ARMY RESEARCH LABORATORY

Origin of the 44-mm Behind-Armor Blunt Trauma Standard

by Erin Hanlon and Patrick Gillich

ARL-RP-390 **August 2012**

A reprint from *Military Medicine,* Vol. 177, pp. 333–339, March 2012.

NOTICES

Disclaimers

Army Research Laboratory
Aberdeen Proving Ground, MD 21005-5068

ARL-RP-390 **August 2012**

Origin of the 44-mm Behind-Armor Blunt Trauma Standard

Erin Hanlon and Patrick Gillich
Survivability/Lethality Analysis Directorate, ARL

A reprint from *Military Medicine*, Vol. 177, pp. 333–339, March 2012.

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED (From - To)
August 2012	Reprint	March 2012

4. TITLE AND SUBTITLE	5a. CONTRACT NUMBER
Origin of the 44-mm Behind-Armor Blunt Trauma Standard	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
Erin Hanlon and Patrick Gillich	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)	**8. PERFORMING ORGANIZATION REPORT NUMBER**
U.S. Army Research Laboratory ATTN: RDRL-SLB-W Aberdeen Proving Ground, MD 21005-5068	ARL-RP-390
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	**10. SPONSOR/MONITOR'S ACRONYM(S)**
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

A reprint from *Military Medicine*, Vol. 177, pp. 333–339, March 2012.

14. ABSTRACT

A number of armed assaults on public officials occurred in the early 1970s, which prompted the Lightweight Soft Body Armor Program to develop modern, concealable, soft body armor. Methodology needed to be developed to (1) determine the effectiveness of the soft body armor to stop bullet penetration and (2) assess the potential injury from nonpenetrating blunt impacts to the body. Extensive research was performed under the program to develop methodologies to assess soft body armor, including behind-armor blunt trauma (BABT) evaluation. This methodology is still used today, and it has been applied extensively beyond the original intent. However, the origin of this methodology is not well understood by many researchers in the various fields in which it is being applied because the original documentation is difficult to obtain. Therefore, the purpose of this report is to provide a comprehensive review of the BABT to offer researchers information about its history and limitations.

15. SUBJECT TERMS

blunt trauma, body armor

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Erin Hanlon
Unclassified	Unclassified	Unclassified	UU	14	19b. TELEPHONE NUMBER (*Include area code*) 410-278-7031

Origin of the 44-mm Behind-Armor Blunt Trauma Standard

Erin Hanlon, PhD; Patrick Gillich, MS

ABSTRACT A number of armed assaults on public officials occurred in the early 1970s, which prompted the Lightweight Soft Body Armor Program to develop modern, concealable, soft body armor. Methodology needed to be developed to (1) determine the effectiveness of the soft body armor to stop bullet penetration and (2) assess the potential injury from nonpenetrating blunt impacts to the body. Extensive research was performed under the program to develop methodologies to assess soft body armor, including behind-armor blunt trauma (BABT) evaluation. This methodology is still used today, and it has been applied extensively beyond the original intent. However, the origin of this methodology is not well understood by many researchers in the various fields in which it is being applied because the original documentation is difficult to obtain. Therefore, the purpose of this article is to provide a comprehensive review of the BABT to offer researchers information about its history and limitations.

INTRODUCTION

Body armor has been used in various forms throughout history to prevent penetrating injury to the wearer.[1] Following the introduction of handguns, various types of soft body armor were investigated to mitigate those threats, but many were not useful for everyday wear. Because of a number of armed assaults on public officials before 1973, the Department of Justice (DOJ) charged the U.S. Army Land Warfare Laboratory and the Wound Ballistic Branch of the U.S. Army Bio-Medical Laboratory to develop a protective garment for everyday wear by these officials.[2] This research, part of the Lightweight Soft Body Armor program begun in 1952, was overseen by the National Institute of Law Enforcement and Criminal Justice (NILECJ), a branch of the Law Enforcement Assistance Administration (LEAA), which was part of the Department of Justice. The NILECJ decided to add police officers to the end user group of this program after police officer deaths in the line of duty increased by 126% from 1966 to 1971.[1] This program led to the initial development and evaluation of modern, concealable, soft body armor, specifically designed for daily use by police officers.[1,2]

The NILECJ needed to be able to determine the effectiveness of newly developed soft body armor. Therefore, it was assessed for its ability to stop bullets and for the injury potential to the wearer resulting from defeated bullets. To defeat a bullet, the soft body armor must dissipate the kinetic energy of the bullet. This energy is dissipated in many ways, including the deformation of the armor, the deformation or fragmentation of the bullet, and the deformation of the underlying body wall. Although the bullet can be effectively stopped from penetrating the body, the energy transfer has the potential to cause serious injury or even death. When the armor deforms and is pushed into the wearer's body, the body wall is forced inward. The nonpenetrating injuries resulting from this energy transfer are termed behind-armor blunt trauma (BABT).[3–12] BABT injuries can also extend to the underlying organs as a result of the rapid acceleration and localized deformation of the thoracic wall.[11]

To develop a method to assess these risks, the NILECJ funded the evaluation of BABT and its relationship to injury. The initial intent of this evaluation was to provide police departments with a quick and inexpensive way to evaluate soft body armor on-site using a simple criterion that would support a pass/fail evaluation. Both of these requirements significantly limited the testing procedures that could be proposed. The resulting research was implemented into the National Institute of Justice (NIJ) 0101 standard that is still in place today (now in its sixth revision, NIJ 0101.06).[12] The standard is used to assess personal body armor in the NIJ Voluntary Compliance Testing Program.

