This is a pre-print of an article published in Human Factors and Mechanical Engineering for Defense and Safety (2019) 3:2. The final authenticated version is available online at http://doi.org/10.1007/s41314-019-0017-5.

Human Effects Assessment of 40mm Nonlethal Impact Munitions

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Abstract

An extensive human effects study was conducted on 40MM nonlethal impact munitions having two different projectile nose configurations: a compliant sponge nose, and a frangible foam nose carrying a powder payload. The study included initial characterization of the rounds using the Blunt Criterion (BC). Injury risk assessment was done using two previously validated surrogates; blunt impact assessment utilized the 3-Rib Ballistic Impact Dummy (3RBID), and penetrating trauma assessment utilized a biomechanical surrogate consisting of ordnance gelatin and a specific combination of layers to simulate skin and underlying soft tissue. Production impact munitions were manufactured to produce a range of energy levels on impact by adjusting the propellant charge in the smokeless propulsion system, resulting in different projectile muzzle velocities. Twenty-three impacts were performed on a biomechanical surrogate at kinetic energy levels in the range of 148 – 257 J to generate Viscous Criterion (VC_{max}) levels for injury assessment. The production configurations of the sponge and frangible-nose munitions were compared to the acceptable values for blunt trauma ($VC_{max} \leq 0.8$). Thirty-nine impacts were done on a penetration surrogate at kinetic energy levels in the range of 170 – 305 J, and the impact energies corresponding to penetrations were identified and compared to the production configurations for these munitions and to the expected energy density values for a 50% risk of penetration for specific areas of the body.

Key words: Nonlethal, kinetic energy munitions, injury risk, viscous criterion

1. Introduction

Specialty impact munitions, or kinetic energy munitions, are used in situations dealing with aggressive subjects when a less-than-lethal response is needed. Impact of a low-density projectile with the body inflicts blunt trauma, causing pain compliance in the subject to alter behavior. These munitions can be divided into two types: multiple and single projectiles. Multiple projectile impact munitions are typically used in crowd control situations to alter the behavior of a crowd. The multiple projectile impact munitions have relatively poor accuracy and are typically skip-fired off the ground at a crowd to impact the lower extremities of the body to avoid serious injury to vital organs such as the eyes. Single projectile impact munitions are designed primarily to target a single individual with a relatively low risk of collateral damage. Their accuracy allows them to be fired directly at the body to inflict blunt trauma to specific areas of the body, with the goal of minimizing the risk of serious injury. The response to the impact can include distraction, behavior alteration, or complete incapacitation. Single projectile impact munitions can be useful to disarm aggressive subjects in hostage or suicide situations, or to target and mark specific individuals in a rioting crowd.

Single projectile impact munitions are available in various calibers and configurations. One of the larger calibers is the 40MM spin-stabilized impact munitions. These munitions are manufactured with different projectile nose configurations, for the delivery of blunt force as well as irritant or marking payloads. Risk of serious injury can be minimized with accurate shot placement, and by incorporation of compliant or frangible materials into the projectile design that dissipate impact energy that would otherwise be delivered to the body [1].

Despite the overall goal of these munitions being nonlethal, there have still been cases of serious and/or fatal injuries as a result of their deployment [2,3]. Hubbs [2] investigated almost 1,000 deployments of less-lethal kinetic energy rounds. Over 80% of these resulted in injuries. The primary injuries were contusions (51%), however fractures and penetrating injuries were also reported. In a review of case reports and scientific literature between 1972 and 2009, Rezende-Neto summarized nine studies related to thoracic injuries as a result of kinetic energy impact munitions [3]. Lung contusions, hemothorax and pneumothorax were commonly reported, some with a fatal outcome. A more recent case report presented a 43 year old who suffered a myocardial infarction after sustaining a dissection of his left anterior descending coronary area caused by an impact to his chest with a rubber bullet [4]. Haar et al conducted a literature survey on death and injury from kinetic impact projectiles used between 1990 and 2017, examining 26 articles that involved 53 deaths and 1931 people injured by kinetic energy munitions. A large percentage of the injuries and permanent disabilities were from rubber-coated metal bullets, bullets made of metal fragments in a plastic matrix, or bean-bag type rounds that used lead shot encased inside a cloth bag [5].

Smaller-caliber projectiles such as rubber bullets or bean bags are more likely to cause penetrating injury to the body due to the smaller surface area of impact. 40MM projectiles that attenuate the impact energy through compliant or frangible nose materials may have reduced penetration risk when impacting the torso and extremities. The most common effect from these types of munitions is intramuscular bruising, a temporary injury that involves swelling and discoloration to the skin and muscle tissues. Figures 1 and 2 show the visual effects of impact from a sponge-nose projectile in actual use-of-force situations.

Figure 1: 40MM Sponge Round Impact to Thigh at 10 Meters. Photo taken 4 hours after impact.
Austin Police Department, Austin TX; used by permission.

Figure 2: 40MM Sponge Round Impact to Torso at 1 Meter. Photo taken 10 minutes after impact.
Dallas Police Department, Dallas, TX; used by permission.

There is an increasing need in current tactical and peace-keeping operations for engagement of subjects at greater stand-off distances, which can be addressed with extended range impact munitions that can accurately engage targets at ranges of 70 meters and beyond. Accurate engagement at these distances requires greater projectile velocity and kinetic energy to achieve an optimum flight trajectory and effectiveness at those ranges. Thorough human effects assessments must be done to define minimum engagement distances, and to assess the risk of blunt trauma and projectile penetration across the entire operational range. Models and simple laboratory tests have been developed to characterize the rounds prior to deployment during the design process [6,7]. In addition, in an effort to evaluate the risk of injury prior to deployment, testing methodologies have been developed [8-13]. These methodologies include the assessment of the accuracy of the rounds, the risk of penetration, and the blunt impact effect.

