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An Approach to Analyze Personnel Injury of Reflective Spall From Small-Arms Protective Body Armor

by Rebecca VanAmburg

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An Approach to Analyze Personnel Injury of Reflective Spall From Small-Arms Protective Body Armor

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14. ABSTRACT

Fragmenting debris from ballistic impacts defeated by the protective plates in body armor, also known as reflective spall, has the potential to injure personnel wearing the protective plate. This has not been evaluated in the past due to difficulties in data collection as well as a lack of information on whether or not there is a legitimate risk of injury. Our objective was to develop a test procedure and analysis process to determine the potential for serious injury from reflective spall.

The testing and analysis was conducted by the U.S. Army Research Laboratory Survivability/Lethality Analysis Directorate. The testing included a custom experimental setup to collect the reflective spall using ballistic gelatin. The fragments recovered in the gelatin were used to quantify the potential for significant injury to the Soldier. Personnel vulnerability modeling and analysis were conducted using the MUVES-S2 modeling and simulation software. This software allowed the analysts to quantify potential hazards to the Soldier. The maximum abbreviated injury score was used to determine the likelihood of significant injury. Our approach of testing and analysis was able to quantify the potential for significant injury to the Soldier.

15. SUBJECT TERMS

ORCA, Warfighter, body armor, injury, models, capabilities, spall

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1. Purpose

Fragmenting debris from ballistic impacts defeated by the protective plates in body armor, also known as reflective spall, has the potential to injure personnel wearing the protective plate. This injury potential has not been evaluated in the past due to difficulties in data collection as well as a lack of information on whether or not there is a legitimate risk of injury. Our objective was to develop a test procedure and analysis process to determine the potential for serious injury from reflective spall.

This report describes an experimental design and the analysis procedure used to determine the potential risk of injury from reflective spall to personnel wearing the protective plate.

2. Experimentation

During the experimentation phase, the plate and ballistic gelatin configuration was designed to simulate protective plate placement on personnel. The gelatin blocks provided backing for the target as well as a witness collection medium for reflective spall fragments. The gelatin block configuration was designed to collect all of the fragments that could potentially impact a Soldier's arms, legs, and head (figure 1). From this point on, all references to gelatin refer to the gelatin used as a witness collection medium for the reflective spall fragments. The distances between the plate and the gelatin were determined using the digital human reference anatomy used in Operational Requirement-based Casualty Assessment (ORCA). This anatomy, referred to as ORCA man, represents a 50th percentile male in stature and is fitted with a medium size protective plate. Representation of the ORCA human anatomy wearing the protective plate system is shown in figure 2.

Four threat impact locations, shown in figure 3, were selected to provide reflective spall data. Eighty ballistic events were conducted, with 20 at each impact location. The resulting fragmentation was characterized in terms of velocity, mass, shape factor, trajectory, entrance point, resting point, density, and material type. All of the data collected during experimentation was used in the personnel injury analysis.