U.S. Army Research Laboratory, RDRL-SLB-W, 328 Hopkins Road, Aberdeen Proving Ground, MD 21005.

METHODOLOGY

The current study evaluated the past literature in the area of BABT and the 44-mm standard. The databases Pubmed/ Medline, Google Scholar, and the Defense Technical Information Center were searched utilizing the following search terms: BABT, backface signature, ballistic blunt trauma, ballistic vest, behind armor, behind armor blunt trauma, behind armour, behind armour blunt trauma, body armor, body armour, bullet proof vest, wound ballistic, and wound ballistics. The search was restricted to articles that were written in English. The reference section of any included journal articles was also reviewed to determine additional references that may be included. Journal articles were included if they related to the development of the 44-mm standard, represented current use of the standard, or attempted to improve upon the standard. When information was not available in the resulting publications, personal communications with those involved in the original testing were utilized.

THE LIGHTWEIGHT SOFT BODY ARMOR PROGRAM OVERVIEW

The initial research funded by the Lightweight Soft Body Armor Program to develop and implement protective armor was performed at Edgewood Arsenal, Aberdeen Proving

Ground, Maryland, by researchers in the U.S. Army Wound Ballistics Program.[13–21] The Army Wound Ballistics Program was started in 1952 and included three Corps within the Army, the U.S. Army Chemical Corp, the U.S. Army Medical Corp, and the U.S. Army Ordnance Corp. The Biophysics Division at Edgewood Arsenal, part of the Army Wound Ballistics Program, completed the experimental work that led to the development of concealable soft body armor, the BABT deformation limit, and original test methodology that is included in the NIJ 0101 set of standards. Experimental research performed by this group included work on antipersonnel munitions, weapons effectiveness, and development and effectiveness evaluation of personal soft body armor. A published account of the majority of the research that was performed within this program is either not available or not easily obtainable, particularly in open literature publications (Edward Davis, personal communication).

Initial Soft Body Armor Research

The initial research program set out to develop lightweight soft body armor for everyday wear by public officials, which is why the original prototypes were implemented into sport coats.[2] The program was later expanded to include police officers (Fig. 1). The development of lightweight soft body armor was possible due to the invention of the Kevlar fiber by DuPont in 1965.[1] The first phases of the research program investigated various materials including Kevlar, their effectiveness in stopping a bullet, and the number of plies required to limit injury to officers while keeping the vest lightweight. Once Kevlar was deemed the best option,[2] tests were developed and performed to assess trauma from bullets that were defeated, and field tests were carried out to determine the vest's wearability and real-world effectiveness.[14–16,20,21]

The objectives of the program were to develop soft body armor that could stop the most common threats against police officers at that time, which were .38 Special rounds and .22 long handgun rounds.[1,2,22] These low-energy rounds were chosen, as opposed to a worst-case scenario, to permit the development of lighter-weight soft body armor while still providing protection against the most prevalent threat at the time. The armor needed to be inconspicuous, lightweight, and worn externally. This new armor was to be used for discreet, everyday wear by public officials and police officers. Resulting garments needed to prevent bullet penetration, limit blunt trauma mortality risk to less than or equal to 10%, and allow an adult male to walk from the site of the shooting.[1,2] These requirements included the assumption that medical attention would be accessed within 1 hour of being shot.[2]

Tests needed to be developed to determine both the stopping ability of the armor as well as the potential blunt-trauma effects for the .38 Special rounds and .22 long rifle rounds. Additional work was to be performed on a more extensive set of rounds to determine the potential blunt-trauma effects, but the funding was stopped.[14,15] Some of this work was completed, 9-mm and .357 impacts to both goats and clay (unpublished data), but was never fully completed or published because of funding limitations.

The first step in the development of lightweight soft body armor was to determine what materials could stop the necessary rounds. In a study carried out by Montanarelli et al,[2] the most promising material candidates for soft body armor, of which Kevlar-29 was the frontrunner, were defined and tested on goats as an initial measure of serious injury and lethality. Armored, anesthetized goats were impacted with both the .38 Special and .22 caliber projectiles. Goldfarb et al[17] performed follow-up studies using the same goat model and the same caliber projectiles to predict the probability of serious injury and lethality. One of the major assumptions was that the 40- to 50-kg goat model accurately represented a 70-kg man, specifically that a 70-kg man would have no more damage than the goat.[17]

Once Kevlar-29 was selected, further goat testing was performed to determine the number of plies needed to provide sufficient protection from blunt trauma, which was indicated by a mortality risk of less than 10% and the ability of an adult male to walk from the site of the incident. More plies of material added more weight, but they also provided more protection. Impacts using a .38 caliber bullet with an 800 fps impact velocity were performed on anesthetized, intubated

