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Injury Evaluation Techniques for Non-Lethal Kinetic Energy Munitions

by David H. Lyon, Cynthia A. Bir,
and Brendan J. Patton

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Injury Evaluation Techniques for Non-Lethal Kinetic Energy Munitions

David H. Lyon and Brendan J. Patton
Weapons and Materials Research Directorate, ARL

Cynthia A. Bir
Institute for Preventative Sports Medicine

Abstract

Numerous types of nonpenetrating kinetic energy (KE) munitions have been developed and deployed throughout both the military and law-enforcement communities. The ability to evaluate the injury potential associated with this class of munitions has presented itself as a novel problem for the scientific community. Although several evaluation methods have been employed, currently, there is no widely accepted method for evaluating injury levels resulting from blunt impact derived from non-lethal projectiles. This paper briefly reviews two existing experimental techniques in addition to introducing a third. Data obtained from each of these procedures were collected for similar impacts and are offered for comparison.

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1. Background

1.1 Ballistic Resistance of Police Body Armor. Along with the deployment of soft body armor, for civilian law enforcement, came the requirement to establish a method to evaluate the performance claims of various manufacturers. As an entity under the Department of Justice, the National Institute of Justice (NIJ) was chartered to assist with law-enforcement issues at a national level. Accordingly, NIJ established a consortium of military and medical personnel, with expertise in the areas of wound ballistics and blunt trauma, to collect and correlate all existing data regarding blunt impact injury. The results of this study represent a comprehensive assembly of available animal data and have been published as "Body Armor - Blunt Trauma Data" [1]. This report also attempts to correlate the identified data using various combinations of parameters. Although no one set of parameters was able to accurately discriminate all data points, a reasonable fit was accomplished using a four-parameter model, which included projectile mass (M) in grams, velocity (V) in meters per second, projectile diameter (D) in centimeters, and target mass (W) in kilograms. The parameters were plotted using the natural log of the projectile kinetic energy (KE) ($\ln MV^2$) along the abscissa vs. the natural log of the product of WD ($\ln WD$) along the ordinate. This model was then extrapolated from the mass of the target animals to that of a typical adult male (70 kg). Incorporated into the plot of Figure 1 are solid discriminant lines, each having a slope of one, which divide the graph into three regions. The X and Y intercepts for these lines were then determined by data fitting. The three areas—(1) a zone of low lethality, (2) a zone of mixed results, and (3) a zone of high lethality—were due to data scatter, a simple live/die outcome, and inconsistencies between the data sets. In addition, dotted lines depicting 40-mm- and 80-mm-diameter projectiles are included for reference.

In conjunction with the aforementioned work, a series of backface signature studies was performed. This investigation examines the cavity created in backing materials placed opposite the impact side of the armor sample. The ultimate goal was to determine the potential level of injury imparted to the torso of an officer wearing soft body armor. The focus was to develop a simple method to allow police departments to conduct their own evaluation against a known standard. Relying heavily on the animal data collected earlier, the consortium adopted a convenient technique

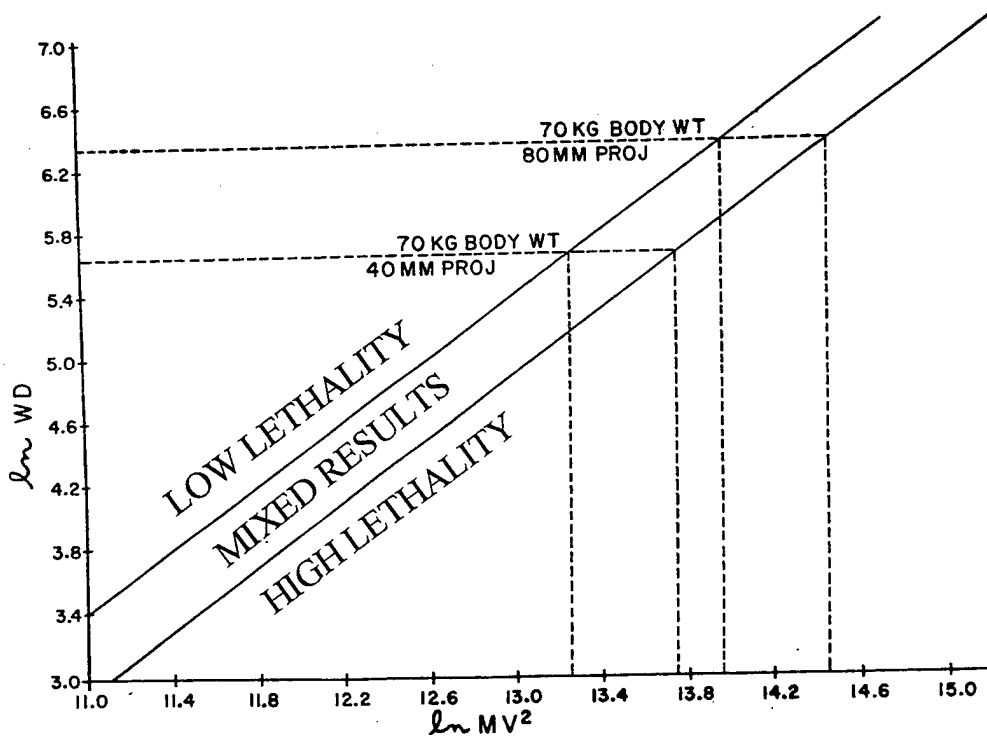


Figure 1. Four-Parameter Generalized Model.

to record the backface signature. This method involves the placement of a body armor sample in front of a 4-in-thick (101.6 mm) block of clay that has passed the NIJ calibration procedure. The threat munition is then fired at this arrangement. Provided no perforation of the soft body armor has occurred, the postshot deformation in the clay is measured. If the cavity depth is 44-mm or larger, the result is considered a failure, with potentially lethal consequences. The detailed procedure is referred to as NIJ standard 0101.03 [2].

