Injury Evaluation Techniques for Non Lethal, Kinetic Energy Munitions

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ABSTRACT

Numerous types of non-penetrating, kinetic energy 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 nonlethal projectiles. This paper briefly reviews two existing experimental techniques in addition to introducing a third. Data obtained from each of these procedures was collected, for similar impacts, and is offered for comparison.

BACKGROUND

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) is chartered to assist with law enforcement issues at a national level. In response, the 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 represented a comprehensive assembly of available animal data and was published as "Body Armor - Blunt Trauma Data".[1] This report also attempted 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 (gm), velocity (m/s), diameter (cm), and target mass (kg). 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; a zone of low lethality, a zone of mixed results, and 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.

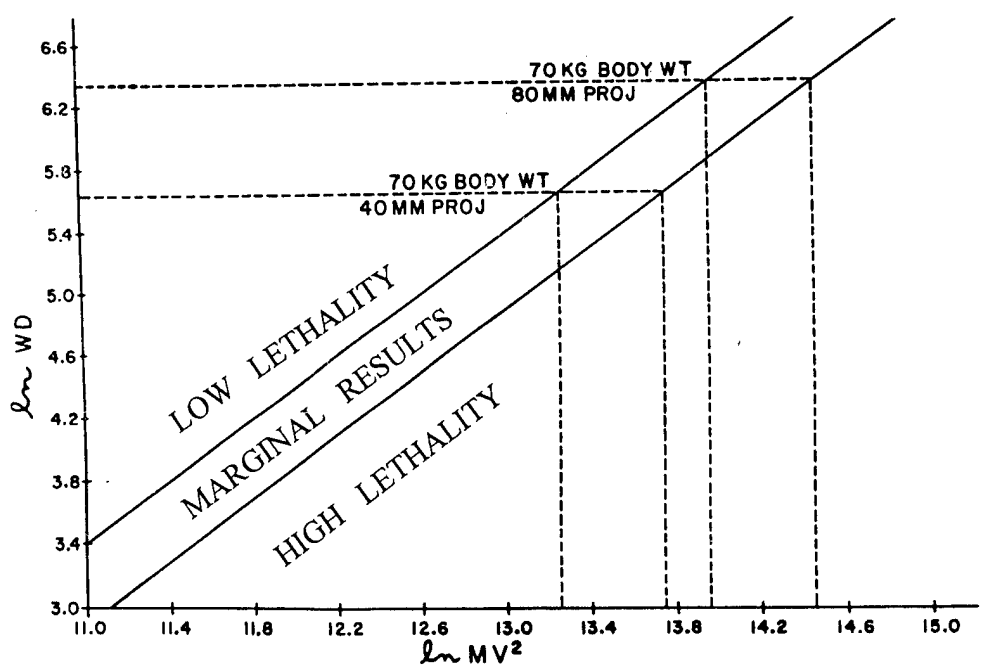

Figure 1. Four parameter generalized model.

In conjunction with the above work, a series of backface signature studies were performed. 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 to record a backface signature. This method involves the placement of a body armor sample in front of a 4 inch thick block of calibrated clay. The threat munition is then fired at this arrangement. Provided no perforation of the soft body armor has occurred, the post-shot deformation in the clay is measured. If the cavity depth is 44 mm or greater, the result is considered a failure, with potentially lethal consequences. The detailed procedure is referred to as NIJ standard 0101.03 - Ballistic Resistance of Body Armor.[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.

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 can be observed with this model as well as the depth of penetration and dispersion of fragments. 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 non-similar effect (non-penetration) 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 revealing other impact phenomena.

As another measure of possible 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 (skin). 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.

