To the Graduate Council

I am submitting herewith a thesis written by Bryce Anderson entitled "Evaluation of Tungsten Tin and Lead Projectiles against Real and Synthetic Bones Encased in Ballistic Gelatin" I have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Industrial Engineering.

Tyler A Kress, Major Professor

We have read this thesis
and recommend its acceptance

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Dean of The Graduate School

EVALUATION OF TUNGSTEN TIN AND LEAD PROJECTILES AGAINST REAL AND SYNTHETIC BONES ENCASED IN BALLISTIC GELATIN

A Thesis Presented for the Master of Science Degree

The University of Tennessee, Knoxville

Bryce Anderson

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For their unfailing support, encouragement, and love, this work is dedicated to my family

Mr. Bruce Anderson
Mrs. Emma Anderson
Ms. Michelle Anderson

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Abstract

In this work a new type of small-arms ammunition is evaluated to determine its capability of producing wound trauma. This new ammunition dispenses the toxic lead core of conventional bullets in favor of a non-toxic pressed tungsten and tin powder core. The testing involved firing rifle and pistol caliber tungsten tin and lead bullets against real porcine bones encased in ballistic gelatin. The lead bullets were used to establish a benchmark of performance for the tungsten tin bullets to be measured against. Various metrics, such as penetration depth, bullet fragment weight and size, and bone fragment weight and size were recorded.

It was found that the tungsten tin rifle bullets averaged a substantially deeper post-bone penetration depth than the lead rifle bullets. It was also found that the tungsten tin pistol bullets behaved in much the same manner as the lead pistol bullets but that the tungsten tin pistol bullets generated a higher collective weight of real organic bone fragments than the lead pistol bullets.

The use of real bones in the evaluation of the new projectiles presented the opportunity to test a real bone substitute under the same projectile impacts. This synthetic bone was shot with the same sequence of bullets used against the real bones. Bone fragments were then measured for weight and size to evaluate uniformity. The synthetic bone was found promising, but was not ultimately more uniform than real bones under projectile impact.

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PART I

INTRODUCTION AND BACKGROUND

CHAPTER 1

JUSTIFICATION

With the environmental fervor that is sweeping the globe today, all aspects of civilization are being scrutinized with respect to their impact on the earth and the natural habitat contained within it. The United States government has proffered no exception to this global conservationism, and leads the way in developing methods that reduce waste and encourage environmental responsibility. It is arguable that the most prolific government agency involved in this cause is the United States Department of Energy, who is responsible for commissioning the majority of work that appears in this thesis. Several years ago, the Department of Energy began the search for an alternative material to replace the toxic lead used in most small-arms ammunition. The most viable solution developed thus far is the substitution of a tungsten and tin powdered-metal core that is designed to replace the conventional lead core of conventional military ammunition. By varying the ratio of tungsten powder to tin powder of the overall mixture, a density similar to lead can be achieved without the inherent toxicity of lead. This promising solution also offers a multitude of previously unrealized ballistic possibilities, such as changing the center of gravity of a projectile and eliminating the phenomena of ricochets. Regardless of how promising this new technology might be, however, the new bullet must be capable of performing the job for which its lead predecessors were designed: to incapacitate adversaries by the creation of penetrating wound trauma. If the new "environmentally friendly" bullets are incapable of performing this primary task, the development of such a bullet is largely meaningless. Advocates may argue that the bullets be used for training purposes in order to prevent further lead contamination of shooting range soils, but this discussion is outside the scope of this work.

This work is designed to explore the wounding potential of these new tungsten tin bullets. Given the controversy that accompanies the field of wound ballistics, it will come as no surprise if proponents on all sides of the wound ballistics arena offer unsolicited opinions regarding the nature of this work. Let it be said here that the Department of Energy specifically requested that these projectiles be tested against bones encased in gelatin, and that lead soft-point bullets be the benchmarks against which the soft-point tungsten tin bullets were to be evaluated.

The nature of the testing against real bones also allowed for the inclusion of a second part of this thesis in which a possible substitute for real bone in projectile impacts is evaluated. While other researchers have conducted projectile impact testing of real bone, and substitutes for real bone exist that possess similar mechanical qualities of real bone, none of these existing replacements has been evaluated with respect to projectile impact. Real bones are inherently non-uniform in shape, size, and composition. A uniform and consistent substitute for real bones that would replicate the mechanical and impaction properties a given single real bone would be greatly welcomed in the scientific community.

CHAPTER 2

WOUND BALLISTICS HISTORY

How do you evaluate the performance of a bullet against a human body? Short of shooting a person, the next best method is to shoot something that behaves in a manner similar to human tissue when shot with a projectile.

Since the advent of firearms, many individuals have made efforts to understand the wounding mechanisms of projectiles, only to be hampered by a lack of suitable technology, esoteric knowledge, or both. Theodore Kocher, a surgeon in the late 1800's, attempted to define a bullet's wounding capacity in terms of its kinetic energy. His primary error was his belief that the bullet energy could be split into four separate areas: heat energy, temporary cavity energy, energy used to produce the permanent cavity, and energy used in deforming the projectile. In reality, the vast majority of a projectile's energy creates the permanent crush cavity and maximum temporary cavity, and that energy then dissipates in the from of heat. While Kocher's work was the first scholarly attempt to explain wound ballistics of it's kind, his research did not accurately model the phenomena of projectile impact (21).

The next serious attempt to quantitatively evaluate the wounding potential of projectiles were the Thompson-Lagarde tests around the turn of the century. In essence, the researchers shot two types of bullets across a wide array of calibers into a number of steers and recorded the number of shots required to cause the steer to fall to the ground. The research essentially consisted of comparing .300 and .355 caliber pistol bullets against .450 caliber pistol bullets. Fewer .450 caliber bullets were required to drop a steer than .300 or .35 caliber bullets, so the researchers concluded that the larger, heavier bullets were more effective than smaller, lighter bullets against steers. They then proceeded to extrapolate this correlation to humans, and based on their recommendation, the United States Army Ordnance Department established that the new U.S. Army sidearm be a pistol of .450 caliber. While the details of the tests are not of interest to this paper, what is of interest is the resulting analysis of the wounds inflicted by the bullets to the steers. It should be stated here that this paper is concerned not with the question of which bullet type or caliber is better than another, but to investigate the effects of a given bullet against a predetermined target.

In his own words on page 78 of the published results, Lagarde explained that the tests were conducted by shooting the steers in three main anatomical areas:

1. Vital parts
2. Non-vital parts
3. The anatomy necessary to locomotion or parts essential to activity

Lagarde concluded the following:

"The stopping power of bullets upon colliding against parts necessary to locomotion or parts essential to activity was considered positive

> when fracture of the long bones occurred. Measured by this standard all the bullets tried possessed sufficient stopping power when for instance the tibia or the femur was fractured. The stopping power of the larger caliber projectiles was considered positive in gunshot wounds of the epiphyseal ends of bones entering into the formation of the ankle, knee, shoulder and elbow, and doubtful when these structures were traversed by the small .30 jacketed bullet of the Luger pistol.
>
> "In those cases where an effort was made to increase shock effects and destruction of tissue by the use of metal patch or marred jacketed bullets, these expedients failed in the soft parts and epiphyseal ends of bones, because the resistance in these tissues was not enough to disintegrate the projectile, or in any way increase its sectional area." (36).

Lagarde's analysis apparently did not include looking at the specific effects of projectiles on bones, as he merely classified the bone as fractured or not. He then equated this to stopping power. Comminution of the bone was not investigated, nor was the type of fracture that occurred.

In 1935, General Julian S. Hatcher of the same aforementioned U. S. Army Ordnance Department wrote a book entitled <u>Textbook of Pistols and Revolvers</u>. It was largely based on his personal experiences in combat and his thoughts on how bullets affect adversaries. Specifically, he was one of the first investigators of the psychological effects of wound ballistics. He talks at length about the state of mind of the adversary and how that mental state can affect the bullet's effect on the adversary. Having qualified his wound ballistics treatise thusly, he then describes his belief on the wounding mechanisms of bullets on page 428 of his book:

> "All the tests of which the author has any knowledge, as well as nearly all the scattered reports received from various sources, indicate that caliber is by far the most important factor

> in the stopping power of any bullet that has adequate energy to carry it well into a body. The nature of flesh is such that a bullet will not cause much destruction outside of a narrow path including the bullet track; and the width of this track, and of the consequent area of destruction of tissue, nerve material, and blood vessels varies with the square of the diameter of the bullet concerned, unless a bone is struck and the bullet thus distorted" (36).

Note that this description is again qualified by the action of a bullet impacting bone.

Hatcher also mentioned the previous Thompson-Lagarde tests earlier in his book. Specifically, he refers to the cadaver shots Lagarde made on dead steers. Here his opinion was that such shots delivered only information about bone, but even here, he is unaware of the effect that the fractured bone has against surrounding tissue. He asserts even that information is unreliable, given the varying conditions and shape of the test animal and hence the bone itself.

Hatcher goes on to say more about the unpredictability of a bullet's effect on bone in live animals:

> "The results of shooting against cadavers do not give a close comparison with what happens when a live animal is shot, for after a man or animal dies, the flesh coagulates more or less as rigor mortis sets in, and this change and hardening of the tissues is rendered more pronounced by the pickling of the body in preserving fluids. About all such tests tell is the relative action of the different bullets on bones, and even here, there is much that is unsatisfactory, because the bones differ greatly in brittleness, according to the age and condition of the subject, and moreover, it is difficult to ensure that all shots strike in the same manner...when a bullet strikes a bone, it may

> turn over, or glance in almost any direction, with widely varying results for similar shots" (36).

The lack of investigative work on the mechanisms of bone fracture at this point are not surprising, but do point to such an area for further exploration.

With the development of high speed film and ballistic gelatin, later studies tended to focus on energy deposit as the primary wounding mechanism. Both the erroneous RII (Relative Incapacitation Index) study of the early 1970's and the later RET (Relative Energy Transfer) scale of wounding potential both were based on this assumption. The enticement for this seemed to be the spectacular temporary cavity that would develop upon initial impact of a bullet into a block of gelatin; however, this maximum temporary cavity would later be proven to negligibly affect elastic tissue, if at all, when dealing with the lower velocities found in handgun bullets. The majority of damage from a handgun bullet is the result of the permanent wound cavity, which is a function of bullet cross-sectional area and penetration depth. (19,23)

The FBI has their own methodology to evaluate the performance of handgun bullets in ballistic gelatin. This testing protocol, formalized in late 1987, focuses on bullet penetration and expansion in ballistic gelatin. Prior to this standard, the FBI depended on the aforementioned RII study for its ammunition selection. The inherent flaw of the RII study (that MTC was a major factor in adversary incapacitation and that penetration was not) was revealed in horrible fashion on April 11, 1986 when seven FBI agents were involved in a firefight with two heavily armed felons. Afterward, an autopsy of one of the felons revealed that early in the battle one of the agents had fired a bullet that headed straight for the heart of one of the felons but stopped short due to inadequate penetration depth. The exact mechanisms will be explained later, but the standard of ammunition selection had been the size of the MTC, not penetration depth or the permanent cavity. The felon continued to fight on for several minutes, eventually killing two of the agents and wounding the other five before being terminated by one of the wounded agents.

The next major step in wound ballistics research occurred in 1990 with the formation of the International Wound Ballistics Association. It should be noted the motivation for the formation of this group came largely from a number of trauma surgeons and forensic pathologists that had experience and interest in wound trauma. It should be noted that some of these individuals had been doing their own research into wound trauma and the various effects of projectiles impacting human tissue for several years. Chief among these researchers is Dr. Martin L. Fackler, who has done volumes of research into the subject and was chosen to be president of the IWBA at its inception. Dr. Fackler has done more to objectively research wound ballistics and uncover the actual mechanisms of tissue damage than any other individual in the literature that was reviewed for this paper.

The most recent exhaustive treatment of wound ballistics, and the most comprehensive to date, is the book Bullet Penetration by Duncan MacPherson. In his book, Mr. MacPherson has pulled together the knowledge from several different disciplines (medical science, physiology, engineering, fluid dynamics, etc.) into what is arguably the most thorough treatment of handgun wound ballistics from a dynamic and theoretical standpoint. The book primarily presents a mathematical method to model the terminal ballistics of bullet wounding effects in ballistic gelatin and human tissue, and backs up the theory by presenting empirical testing performed in ballistic gelatin. Among the many conclusions Mr. MacPherson makes in his book, three stand out for the relevance to this paper. They are intended as performance standards for jacketed hollow-point bullets, but are applicable as rough guidelines for the ammunition evaluated in this paper. They are:

1. Average penetration depth should be about fourteen inches.
2. Velocity for handgun bullets should be between 800 and 1000 feet per second.
3. Weight should be the maximum practical for the given caliber of bullet.

How Bullets Damage Tissue

A bullet causes tissue disruption in two different ways. The first mechanism of disruption is the tissue that is actively crushed by the bullet during the bullet's penetration. This gouged-out hole in tissue becomes filled with blood and pulped cells after the passage of the bullet. This hole of disintegrated tissue is known as the permanent cavity, and is the major cause of tissue damage from low velocity projectiles such as pistol bullets (19,23).

The second mechanism of disruption occurs in the tissue immediately surrounding the permanent cavity milliseconds after the passage of the bullet. The surrounding tissue is forced radially outward, orthogonal to the path of the bullet. The open area formed by this stretched tissue is referred to as the temporary cavity. The maximum diameter of this temporary cavity is typically several centimeters in diameter, and the total temporary cavity volume is proportional to the energy of the impacting projectile (36). Damage to tissue, however, is dependent on the elastic properties of the impacted tissue. The maximum temporary cavity volume represents the stored strain energy contained in the tissues of the target (36). Tissue damage resulting from this strain energy is a function of the elasticity of the tissue itself. The more elastic the tissue, the more strain it can undergo without damage (36). Muscle, bowel wall, fatty tissue, lungs, subcutaneous flesh, etc., can absorb large amounts of strain without damage, whereas organs such as the liver, spleen, and brain may be severely damaged by large amounts of strain. Maximum pressures associated with the temporary cavity are around 60 psi, or four atmospheres, in supersonic projectiles (v = 344m/s) (69,20). These forces are rapidly absorbed by surrounding tissue, and temporary cavity only exists for few milliseconds. Its existence was unknown until the use of high speed film documented the effect in the 1970's. This event is the sonic shock wave generated at the tissue surface as the projectile strikes the tissue. This wave travels into the tissue away from the point of impact at the speed of sound in tissue (v = 1463 m/s). It precedes the passage of the projectile and causes pressures of up to 900 psi (60 atm), though it does not cause any detectable tissue damage or movement due to its extremely short duration (20).

As this paper focuses on the effects of projectile impacts on bone contained in tissue, it has been stated in the literature that these supersonic and transonic pressure waves may contribute to bone fractures. Ming et al. (41) found that 6.35mm spherical fragments impacting at a speed of 1110 m/s can create pressure waves that can cause bone fracture at distances up to 4cm from the wound tract. That same paper, however, reports that no fractures occurred with the impact of 5.56mm projectiles and therefore pressure waves from the supersonic 5.56mm projectiles in this paper can be ignored (41).

Bone Damage Resulting from Bullet Impacts

Bone fragments can contribute to increasing the severity of a wound in soft tissue (3). Even if a synthetic bone replicates the tensile, compressive, shear, torsional, and bending strengths of a real organic bone when subjected to the same forces as the real bone, the synthetic bone may not replicate the fracture and/or the fragmenting characteristics of a real bone under a given loading or impact condition (16). Under impact conditions, the striking projectile loses velocity in the target medium. Kinetic energy is defined as being equal to ½mv^2, and given that the mass of the bullet stays constant, it is the change in velocity that represents the transfer of energy to the target. This energy transfer is then the work done on the target by the projectile (W = F x d). The mechanics of projectile impact on a given target not only include the aforementioned tensile, compressive, shear, torsional, and bending strengths but also the transfer, dissipation, and absorption of the energy.

There are two types of impact testing regarding the strength of materials (Davis et al. 1964), that of impact testing concerning elastic energy absorption by the target material and that of using impact testing to measure energy capacity of the target to failure. In this paper the testing concerns the latter. Whenever the term energy is mentioned in association with the field of wound ballistics, much controversy is bound to ensue. There have historically been two opposing views regarding energy and wound ballistics. One view submits that the amount of energy transferred to the target medium by a projectile is the major cause of wound trauma (5,6). Advocates of this belief frequently refer to the phenomena of temporary cavitation to support this (15, 32, 59).

The other view holds that tissue damage isn't dependent on energy deposition, but rather on how that energy is used. Tissue isn't damaged by kinetic energy absorption, it is damaged by stress (force per area) on the tissue itself (36). This stress results from the way in which the deposited energy is distributed through the tissue. This gives rise to another variable, that of the mechanical and physical properties of the tissue that the energy disperses in. Elastic tissue such as muscle, fat, bowel wall, lung, etc., have a high degree of elasticity and can absorb large amounts of energy and therefore stress with little, if any, damage. Non-elastic tissue such as the brain, spleen, liver, bone, etc., do not absorb large stresses without damage. These tissues, upon exceeding their elastic limit of deformation will deform plastically. The plastic deformation is classified as tissue damage (36,23). It should be noted that some argument still exists as to what energy levels are required to produce the stresses necessary to exceed the elastic limit in human tissue.

Both views concede that handgun projectiles do not possess enough velocity, and therefore energy, to cause a massive enough temporary cavity required to exceed the elastic limit of tissue. Proponents of energy deposition, the first view described, do however argue that rifle projectiles can carry enough velocity to damage tissue by exceeding its elastic limit (15, 32, 59). This hypothesis was put to rest by Fackler (18) in his paper "A Reconsideration of the Wounding Mechanism of very High Velocity Projectiles- Importance of Projectile Shape". In it, he examined the gross wound characteristics in animal tissue produced by these two types of blunt projectiles (spheres and rods) at velocities ranging from 764 m/s to 2049 m/s. He also compared the wounds produced in animal tissue by aerodynamic projectiles with those produced by blunt projectiles.

Here, Fackler is concerned with the shape of the projectile, but the important data relevant to this paper is that when Fackler shot the aerodynamic projectiles into soft tissue at very high velocities the temporary cavities that formed were not enough to stretch the skin beyond its breaking point (18). Fackler doesn't comment on the deeper tissue damage these aerodynamic projectiles produced after penetration, but does show that blunt bodies, which release the majority of their energy close to the surface of the target due to high drag, only had enough energy to split the muscle and skin at the highest velocities used in the test. He does, however, qualify his results with the aerodynamic bullet by stating "rifle bullets, because of their streamlined form, cause little disturbance in passing through air and retain their velocity well.

This performance in air is mirrored in tissue, where the bullet causes minimal disruption at the surface and so long as it remains traveling point forward. If it deforms, yaws, or fragments, it causes its maximum disruption at the point along its path where this occurs but not at or near the surface" (18). It stands to reason that an aerodynamic projectile, which has low drag in tissue and therefore more gradual energy deposition, would require higher amounts of energy than the blunt projectiles, and to release that energy deeper in the tissues, to create the same or greater muscle and skin splits seen at the surface of the skin with the blunt bodies. While it must be conceded to energy proponents that dumping enough energy into tissue to exceed its elastic limit can be done, the velocities required are much higher than any small-arms weapon can currently provide. The velocities used by Fackler to cause the muscle and skin splits with blunt bodies were on the order of 1800 m/s to 2000 m/s, whereas the standard USGI M855 5.56mm ball projectile has a muzzle velocity of around 945 m/s (62).

At this point, one might ask, "If energy isn't directly responsible for tissue damage, then what is?" Clearly, large caliber rifle projectiles produce much more devastating wounds than do handguns, and at greater distances. The mass of common shoulder fired rifle projectiles is usually less than those of handgun projectiles; the only remaining differences are the velocity, and bullet shape and construction. Recall the disclaimer that Fackler made earlier concerning aerodynamic projectiles. He stated that a bullet causes its maximum at the point along its path where the bullet itself deforms, yaws, or fragments. Fackler had published an earlier paper which dealt with looking at bullet fragmentation contributing to wound severity entitled "Bullet

Fragmentation: A Major Cause of Tissue Disruption". In this paper, Fackler fired both fragmenting and non-fragmenting 5.56mm projectiles into living swine tissue and ballistic gelatin. The velocities and weights were kept the same (v = 961 m/s ± 27 m/s and w = 3.1 gm for non-fragmenting projectiles, and v = 959 ± 14 m/s and w = 3.2 gm for fragmenting projectiles). The resulting wound profiles and tissue damage were markedly different. The non-fragmenting projectiles created a permanent cavity that was approximately the same shape as that of a long narrow cylinder with a diameter of 1.8 cm at its maximum point. Average penetration depth was 56.8 cm ± 0.76 cm in ballistic gelatin. The fragmenting bullet caused a much larger permanent cavity than the non-fragmenting bullet. Pieces of detached muscle and tissue in the swine are evident from the photographs, along with the larger permanent cavity diameter, which measured 7.4 cm ± 0.31 cm at its maximum point. Average penetration depth was 21.8 cm ± 0.76 cm in ballistic gelatin (24).

Fackler concluded that the difference in severity if tissue destruction was the result of the fragmenting bullet breaking into pieces and traveling forward into the tissue to cut and detach pieces of tissue. He describes it as follows:

> "We have shown that the soft-point bullet, in addition to 'expanding' its diameter, also loses from 59 to 77% of its weight in fragments which are widely distributed in tissues over an area up to 8 cm in diameter. It appears that this fragmentation is the critical factor in the increased tissue disruption caused by these bullets. We suggest that the multiple fragments are likely to cut across many of the muscle bundles in two places and that the piece between the cuts is then likely to be completely detached by the subsequent sudden stretch of the temporary cavitation. Tissue weakened by fragment passage may be split by a stretch that would otherwise be absorbed by the tissues elasticity (24)."

Fackler goes on to comment on the use of the energy deposition theory and how it relates to tissue disruption by discussing a paper on the subject by Liu et al., saying:

> "The experimental design of Liu et al. mimics the popular 'energy deposit' format, which is unlikely to detect fragmentation. In the 'energy deposit' design, the bullet passes through two chronographs, one before and one after perforating the target. Velocity loss is determined by subtracting exit from entrance velocity, and then energy loss or 'deposit' in the target is calculated. This determination is valid only when the weight of the missile remains constant. If a bullet loses fragments in the target, it will weigh less when passing through the second chronograph and carry less energy when leaving the target. When fragmentation occurs, therefore, the deposited energy figures will be falsely low" (24).

Fackler, in these two papers, has shown that wound severity and tissue damage doesn't arise simply from energy deposition in tissue, but rather how that energy is used. When a projectile fragments in tissue, each fragment becomes a separate tool which contributes to increasing wound severity by cutting tissue. The tradeoff is that when the original projectile loses mass through fragmentation, the depth of penetration of the projectile is reduced. This tradeoff has become a design parameter with special characteristics regarding the varying situations that the projectiles will be used in. This concept of varying fragmentation is directly related another concern of the Department of Energy regarding ricochets against hard targets such as steel, concrete, and glass. Research has been commissioned by DOE to define the actual term "frangibility" and create a system by which frangibility can be objectively measured and categorized, as there is currently no credible scientific formula regarding the degree of fragmentation a bullet can undergo against different types of targets.

Fackler's conclusion that bullet fragments can contribute to and are a major cause of wound severity and tissue disruption beg the question: what about other items that can become secondary missiles in the target tissue? Fackler touches briefly on this subject in his article "Bullet Fragmentation- A Major Cause of Tissue Disruption", page 38:

> "The non-expanding military bullet generally causes minimal tissue disruption and remains undeformed as does the brass bullet in our study. The military bullet can cause massive tissue damage if it: 1.) hits bone, 2.) hits a hard object, such as a belt buckle, before entering the body, 3.) is a ricochet, or 4.) has been altered. Filing of bullet tips to make a full metal cased bullet more lethal has been described as a common practice in the late nineteenth century" (24).

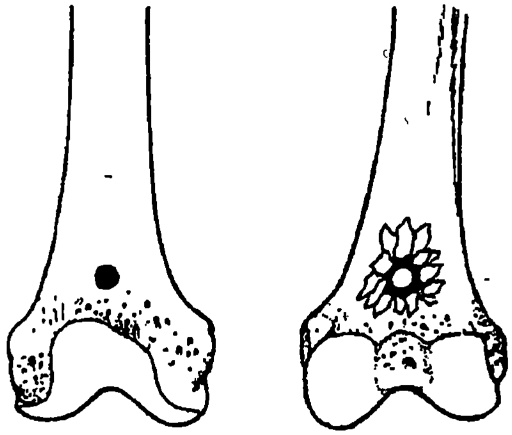
The first item in the list is the main concern of this thesis. As stated previously, bone fragments can contribute to the severity of a gunshot wound. It was this effect that was overlooked by Calendar and French in their 1935 test of high velocity projectiles that led them to mistakenly conclude that fragmentation was not necessary for massive amounts of tissue damage at high velocities. In reality their two shots at 924 m/s and 1088 m/s struck the hip joints of the goat that was their target medium and caused massive bone comminution. These bony fragments acted as secondary missiles and were the cause of the massive tissue damage, not simply the high velocity (24).

There are four main types of femoral fractures that result from gunshots (56).

These are the drill hole fracture seen in figure 2-1, the butterfly fracture seen in figure 2-2, the impaction fracture seen in figure 2-3, and the spiral fracture seen in figure 2-4. Of these, the butterfly fracture may be central or eccentric, and the impaction may be enface or tangential.

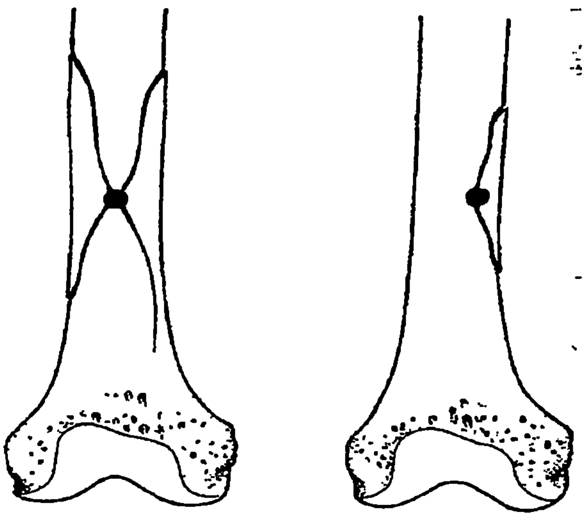
The drill hole and butterfly types of fractures occur with a variable amount of exit site fragmentation. Impaction, the third type of fracture, is also known as the "incomplete" fracture. Complete bony penetration does not occur, but the striking bullet does result in one or more small cortical fragments(s) being chipped off the bone to act as a secondary fragment in the wound. The last fracture, the spiral, is the most complex. Typically this is seen in cases where the femur is under load at the time the bullet strikes. As the femur fails in compression, it twists, resulting in the unique appearance from which it derives its name. This fracture can occur proximal or distal to the other three fractures cited above as a direct result of stress rises in the bone at a distance away from the site of impact. The spiral fracture has been observed as the cause of gunshot thigh wound victims falling down after taking several steps post-wound (56). There have even been cases where the spiral factor occurred without any projectile damage to the bone directly; this is thought to be the result of the elevated pressures caused by the bullet penetrating the thigh tissue surrounding the bone (56) and likely occurs as the temporary cavity reaches its maximum size.

The fragmentation of bone depends on the amount of pressure generated within the bone (56). Bone, as a tissue, has also been shown to form a temporary cavity (3). Given the plastic nature of bone, however, this cavity exists for only a



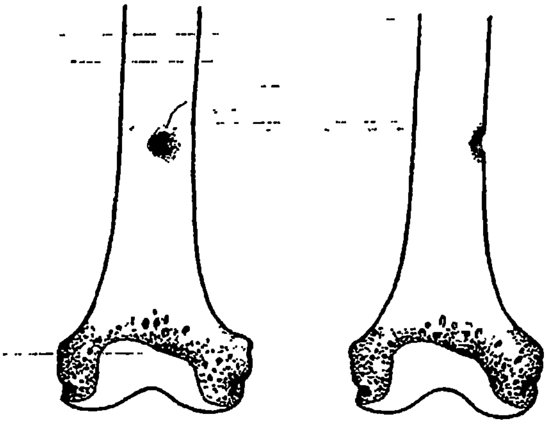
Entry Exit

Figure 2-1: The Drill Hole Fracture



Central Impact Eccentric or Off-Center Impact

Figure 2-2: The Butterfly Fracture



Enface Tangential

Figure 2-3: Impaction Fracture

Figure 2-4: The Spiral Fracture

small time before the bone reaches its yield point and comminution occurs. The comminution that occurs with these bullet impact fractures creates bone fragments that do contribute to the severity of tissue damage. In shooting a bone encased in gelatin and filming the results with a high-speed camera Amato saw that upon initial impact the bone appears intact. When the maximum temporary cavity is formed in the bone, about 10 microseconds after impact, the central portion of the bone can be shattered into fragments. Amato saw that these fragments for a short period of time remained in line with the proximal and distal portion of the bone. As the temporary cavity of the bone increases in size the bone fragments are pressed into the surrounding tissue. At this time, these fragments are not shown to act as secondary missiles, however, they tend to be brought back to the initial point of fracture as the temporary tissue cavity contracts and depressurizes. It is only when the second and subsequent waves of undulation within the temporary cavity that bone fragments are seen to move forward in the direction of the bullet and it is these bone fragments that become secondary missiles (3). The energy of the projectile is then used by these bone spicules to further cut surrounding tissue, just as bullet fragments have been shown to do when the bullet fragments in the tissue (24).