It has been suggested that this technique be adopted for the evaluation of non-lethal munitions by eliminating the body armor and impacting the clay directly [3]. Furthermore, the same 44-mm failure criterion would be utilized. However, the injury-mitigating effects offered by the soft body armor and its influence on the backface signature are not fully understood. Therefore, the validity of modifying this procedure for the purpose of evaluating non-lethal munitions is an area that requires further investigation.

1.2 Ballistic Gelatin. Another technique that was investigated for the evaluation of blunt trauma utilizes ballistic, or ordnance, gelatin. In the past, blocks of both 10% and 20% (by weight) gelatin have been used extensively to model penetrating impacts [4, 5]. Both temporary and

permanent cavities, as well as the depth of penetration (DOP) and dispersion of fragments, can be observed with this model. Although some controversy exists over which formulation is more accurate, this material has been used to determine both the rate of energy deposition and the total energy deposited within a target by a penetrating projectile. Again, the adaptation of an established procedure (penetration) for the determination of a nonsimilar effect (nonpenetration) has yet to be validated. However, if several assumptions are made, a reasonable approach can be attempted. The first is that gelatin offers a similar resistance to deformation as that of living tissue. The second is that the depth of temporary deformation can be related to injury potential for thoracic organs. Even though absolute injury levels have yet to be determined, this method should be suitable for determining relative differences from one impact to another. In other words, various projectile impacts can accurately be ranked from most severe to least severe. With these assumptions, the utilization of high-speed imaging equipment can illustrate the degree of temporary deformation, as well as reveal other impact phenomena.

As another measure of potential tissue response, the level of damage inflicted upon the gelatin could be interpreted as a measure of tissue damage. If a projectile penetrates the gelatin or lacerates the surface, it can be assumed that a similar result would occur in tissue. This is known to be a conservative estimate, due to the fact that the gelatin surface is significantly less elastic than the epidermal layer. Therefore, if no damage to the impacted surface of the gelatin is observed, it can be assumed that soft tissue would respond in a similar fashion. Of course, this method does not account for interactions with underlying bony structures, which could influence the potential for laceration.

1.3 Vehicular Crash Testing. Over the past several decades, the automotive industry has greatly improved the fidelity of its biomechanical surrogates (crash dummies) developed as tools for injury evaluation in vehicular collisions. More specifically, General Motors Research Laboratories (GMRL) has developed a method of analysis to determine injury level to the thorax [6]. Referred to as the viscous criterion (VC), this response has been documented to predict the severity of soft tissue injury and cardiorespiratory dysfunction caused by blunt impact. The technique utilizes measurements taken from a biomechanical surrogate undergoing an impact event.

The VC is then calculated from time-dependent displacement data provided by a chest transducer. The chest compression (C) is defined as the displacement of the chest in relationship to the spine, normalized by the initial thickness of the thorax. The time-dependent product of the velocity of the chest deformation (V) and the amount of compression (C) form the dimensionless VC [7]. The probability and level of injury are then assessed relative to the maximum VC attained, referred to as VC_{max} . Thus, this criterion is dependent upon not only the amount of compression, but also the rate at which the compression occurs.

The adaptation of a biomechanical surrogate for use in evaluating nonpenetrating ballistic events seemed a logical extension. Collaboration between GMRL and the Institute for Preventative Sports Medicine has led to the development of a portable surrogate with biofidelity regarding human chest response due to non-lethal projectile impact. This device is referred to as the three-rib chest structure (3-RCS). The development of the 3-RCS involved the extraction of subunits from a current generation crash dummy, the BIOSID. The rib structures of the BIOSID were considered ideal for nonpenetrating chest impacts because they were continuous in the sternum area and therefore provided realistic loading surfaces. The basic design of the 3-RCS involves three thorax ribs mounted to a spine box opposite the impact face, as shown in Figure 2. Dampening material mounted to the inside of the steel ribs provides for viscous bending resistance and a realistic dissipation of energy. Nylon supports mounted to the sides of the spine box prevent gross upward or downward motion of the ribs. A urethane bib ties the three ribs together on the impact side. The urethane is covered with a sheet of dense foam Ensolite 5/8-in-thick (16 mm) to simulate overlying skin and subcutaneous tissue. A conductive-plastic position transducer was mounted to the interior of the rib structure to allow measurement of the center rib displacement relative to the spine box.