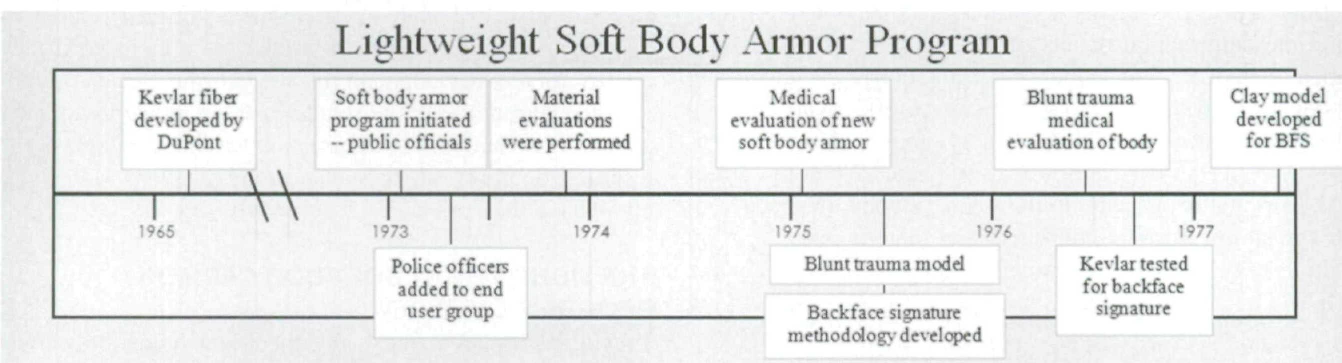

FIGURE 1. Timeline of the soft body armor program.

goats wearing the 7-ply Kevlar-29 protective garments. Impacts were performed over the heart, spine, lung, liver, gut, and spleen.

Human mortality was determined by defining the exposed area of vulnerable human organs in four planes (front, back, sides). Although the exposed area was determined on human organs, vulnerable organs were defined as goat organs with damage following impact. It was assumed that the same organs would be vulnerable in humans. The probability of mortality was calculated by multiplying the vulnerable area by a mortality rate that was assigned to the organ based on previous human surgical data. An average of this probability in the four planes was used to define the mortality rates. Human mortality after being shot with a .38 Special was determined to be 7% to 25% when no garment was worn and 1% to 5% when wearing the 7-ply Kevlar-29, indicating a clear improvement when wearing the garment.[17]

Initial BABT Research

To determine the risk of BABT injury, a standard methodology for measuring back-face signatures (BFS), the maximum deformation of the soft body armor as a result of ballistic impact, in soft body armor successes had to be developed. Metker et al[20] performed a study to characterize BFS and relate it to tissue damage. Gelatin blocks, 20 % ballistic gelatin, were used in the study to determine the loading rate (impulse) of deformation using high-speed photography. The armor was attached to the blocks and shot with either a .38 Special or a .22 caliber at approximately 800 fps. These tests were performed during methodology development, and the velocity for .22 caliber shots was increased to 1000 fps for the remaining tests. Deformation of the gelatin was measured frame-by-frame with a focus on the depth and diameter of deformation. It was determined by Metker et al that BFS could be successfully measured in this way.

Parametric Lethality Model

A parametric lethality model for blunt trauma developed by Clare et al[16] in 1975 was used in developing assessment techniques for BABT. The model was developed to be species-independent to reduce the need for animal testing. To develop the model, existing blunt-trauma data were reviewed and analyzed to assess their usefulness. Because researchers were using these existing datasets, the input data for the model development was limited. In addition to reducing or eliminating the need for animal testing in this application, the model also provided the ability to compare previous blunt-trauma data to the body-armor work that was going on at the time.[14,15,23] A modified, four-parameter model was determined by Clare et al to be the best fit based on its ability to accurately classify fatalities versus nonfatalities. Modifications and refinements have been made to this model since its origination.[23]

Model Validation

The model utilized lethality in all assessments of the thorax data from the goat study discussed previously. However, fracture/no-fracture was used for validation of the abdominal model using liver impacts. The model was validated after determining appropriate limits for three zones: low lethality, mid-lethality, and high lethality. Datasets, which were not used in the creation of the model, were then applied to determine model accuracy, which was found to be conservative in the higher range. Although this model was deemed species-independent because of the use of the body mass parameter, it was only validated using the goat. Researchers suggested that larger animals should be assessed to determine the validity of the model in higher mass ranges and its applicability to humans. Validation using larger animals was not published, but blunt impacts were performed on steer as a method of validating the model (unpublished data).

This methodology was developed using a specific dataset that did not include BABT impacts. Although it successfully provided a nonbiologic measure of the BABT effects, Clare et al[16] recommended further evaluation in order to use BFS parameters as a measure for armor effectiveness. Specifically, BFS measures need to be correlated to the probability that a specific combination of parameters relating to ballistic impact conditions will result in lethal injury. This correlation of BFS measures to BABT injuries still does not exist.

Backing Material

The backing material plays a critical role in quantifying penetration resistance characteristics of the armor material since, when a bullet is defeated by soft body armor, the energy dissipation deforms the armor and the backing material. Traditionally, BFS testing used ballistic gelatin as a backing material,[21] but the use of gelatin was very expensive because of the need for high-speed video to characterize the back-face depth over time. As a result, the NILECJ needed to develop a new test methodology that would be inexpensive and easy-to-conduct to allow law enforcement agencies to perform testing at their own facilities (Russell Prather, personal communication).

Because gelatin had been found to respond similarly to human tissue and had been used in previous studies,[2,20–22] it was determined that a backing material that responded similarly to gelatin was needed. Ideally, the LEAA wanted a new backing material that had a similar deformation depth and rate as gelatin, was reusable, and had a limited material recovery so that high-speed video was not required (Russell Prather, personal communication).

