REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)* 30-11-2012	**2. REPORT TYPE** Research Report	**3. DATES COVERED** *(From - To)* 05-01-2011 to 30-11-2012

4. TITLE AND SUBTITLE

Physical Mechanisms of Soft Tissue Injury from Penetrating Ballistic Impact

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

Amy Courtney and Michael Courtney

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

DFRL
U.S. Air Force Academy
2354 Fairchild Drive
USAF Academy, CO 80840

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT

Distribution A. Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

Most civilian nonfatal gunshot injuries and murders involve handguns. Gunshot wounds are often classified as being due to high-velocity or low-velocity projectiles, e.g. rifle or handgun rounds. However, this is a historical distinction, and there is overlap in energy that can be delivered to tissue by modern rifle and handgun rounds. Also, the same diameter (caliber) bullet can have different impact energies depending on the firearm used. A clearer, physical basis for understanding wounding potential is needed. All bullets lose energy as they travel through tissue, and the local rate of energy loss determines the magnitude of the forces and thus the extent of wounding. The ways the local forces between the bullet and tissue cause injury are often described as 1) permanent cavitation (the hole left after tissue is damaged due to the intense stress field close to the bullet path), 2) temporary cavitation (tissue stretching out of the way due to large retarding forces for a few milliseconds until snapping back into place due to elasticity) and 3) remote injury effects beyond the reach of the temporary cavity due to propagation of a ballistic pressure wave. Regardless of impact energy, if the retarding force is comparable for a given bullet path, the wound will be comparable. Use of the imprecise terms 'high-velocity' and 'low-velocity' impacts, lack of appreciation for the relationship between change in kinetic energy and forces between a bullet and tissue . . .

15. SUBJECT TERMS

Wound ballistics, permanent cavity, retarding force, temporary cavity, ballistic pressure wave

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON** Michael Courtney
a. REPORT **unclassified**	**b. ABSTRACT** **unclassified**	**c. THIS PAGE** **unclassified**	Same as Report (SAR)	9	**19b. TELEPHONE NUMBER** *(include area code)* 719-333-8113

Physical Mechanisms of Soft Tissue Injury from Penetrating Ballistic Impact

Amy Courtney, Ph.D.,[1] Michael Courtney, Ph.D.[2]
[1]BTG Research, PO Box 62541 Colorado Springs, CO 80920 amy_courtney@post.harvard.edu
[2] U.S. Air Force Academy, 2354 Fairchild Drive, USAF Academy, CO 80840 michael.courtney@usafa.edu

ABSTRACT

Most civilian nonfatal gunshot injuries and murders involve handguns. Gunshot wounds are often classified as being due to high-velocity or low-velocity projectiles, e.g. rifle or handgun rounds. However, this is a historical distinction, and there is overlap in energy that can be delivered to tissue by modern rifle and handgun rounds. Also, the same diameter (caliber) bullet can have different impact energies depending on the firearm used. A clearer, physical basis for understanding wounding potential is needed. All bullets lose energy as they travel through tissue, and the local rate of energy loss determines the magnitude of the forces and thus the extent of wounding. The ways the local forces between the bullet and tissue cause injury are often described as 1) permanent cavitation (the hole left after tissue is damaged due to the intense stress field close to the bullet path), 2) temporary cavitation (tissue stretching out of the way due to large retarding forces for a few milliseconds until snapping back into place due to elasticity) and 3) remote injury effects beyond the reach of the temporary cavity due to propagation of a ballistic pressure wave. Regardless of impact energy, if the retarding force is comparable for a given bullet path, the wound will be comparable. Use of the imprecise terms 'high-velocity' and 'low-velocity' impacts, lack of appreciation for the relationship between change in kinetic energy and forces between a bullet and tissue, and inconsistent explanations of the ballistic pressure wave in the literature have hindered a more general understanding of gunshot injury ballistics. Because of variations in energy actually lost as a bullet penetrates and variations in the anatomical location of the penetration, ballistic information can be a valuable guide for the surgeon but does not substitute for careful assessment of the wound.

Introduction

In the United States in 2008, about 68,500 nonfatal civilian injuries and 29,700 murders resulted from gunshots. At least 75% of these involved a handgun (rather than a rifle or shotgun) [42]. Figure 1 shows that half of the nonfatal gunshot injuries in 2008 in the United States were to an extremity. 90% of injuries occurred in males and about 75% of patients were between the ages of 15 and 34. These characteristics are similar across national boundaries, though incidence rates vary widely (e.g., West Africa [37], Ireland [32], Australia [9], Brazil [34], Finland [30]).

There are notable exceptions in which the characteristics of civilian gunshot injuries and deaths differ from the above statistics. In elderly populations, for example, it is far more likely for a gunshot injury to be intentionally self-inflicted, cranial, and fatal [28]. In situations of civil unrest, the characteristics can be similar to military gunshot injuries, though they are suffered by civilians [45].

In 2003, Bartlett [1] provided an extensive review of wound ballistics literature from the clinical and scientific perspectives, summarizing major issues, findings, and areas of clinical consensus and debate. A recent update of Ryan's Ballistic Trauma: A Practical Guide [5] expands on the basic operation of various categories of ballistic weapons and organizes current treatment approaches by anatomical region. The purpose of this article is to present an orderly approach to understanding how forces caused by bullet penetration of soft tissue determine the extent of injury.

