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TECHNICAL NOTE

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Skin Penetration Assessment of Less Lethal Kinetic Energy Munitions*

ABSTRACT: The development of less-lethal technologies has provided law enforcement personnel with an alternative to lethal force. Although the less lethal projectile was produced to engender non-penetrating wounds, case studies show that there have been a number of reported penetrating injuries ranging from minor to significant in morbidity. The objective of this study was to determine the energy per unit area required to penetrate various regions of the body. Eight unembalmed postmortem human specimens were procured for this testing. Each specimen sustained a maximum of 25 impacts consisting of shots to the anterior and posterior thorax, abdomen, and legs. A 12-gauge, fin-stabilized, rubber rocket round was used as the impactor for all of the conducted tests. The energy density required for 50% risk of penetration varied from 23.99 J/cm^2 for the location on the anterior rib ($p = 0.000$) to 52.74 J/cm^2 for the location on the posterior rib ($p = 0.001$).

KEYWORDS: forensic science, ballistics, less-lethal, skin penetration

The increased development of less-lethal technologies has provided law enforcement personnel with an alternative to lethal force. These specialized tools assist officers when confronted with situations that require the use of force without irreversible harm. Less-lethal technologies include some basic types of products: contact weapons, chemical agents, projectiles and directed energy methods. Each is designed, if employed properly, to inflict an appropriate amount of deterring force to control the situation without causing severe or fatal injuries.

Projectiles or kinetic energy munitions offer the largest range of application. Manufacturers of such devices typically offer a variety of munitions to meet various situations. Single fire munitions are available for those encounters with a single individual whereas multiple rounds are designed for encounters with large crowds. Both close-range and standard-range projectiles have been developed to address disturbances from varying distances. The use of similar or the same types of launchers for these munitions as those used for lethal projectiles facilitates escalation from less-lethal force to lethal force when warranted by an increase in the magnitude of the threat. Therefore, these devices offer authorities an additional level of protection.

Although the benefits of the use of less-lethal projectiles are numerous, there is great concern regarding the effects that the munitions have on the assailant. The less lethal projectile was produced to engender non-penetrating wounds; however, case studies show that there have been a number of reported penetrating injuries ranging from minor to significant in morbidity (1–3). These cases studies reported on individuals that had been treated for penetrating wounds due to less-lethal kinetic energy rounds. In all of the reported cases, 12 gauge rounds were employed.

There have been several previous studies conducted regarding skin penetration as it relates to ballistic impact, which have been summarized by DiMaio (4). However, in these studies, different methods have been used, as well as different materials, and therefore it is difficult to compare the various studies. In a recent study, DiMaio et al. (5) performed impacts to lower extremity skin and muscle samples. The missiles for testing consisted of a .177 air rifle pellet, a .22 air gun pellet and a .38 caliber bullet. It was concluded that perforation always occurred at energy densities ranging from 12.75 J/cm^2 for the .22 air gun pellet to 19.03 J/cm^2 for the .38 caliber bullet. The results of the data collected by DiMaio et al. (5) relate well with the values established by both Journée (4) and Mattoo (6). A summary of previous studies can be found in Table 1.

There are some limitations of applying this data to the current range of impacts presented with the deployment of kinetic energy munitions. The mass and velocity of previously tested missiles differs significantly than that seen with the current 12 gauge munitions. In order to quantify the probability of penetrating the skin, the energy, as well as the area of impact, must be considered. Therefore, it is important to determine the energy per area of presentation ratio or E/a value. This value takes into account the mass, velocity, and the cross-sectional area of the projectile. As depicted in Fig. 1, where the icons are scaled to represent cross-sectional area, the current 12 gauge kinetic energy munitions are quite different from the previous data.

Methods

The most accurate means of quantifying the penetrating threshold of the skin without using live human subjects is by using postmortem human subjects (PMHS). Eight specimens, four male and

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TABLE 1—*Experimental data for penetration assessment.*

Researcher	Projectile	Specimen	Energy Density (J/cm^2)
Journee, 1907	Lead Sphere	Human skin and muscle	20.99
Mattoo, 1984	Lead Sphere	Skin and muscle of thigh	20.21
DiMaio et al., 1982	.177 air rifle pellet	Lower extremity skin and muscle	18.14
DiMaio et al., 1982	.22 air gun pellet	Lower extremity skin and muscle	12.75
DiMaio et al., 1982	.38 caliber bullet	Lower extremity skin and muscle	19.03