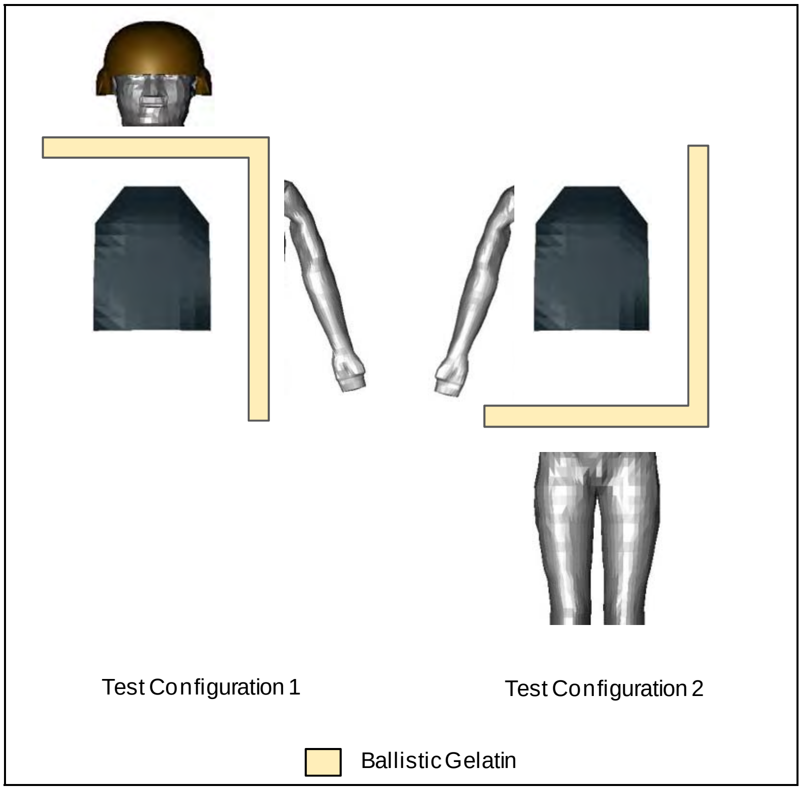

Figure 1. Gelatin block placement for experimental testing.

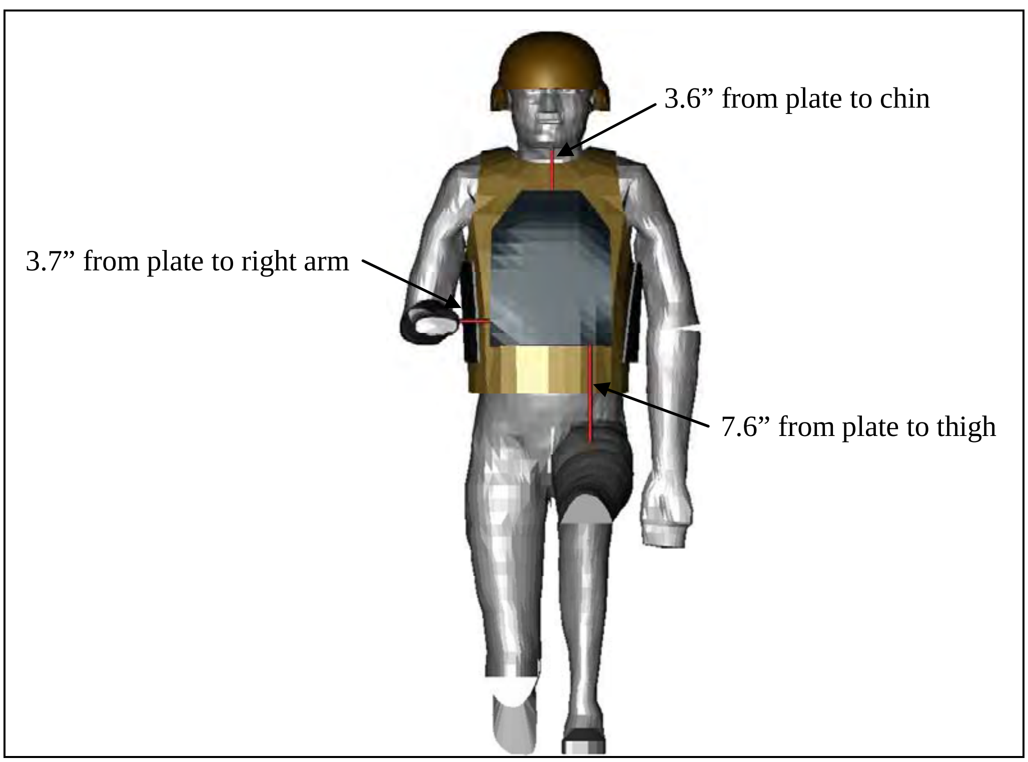

Figure 2. Protective plate system on the ORCA human anatomy.

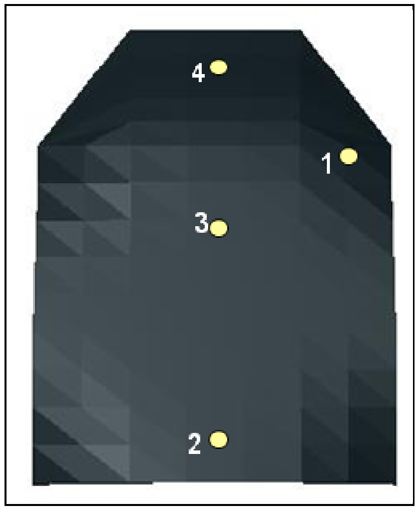

Figure 3. Impact locations for reflective spall collection.