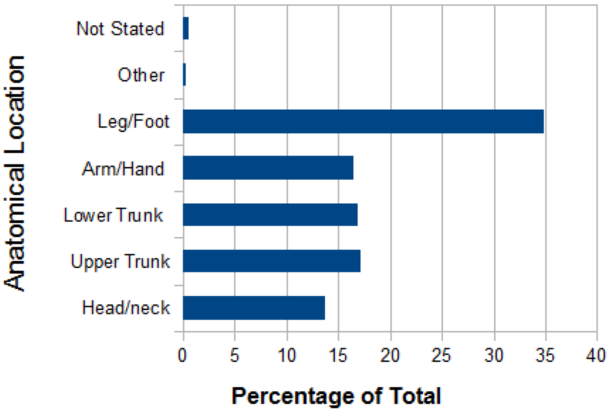


Figure 1 The anatomical distribution of nonfatal firearm injuries is shown for the United States in 2008. This distribution is typical for civilian populations. (Data from the Firearm Injury Surveillance Study, 2011 [42].)

Any part of the body can be injured by a penetrating projectile, though statistically half of gunshot injuries occur to the extremities. Bone fractures caused by gunshots may be plainly visible or easily visualized by x-ray or CT imaging. They range from penetration holes of similar diameter to the projectile to severely comminuted fractures if the impact energy is large and the projectile loses a lot of energy as it penetrates the hard bone [19-21]. Expansion of the temporary wound cavity or a ballistic pressure wave can also cause bone fractures without direct penetration if the forces are high enough [10, 13, 24, 31]. Statistically, while gunshot wounds to the extremities are far less lethal than cerebral or thoracic gunshot wounds, some studies have reported an incidence of bone fracture greater than 50% in extremity gunshot wounds [7] and complication rates of 30% or more. Soft tissue wounding caused by gunshots can be more difficult to assess because the permanent wound tract and extent of the wounding may not be visible by external examination, x-ray or CT imaging. The last part of a wound tract can be very difficult to identify over distances where the bullet penetrates with very little energy left, because the fluid pressure of the tissue surrounding the wound tract causes it to collapse.

With the large variety of firearms and ammunition, it is impractical to impart an understanding of wound ballistics by cataloging the terminal behavior of each combination. Such an attempt would be lacking information as soon as it was published because of new products, and the inclusion of possible intermediate barriers (clothing, walls, automobile glass or doors) would add another layer of complexity. While such studies are useful, it is also important to have an understanding of wound ballistics based on sound physical principles that can be applied to predict or understand individual cases.

Wounding Potential

For diagnosis and treatment purposes, a distinction is sometimes made between high-velocity (usually meaning rifle) and low-velocity (usually meaning handgun) projectiles, but these terms are imprecise and therefore confusing. Mathematically, the kinetic energy of an object is computed as $\frac{1}{2} mv^2$, where m is the mass of the object and v is its velocity. Modern cartridges can be manufactured or custom-loaded to produce a nearly continuous range of energies, bounded by the minimum pressure required to push the bullet out of the barrel and the maximum internal pressure a given firearm can support. The ranges of projectile energies that can be produced by handguns and rifles thus overlap. Moreover, bullets of the same diameter can have different impact energies. For example, a "22 caliber" bullet (5.56 mm diameter) could have been fired from a "Saturday Night Special", a 5.7 x 28 mm rifle or a 5.56 mm NATO rifle. These start with different impact energies and lose different amounts of energy as they penetrate, resulting in significant differences in forces on the tissue and wound profiles.

An influential wound ballistics review paper states, "'Kinetic energy' … reveals nothing about the magnitude, type and location of tissue disruption … The force interactions between penetrating projectile and tissue remain hidden behind the abstract 'kinetic energy' discussions" [16]. Similar statements have been made for years [15]. However, the force between the projectile and the tissue *is* the local rate of change of kinetic energy at a given penetration depth. The equivalence between the two is described by a physics equation called the work-energy theorem. Force and local rate of change of kinetic energy are two ways of expressing the same physical phenomenon, and there is a need for clarity on this point.

All bullets lose energy as they travel through tissue, and the quantity of energy lost is equal to the work done on the tissue – this work is determined by forces acting over some distance. The local rate of energy loss as the bullet penetrates equals the force at each point. The magnitudes of the forces on the tissue determine the extent of tissue damage. The equal and opposite force of the tissue on the bullet is referred to as the *retarding force* and is what slows the bullet as it penetrates. Regardless of the factors that influence impact energy, if the retarding force is comparable, wounding will be comparable for a given bullet path.

The retarding forces cannot be described by the impact energy alone, though they are bounded by the impact energy. The area under a graph of force vs. penetration depth equals the total amount of energy lost by the bullet as it penetrates. Note that the SI unit of energy, the Joule, is equal to one Newton (force) times one meter (distance), that is, one Newton-meter (Nm). The total amount of energy lost cannot be greater than the impact energy but will be less if the bullet exits the tissue with some residual energy. If the force a bullet applied as it penetrated tissue were constant, a bullet impacting with 500 J of energy could potentially exert a force of 2000 N (about 450 lb) at each point for a penetration depth of 25 cm. However, the actual dynamics as a bullet penetrates often involves some combination of expansion, tumbling, fragmenting, and slowing, so the force between a penetrating bullet and tissue usually changes with the depth the bullet has penetrated, as shown in Figure 2.