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 cardio-respiratory 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 VC.[7] 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 non-penetrating 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 sub-units from a current generation crash dummy, the BIOSID. The rib structures of the BIOSID were considered ideal for non-penetrating 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. Dampening material on the inside of the steel ribs provides for viscous bending resistance and increases the dissipation of energy. Nylon supports, mounted to the sides of the spine box, prevent gross upward or downward motion of the ribs. A urethane bibb ties the three ribs together on the impact side. The urethane is covered with a sheet of Ensolite foam (approximately 5/8 inch thick) 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, 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 scheduled to take place over the next two years.

TEST DATA

Backface Signature in Clay

The data obtained using the modified NIJ backface procedure was the result of tests conducted at the Army Research Laboratory, on several occasions. In addition, data was supplied by Defense Technology Corporation. The target consisted of a 24 inch x 24 inch x 4 inch thick 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. Pre-test calibration of the clay was conducted according to NIJ standard 0101.03. Velocity screens provided a projectile velocity approximately 1 meter from target impact. For this study the velocity recorded at this location will be 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 provided had been averaged over the number of test shots (typically 10 - 20 shots per munition). Table 2 contains ARL test results for one 12 gage munition and two versions of the 40mm Sponge Grenade (XM1006) at various impact velocities. Unlike the previous table, each row here contains data from an individual firing.

PROJECTILE TYPE	MASS (gm)	IMPACT VELOCITY (m/s)	CAVITY DEPTH (mm)	IMPACT ENERGY (J)	ENERGY DENSITY (J/cm^2)
12 gage Single Ball #23SB	3.4	283.1	39.5	136.2	74.7
12 gage Shot Bag #23 BR	40.8	87.9	33.3	157.6	N/A
12 ga Wood Baton #23 WB	3.35	276.5	40.3	128.0	N/A
12 gage Fin Slug #23 FS	5.68	154.9	30.6	68.1	N/A
40mm Multi Pellet (.32 cal) #40A	0.27 each	87.4	3.0	1.0	1.93
40mm Multi Pellet (.60 cal) #40B	2.27 each	100.7	6.8	11.5	6.32

40mm Sand Bag #40BR	104.7	69.2	35.0	250.6	N/A
40mm Wood Baton #40W	23.0 each	79.4	25.0	72.5	6.90
40mm Foam Baton #40F	18.6	79.6	6.5	59.0	5.35

Table 1. Defense Technology test results from modified clay signature testing.

PROJECTILE TYPE	MASS (gm)	IMPACT VELOCITY (m/s)	CAVITY DEPTH (mm)	IMPACT ENERGY (J)	ENERGY DENSITY (J/cm^2)
12 gage Wood Baton #23 WB	3.83	207.3	23.8	82.3	N/A
40mm XM1006	57.8	60.9	31.75	107.2	8.53
40mm XM1006	57.8	60.6	25.4	106.1	8.44
40mm XM1006	30.2	87.2	22.2	114.8	9.14
40mm XM1006	30.2	89.3	28.6	120.4	9.58
40mm XM1006	57.8	53.3	22.2	82.1	6.53
40mm XM1006	57.8	50.3	19.0	73.1	5.82
40mm XM1006	30.2	78.4	22.2	92.8	7.39
40mm XM1006	30.2	75.6	22.2	86.3	6.87

Table 2. ARL test results from modified clay signature testing.

As a first order analysis, the kinetic energy of a given impact has been plotted against cavity depth and included as Figure 2. As anticipated, the data displays a roughly linear trend between kinetic energy and cavity depth. Only one projectile type, the 40 mm sand bag, 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 upon impact, while others utilize non-compliant 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 would include an impact area term. 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 3 includes a plot of cavity depth versus energy density, expressed as J/cm^2, 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 that 10 J/cm^2, except for the 12 gage single ball which 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 large enough to produce an oversized crater, thereby dissipating a significant fraction of energy in the radial direction. Whereas the other projectiles contained within this plot impacted with a much lower velocity, producing craters slightly larger than themselves.