To find a backing material that fit the needs of the NILECJ, depth and rate of deformation tests were performed. These tests were performed using a 200-g, 80-mm hemispherical impactor at 55 m/s with no vest material over the backing material.[21] Deformation–time histories of the goat thorax and abdomen were used to compare deformation–time histories of the other backing materials that were tested to determine the ability of each material to simulate a tissue response (Fig. 2). The goat abdomen, goat thorax, 20% gelatin, and two types of clay (Plastilina 1 and 2) were tested to compare the nonbiological backing materials to the goat model. Plastilina 1 is an oil-based modeling clay (Sculpture House, Skillman NJ), but no details were provided about the composition or manufacturer of Plastilina 2. None of the materials successfully mimicked the goat thorax when assessing both deformation and time. It was determined that clay was a more conservative model than the gelatin used previously, and statistically significant differences were not seen. The Roma Plastilina 1 clay that was selected for use is a highly plastic material that undergoes viscous flow when deformed and shows little to no recovery.[21] Roma Plastilina 1 was found to have the same depth of deformation of the thorax, but it reached that depth in a shorter time frame. This study employed the parametric lethality model to determine whether or not impacts fell within the low lethality zone. To use this model with clay, the effective mass and effective velocity had to be calculated using conservation of momentum. When this methodology was used, the estimates of mass and velocity were conservative.

The results of this testing were considered to be preliminary as no lethalities were observed for nonpenetrating bullet impacts on armor, and higher energy rounds had yet to be evaluated.[21] No solid conclusions were drawn as a result of a limited dataset, but the deformation depth was correlated to the probability of lethality that was established using the parametric lethality model, and 15% probability of lethality was determined to occur at a penetration depth of 5 cm. It was determined that Roma Plastilina 1 clay met the NILECJ requirements since it was readily available, inexpensive, and easy to use.[21] It was also determined that Roma Plastilina 1 could be correlated to tissue response, however, deformations in clay were never directly correlated to injury or severity.

Development of the 44-mm BABT Standard

There are two different recollections of how the exact maximum deformation of 44 mm became the BABT standard.[15] Both accounts indicate a relationship to the average of the maximum deformations of shots performed on gelatin with a .38 caliber as seen in Figure 3. These impacts were on gelatin, but the standard would use clay because of the similarities in maximum deformation as demonstrated by Prather et al.[21] Although the accounts are similar, Prather indicates that the LEAA selected the actual average value, 44 mm, as the standard which should be used (Russell Prather, personal communication), but elsewhere it is stated that Goldfarb et al recommended 44 mm based on the average, stated as 4.74 cm, less one sample standard deviation, .33 cm.[15] Both accounts relied on the same empirical datasets that demonstrated a lack of serious injury or death in the goat population at a deformation depth. This fact indicated to researchers and administrators that if the 40 to 50 kg goat was a good model,

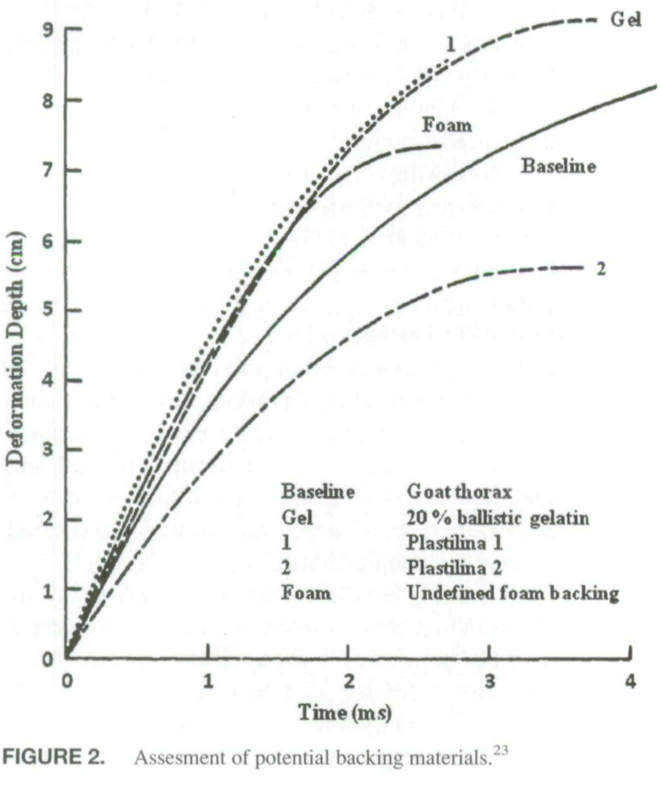

FIGURE 2. Assesment of potential backing materials.[23]