At any point, the instantaneous force between bullet and tissue is equal to the bullet's local rate of energy loss. This is an application of calculus to the work-energy theorem. As an equation, $F = dE/dx$, where F is the force at a given penetration depth x, and E is the bullet's kinetic energy at that depth. For example, if a bullet impacts with 500 J of energy (which is mid-range for a pistol bullet) but loses 100 J of energy over a certain 2 cm of penetration, the average force over that 2 cm of penetration is 100 J/0.02 m = 5000 N (about 1125 lb).

With the same impact energy, different bullet designs can lose their energy with different force vs. penetration depth profiles. For example, a bullet with an expanding tip (such as a hollow point bullet) presents an increasing cross-sectional area as it penetrates and so loses energy faster, which results in a higher peak retarding force between the bullet and tissue. The specific bullet tip design and material govern whether and how a bullet expands as it penetrates tissue. Similarly, a bullet that yaws (the tip turns away from the direction of forward motion) loses more energy as it penetrates because it effectively has a larger cross-sectional area. In contrast, a non-expanding bullet tends to have both a lower rate of energy loss and less variation in the rate of energy loss over the penetration depth. If the bullet does not exit the tissue, the total area under the force-penetration depth curve will be the same for a given impact energy, but the shape of the curve (such as the magnitude and location of the peak forces) will vary between different bullets.

For Figure 2, an experiment was performed to illustrate the different wounding potentials of bullets with the same caliber (9 mm NATO). The four bullets shown were selected because they are popular, commonly used bullets shot from the same cartridge and representative of the range of performance. Details are given in Table 1. High speed video data (20,000 frames per second) was obtained and analyzed for each type of bullet shot into 10% ballistic gelatin. Each part of Figure 2 shows results of an actual, representative trial.

Ballistic gelatin is an isotropic medium intended to simulate soft tissue. Therefore the wound profiles shown, though actual, are somewhat idealized compared to what would happen if the path of the projectile were near to or strikes a bone. Bone impact results in a rapid loss of energy, high forces, and possible fragmenting of the projectile as well as of the bone itself.

The 124 grain[1] full metal jacket (FMJ) projectile (Fig. 2A) exerts relatively low forces on the tissue because it has a lower rate of energy loss in the tissue. It does not have an expanding tip, nor is it designed to fragment. The oscillations in force and wound profile are due to tumbling of the bullet as it penetrates – where the bullet has a larger effective cross-sectional area at a given velocity, the forces are higher and the wound profile larger.

The 127 grain Winchester Ranger SXT is also a 9mm NATO round; however, it has a higher impact energy and the tip expands quickly, so that energy is lost quickly as the bullet penetrates (Fig. 2B). This results in very high forces on the tissue at shallow penetration depths. The result is a much larger wound profile than for the FMJ round (a mathematically rigorous explanation of why this is the case is presented by Peters [33]).

The 147 grain Winchester Ranger SXT (Fig. 2C) has similar physical characteristics but lower impact energy compared to the 127 grain Ranger; so while the shapes of the force-penetration curve and wound profile are similar, they are smaller for the 147 grain Ranger.

The 147 grain Winchester Jacketed Hollow Point (known colloquially as Winchester White Box, or WWB) has the same mass as the 147 grain Ranger but a smaller retarding force due to the slow expansion of the tip. The peak retarding force and the peak diameter of the temporary cavity for this bullet (Fig. 2D) is similar to that for the 124 grain FMJ (Fig. 2A). (Historical note: for a time, this bullet was promoted by the U.S. Federal Bureau of Investigation in a sub-sonic load for law enforcement purposes.)

The results show that bullets of the same caliber can have very different wounding potentials based on penetration into 10% ballistic gelatin. Sometimes bullets pass through intermediate barriers such as heavy clothing, wood, metal, wallboard or auto glass before penetrating tissue. In such situations, the bullet tip can be altered, changing its penetration and energy loss characteristics in tissue [44]. Sometimes these changes may be unexpected. For example, when the 127 grain Winchester Ranger SXT (Fig. 2B) passes through steel, its penetration depth in gelatin *increases* from about 36 cm to 43 cm. Its tip is compressed as it passes through the steel so that it does not expand much in the gelatin and does not lose as much energy as quickly. In this example, the force-penetration profile (and resulting wounding) will look more like that of a 9mm FMJ (Fig. 2A) that has not passed through an intermediate barrier.