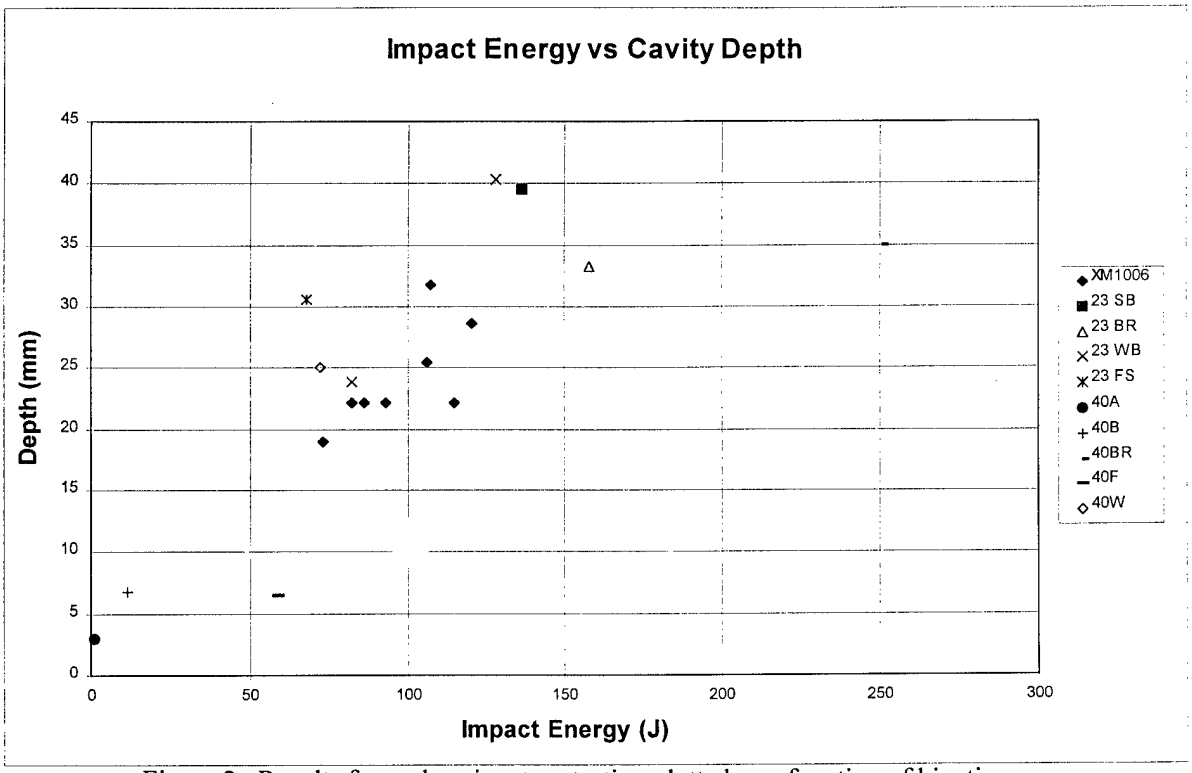

Figure 2. Results from clay signature testing plotted as a function of kinetic energy.