As stated previously, the impact phenomena associated with non-lethal munitions are low-mass and high-velocity in nature, as opposed to the high-mass and low-velocity impacts indicative of automotive collisions. Although preliminary verification testing has been conducted, a comprehensive system validation, over a broad range of impact conditions, has not been completed. However, this work is presently funded through an NIJ grant and is scheduled to be completed over the next 2 yr

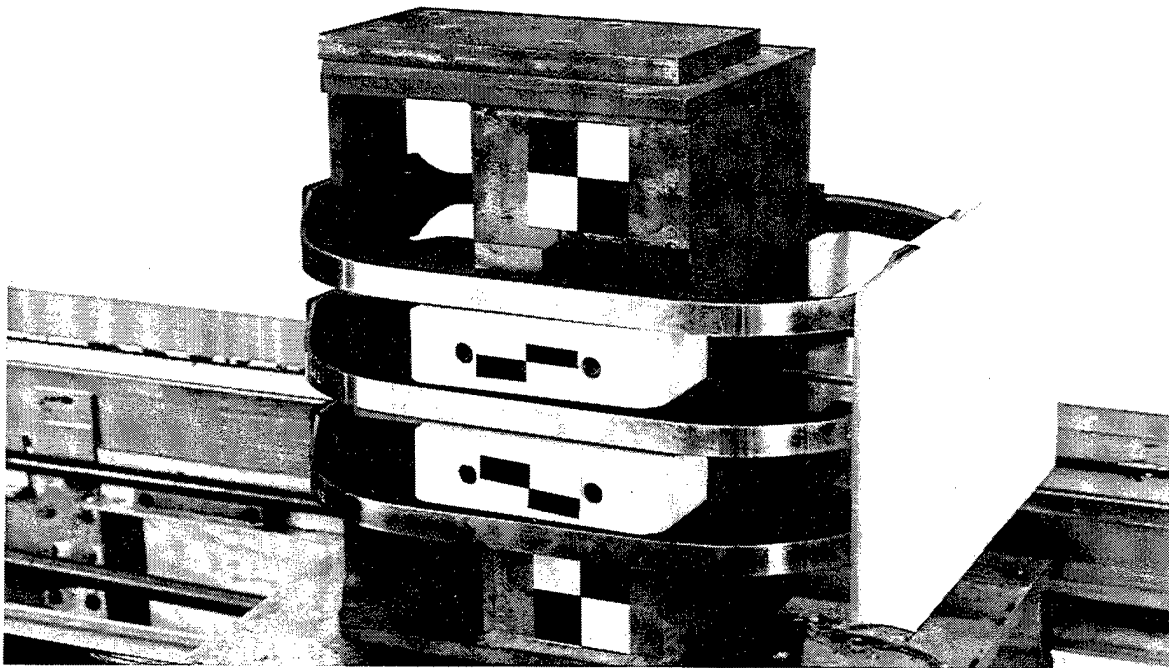


Figure 2. Photograph of 3-RCS.

2. Test Data

2.1 Backface Signature in Clay. The data obtained using the modified NIJ backface procedure were the result of tests conducted at the U.S. Army Research Laboratory (ARL) on several occasions. In addition, data were supplied by the Defense Technology Corporation. The target consisted of a 24-in-square (609.6 mm) by 4-in-thick (101.6 mm) block of clay rigidly confined on all four sides and the rear. The front of the target was situated to present a 0° angle of obliquity, relative to the velocity vector of the projectile. The impact face of the target was exposed clay with no intermediate covering. Pretest calibration of the clay was conducted according to NIJ standard 0101.03. Velocity screens provided a projectile velocity approximately 1 m from target impact. For this study, the velocity recorded at this location is referred to as the impact velocity. Table 1 contains the results of testing conducted by Defense Technology for a variety of munitions [8]. Both the deformation and impact velocities are averaged over the number of test shots (typically 10–20 shots per munition). Table 2 contains ARL test results for one 12-gauge munition and two versions of the 40-mm Sponge Grenade (XM1006) at various impact velocities. Unlike Table, 1 each row in Table 2 contains data from an individual firing.

Table 1. Defense Technology Data From Modified Clay Signature Testing (Averaged)

Projectile Type	Mass (gm)	Impact Velocity (m/s)	Cavity Depth (mm)	Impact Energy (J)	Energy Density (J/cm ²)
12-gauge Single Ball No. 23 SB	3.4	283.1	39.5	136.2	74.70
12-gauge Shot Bag No. 23 BR	40.8	87.9	33.3	157.6	N/A
12-gauge Wood Baton No. 23 WB	3.35	276.5	40.3	128.0	N/A
12-gauge Fin Slug No. 23 FS	5.68	154.9	30.6	68.1	N/A
40-mm Multipellet (.32 cal) No. 40A	0.27 each	87.4	3.0	1.0	1.93
40-mm Multipellet (.60 cal) No. 40B	2.27 each	100.7	6.8	11.5	6.32
40-mm Sandbag No. 40BR	104.7	69.2	35.0	250.6	N/A
40-mm Wood Baton No. 40W	23.0 each	79.4	25.0	72.5	6.90
40-mm Foam Baton No. 40F	18.6	79.6	6.5	59.0	5.35

Table 2. ARL Data From Modified Clay Signature Testing (Individual)

Projectile Type	Mass (gm)	Impact Velocity (m/s)	Cavity Depth (mm)	Impact Energy (J)	Energy Density (J/cm ²)
12-gauge Wood Baton No. 23 WB	3.8	207.3	23.8	82.3	N/A
40-mm XM1006	57.8	60.9	31.8	107.2	8.53
40-mm XM1006	57.8	60.6	25.4	106.1	8.44
40-mm XM1006	30.2	87.2	22.2	114.8	9.14
40-mm XM1006	30.2	89.3	28.6	120.4	9.58
40-mm XM1006	57.8	53.3	22.2	82.1	6.53
40-mm XM1006	57.8	50.3	19.0	73.1	5.82
40-mm XM1006	30.2	78.4	22.2	92.8	7.39
40-mm XM1006	30.2	75.6	22.2	86.3	6.87