1.1 Characterization of rounds and design parameters

Models have been developed to predict the risk of injury due to rigid projectile impacts and they have been used as a guide in the early stages of less-lethal projectile design. One model that has been utilized to evaluate blunt impacts is the Blunt Criterion (BC), which is based on the mass, velocity, and diameter of the projectile, as well as the mass and thickness of the body wall of the target [14] . Bir and Viano validated the BC as a design criterion for use during the development stages of less-lethal kinetic energy munitions by using the cadaver injury data to correlate BC to the probability of injury according to the Abbreviated Injury Scale (AIS). The AIS uses a six-point scale to assess injury level in terms of severity, where AIS 1 is a minor injury, and AIS 6 is currently untreatable. The data analysis predicted that a BC value of 0.37 correlated to a 50% chance of sustaining an injury of AIS 2-3 [7].

Bir and Viano found a linear relationship between the BC and AIS based on the cadaveric injury data, which can be used to develop injury tolerance curves for different energy levels, projectile diameters, and target body types [7]. Other studies by Bir and Eck [15] have shown that the BC had the best predictive ability of the criteria examined for predicting potential injury from blunt ballistic impacts to the abdomen. The data used in this study was collected on cadaver and swine specimens using a 45 gram rigid 37 mm diameter projectile. Analysis of the data indicated that BC values of 0.51 and 1.32 would result in a 50% chance of sustaining an AIS 2-3 liver or bowel injury, respectively. When compliant or energy dissipating projectile nose features are incorporated in the design, the BC calculation may overpredict the potential injury level, however this conservative approach is desirable for a less severe injury outcome.

1.2 Injury assessment

Bir et al. characterized the biomechanical response of the body to blunt ballistic impacts using testing on unembalmed cadavers, noting key differences in the occurrence of injury relative to earlier studies involving impacts during motor vehicle accidents, such as the duration of impact and the amount of rib cage compression [9]. Further analysis of this data, which involved impacting the specimens with a 37-mm-diameter noncompressible baton, resulted in development of an injury criteria based on the combination of velocity of compression and amount of compression, correlated to injury ratings using the Abbreviated Injury Scale (AIS). The Viscous Criterion (VC) is an injury criterion that uses both the compression and the rate of compression to relate the injury tolerance of soft tissue to the energy absorption during rapid impact deformation of the body [17]. Significant work has been done to validate the viscous criterion using cadaver data, and to establish tolerance levels of VC_{max} to predict probability of injury to the thorax due to frontal chest impacts [17] and more specifically, to blunt ballistic impacts [7]. Tolerance levels were developed that indicated that VC_{max} values of 0.6 and 0.8 m/s correlated to a 25 and 50% risk of sustaining a thoracic skeletal injury of AIS 2-3, respectively [7]. Use of the 0.6 m/s VC_{max} criterion value yields a more conservative result, while the 0.8 m/s value is more statistically relevant.

Human response corridors were also developed as part of this effort [9]. These corridors allowed for the validation of a specialized biomechanical structure; the 3-Rib Ballistic Impact Dummy (3RBID). Figure 3 demonstrates the response of the 3RBID (dotted line) within the established force-time corridors (solid lines). By establishing the biofidelity of the 3RBID, testing can be conducted to determine the risk of injury due to blunt ballistic impacts [17]. The 3RBID is comprised of a 3-rib structure from a side impact test dummy mounted to a spine box and coupled with a front-facing polyurethane sheet. The impact surface measures 6.0 inches in height and 8.5 inches in width. A urethane foam pad was modified and placed in front of the polyurethane sheet to achieve biofidelity. A 50-pound mass was attached to the base of the 3RBID to provide the appropriate mass of the thorax. The 3RBID is tested on a Teflon coated table to allow for a low friction interface between the surrogate and table. This version of the 3RBID was used in the current study (Figure 4).

The 3RBID was refined to measure rib displacement using a 3-axis, non-contact RibEye optical measurement system. The RibEye system measures the deflection at the center of each rib, where a light emitting diode (LED) is mounted. The displacement of the LED is measured in absolute X, Y, and Z coordinates, at 20 kHz sampling rate. Data collected from each rib is used to calculate the magnitude and velocity of rib deflection. The maximum Viscous Criterion (VC_{max}) was used to evaluate the severity of each impact, and was calculated from the maximum measured deflection from all three ribs.