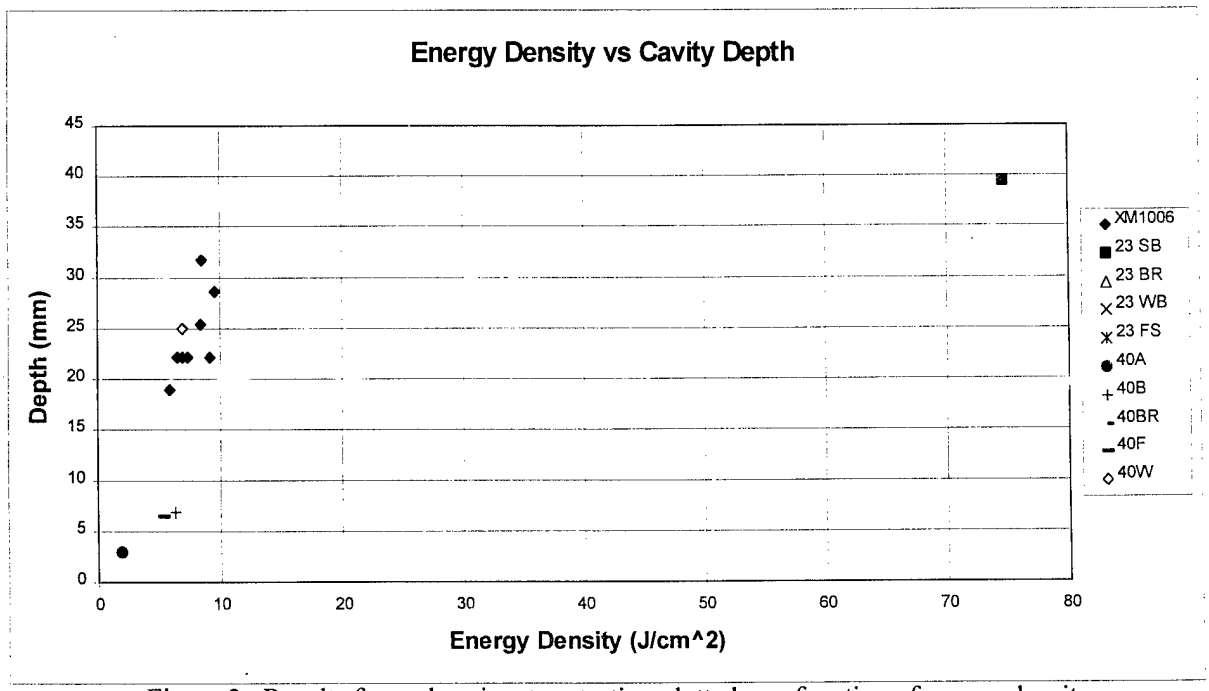

Figure 3. Results from clay signature testing plotted as a function of energy density.

Ballistic Gelatin

A series of firing tests were conducted for this study which utilized blocks of 10% (by weight) ballistic gelatin (type 250A Ordnance Gelatin). This formulation has been shown to provide a close simulant to the disruption experienced in living tissue, such as muscle, when subjected to projectile penetration.[9] The gelatin powder was reconstituted using 180° F (82.2 C) water, surface bubbles skimmed, then poured into

molds and chilled to 40° F (4.4 C). Approximately 24 hours 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 hours. The face of each block measured roughly 5 inch x 5 inch with a length of 15 inches. 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 minutes of removal from the refrigerator to minimize temperature effects. Several blocks were calibrated using an air rifle, firing a 0.177 inch BB at 590 ft/s +/- 15 ft/s (179.8 m/s +/- 4.5 m/s). The calibration specification states an ideal static penetration of 8.5 cm +/- 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 framing through the recorded video image, a maximum deformation could be measured. The following table (Table 3), contains the results of testing conducted by ARL on several occasions with various munitions.

