

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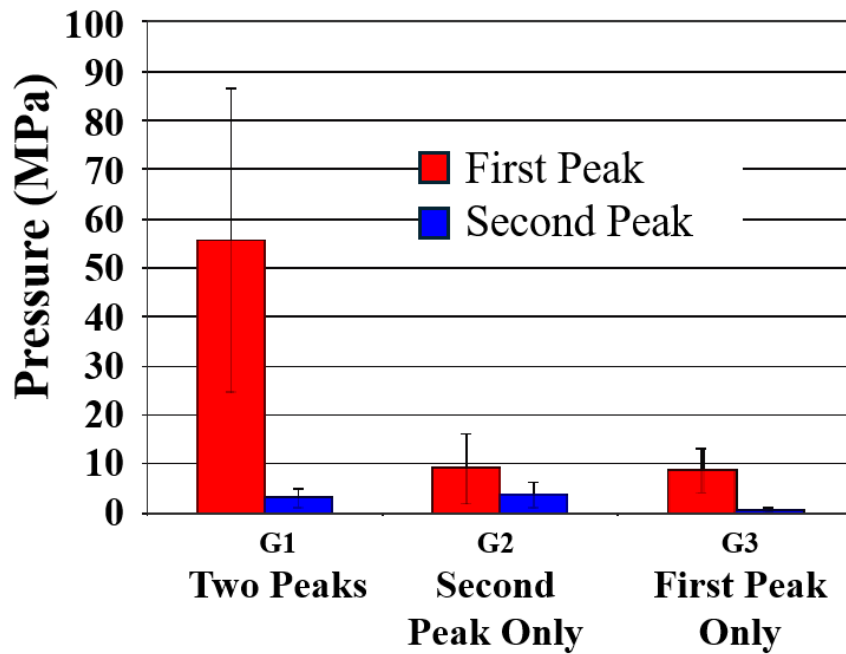


Figure A3. The average first and second peak pressures that resulted during the Oksboel trials are shown in red and blue, respectively. Reproduced from Sarron et al. (2000) with permission from The National Academies Press.

All animals tested were injured. Post-mortem lung mass as shown in Figure 4A appears to be a more specific injury measure as all the animals were sacrificed within 60 minutes. In general testing, however, different expiration times and the dynamic effects of hemorrhage may confound lung mass measurements (Figure A4).

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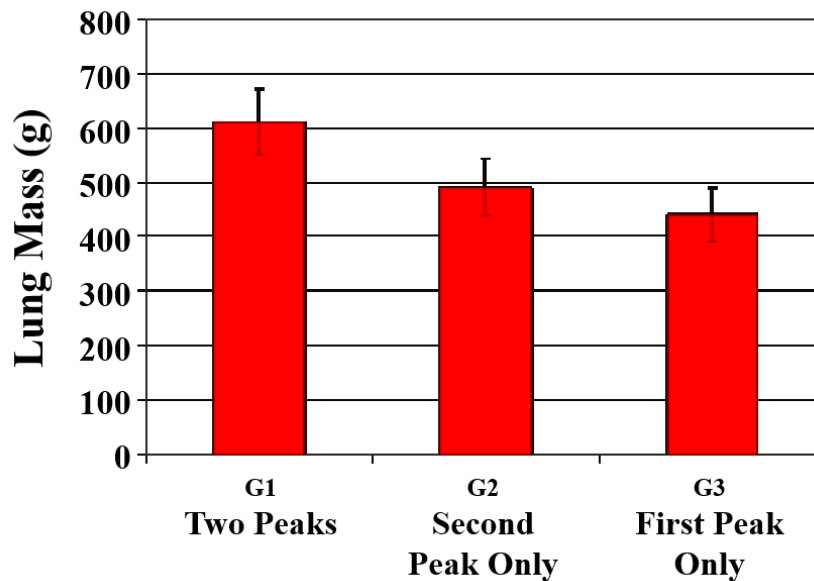


Figure A4. The average post-mortem lung mass that resulted during the Oksboel trials was separated by resulting peaks. Data show that the G1 case has larger post-mortem lung mass than either the G2 or G3 conditions for the same incoming round and impact velocity. This suggests that phenomena associated with both peaks contribute to the injury potential for BABT in the lungs. Reproduced from Sarron et al., (2000) with permission from The National Academies Press.