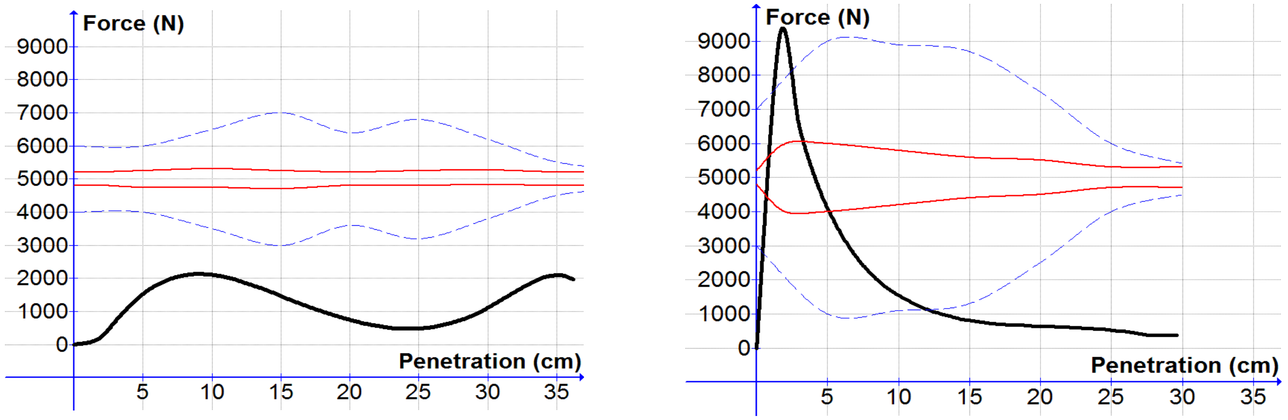
---

[1] For historical reasons, bullet names that include the weight specify the weight in grains. One grain is approximately equal to 0.065 grams.

***Table 1.** Characteristics of four, 9mm NATO projectiles tested in 10% ballistic gelatin.*

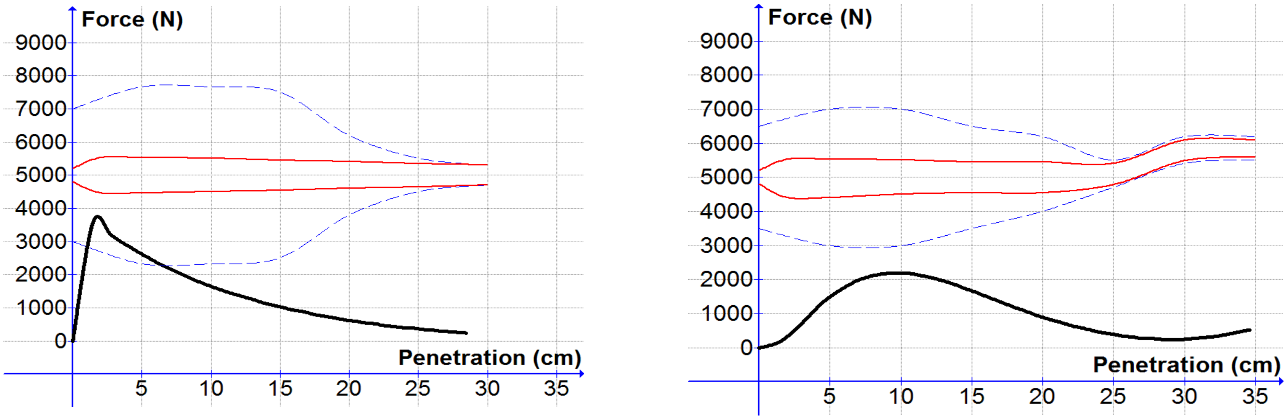
Caliber	Projectile	Mass (g)	Impact Velocity (m/s)	Impact Energy (J)	Notes
9 mm NATO	124 grain Full Metal Jacket (FMJ)	8.04	352	498	non-expanding
9 mm NATO	127 grain Winchester Ranger SXT	8.23	376	582	rapid-expanding
9 mm NATO	147 grain Winchester Ranger SXT	9.53	293	409	rapid-expanding
9 mm NATO	147 grain Winchester Jacketed Hollow Point*	9.53	290	401	slow-expanding

**commonly known as Winchester White Box (WWB)*



(A) 124 grain Winchester Full Metal Jacket (FMJ)

(B) 127 grain Winchester Ranger SXT



(C) 147 grain Winchester Ranger SXT

(D) 147 grain Winchester Jacketed Hollow Point (JHP)

***Figure 2A-D:** Wound profiles are shown for four 9mm diameter NATO bullets, (A) 124 grain Full Metal Jacket (FMJ), (B) 127 grain Winchester Ranger SXT, (C) 147 grain Winchester Ranger SXT, and (D) 147 grain Winchester Jacketed Hollow Point (JHP). Data are from analysis of high speed video (20,000 fps) of penetration in 10% ballistic gelatin. The thick, solid curve is the force (N) vs. penetration depth (cm, labeled on the axes). The outer, dashed curve of each profile shows the extent of temporary cavitation, and the inner curve depicts the permanent cavity.*

Though many factors contribute to a specific wound profile, the mechanism of wounding is the force applied to the tissue. Wounding as it relates to the retarding force profile is often categorized as being the result of 1) permanent cavitation (the hole left after tissue is damaged due to the intense stress field close to the bullet path), 2) temporary cavitation (tissue stretching out of the way due to large retarding forces for a few milliseconds until snapping back into place due to elasticity) and 3) remote injury effects beyond the reach of the temporary cavity due to propagation of a ballistic pressure wave [2]. One common paradigm bases wounding potential only on the sizes of the permanent and temporary (or stretch) cavities, and it downplays the wounding potential of the temporary cavity [15]. Casual use of the terms 'high-velocity' and 'low-velocity' impacts, lack of appreciation for the relationship between rate of kinetic energy loss and the forces between a bullet and tissue, along with imprecise explanations of the ballistic pressure wave have hindered a more general understanding of wound ballistics.