As a first-order analysis, the KE of a given impact has been plotted against cavity depth and included as Figure 3. As anticipated, the data display a roughly linear trend between KE and cavity depth. Only one projectile type, the 40-mm sandbag, deviated considerably from this trend. Although not thoroughly understood, it is conjectured that the conforming nature of this device contributes significantly to its ability to dissipate higher energy levels, without producing a deeper cavity. However, this simple energy approach ignores many factors such as the area over which energy is deposited, the projectile shape, and the materials used in its construction. It should be noted that a number of these projectiles are fabricated using compliant materials, which will deform

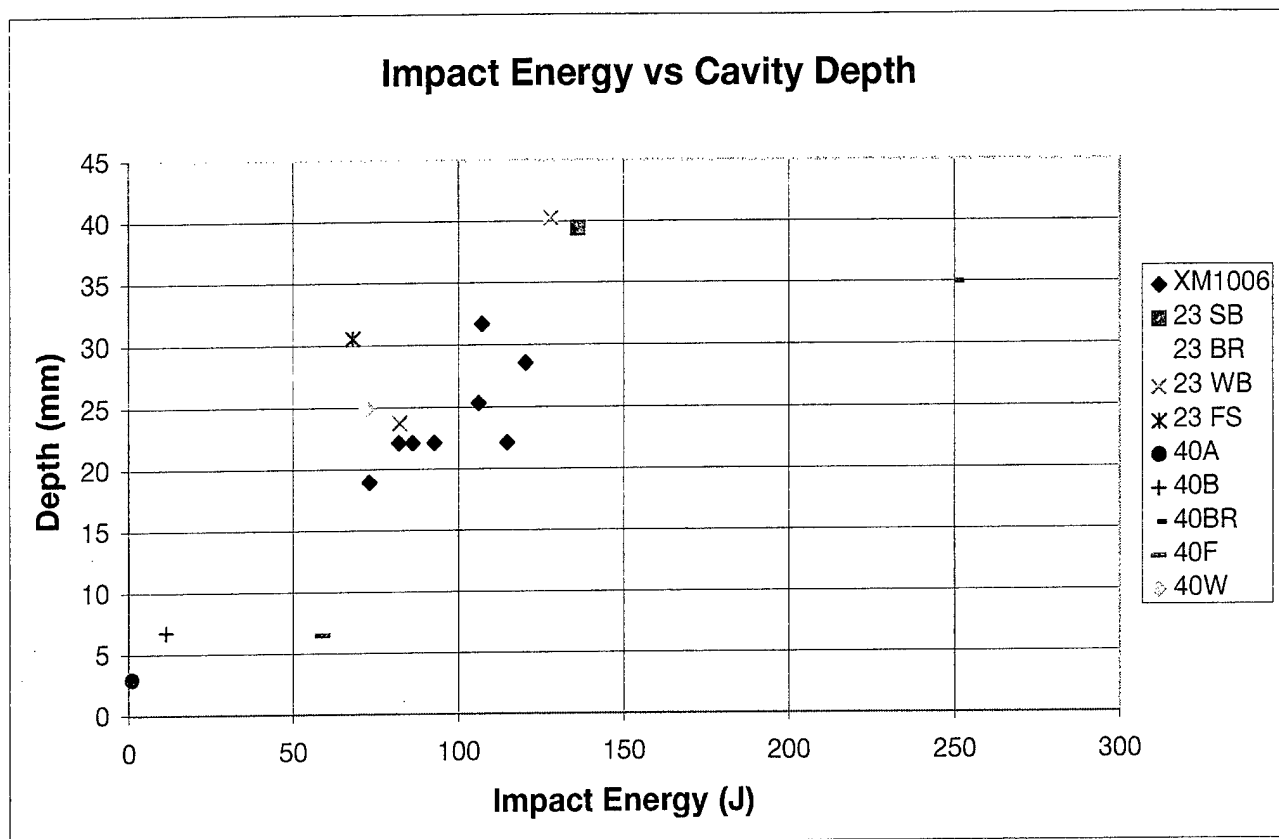


Figure 3. Results From Clay Signature Testing Plotted as a Function of KE.

upon impact, while others utilize noncompliant materials. The exact influence that these factors have on cavity formation is largely unknown.

A more appropriate approach may be to plot the cavity depth as a function of energy density. This term is computed by dividing the impact energy by the impact area. However, such an area is difficult to assume for certain munitions, such as unstable projectiles, which tumble during flight, as well as shot bags. Therefore, Figure 4 includes a plot of cavity depth vs. energy density (expressed in joules/centimeter squared) for those devices that allowed a reasonable determination of impact area. An interesting result is obtained from this analysis. Each munition possesses an energy density of less than 10 J/cm^2 , except for the 12-gauge single ball that delivers almost 75 J/cm^2 , displacing itself to the far right side of the plot. It was observed that this rubber sphere impacted with a velocity ample to produce an oversized crater, thereby dissipating a significant fraction of energy in the radial direction. It is also possible that the impact velocity is sufficient to deform the