The effect of the first peak only may be best studied by comparison with shock impingement. To get a qualitative idea of the effect of this pressure peak, we can compare the Oksboel peak uncorrected for the location of the pressure transducer in the tissue with the Bowen curves as shown in Figure A5. While using this internal pressure is inappropriate for the Bowen curves, it is likely conservative for an injury threshold assessment. The Oksboel experiments saw pressure peaks above 30 megapascal (MPa) with durations of 0.3 to 0.4 ms. The 100% blast lethality curve (Bowen, 1966) is far below this value. This suggests that local lung damage may occur from transmitting a high-amplitude pressure wave. Indeed, lung mass injury from the Oksboel tests scales directly with the first peak only.

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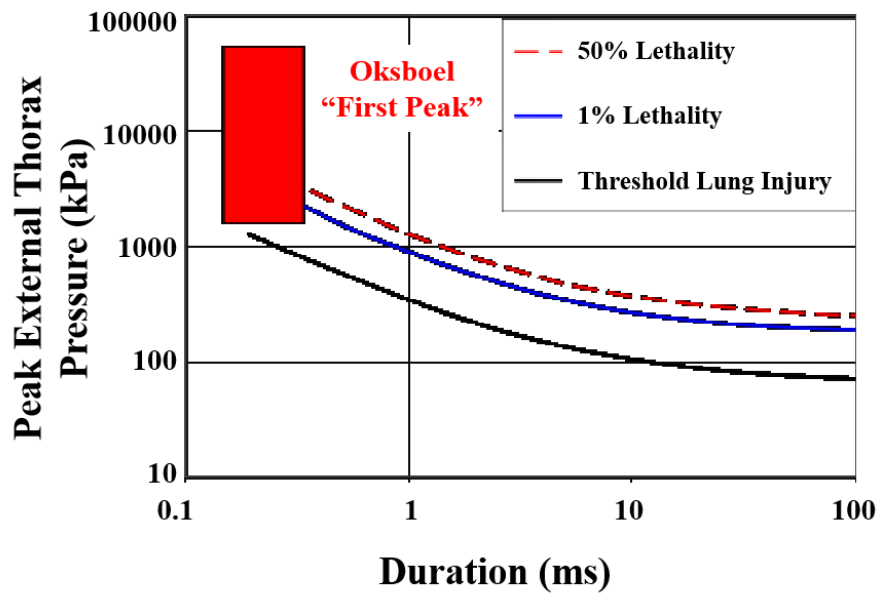


Figure A5. The peak external thorax pressures during the first peak that resulted from lethal and nonlethal impacts are depicted on the Bowen curve. Reproduced from Sarron et al. (2000) with permission from The National Academies Press.

The results showed significant injury and high mortality for most of the study groups, along with surprisingly significant thorax and lung injuries from hard armor having areal densities up to 24 kg/m^2 with foam backing. Pressure and accelerometer recordings were incomplete as many studies experienced saturation of the instruments with pressures exceeding 34 MPa. Nevertheless, some very important observations and correlations were made for high-velocity ballistic impacts and the subsequent deformations of the backface of body armor. From the extensive studies in anesthetized pigs by the French investigators and reported in a NATO summary of international studies (Mayorga and North Atlantic Treaty Organization, 2010), a synopsis of the relationships between lung contusion areas, recorded pressures, and deformation measurements can be made. Since Figure 3 presents the superimposition of a series of cine-radiographs, the timing of the chest deformation relative to the BFD cannot be related to the maximum deformation shown in Figure A6, or to the pressure measurements shown in Figure A7.