Wound Classifications

It can be said that no two injuries of any type are exactly the same. When a projectile impacts human tissue, the sheer number of variables involved statistically preludes any chance of identical injuries. Projectile velocity, projectile weight, tissue location, tissue condition, or even whether the muscle fibers were contracted or relaxed are only a few of the factors affecting wound severity. Various attempts have been made to categorize wound damage, with most of the systems having military beginnings. Civilian systems are typically lengthy and concerned with complex details, and are used mainly as an aid to triage and/or for use in physiological outcome prediction. Almost every major standing military force in the world has developed a scoring system intended to gather information on casualty rates. For one example, the British Army has been using a system known as the "Hostile Action Casualty System", or HACS, which is in essence a large database that records data on military wounds. The system is designed to collect a large amount of information in the triage stage of wound assessment, but due to the length and detail of the form it is often left incomplete. In an emergency situation, time is precious, and the attention of the medical personnel is better spent on the wound than in writing about it. This is reflected in the number of HACS forms that are often substantially incomplete.

The Red Cross uses a system that is much simpler than the HACS method. It consists primarily of grading a wound by the features it presents, with six basic features used: Entry wound, or "E"; Exit wound, "X"; Cavity, "C"; Fracture, "F";

involvement of vital structure, "V"; and presence of a metallic body in the wound, "M" (11).

In the planning stages of this testing, categorization of the type of damage each type of bullet effects upon each target was intended to be one of the metrics of data collected. Using such a system, only eight classifications would be expected, based on the eight combinations of projectiles and targets. All wounds are expected to generate fractures of the bone, and therefore all fractures should be classified as a Type F or VF, depending upon comminution. The grades of the wounds are then limited to three possible types: grade 1, grade 2, or grade 3.

A grade 1 wound requires that the mathematical sum of the maximum diameter of the entry wound and the maximum diameter of the exit wound measured in centimeters must be less than 10, in addition to a wound cavity prior to surgery that is too small to admit two fingers. If a fracture occurred, it must also have no clinically significant comminution.

A grade 2 wound conforms to the same summed entry and exit diameters being less than 10 cm as grade 1, but one of the following two conditions must also exist: the pre-surgical wound cavity is large enough to admit two fingers, or the fracture associated with the wound must have undergone clinically significant comminution. No objective measure of comminution is offered.

A grade 3 wound is in essence a grade 2 wound that has an entry and exit diameter, when summed, greater than 10 cm.

While the Red Cross Scoring System has a scoring letter for the presence of metallic bodies in the wound (M), it is not used in the subsequent official wound analysis. Some mention is made in the literature that the distinction between high-velocity metal bodies, such as rifle bullets, are not allowed a distinction between slower metallic bodies, such as blunt fragments. This paper is only affected by this in the sense that the pistol bullets could be perceived as being slow blunt bodies. Regardless, the analysis performed in this paper will use the "M" designation as an indication of whether or not it is believed that the fragments of the projectiles would have remained in the simulated thigh circumference of the gelatin target.

This yields a total of twelve possible categories that each of the targets in this testing may fall into. In ascending order of severity they are: grade 1 type F, grade 1 type FM, grade 1 type VF, grade 1 type VFM, grade 2 type F, grade 2 type FM, grade 2 type VF, grade 2 type VFM, grade 3 type F, grade 3 type FM, grade 3 type VF, or grade 3 type VFM.

The empirical differences between the bullet types and bone types may be largely of academic interest, but the application of a wound scoring system illustrates how a field surgeon may apprise the wounds in an actual human body.

In researching femoral gunshot fractures, a great amount of literature was reviewed that dealt with the repair of such a fracture using intramedullary nailing (8, 30, 33, 68). This method of using nails to reconnect broken pieces of a femur can be performed immediately after exploration and debridement of the wound or delayed in cases where infection was deemed a greater risk. The fractures tended to be severe in almost all cases, and the authors of the papers classified the fractures according to a categorization scale developed by Dr. Robert Winquist and Dr. Sigvard Hansen in a 1980 paper entitled "Comminuted Fractures of the Femoral Shaft Treated by

Intramedullary Nailing" (66). In this paper, Winquist and Hansen base their classifications on the pattern of the femoral fracture and the degree of its stability. This more narrow classification according to the bone contrasts with the much broader wound scoring systems used by military forces. Each is designed for different applications and should not be confused, but they are both relevant to the evaluation of injuries caused by the bullets used in this testing. While the shots made in this testing have been categorized using the Red Cross Wound Scoring system, the Winquist and Hansen method may provide a means of distinguishing the individual fractures on a more detailed level.

Winquist and Hansen created five categories in which most femoral fractures would fall: segmental fractures and grade I, grade II, grade III, and grade IV comminuted fractures. The segmental fracture is a double level fracture of the femoral shaft where the femur has broken into three segments. The proximal fracture can range as high as the subtrochanteric level, while the distal fracture may appear as far down as the supracondylar level.

The grade I comminuted fracture is a case in which a very small piece (or few pieces) of bone have broken off from the main segments of the femur. Winquist and Hansen describe that it is to be treated as if it were non-comminuted, implying that there must be so little comminution as to not affect the stability of the main fracture in any noticeable manner.

The grade II comminuted fractures feature a larger fragment size than the grade I fractures. In the grade II fracture, there must be at least fifty percent contact between the abutting femoral cortices to prevent shortening and rotation of the bone.

There must also be enough proximal and distal contact of the nail to the bone to prevent translation and shortening of the bone. Winquist and Hansen also recommend searching for additional cracks in the femur which may result in a loss of fracture stability.

A grade III comminuted fracture has less than fifty percent cortical contact between the two bone shafts or poor purchase of intramedullary nail in either the distal or proximal end of the femur. It is in this fracture that shortening, translation, and rotation are most likely to occur. Fragment size does not affect the grade classification, but the location of fragments may determine if this fracture falls into a grade II or grade III category. A fragment of a certain size in the midshaft region will be classified as a grade II fracture if there is good proximal and distal nail contact. A fragment of the same size found in the proximal or distal areas of the femur will result in a grade III fracture classification due to poor nail contact and the increased likelihood of translation and shortening. This type of fracture will require the use of cerclage wiring, postoperative traction, casting, or a combination of these methods in order to prevent the translation and shortening commonly seen with this type of fracture.

The most devastating fractures appear to fall in the grade IV category. These comminuted fractures have lost the circumferential buttress of the bone. There is no fixed contact between the proximal and distal ends of the bone to prevent shortening. Split segmental fractures fall into this category. A multi-fragmented fracture that has substantial circumferential comminution will also shorten and likely rotate. Intramedullary nailing alone will not maintain the appropriate length or positively prevent rotation of the bone shafts. Cerclage wiring or traction are necessary in order to maintain the proper length of the bone.

Two other types of femoral fractures mentioned by Winquist and Hansen are the long oblique and longitudinal fractures. These fractures are not comminuted, but do possess the ability to shorten and rotate. In these instances intramedullary nailing should be used in conjunction with cerclage wiring.

The Winquist and Hansen method for grading femoral fractures is expected to assist in analyzing the fractures of the porcine bones. The results of this testing will be discussed in the analysis section of this thesis.

CHAPTER 3

WHAT IS BONE?

Microstructure of Bone

At this point, some background on the essence of bone is in order. The general definition of bone is that it is the dense, hard, and somewhat flexible connective tissue constituting the bones of the human skeleton. It is composed of compact osseous tissue surrounding spongy cancellous tissue permeated by many blood vessels and nerves and enclosed in a membranous periosteum (4).

Bone tissue itself is composed of about one-third by weight organic matter and two-thirds by weight inorganic matter. The organic matter is a framework of fibrous tissue and cells, consisting mainly of collagen and polysaccharides. Collagen is a fibrous protein that has a tertiary structure made up of twisted α-helices. The very nature of α-helices maximizes hydrogen bonding between peptide linkages, resulting in a structure that can be twisted, folded, or folded and twisted into a definite geometric pattern. The structures are then stabilized by dispersion forces, hydrogen bonding, and other intermolecular forces. In collagen, the structures are made up of twisted α-helices. Three polypeptide chains, each of which is a left-handed helix, are twisted into a right-handed super helix to form an extremely strong tertiary structure. The end result is a protein structure that has remarkable tensile strength, plus contributing to the strength of mammalian bone.

Polysaccharides, which make up the remaining organic structure of bone, are one of three classes of carbohydrates, the other two being mono- and disaccharides. Polysaccharides are condensation polymers containing anywhere from several hundred to several thousand monosaccharide units. These monosaccharide units cannot be chemically broken down into simpler carbohydrates (38).

The polysaccharides in mammalian bone are called glycosaminoglycans (GAGS). These glycosaminoglycans contain chondroitin sulfate, which gives resilience and toughness to bones (38).

The inorganic constituents of bone, which make up the other two-thirds (by weight) of bone consists mainly of calcium and phosphorus salts deposited within the organic framework. These salts give hardness and rigidity to bones and make them resist the passage of x-rays.

To illustrate how the organic and inorganic parts of bone contribute to the actual physical characteristics of the bone, each of the two parts can be removed from the bone rather easily. The inorganic salts can be removed by soaking the bone in a dilute acid, such as EDTA. This decalcification process yields a bone that contains largely only organic matter. This organic bone will then be flexible and elastic enough to be tied into a knot (1, 28), yet still retain its original shape. Conversely, if the organic matter is removed by charring the bone in a furnace so that only the inorganic salts remain, the bone will still retain its original form but be extremely brittle and easily broken (28). Thus it can be seen how the organic and inorganic matter interact to yield the physical and mechanical properties found in mammalian bone.

On a larger scale, mature adult bone is made up of bone cells, called osteocytes, that are surrounded by an intercellular matrix composed of calcified osteoid (bone) material. The osteocytes are located in small cavities inside the bone called lacunae. Systems of tiny canals called canaliculi connect the osteocyte cavities (lacunae) to each other within the substance of the bone. These canaliculi transmit life-sustaining tissue fluid to the osteocytes.

The mechanical properties of bone relate directly to the macroscopic structure of bone. The hollow-spaced lattice work in the interior of bones is called cancellous bone (Latin for lattice). In long bones, such as the femurs being used in this testing, cancellous bone is found in the extremities of the bones where resistance to compression without excess weight is required.

Compact bone, which is found in the shafts of long bones, is made up of many laminated tubes known as Haversian, or osteonal, systems. Each Haversian system consists of one canal containing vessels and nerves surrounded by circular plates of bone forming the laminated cylinder. During construction of these canals, these plates of bone are laminated onto each other from the outside of the bone towards the center. After the lamination is complete, the resulting columnar structure resembles in cross section the rings of a tree, with the difference being that the rings on a tree grow outward, as opposed to the inward growth of these bony plates. The amalgamation of these bony plates into concentric lamellae. Taken as a whole, these concentric lamellae make up the compact bone found in mammalian bone. As the concentric lamellae are laid down, the individual bone-forming cells known as osteoblasts are changed into or re-identified as bone cells called osteocytes. The immediate space surrounding each osteocyte then resembles a "little lake", and these "little lakes" are called lacunae. Small canals that branch off from these lacunae are known as canaliculi, and it is in these small canaliculi that the cell processes take place. As the bone grows in diameter, new Haversian systems are added along the outside of the shaft of the bone. Blood vessels which extend from the periosteum to the Haversian canals are called Volkmann's Canals, and are found at right angles to the Haversian Canals.

The bone forming cells called osteoblasts originate mostly from mesenchymal cells. These mesenchymal cells are the parent cells of all connective tissues. Not all osteoblasts are used to create bone; some are stored in a section of the periosteum known as the osteogenic layer, while other osteoblasts are stored in the endosteum of the marrow cavity and Haversian canals. These reserve cells divide and form more osteoblasts whenever more bone is needed, as in the repair of fractures or increase in bone due to a changing environment. New bone can only be added on the surface of old bone, which dictates that the bone grows outward at a relatively fixed density.

Bone can also be resorped back into the biological system. Large multi-nucleated cells known as osteoclasts, derived from macrophages, release organic acids and enzymes that break down existing bone. This action is important in that as long bones grow, they increase in diameter by producing new bone from the periosteum. As new bone is laid down, portions of the deeper bone are removed to increase the size of the marrow cavity.

Regarding the inorganic portion of bone, calcium phosphate makes up about 80% of the mineral matter in a given bone. The remainder of the mineral matter is mostly calcium carbonate and magnesium phosphate. One hundred cubic centimeters of bone contains about 10,000mg of calcium. For comparison, most other tissues have 6mg Ca per 100cc of tissue, and about 10mg of Ca per 100ml for blood. Bone serves a secondary function as being a mineral reservoir for other parts of the body, and this characteristic likely has an impact on the mechanical properties of the bone as these mineral stores change over time (28). The term ossification refers to the creation of true bone by the deposition of calcium salts in a matrix of osteoid tissue. Calcification is the process of calcium salts being deposited in any tissue besides osteoid tissue.

Bone is white or yellowish-white in color. It feels hard, dense, and inelastic when handled. The specific gravity of fresh compact bone is about 1.9, and very resistant to pressure. The compressive strength is on the order of 20,000psi, with a tensile strength of around 15,000psi, both of which are higher than many types of wood, including white oak (29). Steindler (1955) reported the tensile strength of bone as being 10kg/mm^2 (14,193.52psi) and compressive strengths of 16.86kg/mm^2 (23,930.27psi). Evans (1973), however, also reports that McElhaney and Byars demonstrated that certain mechanical properties of compact bone are rate sensitive (16). This has particular relevance to the work of this thesis, as the energy absorbing capacity of bone at high strain rates of loading that McElhaney and Byars found directly relates to impact fractures of long bones. The results that McElhaney and Byars obtained showed that the ultimate compressive stress and modulus of elasticity of their specimens of cattle and human cortical bone progressively increased with high strain rates (1.0in/in/sec or greater) while the maximum strain at failure and energy absorbing capacity decreased. Poisson's ratio was seen to decrease progressively with increasingly high strain rates of loading. This decreased energy absorbing capacity of bone at high strain rates of loading relates directly to bone fractures, as most fractures arise from impacts involving high strain rates. Bonfield and Li (1966) used a Charpy impact tester to determine that beef cortical bone from femurs and tibias had a surface strain rate of 60 sec-1 at the moment of impact. They also found that maximum energy was absorbed by the bone at 0 degree centigrade and decreased as the temperature was raised or lowered.

The mechanical properties of bone can be altered by the body when the bone is in its natural environment by rearranging its internal structure to best resist stresses and strains. Under normal and pathologic conditions bone can also reshape itself to sustain a maximum of stress with a minimum of bone tissue. Atrophy, or decrease in size, can occur when pressure on the bone is constant and excessive, when periods of pressure exceed periods of release, and when there is little or no stress on the bone, as in periods of weightlessness. Bone proliferation can occur, however, in response to concussion or intermittent pressure. Excessive pressure in growing bone will slow down or stop bone growth, whereas the same conditions applied to mature bone may trigger either excess growth or internal rearrangement of structure (28).

The elasticity of bone is very low. A rod of bone can be elongated only about $1/200^{th}$ of its length before failing in fracture. The deformity to point of failure is plastic in nature and the bone will not return to its original length after the load is removed (28). A bone in a static situation will behave differently under dynamic loading. While the resulting effects are beyond the scope of this paper, it suffices to say that the femurs shot in this work will be preloaded with approximately 25 lbs. of weight bearing directly down on the femur to simulate body weight. The leg will not be moving before impact, but after impact the bone will collapse as the weights fall a short distance. There is also little question of fracture. As this paper was commissioned to look at the effects of tungsten-tin bullets on bones encased in ballistic gelatin, with resulting energies and velocities quite high enough to ensure fracture from a direct hit.

A study by Bird et al. (1968) is of more pertinent interest to this paper. In the study, specimens of cortical bone from fresh beef femurs were struck by a steel impacter which sent the specimens flying through two photoelectric gates. The specimens were then caught in soft cotton waste and analyzed with respect to fracture. Three classifications were established to categorize the results: 1.) survival, with no observable evidence of cracks, 2.) microcracking, with the presence of continuous cracks varying from 1x10 –3 to 1x10-2 inches in width at magnifications of 50x-100x, and 3.) gross failure, where the recovered specimen had been broken into two or more pieces. Of relevance to this paper are the latter two categories, as it is expected that all the bones shot in this work will undergo fracture (16).

In the specimens that exhibited microcracking, Bird found the microcracks tended to follow the contours of the osteons, or Haversian systems, which suggest the presence of stress concentration factors greater than unity at those locations. This has direct relevance to the expected comminution of bones in this work, as the individual fragments will likely follow the same method or initial cracking prior to full comminution and fracture (16).

The bone fragments obtained from the first part of this thesis will be measured with respect to weight and size, and the work of Bird et al. may assist in classifying the fracture occurrence and mechanism of the fragments with respect to the different bullet types. The second part of the thesis, dealing with the evaluation of synthetic bone with respect to real bone, will benefit from Bird's description of fractures as the mechanisms of failure of the synthetic bone are classified and compared to those of real bone.

Macrostructure of Bone

Having discussed the microstructure of bone in detail, some text should be devoted to an overview of the macrostructure of bone, specifically the femur.

The femur belongs to the class of bones known as *ossa longa*, or long bones. It is commonly referred to as the thighbone, and extends from the pelvis to the knee. The shape is that of a long narrow cylinder. It has a large, round, ball-shaped projection near the top, known as the head, that fits into the acetabulum, or socket, of the hip. This "ball and socket" connection permits a generous range of movement and rotation. The short piece of cylindrical bone that connects the head of the femur to the main portion of the bone is the neck. The sharp ridge across from the head of the femur is the greater trochanter, and the sharp ridge immediately underneath the head is called the lesser trochanter. There is a distinctive raised ridge of bone that runs from the greater trochanter to the lesser trochanter, known as the intertrochanteric line. All the features mentioned above are located at the upper part of the femur. This general area is referred to as the proximal epiphysis, where "epiphysis" refers to either extremity of a long bone, and the term proximal denotes the end closest to the body.

The flared area of the bone at either end of the long thin central section is known as the metaphysis. It is adjacent to the epiphysis at either end. The long central portion is known as the diaphysis.

At the distal end of the femur the epiphysis is rounded, with a notch bisecting the curved part. The notch runs anterior-posterior in relation to the body. It is in this notch, called the trochlea, that the medial condyle of the femur rotates in, thus resulting in the knee joint. The rounded shafts on each side of the trochlea are known as the condyles. The condyle facing the body is the medial condyle, and the condyle on the outside is the lateral condyle. The rough areas above each of these condyles are known as the medial and lateral epicondyles. Above these epicondyles is the distal metaphysis, which then runs into the diaphysis of the femur.

To this point no distinction has been made between human and porcine femurs. This is largely because there aren't any major physical differences to be found between the two. The above descriptions can apply to both species, although the location of the head in the human femur is above the greater trochanter, where as the head of the porcine femur is below the greater trochanter. Any differences relevant to this testing would be of more concern in the microstructure of the diaphysis of the bone, as this is where all the projectiles will impact the femurs.

Studies have been conducted by Yamada in 1970 which found that the ultimate tensile strength and mean tensile strain of human bone (12.5kg/mm^2 and 1.4% elongation, respectfully) is greater than that of most other mammals, including pigs (9kg/mm^2 and 0.7% elongation, respectfully). Mean compressive strength of femoral bone is also greater in humans (12kg/mm^2), though the mean modulus of elasticity (1750kg/mm^2) and compressive strain (1.8%) of human bone are intermediate with respect o other mammals (Yamada, 1970; 16). Pig bone, however, is still weaker than human bone in these areas, with a compressive strain contraction of 1.9%, and 1500kg/mm^2 modulus of elasticity and mean compressive strength of 10kg/mm^2.

Despite this data on species differences for the above mentioned strengths and strains, no data could be found comparing impact characteristics between pigs and humans, although Hert et al. (1965) did investigate compressive and impact bending strength of Haversian cortical bone from the long bones of cattle, turtle, rabbit, and man. No essential differences were revealed. The authors state "the values of impact bending tests keep constantly the same level." A large variability was noted, however, changing from 0.7 to 2.0kg-cm. Evans believed this variability could have been the result of the low sensibility of the impact tester at low values, or even differences in the orientation of the specimens; they note it was impossible to determine whether or not the specimens were subjected to tangential or to radial impact stress (16).

Synthetic Bones

The synthetic bone substitutes used in this testing were developed by a group of researchers at UT in the early 1990's. The material of these "bones" consists primarily of a nylon based polymer which contains fibers in a non-directional matrix. The "bones" are formed by injecting the molten nylon fiber mixture into a mold of the desired finished shape.

The physical shape of the bones used in this testing were cylinders approximately 14" long and 1" in diameter. The ends are rounded. This shape is designed to resemble the diaphysis of human long bones.

These bones have been evaluated previously for stress and strain properties, but no impact testing has been performed. The original intent of this testing was to evaluate tungsten-tin and lead bullets against real bones encased in gelatin. The goal was to learn about how the tungsten-tin bullets fragment when impacting bone, and what the differences were between the tungsten-tin bullets fragmentation and lead bullet fragmentation upon impacting bone. Due to DOE policy, it wasn't possible to use actual human bones in this testing, and porcine femurs were selected as an appropriate substitute. After the testing protocol had been established, it was decided that a subsequent part of this thesis should evaluate the synthetic bone substitutes under the same aforementioned bullet impacts. This would provide valuable information with respect to the impaction properties of this synthetic bone, and shed light on its viability as a real bone substitute by comparing the fracture behavior and comminution of the synthetic bone to that of the real porcine bones.

Impact Testing of bone

Impact testing on the microstructure of human bone has been carried out by several researchers (16; Dempster and Coleman, 1960; Evans and Bang 1966, 1967) that revealed microcracks resulting from impact seemed to follow contours of osteons. It should be noted that in addition to the propagation of microcrack along osteons, large physical irregularities on the surface of the femur can act as stress risers and contribute to fracture paths. It is expected that fracture paths in the pig bone will follow the osteon pattern in a manner similar to human bone. It is expected that the differences in the compressive and tensile strengths and strains will have less of an effect on the comminution of the bone under impact than will the microstructures of each type of bone, which is very similar. These large, physical irregularities can be classified as depressions or projections, and articular (forming an integral part of a joint) on non-articular (located outside of joints). Most provide attachment points for muscle tendons or ligaments.

The previously described features of the epiphysises of the femur are considered articular projections and depressions. As this testing involves the diaphysis of the femur, non-articular projections and depressions are more relevant and demand investigation and identification.

Articular Projections include:

Head	A spherical articular projection, such as the head of a femur.
Condyle/Condylus	More or less a cylindrical articular mass, such as the condyles on the distal end of a femur.
Trochlea	Pulley-like articular mass, as found at the distal end of the femur, on which the patella slides.
Facet	Relatively flat articular surface, as found between adjacent carpal bones.

Non-Articular Projections include:

Process	General term for a bony projection, such as the spinous process of a vertebra.
Tuberosity/Tuber/Tuberus	A large non-articular projection, such as the major (lateral) tuberosity on the proximal end of the humerous.

Tubercle/Tuberculum	Smaller non-articular projection.
Spine/Spina	May be a pointed projection, such as the spine at the proximal end of the tibia, or it may refer to a ridge, such as the spine of the scapula.
Crest	A sharp ridge of bone.
Neck	A cylindrical part of a bone to which a head is attached.
Line/Linea	A small ridge or mark on a bone, often caused by the pull of a muscle.

Articular Depressions include:

Glenoid Cavity	(Cavity glenoidalis) is a shallow depression found on the articular surface of the scapula.
Cotyloid Cavity	Deep articular cavity, such as the acetabulum of the hip.

Notch	An articular indentation or nonarticular indentation in the margin of a bone.

Non-Articular Depressions include:

Fossa	A large non-articular depression.
Fovea	Small non-articular depression, such as the fovea capitis on the head of the femur.
Foramen	A circumscribed hole in a bone.
Canal	A tunnel through one or more bones.

Projectile Impacts Against Bone Encased in Ballistic Gelatin

It must be reminded that the primary targets in this testing were the bones encased in the gelatin and not the gelatin itself. While every effort was made to ensure the replication of tissue properties, the gelatin served mainly to capture the bone fragments in a manner similar to actual tissue. Drs. Ragsdale and Amato have both conducted research using this method (51,3). Pertinent to this paper, Ragsdale and Amato both separately found that there was indeed a correlation between increased gelatin disruption and the generation of bone fragments that act as secondary missiles, as well as projectile fragmentation (3). Ragsdale also notes that comminution of long bone segments can differ markedly within temporary cavities of similar size, although in this testing it was found that bone comminution was fairly consistent within each caliber. This difference is likely because of the similar calibers used in this testing, versus the twelve different calibers Ragsdale shot. No multiple shots of one caliber and bullet type were performed in Ragsdale's testing. This has significant impact on the validity of the testing, as the exact placement of the shot can affect how a bone fragments and the degree of comminution it undergoes. In an attempt to minimize this variability three shots of each type of bullet and bone combination were made in this testing. While this method may not provide enough shots to satisfy even the most lax statistician, it does increase the probability of more uniform shot placement. It also provides the researcher with a better understanding of what a shot looks like and precludes the inclusion of mis-aimed shots in the data.

In his paper, Ragsdale uses repositioned cortical fragments of bone as the index of comminution. To achieve quantifiable indices of target damage, he combines this with the diameter of the maximum temporary cavity in the surrounding gelatin. He goes on to state that when comparing weapons and cartridges of great wounding capacity, additional data should be obtained, such as the size of osseous cortical defects, weight of residual unassembled bone fragments, degree of paracortical vapor dissection, the violence with which the target leaves the stand, and the residual energy of any exiting components. The third and fourth metrics that Ragsdale advocates recording are arguably difficult to quantify, and were not considered for this paper. The last metric of residual energy is viable, but if it occurs there is no finite measurement on depth of penetration. Osseous cortical defect size is also reasonable, but obviated in this testing by the shot placement being in the diaphysis. Ragsdale made all of his shots into the metaphysises of bones, which exhibit considerably less uniform surfaces than do the diaphysis, which is relatively smooth and uniformly cylindrical. In the testing done in this paper, the number of fragments found completely detached from the periosteum of the main sections of bone were collected. This included any bone fragments that were found projected into the permanent cavity of the target as well as at the bone itself. The rationale behind this selectivity was that it was likely that only those bone fragments that became completely detached would be propelled out into the edges of the temporary cavity as it expanded to its maximum diameter. These fragments would then be responsible for the majority of tissue damage not directly attributable to the bullet itself. These fragments were later divided into one of two size categories (large or small) and the weight of the collective fragments in each category was recorded to the nearest 0.02 grain.

Amato's research also states that bone fragments can act as secondary missiles and increase the severity of tissue damage (3). Amato also states in his paper that the critical velocity for fracturing bone is approximately 200 feet per second, though he gives no specific bullet mass required to achieve this, nor does he elaborate on what type of bone was used to establish this velocity. The data generated in this paper's testing doesn't refute that, however, as all synthetic and real bones readily fractured at all velocities in this test. The velocities of the projectiles used in this test were between 900 Fps and 2800 Fps.

Amato offers no objective data in his paper, relying instead on frames of film from high-speed cameras to illustrate the phenomena of the temporary cavity and the bone fragments that project out to the edges of the cavity when it is at its maximum diameter. These photos do present evidence that bone fragments and spicules can and do act as secondary missiles in tissue and contribute to wound severity by acting as cutting tools for the dispersion of the projectiles energy. At least one of the frames of film in Amato's paper shows the presence of bone fragments in front of the main sections of bone. This effect of bone fragments being propelled forward into the permanent cavity in front of the main sections of bone was recreated in the testing performed in this paper.

While some experts may be critical of evaluating projectile impacts against bone in gelatin, Ragsdale writes that "the treatment decisions of surgeons must be based upon a knowledge of mechanisms of injury and an ability to correlate various technical parameters (ordnance design) with the ensuing medical events (wounding). The gelatin/bone target system is an explicit means of integrating these considerations. Since it approximates a thigh it is particularly relevant to extremity wounds where the question of extent of debridement required is most frequently raised" (51). Amato reports on the relevance of testing projectile impact against bone encased in gelatin by saying that it creates an environment that clearly visualizes bone destruction (2). In addition to these justifications, this work is being funded by the

United States Department of Energy which has specifically requested that the new tungsten-tin bullets be evaluate against bone.