1. Permanent cavitation

The permanent cavity, or wound tract, is the tract of tissue directly damaged by the local forces generated as the projectile loses energy. It may be unexpected that the permanent cavity is not shaped like a cylinder (Fig. 2). It tends to be larger where the retarding forces are higher and to taper once the bullet has slowed.

In elastic tissues such as lungs and muscle, where the tissue tends to spring back into place with little damage from temporary stretch, most tissue damage is caused from the intense field of compressive and shear stress within a few centimeters of the bullet path. This intense stress field propagates outward from the retarding force between the bullet and tissue, but falls off quickly with distance. Consequently, the permanent cavity tends to be the largest at penetration depths where the retarding force between bullet and tissue is the greatest. Fragments that create small holes as they penetrate a short distance from the main bullet can also contribute to the permanent wound.

C.E. Peters [33] described the damage due to the localized stress field in the immediate vicinity of the passing bullet as “prompt damage” because it happens so quickly (microseconds). This damage occurs even before the tissue is stretched by temporary cavitation and it has been observed in careful experiments where the temporary cavity is suppressed by the experimental design.

In the Textbook of Military Medicine, Bellamy and Zajtchuk [2] reported that the mass of tissue damaged at a certain penetration depth correlates with the local rate of energy loss of the projectile at that depth. The total tissue destroyed also correlates with projectile energy loss. For example, experiments show between 0.24 and 0.5 grams of muscle tissue destroyed for each Joule of energy lost by a penetrating 7.62 mm diameter [30 caliber] projectile. In contrast, for a full metal jacket projectile that loses little of its kinetic energy as it penetrates soft tissue, the temporary cavity may collapse onto the permanent cavity in such a way as to obscure the bullet path.

2. Temporary cavitation

The force of the bullet on the tissue rapidly accelerates tissue radially away from the bullet path, forming a temporary cavity. After the temporary cavity forms, tissue elasticity and fluid pressure cause tissue to return into the empty volume. The temporary cavity has a maximum diameter near (but not exactly at) the penetration depth where the retarding force is a maximum [33], but its formation lags in time behind the passage of the bullet. Describing the temporary cavity in terms of its diameter has the potential to be misleading, because the temporary cavity is three-dimensional. For example, a temporary cavity that is twice the diameter of another occupies a volume that is four times larger.

The potential for temporary cavitation to cause wound trauma is related to the anatomical location of the bullet path, the degree of bullet fragmentation (if any) and the size of the temporary cavity, usually expressed in a maximum diameter or volume. Some have posited that the temporary stretch cavity causes little wounding unless it includes inelastic tissue. Indeed, less elastic tissues such as liver, kidney, and neural tissue can be seriously damaged by temporary stretch, even in the absence of fragmentation [2]. However, in a study comparing penetrating thoracic wounds caused by stab injuries to those caused by gunshot injuries, the occurrence of lung contusions around the trajectory was 43% for gunshot injuries but only 2% for stab injuries (which do not include a temporary cavitation component) [29], suggesting that the sudden expansion of the temporary cavity and/or its collapse can injure even elastic tissues. In addition, as tissue stretches in the bullet wake due to temporary cavitation, small holes created by fragments are areas of stress concentration where additional permanent tears in tissue originate as tissue rapidly stretches.

In fact, wounding associated with the temporary cavity can be discrete, some distance from the permanent cavity, and might otherwise appear illogical. For example, peripheral nerves can lose function after being stretched by the temporary cavity while muscle immediately surrounding the nerve may escape injury due to its elasticity [6]. Spinal trauma can result if the temporary cavity impacts the spine [22]. If the bullet path is sufficiently close to a bone, the bone can be broken by the impact of the temporary cavity [13, 24]. Similar injuries associated with temporary cavitation have been described at least since World War II:

For instance, fractures occur at some distance from the missile tract without any direct contact between the bone and the missile. Forces may be transmitted through the essentially incompressible blood and rupture a vein some distance from the missile's path. Nerves may be paralyzed yet fail to show gross evidence of physical damage. In some wounds in muscle, splitting along fascial planes will be noted for a considerable distance from the path of the bullet. Fluid filled viscera are often blown asunder by the operation of hydraulic forces. [3, pp. 135-136].

The extent of wounding described above occurs more often with injuries from rifle shots, though as mentioned earlier, a subset of handgun loads also lose large amounts of energy in short penetration distances, and the resulting large forces can create similar injuries. In addition to these effects, the temporary cavity creates a region of extravasation of hemorrhagic tissue. Though somewhat smaller than the full extent of the temporary cavity, observation of this zone of extravasation suggests to the surgeon that there may be blood vessel or nerve damage for a few centimeters beyond the bullet path [3, p. 136].

The average volumes of the permanent cavity, zone of extravasation, and temporary cavity have been found to increase linearly with the local rate of energy loss, or the force applied over the penetration depth, as the bullet passes through tissue. It has been estimated that the average volume of the permanent cavity is 0.030784 cubic centimeters for each Joule (Nm) of mechanical work, and the volume of the temporary cavity is 0.800693 cubic centimeters for each Joule (Nm) of mechanical work done by the bullet passing through tissue [converted from 3, pp. 140-141].