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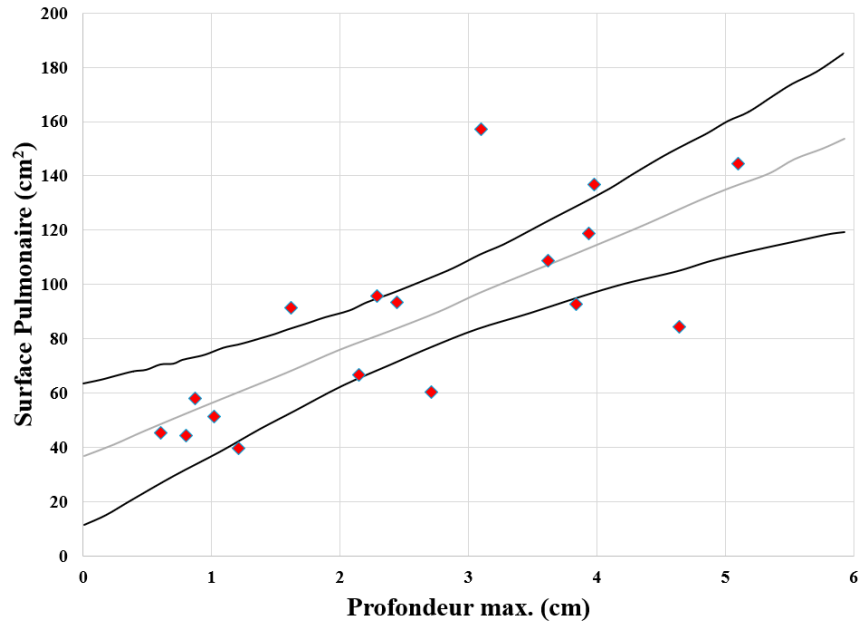


Figure A6. The relationship between area of lung surface contusion (surface pulmonaire) and maximum backface deformation (profondeur max.) of body armor is shown. Increased backface deformation up to 6 cm is associated with increased maximum pressure measured in the lung. Deformation was measured with high-speed x-ray and lead markers under the impact. Modified from Sarron et al. (2000) with permission from The National Academies Press.

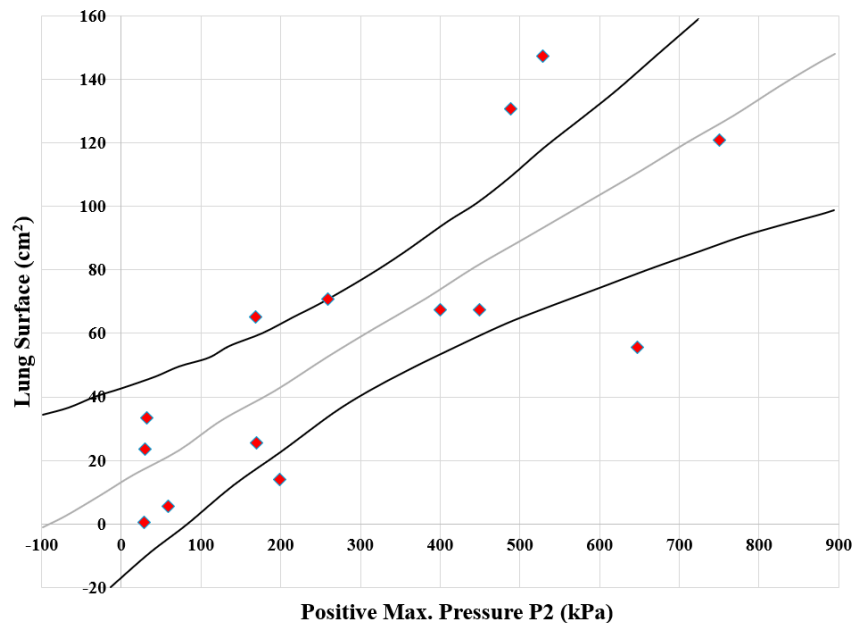


Figure A7. The relationship between the area of lung surface contusion and pressure 6 cm from the point of impact was graphed for each test. The typical lung surface damage increased with positive maximum pressure measured in the lung. Modified from Sarron et al. (2000) with permission from The National Academies Press.

Délégation Générale pour L'Armement (DGA) – France (Sendowski et al., 1994; Sarron et al., 2001).