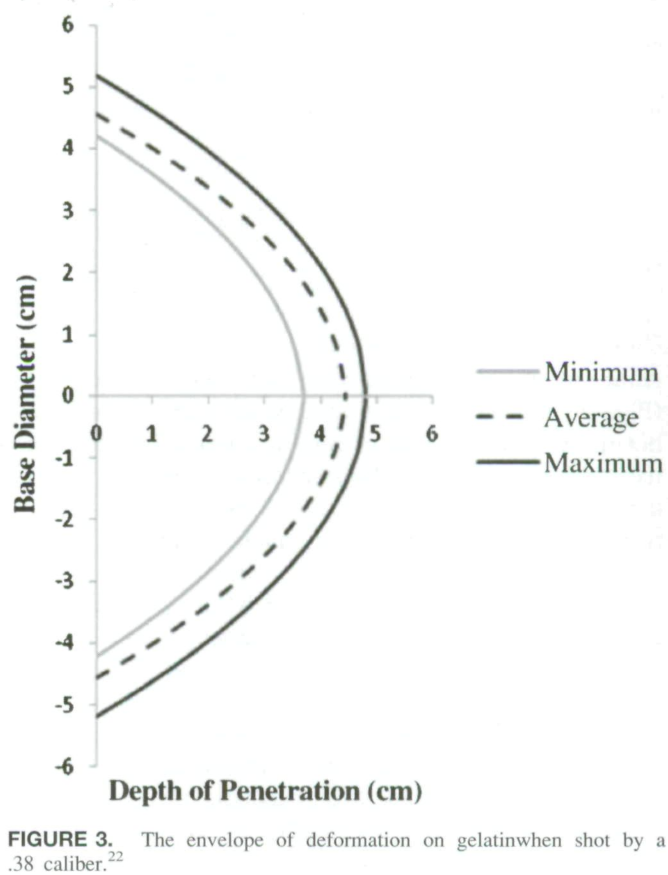

FIGURE 3. The envelope of deformation on gelatinwhen shot by a .38 caliber.[22]

then men sustaining similar impacts would also lack life-threatening injuries.

To develop the 44-mm BABT standard in clay, correlations needed to be made to assess the probability of lethality. To achieve this correlation, some very tenuous relationships were established. The maximum depth of the BFS in clay backing was compared to the maximum instantaneous depth created by a blunt projectile in gelatin and determined to be a suitable substitute. These correlations were all based on a single impact per backing material. To correlate clay to lethality, it was first correlated to gelatin that had been correlated to the ballistic parameters using the parametric lethality model. Lethality versus nonlethality in goats was used to develop the parametric lethality model and that goat model was determined to be valid for lethality and nonlethality in humans.[14–17,19–21] Although clay and gelatin deformation–time histories were both compared to the goat thorax-deformation response, neither were a match; however, gelatin had been used in previous deformation studies successfully and had been related to potential lethality in goats. Since the clay had a similar maximum deformation to gelatin, it was believed that the same correlation to goat lethality developed using gelatin would be acceptable for use with clay.

No direct relationship to injury was established for the 44-mm BABT standard, and only an indirect relationship to nonlethality is evidenced, but it has been shown to be very effective in practice. Although there is no direct correlation to injury, since 44-mm of deformation became the standard, BABT has not been responsible for any documented lethalities. Similar success with the standard has been seen in military applications; however, it is challenging to track these types of data in the field. The lack of field data in military environments also limits epidemiological studies to assess body-armor effectiveness and BABT injuries.

In addition to determining a new backing material for the evaluation of BABT, Prather et al also related the depth of penetration into goats with probability of lethality (Fig. 4) showing that a 44-mm deformation demonstrated a 6% probability of lethality.[15,21] The relationship between goat-thorax deformation and probability of lethality was developed (Fig. 4) using the original blunt impactor data,[16,21] but it does not relate a deformation in clay to a probability of lethality.[15,21] As stated earlier, the clay response was not representative of the goat thorax response. None of the backing materials tested matched the deformation of the goat thorax.

The initial objectives for the Lightweight Soft Body Armor program were met successfully, as indicated by the completion of the program. It was determined that the newly developed, soft body armor could stop the indicated threats as shown by Montanarelli et al[2] in the initial research. After developing methodology to assess blunt-trauma mortality risk, it was shown that the 44-mm standard deformation in clay provided a 6% probability of lethality, which fell under the initial requirement of less than or equal to 10%. One requirement that was not explicitly met, allowing an adult

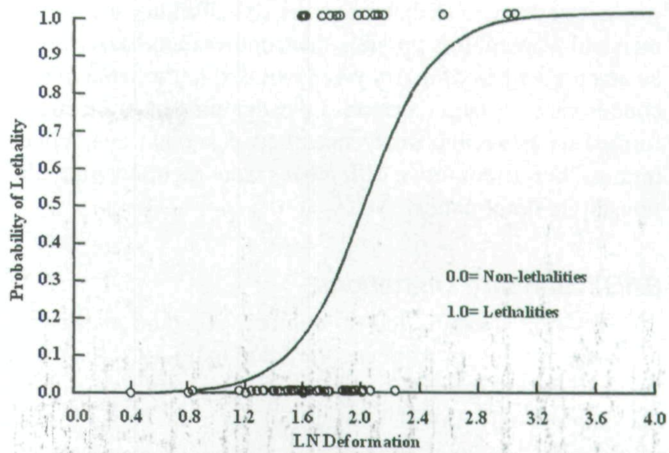

FIGURE 4. Relationship between the natural log of the deformation of goat thorax and the probability of lethality[23] using the data from the development of the blunt trauma model where unarmored goats were impacted with a blunt impactor.

male to walk away from the site of the shooting, was assumed to be met. This assumption was made since none of the armored goats died within the 24-hour postimpact window.