CHAPTER 4

BALLISTIC GELATIN

Given the previous discussions on wound ballistics, bones, and wound severity, it stands to reason that there is demand for some medium that simulates the mechanical properties of human tissue. Short of shooting an actual human being, which is generally frowned upon in scientific circles, the next best attempt is to shoot something that behaves in a manner similar to human tissue, and gives as exemplar performance as possible in a repeatable, uniform manner.

The current favorite in scientific research is called ballistic gelatin. Not unlike the commercially available Jell-O food product, ballistic gelatin is a substance derived from organic bones. In its raw state it resembles a light peach-colored powder. It is soluble in water.

Prior to the standardization of gelatin as a viable substitute for human tissue, several other materials were used as research media. Clay, duct compound, soap, wax, and even saturated paper pulp (from wet telephone books) were used in attempts to measure the performance of projectiles. No research was uncovered in the course of this testing that indicates that any of these materials were objectively measured against real tissue in an attempt to justify the validity of media, at least into the mid-

1980's. It was at this time that a wound ballistician and veteran US Army surgeon by the name of Martin L. Fackler performed a series of tests that evaluated these various materials (including ballistic gelatin) against real organic tissue (striated swine tissue) (24, 25). In the course of his testing, Dr. Fackler was able to show that ordnance ballistic gelatin "reproduces the penetration depth, deformation and fragmentation pattern, and yaw behavior seen in living muscle tissue. Measurement of the radial cracks in the gelatin caused by the stretch or temporary cavitation also gives an approximation of the magnitude of this disruption at any point along the missile path" (23). Fackler states in the same paper that the ballistic gelatin, when prepared properly, reproduced within 3% the penetration depth measured in living swine leg muscle. The deformation of bullets and the location of their fragments in living swine muscle were also duplicated in properly prepared gelatin.

"Properly prepared" is the main distinguishing difference between previous ballistic gelatin studies and those following Dr. Fackler's work. To start, the gelatin must be mixed using the correct raw material (powder). Type 250 A ordinance gelatin is the specific type used in Fackler's work. He procured his from the Kind and Knox Co. in Sioux City, IA, but other manufacturers have begun producing the powder at lower costs. The gelatin is mixed 10% by weight with ordinary water. MacPherson, in his book Bullet Penetration, provides a complete and detailed description of the mixing procedure on page 79. This mixing procedure calls for slowly stirring the gelatin powder into cold water, then placing the mixture in a refrigerator for two hours to ensure saturation of the gelatin powder. After removal, the gelatin mixture is to be slowly heated to 104 degree F and slowly stirred until the gelatin is evenly mixed throughout the container. The gelatin should then be poured into molds and placed into a refrigerator at 40 degrees F for at least forty-eight hours prior to use (36).

We found that the gelatin powder didn't achieve suspension in the initial cold water recipe, and had much skepticism with the necessity of the complicated mixing procedure. Instead, we followed an alternate set of mixing instructions written by Dale Towert that recommended heating the water to 140 degree F (60 degree C) before slowly stirring in the gelatin powder (61). After adding cinnamon oil to retard foaming, the mixture was poured into prepared molds and left to set up overnight. After the gelatin had firmed, it was pulled from the molds and wrapped as tightly as possible in a plastic bag to prevent dehydration. The gelatin was cooled to 40 degree F (4 degree C), and subsequently shot at that temperature. This method was much more reliable in providing consistent density gelatin that possessed excellent clarity, as well as being much simpler and less time-consuming to prepare. Subsequent calibration tests showed consistent penetration depths of approximately 3 inches at 39 degree F from a BB traveling approximately 565 feet per second. While tissue replication specs call for 3.35 in, or 8.5 cm, MacPherson does include a correction table in his book that is reproduced here. He also notes that even experienced gelatin makers cannot guarantee perfect uniformity between batches, and the table was created for this reason. The gelatin used in this testing is type 250 A ordinance gelatin.

The actual physical appearance of the gelatin is very similar to the Jell-O food product commonly served as desert. The two products have the same "feel" and texture, although ballistic gelatin is more dense than the food product. Ballistic gelatin also has an inherent yellowish tint that makes a large block appear opaque at a distance, but clear up close. As cross sections are removed from the block and the width decreases, clarity also improves.

CHAPTER 5

TARGET SHAPE

When the Department of Energy requested that the tungsten-tin bullets be tested against bone, this provided the opportunity to evaluate a synthetic bone that researchers had developed at the University of Tennessee in the early nineties. It also helped to determine what the overall shape of the target should be. The targets used in this testing were in the shape of long, narrow, upright rectangles. One end of the rectangular gelatin block contained one of the two types of bone positioned transversely and completely encased in the gelatin. The end that contained the bone was also rounded, so that the width of gelatin on either side of the bone was the same depth as the front of the gelatin target was to the longitudinal centerline of the bone. The targets were placed on the target stand on their side with the rounded end toward the shooter. This presented a tall, narrow target face to the shooter with the bone standing upright in the middle of the target face. Each target is 24" long, 8" wide, and 16" high. Each target was cut in half while still in the mold to facilitate removal, then reassembled on the target stand. Each target required approximately 36 liters of water and 4kg of gelatin powder to yield the required 10% gelatin mixture. The resulting weight of each target was approximately 90lbs.

The targets were cast in aluminum molds built exclusively for this testing. The bones were held upright in the molds by means of a specially constructed stand. Once the bones were secured upright in the empty mold, hot liquid gelatin was poured into the mold, immersing the bone completely. The shape of the target was determined by several constraints. The height of the mold was determined by the need to fully encase the bone in ballistic gelatin. The length of the mold was designed to be able to capture the entire penetration of each projectile after it had penetrated the bone. The width of the mold was governed by two constraints: the first was that there be enough gelatin on either side of the bone to fully contain any MTC that might be generated, and secondly to approximate the width of a human thigh. This second reason also determined the shape of the front of the mold. The 3.5" radius of the gelatin around the bone in the front of the mold was determined from 50^{th} percentile Army male anthropometric data (67).

A caveat is required at this point. While the target mold was in part designed to approximate a human thigh, it should not be construed that the resulting wound paths directly simulate a projectile impact into a real human thigh. The actual human thigh is composed of many different types of tissue (muscle, fat, bone, tendons, ligaments, arteries and veins) that were not modeled in the simplistic bone and gelatin target used in this testing. It must be reminded that the purpose of the gelatin surrounding the bone was to simulate the retentive forces of human tissue surrounding the femur and to capture the bone and bullet fragments in positions that may reflect similar locations in human thighs.

Long bones were decided upon as test subjects primarily for the uniformity of the diaphysis of that particular type of bone. Indeed, the real bones used in this test all exhibited similar diameters (~1.5") and presented a large vertical target area that would enhance the repeatability of a consistent impact in the actual shooting. Further research on U.S. Army combat mortality and morbidity data reaffirmed the choice of long bones, and contributed to the design of the front of the target mold to resemble a 50^{th} percentile male US Army soldier's thigh. According to U.S. Army research, extremity hits make up a majority of the wounds inflicted to U.S. soldiers in every major war of this century. In World War One, 68% of all wounds involved the extremities, in World War Two it was 60%, in Korea it was 66.3%, and in Vietnam extremity wounds represented 69% of total wounds suffered (14).

Unfortunately, DOE regulations prohibited the use of actual human femurs to be used in projectile impact studies. This meant that a substitute would be required to simulate human bone, and after some research into the biomechanical properties of other species it was decided that porcine femurs would adequately serve in the absence of human femurs. The physical properties of the porcine femurs versus human femurs were covered in an earlier section of this thesis pertaining to bones.

The decision to use long bones as a test medium also played a large role in the existence of the second part this thesis. The real bones used in the first part of this thesis provided the ability to compare projectile impacts between the real bones and the synthetic bones that had been developed previously by a group of researchers at UT.

CHAPTER 6

PROJECTILES

"It's not the launcher that gets you, it's the projectile." R. Marcinko

Two different classes of bullets were used in the testing. The first class is pistol caliber with a velocity of approximately 300 meters per second, and the second class is rifle caliber with a velocity of approximately 1000 meters per second. The representative type of projectile from each class was specified by DOE. The pistol bullet caliber was specified to be 9mm x 19mm, whereas the rifle bullet caliber was specified to be 5.56mm x 45 mm. In each class, the first number designates the diameter of the projectile and the second number denotes the overall length of the entire cartridge (both bullet and shell casing). The type of bullet specified by DOE for the pistol testing was a 124 gr. semi-jacketed soft-point. This particular type of bullet has a copper jacket enclosing the base and sides (much like a cup) but the top of the round nose is left exposed with no covering. DOE requested this pistol caliber be used in the testing as it is the caliber of the current DOE issue service sidearm, the SIG-Sauer P226.

The type of projectile specified by DOE for the rifle testing was a 60 gr. soft point bullet. Like the pistol bullet, this rifle has a copper jacket enclosing the base and sides. Unlike the pistol bullet, however, this jacket encloses all but the very top point of the bullet, which is a small tip of exposed core material. The size of this tip is approximately that of the roller ball of a fine ink pen. This caliber was requested because the current DOE issue long arm is the M-4 carbine chambered for 5.56mm x 45mm cartridge.

For each type and caliber of projectile, two different versions were produced. One version used lead as a core, while the other used tungsten tin as a core. Thus, there were four separate types of projectiles evaluated in this test:

1. 9mm Pb
2. 9mm W-Sn
3. 5.56 mm Pb
4. 5.56 mm W-Sn

Figure 6-1 shows the 9mm lead bullets, figure 6-2 shows the 9mm tungsten tin bullets, figure 6-3 shows the 5.56mm lead bullets, and figure 6-4 shows 5.56mm tungsten tin bullets.

The ratio of tungsten to tin was varied for each caliber so that each tungsten tin bullet weighed the same as its lead counterpart.

The bullets used in this testing were made specifically for this testing. It should be reminded that within each caliber, the tungsten tin and lead bullets must be the same weight, height, and diameter. The only difference between each type of bullet, within caliber, is the core material. Lead bullets were considered to be the

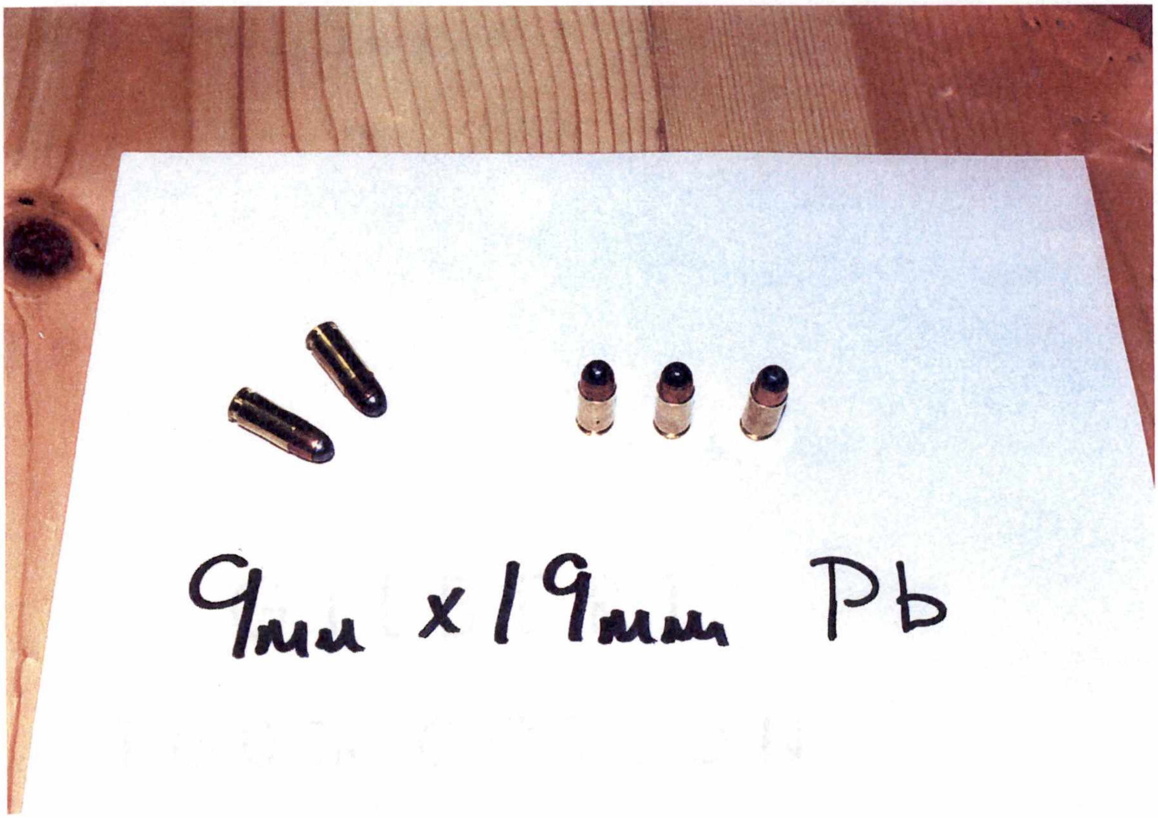


Figure 6-1: Lead soft-point pistol bullets.

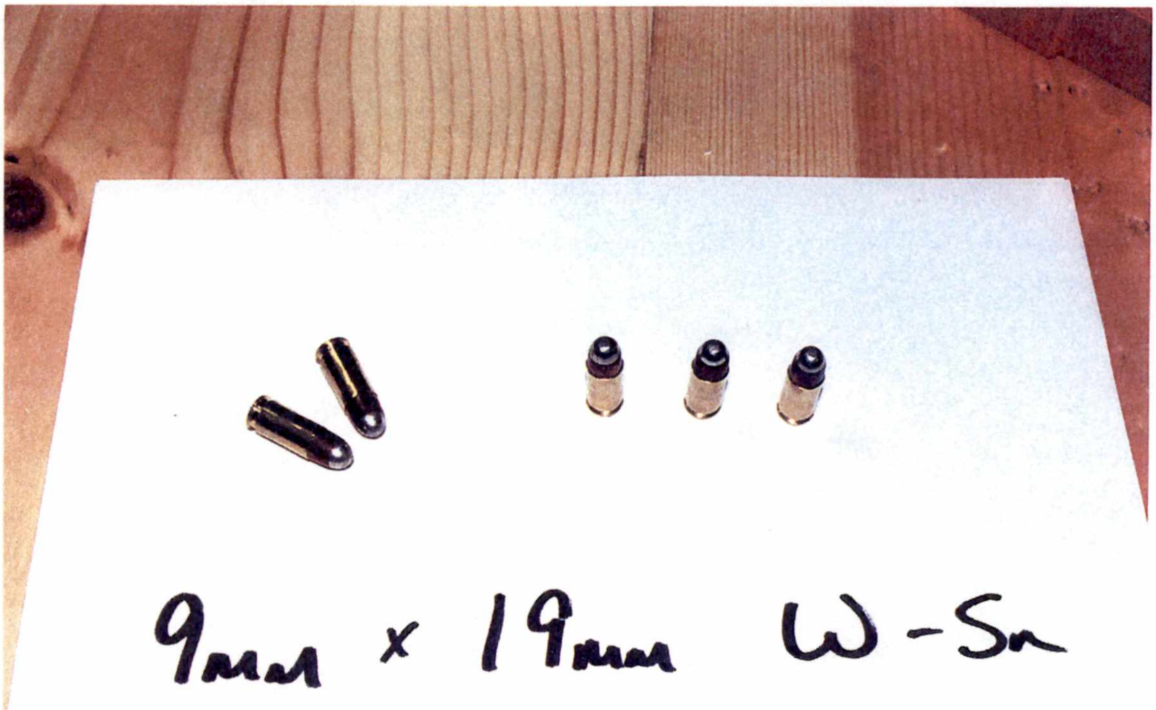


Figure 6-2: Tungsten tin soft-point pistol bullets.

Figure 6-3: Lead soft-point rifle bullets.

Figure 6-4: Tungsten tin soft-point rifle bullets.

benchmark for this testing, so it followed that the lead bullet be made first and then those parameters used as the specifications for the tungsten tin bullets.

The design of the lead bullets began with establishing the total desired weight of 60 grains for the finished rifle bullet and 124 grains for the finished pistol bullet. From this sum, the weight of the copper jacket was subtracted. The resulting figure represented the weight of the lead core.

The following illustrates the weights of the bullets and the subsequent weights of the cores.

9mm Soft Point:

Total weight	124.00 gr.	
-Jacket weight	19.50 gr.	(Jacket length = 0.435")
Core weight	104.50 gr.	

5.56mm Soft Point:

Total weight	60.00 gr.	
-Jacket weight	14.28 gr.	(Jacket length = 0.725")
Tip weight	1.60gr.	
Core weight	44.12 gr.	

To make the lead cores, lead wire was drawn through specially made dies to a diameter slightly less than the diameter of a finished bullet. This was necessary to account for the increase in diameter that the copper jacket would add to the core. The core diameters were 0.309" for the pistol caliber and 0.190" for the rifle caliber. This ensured that the cores would fit tightly in the jacket and leave no air space when the jacket was swaged over the core to its final diameter of .223" (5.56mm) for rifle and .355" (9mm) for pistol. The lengths of the cores were a function of the weights that had been specified for the finished test bullets. Fifty-two lead cores were made in each caliber and measured for length. Average weights and lengths were 0.461" (104.5gr) for the lead pistol cores and 0.720" (45.72gr) for the lead rifle cores. These measurements then became the targets weights and lengths for the tungsten tin cores.

The tungsten tin cores are manufactured using a powdered metallurgy process. Raw tin powder is mixed with raw tungsten powder in specific quantities based on weight. It is this ratio of tungsten weight to tin weight that will yield the final density of the bullet core. This density can be anywhere from 0% tungsten-100% tin to 100% tungsten-0% tin, but for this test a mixing ration of 68% tungsten and 32% tin by weight was selected because it yielded a density nearly identical to lead. This mixture was then weighed out on a digital scale (0.02gr precision) in small individual amounts of 104.5gr for pistol cores and 44.12gr for rifle cores. The core weight of the rifle slug is adjusted lower to account for the addition of a tin "tip" that is inserted above the core during the process of seating the core in the copper jacket. This tip prevents the tungsten-tin rifle core from cracking apart during the swaging process due to the narrow diameter of the rifle bullet.

These powder amounts are then poured into a specially made die of the correct diameter for the particular application (0.190" for rifle, 0.309" for pistol). This die is then placed in a press and 50,000psi is applied to the powdered core material in the die. This pressure is maintained for approximately 7 seconds, then released. The core is then pressed out from the die, and is now a shiny cylinder of tightly packed tungsten-tin metal powder. This is the finished core of the tungsten-tin bullet. This core is then slipped inside a copper jacket and run through the same swaging processes as the lead bullet to form it into the desired finished tungsten-tin bullet.

The tungsten-tin bullet technology was borne from a unique set of needs. First, the toxicity of lead meant that there was a desire to replace conventional lead bullets with an environmentally safer alternative. Second, DOE had expressed the desire for a bullet that would not ricochet into harmful fragments upon hitting a hard surface such as the steel or concrete commonly found in sensitive areas at DOE facilities. The tungsten-tin bullet technology has met both of these requirements, as neither tungsten nor tin has inherent toxicity (both are inert metals), and the tungsten-tin cores have been shown to fragment back into the original powder state upon impacting very hard surfaces.

Before fully accepting the tungsten-tin bullet technology into service, however, DOE requested that this new technology be evaluated against synthetic tissue targets containing real bones. Testing of this kind has never been performed, and it is a valid concern to determine the effect on tissue simulant. These bullets must first be capable of incapacitating aggressors before the benefits of reduced ricochet and toxicity can be realized.

The bullets were then hand loaded into shells to form the complete cartridge by a DOE employee in his own garage. A description of the firearms and firing procedure is found in the next section.

PART II

COMPARISON OF THE TERMINAL BALLISTICS OF TUNGSTEN TIN AND LEAD BULLETS

CHAPTER 1

METHODOLOGY

Originally, the contract for this work called for the creation of a wound ballistics laboratory at Oak Ridge National Laboratory, and that the testing for this thesis be performed there. After considerable delay, it was decided by the author of this work to perform the testing at an alternative location. This actual location took the form of a private residence in Morristown, Tennessee.

The bullets used in this testing were manufactured at ORNL. A total of 52 bullets were made in each caliber for each type the bullets were loaded into cartridges by a DOE employee to factory specifications.

The original testing called for the use of a universal receiver with interchangeable barrels as the "firearm" for shooting the bullets. Due to forces beyond the scope of this discussion, however, it was unavailable for use at the location of the testing. In light of this it was decided that the actual types of weapons themselves, or weapons as similar as possible, be used to shoot the bullets. A benefit of this method is that more variables are eliminated, as there will be no doubt that the rifling in the barrel, barrel length, gas bleed (in the case of the rifle), and chamber are exemplar to the actual issue firearms that will be firing these bullets.

Although the thesis is split into two parts with respect to real bone first and synthetic bone second, the actual procedure consisted of the following:

1.	Pistol	W-Sn	Real Bone
2.	Pistol	Pb	Real Bone
3.	Pistol	W-Sn	Synthetic Bone
4.	Pistol	Pb	Synthetic Bone
5.	Rifle	Pb	Synthetic Bone
6.	Rifle	W-Sn	Synthetic Bone
7.	Rifle	Pb	Real Bone
8.	Rifle	W-Sn	Real Bone

Three shots were made of each type, resulting in a total of twenty-four shots for the entire testing. While three observations aren't nearly large enough of a sample size for an objective statistical analysis, it did provide the researchers with an idea of the repeatability and consistency of the exact placement and behavior of each shot. There were several times when targets were discarded and new shots made due to non-optimum shot placement or non-uniform bone placement inside a target.

The wound ballistics laboratory was made up of three large rooms. Each room was used for a separate stage of the testing. The first room involved the manufacture of the targets, as seen in figure 1-1. This stage was the most time and labor intensive part of the testing. A gelatin target began its existence as raw powder

Figure 1-1: Photograph of the mold preparation room. The hot plate and mixing drill can be seen on the bench against the right wall. The two molds can be seen in bottom left of the photo.

stored in an airtight container and common tap water. A large five gallon stainless steel cooking pot was used as the mixing container. Since this testing called for a ten percent gelatin mixture, nine liters of water were measured into the pot, then heated on a hot plate to a temperature of 140 degrees F. The water temperature was measured using an Accurite digital thermometer purchased from Lowes. The water was gently stirred with a drywall compound stirring tool at approximately 350 rpm as one liter of gelatin powder was added slowly to the water. This process often took several minutes. One milliliter of cinnamon oil was added after all the powder had reached suspension to retard foaming. Once the batch was complete, it was poured into a larger fifteen gallon stainless steel pot that had heating elements on its sides. This kept the batches of gelatin hot until they could be poured into the molds.

Each target required four of these batches of gelatin to completely immerse the bone. While the gelatin was being heated, the molds were prepared. The sides of the mold were wiped clean from any previous gelatin residue and rubber plugs were pushed into the two pressure relief holes in the bottom of the mold. A food-grade mold release agent was then liberally sprayed on the interior surfaces of the mold. Next, a porcine femur was removed from the freezer and inspected for fitness. Thirty femurs had previously been secured from Wampler's Farms of Lenoir City, Tennessee, in order to ensure that there would be at least twelve usable femurs that were as similar as possible. The femurs were chosen with an eye for a bare diaphysis (no tissue) and a completely intact periosteum. The overall length of all the femurs selected were between ten and a half and twelve inches long. Excess tissue was removed from the ends of the femurs in an attempt to minimize variance between the femurs.

Having been prepared, the femur was then secured to the stand which would hold it vertically immobile as the gelatin is poured around it. In the case of the real bone femur this stand was made from a half-liter plastic lab measuring cup that had been sawed in half. Notches were then made in the upper half of this cup to accommodate the trochlea and condyles of the real bone femur. This assembly was then placed inside the mold, near the front. A specially constructed brace was then placed across the top of the mold that secured the top of the femur. The synthetic bones utilized a slightly different stand due to their lack of articular projections and depressions. These stands were made from fifty-milliliter plastic cups that had 7/8" holes drilled into the bottom. The ends of the synthetic bone were placed in these cups and secured with narrow cellophane tape to the edges of the hole in the cups. These bones were then placed inside the molds in the same manner as the real bones were, and the same brace was used to secure the top of the synthetic bone once it was set up inside the empty mold.

The large self-heated pot of gelatin was then lifted onto a chair and slowly tipped into the mold. The gelatin was poured slowly in this manner in order to minimize turbulence and improve the clarity of the finished product. At the exhaustion of the large pot, the remaining batch in the small pot was added into the mold and completely immersed the bone in gelatin.

At this point the mold was left to congeal. Through painful experience it was determined that the gelatin targets could not be pulled from the mold until it had been allowed to set-up for at least two days. If an attempt was made to remove the gelatin target before this amount of time had elapsed, the gelatin would split and fall apart under its own weight. This could have been avoided with the use of a walk-in refrigerator, but none was available in the course of this testing.

After the requisite amount of time had passed, the sides of the gelatin were cut away from the mold with a 10" long boning knife. A long Plexiglas divider was then forced through the middle of the mold. This divided the mold into two more easily managed parts upon release. The mold was then laid upon its side and the rubber stoppers were removed from the pressure relief holes in the bottom. Tilting the mold upward then allowed the gelatin to slide out of the mold and onto a plastic sheet. Once out of the mold, each half of the gelatin target was tightly wrapped in a large clear plastic bag. This bag helped retain gelatin hydration and also served to hold the gelatin intact, as it was still weak enough to split if not handled gently. This, too, had been learned painfully by experience.

A refrigerator large enough to accommodate the gelatin blocks was not able to be procured, so a large 16 cubic foot Frigidaire freezer was relied upon instead. To prevent the blocks from freezing, a wooden platform was built to keep the blocks off of the freezer floor, and the blocks were kept away from the sides of the freezer walls. The door of the freezer was also left open. An Accurite outdoor digital thermometer was used to monitor the temperature inside the freezer near the blocks. Through experience it was determined that twelve hours were needed to adequately chill the blocks down to approximately 40 degrees F. After the blocks had chilled to the correct temperature, they were removed from the freezer and carried into an adjacent room in which the shooting was performed.

The shooting area consisted of a large concrete-floored area with block walls approximately 30' long and 15' wide as shown in figure 1-2. A bullet trap was constructed at one end of the room. This trap consisted of a large wooden box (5.5'high x 4.5'wide x 3'deep) surrounded by 3/8" thick steel armor plate on the sides and back. Sandbags were placed against the bottom half of the armor plates to brace them against the box. A target stand was placed in front of this box and served as a platform for the target to sit on and also support the weight platform that pre-loaded the bone in the gelatin. Different target stands were used with the pistol and rifle, as seen in the photographs. The chronograph used to record the bullet velocities for the pistol was a Pact-II mounted on a camera tripod, whereas an Alpha Chrony F-1 was used to record the velocities of the rifle. This second chronograph was mounted on the target platform itself during testing.

The pistol chosen for the testing was a SIG-Sauer P-226 in 9mm caliber. This pistol is currently the issued sidearm for DOE security teams. It has a 4.4" barrel length with a 1 turn in 10" barrel twist. The pistol was fired from a Ransom pistol test for stability. A photograph of the pistol in the Ransom Rest is provided in figure 1-3. The muzzle to target distance was 10 feet, modeled after the testing protocol used by the FBI.

The rifle chosen for the testing was an Armalite AR-15 carbine in 5.56 mm x 45mm caliber. This rifle is currently in use with various security and anti-terrorist

Figure 1-2: Photograph of the shooting area. The pistol stand can be seen in the lower right hand corner. The chronograph is in the center of the photo, and the target stand is in the right-hand side of the photo behind the chronograph. The bullet trap is the large wooden box behind the target stand.

Figure 1-3: Photograph of the 9mm SIG-Sauer P-226 in the Ransom pistol rest. Also seen below the pistol is the Daisy Model 880 BB rifle used to calibrate the gelatin.

teams, though with a few differences from the rifle used in testing. The issue weapon is referred to as the M-4 carbine, and has a 14.5" barrel with 1 turn in 7" twist rifling. It is also a selective-fire weapon, in that the firing mode includes the usual semi-automatic as well as a three round burst setting. Given the difficulties in trying to obtain an M-4 carbine, a readily available civilian counterpart was used instead. The civilian model differs from the M-4 carbine in that it has a 16" barrel and is not capable of select fire. The barrel of the test carbine is also of stainless steel, whereas the M-4's is chrome-lined carbon steel, but this did not impact the performance of the bullets. A photograph of the rifle is provided in figure 1-4. The previously mentioned difference in barrel length might increase the muzzle velocities of the projectile, but a small increase in velocity is not expected to noticeably affect the performance of the projectiles. It should be noted here that the handloaded cartridges were not meant to replicate the velocities of the current issue rounds but rather provide the entire testing with bullets traveling at consistent velocities. A rifle rest was not available for the CAR-15, so it was shot by hand. Several cloth bags filled with sand blasting media was used to stabilize the stock and forearm during shooting.