The Délégation Générale pour L'Armement (DGA) performed an extensive test series using porcine subjects during the 1990s and early 2000s. The model selected was a female swine. The swine had masses of 60 kg (+/- 5 kg). Four impact areas were selected:

1. Pulmonary near the seventh right dorsal vertebra. The animals were observed for two hours after the trauma.
2. Lateral cardiac area at the fifth left thoracic vertebra. The animals were observed for two hours after the trauma. This condition was chosen to investigate cardiac contusion.
3. Mediastinum opposite the apex of the heart. The animals were observed 15 minutes before euthanasia. This condition was chosen to investigate induced ventricular fibrillation.
4. Liver. The animals were observed for 15 minutes.

As with most extant animal experiments, the DGA animals were not observed for a substantial time post-test. This prevents the investigation of injuries such as ARDS and others that require long-term physiological monitoring.

All shots occurred at the end of the inhale cycle, except for the lateral cardiac tests in which shots occur at the end of the exhale cycle. Body armor used included UHMWPE. Test rounds included a 7.62 mm round at 829 m/s into plates of 23 kg/m² and a 5.56 mm round at 989 m/s into plates of 10 kg/m². Five tests were performed for each round for each test condition (40 tests).

Instrumentation included an accelerometer on the rib and impact pressure measured using a balloon gauge inside the thoracic esophagus. The accelerometer, however, did not function for most of the tests, and the systemic pulmonary pressures were very low (~1.8 millimeters of mercury). Physiological measurements included respiration and ECG. Vascular pressure measurements include pulmonary arterial pressure, occlusion pulmonary arterial pressure, abdominal aortic pressure, and vena cava pressure. Blood gases and cellular enzymes (creatine phosphokinase and lactate dehydrogenase) were measured.

Post-test measures included extensive grading of skin damage. The cutaneous wound was statistically significantly greater for the 7.62 series than for the 5.56 series. The average diameter of the cutaneous wound was found to be ~14 cm for the 7.62 series and ~12 cm for the 5.56 series.

Pulmonary wounds were assessed from the right thoracic shots. Phenomenologically, a bruise developed under the pleura surrounded by a region with inflammation. In some tests, emphysema developed at the center of the impact. The percentage of injured lungs for the 7.62 mm (13%) and the 5.56 mm (7.4%) rounds is statistically significantly different. Cardiac wounds were assessed using the lateral cardiac area shots and the mediastinal shots. The tests were highly variable due to the shape of the sternum.

Initial apnea was seen in 30 tests, averaging 15 seconds in the 7.62 mm round tests and 8 seconds in the 5.56 mm round tests. This includes all shots in the sternal area. Secondary apneas occur in several of the tests. These are generally associated with advanced shock. Deaths seen in these tests are shown in Figure A8.