TABLE 2—*Postmortem human subject data.*

Cadaver ID	Sex	Age (yrs)	Height (cm)	Weight (kg)
UM 31155	M	76	174.0	73.0
UM 31222	F	58	162.5	71.2
WSU 430	M	75	174.0	84.1
UM 31234	M	58	175.5	57.6
WSU 545	F	78	155.0	52.2
UM 31480	M	77	172.0	78.0
WSU 562	F	72	168.0	72.6
WSU 563	F	80	164.0	68.0

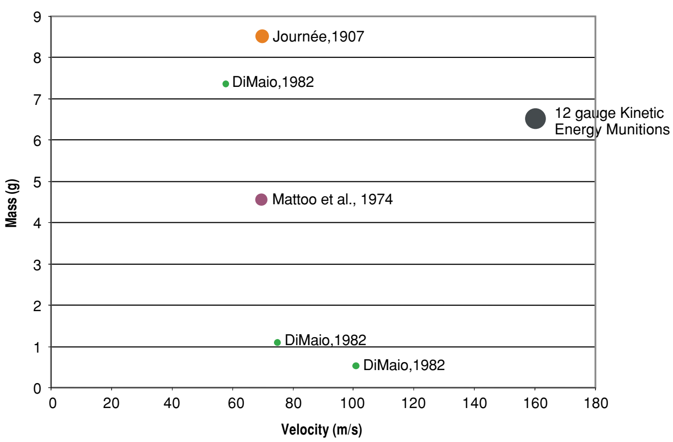


FIG. 1—*Current study compared to previous skin penetration studies.*

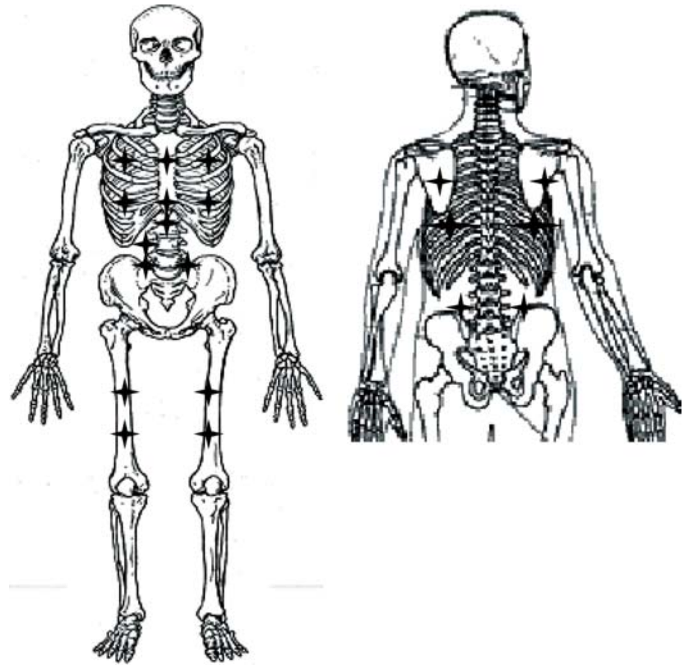


FIG. 2—*Anterior and posterior impacts. Locations illustrated as stars.*

FIG. 3—*The 12 gauge, fin-stabilize rubber rocket kinetic energy munition.*

four female were procured from the Wayne State University Body Bequest Program and the University of Michigan Anatomical Donations Program. The specimens were treated in accordance with ethical practices of cadaver usage (7). Consents are garnered by the Willed Body Program from donors that include the identification of impact biomechanics as a potential type of research. The cadavers were fresh and unembalmed to ensure that skin conditions during experimentation related as closely as possible to living skin. A detailed summary of the specimens is located in Table 2.

Since the skin thickness and underlying structures are variable, each specimen sustained a maximum of 25 impacts consisting of shots to the anterior and posterior thorax, abdomen, and legs. Figure 2 represents the various points of impact, including areas where bone lie directly under the skin and fleshy areas devoid of bone such as the ribs and abdomen, respectively.

A 12-gauge, fin-stabilized, rubber rocket round was used as the impactor for all of the conducted tests and is depicted in Fig. 3. The average mass of the impactor was 6.40 g. The hard rubber projectile was chosen for the research due to desire to achieve consistent impacts. The solid projectile has a rounded head with no edges; therefore the projectile will hit the intended target squarely creating an impact area of 2.45 cm^2. In addition, the projectile maintains its shape during impact allowing for the worst-case scenario for all 12 gauge less-lethal munitions. The amount of gunpowder was customized to achieve velocities ranging from 61–183 m/s (200–600 ft/s), this range covers the upper and lower velocity limits used by law enforcement.