CURRENT BABT STANDARD USE AND LIMITATIONS

The current BABT standard is used in both civilian and military applications as well as in other countries.[24] In military testing, the back-face deformation limit of 44 mm is used in first article testing and lot acceptance testing for both soft body armor and hard plate armor. In the civilian environment, all personal body armor that is submitted to the NIJ Voluntary Compliance Testing Program is assessed using this standard.[12] In addition to testing currently manufactured body armor, there is research being done that uses this measure. The use of clay and the 44-mm standard was intended to be preliminary and was not meant to have the widespread use it has today.[21] Following the Prather et al assessments, additional follow-up research to address the limitations was recommended by the researchers, but this work was never completed because of a discontinuation of the funding.[14,15]

BABT Standard Misuse

The BABT standard is also being used in applications for which it was never intended nor validated. Examples include the use of the 44-mm back-face measure to assess hard-body armor, body armor for small individuals, and impacts with rounds other than a .38. Impacted hard-armor plates load the torso differently than soft body armor, which could create different injury patterns in BABT situations. Therefore, a different evaluation technique may be needed to assess plate armor. It was also indicated by researchers that the current standard may not be valid for small individuals and women and that further research needed to be performed to address this limitation.[17,24] The standard was developed using a model that was designed to represent a 70-kg man, and testing was not performed to determine the risk of injury for smaller men and women. It is possible that smaller individuals would be at a higher risk of injury when exposed to the same impact conditions as a larger person. Investigations have been performed to assess the differences between male and female injuries, but no definitive differences were reported with relationship to deformation.[24]

BABT Standard Limitations

The 44-mm standard has a number of additional issues including the lack of a direct correlation to injury. Along with the inability to assess injury level or a probability of injury, the standard only provides a pass/fail criterion. No additional information can be gleaned from the depth of an impression in clay. Additionally, the current standard was developed using a single type of armor with only .38 Special and .22 long rifle rounds traveling with an 800 and 1000 fps impact velocity, respectively, without validation of other rounds or armor configurations. The original intention was to include higher energy rounds in the BABT standard development, but these were not included. However, Prather et al[21,22] performed a portion of these shots on various backing materials using a .357, 9 mm, and .44 magnum, but the corresponding shots were not performed using the goat model to assess injury. Additional research would be required to determine the applicability to higher energy rounds. These issues with the current standard are all related to the actual tolerance limit, but there are also many issues with the use of clay for the backing material.[25–27] These include problems with variability in clay response because of handling, thixotropic effects, and changes in clay formulation since its implementation into the standard is dictated by requirements for its use in the art community.

CURRENT RESEARCH

Current research is being conducted to address the issues described in the BABT standard limitations section. Much of this research is focused on alternative backing materials and mechanical surrogates, but direct-injury correlations and repeatability remain challenging. In addition to these challenges, finding a sensor system that successfully captures the necessary measures at ballistic rates without resulting in sensor damage remains difficult. Some of the directions that researchers have taken in this area are (1) making comparisons of cadaveric injury responses to mechanical surrogates,[28] (2) developing new mechanical surrogates, and (3) developing both mathematical computer models[6,29–31] and finite element models[29–34] to assess BABT injury.

In addition to these efforts, there is research underway to develop clay specifically for ballistic testing. Requirements for this development include clay use at room temperature, consistent batch properties, and a lack of age and temperature dependency. By eliminating the variation in clay testing, researchers may be able to more accurately provide injury relationships to the clay measures, which are currently being collected in testing.

Other attempts to improve the current BABT standard include trying to determine a different backing material to remove variability associated with clay testing,[27] comparing animal injuries with depressions in soap,[35] and assessing animal injury when the animal is wearing armor.[5] Researchers have also made attempts to quantify the level of injury and correlate that to varying impressions in clay backing.[7,8,14,15,24,36] This research has been done both through re-creating officer incidents in a laboratory setting with the same armor and ammunition on clay backing[14,15,24,36] and comparing the injuries sustained by the officers to the impressions created in the clay. The re-creations that have occurred have been civilian cases because of a lack of military data. This lack of data is caused by challenges that occur in collecting military field data. Researchers are also comparing animal injury to the sensitivity of measurements in clay using the same input conditions for the animal impacts and the clay impacts.[7,8]

Although much research is being conducted to replace clay, it is still being used in current military and civilian standards and acceptance testing. In addition, the BABT standard has been successful since its implementation in preventing blunt trauma injuries in both the civilian and military settings. To improve current standards testing using clay, it is necessary that researchers understand the origin of the BABT standard. In addition to understanding what the standard was designed to do, this historical information provides insight into the limitations along with the successes the standard has had in limiting lethality caused by BABT.

ACKNOWLEDGMENTS

This research was supported in part by an appointment to the Postgraduate Research Participation Program at the U.S. Army Research Laboratory administered by the Oak Ridge Institute for Science and Education through an interagency agreement between the U.S. Department of Energy and USARL. The research was funded internally through the US Army Research Laboratory's Survivability/Lethality Analysis Directorate.