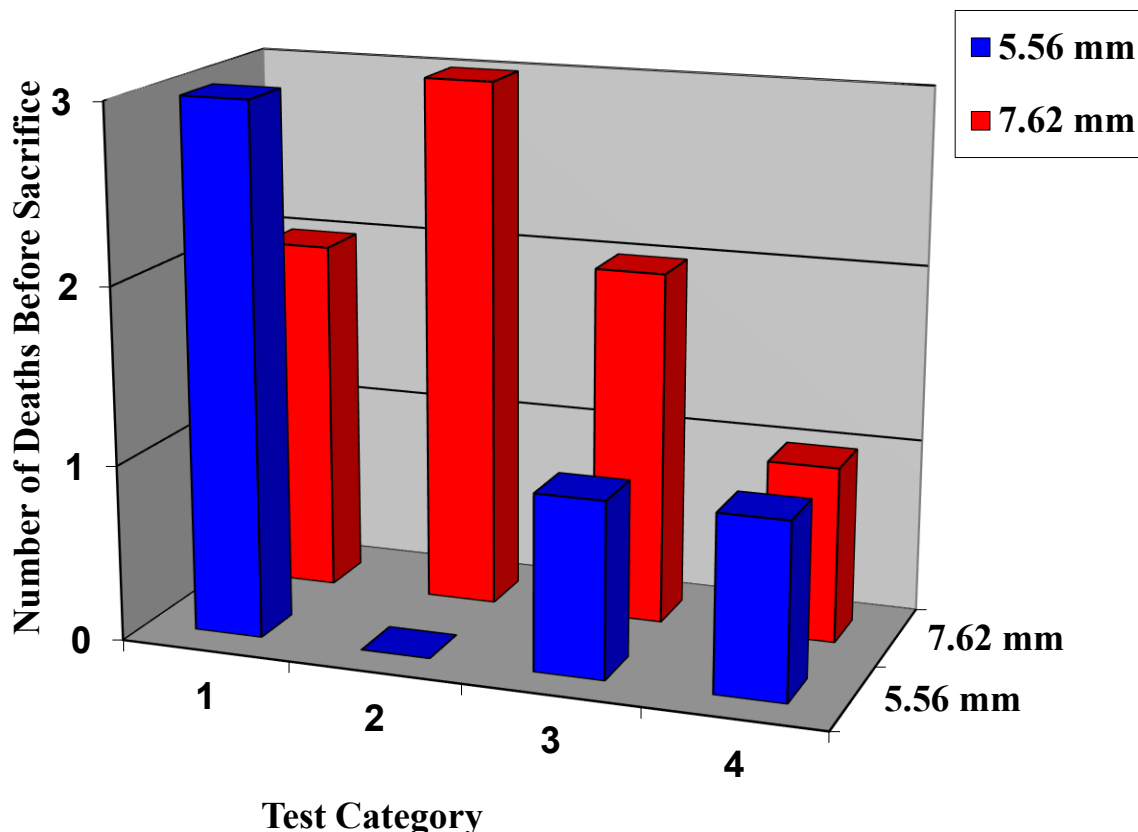


Figure A8. Animal fatalities during the monitoring period were recorded. There was an increasing trend of early deaths with increasing severity of exposure (category 1 = most severe; category 4 = least severe). Reproduced from Sendowski et al. (1994) after modification by Bass with permission from The National Academies Press.

Experiments at the French DGA (Sarron et al., 2001) used 7.62 mm test rounds fired into laminated UHMWPE body armor. These experiments concentrated on investigating physical measurements of the thoracic wall using a flash x-ray technique with lead markers as shown in Figure A9. This technique has been found to provide a good representation of the motion of the chest wall up to a maximum velocity of 30 m/s. These studies see a large negative pressure (~3 MPa) in preliminary data, suggesting a cavitation injury mechanism may be possible. They find that the shock wave arrives before significant displacement and that the pressures are not well associated with the local displacements.