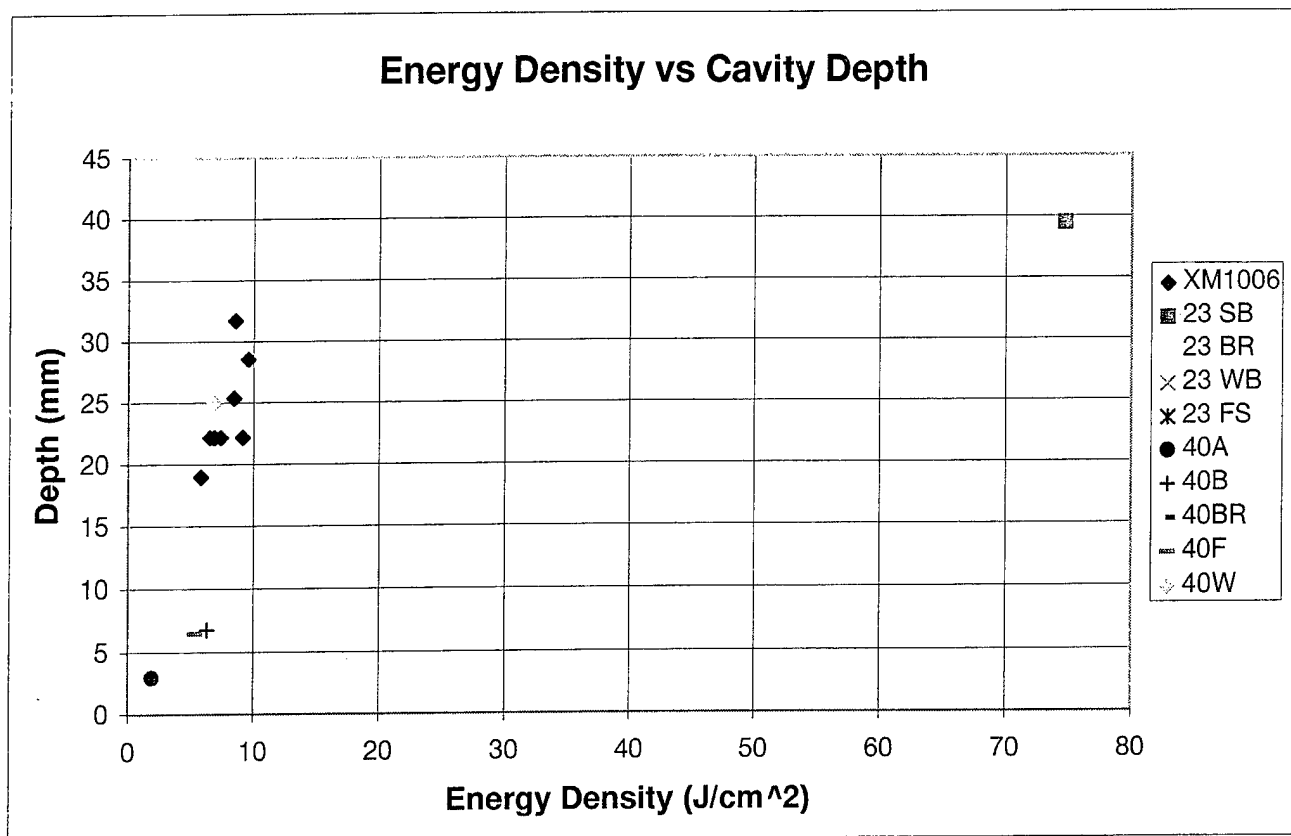


Figure 4. Results From Clay Signature Testing Plotted as a Function of Energy Density.

rubber ball such that the presented area is significantly larger than its original diameter, effectively reducing the energy density. By comparison, the other projectiles contained within this plot impacted with a much lower velocity, producing craters slightly larger than their presented areas.

2.2 Ballistic Gelatin. A series of firing tests that utilized blocks of 10% (by weight) ballistic gelatin (type 250A Ordnance Gelatin) was conducted for this study. This formulation has been shown to provide a close simulant to the disruption experienced in living tissue (e.g., muscle) when subjected to projectile penetration [9]. The gelatin powder was reconstituted using 180° F (82.2° C) water; the surface bubbles were skimmed, and then the liquid was poured into molds and chilled to 40° F (4.4° C). Approximately 24 hr later, the blocks were removed from the molds, wrapped in air-tight plastic bags, and, again, stored at 40° F (4.4° C) for an additional 24 hr. The face of each block measured roughly 5 in square (127 mm) with a length of 15 in (381 mm). In preparation, the impact surface was covered with a single layer of T-shirt material (100% cotton, 48 threads per

inch). All testing was conducted within 30 min of removal from the refrigerator to minimize temperature effects. Several blocks were calibrated using an air rifle, firing a 0.177-in BB at 590 ft/s \pm 15 ft/s (179.8 m/s \pm 4.5 m/s). The calibration specification states a postshot penetration of 8.5 cm \pm 1.0 cm [10]. All calibration shots resulted in penetration numbers within these limits. Impact events were recorded using a high-speed video system, set to record at a frame rate of 9,000 frames per second. In order to provide a reference distance with which to measure temporary deformation, a transparent ruler was attached to the side of each test block. By sequencing through the recorded video image frame by frame, a maximum deformation could be measured. Table 3 contains the results of testing conducted by ARL on several occasions with various munitions.

Several of these impacts resulted in penetration of the gelatin, in addition to temporary deformation. These instances are noted by an additional entry in the temporary deformation column, denoted using ()^P. A data analysis similar to that applied with the clay data was employed. Figure 5 contains the deformation as a function of impact energy, while Figure 6 plots the energy density as a function of deformation.