PROJECTILE TYPE	MASS (gm)	IMPACT VELOCITY (m/s)	TEMPORARY CAVITY (mm)	IMPACT ENERGY (J)	ENERGY DENSITY (J/cm^2)
40mm XM1006	28.53	88.7	63.5	112.2	8.93
40mm XM1006	28.80	91.1	61.9	119.5	9.51
40mm XM1006	29.30	91.7	63.5	123.2	9.80
40mm XM1006	29.17	75.9	60.3	84.0	6.68
40mm XM1006	28.85	56.7	47.6	46.4	3.69
40mm XM1006	28.43	59.1	52.4	49.7	3.96
40mm XM1006	27.32	100.0	63.5	136.6	10.87
12 gage Single Ball #23 SB	3.40	306.8	95.25 (73.1) ^{P}	160.0	87.7
12 gage Shot Bag #23 BR	39.79	108.4	158.8 (133.3)^{P}	233.8	N/A
12 gage Shot Bag #23 BR	40.46	92.5	146.1 (101.6)^{P}	173.1	N/A
12 gage Shot Bag #23 BR	39.87	91.9	130.2 (79.4)^{P}	168.4	N/A
12 gage Multi Pellet #23RP	0.41 each	110.9	15.9	2.5	4.82
12 gage Fin Slug #23 FS	5.59	159.3	50.8 (26.7)^{P}	71.2	N/A
12 gage Fin Slug #23 FS	5.61	166.6	57.2 (25.4)^{P}	77.9	N/A
12 gage Fin Slug #23 FS	5.60	127.9	47.6	45.8	N/A
40mm Multi Pellet (.32 cal) #40A	0.41 each	61.4	12.7	0.77	1.48
40mm Multi Pellet #40A	0.41 each	73.8	9.5	1.1	2.12
40mm Multi Pellet #40A	0.41 each	78.8	19.1	1.3	2.51
40mm Multi Pellet #40A	0.41 each	83.1	12.7	1.4	2.70
40mm Multi Pellet (.60 cal) #40B	2.20 each	93.4	47.6	9.6	5.26
40mm Multi Pellet #40B	2.20 each	92.8	41.3	9.5	5.21
40mm Multi Pellet #40B	2.20 each	88.5	41.3	8.6	4.71
40mm Multi Pellet #40B	2.20 each	86.7	28.6	8.3	4.55
40mm Multi Pellet #40B	2.20 each	109.1	27.0	13.1	7.18
40mm Foam Baton #40F (3 each)	14.0 each	105.2	63.5	77.6	7.04
40mm Foam Baton #40F	14.0 each	103.0	50.8	74.3	6.74
40mm Foam Baton #40F	14.0 each	101.9	63.5	72.7	6.59

40mm Foam Baton #40F	14.0 each	102.6	60.33	73.7	6.68
40mm Wood Baton #40W (3 each)	20.0 each	78.2	95.3 (19.0)^{P}	61.2	6.16
40mm Wood Baton #40W	20.0 each	77.1	114.3 (31.2)^{P}	59.4	5.98
40mm Wood Baton #40W	20.0 each	81.8	101.6	66.9	6.74

Table 3. Results from ballistic gelatin testing.

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}. This number refers to the static penetration of the block, relative to the impact surface. A data analysis similar to that applied with the clay data was employed. Figure 4 contains the deformation as a function of impact energy while Figure 5 plots the energy density as a function of deformation.