In the articles that were researched for this testing, the few papers that studied projectile impacts on bone did not account for any weight or stress the bone would be experiencing at time of impact. In light of this, it was decided early on in the planning stages of this testing that pre-loading the bones in the gelatin would add another relevant variable to the bones. While there wasn't any effort to record exactly what loading the bones experienced at time of impact, every bone was subjected to a 25lb weight applied directly down its longitudinal axis. It was felt that

Figure 1-4: Photograph of the CAR-15 used in the testing.

this preloading would address shortcomings of previous research and more realistically replicate the environment of a long bone under going projectile impact. To facilitate this loading, a steel stand was constructed that straddled the target and supported and guided a sliding platform. A long metal cylinder attached to the bottom of this platform fit through the platform directly into the top of the stabilizing cup that had been attached to the top of the bone prior to gelatin immersion. This stabilizing cup protrudes from the gelatin block. The platform was adjusted so that the distance it could fall was not more than a ½", and immediately prior to shooting the weight was placed on the platform thus preloading the bone. The temperature of the gelatin was recorded using an Accurite digital meat thermometer prior to shooting as seen in figure 1-5. After the shot was made, a Daisy Model 880 Powerline air-gun was used to calibrate the gelatin block. Six pumps of the air cylinder were used, as it gave a repeatable velocity of 570 feet per second, on average. This was the closest velocity that could consistently be achieved near the required gelatin calibration velocity of 590fps $\pm$ 20fps. Three shots were made into each block after the main shot, and the depth of the BB penetration were recorded. All BB penetrations were within gelatin calibration specifications.

At the conclusion of each main shot, the gelatin block was taken into the third room of the wound ballistics lab. Essentially a large, well-lit kitchen with a double basin stainless steel sink and a specially built 4' high countertop, this room was where the dissection of each gelatin block occurred. A photograph of this room can be seen in figure 1-6.

Figure 1-5: Temperature of gelatin target being recorded.

Figure 1-6: Photograph of the room where the target dissections occurred.

A large light box on the 4' countertop was used as the dissection table. The back lighting provided excellent clarity of the projectile path and location of bullet and bone fragments. A 10" Marttinen boning knife was used to cut sections of gelatin away in order to expose the wound path and bone. It was also used to dig out bullet and bone fragments from the gelatin and bone itself.

A Stanley 25' steel tape measure was used to illustrate scale in each photograph. A Pentax ZX-50 35mm camera was used to record various stages of each dissection. Annotations were made on yellow note cards describing the particular step being photographed. Any unusual or significant items in the target were also noted in this manner.

The dissection of the targets occurred in five separate steps. First, the target is laid on its side on the light box with the front of the block (bullet entry) to the observer's left. The top layer of gelatin is sliced off to expose the path of the projectile and the maximum temporary cavity. The maximum temporary cavity is defined as being the largest fissure split in the gelatin, and sometimes more than one cut was needed to uncover this. At this point, the second step of measuring specific characteristics of the target and photographing it in detail is performed. The third step consists of digging out any and all bone and bullet fragments from the surrounding gelatin and bone itself after notations have been made with respect to locations of the fragments. The fourth step is to remove the main intact bone segments from the target and attempt to reconstruct them in the original position of impact. The fifth and final step is to photograph the reconstructed bone by itself on the light box. Anywhere from four to twelve shots were taken of each target in this manner. The gelatin from all targets was discarded at this point. Due to biological hazard concerns, the real bone segments were discarded as well. Only the synthetic bones were retained for possible further inspection.

The bone and bullet fragments were placed in separate containers about the size of salt shakers. Each container was labeled with respect to the step number, shot order, bullet caliber and type, and whether the target was real porcine bone or synthetic bone. In obtaining bone fragments from the target, it should be noted that only those fragments fully separated from the main segments of bone were collected. Any bone fragments retained by the unbroken periosteum of the main pieces of bone were not detached to be collected. This decision was made because it is not believed that these fragments would significantly contribute to the severity of the wound, whereas bone fragments found throughout the temporary and permanent cavities may have acted as secondary missiles to contribute to wound severity (3).

The aforementioned specific characteristics of each target are the performance metrics that were decided upon to be recorded from each bullet-target interaction. These metrics are the raw data that was generated in this testing. Each of these metrics was listed out on a master sheet, and copies of this master sheet were filled out during the dissection of each target. An example of this sheet is found in figure 1-7.

This manner of data collection insured against errors or omissions in the data recorded from each target. It also facilitated straightforward analysis and comparison

Data Collection Sheet

Step #: Shot #:

I. Bullet Data

Bullet Caliber:

Bullet Velocity:

Total Bullet Penetration:

Bullet Fragmentation:

II. Calibration Data

BB Velocity:

BB Penetration:

Gelatin Temperature

III. Gelatin Target Data

Target Type

Bone Depth:

Bone Diameter:

Fracture Type

Comminution:

MTC Diameter:

MTC Location:

IV. Observations and Comments:

Figure 1-7: Data Collection Sheet

of data between different targets. The step and shot number were recorded first. These correspond to the order in which the shots were scheduled according to a previous outline of the testing, found in the appendix of this thesis. The bullet caliber was recorded as either 9mm or 5.56mm. The velocity of each shot was recorded next. Similar velocities between the tungsten-tin and lead bullets are necessary in order to limit any differences observed to the materials of the bullets and not the velocities. The bullet fragmentation was graded subjectively on a Likert scale. The fragmentation was classified as one of the following: very little, little, marked, or extreme. This parameter served to illustrate the behavior of the bullet against whatever target it impacted against.

The calibration data was recorded in order to ensure that the gelatin was indeed representative of human tissue according to accepted calibration standards. Although every effort was made to maintain consistency in the testing there were variations in target chill time due to time constraints. There were also variations in the density of the gelatin simply because of the sheer volume of powder and water used in making each target. A gelatin block that was mixed at higher densities but chilled to the correct temperature will result in a shorter than recommended BB penetration. The overall goal is to ensure valid comparable testing, and the temperature of the block in conjunction with the known BB penetration depth can reveal a measure of the density of the gelatin. No attempt has been made to theoretically establish a correction factor for gelatin in this paper. MacPherson cites a gelatin correction table in his book Bullet Penetration. It accounts for lower or higher BB velocities and the measured penetration they achieve. It was adequate for correcting the lower than desired BB velocities found in this testing. It essentially adds or subtracts a linear correction factor to a measured depth at a given velocity; the average penetration depth of the BB's in this testing was around 3.00", and the correction table in MacPherson's book recommended added 0.25" to this depth if the BB was traveling at 570 feet per second. This resulted in corrected calibration depths of approximately 3.25", which is 0.10" short of the 3.35" optimum depth specified by MacPherson in his book (36).

The gelatin target data provides information about the behavior of both types of the bones under projectile impact. The target type is recorded as being either real bone or synthetic bone. The bone depth refers to the amount of gelatin between the front of the gelatin block and the forward face of the diaphysis of the bone encased in the gelatin. It is this small amount of gelatin that the bullet must pierce before impacting the bone. The bone diameter was recorded to illustrate the similar sizes of the real bones used in this experiment and to ensure that no abnormally sized bone was used in the testing. The bone comminution was graded on the same Likert scale used for bullet fragmentation, with the following classifications: very little, little, marked, and extreme. The diameters and locations of the maximum temporary cavities were recorded as well. These data provide an understanding of bullet behavior by showing the point at which the bullet caused the largest amount of tissue disruption, in addition to revealing the extent of travel of the bone fragments in the MTC.

The observations and comments were recorded as a subjective tool for quantitative evaluation by the researcher. Any unique or interesting visual phenomena is likely to be recorded here.

This recorded data and the fragments in the specimen containers represent the bulk of the data obtained from this testing. The fragments in the specimen containers are then counted out onto a digital scale. The entire number of fragments are recorded. In this counting process, a subjective demarcation was made with respect to the size of the fragments. Each fragment was classified as either small or large. It was seen that the difference between the two classes was readily apparent to the observer. Large fragments were almost always 3/8" long in one or more dimensions, while small fragments were always less than or equal to 1/8" long in any dimension. Typically these small fragments were less than 1/16" of long in any dimension. These small fragments are believed to be interior cancellous and trabecular bone fragments of real bone, and the interior plastic fiber composite from the synthetic bone. After the cumulative total of fragments had been placed on the zeroed digital scale, the entire summed weight of all the fragments was recorded to the nearest 0.02 grains.

This method of data collection was performed on both the bone and bullet fragments. The purpose of this data was to provide a means of comparison of the effect that each type of bullet had on each bone and provide a means of comparing the comminution of the synthetic bones to that of the real porcine bones. The complexities of this analysis are not unacknowledged; every effort has been made to present the data and the analysis as clearly as possible.

CHAPTER 2

DATA FROM PROJECTILE IMPACTS AGAINST REAL PORCINE BONE

The data in this thesis is presented in tabular format. The individual shot data for the real bone targets will be presented first, followed by the recovered real bone fragment data. Table 2-1 shows the shot data from lead pistol bullets against real bone targets, table 2-2 shows the shot data from tungsten tin pistol bullets against real bone targets, table 2-3 shows the shot data from lead rifle bullets against real bone targets, and table 2-4 shows the shot data from tungsten tin bullets against real bone targets.

Table 2-5 shows the bone fragment data from lead pistol bullets against real bone targets, table 2-6 shows the bullet fragment data from lead pistol bullets against real bone targets, table 2-7 shows the bone fragment data from tungsten tin pistol bullets against real bone targets, and table 2-8 shows the bullet fragment data from tungsten tin pistol bullets against real bone targets.

Table 2-1: Shot Data for 9mm Lead Pistol Bullets Against Real Bone Targets

	Shot #1	Shot #2	Shot #3
Bullet Vel. (fps):	1067.9	1026.1	1051.2
Tot. Pen. (in.):	13.50	13.50	12.50
Bullet Frag.:	Very little	Marked	Marked
BB Vel. (fps):	~570	~570	~570
BB Pen. (in.):	3.00	3.50	3.50
Gel Temp. (° F):	39	39	39
Bone Depth (in.):	4.00	5.00	5.00
Bone Dia. (in.):	1.75	1.70	1.70
Frac. Type:	Complete	Butterfly	Butterfly
Comm.:	Little	Extreme	Marked
MTC Dia. (in.):	1.25	0.80	1.10
MTC Loc. (in.):	1.25" post-bone	1.10" post-bone	0.75" post-bone

Table 2-2: Shot Data for 9mm Tungsten Tin Pistol Bullets Against Real Bone Targets

	Shot #1	Shot #2	Shot #3
Bullet Vel. (fps):	1033.5	1041.5	1030.1
Tot. Pen. (in.):	15.75	14.00	13.00
Bullet Frag.:	Little	Very little	Marked
BB Vel. (fps):	~570	~570	~570
BB Pen. (in.):	3.25	3.50	3.00
Gel Temp. (° F):	39	40	39
Bone Depth (in.):	3.00	4.00	4.00
Bone Dia. (in.):	1.60	1.40	1.40
Frac. Type:	Spiral	Butterfly	Complete
Comm.:	Extreme	Extreme	Little
MTC Dia. (in.):	1.50	1.00	1.25
MTC Loc. (in.):	4.00" post-bone	2.00" post-bone	1.50" post-bone

Table 2-3: Shot Data for 5.56mm Lead Rifle Bullets Against Real Bone Targets

	Shot #1	Shot #2	Shot #3
Bullet Vel. (fps):	2844	2865	2666
Tot. Pen. (in.):	4.50	7.00	7.00
Bullet Frag.:	Extreme	Marked	Extreme
BB Vel. (fps):	~570	~570	~570
BB Pen. (in.):	3.25	3.40	3.00
Gel Temp. (° F):	46	48	39
Bone Depth (in.):	4.50	3.75	4.00
Bone Dia. (in.):	1.75	1.50	1.50
Frac. Type:	Complete	Complete	Complete
Comm.:	Marked	Marked	Extreme
MTC Dia. (in.):	5.50	4.00	4.50
MTC Loc. (in.):	0.00" post-bone	0.00" post-bone	0.00" post-bone

Table 2-4: Shot Data for 5.56mm Tungsten Tin Rifle Bullets Against Real Bone Targets

	Shot #1	Shot #2	Shot #3
Bullet Vel. (fps):	2907	2652	2969
Tot. Pen. (in.):	14.50	16.00	18.00
Bullet Frag.:	Marked	Little	Extreme
BB Vel. (fps):	~570	~570	~570
BB Pen. (in.):	3.00	2.90	2.75
Gel Temp. (° F):	39	46	42
Bone Depth (in.):	4.50	4.00	4.25
Bone Dia. (in.):	1.75	1.40	1.60
Frac. Type:	Complete	Complete	Complete
Comm.:	Extreme	Marked	Extreme
MTC Dia. (in.):	3.00	3.75	3.50
MTC Loc. (in.):	2.00" post-bone	3.75" post-bone	0.00" post-bone

Table 2-5: Bone Fragment Data from 9mm Lead Pistol Bullets Against Real Bone Targets

	Small Bone Fragments		Large Bone Fragments	
Shot #	Qty.	Wt. (gn)	Qty.	Wt. (gn)
1	23	31.56	1	22.4
2	72	19.54	7	32.54
3	33	24.14	4	87.30

Table 2-6: Bullet Fragment Data from 9mm Lead Pistol Bullets Against Real Bone Targets

	Small Bullet Fragments		Large Bullet Fragments	
Shot #	Qty.	Wt. (gn)	Qty.	Wt. (gn)
1	0	NA	1	122.40
2	15	7.32	3	108.18
3	4	13.78	5	96.96

Table 2-7: Bone Fragment Data from 9mm Tungsten Tin Pistol Bullets Against Real Bone Targets

	Small Bone Fragments		Large Bone Fragments	
Shot #	Qty.	Wt. (gn)	Qty.	Wt. (gn)
1	76	48.40	7	236.38
2	76	35.95	11	171.18
3	85	47.52	0	NA

Table 2-8: Bullet Fragment Data from 9mm Tungsten Tin Pistol Bullets Against Real Bone Targets

	Small Bullet Fragments		Large Bullet Fragments	
Shot #	Qty.	Wt. (gn)	Qty.	Wt. (gn)
1	6	18.86	1	98.50
2	10	13.14	1	100.32
3	34	32.28	2	77.20

Table 2-9 shows the bone fragment data from lead rifle bullets against real bone targets, table 2-10 shows the bullet fragment data from lead rifle bullets against real bone targets, table 2-11 shows the bone fragment data from tungsten tin rifle bullets against real bone targets, and table 2-12 shows the bullet fragment data from tungsten tin rifle bullets against real bone targets.

Table 2-9: Bone Fragment Data from 5.56mm Lead Rifle Bullets Against Real Bone Targets

Shot #	Small Bone Fragments Qty.	Small Bone Fragments Wt. (gn)	Large Bone Fragments Qty.	Large Bone Fragments Wt. (gn)
1	~100	12.34	8	217.90
2	73	37.88	12	263.02
3	~100	52.10	14	277.04

Table 2-10: Bullet Fragment Data from 5.56mm Lead Rifle Bullets Against Real Bone Targets

Shot #	Small Bullet Fragments Qty.	Small Bullet Fragments Wt. (gn)	Large Bullet Fragments Qty.	Large Bullet Fragments Wt. (gn)
1	44	16.86	1	11.18
2	17	8.52	1	28.80
3	32	22.38	2	17.30

Table 2-11: Bone Fragment Data from 5.56mm Tungsten Tin Rifle Bullets Against Real Bone Targets

	Small Bone Fragments		Large Bone Fragments	
Shot #	Qty.	Wt. (gn)	Qty.	Wt. (gn)
1	51	44.46	21	292.38
2	28	9.84	4	173.30
3	34	27.96	10	248.92

Table 2-12: Bullet Fragment Data from 5.56mm Tungsten Tin Rifle Bullets Against Real Bone Targets

	Small Bullet Fragments		Large Bullet Fragments	
Shot #	Qty.	Wt. (gn)	Qty.	Wt. (gn)
1	29	12.76	3	11.02
2	5	3.52	1	27.24
3	9	5.18	2	14.68

CHAPTER 3

COMPARISON OF TERMINAL BALLISTICS OF TUNGSTEN TIN AND LEAD PISTOL BULLETS

In looking at the differences between the 9mm lead bullets and the 9mm tungsten-tin bullets against real porcine bones, several items come to light. First it must be noted that each type of bullet did fragment against the bone and the total number of fragments recovered for each type yielded approximately the same total weight. The tungsten tin bullet fragments recovered were on average 113.43 grains of its 124 grain initial weight, and the lead bullet fragments that were recovered accounted for 116.21 grains of the initial 124 grain weight. That said, however, the tungsten-tin bullets on average broke into almost twice the number of fragments than did lead bullets. For the three tungsten tin shots against real porcine bone, each bullet broke into an average of 18 total fragments and had a deviation of 15.72. The lead bullet against the same target broke into an average of 9.33 fragments and carried a deviation of 8.50. The deviation renders these numbers dangerously close to irrelevant, but this difference in bullet fragmentation is also reflected in the breakdown of the fragments into categories of large and small. The tungsten tin bullet against real porcine bone broke into 16.67 small fragments and 1.33 large fragments on average, whereas the lead bullet broke into 6.33 small fragments and 3.00 large fragments on average against the same target. One could point out that the tungsten tin bullet had fewer large fragments than did the lead bullet, but this reflects in favor of the tungsten tin bullet by the nature of the fragmentation; namely, that the tungsten tin bullet, when it does fragment, does so into smaller pieces than does the lead bullet, on average. While it is tempting to state that in this testing the tungsten tin pistol bullets exhibited a higher degree of small fragmentation than did the lead pistol bullets against real porcine bones encased in gelatin, this conclusion is contradicted by applying the student t-test to this data, as it reveals no statistical difference in fragmentation between tungsten tin and lead pistol bullets.

The location of the these bullet fragments varied for each bullet type. In the tungsten tin bullet, the fragment pattern did not begin until after the bullet had exited the bone. This effect can be clearly seen in figures 3-1 and 3-2. Upon exiting the bone the tungsten tin bullet appeared to leave a trail of tungsten tin powder through the wound tract for the entire length of the permanent cavity. It appeared that the tungsten tin bullets may have cracked upon hitting the bone, but did not shatter as was expected. The bullets penetrated the bone and began shedding powder only after penetrating the first anterior wall of compact bone. The shedding appeared to take place as a reverse "snowballing" effect. It appeared that larger fragments would break off from the main bullet at slight angles and penetrate into the tissue surrounding the main permanent cavity. The average depth of these offshoots depended on the size, and therefore the weight, of the broken fragment. Each offshoot could be clearly seen

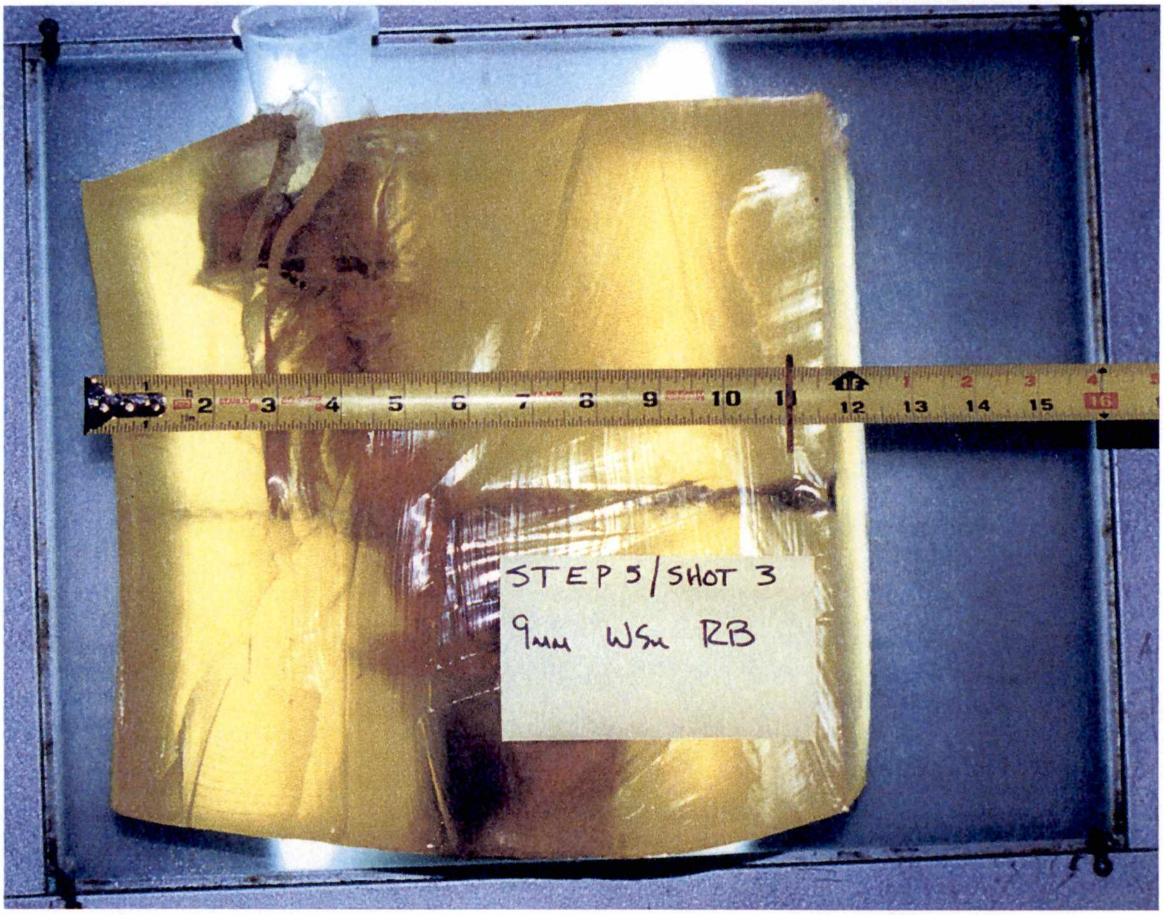


Figure 3-1: Tungsten tin pistol shot showing the trail of tungsten tin powder post-bone.

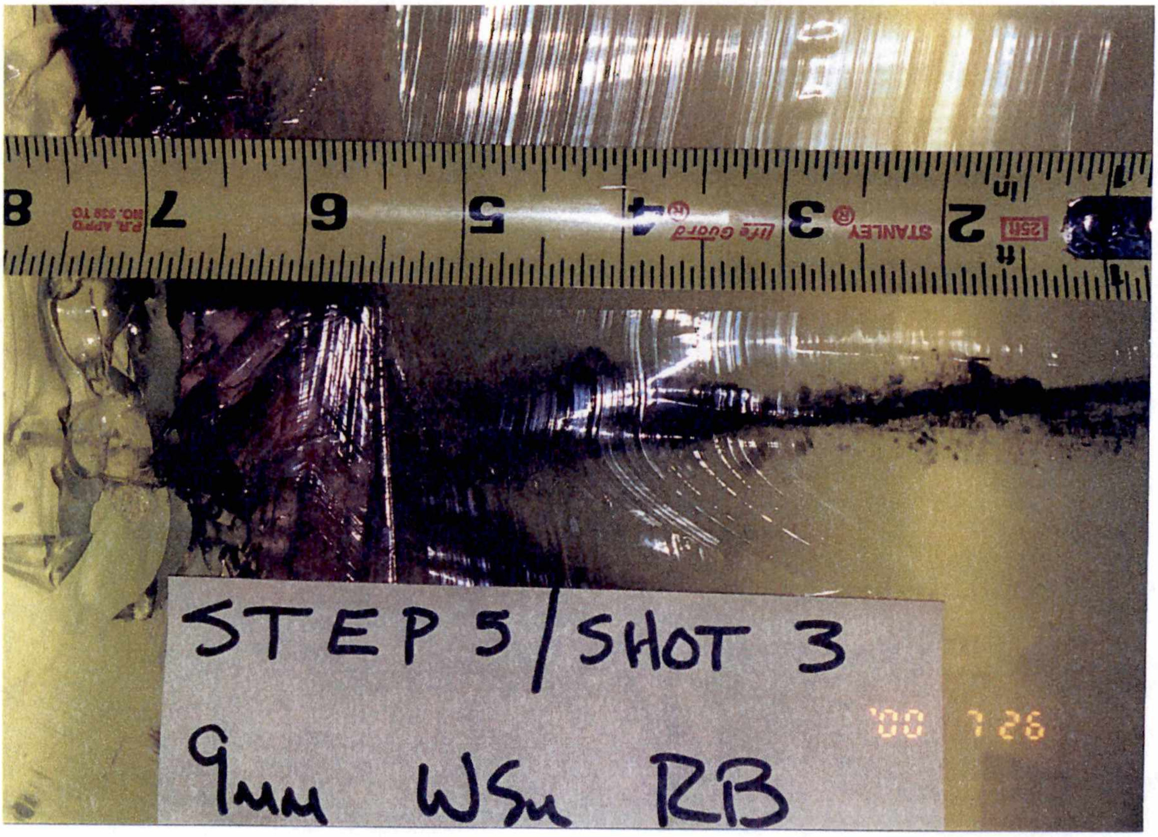


Figure 3-2: Close-up of tungsten tin powder trail post-bone.

as the fragments shed powder and slowly disintegrated until its energy had been spent or there was no longer a particle of tungsten tin to penetrate any further. The small tungsten tin fragments were all recovered in this manner. The entire tungsten bullet did not disintegrate, though, as the larger fragments were usually found at the end of the permanent cavity. These fragments can be clearly seen at the end of the permanent cavity in figure 3-3. These few large fragments were the bottoms of the cores of the tungsten tin bullets, and could be identified as such by their perfectly cylindrical cross section and smooth, flat base.

The majority of jacket fragments of the tungsten tin bullets were found in the area of gelatin prior to the bone, suggesting that the copper jackets peeled off the tungsten tin cores within the first few inches of penetrating the gelatin and prior to hitting the bone. When jacket fragments were found post-bone, they were usually still bonded in some way to the bottom of a large fragment of tungsten tin core.

The tungsten tin bullets exhibited deeper penetration depth than the lead bullets on average, although with a higher deviation. The average penetration depth of the tungsten tin bullets for the three shots was 14.25" with a SD of 1.39". The average velocity of these shots was 1035 feet per second. The average penetration depth of the lead bullets was 13.17", with a corresponding SD of 0.58". The average velocity for these shots was 1048.4 feet per second. While the larger deviation on the tungsten tin bullet makes this increase in penetration depth less important, what is more telling of the bullet's capability is the penetration depth of each bullet after the bone. The tungsten tin bullet penetrated an average of 9.12" post bone (SD = 1.83") while the

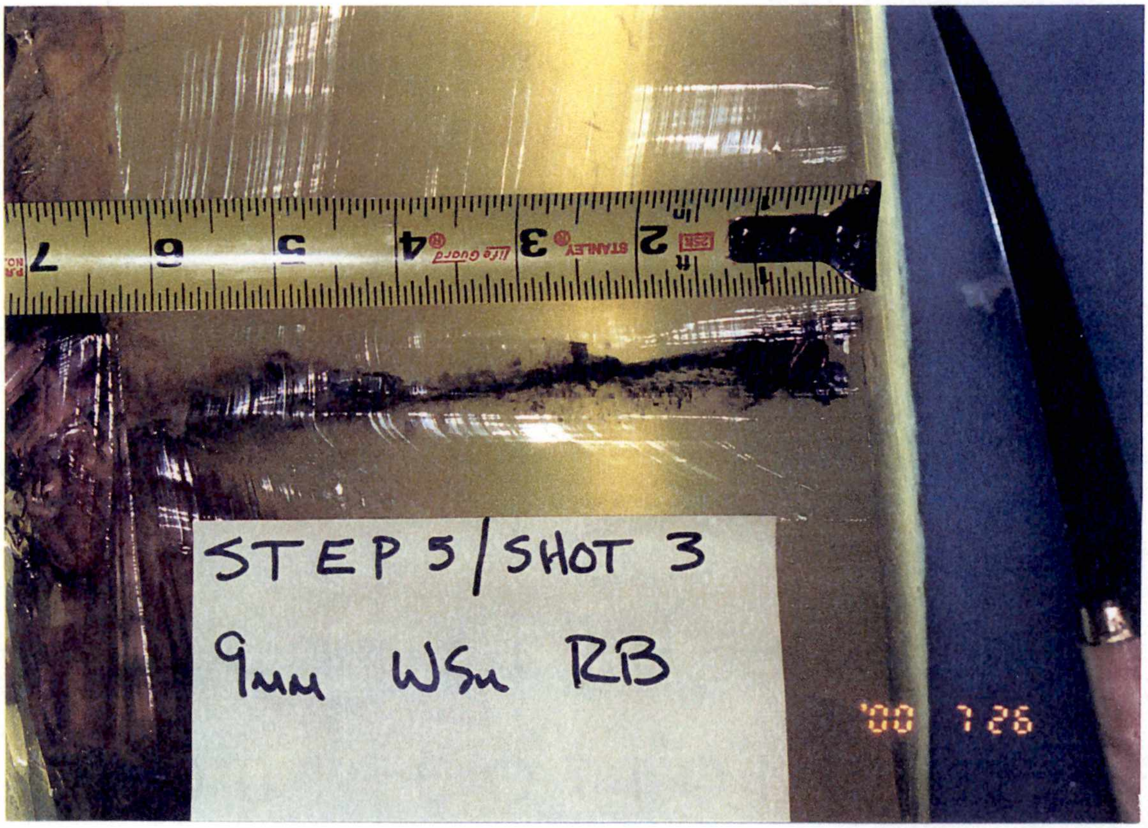


Figure 3-3: Tungsten tin pistol bullet fragments at the end of the permanent cavity.

lead bullet penetrated an average of 6.78" post bone (SD = 0.98"). In this case the more substantial difference in penetration depth helps offset the larger deviation. This increase in penetration depth suggests that the tungsten tin bullets retain a higher mass over a longer distance than do the lead bullets; i.e., that the tungsten tin bullets hold together longer and fragment later in the tissue than the lead bullets. From a wound ballistics standpoint, this increased depth is less important than controlling the depth at which the fragmentation happens. The increased deviation of the tungsten tin bullet penetration suggests that the penetration depth is not as predictable as that of the lead bullet due to the less uniform nature of its fragmentation. The fragments from the tungsten tin bullets were found throughout the permanent cavity post bone. The path can be clearly seen for its entire length due to the aforementioned tungsten tin powder residue that permeates the tract. As previously stated, there were only 1.33 large bullet fragments on average from these bullets. The lead bullet fragments displayed very different behavior by fragmenting into an average of 3.00 large pieces. These fragments were usually found in line with and at the end of the permanent cavity. There is no pattern of bullet fragments throughout the wound cavity, although there are bone fragments in the permanent cavity starting immediately after the bone and extending past the bone for several inches. These effects can be clearly seen in figures 3-4, 3-5, and 3-6.