3. Injury Analysis

This personnel injury analysis focused on areas of the body not covered by body armor and would most likely witness reflective spall. These body regions were the arms, upper legs, and head.

The personnel injury severity analysis consisted of the following three steps:

1. Filter recovered fragments based on potential to penetrate skin and potential to encounter a body region.
2. Model remaining fragments using MUVES-S2 to determine injury risk to the body regions of interest.
3. Determine the likelihood of significant injury.

3.1 Injury Analysis Step 1: Filtering Recovered Fragments

The first step in the analysis process was to filter the recovered fragments by eliminating those with no potential to cause injury. This analysis filtered the recovered fragments in two stages: (1) based on the trajectory angle and (2) on the fragment's ability to penetrate skin.

During experimentation, two trajectory angles, θ_1 and θ_2 (figure 4), were recorded for each fragment. The fragment trajectory angles were used to determine if it was even feasible for a fragment to encounter a body region.

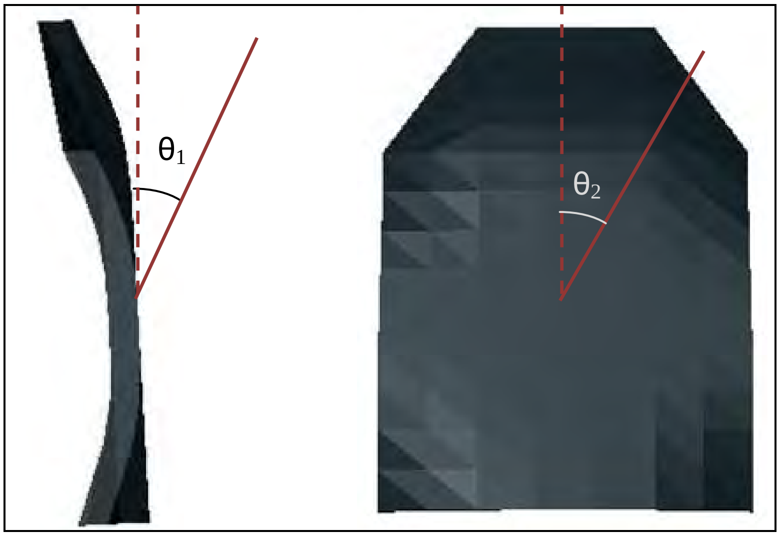

Figure 4. Fragment trajectory angles θ_1 and θ_2.

Before the fragments could be filtered using the trajectory angles, the potential position of the body regions of interest had to be considered. A Soldier's arms and legs can be in countless positions at the moment their protective plate is impacted with a threat; therefore, any reflective spall fragment could potentially impact the arms and legs. This unpredictability prohibited fragments impacting those body regions from being filtered based on trajectory angles. A Soldier's head, however, is much more limited in its position. Therefore, fragments impacting the head can be filtered based on trajectory angle. This analysis used the ORCA human anatomy to estimate the cut-off values for θ_1 and θ_2. These cut-off values were measured from the top of the protective plate at shot location 4 because it provided the largest possible angle estimations and the most conservative estimates for θ_1 and θ_2. When estimating θ_1, the head of the ORCA human anatomy was tilted forward in order to find the largest possible θ_1 value. The cut-off value estimates for θ_1 and θ_2 are pictured in figure 5. Any fragments with θ_1 and θ_2 angles larger than the cut-off values were not used in this analysis. The remaining fragments were then filtered by eliminating the fragments with less than a 50% probability to penetrate skin.

In April 1978, Lewis, Coon, Clare, and Sturdivan conducted a study to investigate the hazard of debris from the exhaust of small rocket-motor-launched weapons.[1] This model is embedded within the ORCA model. The study fired a variety of projectiles over a range of velocities at goat skin backed with gelatin. Using the test data, a model for the probability of skin penetration was derived.

[1] Lewis, J.; Coon, P.; Clare, V.; Sturdivan, L. An Emperical/Mathematical Model to Estimate the Probability of Skin Penetration by Various Projectiles. Chemical Systems Laboratory: Aberdeen Proving Ground, MD, 1978.