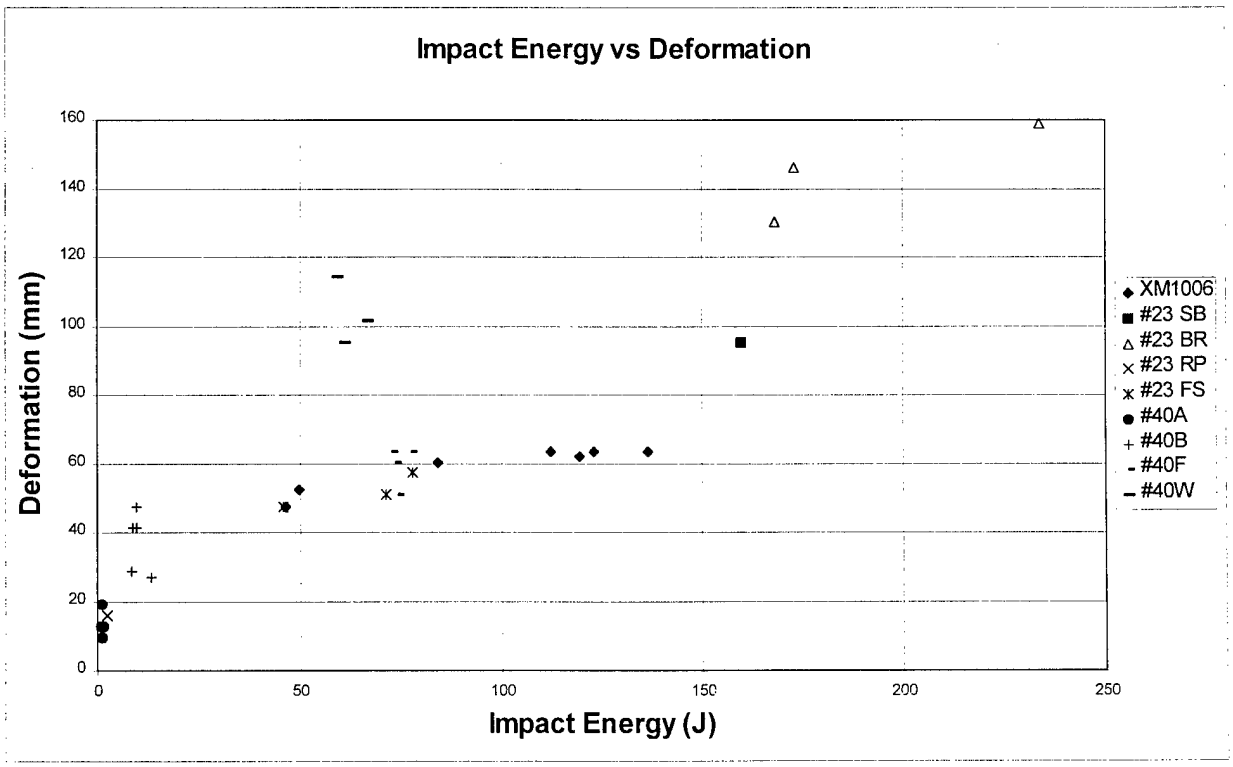

Figure 4. Results from gelatin testing plotted as a function of kinetic energy.