The maximum temporary cavities occurred on average 2.5" past the posterior wall of compact bone and averaged 1.25" in diameter for the tungsten tin bullet, while the maximum temporary cavities for the lead bullet were on average 1.05" in diameter and occurred about 1.03" past the anterior wall of compact bone. This

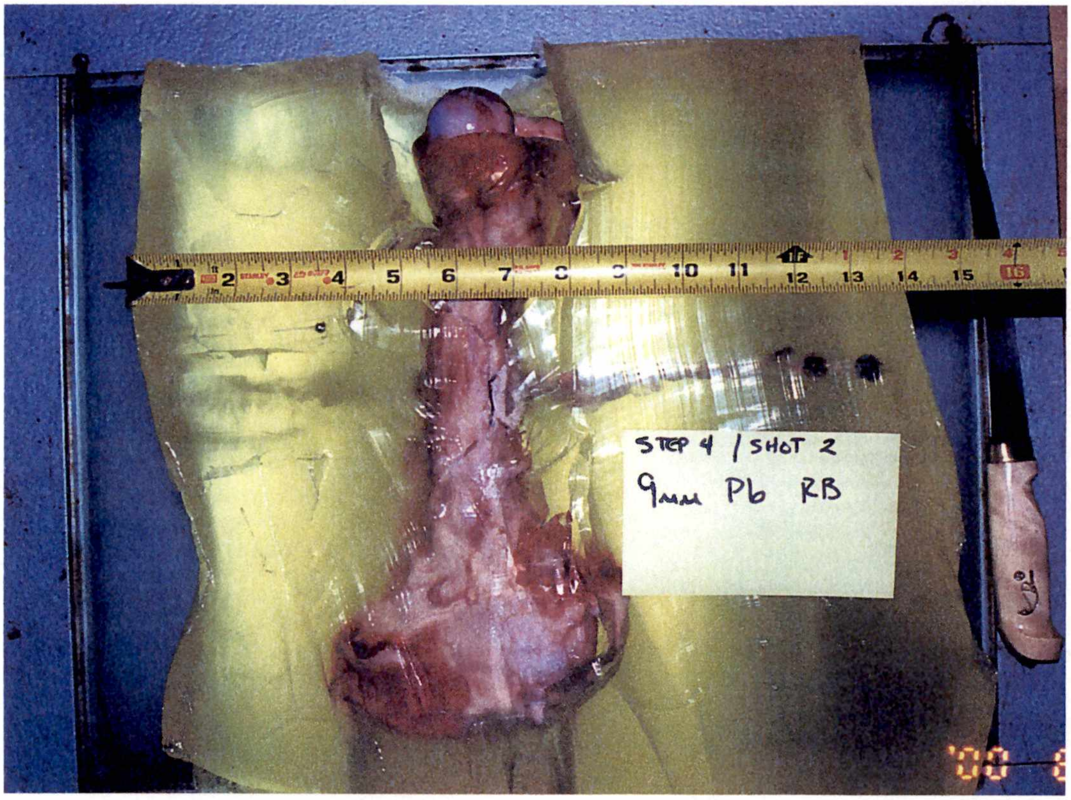


Figure 3-4: Lead bullet fragments seen at the end of the permanent cavity, with no evidence of significant bullet fragments throughout the permanent cavity.

Figure 3-5: Close-up of the lead pistol bullet fragments at the end of permanent cavity. Also note trailing bone fragments.

Figure 3-6: Lead pistol bullet target showing bone fragments in the permanent cavity immediately after the bone.

difference in MTC diameters between bullet types is negligible. The difference in location of maximum temporary cavities can largely be traced to the inconsistent depth of one of the tungsten tin bullets, which relegates this measure as being somewhat misleading. In reality, the maximum temporary cavities of both bullet are quite similar. The effect of the tungsten tin bullets fragmenting into many pieces throughout the wound, rather than a few fragments at one location, may contribute to increased wound severity in real tissue.

CHAPTER 4

EFFECTS OF TUNGSTEN TIN AND LEAD PISTOL BULLETS AGAINST REAL PORCINE BONE

In the cases of both bullet types, bone fragments were found throughout the permanent cavity post bone. It is these bone fragments that Amato suggests can be construed as secondary missiles and contribute to wound severity (3). In the case of the tungsten tin bullet, an average of 179.83 grains of real porcine bone fragments were collected from the wound tracts of each target. The standard deviation was very large at 96.89 grains, but like the previous MTC deviation, this is misleading. The last tungsten tin shot yielded several large bone fragments commensurate with the previous two tungsten tin shots, but these fragments were still connected to the main segments of bone by shreds of tissue that had not been adequately removed prior to shooting. These large bone fragments can be seen in figure 4-1. In the interests of consistency the decision was made to not collect these fragments. Ignoring this third shot, however, reveals that the large bone fragments from the previous two shots were reasonably consistent at 236.38 grains and 171.18 grains, respectively. The small bone fragments were very consistent, yielding an average of 43.98 grains (SD = 6.97gn) for each shot.

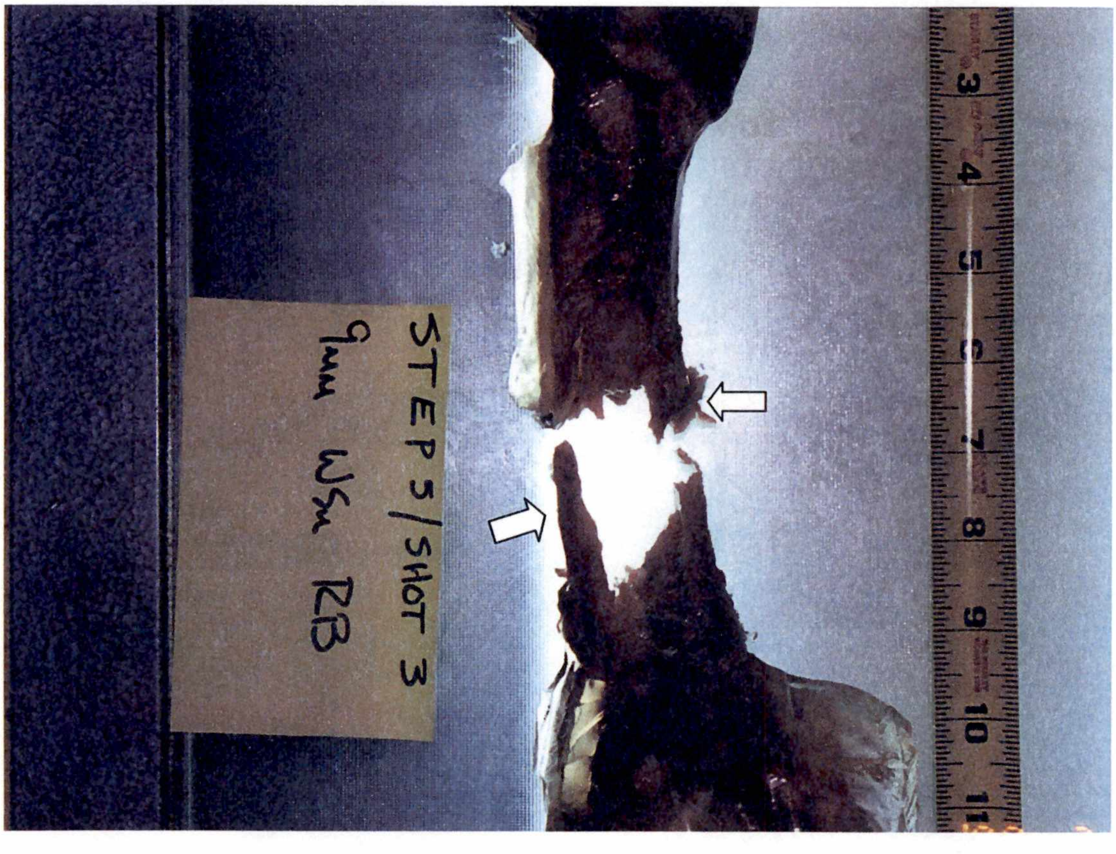


Figure 4-1: Third tungsten tin pistol shot showing at least two large bone fragments retained by excess tissue.

The lead bullets generated an average of 72.49 grains of bone fragments from each shot. The deviation of the lead bullet bone fragments was 33.74 grains. Like the tungsten tin bullet shots, this can largely be traced to the second lead bullet shot. The bone fragments in this shot that were classified as "large" were actually much smaller than the other large bone fragments seen in the other tungsten tin and lead bullet shots but were not small enough to be considered "small". While this might have prompted the addition of a "medium" size category, it also would have unnecessarily complicated the subsequent analysis of the other shots. As stated before, the decision criteria for "large" and "small" was based on a clear difference in size of the fragments collected and the likely different contribution each fragment would have on wound severity. Simply put, a big fragment would cause more secondary damage than would a tiny fragment. What is of importance to note is the marked difference between the average weights of the bone fragments generated by each type of bullet. The tungsten tin bullet caused more comminution by weight in the porcine real bone than did the lead bullet (179.83 grains versus 72.49 grains, respectively).

By dividing the weight of the fragments from each shot by the number of large fragments collected, an idea of the individual large fragment weight, and therefore size, can be determined. The collective weight of the large fragments from the tungsten tin shots against real bone was 135.85 grains with a deviation of 122.09 grains. This large deviation is the direct result of having no large bone fragments collected from the third shot. If the third shot is discounted, the average collective large fragment weight becomes 203.78 grains with a deviation of 46.1 grains. The lead pistol bullets generated a collective average of 47.41 grains of large real bone fragments and had a deviation of 34.91 grains. The average large bone fragment size (weight) of the tungsten tin bullet shots, discounting the third shot where none were collected, was 24.64 grains. This contrasts with the individual large fragment size of the lead shots at 16.29 grains. Also telling is the number of large fragments that were generated by the tungsten tin bullets. Ignoring the third shot, there were an average of 9.00 large bone fragments generated, whereas there were an average of 6.00 large fragments generated if the last shot that generated zero large fragments is included. There were only 4.00 large fragments generated on average from the lead bullet shots, each having an average weight of 47.41 grains and a deviation of 34.91 grains.

The small bone fragments reveal that the tungsten tin bullets caused more bone comminution by weight on a smaller scale than the lead bullets, as well. There were an average of 79 small bone fragments generated in the real porcine bone targets from the tungsten tin bullets. Their collective weight averaged 43.98 grains with a very small deviation of 6.97 grains. This suggests that the tungsten tin bullets cause consistent comminution on a smaller scale than on a larger scale. The lead bullets generated an average of 42.67 small fragments against real porcine bones, nearly half that of the tungsten tin bullets. The average collective weights of these fragments was 25.08 grains with a deviation of 6.06 grains. Like the tungsten tin bullets, it appears that the smaller scale comminution is more consistent than the comminution that occurs on a larger scale, although in both cases there really weren't enough large fragments generated to statistically objectify this observation. When the Student t-test was applied to this data, it supported the conclusion that the tungsten tin pistol bullets generated greater collective weights of bone fragments than did lead pistol bullets.

The t-test revealed a 0.976 probability that the collective small fragment weights from the tungsten tin shots were greater than those of the lead shots, and a 0.978 probability that the collective large fragment weights from the tungsten tin shots were greater than those of the lead shots. The t-test did not support any other statistical differences between bone fragment sizes and weights from the different tungsten tin and lead pistol shots, even though calculation of the simple means suggests otherwise, as previously mentioned.

The real porcine bones used in all targets in this testing came from similar sows, which should discount any possible differences in bone density. This assumption is required before any comparisons between sizes of fragments given the weights can be made. Amato states that bone fragments can become secondary missiles in tissue, and it stands to reason that a larger quantity of larger sized fragments would likely cause more tissue damage than a fewer quantity of fragments of a correspondingly decreased size would, assuming that the terminal locations of these fragments was similar. This introduces the second set of observations made on the bone fragments, which is the location where the greatest concentrations of bone fragments were found in the target.

The majority of bone fragments for both the tungsten tin and lead bullets were found in a cone-shaped pattern surrounding the permanent cavity. In all instances, this cone-shaped pattern was found almost immediately after the anterior wall of compact bone. These cones extend for approximately two or three inches past the bone and taper into the permanent cavity. Bone fragments are found throughout the permanent cavities of both types of bullets, but the cavities created by the tungsten tin bullets had a greater density of fragments than the cavities of the lead bullets. This correlates with the increased number of fragments generated by the tungsten tin bullets. Given that the locations of the fragments for each bullet type were in approximately the same areas, the greater number of bone fragments generated by the tungsten tin bullets suggests that more tissue in the same volume would be affected by the cutting action of these fragments than by the fewer bone fragments generated by the lead bullets. It does not, however, imply that there would necessarily be a greater *volume* of tissue disrupted by the tungsten tin bullets as compared to the lead bullets.

The Red Cross wound classifications of the tungsten tin and lead pistol bullet impacts against the real bone target were all of the grade 2 type FM or VFM category. All real porcine bones demonstrated marked comminution. The difference between an FM or VFM classification would depend upon major vessel disruption such as the femoral artery being damaged in some manner. In every case there was at least one bullet fragment found in or at the bone. The powder trail of the tungsten tin bullets becomes very obvious in every case after exiting the bone, and in the cases of both the tungsten tin and lead pistol bullets, parts of the copper jackets are almost always invariably found in the gelatin prior to the bone itself. This is likely due to the use of the soft-point bullet design of the projectiles used in this testing.

In every case of both the tungsten tin and lead bullet impacts, the resulting femurs were classified as a grade IV comminuted fracture according to the Winquist and Hansen method of femoral fracture classification. No major differences between the wound severity caused by tungsten tin and lead pistol bullets were observed when graded by the Red Cross Wound Severity Scoring System, nor were the fracture types of each bullet impact observably different according to the Winquist and Hansen method of grading femoral fractures.

CHAPTER 5

COMPARISON OF TERMINAL BALLISTICS OF TUNGSTEN TIN AND LEAD RIFLE BULLETS

Having analyzed the data from the pistol bullets first, and believing that there can't be that much difference between a few grams of material's difference in both the tungsten tin and lead bullets as they fly through the air, one might expect that the rifle bullets would behave in a manner similar to the pistol bullets. Simply stated, such an assumption would be a gross error. As mentioned in the beginning of this work, there are quite different phenomena that occur in tissue and gelatin when the velocity of a projectile is increased threefold and the weight is reduced twofold. It is medical fact that wounds produced by high velocity projectiles, such as rifle bullets, produce markedly different wound patterns than those of lower velocity pistol bullets. The wounds resulting from rifle projectiles tend to be deeper with a correspondingly larger maximum temporary cavity. Soft-nosed lead rifle projectiles are also designed to fragment in tissue, not simply expand as soft-nosed lead pistol bullets are designed to do. This fragmentation markedly increases wound severity by controlling the depth of tissue destruction. The increased energy of the rifle projectiles is also more efficiently used by these fragments than by a single intact bullet. The individual fragments disperse the energy of the initial projectile by acting as cutting tools through the tissue. Due to the fibrous nature of real tissue, a muscle bundle cut by a fragment can be completely detached and result in increased hemorrhage (19, 23). This is the benefit to achieving fragmentation and utilizing the increased energy associated with rifle projectiles. It is not typically desirable for a pistol bullet to fragment, as the reduced mass of the bullet will prohibit adequate penetration depths. Instead, it is expansion that is the accepted method of deformation used in pistol bullets to increase the destruction of tissue. This expansion is not necessarily to increase the diameter of the permanent cavity, but to increase drag so that the depth at which the maximum tissue destruction occurs can be controlled (36). Pistol bullets do not possess enough velocity, and therefore energy, to take advantage of fragmentation.

This discussion is largely meaningless, however, when the target is hard enough to make the bullets fragment on their own as was seen with the pistol bullets. The fact that conventional rifle bullets do create different wounds than conventional pistol bullets is important. The resulting analysis illustrates the effects of high velocity tungsten tin rifle bullets versus those of high velocity lead bullets against bones encased in ballistic gelatin.

In looking at the differences between the 5.56mm lead bullets and the 5.56mm tungsten-tin bullets against real porcine bones, several items come to light. Each type of bullet did fragment against the real porcine bone. The tungsten tin bullet fragments recovered were on average 24.80 grains (SD = 5.52 grains) of its 60 grain initial weight, and the lead bullet fragments that were recovered accounted for 35.01 grains

(SD = 6.15 grains) of the initial 60 grain weight. These differences in recovered weights serve to illustrate the effect of disintegration of the tungsten tin bullet and not an effect of fragmentation. The wound tracts of the tungsten tin rifle bullet displayed the same characteristic powder dispersion as that of the tungsten tin pistol bullet, but to a much greater degree as seen in figure 5-1. The small deviation associated with the recovered weight shows that a consistent amount of fragments were recovered from each shot of each bullet type.

The lack of complete recovery of lead rifle bullet to the same degree as the pistol bullets (58% versus 91%) is not completely understood, and may contribute partially to the lack of recovery of more weight from the tungsten tin rifle bullet as compared to the lead rifle bullet (41% versus 58%). It appears that the lead bullet tended to break into tiny slivers of lead upon impacting the bone, and these lead slivers were prohibitively difficult to locate in the ballistic gelatin. These slivers were not deemed crucial to contributing to wound severity because of their small individual size and close proximity to the bone. The tungsten tin remnants were easily located in the wound tract due to the high visibility of the powder as it coated the wound tract. The locations of the respective bullet fragments were also very different, and will be discussed later.

Fragmentation of the rifle bullets occurred in a manner almost exactly opposite that of the pistol bullets. The tungsten-tin bullets on average broke into half the number of large fragments that lead bullets did. For the three tungsten tin rifle shots against real porcine bone, each bullet broke into an average of 16.33 total

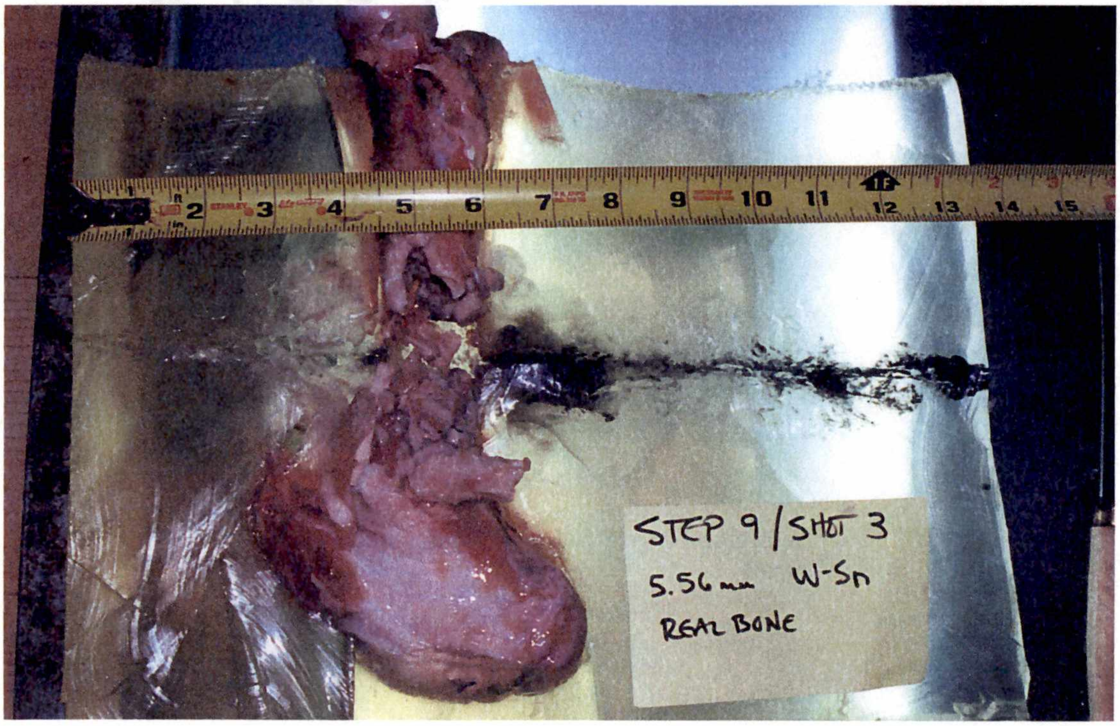


Figure 5-1: Tungsten tin rifle bullet target showing tungsten tin powder dispersion throughout the permanent cavity.

fragments. The lead bullet against the same target broke into an average of 32.33 fragments. This difference in bullet fragmentation is also reflected in the small fragments collected form each shot, but not the large fragments. The tungsten tin bullet against real porcine bone broke into 14.33 small fragments and 2 large fragments on average, whereas the lead bullet broke into 31 small fragments and 1.33 large fragments on average against the same target. The small fragments support the conclusion that the lead bullet demonstrated more fragmentation, but the large fragment count superficially does not. When looking at the actual bullets, however, it becomes apparent that there were no more large fragments to recover from the lead bullets; each shot had fragmented so severely upon impacting the face of the bone that there were no other large fragments to be found. Combining this with the recollection that a substantially greater portion of the lead bullet was recovered as opposed to the tungsten tin bullet leads to the possibility that the lead bullet did splinter into more fragments when striking real porcine bone encased in gelatin than did the tungsten tin bullets and that those fragments are of a smaller size on average. A t-test run on the bullet fragmentation data, however, did not support that conclusion based on a 0.95 confidence level. The t-test did not support any differences between the fragmentation of tungsten tin and lead rifle bullets.

The penetration depth of each type of bullet, and the subsequent location of the bullet fragments, revealed the greatest difference between the tungsten tin and lead bullets. The tungsten tin bullets penetrated a total average depth of 16.17" (SD = 1.76"). The lead bullets penetrated an average depth of 6.17" (SD = 1.44").

Corresponding velocities of the tungsten tin bullet averaged 2842.67 feet per second (SD = 168.01 fps) and those of the lead bullets averaged 2791.67 feet per second (SD = 109.34 fps). The substantially greater penetration of the tungsten tin bullets illustrates the lesser degree of fragmentation the tungsten tin bullets underwent. As a bullet loses mass through fragmentation, less penetration depth is achieved due to the lower mass of each fragment. The tungsten tin bullets appeared to smash through the anterior wall of compact bone largely intact, then crack upon breaking through the posterior wall of compact bone. The bullet then appears to slowly lose small fragments before, during, and after yawing to create the maximum temporary cavity. After the creation of the MTC, the bullet continues on for several inches before finally coming to rest an average of 16.17" from the beginning of the target. The maximum temporary cavities had an average diameter of 3.42" and were found an average of 3.08" post-bone. Tungsten tin powder and very small tungsten tin fragments were found throughout the wound tract, with greatest concentrations found just after the posterior wall of bone and at the end of the bullet path.

As stated, the penetration depth of the lead bullets averaged 6.17" (SD = 1.44"). This is consistent with the explosive nature that the lead bullets demonstrated against bone. The lead bullets appeared to transfer the majority of their energy into the bone, and in the process broke up into a cloud of tiny slivers of lead. In only one shot of the three did a lead bullet penetrate beyond the bone a significant distance. The maximum temporary cavities also occurred at the bone in all three shots and averaged 4.67" in diameter. This difference in location and diameter of maximum temporary cavities reflects how the bone affects each type of bullet; namely, that the lead bullet is impeded by the bone and the bone becomes the location of maximum energy deposition, whereas the tungsten tin bullet penetrates through the bone without any different observable effects from that of the lead bullet. One might speculate that bone damage from the lead bullet would be more severe than bone damage from the tungsten tin bullet, but there is no pictorial evidence to support this claim. Any objective evidence of this will be revealed in the analysis of the bone fragments.

A more relevant illustration of the nature of the rifle bullets against bone is seen in the post-bone penetration depths. The tungsten tin bullets penetrated an average 10.33" (SD = 1.96") past the bone, while the lead bullets penetrated an average of 1.08" (SD = 0.95") past the bone. This remarkable difference reinforces the theory that the tungsten tin bullets broke through the bone with a minimum of bullet fragmentation at the bone, and that the lead bullets all but disintegrated when they hit bone. This suggests that the tungsten tin rifle bullets "hold together" under the pressures of impacting bone better than lead rifle bullets and fragment later in the wound path.

In the tungsten tin bullet, the fragment pattern did not begin until after the bullet had exited the bone. In one such shot, seen in figure 5-2, the tungsten tin bullet broke into three distinctly separate large fragments that all achieved close to maximum penetration depth. Upon exiting the bone the tungsten tin bullet appeared to leave a trail of tungsten tin powder through the wound tract for the entire length of the permanent cavity, much like that of the tungsten tin pistol bullet. It appeared that the tungsten tin bullets may have cracked upon hitting the bone, but did not shatter as

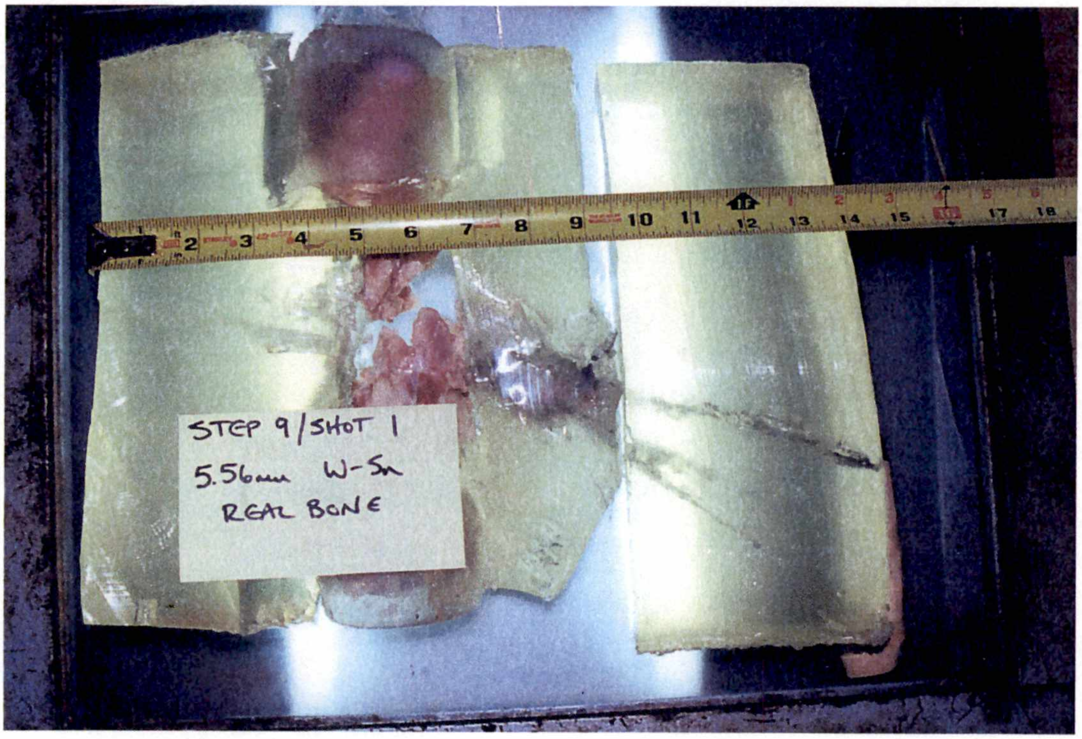


Figure 5-2: Tungsten tin rifle shot showing three distinct fragment tracts penetrating the entire depth of the target.

was expected. The bullets penetrated the bone and began shedding powder only after penetrating the first anterior wall of compact bone. The shedding appeared to take place as a reverse "snowballing" effect. It appeared that larger fragments would break off from the main bullet at slight angles and penetrate into the tissue surrounding the main permanent cavity. The average depth of these offshoots depended on the size, and therefore the weight, of the broken fragment. Each offshoot could be clearly seen as the fragments shed powder and slowly disintegrated until its energy had been spent or there was no longer a particle of tungsten tin to penetrate any further. The small tungsten tin fragments were all recovered in this manner. The entire tungsten-tin bullet did not disintegrate, though, as the larger fragments were usually found at the end of the permanent cavity. These few large fragments were the bottoms of the cores of the tungsten tin bullets, and could be identified as such by their perfectly cylindrical cross section and smooth, flat base. (The diligent reader will recognize that most of the preceding analysis on the behavior of the tungsten tin rifle bullet mirrors that of the tungsten tin pistol bullet. This is not unintentional. Both calibers of the tungsten tin bullets behaved in very similar and proportional ways. The greatest difference between the two is the depth of penetration, with the rifle bullet penetrating further into the target than the pistol bullet. The rifle bullet also caused a larger maximum temporary cavity diameter, consistent with the increased velocity (energy) of the rifle bullet.)