2.3 3-RCS. Experimental evaluations have also been conducted with the 3-RCS on a variety of non-lethal munitions. As the testing procedures have evolved, the analysis of the measurement data has been refined. Based on testing conducted in the fall of 1997, where high-speed video was utilized, several limitations were placed on the resulting data from the 3-RCS. (See Table 4 for results from the 3-RCS testing.) Specifically, due to the high rib velocities that these impacts induce, the transducer must be capable of tracking higher velocity rib displacements than those seen in automotive impacts. From observing the video and comparing it to the measured displacement, it was noted that the maximum transducer displacement did not always correspond with the video. This was especially true with the higher KE impacts, which produced much higher rib velocities. This high rate of displacement creates a large spike of noise in the output signal. By applying the proper filter the majority of this phenomenon is eliminated, without significant loss of actual displacement data. Therefore, a maximum velocity constraint of ≤ 10 m/s was established for the measurement data. This roughly corresponded to the transducer specifications provided by the manufacturer.

Table 3. Results From Ballistic Gelatin Testing

Projectile Type	Mass (gm)	Impact Velocity (m/s)	Cavity Depth (mm)	Impact Energy (J)	Energy Density (J/cm ²)
40-mm XM1006	28.53	88.7	63.5	112.2	8.93
40-mm XM1006	28.80	91.1	61.9	119.5	9.51
40-mm XM1006	29.30	91.7	63.5	123.2	9.80
40-mm XM1006	29.17	75.9	60.3	84.0	6.68
40-mm XM1006	28.85	56.7	47.6	46.4	3.69
40-mm XM1006	28.43	59.1	52.4	49.7	3.96
40-mm XM1006	27.32	100.0	63.5	136.6	10.87
12-gauge Single Ball No. 23 SB	3.40	306.8	95.3 (73.1) ^P	160.0	87.7
12-gauge Shot Bag No. 23 BR	39.79	108.4	158.8 (133.3) ^P	233.8	N/A
12-gauge Shot Bag No. 23 BR	40.46	92.5	146.1 (101.6) ^P	173.1	N/A
12-gauge Shot Bag No. 23 BR	39.87	91.9	130.2 (79.4) ^P	168.4	N/A
12-gauge Multipellet No. 23 RP	0.41 each	110.9	15.9	2.5	4.82
12-gauge Fin Slug No. 23 FS	5.59	159.3	50.8 (26.7) ^P	71.2	N/A
12-gauge Fin Slug No. 23 FS	5.61	166.6	57.2 (25.4) ^P	77.9	N/A
12-gauge Fin Slug No. 23 FS	5.60	127.9	47.6	45.8	N/A
40-mm Multipellet (.32 cal) No. 40A	0.41 each	61.4	12.7	0.77	1.48
40-mm Multipellet No. 40A	0.41 each	73.8	9.5	1.1	2.12
40-mm Multipellet No. 40A	0.41 each	78.8	19.1	1.3	2.51
40-mm Multipellet No. 40A	0.41 each	83.1	12.7	1.4	2.70
40-mm Multipellet (.60 cal) No. 40B	2.20 each	93.4	47.6	9.6	5.26
40-mm Multipellet No. 40B	2.20 each	92.8	41.3	9.5	5.21
40-mm Multipellet No. 40B	2.20 each	88.5	41.3	8.6	4.71
40-mm Multipellet No. 40B	2.20 each	86.7	28.6	8.3	4.55
40-mm Multipellet No. 40B	2.20 each	109.1	27.0	13.1	7.18
40-mm Foam Baton No. 40F (3 each)	14.0 each	105.2	63.5	77.6	7.04
40-mm Foam Baton No. 40F	14.0 each	103.0	50.8	74.3	6.74
40-mm Foam Baton No. 40F	14.0 each	101.9	63.5	72.7	6.59
40-mm Foam Baton No. 40F	14.0 each	102.6	60.33	73.7	6.68
40-mm Wood Baton No. 40W (3 each)	20.0 each	78.2	95.3 (19.0) ^P	61.2	6.16
40-mm Wood Baton No. 40W	20.0 each	77.1	114.3 (31.2) ^P	59.4	5.98
40-mm Wood Baton No. 40W	20.0 each	81.8	101.6	66.9	6.74

Note: The number denoted as ()^P refers to the static penetration of the block relative to the impact surface.