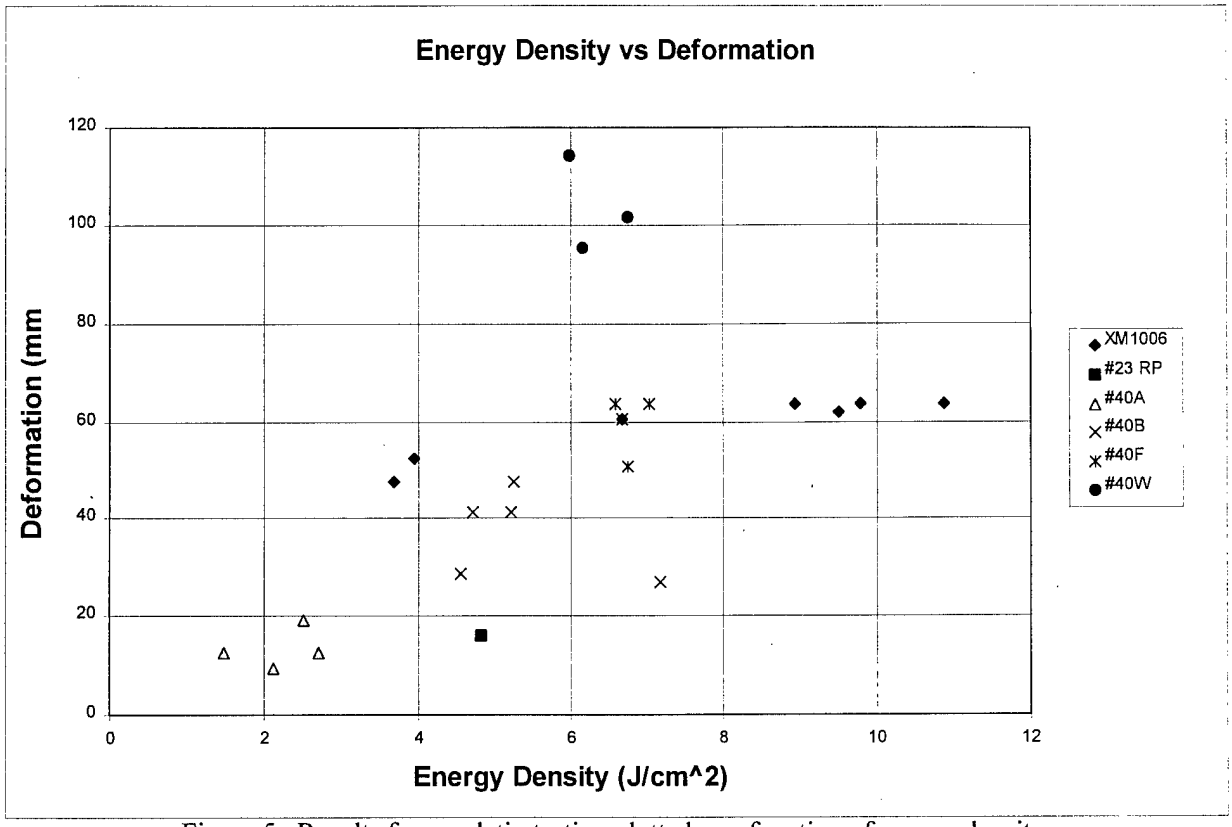

Figure 5. Results from gelatin testing plotted as a function of energy density.

3-Rib Chest Structure

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. Specifically, due to the high rib velocities which 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 kinetic energy impacts, which produced much higher rib velocities. This energy transfer rate creates a large spike of noise in the output. By applying the proper filter, the majority of this phenomenon is eliminated, without clipping real displacement data. Therefore, a maximum velocity constraint of $\leq$10m/s was established for the measurement data. This also corresponded to specifications of the transducer.

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 transfer, 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 impacts where impact was made in the center region and the displacement measurement was less than 10 m/s are presented.

PROJECTILE TYPE	MASS (gm)	IMPACT VELOCITY (m/s)	CHEST DISPLACEMENT (mm)	IMPACT ENERGY (J)	VC
40mm XM1006	28.83	71.0	7.22	72.7	0.08
40mm XM1006	29.30	70.0	7.12	71.8	0.08
40mm XM1006	57.68	52.0	8.21	78.0	0.19
40mm XM1006	29.17	76.0	6.44	84.2	0.08
40mm XM1006	28.50	77.0	6.68	84.5	0.12
40mm XM1006	28.88	77.0	7.66	85.6	0.14
40mm XM1006	58.09	55.0	8.78	87.9	0.16
40mm XM1006	28.61	80.0	5.90	91.6	0.09
40mm XM1006	57.18	57.0	7.41	92.9	0.19
40mm XM1006	56.91	58.0	8.00	95.7	0.16
40mm XM1006	57.95	60.0	9.64	104.2	0.19
40mm XM1006	28.00	87.0	9.00	106.0	0.14
40mm XM1006	28.99	88.0	9.36	112.2	0.20
12 gage Single Ball #23 SB	3.70	346.0	5.00	221.4	0.09
12 gage Single Ball #23 SB	3.70	326.0	7.58	196.6	0.02
12 gage Shot Bag #23 BR	41.0	94.0	10.90	181.1	0.28
12 gage Shot Bag #23 BR	41.0	92.0	9.50	173.5	0.24
12 gage Shot Bag #23 BR	41.0	98.0	12.06	196.9	0.19
40mm Sand Bag #40 BR	100.0	66.0	12.70	217.8	0.20

Table 4. Results from 3-RCS testing.

Figure 6 contains a plot of VC versus impact energy. This plot does reveal a positive correlation for the XM1006 data (R=.494). However, there are too few data points from any other munition to allow a similar analysis.