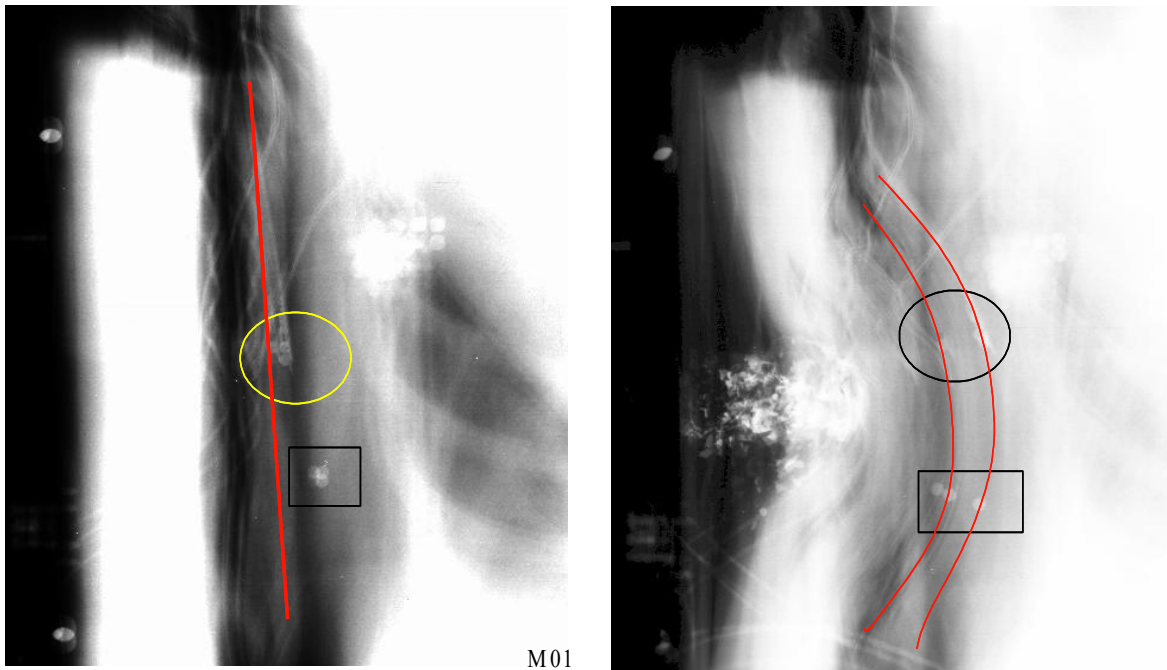


Figure A9. Flash x-rays were taken of behind armor blunt trauma. The x-ray on the left shows initial time, and the x-ray on the right shows the deformation at 0, 1.5, 2, and 2.5 ms. The left image shows undisturbed armor and the thoracic interface on the right (red line). The image on the right shows superimposed images at the times listed with surface traces of the armor and torso at the final time (2.5 ms following impact). Reproduced from Sarron et al. (2001) with permission from The National Academies Press.

To find a correlation between intrathoracic pressure, BABT, and high- versus low-velocity bullets, 20 pigs, protected by a NIJ Level 3 or 4 bulletproof vest, were shot with 7.62 mm NATO bullets (2.4 kJ and 3.2 kJ) and 10 unprotected pigs were shot with an air gun with 40 mm rubber projectiles (0.07 to 0.2 kJ) (Prat et al., 2010). Rib fractures occurred in 21 of the 30 animals with no correlation to the projectile kinetics, but intrathoracic peak pressures showed a good correlation with the volume of lung contusions. Other studies by the French are reviewed under the NATO studies section of this report.

U.S. Army Aeromedical Research Laboratory (Haley et al., 1996).

Tests were performed to evaluate the effect of polyvinyl chloride foam at standoffs of 14 mm, 21 mm, and 27 mm. Seventeen pigs (91 kg) were tested using ceramic body armor with a 12.7 mm test round. Three control pigs were used, and the animals were monitored for three hours after the tests. The subjects were instrumented with accelerometers on the top and bottom of the armor plate, and load cells were placed behind the pig to evaluate the global force. In initial testing, eight thin load cells were placed between the thorax and the armor. The presence of the load cells decreased the local standoff. So, six load cells were used in the remaining tests. Heart rate and respiration rate were monitored. The standoff foam was found to be rate-sensitive, transmitting large pressures to the thorax. The researchers concluded that a 25 mm standoff is necessary to effectively protect the thorax.

Anter Corporation (Mirzeabassov et al., 2000).

Anter Corporation reported an investigation of behind armor blunt trauma on small dogs with various vest types; these included two thicknesses of titanium plates and ceramic body armor. Rounds included 7.62 mm with two impact energies, a .45 caliber M11911A1, and a 9 mm round. They reported impact kinetic energy ranging from approximately 0.3 kJ to 3.2 kJ on 21 canine subjects. Tests were performed under high-speed flash x-ray. Injuries received included superficial wounds, rib fractures, hemorrhages, and deep lacerations. The tests were correlated to both cadaveric tests and limited epidemiology discussed below, though extensive information on instrumentation of the animal testing is not reported.

The researchers found that backface deformation with soft body armor has a maximum depth of penetration (H) comparable to the diameter (L) of the maximum area of contact (S). In contrast, the action of ceramic plates tends to lower the penetration depth relative to the contact diameter (L). For these experiments, the depth and area of contact are measured using a high-speed flash x-ray. The volume was inferred, assuming an ellipsoid of revolution as $W = S^2/H$.

Swedish Studies (2000s).