REFERENCES

1. National Institute of Justice: Selection and Application Guide to Personal Body Armor. NIJ Guide 100-01. 2001. Available at National Criminal Justice Reference System https://www.ncjrs.gov/pdffiles1/nij/189633.pdf; accessed August 19, 2011.
2. Montanarelli N, Hawkins C, Goldfarb M, Ciurej T: Protective Garments for Public Officials. LWL-TR-30B73. Aberdeen Proving Ground, MD, Edgewood Arsenal, 1973. Available at Defense Technical Information Center http://www.dtic.mil/cgi-bin/GetTRDoc?AD=ADA089163&Location=U2&doc=GetTRDoc.pdf; accessed August 19, 2011.
3. Cannon L: Behind armour blunt trauma—an emerging problem. J R Army Med Corps 2001; 147: 87–96.
4. Carroll A, Soderstrom C: A new nonpenetrating ballistic injury. Ann Surg 1978; 188: 753–7.
5. Drobin D, Gryth D, Persson JK, et al: Electroencephalogram, circulation, and lung function after high-velocity behind armor blunt trauma. J Trauma 2007; 63(2): 405–13.
6. Grimal Q, Naili S, Watzky A: A high-frequency lung injury mechanism in blunt thoracic impact. J Biomech 2005; 38(6): 1247–54.

7. Gryth D, Rocksen D, Arborelius UP, et al: Bilateral vagotomy inhibits apnea and attenuates other physiological responses after blunt chest trauma. J Trauma 2008; 64(6): 1420–6.
8. Gryth D, Rocksen D, Persson JK, et al: Severe lung contusion and death after high-velocity behind-armor blunt trauma: relation to protection level. Mil Med 2007; 172(10): 1110–6.
9. Merkle AC, Ward EE, O'Connor JV, Roberts JC: Assessing behind armor blunt trauma (BABT) under NIJ standard-0101.04 conditions using human torso models. J Trauma 2008; 64(6): 1555–61.
10. Sarron JC, Caillou JP, Da Cunha J, Allain JC, Tramecon A: Consequences of nonpenetrating projectile impact on a protected head: study of rear effects of protections. J Trauma 2000; 49(5): 923–9.
11. Sonden A, Rocksen D, Riddez L, et al: Trauma attenuating backing improves protection against behind armor blunt trauma. J Trauma 2009; 67(6): 1191–9.
12. National Institute of Justice: Ballistic Resistance of Body Armor. NIJ Standard–0101.06. 2008. Available at National Criminal Justice Reference System https://www.ncjrs.gov/pdffiles1/nij/223054.pdf; accessed August 19, 2011.
13. Bellamy R, Zajtchuk R: The management of ballistic wounds of soft tissue. In: Textbook of Military Medicine: Part I Warfare, Weaponry, and the Casualty, pp 163–220. Edited by Zajtchuk R. Washington DC, Department of the Army, Office of the Surgeon General, 1998.
14. US Congress, Office of Technology Assessment: Police Body Armor Standards and Testing: Volume I. OTA-ISC-534. 1992. Available at Federation of American Scientists http://www.fas.org/ota/reports/9229.pdf; accessed August 19, 2011.
15. US Congress, Office of Technology Assessment: Police Body Armor Standards and Testing, Volume II–Appendixes. OTA-ISC-535. 1992. Available at Princeton University http://www.princeton.edu/~ota/disk1/1992/9230/923001.PDF; accessed August 19, 2011.
16. Clare V, Lewis J, Mickiewicz A, Sturdivan L: Body Armor-Blunt Trauma Data. EB-TR-75016. Aberdeen Proving Ground, MD, Edgewood Arsenal, 1975. Available at Defense Technical Information Center http://www.dtic.mil/cgi-bin/GetTRDoc?Location=U2&doc=GetTRDoc.pdf&AD=ADA012761; accessed August 19, 2011.
17. Goldfarb M, Clurej T, Weinstein M, Metker L: A Method for Soft Body Armor Evaluation: Medical Assessment. EB-TR-74073. Aberdeen Proving Ground, MD, Edgewood Arsenal, 1975. Available at Defense Technical Information Center http://www.dtic.mil/cgi-bin/GetTRDoc?AD=ADA005575&Location=U2&doc=GetTRDoc.pdf; accessed August 19, 2011.
18. Jandial R, Reichwage B, Levy M, Duenas V, Sturdivan L: Ballistics for the neurosurgeon. Neurosurgery 2008; 62(2): 472–80; discussion 80.
19. Metker L, Prather R, Coon P, Swann C, Hopkins C, Sacco W: A Method for Soft Body Armor Evaluation: Cardiac Testing. ARCSL-TR-78034. Aberdeen Proving Ground, MD, Edgewood Arsenal, 1978. Available at Defense Technical Information Center http://www.dtic.mil/cgi-bin/GetTRDoc?AD=ADA329410&Location=U2&doc=GetTRDoc.pdf; accessed August 19, 2011.
20. Metker L, Prather R, Johnson E: A Method for Determining Backface Signatures of Soft Body Armors. EB-TR-75029. Aberdeen Proving Ground, MD, Edgewood Arsenal, 1975. Available at Defense Technical Information Center http://www.dtic.mil/cgi-bin/GetTRDoc?AD=ADA012797&Location=U2&doc=GetTRDoc.pdf; accessed August 19, 2011.
21. Prather R, Swann C, Hawkins C: Backface Signatures of Soft Body Armors and the Associated Trauma Effects. ARCSL-TR-77055. Aberdeen Proving Ground, MD, Edgewood Arsenal, 1977. Available at Defense Technical Information Center http://www.dtic.mil/cgi-bin/GetTRDoc?AD=ADA049463&Location=U2&doc=GetTRDoc.pdf; accessed August 19, 2011.
22. Prather R, Metker L: Ballistic Test Matrix for Kevlar Material. EB-TR-76054. Aberdeen Proving Ground, MD, Edgewood Arsenal, 1976. Available at Defense Technical Information Center http://www.dtic.mil/cgi-bin/GetTRDoc?AD=ADA029006&Location=U2&doc=GetTRDoc.pdf; accessed August 19, 2011.
23. Sturdivan L, Viano D, Champion H: Analysis of injury criteria to assess chest and abdominal injury risks in blunt and ballistic impacts. J Trauma 2004; 56(3): 651–63.
24. Wilhelm M. A Biomechanical Assessment of Female Body Armor. Wayne State University, Dissertation, Detroit, 2003. Available at Wayne State University Digital Commons http://digitalcommons.wayne.edu/dissertations/AAI3117255/; accessed December 13, 2011.
25. US Government Accountability Office: Warfighter Support Independent Expert Assessment of Army Body Armor Test Results and Procedures Needed Before Fielding. Report GAO-10-119. 2009. Available at Government Accountability Office Website http://www.gao.gov/new.items/d10119.pdf; accessed August 19, 2011.
26. The National Academies Committee to Review the Testing of Body Armor Materials for Use by the US Army—Phase II. Phase II Report on Review of the Testing of Body Armor Materials for Use by the U.S. Army. 2010. Available at The National Academies Press http://www.nap.edu/catalog.php?record_id=12885#toc; accessed August 19, 2011.
27. Roberts G, Bullian M: Protective Ability of the standard U.S. Military Personal Armor System, Ground Troops (PASGT) fragmentation vest against common small arms projectiles. Mil Med 1993; 158(8): 560–3.
28. Bass C, Salzar R, Lucas S, et al: Injury risk in behind armor blunt thoracic trauma. Int J Occup Saf Ergon 2006; 12(4): 429–42.
29. Shen W, Niu E, Mattrey RF, et al: Development and validation of subject-specific finite element models for blunt trauma study. J Biomech Eng 2008; 130(2): 021022.
30. Shen W, Niu E, Stuhmiller J: Biomechanically based criteria for rib fractures induced by high-speed impact. J Trauma 2005; 58(3): 538–45.
31. Shen W, Niu E, Bykanova L, Laurence P, Link N: Characterizing the interaction among bullet, body armor, and human and surrogate targets. J Biomech Eng 2010; 132: 121001.
32. Roberts JC, Ward EE, Merkle AC, O'Connor JV: Assessing behind armor blunt trauma in accordance with the National Institute of Justice Standard for Personal Body Armor Protection using finite element modeling. J Trauma 2007; 62(5): 1127–33.
33. Raftenberg M: Modeling Thoracic Blunt Trauma; Towards A Finite-Element-Based Design Methodology for Body Armor. Army Science Conference, 2005 November 29–December 2. Orlando, FL. Available at Defense Technical Information Center http://www.dtic.mil/cgi-bin/GetTRDoc?Location=U2&doc=GetTRDoc.pdf&AD=ADA433234; accessed August 19, 2011.
34. Roberts JC, O'Connor JV, Ward EE: Modeling the effect of non-penetrating ballistic impact as a means of detecting behind armor blunt trauma. J Trauma 2005; 58(6): 1241–51.
35. Liden E, Berlin R, Janzon B, Schantz B, Seeman T: Some observations relating to behind-body armour blunt trauma effects caused by ballistic impact. J Trauma 1988; 27(1): S145–8.
36. Wilhelm M, Bir C: Injuries to law enforcement officers: the backface signature injury. Forensic Sci Int 2008; 174(1): 6–11.