3. Ballistic pressure wave

Pressure waves imparted by the retarding forces between bullet and tissue both radiate outward from the bullet path and propagate from the impact location [11, 25]. Experiments in live animal models have used high-speed pressure transducers to detect these remote ballistic pressure waves in the abdomen, neck, brain, and contralateral thigh of pigs shot in the thigh [39, 40]. Ballistic pressure waves can cause vascular and visceral injuries and indirect bone fractures [27]. Even in the absence of major musculoskeletal effects, remote neural effects have been documented in the lungs [2], spinal cord [38, 39] and brain both in animal experiments [39, 43] and human case studies [23].

Pressure is simply defined as force per unit area. This means that the pressure on the front of a bullet is the force divided by the frontal area of the bullet. Because the frontal area of a bullet is small, the pressure at the front of the bullet is large. Once created, this large pressure front travels outward from its source in all directions in a viscous or viscoelastic medium. As the wave propagates outward, the decrease in peak pressure is dominated by the increasing total area the pressure wave covers.

Behind-armor trauma illustrates the independent wounding potential of a ballistic pressure wave because there is no penetration. Thus there is neither a permanent cavity nor a temporary cavity. When a protective vest stops a bullet, all of the bullet's impact energy is transferred to the armor. The resulting force accelerates the chest wall, propagating a pressure wave that will be reflected many times by the walls of the chest cavity. Carroll [8] documented the wounding potential of pistol bullets striking soft body armor, noting that "the severity of underlying injury may not correlate with the seemingly innocent skin lesions." Superposition of reflected waves can result in localized regions of high pressure by focusing the wave, just as a concave mirror can focus a light wave. Focal lesions can result in various places within the thoracic cavity. Ballistic pressure waves have also been implicated in focal, delayed perforation of intestines without direct penetration following abdominal gunshot wounds [2, pp. 149-152; 41] This type of wounding can be life-threatening in itself when armor stops rounds such as the 150 grain 7.62 x 51 mm NATO [14,17,18].

Discussion and Summary

This article presents a physical description of how forces caused by penetration of ballistic projectiles injure tissue. The factors that contribute to the extent and distribution of wounding have been presented. For a given caliber, the bullet design has a strong influence on the force vs. penetration depth profile. Projectiles that lose more energy as they penetrate (by expanding or tumbling, for example) introduce the possibility of remote wounding via a larger temporary cavity and propagation of a ballistic pressure wave, resulting in more extensive soft tissue injury than the entrance wound might first suggest.

Projectiles that pass through soft tissue and exit with residual velocity lose less energy during penetration and cause less wounding. In addition, for a given bullet caliber and design, passing through an intermediate barrier can change the bullet shape and velocity, altering its terminal ballistics [44].

In the most general terms, wounding will likely be limited to a short distance beyond the permanent cavity if the projectile lost a relatively small amount of energy as it penetrated. This may be because the projectile had relatively low impact energy, because it did not expand quickly to sharply increase local forces, and/or because it penetrated through-and-through without losing a lot of energy. In contrast, high impact energy, an expanded projectile, or a projectile stopped in tissue suggest the possibility of more extensive wounding.

The basic approach to treatment of non-lethal penetrating ballistic injuries in civilians is based on years of consensus as well as clinical data: irrigate the wound thoroughly, treat the patient with antibiotics prophylactically or at signs of infection, and delay closure of the wound [1, 26]. This general therapeutic approach assumes that most non-lethal gunshot injuries are "low velocity" and that wounding does not extend far beyond the permanent tract. Incidence of infection with this approach when only soft-tissue injury is present is 3-5% in most studies and somewhat higher in non-hospitalized patients with suboptimal wound care [e.g., 35]. If bone fractures caused by ballistic penetration are unstable, they are treated more aggressively, as if they were high energy, open fractures. These are associated with a high rate of complications but lower lethality than cranial or thoracic gunshot injuries [7].

Other aspects of medical treatment of gunshot injuries remain topics of debate, such as the optimal extent of wound debridement and criteria for imaging and surgical intervention. A prevalent view is that surgery is indicated if there is vascular or nerve damage, unstable fractures or intra-articular injuries, or significant soft-tissue injury (such as may require extensive debridement or skin grafting) [1, 7, 12]. In these cases, multiple surgeries are sometimes indicated because the true extent of tissue damage is not recognized, and the fact that additional tissue is nonviable and should be debrided becomes apparent over time. The data and discussion presented above help to explain why this can be the case.

Quantitative measures of the physical mechanisms of soft tissue injury are highly correlated with rapid incapacitation [11, 45, 46]. Rapid incapacitation is necessary for stopping determined attackers in law enforcement applications and for accomplishing objectives in military encounters [46, 47]. The physical parameters most strongly correlated with rapid incapacitation are peak retarding force, temporary cavity volume, peak ballistic pressure wave, and energy transfer [45, 46]. Consequently, 9mm NATO loads like the 127 grain Winchester Ranger (Figure 2B) will incapacitate a target faster, on average, than loads like the 124 grain FMJ (Figure 2A) or the 147 grain Winchester JHP (Figure 2D), which have much smaller peak retarding force and much smaller temporary cavity volume. It should be no surprise that loads which produce greater soft tissue damage perform better from the standpoint of military and law enforcement applications, because increased soft tissue damage is necessary for the intended purposes.