The Swedish studies, conducted 32 years after the NATO sponsored activities, demonstrated that the U.S. criterion that allowed a 40 mm impression behind the vest was not protective for the higher velocity projectiles (Gryth et al., 2007). They studied 22 pigs protected by armor and impacted by 7.62 mm by 51 mm (800 m/s) rifle bullets. The anesthetized animals were monitored for brain, circulatory, respiratory, and blood chemistry changes during the acute period after the ballistic exposure. Extensive anatomical examinations were performed. The principal conclusion was that 50% of the animals died in the group with vests protective to 40 mm. Indeed, 25% of animals died in heavier armor that was protective to 34 mm impressions. It is important to note that the type of clay and the temperature conditions, well known to be important variables for the clay surrogate, were not stated for the Swedish studies. Another important point is that the velocity of the projectiles used was over two times that of the earlier U.S. handgun studies using .38 caliber, 128 grain bullets on goats.

Other Swedish studies involving animals and body armor used larger caliber projectiles in soft armor-protected pigs and compared the pathological results to a depth of penetration in a tissue surrogate consisting of soap to emulate the U.S. clay surrogate. In addition to 9 mm, they used 44 magnum and 12-gauge single-shot shot-gun projectiles. The soft armor protection consisting of various layers of Kevlar® with and without foam backing was minimally protective for most of the nine experiments (Lidén et al., 1988). One of the most important studies with hard armor was an electroencephalography (EEG)-based study on pigs impacted with 7.62 mm (800 m/s) bullets. Although the armor was not pierced, five of the eight pigs showed temporary EEG changes and all pigs showed lung injuries (Drobin et al., 2007).

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The most recent Swedish studies evaluated the efficacy of adding lightweight material to hard body armor to attenuate the transmission of pressure waves (Sondén et al., 2009). This material is now generally called trauma attenuating backing (TAB). Twenty-four pigs, protected by a ceramide/aramid body armor without ($n = 12$) or with TAB ($n = 12$), were shot with a standard 7.62 mm assault rifle. The TAB significantly decreased the size of the lung contusion, decreased hemoptysis, and reduced peak pressures by 91%.

French Studies (Prat et al., 2010).

To find a correlation between intrathoracic pressure, BABT, and high- versus low-velocity bullets, 20 pigs, protected by a NIJ Level 3 or 4 bulletproof vest, were shot with 7.62 mm NATO bullets (2.4 kJ and 3.2 kJ) and 10 unprotected pigs were shot with an air gun with 40 mm rubber projectiles (0.07 to 0.2 kJ) (Prat et al., 2010). Rib fractures occurred in 21 of the 30 animals with no correlation to the projectile kinetics, but intrathoracic peak pressures showed a good correlation with the volume of lung contusions. Other studies by the French are reviewed under NATO studies.

United Kingdom Studies on the cardiac trauma threshold.

The most extensive live-animal, live-fire tests using body armor and 48 pigs were conducted in the 1980s. Anesthetized animals were instrumented with pressure transducers and accelerometers. High-speed photography and cine-radiography observations were used to define the kinetics of deformations in the armor and the chest, and temporal and spatial pressure changes were measured. Using an air gun with projectiles of 0.14 and 0.38 kg, and velocities between 20 to 74 m/s, animals were studied for the consequences of 64 to 363 Joules delivered mostly to the anterior sternum (Cooper et al., 1982). The principal findings were that the degree of heart damage was related to the ratio of chest wall displacement to anterior-posterior chest diameter, and this was proportional to the energy of the impact divided by the product of the diameter of the impactor and the body mass. The diameters of the impactors (i.e., 3.7 and 10 cm) are much larger than live-fire projectiles but are in the range of the diameters of the backface displacements.

In another study, small steel ball fiduciarities were implanted in and around the heart to measure displacements using cineradiography (Cooper et al. 1984). These studies give important basic information regarding the thresholds for cardiac damage from energy delivered to the chest wall and the diameter of the backface displacement. Thus, this information can be included as criteria for body armor design, to defeat a high-velocity and high energy projectile delivery (e.g., 3 kJ to 13 kJ) and protect personnel from BABT.

In a recent meeting (2024) at Wayne State University including the UK group, the U.S. Army, researchers involved in assessing early hard armor (DeMaio, 2001), WSU, UVA, and MCW, and others discussed the reanalysis of these earlier tests in the context of ongoing testing by the MCW/UVA/WSU on thoracic BABT.