The location of fragments from the lead rifle bullets were almost all contained in the area before or at the bone. The fragments of the lead bullets appear as dark cloudy areas just after the diaphysis of the bones. These fragments did not scatter deeply into the surrounding ballistic gelatin. It appears that the soft nature of lead allows the bullet to drastically deform when impacting the bone, while the hard brittle nature of the tungsten tin bullet allows it to punch through the bone with minimal damage and continue much further into the targets.

The Red Cross wound classifications of the tungsten tin rifle bullet impacts against the real bone target were all of the grade 2 type F or VF category. This category is chosen even though the tungsten tin rifle bullets would leave a trail of fine powder post-bone because no significant tungsten tin fragments were found in the gelatin within several inches of the bone. Although the third tungsten tin shot appears to have left fragments before and after the bone, none were recovered. The post-bone black cloud seen in the photograph is the result of the tungsten tin powder covering the fissures of the temporary cavity. While it could be argued that the tungsten tin rifle shots should be classified as type "M" shots because of this powder residue, this category was not selected because of this "M" category is intended to represent that the majority of the metallic fragments from the wounding projectile are proximate to the wound itself. In the case of the tungsten tin rifle bullets, these major fragments were all found outside the reasonable diameter of thigh tissue. It is possible, however, that the tungsten tin rifle bullets could have caused the more severe grade 3 injury if the exit wound diameters measured more than 9 cm. This is suggested because the tungsten tin bullets all achieved complete penetration of the reasonable thigh diameter, and it is possible that the summed entrance and exit wounds could have exceeded the requisite 10 cm and been reclassified as a grade 3 type F or VF wound.

This was not the case with the lead rifle bullets, however. The Red Cross wound scoring system for each of the lead rifle bullets was of the grade 2 type FM or VFM category. In every lead rifle target, the lead rifle bullet fragments were all contained within this reasonable thigh diameter.

All real porcine bones demonstrated marked comminution. The difference between an F or VF classification would depend upon major vessel disruption such as the femoral artery being damaged in some manner. It is possible that the tungsten tin rifle bullets would produce a more severe grade 3 wound than the lead rifle bullets due to the greater penetration of the tungsten tin rifle bullets, but the lead bullets would certainly cause more localized damage due to their more extreme localized fragmentation.

In every case of both the tungsten tin and lead rifle bullet impacts, the resulting femurs were classified as a grade IV comminuted fracture according to the Winquist and Hansen method of femoral fracture classification. The fracture types of each rifle bullet impact were not observably different according to the Winquist and Hansen method of grading femoral fractures.

CHAPTER 6

EFFECTS OF THE TUNGSTEN TIN AND LEAD RIFLE BULLETS AGAINST REAL PORCINE BONE

In the cases of both bullet types, bone fragments were found throughout the permanent cavity post bone. It is these bone fragments that Amato suggests can be construed as secondary missiles and contribute to wound severity (3). In the case of the tungsten tin bullet, an average total of 265.62 grains of real porcine bone fragments were collected from the wound tracts of each target. The standard deviation was 77.47 grains. The collective bone fragments recovered from the lead bullet targets averaged 286.79 grains with a deviation of 50.89 grains. These remarkably similar numbers indicate that on a collective level, each type of rifle bullet caused a similar quantity of damage to the bones. There were on average 11.67 large bone fragments collected from the tungsten tin targets. The total average weight of these large fragments was 238.20 grains (SD = 60.26 gn), yielding an average large fragment weight of 20.41 grains. From the lead bullet targets, an average of 11.33 large bone fragments were collected that had an average total weight of 252.65 grains (SD = 30.90 gn), giving an average individual large fragment weight of 22.30 grains. Again, the similarity of the large bone fragment sizes and weights between the bullet types is surprising, suggesting that for large bone fragments and overall bone damage (by weight) there is no discernable difference between the tungsten tin and lead bullets. The only difference between these bullets with respect to bone is found in the generation of small bone fragments. There were an average of 37.67 small bone fragments recovered from each of the tungsten tin bullet targets, while an average of 91.00 small bone fragments were recovered from each of the lead bullet targets. The sizes of these fragments were again very similar between bullet types. The average total weight for the small bone fragments from the tungsten tin targets were 27.42 grains (SD = 17.32 gn) and yielded an average size (by weight) of 0.73 grains. The average total weight of the small bone fragments recovered from the lead bullet targets was 34.11 grains (SD = 20.15 gn) which resulted in an average fragment size (again, by weight) of 0.37 grains. The phenomena of the lead bullet generating almost 2.5 times as many small bone fragments as the tungsten tin bullet is not clearly understood. It is possible that the increased fragmentation of the lead rifle bullets may have some relation to this increase in small bone fragment generation. A t-test supports these conclusions, as it produced a 0.991 confidence level that the lead rifle bullets produced a greater quantity of small bone fragments than the tungsten tin rifle bullets. All other metrics were found to have no statistical difference between the means.

This similarity between bone comminution under the two separate types of bullet impacts leads to the conclusion that the tungsten tin bullet affects the real porcine bone in much the same manner as the lead bullet. While bone comminution is unquestionably severe for each type, the primary difference between the two rifle bullets remains the difference in post-bone penetration depth. It is here that the tungsten tin bullets take more full advantage of the bone fragments they have generated by pulling them deeper into the permanent cavity past the bone and likely contributing to increased tissue damage over the lead bullets. The bone fragments in the tungsten tin targets were mainly found in the permanent cavity behind the bone. The depth of these fragments into the permanent cavity ranged from zero to three inches away from the bone. The bone fragments retrieved from the lead bullet targets were mainly clustered around the bone itself. There were also more bone fragments found in the gelatin prior to the bone in the lead bullet targets. All of these fragments were small. There were no discernable bone fragments in the gelatin prior to the bone in the tungsten tin bullet targets.

PART III

COMPARISON OF SYNTHETIC BONE AND REAL PORCINE BONE UNDER PROJECTILE IMPACT

CHAPTER 1

JUSTIFICATION

The second part of this thesis examines the viability of a synthetic bone as a replacement for real bone in projectile impact testing. A group of researchers at the University of Tennessee, Knoxville have developed a proprietary material that was designed to simulate the mechanical properties of real bone. The material can be injection-molded into almost any desired shape, and a number of specimens were made in the shape of a long narrow cylinder. Each specimen was approximately fourteen inches long and one inch in diameter.

It was decided in the planning stages of the first part of this thesis that the existing specimens would be cast into the same thigh-shaped gelatin mold as the real bones used in the first part of this testing. A total of twelve targets were made with the synthetic bones cast inside. This yielded an equal number of synthetic bone targets to real porcine bone targets, allowing a direct comparison of the effects of the same types and calibers of bullets against the synthetic bone and the real porcine bone.

The rationale for developing a real bone substitute initially seems to be a self-defeating proposition. Why bother to develop such a thing when real bones already behave like real bones? Several issues arise that quickly reveal the justification of such research. Like snowflakes, no two bones are exactly the same size and shape. This is the single most important reason for the development of a real bone substitute. The size and shape of each bone affects the mechanical properties of that particular bone. In conducting valid, repeatable scientific research, all known variables must be controlled as tightly as possible. A mass-produced synthetic bone of which each piece possesses the same mechanical properties of a single given real bone would be greatly welcomed in the scientific community. This is especially true with regard to biomedical research and the projectile impact research that this paper deals with.

Real bones also have a distinct shelf life. The properties of bone change as a function of the time the bone spends outside of its natural environment. Real bones must also be stored properly in order to maintain their natural mechanical properties. The synthetic bones tested here are not affected by time, nor do they require any expensive and difficult handling and storage procedures.

CHAPTER 2

METHODOLOGY

The effects of bullets against real porcine bones has been discussed in the first part of this thesis. The same types of bullets were also shot against synthetic bone cylinders contained in the same type gelatin targets. The intention of these tests were to measure the comminution of the synthetic bones under each type of projectile impact. These results would then be compared against the results obtained from the real porcine bone comminution that occurred from each type of bullet impact. For the synthetic bone to be a truly viable replacement for real bone in impact testing, the synthetic bone must fracture and comminute in a more consistent manner than the real bone. The same bone fragment analysis will be performed on the synthetic bone as was performed on the real porcine bone. The following parameters will be compared:

1. Average overall fragment weight
2. Average large fragment quantity
3. Average large fragment weight
4. Average large fragment size (as a function of weight)

5. Average small fragment quantity
6. Average small fragment quantity
7. Average small fragment size (as a function of weight)
8. Post-bone penetration depth
9. Average velocity of the impacting projectile

If the synthetic bones demonstrate smaller deviations than the real bones in most or all of these parameters, the synthetic bones will be deemed as suitable substitutes for real bone in projectile impacts. If, however, the deviations turn out excessively large, more work will be needed to refine the existing synthetic bone.

The procedural steps of making, shooting, and dissecting the synthetic bone targets were exactly the same as the real bone targets previously discussed in Chapter 1 of Part II of this thesis.

CHAPTER 3

DATA FROM PROJECTILE IMPACTS AGAINST SYNTHETIC BONE

The data in this chapter is presented in tabular format. The individual shot data for the synthetic bone targets will be presented first, followed by the recovered synthetic bone fragment data. Table 3-1 shows the shot data from lead pistol bullets against synthetic bone targets, table 3-2 shows the shot data from tungsten tin pistol bullets against synthetic bone targets, table 3-3 shows the shot data from lead rifle bullets against synthetic bone targets, and table 3-4 shows the shot data from tungsten tin bullets against synthetic bone targets.

Table 3-5 shows the bone fragment data from lead pistol bullets against synthetic bone targets, table 3-6 shows the bullet fragment data from lead pistol bullets against synthetic bone targets, table 3-7 shows the bone fragment data from tungsten tin pistol bullets against synthetic bone targets, and table 3-8 shows the bullet fragment data from tungsten tin pistol bullets against synthetic bone targets.

Table 3-1: Shot Data for 9mm Lead Pistol Bullets Against Synthetic Bone Targets

	Shot #1	Shot #2	Shot #3
Bullet Vel. (fps):	1006.3	1053.6	1065.0
Tot. Pen. (in.):	7.50	8.50	14.50
Bullet Frag.:	Marked	Extreme	Little
BB Vel. (fps):	~570	~570	~570
BB Pen. (in.):	2.75	3.50	3.10
Gel Temp. (° F):	35	37	41
Bone Depth (in.):	4.75	4.50	4.75
Bone Dia. (in.):	1.00	1.00	1.00
Frac. Type:	Complete	Complete	Complete
Comm.:	Very little	Very little	Extreme
MTC Dia. (in.):	None Observed	None Observed	1.90
MTC Loc. (in.):	None Observed	None Observed	1.00" post-bone

Table 3-2: Shot Data for 9mm Tungsten Tin Pistol Bullets Against Synthetic Bone Targets

	Shot #1	Shot #2	Shot #3
Bullet Vel. (fps):	928	1030.7	1048.6
Tot. Pen. (in.):	7.10	7.00	6.75
Bullet Frag.:	Extreme	Very little	Little
BB Vel. (fps):	~570	~570	~570
BB Pen. (in.):	3.00	2.75	2.75
Gel Temp. (° F):	41	39	37
Bone Depth (in.):	4.25	4.50	4.25
Bone Dia. (in.):	1.00	1.00	1.00
Frac. Type:	Complete	Complete	Complete
Comm.:	Marked	Extreme	Little
MTC Dia. (in.):	1.00	None Observed	None Observed
MTC Loc. (in.):	0.50" post-bone	None Observed	None Observed

Table 3-3: Shot Data for 5.56mm Lead Rifle Bullets Against Synthetic Bone Targets

	Shot #1	Shot #2	Shot #3
Bullet Vel. (fps):	Not Recorded	Not Recorded	Not Recorded
Tot. Pen. (in.):	7.75	6.75	6.75
Bullet Frag.:	Extreme	Extreme	Extreme
BB Vel. (fps):	~570	~570	~570
BB Pen. (in.):	2.75	2.50	3.75
Gel Temp. (° F):	35	37	50
Bone Depth (in.):	5.00	3.50	5.00
Bone Dia. (in.):	1.00	1.00	1.00
Frac. Type:	Complete	Complete	Complete
Comm.:	Very little	Little	Very little
MTC Dia. (in.):	4.75	5.50	4.50
MTC Loc. (in.):	3.00" post-entry	3.00" post-entry	0.00" post-bone

Table 3-4: Shot Data for 5.56mm Tungsten Tin Rifle Bullets Against Synthetic Bone Targets

	Shot #1	Shot #2	Shot #3
Bullet Vel. (fps):	2768	2791	2764
Tot. Pen. (in.):	15.00	14.50	14.00
Bullet Frag.:	Extreme	Extreme	Extreme
BB Vel. (fps):	~570	~570	~570
BB Pen. (in.):	3.75	3.00	3.10
Gel Temp. (° F):	48	37	35
Bone Depth (in.):	4.50	4.50	4.00
Bone Dia. (in.):	1.00	1.00	1.00
Frac. Type:	Complete	Complete	Butterfly
Comm.:	Marked	Marked	Extreme
MTC Dia. (in.):	4.25	3.50	4.50
MTC Loc. (in.):	0.00" post-bone	0.00" post-bone	0.00" post-bone

Table 3-5: Bone Fragment Data from 9mm Lead Pistol Bullets Against Synthetic Bone Targets

	Small Bone Fragments		Large Bone Fragments	
Shot #	Qty.	Wt. (gn)	Qty.	Wt. (gn)
1	14	1.92	0	NA
2	17	2.88	2	3.02
3	>120	8.38	8	65.12

Table 3-6: Bullet Fragment Data from 9mm Lead Pistol Bullets Against Synthetic Bone Targets

	Small Bullet Fragments		Large Bullet Fragments	
Shot #	Qty.	Wt. (gn)	Qty	Wt. (gn)
1	46	52.04	8	73.62
2	43	52.94	4	72.96
3	11	10.66	2	113.34

Table 3-7: Bone Fragment Data from 9mm Tungsten Tin Pistol Bullets Against Synthetic Bone Targets

	Small Bone Fragments		Large Bone Fragments	
Shot #	Qty.	Wt. (gn)	Qty.	Wt. (gn)
1	~100	38.16	2	47.08
2	~100	45.16	1	7.98
3	85	38.70	0	NA

Table 3-8: Bullet Fragment Data from 9mm Tungsten Tin Pistol Bullets Against Real Bone Targets

	Small Bullet Fragments		Large Bullet Fragments	
Shot #	Qty.	Wt. (gn)	Qty.	Wt. (gn)
1	20	25.26	5	80.86
2	20	5.76	2	115.74
3	31	43.30	2	76.90

Table 3-9 shows the bone fragment data from lead rifle bullets against synthetic bone targets, table 3-10 shows the bullet fragment data from lead rifle bullets against synthetic bone targets, table 3-11 shows the bone fragment data from tungsten tin rifle bullets against synthetic bone targets, and table 3-12 shows the bullet fragment data from tungsten tin rifle bullets against synthetic bone targets.

Table 3-9: Bone Fragment Data from 5.56mm Lead Rifle Bullets Against Synthetic Bone Targets

	Small Bone Fragments		Large Bone Fragments	
Shot #	Qty.	Wt. (gn)	Qty.	Wt. (gn)
1	1	0.22	0	NA
2	43	2.74	3	10.74
3	1	0.14	0	NA

Table 3-10: Bullet Fragment Data from 5.56mm Lead Rifle Bullets Against Real Bone Targets

	Small Bullet Fragments		Large Bullet Fragments	
Shot #	Qty.	Wt. (gn)	Qty.	Wt. (gn)
1	54	15.88	4	30.06
2	56	14.92	2	28.12
3	41	17.78	3	23.18

Table 3-11: Bone Fragment Data from 5.56mm Tungsten Tin Rifle Bullets Against Synthetic Bone Targets

	Small Bone Fragments		Large Bone Fragments	
Shot #	Qty.	Wt. (gn)	Qty.	Wt. (gn)
1	62	6.92	0	NA
2	~100	13.56	0	NA
3	~100	17.24	4	15.04

Table 3-12: Bullet Fragment Data from 5.56mm Tungsten Tin Rifle Bullets Against Real Bone Targets

	Small Bullet Fragments		Large Bullet Fragments	
Shot #	Qty.	Wt. (gn)	Qty.	Wt. (gn)
1	35	22.98	0	NA
2	42	13.12	1	13.12
3	38	30.18	3	18.10

CHAPTER 4

COMPARISON OF SYNTHETIC AND REAL PORCINE BONES UNDER LEAD PISTOL BULLET IMPACTS

The lead pistol bullet shots made into the synthetic bone targets had an average velocity of 1041.63 feet per second with a deviation of 31.13 feet per second. The lead pistol bullets fired into the real porcine bone targets averaged 1048.4 feet per second with an accompanying deviation of 21.04 feet per second. These similar, consistent velocities were the only similar, consistent aspects of the synthetic bone testing.

The synthetic bones shot with lead pistol bullets yielded a total overall average fragment weight of 27.11 grains. The deviation is large at 40.23 grains. The fact that the deviation is larger than the mean indicates gross non-uniformity of comminution of the synthetic bones, assuming that all shots impacting in the same area of each of the bones. This contrasts with the overall total fragment weight of the real bone targets shot with lead pistol bullets at 72.49 grains with a deviation of 33.74 grains. While the deviation for the real bones is large, it indicates a much higher degree of consistency than the synthetic bone.

This exceedingly large deviation is further reflected in the other measured parameters of synthetic bones. The average number of large fragments generated by the impact of the lead pistol bullet was 3.33 fragments, with a deviation of 4.16 fragments. Here again we see a deviation larger than the mean number of fragments generated. There were 4.00 large bone fragments generated by the lead pistol bullet against real bone, with an accompanying deviation of 3.00 fragments. While this deviation isn't acceptably uniform, it is better than that of the synthetic bones. The average collective weight of the large synthetic bone fragments was 22.71 grains, with a deviation of 36.76 grains. This yielded an average fragment size of 6.82 grains. The average collective weight of the large real bone fragments were 47.41 grains with a deviation of 34.91 grains. Again, this doesn't speak well for the real bone, but it is still better than that of the synthetic bone. The average size of the large synthetic bone fragments is much less than the average size of the large real bone fragments which averaged 16.29 grains.

The average quantity of small fragments generated from the synthetic bone under lead pistol bullet impacts was 50.33 with a deviation of 60.35. The same shots against the real bone yielded an average of 42.67 fragments generated and a deviation of 25.89. While the means are close, the deviation again destroys any uniformity that this implies. The average small fragment collective weights were 4.39 grains with a deviation of 3.49 grains, yielding an average individual small fragment size of 0.09 grains. The average small fragment collective weight from the real porcine bone was 25.08 grains with a deviation of 6.06 grains, resulting in an average individual fragment size of 1.70 grains. Even accounting for any realistic differences in density, it is evident that the synthetic bone does not mimic the small fragment comminution of real porcine bone.

The synthetic post-bone penetration depth was also not similar to real porcine post-bone penetration depth. The lead pistol bullets penetrated an average of 4.50" past the synthetic bone into the ballistic gelatin and had a deviation of 3.73". The lead pistol bullets penetrated the past the real bone an average of 6.78" into the gelatin with a fairly consistent deviation of 0.98". The synthetic post-bone penetration was not only over two inches less on average but was also very inconsistent when compared to the real bone.

The synthetic bones have been shown to possess little or no uniformity when compared to real porcine bone under lead pistol bullet impacts. Lead rifle bullet impacts will be analyzed next.

CHAPTER 5

COMPARISON OF SYNTHETIC AND REAL PORCINE BONES UNDER LEAD RIFLE BULLET IMPACTS

The velocities of the lead rifle bullets shot into the synthetic bone target were unfortunately not recorded due to a faulty chronograph. The velocities of lead rifle bullets from the same batch were recorded from the real bone shots and it is expected that the velocities are likely to be very similar, and these velocities will be used for the sake of this comparison. The velocities of the lead rifle bullets shot into the real bone target averaged 2791.67 feet per second with a deviation of 109.43 feet per second.

The synthetic bones shot with lead rifle bullets yielded a total overall average fragment weight of 4.61 grains. The deviation is laughably large at 7.68 grains. The fact that the deviation is larger than the mean indicates gross non-uniformity of comminution of the synthetic bones, assuming that all shots impacting in the same area of each of the bones. This contrasts with the overall total fragment weight of the real bone targets shot with lead rifle bullets at 286.79 grains with a deviation of 50.89 grains. While the deviation for the real bones is large, it indicates a much higher degree of consistency than the synthetic bone.

This exceedingly large deviation is further reflected in the other measured parameters of synthetic bones. The average number of large fragments generated by the impact of the lead rifle bullet was 1 fragment, with a deviation of 1.73 fragments. Here again we see a deviation larger than the mean number of fragments generated. There were 11.33 large bone fragments generated by the lead rifle bullet against real bone, with an accompanying deviation of 3.06 fragments. While this deviation isn't acceptably uniform, it is better than that of the synthetic bones. The average weight of a large synthetic bone fragment was 3.58 grains, with a deviation of 6.20 grains. This yielded an average fragment size of 3.58 grains. The average weight of the large real bone fragments were 252.65 grains with a deviation of 30.90 grains. Again, this doesn't speak well for the real bone, but it is still better than that of the synthetic bone. The average size of the large synthetic bone fragments is much less than the average size of the large real bone fragments which averaged 22.30 grains.

The average quantity of small fragments generated from the synthetic bone under lead rifle bullet impacts was 15.00 with a deviation of 24.25. The same shots against the real bone yielded an average of 91.00 fragments generated and a deviation of 15.59. While the means are close, the deviation again destroys any uniformity that this implies. The average small fragment collective weights were 1.03 grains with a deviation of 1.48 grains, yielding an average individual small fragment size of 0.07 grains. The average small fragment collective weight from the real porcine bone was 34.11 grains with a deviation of 20.15 grains, resulting in an average individual fragment size of 0.37 grains. Even accounting for any realistic differences in density, it is evident that the synthetic bone does not mimic the small fragment comminution of real porcine bone.

The synthetic post-bone penetration depth was very similar to real porcine post-bone penetration depth. The lead rifle bullets penetrated an average of 1.58" past the synthetic bone into the ballistic gelatin and had a deviation of 0.76". The lead rifle bullets penetrated the past the real bone an average of 1.08" into the gelatin with a fairly consistent deviation of 0.95". The synthetic post-bone penetration was demonstrably more consistent than any of the other parameters measured. In this instance, the lead rifle bullet penetrated to a more consistent depth after passing through the synthetic bone than after passing through the real porcine bone. It must be noted that this difference only applies to the higher velocity, lower mass rifle bullets, and not the pistol bullets. It also must be noted that the difference between the synthetic bones and real porcine bones is marginal at best.

The synthetic bones have been shown to possess little or no uniformity when compared to real porcine bone under lead rifle bullet impacts with the possible exception of post-bone penetration depth. Tungsten tin pistol bullet impacts against synthetic bones will be analyzed next.

CHAPTER 6

COMPARISON OF SYNTHETIC AND REAL PORCINE BONES UNDER TUNGSTEN TIN PISTOL BULLET IMPACTS

The tungsten tin pistol bullet shots made into the synthetic bone targets had an average velocity of 1002.43 feet per second with a deviation of 65.08 feet per second. The tungsten tin pistol bullets fired into the real porcine bone targets averaged 1035.03 feet per second with an accompanying deviation of 5.85 feet per second. The large disparity between the two is not understood, as the bullets were loaded in the same batch.

The synthetic bones shot with tungsten tin pistol bullets yielded a total overall average fragment weight of 59.03 grains. The deviation is 23.82 grains. This is the first instance of synthetic bone comminution where the deviation is significantly less than the mean. This lends credence to the possibility of uniformity of comminution of the synthetic bones shot with tungsten tin pistol bullets, assuming that all shots impacting in the same area of each of the bones. This contrasts with the overall total fragment weight of the real bone targets shot with tungsten tin pistol bullets at 179.83 grains with a deviation of 96.89 grains. The comparatively smaller deviation of the synthetic bones suggests that the synthetic bone is more uniform with respect to comminution, but the difference in overall fragment weight is indicative of the synthetic bone not fully replicating the amount of fragmentation of real bone. The diameter of the synthetic bones are less than those of the real bones (1.00" versus 1.47", respectively), but the 32% reduction in diameter from real bone to synthetic bone does not correspond with the 67% percent decrease of fragment weight from real bone to synthetic bone. Granted, this comparison would truly only be valid if the bullet diameter were reduced for the synthetic bone as well, and the possible difference in density between the real bone and synthetic bone be accounted for as well. Even in light of this, it is not believed that the synthetic bone reasonably replicates the overall fragmentation of real bone, although it does demonstrate more uniformity than the real bone does under tungsten tin bullet impacts. This conclusion shows promise for the synthetic bone as a future viable replacement for synthetic bone, but only after more research and refinement is done on the shape and composition of the synthetic bone.

There was only 1.00 large bone fragment generated on average by the tungsten tin pistol bullet impacting the synthetic bone, with a deviation of 1.00 fragment. There were 9.00 large bone fragments generated by the tungsten tin pistol bullet against real bone (6.00 if the second shot is not discounted), with an accompanying deviation of 2.82 (5.57) fragments. While this deviation isn't acceptably uniform, it is better than that of the synthetic bones. The average weight of the large synthetic bone fragment was 18.35 grains, with a deviation of 25.20 grains. This yielded an average fragment size of 18.35 grains. The average weight of the large real bone fragments was 135.85 grains with a deviation of 122.08 grains. The average size of the large real bone fragment was 15.09 grains, or 22.64 grains including the second shot. The appearance of previous overall fragment consistency does not extend to the large fragments of each bone type. Both bones exhibited poor uniformity in this regard.

The average quantity of small fragments generated from the synthetic bone under tungsten tin pistol bullet impacts was 95.00 with a deviation of 8.66. The same shots against the real bone yielded an average of 79.00 fragments generated and a deviation of 5.20. It is evident that the uniformity seen in the overall fragment quantity stems largely from the effect of small fragment generation in each type of bone. The average synthetic bone small fragment collective weights were 40.67 grains with a deviation of 3.89 grains, yielding an average individual small fragment size of 0.43 grains. The average small fragment collective weight from the real porcine bone was 43.98 grains with a deviation of 6.97 grains, resulting in an average individual fragment size of 0.57 grains. This small bone comminution is remarkably consistent and similar between synthetic bone and real bone, and it suggests that on a micro scale the synthetic bone may be a viable replacement for real bone in projectile impact tests. This testing shows that more work is needed on the synthetic bone to make it replicate the macro effects of projectile impacts on real bone, however.

The synthetic post-bone penetration depth was not similar to real porcine post-bone penetration depth although the penetration depths achieved displayed less variation than those in the real bone target. The tungsten tin pistol bullets penetrated an average of 1.62" past the synthetic bone into the ballistic gelatin and had a deviation of 0.20". The tungsten tin pistol bullets penetrated the past the real bone an average of 9.12" into the gelatin with a larger comparative deviation of 1.83". This huge difference in synthetic post-bone penetration suggests that the synthetic bones affect tungsten tin pistol bullets in a remarkably different manner than real bones do. The tungsten tin pistol bullets appear to lose more energy in synthetic bones than real bones. The synthetic bones may be harder and more resistant to fracture than the real bones are, and instead of the tungsten tin pistol bullets fracturing the real bones, the synthetic bones may be fracturing the tungsten tin pistol bullets. To investigate this, a look at the bullet fragments is in order. The total recovered weight of the tungsten tin pistol bullets against the synthetic bone targets averaged 115.94 grains and had a deviation of 8.53 grains. The total recovered weight of the tungsten tin pistol bullets against real bones averaged 113.43 grains and had a deviation of 3.94 grains. There are no stellar differences evident here. The tungsten tin pistol bullets against synthetic bones broke into an average of 26.67 fragments with a deviation of 5.69. The tungsten tin pistol bullets against real porcine bones broke into an average of 18.00 total fragments and had a deviation of 15.72. This suggests that the tungsten tin pistol bullets broke into more fragments and did so in a more consistent fashion against the synthetic bones than they did against the real bones. The breakdown of these fragments into large and small categories also reflects this conclusion. The tungsten tin pistol bullets against the synthetic bones broke into 3.00 large fragments on average and had a deviation of 1.73. The same bullets against the real bone targets broke into an average of 1.33 large fragments and had a deviation of 0.58. It appears that the tungsten tin pistol bullets broke into approximately twice as many fragments against synthetic bones than against real bones. The tungsten tin pistol bullets against the synthetic bones broke into 23.67 small fragments on average and had a deviation of 6.35. The same bullets against the real bone targets broke into an average of 16.67 small fragments and had a deviation of 15.14. This metric also indicates that the synthetic bones affect the tungsten tin pistol bullets in a different manner than the real bones do. It seems that the synthetic bones produce more consistent fragmentation against tungsten tin pistol projectiles than real bones.