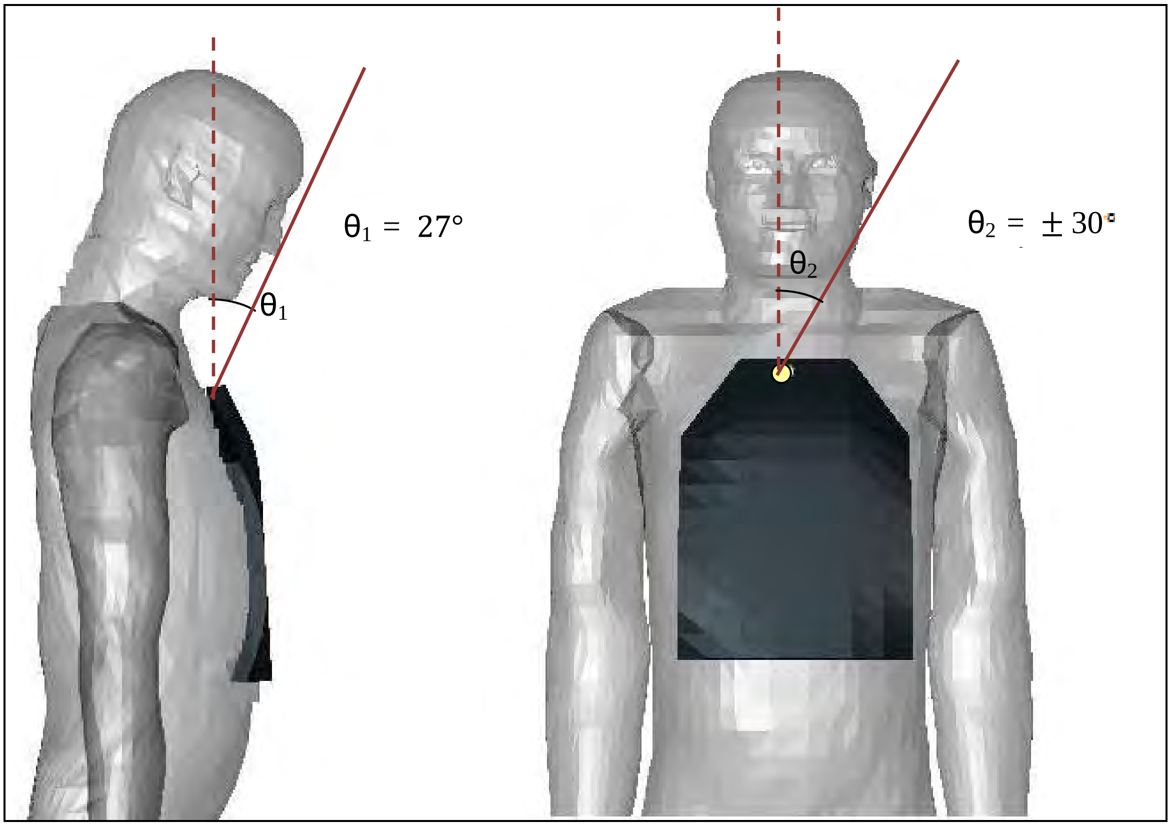

Figure 5. Estimating cut-off values for θ_1 and θ_2.

Before the model can be used to predict the probability of skin penetration, the striking velocity for each fragment must be calculated. The striking velocity was estimated using the muscle retardation equation embedded in the ORCA model.[2] The calculated striking velocity and the mass, density, and shape factor from the experimental data were then used to determine the probability of skin penetration for each fragment. For this analysis, any fragment with a probability of skin penetration of less than 50% was discarded. This threshold agrees with the ballistic grading criteria typically used for material body armor testing.

3.2 Injury Analysis Step 2: Modeling and Simulation

Injury analysis step 1 filtered all of the recovered fragments by their potential to cause injury, leaving only the fragments that could impact body regions of interest and have the potential to penetrate skin.

[2] Saucier, R.; Kash, H., III. Computer Man Model Description. U.S. Army Research Laboratory: Aberdeen Proving Ground, MD, 1994.