Cadaver Experiments for Behind Armor Blunt Trauma

A limited number of cadaver experiments with ballistic behind armor impact have been performed. For injury association using animal experiments, such cadaveric experimentation is likely crucial as there are significant differences between livestock anatomy and human anatomy, especially in the mediastinal region.

Anter Corporation (Mirzeabassov et al., 2000).

In addition to the animal experimentation reported by Mirzeabassov et al. (2000), thirteen cadaver experiments were reported. The tests used various vest types, which included two thicknesses of titanium plates and ceramic body armor. Rounds included 7.62 mm with two impact energies, a .45 caliber M11911A1, and a 9 mm round. The researchers reported impact kinetic energy ranging from approximately 0.3 to 3.2 kJ. Details regarding the preparation of the cadavers and conditions under which the tests were conducted were not reported. The authors stated some differences in tolerance between animal and cadaver results for the internal organs; however, the differences are not quantified.

DeMaio (DeMaio, 2001).

In a study of body armor, researchers instrumented seventeen cadaveric specimens, including six females and eleven males with a mean age of 73 years. Various body armors with different velocity regimes are reported by DeMaio (2001). Instrumentation included accelerometers at the sternum, seventh thoracic vertebra (T7), carina, and ligamentum arteriosum and pressure sensors in the right and left ventricle and left chest. There was an attempt to measure the impact pressure between the armor and chest wall that was reportedly unreliable. Pressurization of the lungs and cardiovascular system was performed. A post-test evaluation was completed for exterior wounds, sternal and rib fractures, cardiac bruising, and other injuries including pulmonary injuries and spinal fractures.

Three body armor systems were tested, a soft vest with 9 mm test rounds, a light plate with a 7.62 mm round at two representative velocities, and a heavy plate with a 7.62 mm round at one representative velocity. Three injury levels were defined. These are survivable (with minimal trauma), immediately survivable (non-lethal if treated within one hour), and lethal (fatal even with treatment within one hour). Injuries received ranged from light surface friction to deep extensive bilateral open chest wounds. The most severe injuries arose from complete plate penetration; an estimated three-quarters of the cases where the round went fully through the plate were lethal.

The use of data from instrumentation for this study poses several difficulties. The accelerometers were attached to the sternum using suture material. However, accelerations exceeding 1000 G were seen in some tests. The effective mass of a typical shock accelerometer (nominal mass ~1 g) at this acceleration level exceeds 1 kg. To ensure repeatable results, some rigid connection is exceedingly desirable. Second, the measurement of uniaxial accelerations on viscoelastic components within the thorax, such as the carina and ligamentum arteriosum, is questionable. Results will vary significantly based on local details of mounting and local viscoelastic behavior of the compliant structures of the carina and ligamentum arteriosum. While

it may be possible to use these measurements for qualitative estimation of the gross arrival of local tissue deformation owing to the significantly increased density of the accelerometer compared with the surrounding tissue, intra-specimen comparisons are questionable. So, this work is most useful for the quantitative injury performance of the articles tested. No injury risk function has been developed in terms of measured dynamic variables.

Bass et al., 2006.

This study used a highly deforming hard body armor to estimate the mechanical correlates of BABT injury in nine cadavers and two anthropomorphic test dummies (AUSMAN, clay). A range of velocities were tested including low-, medium-, and high-severity impacts based upon risk of sternal fracture. Thoracic injuries ranged from minor skin abrasions (AIS 1) to severe sternal fractures (AIS 3+) and were well correlated with impact velocity and bone mineral density. Eight male cadavers were used in the injury risk criterion development. A 50% risk of AIS 3+ injury corresponded to a peak impact force of $24,900 \pm 1,400$ N. This study also investigated spinal impacts behind body armor in a single test. The correlation of injuries to the sternum and spine in the same specimen under the same threat round velocity suggests that sternal impact may not be the worst case for behind hard armor impact. Preliminary data from a single specimen with a matched sternal and spinal impact behind the body armor suggests that additional spinal impact research would be of significant value. This study, however, did not assess impacts to the ribs or more general loading conditions with body armors of different characteristics.

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