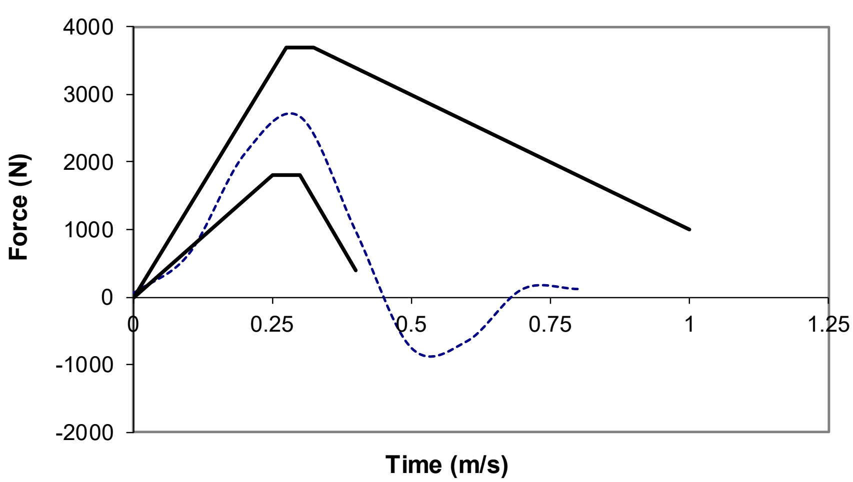


Figure 3: Response of 3RBID within biomechanical response corridors

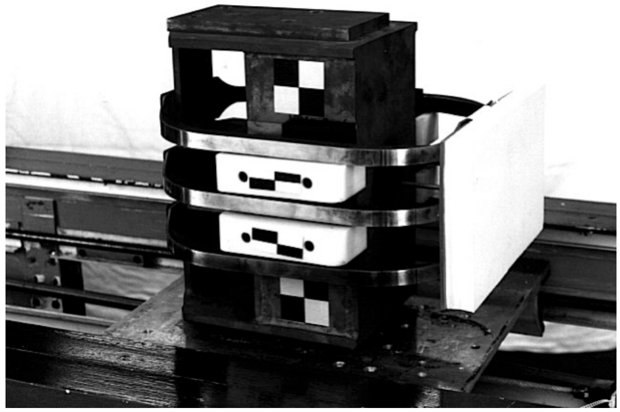


Figure 4: 3-Rib Ballistic Impact Dummy (3RBID) modified based on corridors developed by Bir et al. [9].

Although the 3RBID allows for the assessment of blunt ballistic impacts to the thorax, the risk of penetrating injury also needs to be assessed. Based on this need, Bir et al. [18] determined energy densities for penetration over various regions of the body using testing on human cadaveric specimens. This work calculated that energy densities required for 50% risk of penetration from a less lethal 12-gauge munition varied from 23.99 J/cm^2 for the anterior rib location, to 52.74 J/cm^2 for the posterior rib location. The data were used to develop and validate the surrogate for penetration assessment of nonlethal projectiles [8].

The penetration surrogate was developed to produce approximately the same penetration response of the anterior rib using multiple layers of materials to represent skin, subcutaneous fat, and underlying soft tissue and organs. A Penetration Assessment Layer (PAL) simulating the underlying soft tissue was made of 20% ordnance gelatin that was poured into a rectangular shape with the approximate finished dimensions of 5.5 x 5.5 x 14 inches. The gelatin block was conditioned at 10 degrees Celsius for 24 hours prior to use. A Laceration Assessment Layer (LAL) simulating skin and subcutaneous fat was made of a single layer of natural sheepskin chamois and a single layer of 0.60 cm closed cell foam. These materials were attached to the PAL over the impact area by elastic straps. Prior to testing, the PAL was calibrated to achieve an acceptable penetration depth using a 0.177 caliber copper-plated sphere BB [8]. The penetration surrogate configuration is shown in Figure 5.

Figure 5: Ordnance gelatin used as penetration surrogate.

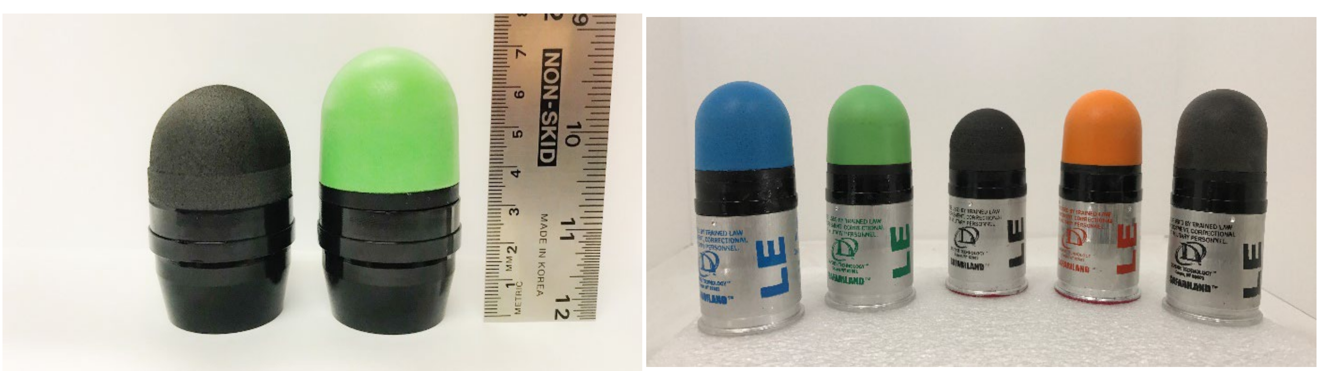
More recent efforts have attempted to standardize the evaluation of nonlethal impact munitions with the NATO Standardization Recommendation (STANREC) [10]. The STANREC recommends testing methodologies that include the assessment of the accuracy of the rounds [13], the risk of penetration [11], and the blunt impact effect [12]. In an effort to complete a thorough human effects assessment of the 40MM impact munitions, both the basic design characterization methods and injury risk assessment methodologies were employed. The current study demonstrates how these methodologies can be applied to ascertain the overall effects of a given round during development and prior to deployment in the field.