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 which included plotting as functions of both energy and energy density. This approach showed linear trends with one munition falling far outside the established bounds. The third technique (3-RCS) assigned a VC to each impact which corresponds to a level of injury. This device resulted in a correlation between kinetic energy and VC for the for Sponge Grenade (XM1006) data.

It should be noted that none of the available techniques have been fully validated for the assessment of non-penetrating, blunt impacts. Therefore, a more extensive analysis of both the methodology and data are warranted. However, this study represents the first attempt to compare results obtained from different experimental techniques, in an effort to evaluate injury levels. 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, relative to one another.

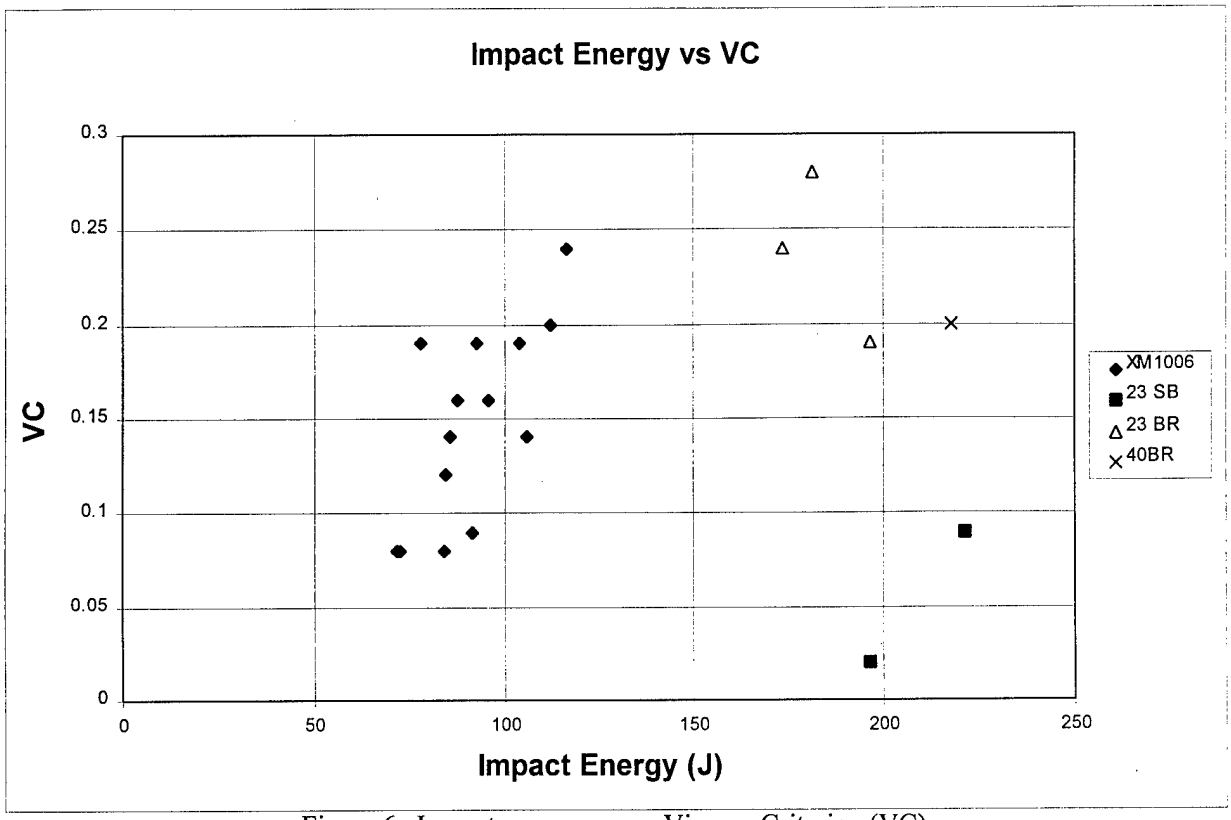

Figure 6. Impact energy versus Viscous Criterion (VC).

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