The difference between the post-bone penetration depths of lead pistol bullets and tungsten tin pistol bullets suggests that the synthetic bones may be much harder to fracture than the real bones are. The real bones are more brittle than the synthetic bones, while the synthetic bones possess more ductility than the real bones. It is believed that the tungsten tin bullets were prone to losing more energy when breaking through the synthetic bones than the real bones, even though the synthetic bones were 32% smaller in diameter on average. The more consistent and uniform tungsten tin bullet fragmentation against synthetic bones can be the result of two possible situations: that the synthetic bone has a more uniform density than the real bones do, and/or the synthetic bones are much stronger and resistant to projectile impacts than are real bones. Either scenario would cause the tungsten tin pistol bullet to fragment to a greater degree than penetration into a softer medium in general.

The synthetic bones have been shown to possess little or no uniformity when compared to real porcine bone under tungsten tin pistol bullet impacts. Tungsten tin rifle bullet impacts will be analyzed next.

CHAPTER 7

COMPARISON OF SYNTHETIC AND REAL PORCINE BONES UNDER TUNGSTEN TIN RIFLE BULLET IMPACTS

The tungsten tin rifle bullet shots made into the synthetic bone targets had an average velocity of 2774.33 feet per second with a deviation of 14.57 feet per second. The tungsten tin rifle bullets fired into the real porcine bone targets averaged 2842.67 feet per second with an accompanying deviation of 168.01 feet per second.

The synthetic bones shot with tungsten tin rifle bullets yielded a total overall average fragment weight of 17.59 grains. The deviation is large at 13.15 grains. This contrasts with the overall total fragment weight of the real bone targets shot with tungsten tin rifle bullets at 265.62 grains with a deviation of 77.47 grains. While the deviation for the real bones is large, it indicates a much higher degree of consistency than the synthetic bone.

The average number of large fragments generated by the impact of the tungsten tin rifle bullet into the synthetic bone was 1.33 fragments, with a deviation of 2.31 fragments. Here we see a deviation larger than the mean number of fragments generated. There were 11.67 large bone fragments generated by the tungsten tin rifle bullet against real bone, with an accompanying deviation of 8.62 fragments. While this deviation isn't acceptably uniform, it is better than that of the synthetic bones. The average weight of a large synthetic bone fragment was 13.23 grains. The average weight of the large real bone fragments were 20.41 grains. Again, this doesn't speak well for the real bone, but it is still preferable to that of the synthetic bone.

The average quantity of small fragments generated from the synthetic bone under tungsten tin rifle bullet impacts was 87.33 with a deviation of 21.94. The same shots against the real bone yielded an average of 37.67 fragments generated and a deviation of 11.93. These numbers indicate that the synthetic bone possesses more uniform small fragment comminution than the real bone under the high velocity, low mass impact of tungsten tin rifle bullets. This does not seem to apply to the lead rifle bullets, however. The greater comminution of the synthetic bone from tungsten tin bullets is surprising when compared to that of the synthetic bone comminution from lead rifle bullets (15.00 average small fragments generated, with a deviation of 24.25).

The average small fragment collective weights from the tungsten tin rifle bullet impacting the synthetic bone were 12.57 grains with a deviation of 5.23 grains, yielding an average individual small fragment size of 0.14 grains. The average small fragment collective weight from the real porcine bone was 27.42 grains with a deviation of 17.32 grains, resulting in an average individual fragment size of 0.73 grains. While this small difference in average individual small fragment weight could be attributed to differing densities of synthetic bone and real bone, the actual quantity of fragments generated in categories of both size and weight precludes the conclusion that synthetic bone is a viable replacement for real bone in impact projectile studies.

The greater uniformity of comminution of the synthetic bone over the real bone on a small scale, though, is very encouraging and suggests that with refinement the synthetic bone can act as a suitable alternative. The subsequent analysis of post-bone penetration depth further reinforces this belief.

The synthetic post-bone penetration depth was very similar to real porcine post-bone penetration depth. The tungsten tin rifle bullets penetrated an average of 9.17" past the synthetic bone into the ballistic gelatin and had a deviation of 0.29". The tungsten tin rifle bullets penetrated the past the real bone an average of 10.33" into the gelatin with a fairly consistent deviation of 1.96". The synthetic post-bone penetration was remarkably more consistent than the real bone in this measurement. The differences between the favorable behavior of the tungsten tin and lead rifle bullets against the synthetic bones and the unfavorable behavior of the pistol bullets, particularly the tungsten tin pistol bullets, can likely be traced back to the very differences of the bullets themselves. The increased energy due to increased velocity, smaller size, and lower mass of the rifle projectiles allows them to overcome the mechanical properties of the synthetic bones that in turn cannot be overcome by the decreased velocity, increased size, and increased mass of the pistol bullets.

PART IV

CONCLUSIONS

CHAPTER 1

TUNGSTEN TIN PROJECTILES VERSUS LEAD PROJECTILES

The tungsten tin pistol bullets may cause more significant wound trauma against bones encased in ballistic gelatin than lead pistol bullets solely due to the greater collective bone fragment weights generated by the tungsten–tin pistol bullet impacts against real porcine bones over lead pistol bullets. Bone comminution is observed under both types of bullets impacts, but in every other metric there was no statistically significant difference observed between the two types of pistol bullets.

There were no statistically significant differences between the fragmentation of each type of pistol bullet. Although it appeared from looking at the simple means that the tungsten-tin pistol bullet generated a greater quantity of small bullet fragments than lead bullets, a subsequent t-test did not support this.

The tungsten tin rifle bullets did perform significantly different from the lead rifle bullets in the overall and post-bone depth of penetration into the target. The tungsten tin bullets also demonstrated less bullet fragmentation than did the lead bullets on average. Due to this increased penetration depth, it is possible that the tungsten tin rifle bullets can damage a greater depth of tissue than the lead rifle bullets. The lead rifle bullets did generate a greater number of small bone fragments than the tungsten tin rifle bullets against real porcine bone, but these fragments are likely too small to cause significant tissue damage.

There were no statistically significant differences between the fragmentation of each type of rifle bullet. None were observed or inferred through the simple means, and a subsequent t-test reinforces this.

Having reported the objective data about the differences between the tungsten tin and lead bullet types, the more interesting and useful part of this work lies in the interpretation of these findings. Many questions that are likely to be posed would concern the applicability of tungsten tin bullets in situations that are currently served by conventional lead bullets, as well as how the different characteristics of tungsten tin bullets can be utilized in an advantageous manner over lead bullets. Finally, after all the paper and time that this testing has consumed, one might ask what the "real world" benefits and detriments of the tungsten tin bullets are.

The tungsten tin bullets do perform differently than lead bullets. The differences can be mostly attributed to the mechanical properties of the tungsten tin powdered metal core versus those of the conventional lead core. The tungsten tin cores are much harder than the soft lead used in conventional bullet cores. This is easily observed by scratching each material with a knife, or even a fingernail. The hardness of the tungsten tin core is a result of the tungsten metal, and a rough estimation of the tungsten ratio in a tungsten tin core can be made in this manner. While reducing the amount of tungsten may result in a softer bullet, the resulting density would also be less than that of lead.

Another property of lead that the tungsten tin bullets did not emulate was that of ductility. The majority of lead used in small arms ammunition is ductile and malleable. It is these properties, combined with high density, that combine to make lead a desirable bullet material. Under the pressures of impact in soft tissue, lead deforms plastically. A lead core bullet is typically designed to take advantage of these properties by expanding to a greater diameter in the handgun bullet and fragmenting in the case of rifle bullets. The expansion in the handgun bullet serves to control the depth at which maximum tissue damage occurs, and the fragmentation that soft-point rifle bullets undergo is designed to efficiently use the great amounts of energy from the rifle bullet's high velocity in that each fragment becomes a cutting tool in the tissue. This disperses the energy through the tissue in a destructive manner, as it should be recalled that tissue isn't damaged solely from energy deposition but rather how that energy is used.

The tungsten tin composite cores do not possess the ductility and malleability of lead. They are very brittle, and in many cases it is this brittle nature that makes the manufacture of these bullets difficult, as the cores are prone to crack at any point in the manufacturing process. This brittle nature is exemplified when the tungsten tin bullets shed their soft copper jackets early in the gelatin and continue through the gelatin and bone without significant deformation. The bullets can and do fragment, but they are never molded into a different shape under the pressures of impact with gelatin or bone. The main cores will crack upon striking the bone, and will shed small fragments throughout the wound tract, but they will never expand to a greater diameter as lead handgun bullets are designed to do. In rifle bullets, the nature of the tungsten tin bullet fragmentation is not exactly similar to lead bullets, as the lead bullets tend to decrease their penetration depth as they expand before fragmenting. The tungsten tin rifle cores tend to begin their fragmentation from the forward end of the core down, but do not expand and increase their drag in tissue in order to control the depth of penetration at which maximum tissue damage occurs. This is believed to be one of the reasons that the enabled the tungsten tin rifle bullets to penetrate further into the gelatin blocks than the lead rifle bullets after striking bone.

This brittle nature isn't necessarily an undesirable characteristic. One of the attractive aspects of the tungsten tin bullet is its inherent frangibility. The brittle nature of the tungsten tin core allows it to literally disintegrate upon impact with a material that is much harder than the composite tungsten tin core. Concrete and steel are two materials that readily spring to mind, and the tungsten tin bullets have been shown to produce virtually no ricochets when striking such surfaces. Slow motion video documents the tungsten tin cores turning to fine powder upon impacts with steel, and similar results are expected from concrete. In applications such as close quarters battle (CQB) in areas of concrete structures and around sensitive equipment such as nuclear weapons, the increased frangibility and zero ricochets of the tungsten tin bullets is a desirable characteristic. Lead bullets will often flatten out into razor-sharp fragments that ricochet off in unpredictable directions, easily inflicting damage on an unintended target. Lead armor-piercing ammunition is also ricochet-prone and has the ability to damage sensitive equipment to greater degree than conventional lead bullets. In both applications, tungsten tin bullets have particular value. What must be kept in mind are the effects that the tungsten tin bullets produce against soft targets, such as human tissue. In their current state of design, the mechanical properties of the tungsten tin bullets do not behave in the same manner as lead bullets in either rifle or pistol calibers. A tungsten tin hollowpoint pistol bullet is not likely to expand in tissue and control the depth at which maximum tissue damage occurs, so another method of increasing its drag in soft tissue will likely need to be developed. This new method would need to utilize the brittle nature of the tungsten tin core, or a method of modifying the tungsten tin core with additional materials is required to increase the ductility of the tungsten tin core so that the core will expand in a manner similar to lead.

These same recommendations apply to rifle bullets, but to a lesser extent. Tungsten tin rifle bullets have been shown to fragment to a comparable degree to lead rifle bullets against impacts with bone, although as mentioned previously, the distinguishing difference between the two types of rifle bullets is penetration depth. The tungsten tin bullets penetrate the bone easily, often staying largely intact until well past the bone. Any large fragments are usually found in close proximity to the other large fragments. Lead rifle bullets did not easily penetrate bone, and in every case the forward motion of the lead rifle bullet all but ceased when it hit the bone. The lead rifle bullets also deformed and fragmented in or at the bone in every instance.

The greater penetration depth due to the decreased large-scale frangibility of the tungsten tin rifle bullets can be beneficial or detrimental, depending on the specific target. If the target is covered by a material of the consistency of bone, the greater penetration depth of the tungsten tin rifle bullet would be an asset. If the target was obscured by a greater than normal depth of tissue, such as a medial-lateral chest shot, the greater penetration depth of the tungsten tin rifle bullet would also be welcome. If, however, the target were an extremity, the tungsten tin bullet would likely over-penetrate the target, and total energy deposition in the target would likely be less than that of the lead rifle bullet. The lead bullet also likely possesses an advantage over tungsten tin bullets in anterior-posterior impacts against an unarmored human body, as the fragmentation of the lead rifle bullets controls the depth of maximum tissue damage to an optimum shorter distance versus the possible over-penetration of the tungsten tin rifle bullets. It is not believed that the tungsten tin rifle bullets would penetrate hard body armor, as they would likely disintegrate, but it would be interesting to see their effects against soft body armor. It is possible that the tungsten tin bullets may behave differently than lead bullets against soft body armor because of their lack of ductility and greater hardness.

These comments on the nature of the tungsten tin bullets and their differences with respect to lead bullets are not mean to be objective facts. The previous discussion merely attempts to characterize the behavior of the tungsten tin projectiles based on preliminary results obtained in the evaluation of the projectiles against real and synthetic bones encased in ballistic gelatin.

CHAPTER 2

SYNTHETIC BONES VERSUS REAL BONES

The synthetic bones tested here did not exhibit more uniform comminution under projectile impacts than real bone. The synthetic bones were not as brittle as real organic bone, and behaved differently from real organic bone under projectile impacts. The synthetic bone appeared to possess more ductility than real bones, and some large synthetic bone fragments exhibited plastic deformation zones around their edges. A greater degree of ductility of the synthetic bones over the real bones may help explain why the fragmentation and comminution of the real bones was much more sever than that seen in synthetic bones. Increasing the hardness of the synthetic bones may yield fragmentation and comminution results more similar to those of real bone.

The physical appearance of the interior of the synthetic bones was very similar to that of real bone. Interior portions of synthetic bone fragments and segments strongly resembled the cancellous and trabecular bone structure found in the real bone fragments and segments.

The interiors of the real bones were also filled with thick, fluid marrow. It is possible that the incompressibility of this marrow could contribute to distributing the interior pressure, caused by the passage of the projectile, further into each half of the bone segments. This might also contribute to the greater degree of comminution and fragmentation seen in real bone as compared to the synthetic bone.

The consistency of the synthetic bone material seemed to present more uniformity than real bone material due to more consistent post-bone penetration by both types of rifle bullets. This holds promise for further development of the synthetic bone. It has already been suggested that drilling out the centers of these synthetic bones may yield more consistent large bone fragment comminution. If this is done, the wall thickness of the synthetic bone should be scaled proportionately to that of the wall thickness of real bones. Improving the physical shape of the synthetic bones would also likely increase the probability of behaving like real bones. Flaring the ends of the synthetic bone might more accurately model real long bones, as would an increase in general size and length. It should be said that the exterior surface of the synthetic bone in its current guise closely resembles that of real bone. Tiny surface irregularities in the synthetic bone from the injection molding process made for a surface that mimicked the surface irregularities of real bone.

The addition of a synthetic periosteum would also assist in replicating the fracture characteristics of real bone, as would the development of a more uniform injection molding manufacturing method.

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APPENDIX

Figure A-1: First lead pistol shot against a real bone target.

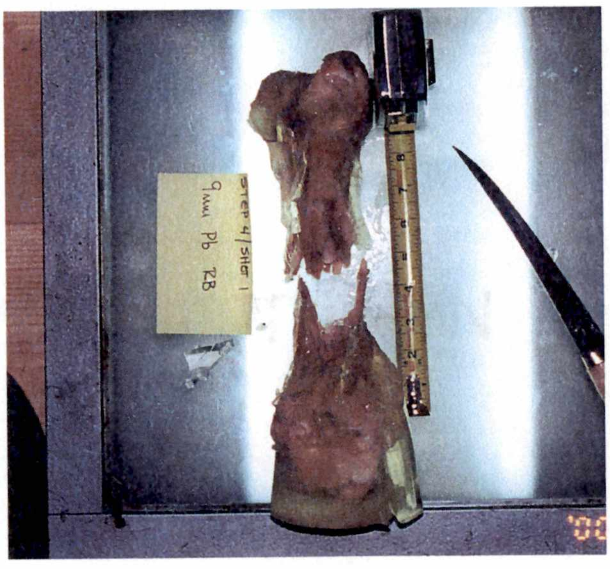

Figure A-2: Real porcine bone from first lead pistol shot.

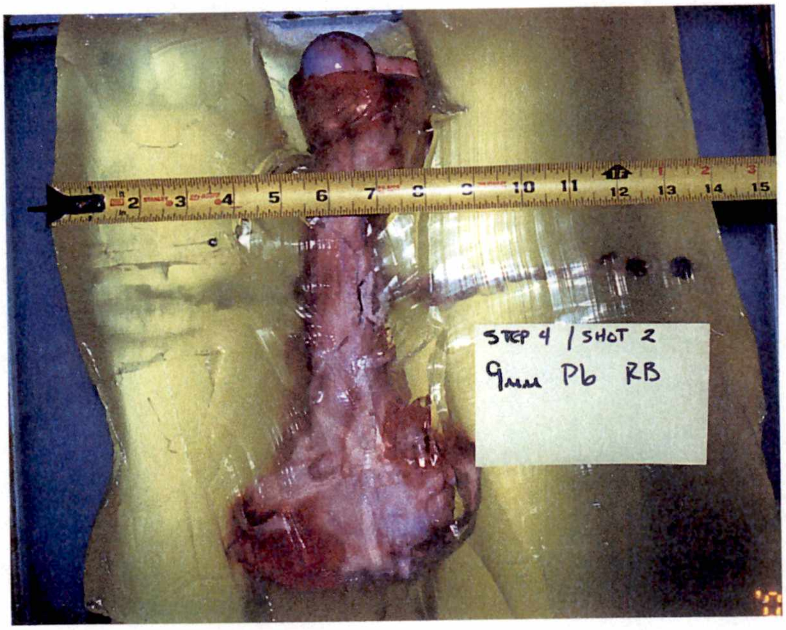

Figure A-3: Second lead pistol shot against a real bone target.

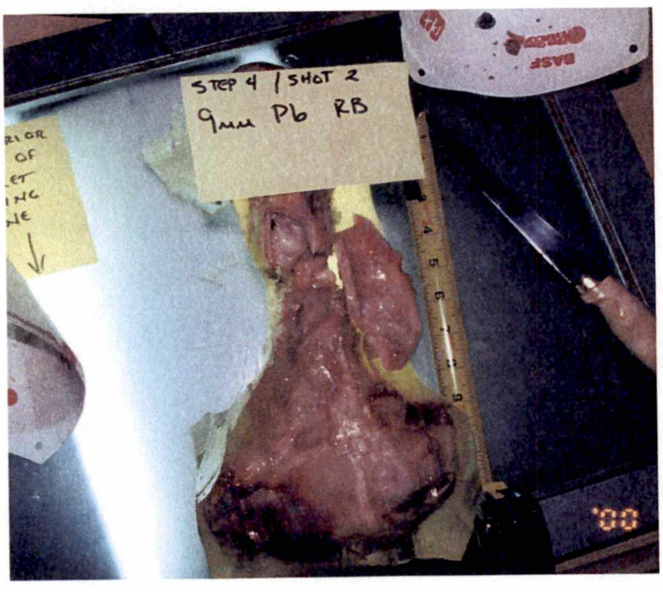

Figure A-4: Real porcine bone from second lead pistol shot.

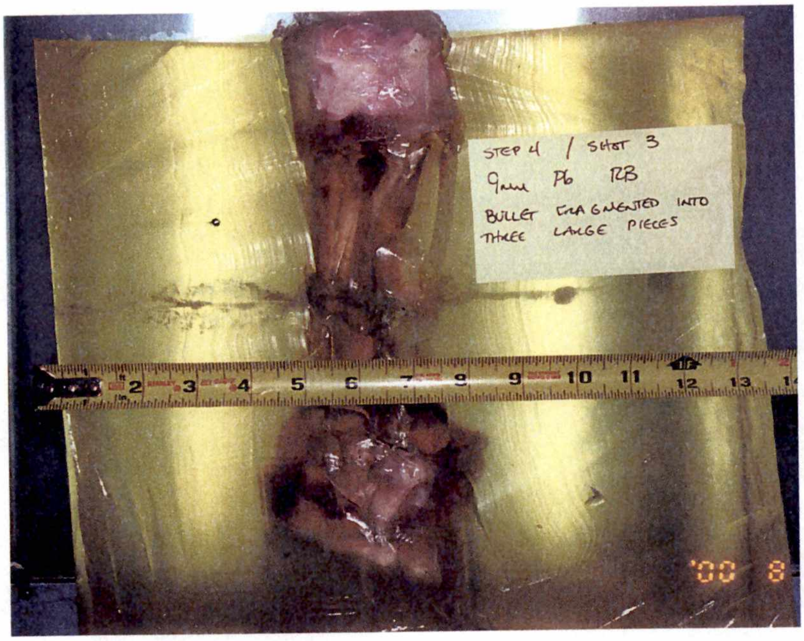

Figure A-5: Third lead pistol shot against a real bone target.

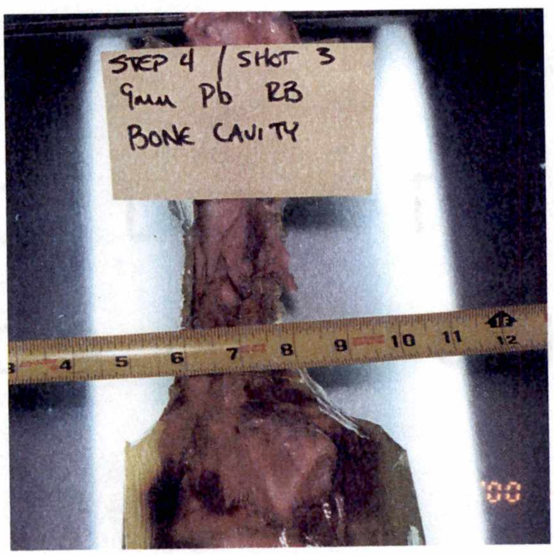

Figure A-6: Real porcine bone from third lead pistol shot.

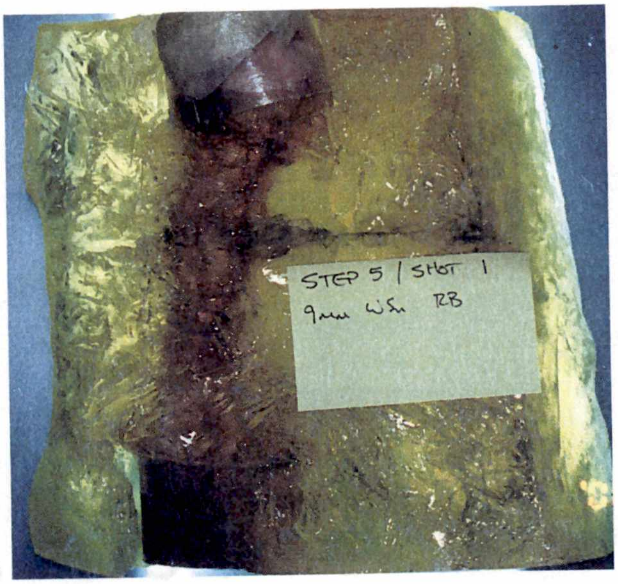

Figure A-7: First tungsten tin pistol shot against a real bone target.

Figure A-8: Real porcine bone from first tungsten tin pistol shot.

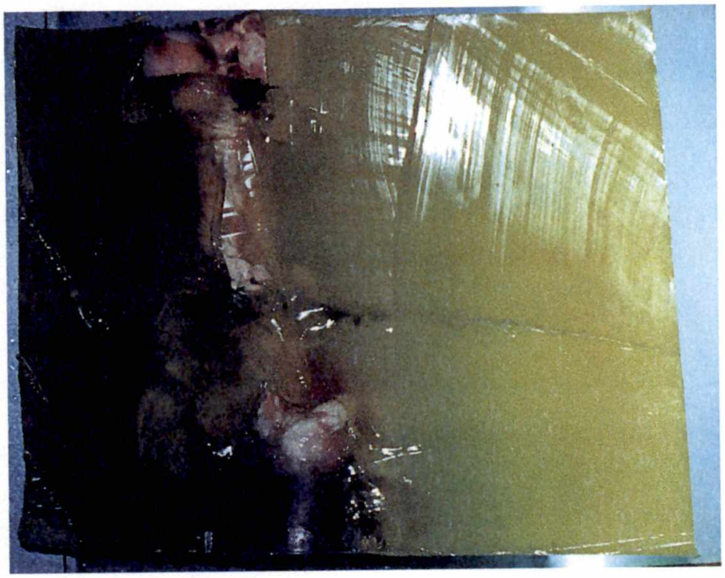

Figure A-9: Second tungsten tin pistol shot against a real bone target.

Figure A-10: Real porcine bone from second tungsten tin pistol shot.

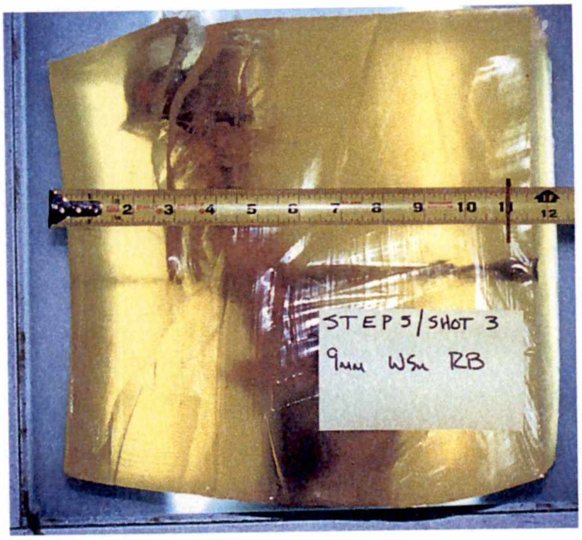

Figure A-11: Third tungsten tin pistol shot against a real bone target.

Figure A-12: Real porcine bone from third tungsten tin pistol shot.

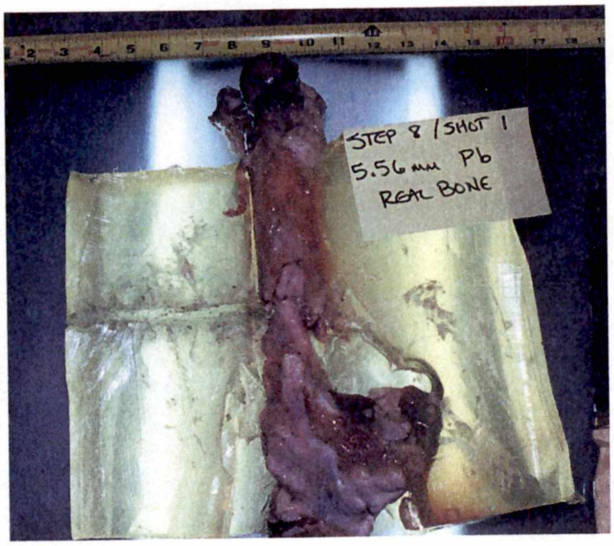

Figure A-13: First lead rifle shot against a real bone target.

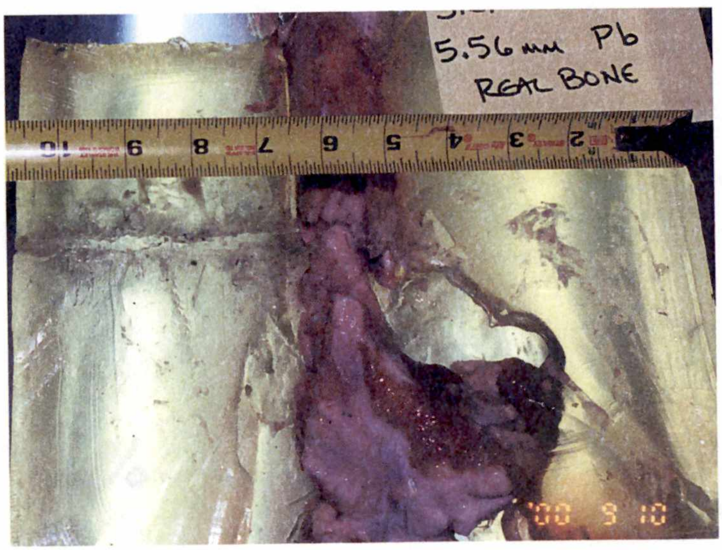

Figure A-14: Closer view of the real porcine bone from first lead rifle shot.