NO. OF COPIES	ORGANIZATION
1 (PDF only)	DEFENSE TECHNICAL INFORMATION CTR DTIC OCA 8725 JOHN J KINGMAN RD STE 0944 FORT BELVOIR VA 22060-6218
1	DIRECTOR US ARMY RESEARCH LAB IMAL HRA 2800 POWDER MILL RD ADELPHI MD 20783-1197
1	DIRECTOR US ARMY RESEARCH LAB RDRL CIO LL 2800 POWDER MILL RD ADELPHI MD 20783-1197

NO. OF COPIES	ORGANIZATION
1	USARL RDRL SLE R FLORES WSMR NM 88002-5513
	ABERDEEN PROVING GROUND
1	DIR US ARMY EVALUATION CTR HQ TEAE SV P A THOMPSON 2202 ABERDEEN BLVD 2ND FL APG MD 21005-5001
3 (2 HC 1 PDF)	DIR USARL RDRL SL J BEILFUSS P TANENBAUM RDRL SLB A M PERRY (PDF only)

NO. OF COPIES	ORGANIZATION
1	US ARMY NSRDEC RDNS WD B J WARD KANSAS ST NATICK MA 01760
1	US ARMY NSRDEC M MAFFEO KANSAS ST NATICK MA 01760

ABERDEEN PROVING GROUND

2	US ARMY ABERDEEN TEST CTR A FOURNIER S ESOLA 400 COLLERAN RD APG MD 21005
8	DIR USARL RDRL SLB R BOWEN RDRL SLB D D HISLEY RDRL SLB W J GURGANUS E HANLON (2 CPS) K RAFAELS L ROACH R SPINK