2. Methodology

The munitions evaluated in this study were the Defense Technology™ 40MM eXact iMpact™ and Direct Impact™, which are available in standard and extended range variants. The eXact and Direct Impact will be referred to as the XM and DI, respectively, with the designation of "LE" used to indicate the extended range versions of the munitions. They are intended to be direct fired at the body and the recommended target area is below the breast line to avoid impact of the head or neck region. The current study used production munitions that utilized different propellant charges to produce a range of muzzle velocities and kinetic energies that included both standard and extended range versions of these munitions. The data comparisons used in this study will focus on the extended range (LE) munitions, as they have the highest delivered energy of the 40MM XM/DI munitions family. The human effects assessment for the lower-energy XM and DI variants can be inferred from these results.

Both XM and DI munitions utilize a plastic projectile body with an incorporated driving band to engage the 40MM launcher barrel rifling and impart spin to the projectile (Figure 6a). The XM and DI projectiles have approximate masses of 30 and 40 grams, respectively. The projectile is loaded into an aluminum shell base designed with a modified high pressure/low pressure propulsion system utilizing smokeless powder as the propellant. The XM incorporates a compliant foam nose, while the DI incorporates a hollow, frangible foam nose that breaks on impact to release an irritant or marking payload. (See Figure 6b). The foam noses on the XM and DI projectiles have approximate masses of 3 and 11 grams, respectively.

Initial characterization of the rounds was completed followed by testing with the injury risk surrogates at varying impact energy levels covering the entire operating range of the munitions. The launching platforms used for the testing were standard 40MM rifled barrel launchers, including the M203 Grenade Launcher or the Defense Technology Model 1325 Single Shot Launcher. The specific testing methodology is described in the following sections.



(a) (b)

Figure 6: 40MM eXact (XM) and Direct (DI) Impact LE projectiles (a) and the extended range munitions (b).

2.1 Characterization and design methods – BC

Using the method of Bir and Viano, injury tolerance curves were generated for a 40 mm diameter projectile, using a BC = 0.37, and varying the projectile mass and velocity, and size of the target. The following equation was used to calculate the BC:

$$BC = \ln[1/2mv^2/M^{1/3}Td]$$

Figure 7 shows the resulting curves, which indicate that a 30 g projectile could be fired at 56 and 77 m/s with a 50% risk of AIS 2-3 injury to a small female or large male subject, respectively.

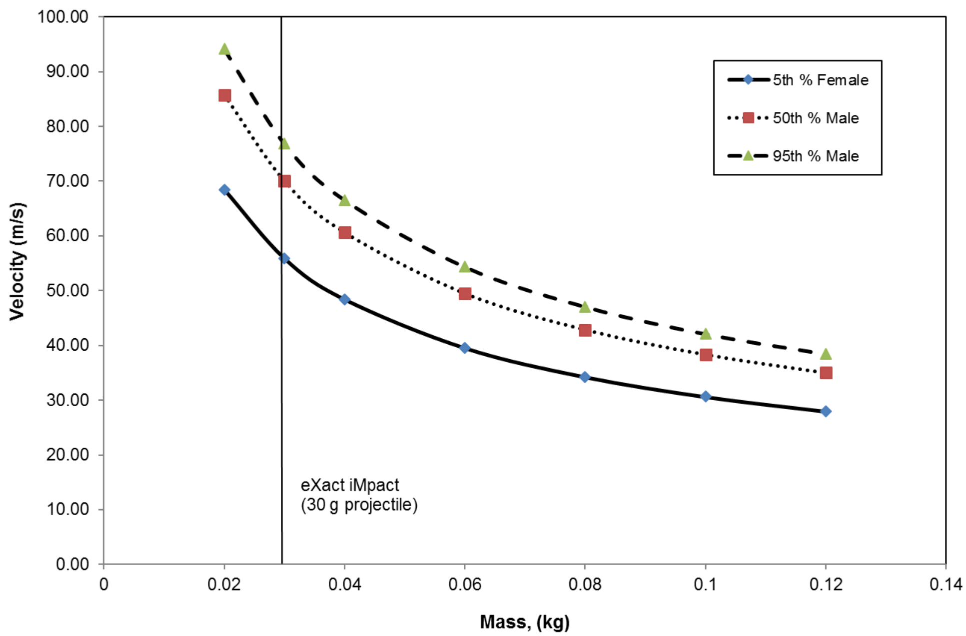


Figure 7: Design criteria curves based on BC = 0.37 and impact diameter of 40 mm

2.2 Injury assessment methods – 3RBID

Blunt ballistic impact assessment was conducted using the 3RBID. Projectiles were fired at the 3RBID from a distance of 5 meters. Velocity was measured one meter from the target and high-speed video was collected for each impact. The maximum Viscous Criterion (VC_{max}) was used to evaluate the severity of each impact, and was calculated from the maximum measured deflection from all three ribs.

2.3 Injury assessment methods – Penetration

Initial assessment of the standard Energy Density ($1/2mv^2/\pi r^2$) of the standard production rounds were compared to the PMHS data generated by Bir et al. [8]. After it was determined these rounds would fall beneath the 50% risk of penetration (Figure 8), a test matrix was developed with a modified velocity of both the DI and XM rounds to determine the V_{50} of each. The rounds were then tested against the validated surrogate. The velocity was measured at one meter from the target and high-speed video was collected for each impact.