References

1. Bartlett CS. Clinical update: gunshot wound ballistics. *Clin Orthop Relat Res*. 2003; 408:28-57.

2. Bellamy RF, Zajtchuk R. The physics and biophysics of wound ballistics. [ed.] Zajtchuk R. *Textbook of Military Medicine, Part I: Warfare, Weaponry, and the Casualty, Vol. 5.* Washington, D.C.: Office of the Surgeon General, Department of the Army, 1990.

3. Beyer JC, ed. *Wound Ballistics in World War II.* Medical Department, United States Army. Washington, D.C. : Office of the Surgeon General, Department of the Army, 1962. Available at: http://www.dtic.mil/cgi-bin/GetTRDoc?AD=ADA291697&Location=U2&doc=GetTRDoc.pdf . Accessed July 15, 2012.

4. Bowyer GW, Rossiter ND. Management of gunshot wounds of the limbs. *J Bone Joint Surg Am.* 1997; 79-B(6):1031-1036.

5. Brooks AJ, Clasper J, Midwinter M, Hodgetts TJ, Mahoney PF, eds. Ryan's Ballistic Trauma: A Practical Guide. Springer, 2011.

6. Bryant MD, Robinson PR. Peripheral Nerve Injuries. *Rehabilitation of the Injured Combatant.* Washington D.C.: Office of the Surgeon General, Department of the Army, 1999;9:419-574.

7. Burg A, Nachum G, Salai M, Haviv B, Heller S, Velkes S, Dudkiewicz I. Treating civilian gunshot wounds to the extremities in a Level 1 trauma center: our experience and recommendations. *Isr Med Assoc J.* 2009; 11:546-551.

8. Carroll AW, Soderstrom CA. A new nonpenetrating ballistic injury. *Annals of Surgery* 1978; 188(6):753-757.

9. Chambers AJ, Lord RS. Management of gunshot wounds at a Sydney teaching hospital. *ANZ J Surg.* 2000;70(3):209-215.

10. Cooper GJ, Ryan JM. Interaction of penetrating missiles with tissues: Some common misapprehensions and implications for wound management. *Br J Surg.* 1990; 77(6):606-610.

11. Courtney AC, Courtney MW. Links between traumatic brain injury and ballistic pressure waves originating in the thoracic cavity and extremities. *Brain Inj.* 2007; 21:657-662.

12. Dougherty PJ, Najibi S, Silverton C, Vaidya R. Gunshot wounds: epidemiology, wound ballistics, and soft tissue treatment. *Instr Course Lect.* 2009; 58:131-139.

13. Dougherty PJ, Sherman D, Dau N, Bir C. Ballistic fractures: indirect fracture to bone. *J Trauma.* 2011; 71(5):1381-1384.

14. Drobin D, Gryth D, Persson JK, Rocksen D, Arborelius UP, Olsson LG, Bursell J, Kjellstrom BT. Electroencephalogram, circulation and lung function after high-velocity behind armor blunt trauma. *J Trauma.* 2007; 63(2):405-413.

15. Fackler ML. Wound ballistics: a review of common misconceptions. *JAMA.* 1988; 259(18):2730-2736.

16. Fackler ML. Gunshot wound review. *Ann Emerg Med.* 1996; 28(2):194-203.

17. Gryth D, Rocksen D, Arborelius UP, Drobin D, Persson JK, Sonden A, Bursell J, Olsson LG, Kjellstrom BT. Bilateral vagotomy inhibits apnea and attenuates other physiological responses after blunt chest trauma. *J Trauma.* 2008; 64(6):1420-1426.

18. Gryth D, Rocksen D, Persson JK, Arborelius UP, Drobin D, Bursell J, Olsson LG, Kjellstrom BT. Severe lung contusion and death after high velocity behind-armor blunt trauma: relation to protection level. *Mil Med.* 2007; 172(10):1110-1116.

19. Huelke DF, Buege LJ, Harger JH. Bone fractures produced by high velocity impacts. *Am J Anat.* 1967; 120:123-132.

20. Huelke DF, Harger JH, Buege LJ, Dingman HG, Harger DR. An experimental study in bio-ballistics: femoral fractures produced by projectiles. *J Biomech.* 1968; 1:97-105.

21. Huelke DF, Harger JH, Buege LJ, Dingman HG. An experimental study in bio-ballistics: femoral fractures produced by projectiles – II Shaft impacts. *J Biomech.* 1968; 1:313-321.

22. Klack F, Tassin C, Cotton F, Luaute J, Gauthier J, David JS. Gunshot injury without direct injury to the cord may lead to complete paraplegia. *Eur J Trauma Emerg Surg.* 2011; 37:49-51.

23. Krajsa J. Příčiny vzniku perikapilárních hemoragií v mozku při střelných poraněních (Causes of pericapillar brain haemorrhages accompanying gunshot wounds). Brno: Institute of Forensic Medicine, Faculty of Medicine, Masaryk University, 2009. http://is.muni.cz/th/132384/lf_d/Autoreferat.pdf Accessed September 20, 2012.

24. Krauss M, Miller JF. Studies in Wound Ballistics: Temporary Cavities and Permanent Tracts Produced by High-Velocity Projectiles in Gelatin. Chemical Warfare Laboratories, U.S. Army. Washington, D.C.: Defense Technology Information Center, 1960; AD233840. Available at: http://www.dtic.mil/cgi-bin/GetTRDoc?AD=AD233840&Location=U2&doc=GetTRDoc.pdf . Accessed July 12, 2012.