A universal receiver with 12-gauge barrel attachment as displayed in Fig. 4 was used to fire the projectile from a distance of 1.5 m. This allowed for accurate shot placement. A chronograph, placed 0.55 m from the specimen, was used to determine the exact terminal velocity of the projectile upon firing. All testing was recorded using high-speed video at 20,000 frames per second.

Following each impact to a given location a visual inspection of the injury was performed. The wound was labeled penetrating or non-penetrating and further assessment of injury was performed after testing was completed. Penetrating wounds were determined as such by evaluating whether the impactor disrupted not only the skin, but underlying tissue such as subcutaneous fat and/or muscle

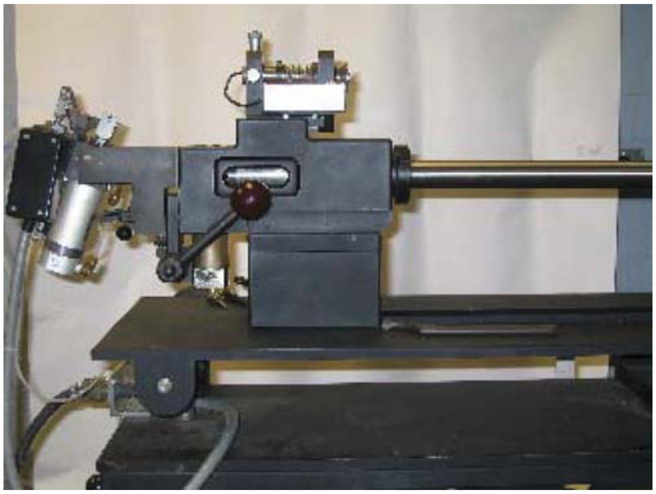
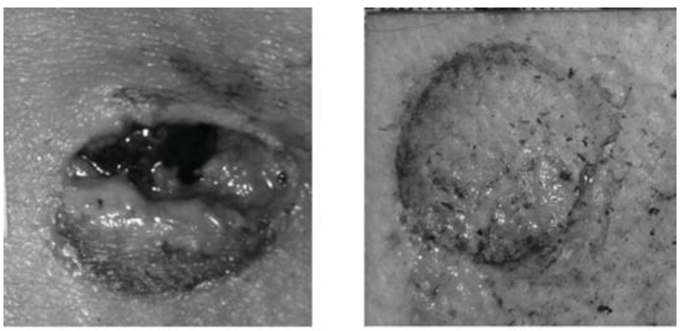


FIG. 4—*Universal receiver fitted with 12-gauge barrel.*



(a) (b)

FIG. 5—*Example of penetrating (a) and non-penetrating (b) wounds.*

as depicted in Fig. 5*a*. Slight tearing, discoloration or marking of the skin without damage to underlying tissue was regarded as non-penetrating as depicted in Fig. 5*b*. Following visual inspection, the impacting projectile was retrieved; mass and diameter of the round were measured and the energy density was mathematically determined. The same location was then targeted on the other side of the medial plane of the specimen. The second location was impacted at an increased velocity when the previous wound was labeled non-penetrating and a lower velocity was used when the mirroring wound was labeled penetrating. The tests were performed using energy densities ranging from 4.61–65.26 J/cm^2 and resulted in both penetrating and non-penetrating wounds.

A logistic regression analysis was performed on the data that evaluated the significance of specimen variability. In the current study, energy-density was chosen as the parameter for the prediction of penetration. The binary logistic regression is considered the optimal statistical tool for the purposes of this study as the observed outcome is restricted to two values, penetration and no penetration. By dividing the probability of an event occurring, in this case penetration (α), by the probability of the event not occurring, no penetration (β), an odds ratio or predictor value is established. This predictor value, which will be called the 50% risk, is the energy density where penetration is 50% likely.