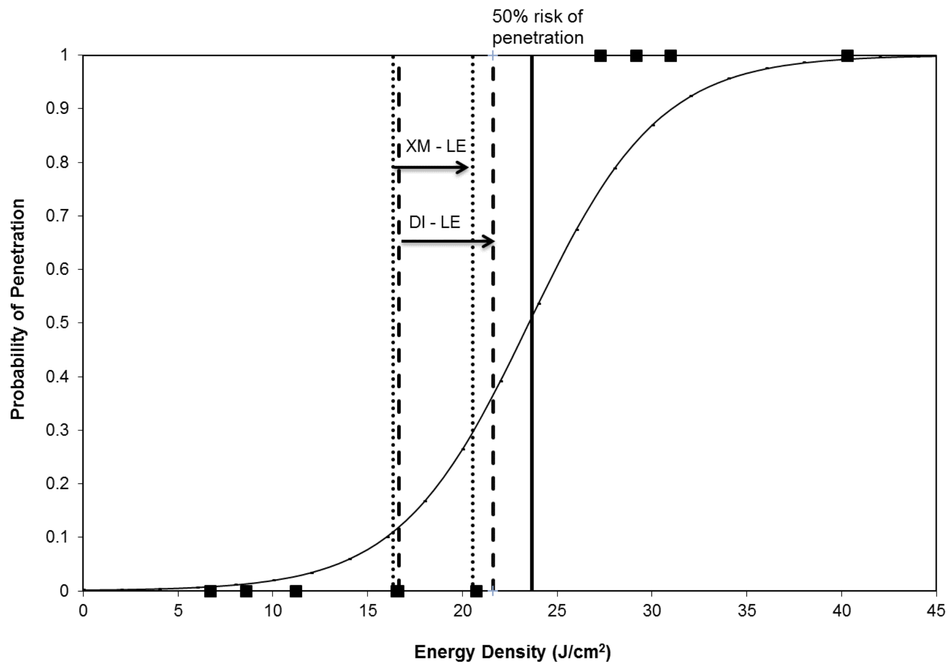


Figure 8: Range of energy densities of XM and DI production rounds with respect to injury risk curve from PMSH testing by Bir et al. [18].

The impact area was examined for evidence of damage to the LAL or PAL. Perforation of any layer of the LAL was identified as a laceration, and any permanent cavity formed in the gelatin PAL was identified as a penetration. The penetration surrogate has not been validated for evaluating lacerations, so this information was only recorded to note damage to the layers covering the gelatin block. To assess penetration risk, a total of 24 tests were conducted for the XM configuration, and 15 tests were conducted for the DI configuration. Each impact was examined and scored according to the damage to the LAL and PAL.

3. Results

Over 60 shots were conducted to assess the blunt trauma and penetration injury risk of the DI and XM less-lethal munitions. The results are presented in the following sections.

3.1 Characterization and design results – BC

The standard and extended range versions of the XM projectiles used in this study have calculated BC values of 1.06 and 1.48, respectively, which is higher than the BC values calculated by Bir and Eck that would result in a 50% chance of sustaining an AIS 2-3 abdominal injury [15]. Figure 9 shows the calculated curves and the Energy/Diameter (E/D) values for the standard and extended range XM projectiles. These calculations predict that a 50th percentile male subject could be impacted by an XM projectile with an energy level of 147 – 224 J with potential for moderate injury (AIS 2). However, a 5th percentile female subject could sustain a more serious injury (AIS 3) from the same impact.

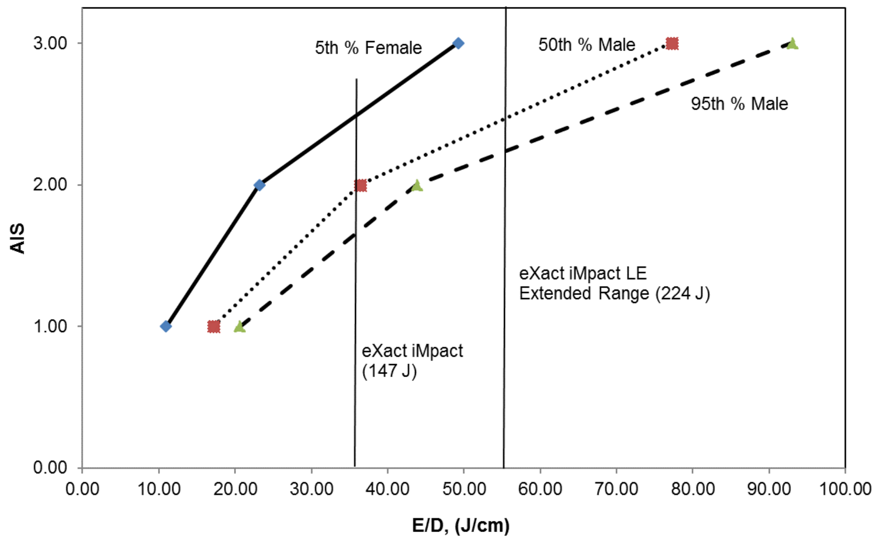


Figure 9: Injury Tolerance Curves for Various Body Types, as a Function of Projectile Energy/Diameter

3.2 Injury assessment results – 3RBID

A total of 29 tests were performed using the 3RBID, with progressively increasing projectile velocities and impact energies. Due to data collection or impact location errors, six of these data points were not usable in the analysis. The middle rib of the 3RBID was the point of aim for the testing and typically measured the greatest deflection. Only impacts centered on the middle rib were used in the final data analysis; impacts on the upper or lower ribs were discarded. In two instances, the upper or lower rib registered a deflection that was marginally higher than the central rib, and the larger value was used for the VC_{max} calculation, with values ranging from 0.27 to 0.89. Using the projectile velocity measured at one meter from the target, and the actual projectile mass, the impact energy was calculated in the range of 148 – 257 J (See Figure 10).