Impact Energy vs Deformation

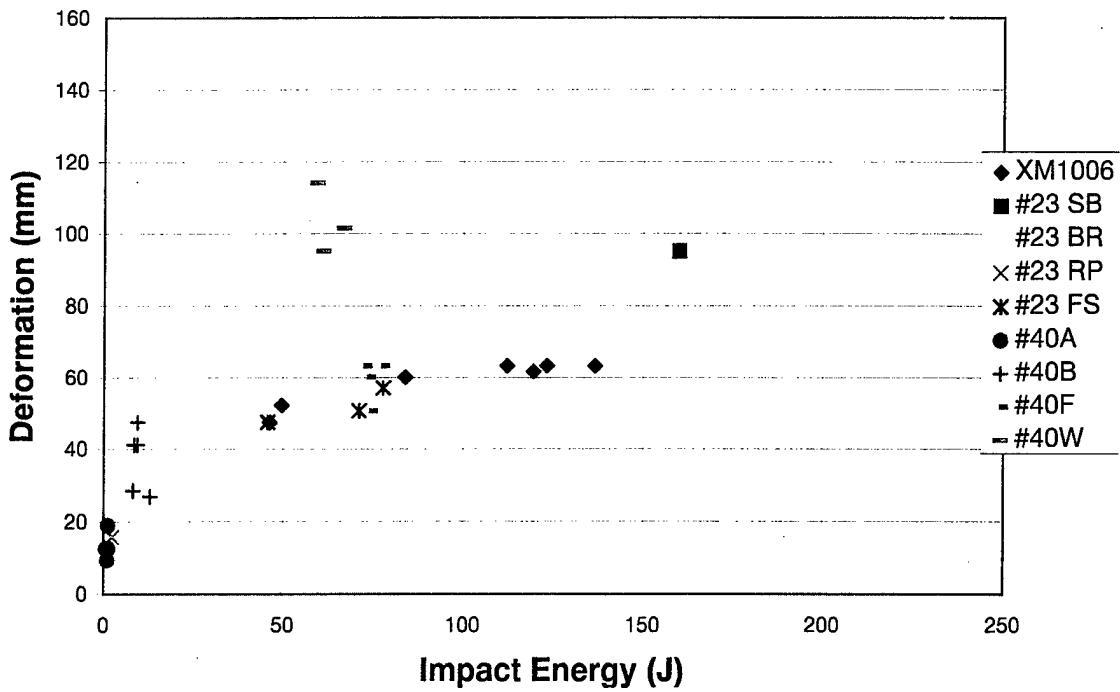


Figure 5. Results From Gelatin Testing Plotted as a Function of KE.

Energy Density vs Cavity Depth

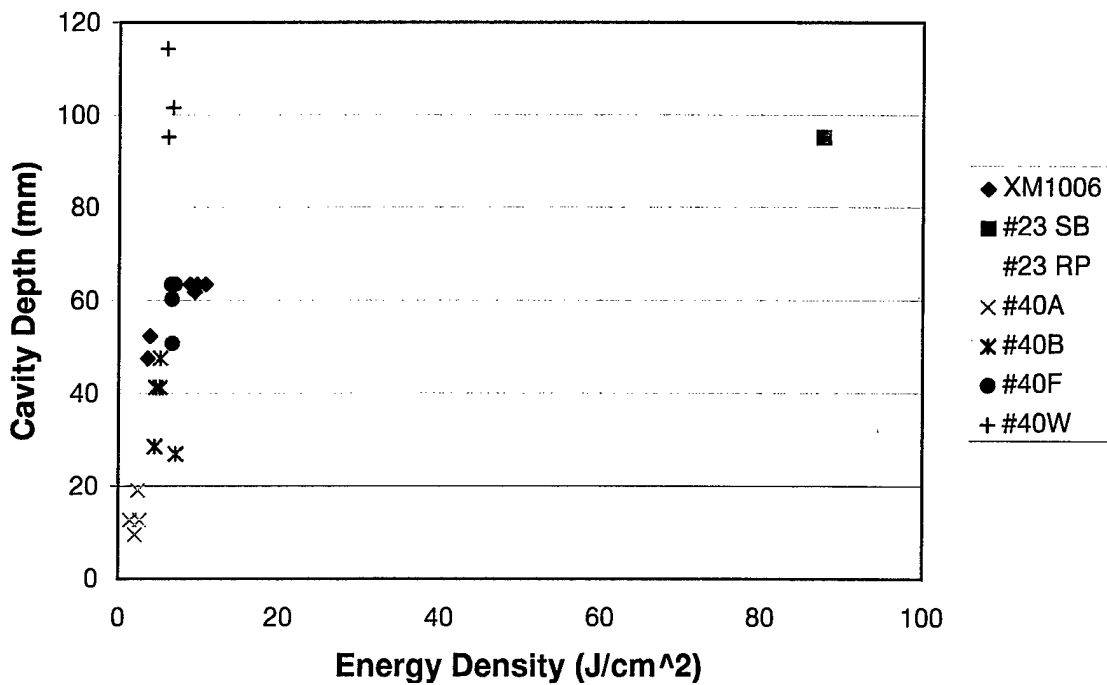


Figure 6. Results From Gelatin Testing Plotted as a Function of Energy Density.

Table 4. Results From 3-RCS Testing

Projectile Type	Mass (gm)	Impact Velocity (m/s)	Chest Displacement (mm)	Impact Energy (J)	VC _{MAX}
40-mm XM1006	28.83	71.0	7.22	72.7	0.08
40-mm XM1006	29.30	70.0	7.12	71.8	0.08
40-mm XM1006	57.68	52.0	8.21	78.0	0.19
40-mm XM1006	29.17	76.0	6.44	84.2	0.08
40-mm XM1006	28.50	77.0	6.68	84.5	0.12
40-mm XM1006	28.88	77.0	7.66	85.6	0.14
40-mm XM1006	58.09	55.0	8.78	87.9	0.16
40-mm XM1006	28.61	80.0	5.90	91.6	0.09
40-mm XM1006	57.18	57.0	7.41	92.9	0.19
40-mm XM1006	56.91	58.0	8.00	95.7	0.16
40-mm XM1006	57.95	60.0	9.64	104.2	0.19
40-mm XM1006	28.00	87.0	9.00	106.0	0.14
40-mm XM1006	28.99	88.0	9.36	112.2	0.20
12-gauge Single Ball No. 23 SB	3.70	346.0	5.00	221.4	0.09
12-gauge Single Ball No. 23 SB	3.70	326.0	7.58	196.6	0.02
12-gauge Shot Bag No. 23 BR	41.0	94.0	10.90	181.1	0.28
12-gauge Shot Bag No. 23 BR	41.0	92.0	9.50	173.5	0.24
12-gauge Shot Bag No. 23 BR	41.0	98.0	12.06	196.9	0.19
40-mm Sandbag No. 40BR	100.0	66.0	12.70	217.8	0.20