Results

A total of 166 impacts were performed with at least 10 impacts conducted for each region identified. As demonstrated in Table 3,

TABLE 3—*Average energy densities in relation to region and assessment of penetration/no penetration.*

Region	Result	Number	Average Energy Density (J/cm^2)
Between Rib	No Penetration	11	21.01 (11.72–41.58)
	Penetration	6	33.14 (18.37–58.20)
Distal Femur	No Penetration	8	17.72 (4.61–30.96)
	Penetration	8	35.67 (18.01–51.77)
Lateral to Umbilicus	No Penetration	6	24.51 (11.54–45.53)
	Penetration	4	37.73 (25.56–51.52)
Liver	No Penetration	7	23.50 (10.71–54.26)
	Penetration	5	36.23 (29.24–44.61)
Lower Back	No Penetration	12	25.73 (10.27–60.17)
	Penetration	7	41.88 (29.45–53.28)
On Anterior Rib	No Penetration	6	13.39 (6.70–20.73)
	Penetration	6	38.10 (27.26–53.31)
On Posterior Rib	No Penetration	22	34.65 (10.96–57.55)
	Penetration	6	55.90 (44.00–65.26)
Proximal Femur	No Penetration	7	16.56 (4.61–28.17)
	Penetration	9	34.91 (17.88–52.80)
Scapula	No Penetration	12	30.01 (10.74–56.94)
	Penetration	6	42.60 (26.76–59.75)
Sternum	No Penetration	10	25.78 (15.11–47.78)
	Penetration	8	37.93 (20.94–61.33)

TABLE 4—*Energy densities reported for a 50% risk of penetration for varying regions of the body based on logistic regression analysis results.*

Location	Energy Density (J/cm^2)	Chi-Square	P-value	α	β
Sternum	32.88	1.820	0.177	−1.907	0.058
On Anterior Rib	23.99	16.636	0.000‡	−126.513	5.274
Between Anterior Rib	33.30	3.563	0.059	−2.731	0.082
Liver	39.88	2.885	0.089	−3.789	0.095
Lateral to Umbilicus	34.34	2.842	0.092	−3.424	0.098
Proximal Femur	26.13	9.747	0.002‡	−5.147	0.197
Distal Femur	28.13	8.397	0.004‡	−4.895	0.174
Scapula	50.60	5.336	0.021†	−5.262	0.104
On Posterior Rib	52.74	10.964	0.001‡	−10.021	0.190
Lower back	38.13	7.746	0.005‡	−4.004	0.105

‡ $p < 0.01$ † $p < 0.05$.

the average energy density required for penetration varied by region. The region with the lowest average energy density for all penetrating impacts was the area between two ribs with a value of 33.14 J/cm^2. The posterior rib had the highest average energy density of 55.90 J/cm^2 for all penetrating events.

Based on the logistic regression results, the 50% risk of penetration was calculated for each region. Figure 6 provides an example of the resulting logistic regression curve for the proximal femur. As seen in Table 4, each body region had a specific energy density (J/cm^2) required to produce a 50% risk of penetration. Statistical significance was obtained for all regions of the body except the sternum, between the anterior ribs, the liver and lateral to the umbilicus. This was mainly due to an inability to perform impacts to the regions for all specimens due to surgical histories and existing pre-mortem pathologies. Even though significance was not achieved, the data indicate a trend towards significance.

As demonstrated by the data, the energy density required for 50% risk of penetration varied from 23.99 J/cm^2 for the location on the anterior rib to 52.74 J/cm^2 for the location on the posterior rib. The large differences between the anterior and posterior rib locations are likely due to the comparative muscle and contours of the rib in

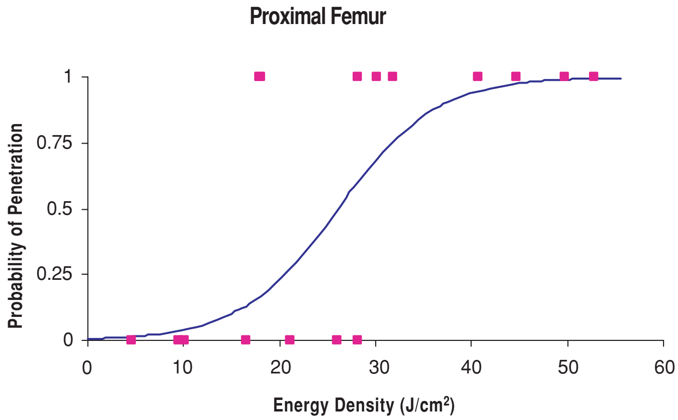


FIG. 6—*Logistic regression curve of impacts to proximal femur demonstrating a 50% risk at 26.13 J/cm^2.*