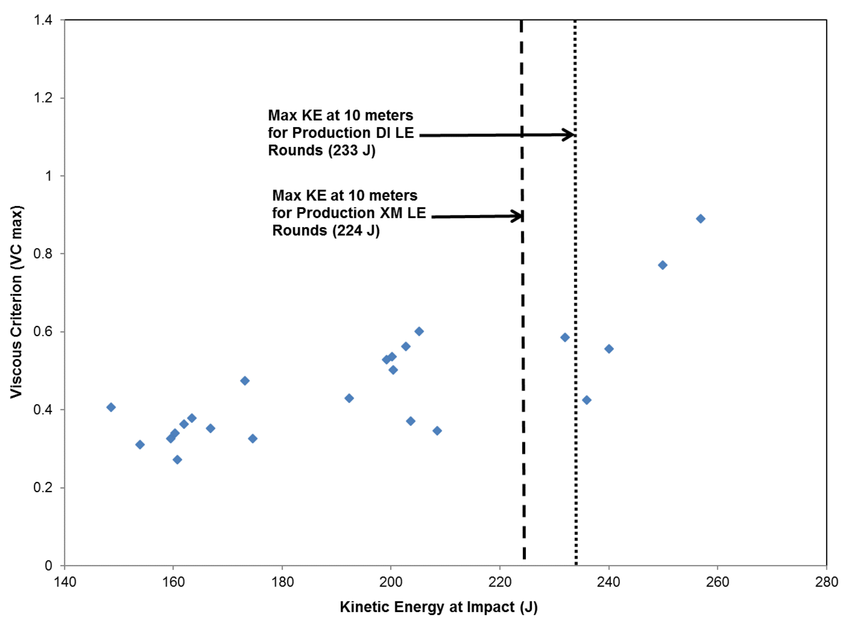


Figure 10: Measured VC_{max} Values for Different 40MM XM and DI Kinetic Energy Levels.

As the projectile impact energy increased, the spread in the VC_{max} data also increased. This is presumed to be due to the greater variability in the mechanical response of the 3RBID surrogate components at the higher deflection levels.

Also shown on Figure 10 is a vertical line representing the maximum impact energy level of the production XM LE and DI LE extended range 40MM Munitions at 10 meters. This value was calculated using the initial muzzle energy for the rounds and applying a retardation factor based on measured Doppler velocity data to calculate the velocity degradation. The retardation factor was calculated from the velocity vs. range data for several XM LE and DI LE projectiles in flight, (Figures 11 and 12) and can be used to correlate between the muzzle and impact energies.

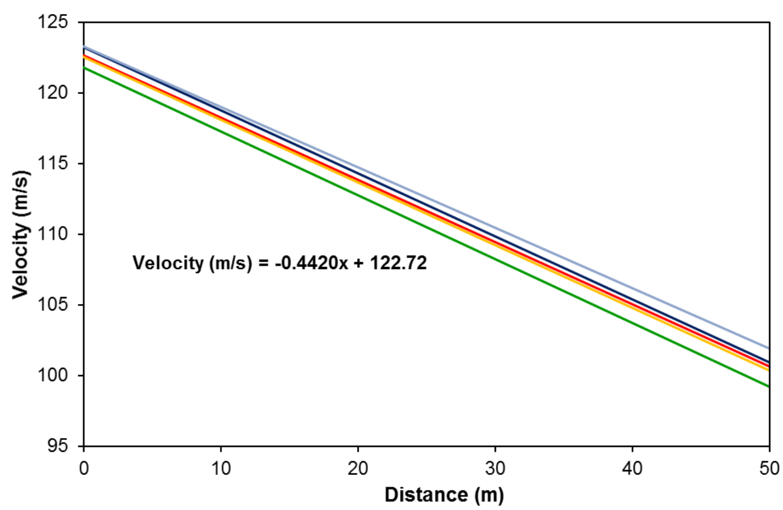


Figure 11: Doppler Radar Data Showing Velocity Degradation for the XM LE Projectile

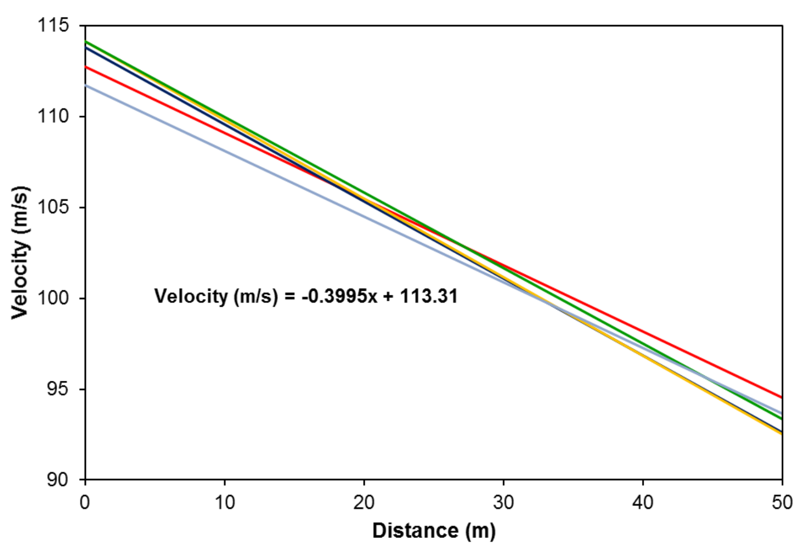


Figure 12: Doppler Radar Data Showing Velocity Degradation for the DI LE Projectile

3.4 Injury assessment results – Penetration

Figure 13 is a plot of the penetration results for the XM and DI, for the corresponding projectile masses and impact energies. The upper and lower groupings of data points are for the DI and XM projectiles, respectively. Also shown on Figure 13 are vertical lines describing the maximum expected energy levels for the XM LE and DI LE (extended range) production rounds, based on their design specifications. For both the XM and DI projectiles, all penetrations measured in the surrogate occurred at energy levels above the specification muzzle energy for the rounds (224 – 240 J for the XM LE, and 233 – 253 J for the DI LE). Based on the testing with the skin penetration surrogate, the V_{50} of the XM round was calculated to be 422.2 fps (Figure 14). For the DI round, the V_{50} was calculated at 396.5 fps (Figure 15). Both of these values were above the specification velocities of the rounds.