The ORCA model, which is embedded within the MUVES-S2 vulnerability model, was used to conduct injury analysis for the remaining fragments. Eberius et al.[3] describe ORCA as a high-resolution, computerized human vulnerability model that is used to evaluate the effect of various casualty-causing insults on personnel. ORCA determines the type, severity, and frequency of injuries sustained by personnel as well as the percent reduction in human capability from impacting fragments. Features provided by ORCA include a precise anatomical representation, the ability to map injury to physical and cognitive impairment, the evaluation of basic human capability requirements to postinjury capabilities, and an accommodating methodology for improvements. ORCA classifies each computed penetrating injury using the Abbreviated Injury Scale (AIS),[4] which is a international standard measure of anatomical injury. AIS is an anatomically-based, consensus-derived, international severity scoring system that classifies each injury by body region according to its relative importance on a 6-point ordinal scale. Examples of AIS levels are outlined in table 1. The significant injury threshold criterion for this analysis is a serious injury (AIS = 3) as defined by AIS. A serious injury is one that requires immediate medical attention, and untreated serious injuries can deteriorate and cause loss of life. The metric used in this analysis is the maximum abbreviated injury score (MAIS) which classifies injury severity on the basis of the single injury having the greatest AIS severity.[3]

Table 1. Abbreviated injury scale.

AIS	Injury Level	Type of Injury
1	Minor	Superficial
2	Moderate	Reversible injuries; medical attention required
3	Serious	Reversible injuries; hospitalization required
4	Severe	Life threatening; not fully recoverable without care
5	Critical	Non-reversible injuries; not fully recoverable even with care
6	Maximal	Nearly Unsurvivable

The injury analysis outlined in this report was conducted using fragment penetration data collected from the experiments using ballistic gelatin as a witness material. MUVES-S2 was used to model and fly each fragment in three dimensions into the three-dimensional ORCA human anatomy. The fragments were modeled at a 0° attack aspect (frontal view of target) for the fragments that impacted the witness material representing the arms, legs, and face. The fragments were modeled at a –90° attack aspect (attack from under the target) for the fragments that were determined to potentially impact under the chin. This analysis was completed using grid runs in MUVES-S2. A grid run plane of 5- × 5-mm cells is placed in front of the ORCA human anatomy. MUVES-S2 then shoots a fragment into each cell in the plane. ORCA models

[3] Eberius, N.; Gillich, P.; Doonan, K.; Polesne, J.; Kinsler, R. Risk Analysis of the Enhanced Small Arms Protective Insert (ESAPI) Edge Vulnerability of the Modular Body Armor Vest (MBAV). U.S. Army Research Laboratory: Aberdeen Proving Ground, MD, to be published.

[4] Association for the Advancement of Automotive Medicine (AAAM). The Abbreviated Injury Scale 2005 Update 2008; Des Plaines, IL, 2005.

the permanent wound cavity of fragment and scores the maximum severity (MAIS) of each penetrating wound in every 5- × 5-mm cell. The MAIS values are then used to determine each fragment's likelihood of significant injury.

3.3 Injury Analysis Step 3: Analysis of Results

During the analysis process, each fragment was modeled and individually run in MUVES-S2. This means that each fragment has unique MAIS values for every 5- × 5-mm cell in the plane. In order to determine each fragment's potential to cause significant injury, the P(MAIS ≥ 3) was calculated. P (MAIS ≥ 3) was calculated using the following formula:

$$P(\text{MAIS} \geq 3) = \frac{\text{Number of Cells with MAIS} \geq 3}{\text{Total Number of Cells}}. \quad (1)$$

To accurately calculate this value, only the MAIS scores from the body region represented by the fragment's location in gelatin were used. For instance, if a fragment was recovered from the arm gelatin block, only the MAIS scores and total number of cells from the arm were used in the calculations.

At this point in the process, each fragment has a P(MAIS ≥ 3). However, to make conclusions on the likelihood of serious injury from reflective spall fragments, the P(MAIS ≥ 3) in each body region of interest from each shot location must be determined. To determine this probability, the fragments and P(MAIS ≥ 3) values were first grouped by shot location. With this complete, the fragments in each shot location group were then separated by body region. Finally, the P(MAIS ≥ 3) values in each body region group were averaged together. This average P(MAIS ≥ 3) value provides the probability of significant injury from a shot impacting location x to body region y, where x is shot locations 1–4 and y is all the body regions of interest.

4. Conclusions

Reflective spall has the potential to injure personnel wearing the protective plate. In the past, the risk of injury had not been evaluated due to difficulties in data collection as well as a lack of information on whether or not there was a legitimate risk on injury. With our new test procedure and analysis method, the potential for significant injury to the Soldier can be evaluated and quantified.

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