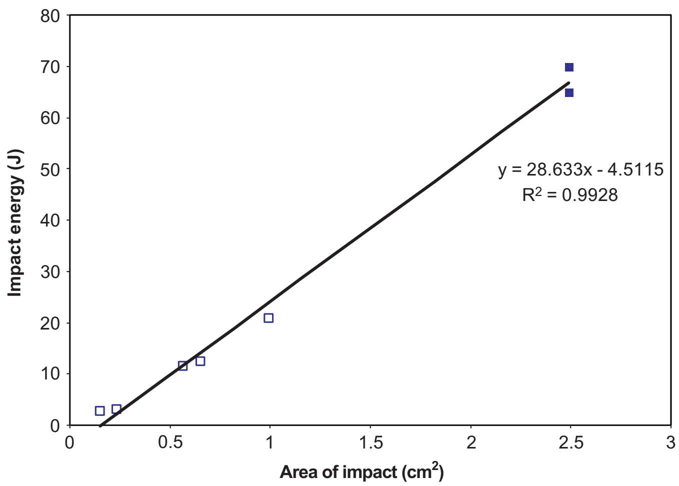


FIG. 7—*Correlation between current (■) and existing (□) data for impacts to the thigh.*

the respective areas. In addition, the average skin thickness of the anterior skin overlying the ribs was found to be 0.0161 cm whereas the skin of the posterior torso located over the rib had a significantly higher thickness of 0.0255 cm.

Discussion

The current effort represents a comprehensive analysis of the risk of penetration of 12-gauge kinetic energy munitions for all regions of the body. Previous studies focused only on one region of the body and concentrated on a different range of impact conditions. These data provide guidance for the development of surrogates for the assessment of currently existing and newly developed impact munitions prior to deployment in the field. In addition, these data can provide critical information into the energy required to penetrate in a given region of the body.

The current dataset compares well with previous data when the specific body region is analyzed. Figure 7 represents impacts to the thigh for both the existing (□) and current data (■). As indicated in the figure, the current data have a high correlation with the data previously reported by DiMaio (1981, 1982), Mattoo (1974) and Journée (1907) for impacts in the same location ($R^2 = .99$). However, it should be noted that the inclusion of varying impact regions does not produce a significant correlation with the previously reported data. This is likely due to the specific structural differences between each region of the body tested. It is suggested that individual models should be developed to represent the various impact locations.

There are obvious limitations to the current study. The lack of muscle tone and soft tissue changes that occur post-mortem can alter the response. In an effort to minimize soft tissue changes, the specimens were tested fresh and were stored in a cooler prior to testing. The age of the specimen is also a factor since the visco-elastic properties of the soft tissue change with age. However, the use of older postmortem human specimens provides a conservative estimate of the human body response. In addition, the impact is relatively short in duration compared to normal tissue constraints. Therefore, it is unlikely that changes in visco-elastic properties would significantly alter the results.

The current study fills a void in the ability to determine the likelihood of penetration related to larger impact areas and higher impact velocities than previously reported. Although a correlation with the previously reported data for the thigh region, other regions have a unique tolerance level. Therefore, individual models should be developed and employed for each specific region.

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References

1. Charles A, Asensio J, Forno W, Petrone P, Roldan G, Scott RP. Penetrating bean bag injury: intrathoracic complication of a nonlethal weapon. J Trauma 2002;53(5):997–1000. [PubMed]
2. Grange JT, Kozak R, Gonzalez J. Penetrating injury from a less-lethal bean bag gun. J Trauma 2002;52(3):576–8. [PubMed]
3. Wawro PA, Hardy WR. Penetration of the chest by less-than-lethal "beanbag" shotgun rounds. J Trauma 2002;52(4):767–8. [PubMed]
4. DiMaio VJM. Penetration and perforation of skin by bullets and missiles. A review of the literature. Am J Forensic Med Pathol 1981;2(2):107–10.
5. DiMaio VJM, Copeland AR, Besant-Matthews PE, Fletcher LA, Jones A. Minimal velocities necessary for perforation of skin by air gun pellets and bullets. J Forensic Sci 1982;27(4):894–8. [PubMed]
6. Mattoo BN, Wani AK, Asgekar MD. Casualty criteria for wounds from firearms with special reference to shot penetration II. J Forensic Sci1974;19(3):585–9. [PubMed]
7. King AI, Viano DC, Mizeres N, States JD. Humanitarian benefits of cadaver research on injury prevention. J Trauma 1995;38(4):564–9. [PubMed]
8. Committe on Injury Prevention and Control, Institute of Medicine. Reducing the burden of injury: advancing prevention and treatment. Washington, DC: National Academy Press, 1999.

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