Impact location was also considered a critical parameter. Currently, the transducer only records the amount of chest displacement experienced by the middle rib. By virtue of this design, if one of the other ribs experiences the majority of the energy deposition and resulting displacement, the transducer is unable to track an accurate amount of chest displacement. This is best seen on the high-speed video, where an impact to the upper or lower rib causes large displacements in the respective rib and minimal displacement in the middle rib. The establishment of a region of acceptable impact locations overcomes this problem.

Given these limitations, data were analyzed for a variety of munitions. Only those hits where impact was made in the center region and the displacement velocity was less than 10 m/s are presented.

Figure 7 contains a plot of VC_{MAX} vs. impact energy. This plot does reveal a positive correlation for the XM1006 data ($R = 0.494$). However, there are too few data points from any other munition to allow a similar analysis.

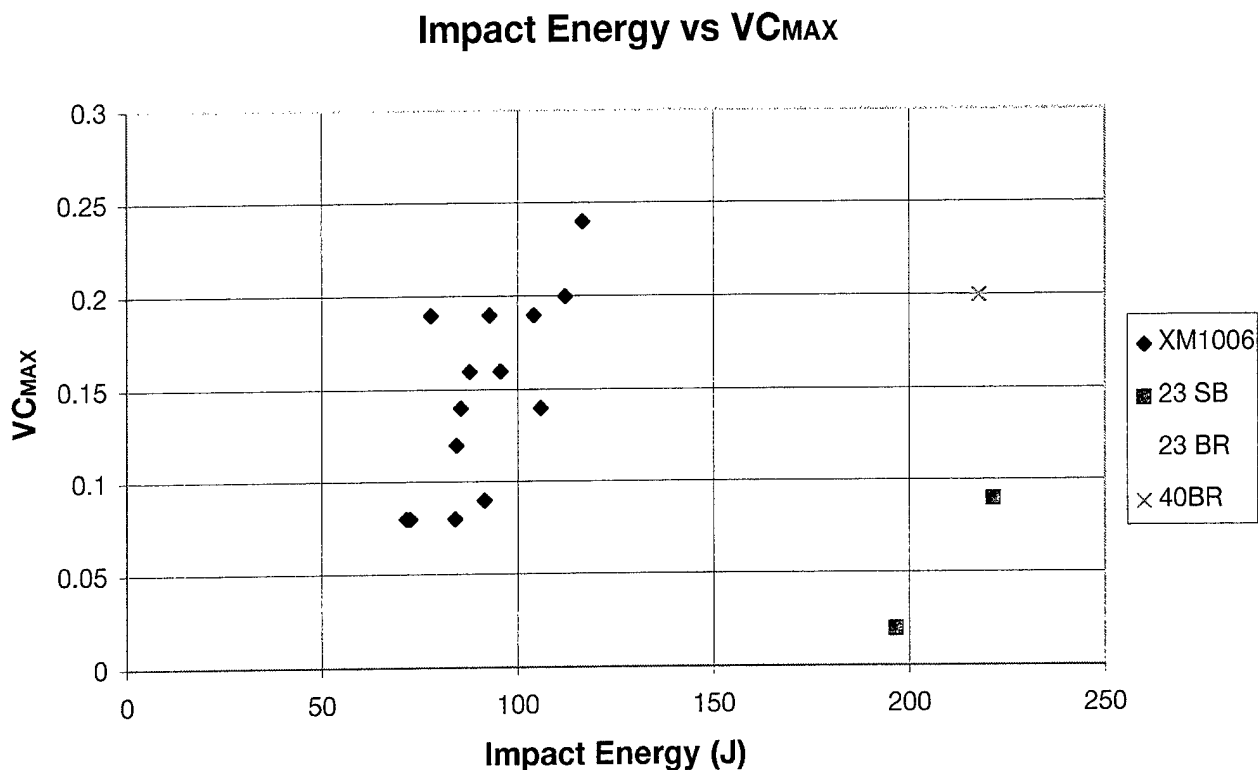


Figure 7. Impact Energy vs. VC.

3. Summary and Conclusions

Three experimental evaluation techniques have been described and exercised using a variety of non-lethal munitions. Results from the first two (clay backface signature and ballistic gelatin) have been presented in the form of raw data, followed by a basic data analysis that includes plotting as functions of both energy and energy density. This approach shows linear trends with one munition falling far outside the normal bounds. The third technique (3-RCS) assigned a VC_{MAX} to each impact that corresponds to a level of injury. This device resulted in a correlation between KE and VC_{MAX} for the sponge grenade (XM1006) data.

It should be noted that none of the available techniques has been fully validated for the assessment of nonpenetrating blunt impacts. Therefore, a more extensive analysis of both the methodology and data is warranted. However, this study represents the first attempt to compare results obtained from different experimental techniques in an effort to standardize non-lethal testing and injury evaluation. The estimate of injury, even for a single region of the body, is an extremely complex undertaking. It is not clear that any of the techniques included here are able to fully predict actual injury level. Be that as it may, the results provide a comparative ranking of injury severity.

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