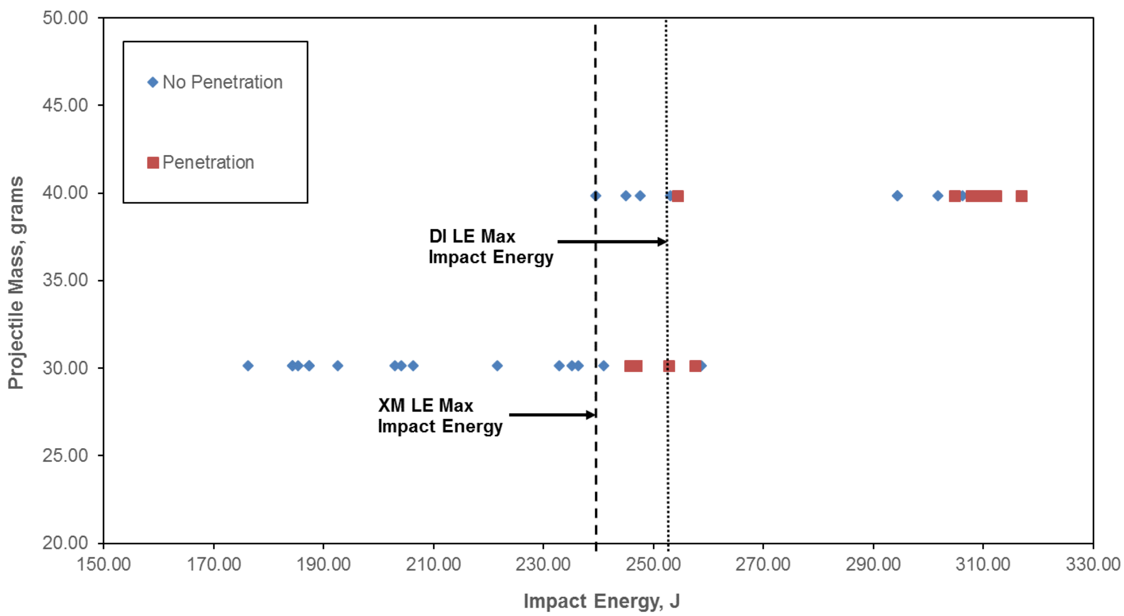


Figure 13: Penetration Assessment Results for XM LE and DI LE Impact Energy Levels

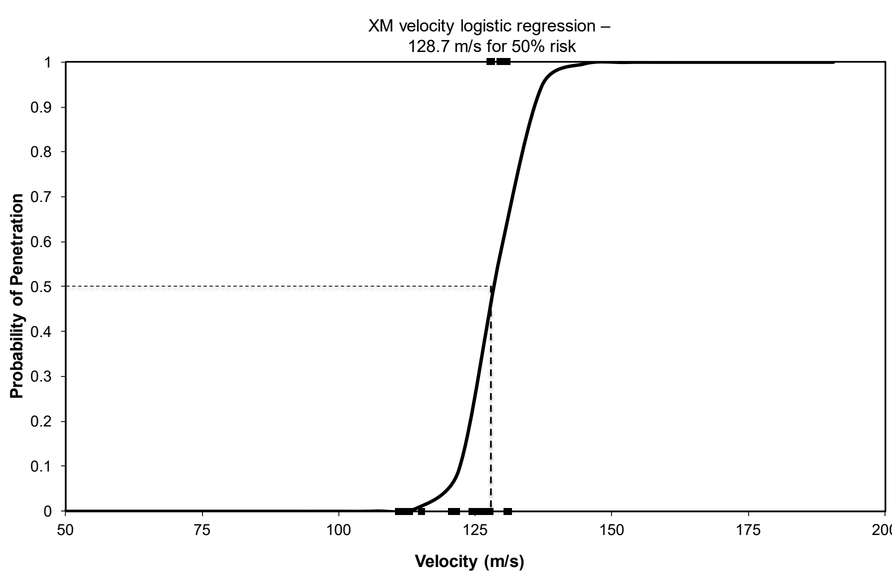


Figure 14: V_{50} for XM based on skin penetration assessment.