25. Lee M, Longoria RG, Wilson DE. Ballistic waves in high-speed water entry. *J Fluids Struct.* 1997; 11:819-844.

26. Lichte P, Oberbeck R, Binnebosel M, Wildenauer R, Hans-Christoph P, Kobb P. A civilian perspective on ballistic trauma and gunshot injuries. *Scand J Trauma Resusc Emerg Med.* 2010; 18:35.

27. Liu Y, Chen Y, Li S. Mechanism and characteristics of the remote effects of projectiles. *J Trauma (China) Supp.* 1990; 6:16-20.

28. Lustenberger T, Inaba K, Schnuriger B, Barmparas G, Eberle BM, Lam L, Talving P, Demetriades D. Gunshot injuries in the elderly: patterns and outcomes. A national trauma databank analysis. *World J Surg.* 2011; 35(3):528-534.

29. Madiba TE, Thomson SR, Mdlalose N. Penetrating chest injuries in the firearm era. *Injury* 2001; 32(1):13-16

30. Makitie I. Ballistic trauma in Finland: an epidemiologic and clinical study of firearm and explosion injuries. Dissertation, University of Helsinki, Finland. 2006. ISBN 952-10-3050-X (PDF).

31. Nunamaker DM, Berg P. Open fractures and gunshot injuries. In: *Textbook of Small Animal Orthopaedics.* Newton CD, Nunamaker DM, eds. International Veterinary Information Service, Ithaca, New York, 1985.

32. O'Kelly F, Gallagher R, Lim K, Smyth P, Keeling P. Gun Shot-101: an 8-year review of gunshot injuries in an Irish teaching hospital from a general surgical perspective. *Ir J Med Sci.* 2010; 179(2):239-243.

33. Peters, Carroll E. A mathematical-physical model of wound ballistics. *J Trauma (China)* 1990; 2(6, Supp):303-318.

34. Phebo LB. The impact of firearm injury in Brazil. Meeting of the International Collaborative Effort on Injury Statistics, June -2, 2005 Cuernavaca, Mexico. Available at: http://www.cdc.gov/nchs/injury/ice/mexico2005/mexico2005_agenda.htm. Accessed July 15, 2012.

35. Rahman M, Sikder AI, Haque M, Asaduzzaman AKM. Outpatient management of low velocity gunshot wound experience in United Nations Level-II hospital. *JAFMC Bangladesh.* 2011; 7(2):12-14.

36. Rehman S, Han RJ, Garvey M. Handgun injuries in 2012: What the orthopaedic surgeon needs to know. Proceedings of the American Academy of Orthopaedic Surgeons, San Francisco, California, USA, February 7-11, 2012; paper SE84.

37. Solagberu BA. Epidemiology and outcome of gunshot injuries in a civilian population in West Africa. *Eur J Trauma Emerg Surg.* 2003; 29(2):92-96.

38. Sturtevant B. Shock wave effects in biomechanics. *Sadhana*, 1998; 23:579-596.

39. Suneson A, Hansson HA, Seeman T. Pressure wave injuries to the nervous system caused by high-energy missile extremity impact: part I. local and distant effects on the peripheral nervous system. A light and electron microscopic study on pigs. *J Trauma.* 1990; 30:281-294.

40. Suneson A, Hansson HA, and Seeman T. Pressure wave injuries to the nervous system caused by high energy missile extremity impact: part II. distant effects on the central nervous system. A light and electron microscopic study on pigs. *J Trauma.* 1990; 30:295-306.

41. Tien HC, van der Hurk TWG, Dunlop P, *et al*. Small bowel injury from a tangential gunshot wound without peritoneal penetration: a case report. *J Trauma.* 2007;62:762-764.

42. U.S. Dept. of Health and Human Services, Centers for Disease Control and Prevention, National Center for Injury Prevention and Control, and United States Consumer Product Safety Commission. Firearm Injury Surveillance Study, 1993-2008 [Computer file]. ICPSR30543-v1. Atlanta, GA: U.S. Dept. of Health and Human Services, Centers for Disease Control and Prevention, National Center for Injury Prevention and Control [producer] Ann Arbor MI: Inter-university Consortium for Political and Social Research [distributor], 2011.

43. Wang Q, et al. Alterations of the myelin basic protein and ultrastructure in the limbic system and the early stage of trauma-related stress disorder in dogs. *J Trauma*. 2004; 56:604-610.

44. *Website:* Winchester. *Handgun Bullet Barrier Testing Protocol*. http://winchesterle.com/SiteCollectionDocuments/pdf/Handgun%20Bullet%20Barrier%20Testing%20Protocol.pdf . Accessed August 18, 2012.

45. Marshall E, Sanow E. Stopping Power. Paladin Press, 2001.

46. Courtney M, Courtney A. Relative incapacitation contributions of pressure wave and wound channel in the Marshall and Sanow data set. Cornell University Library, Medical Physics arXiv:physics/0701266v2 , 2007.

47. Neades DN, Prather RN. The modeling and application of small arms ballistics. United States Department of Defense, ADA240295, 1991.