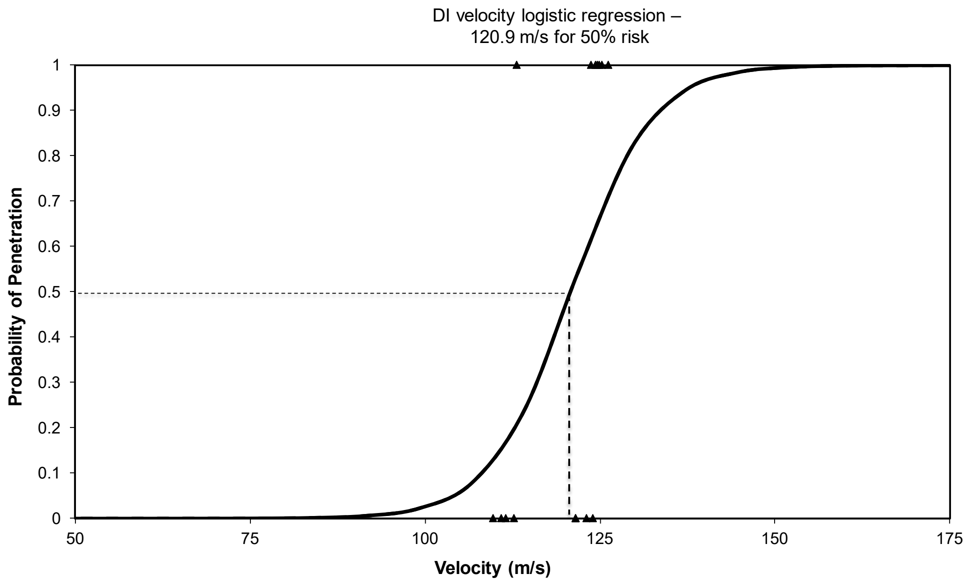


Figure 15: V_{50} for DI based on skin penetration assessment.

4. Discussion

The data presented represent a complete assessment of two less lethal kinetic energy impact munitions. Both characterization/design parameters and injury assessments were conducted and provide important insights into the overall effects of deployment of the rounds. While the 3RBID and skin penetration surrogates provide specific data related to the risk of injury, the design and characterization techniques provide the ability to conduct initial, low-cost analysis of the rounds before production. It should be understood that there might not always be a correlation back to the injury risk. This was seen in the current study where the result of the BC design parameter calculation does not appear to correlate with the injury potential calculated using the VC_{max}, which predicted AIS 2-3 for a 30 g projectile at a much higher velocity (122 m/s) and energy level. The reason for this difference is that the BC calculation does not take into account the compliance or energy dissipating features of the 40 mm projectile noses on the XM and DI rounds. Deformation or breakage of the compliant or rigid foam nose materials dissipates energy that would otherwise be transferred to the target. The energy dissipation is captured during the 3RBID testing, which results in a lower VC_{max} number for a given energy level. As with the previous injury tolerance calculation in Figure 7, the calculation in Figure 9 may overpredict the potential injury level, as it does not account for energy dissipation through deformation of the projectile nose. While the BC calculations yielded a conservative result in this case, these calculations indicate the limitations of using the BC as a design criterion in the early stages of blunt impact projectile design.

The penetration surrogate used for this study allowed assessment of injury risks from ballistic impacts, primarily damage to underlying soft tissue. The surrogate is not validated for evaluating laceration, so damage to the soft tissue was the focus of further analysis. The information obtained from the LAL is useful only for comparison purposes as an indicator of laceration potential. As shown in Figure 13, there were no penetrating injuries observed with the surrogate testing for the XM LE or DI LE projectiles at their operational energy levels. Beyond these operational energy levels, the no penetration/penetration transition occurred over a range of impact energies, with differing results sometimes observed for the same energy level.

The energy densities required for a 50% risk of penetration on various areas of the body were studied by Bir et al. using 12 gauge rigid projectile impacts on cadaver specimens [18]. Logistic regression analysis of the penetration data resulted in a value of 23.99 J/cm^2 for the anterior torso, which was the lowest calculated penetration energy density for any area of the body in the study. The energy density values for the XM and DI projectiles were calculated for comparison to threshold values for a 50% risk of penetration, shown in Table I. The energy density based on the muzzle velocity for the standard XM and DI rounds is well below the threshold for penetrating injury (See Figure 8). The energy density for the extended range rounds is closer to the 50% risk of penetration threshold than the standard rounds. Testing with the skin penetration surrogate using XM and DI rounds that had been modified to fire with an increased velocity demonstrated the V_{50} of the rounds is above all production round specifications.

Table I: Calculated energy densities for 40MM eXact (XM) and Direct (DI) Less Lethal Impact Munitions

Munition	Range (meters)	Energy Density (J/cm^2)
XM, Std. Velocity	muzzle	13.41
XM LE Extended Range	muzzle	20.58
XM LE Extended Range	10	19.11
DI, Std. Velocity	muzzle	14.68
DI LE Extended Range	muzzle	21.61
DI LE Extended Range	10	19.88

5. Conclusions

This human effects study has evaluated the eXact iMpact™ and Direct Impact™ family of 40MM nonlethal impact munitions, with respect to injury potential from blunt ballistic impact or penetrating trauma. Validated biomechanical surrogates and standard test methodologies were used to determine risk of injury, and initial characterization was performed using the BC design criterion.

Blunt impact assessment using the 3RBID biomechanical surrogate of a human rib cage characterized the blunt trauma risk across a range of impact energies. The data indicated that all production 40MM XM and DI impact munitions were within acceptable values for blunt trauma, based on the maximum Viscous Criterion ($VC_{max} \leq 0.8$).

Assessment of penetrating trauma utilized a validated biomechanical surrogate consisting of ordnance gelatin and a specific combination of layers to simulate skin and underlying soft tissue. All production 40MM XM and DI impact munitions were within the demonstrated penetration thresholds, with energy density values below those that would be expected to produce a 50% risk of penetration on various areas of the body.

The BC was evaluated as a design criterion used during development of the 40MM projectiles in this study, but comparisons with the injury assessments generated from the surrogate testing indicated its limitations when used with projectiles having compliant or energy dissipating features.

Acknowledgements

The authors thank Don Sherman, John Hultman, Adam Rauch, Mike Kramer, Mark Warr, and Ethan Smith for assistance with the experimental testing and data reduction.

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