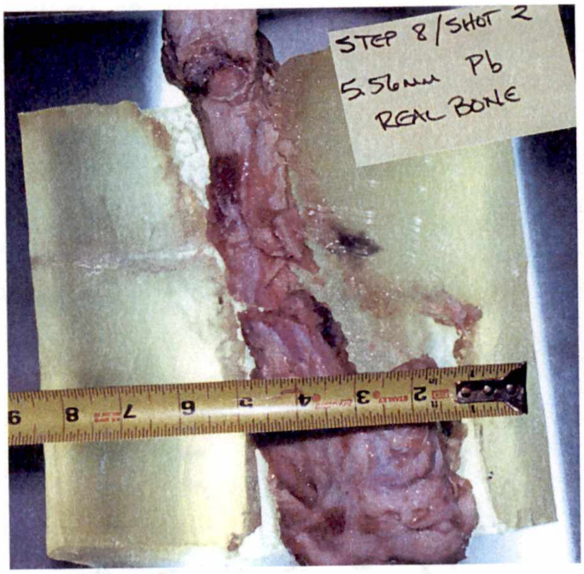

Figure A-15: Second lead rifle shot against a real bone target.

Figure A-16: Closer view of the real porcine bone from second lead rifle shot.

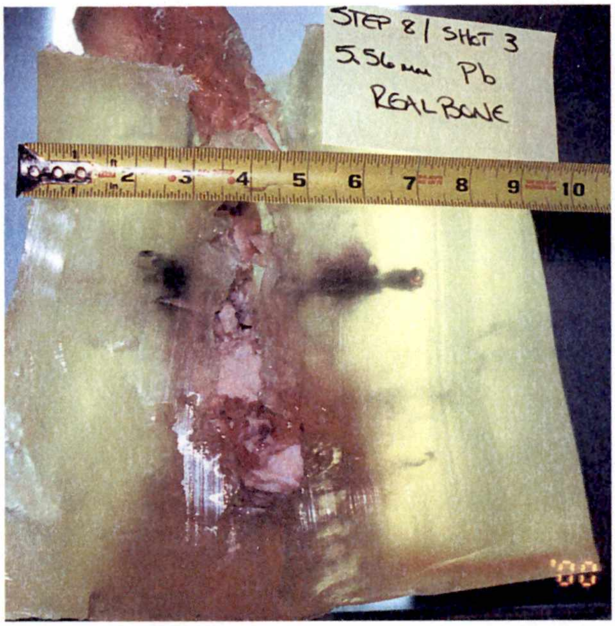

Figure A-17: Third lead rifle shot against a real bone target.

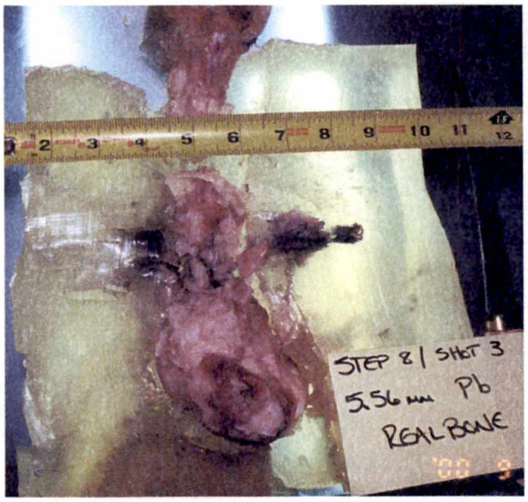

Figure A-18: Closer view of the real porcine bone from third lead rifle shot.

Figure A-19: First tungsten tin rifle shot against a real bone target. Note increased penetration depth compared to lead rifle bullets.

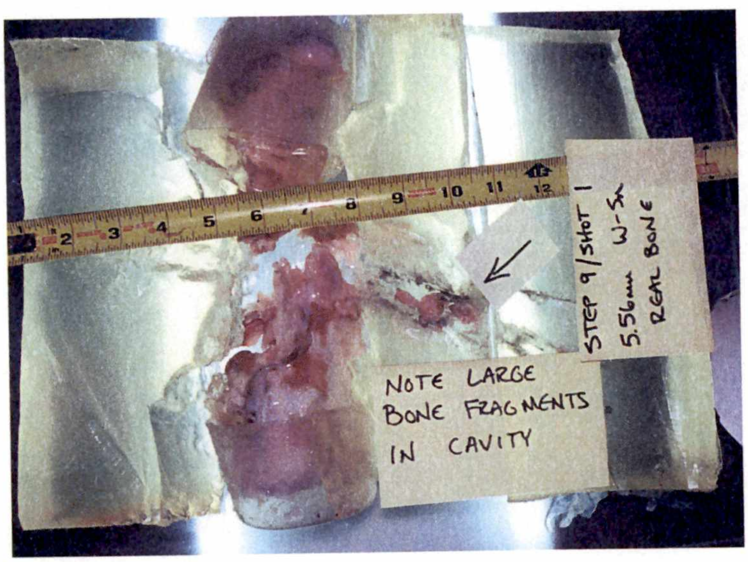

Figure A-20: Closer view of the real porcine bone from first tungsten tin rifle shot.

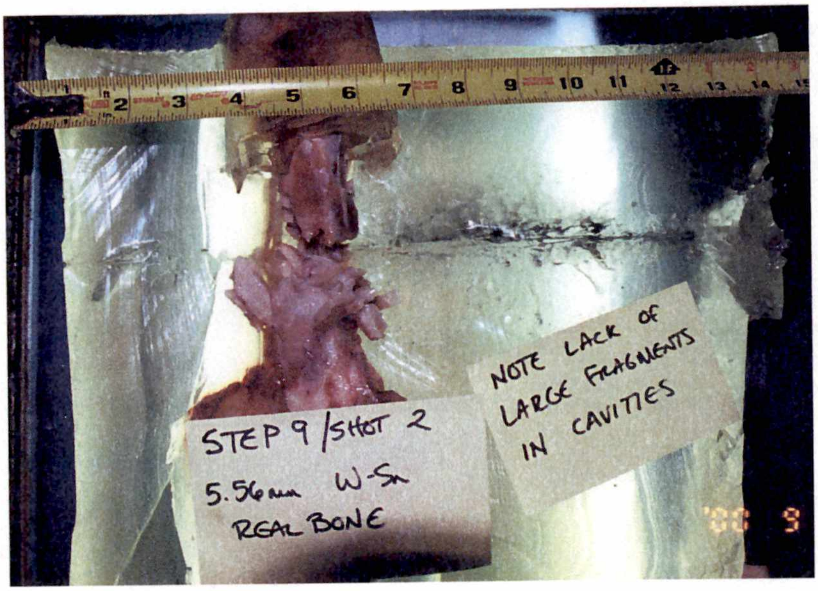

Figure A-21: Second tungsten tin rifle shot against a real bone target. Note increased penetration depth compared to lead rifle bullets.

Figure A-22: Closer view of the real porcine bone from second tungsten tin rifle shot.

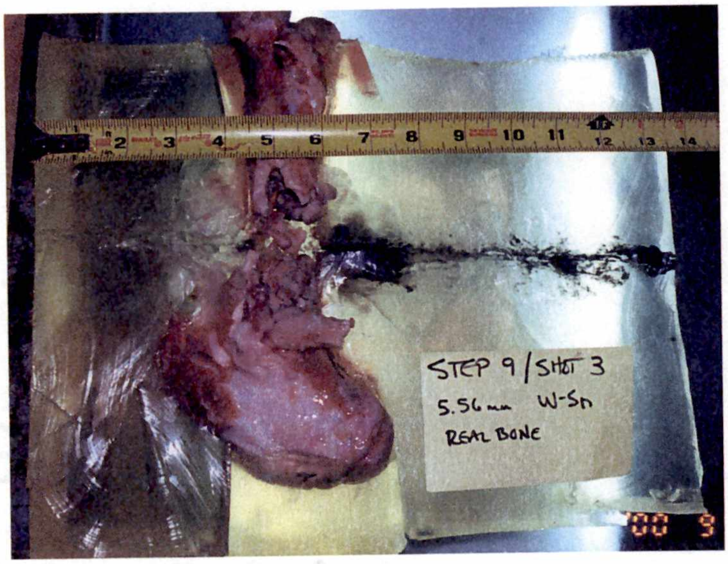

Figure A-23: Third tungsten tin rifle shot against a real bone target. Note increased penetration depth compared to lead rifle bullets.

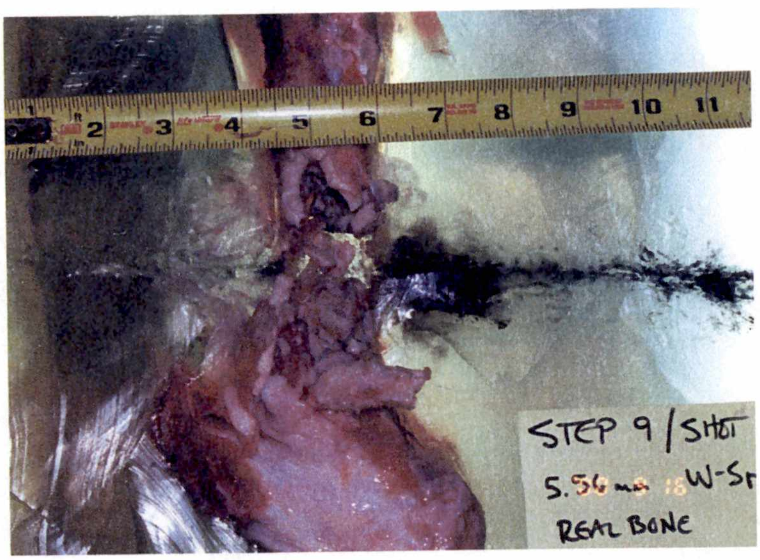

Figure A-24: Closer view of the real porcine bone from third tungsten tin rifle shot.

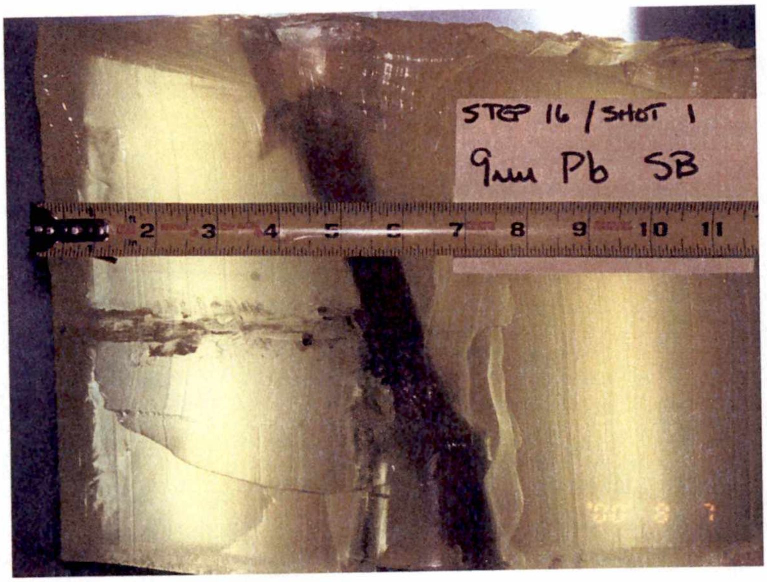

Figure A-25: First lead pistol shot against a synthetic bone target.

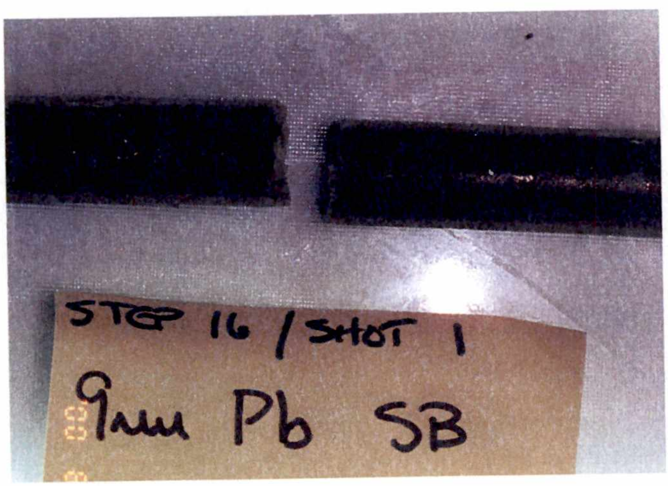

Figure A-26: Closer view of the synthetic bone from first lead pistol shot.

Figure A-27: Second lead pistol shot against a synthetic bone target.

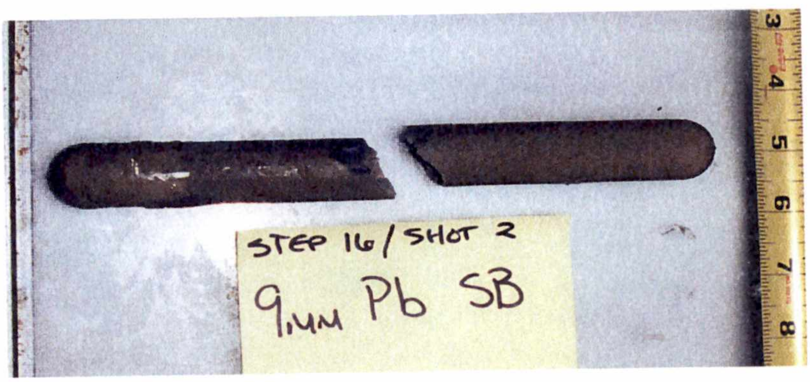

Figure A-28: Closer view of the synthetic bone from second lead pistol shot.

Figure A-29: Third lead pistol shot against a synthetic bone target.

Figure A-30: Closer view of the synthetic bone from third lead pistol shot.

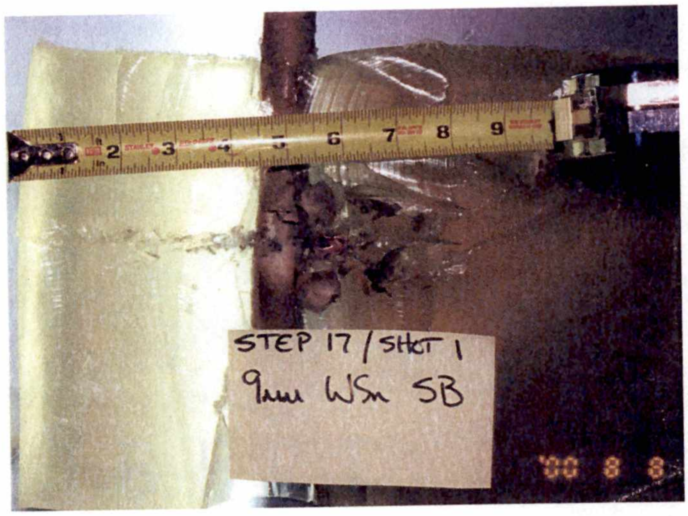

Figure A-31: First tungsten tin pistol shot against a synthetic bone target.

Figure A-32: Closer view of the synthetic bone from third lead pistol shot.

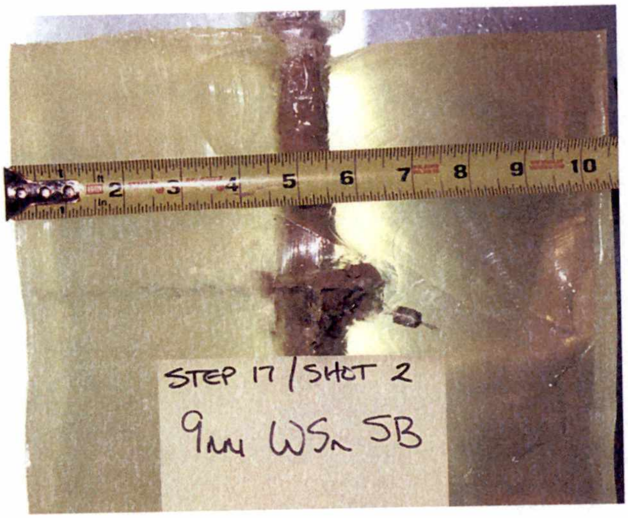

Figure A-33: Second tungsten tin pistol shot against a synthetic bone target. Note the unfragmented tungsten tin bullet core immediately past the bone.

Figure A-34: Closer view of the synthetic bone from second tungsten tin pistol shot.

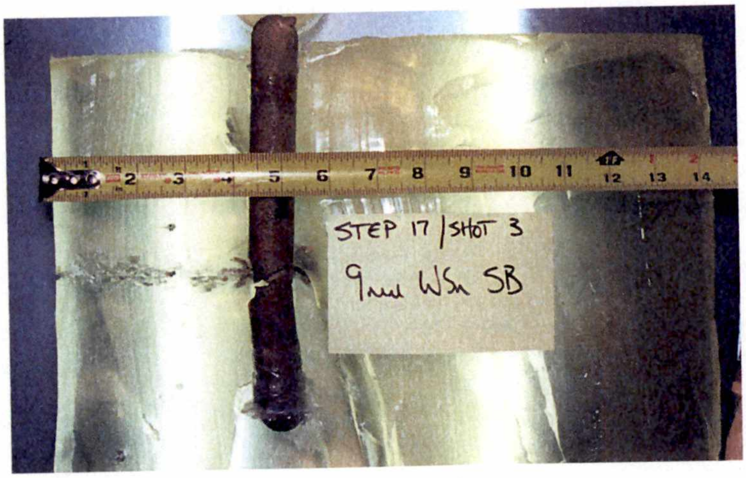

Figure A-35: Third tungsten tin pistol shot against a synthetic bone target.

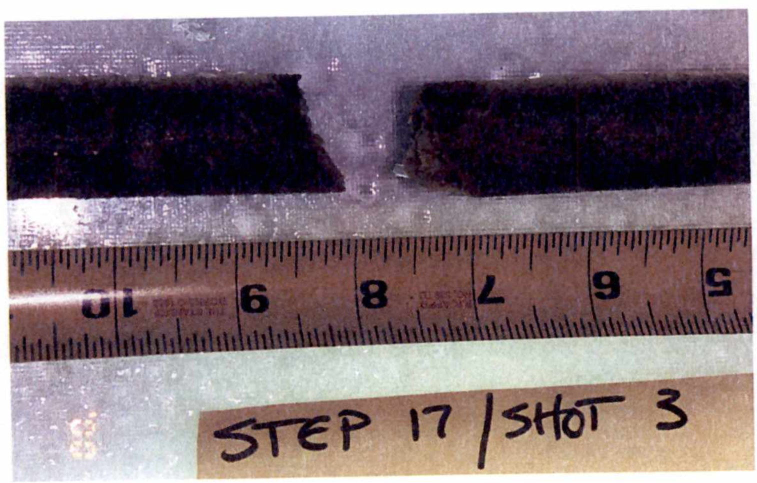

Figure A-36: Closer view of the synthetic bone from third tungsten tin pistol shot.

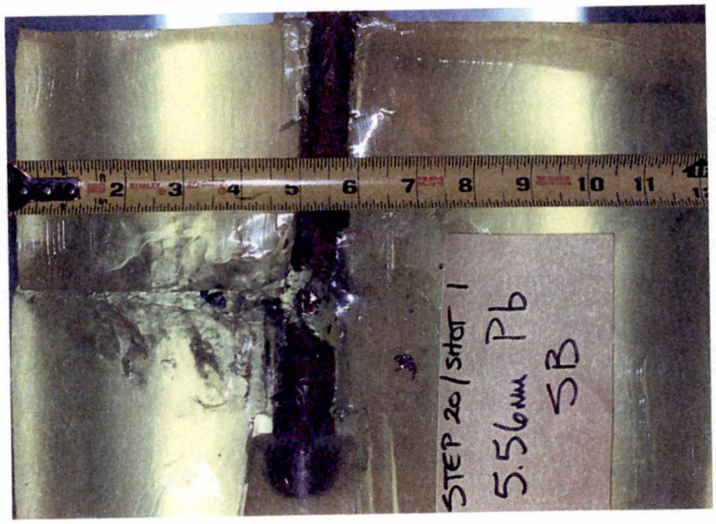

Figure A-37: First lead rifle shot against a synthetic bone target. Note the similar penetration depth to the real bone for the same type of bullet.

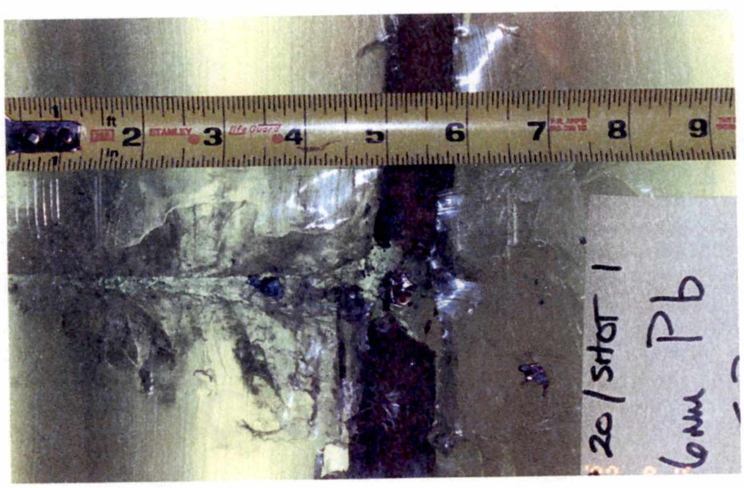

Figure A-38: Closer view of the synthetic bone from first lead rifle shot. The large metallic fragment to the lower right of the bone is the bullet jacket.

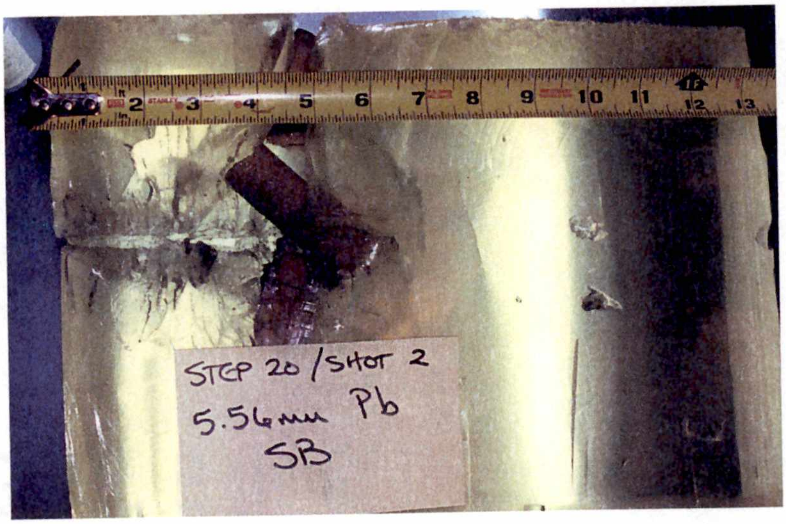

Figure A-39: Second lead rifle shot against a synthetic bone target. Note the segmented fracture type.

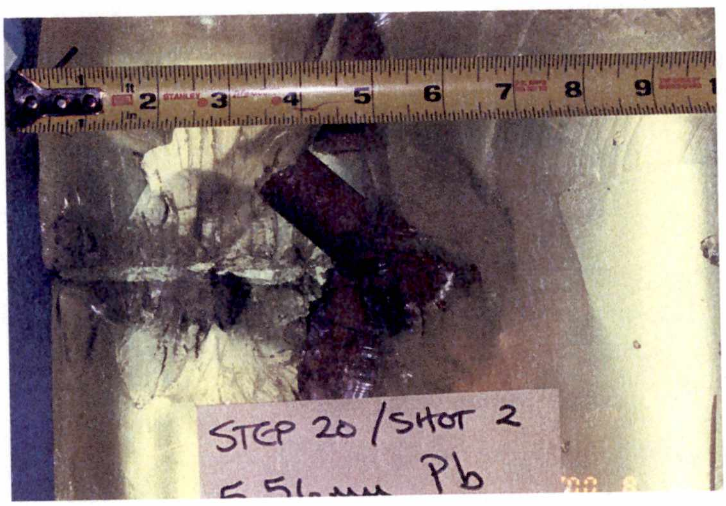

Figure A-40: Closer view of the synthetic bone from second lead rifle shot.

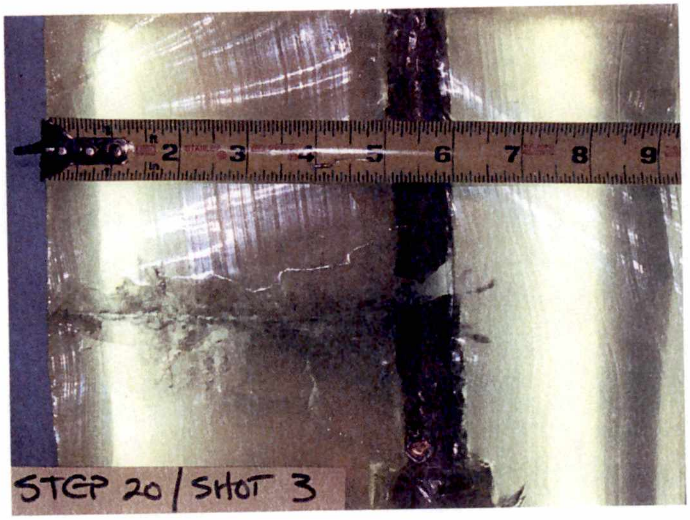

Figure A-41: Third lead rifle shot against a synthetic bone target.

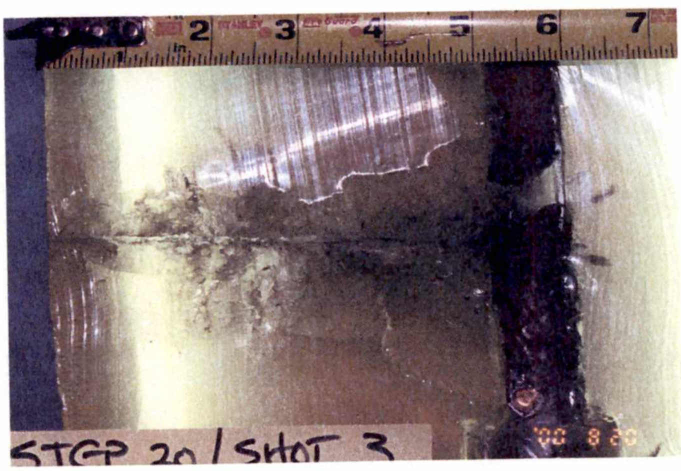

Figure A-42: Closer view of the synthetic bone from third lead rifle shot.

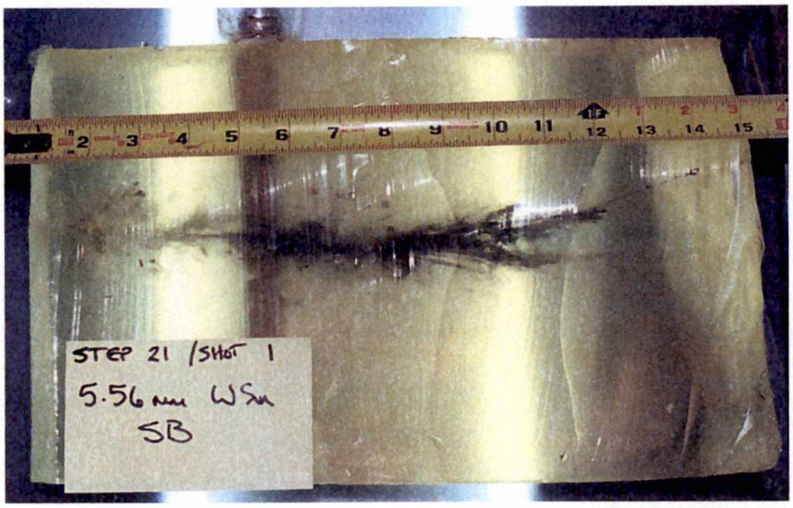

Figure A-43: First tungsten tin rifle shot against a synthetic bone target.

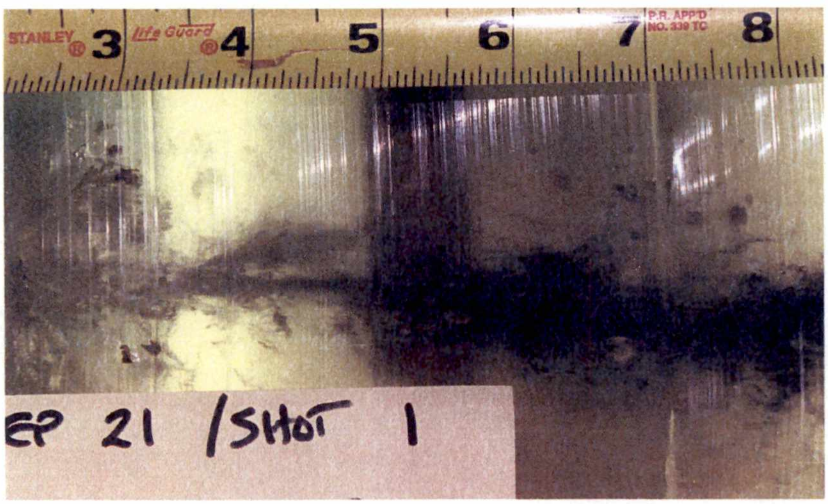

Figure A-44: Closer view of the synthetic bone from first tungsten tin rifle shot. Note the dispersion of bone fragments past the bone.

Figure A-45: Second tungsten tin rifle shot against a synthetic bone target.

Figure A-46: Closer view of the synthetic bone from second tungsten tin rifle shot. Note the comet-like dispersion of bullet fragments past the bone.

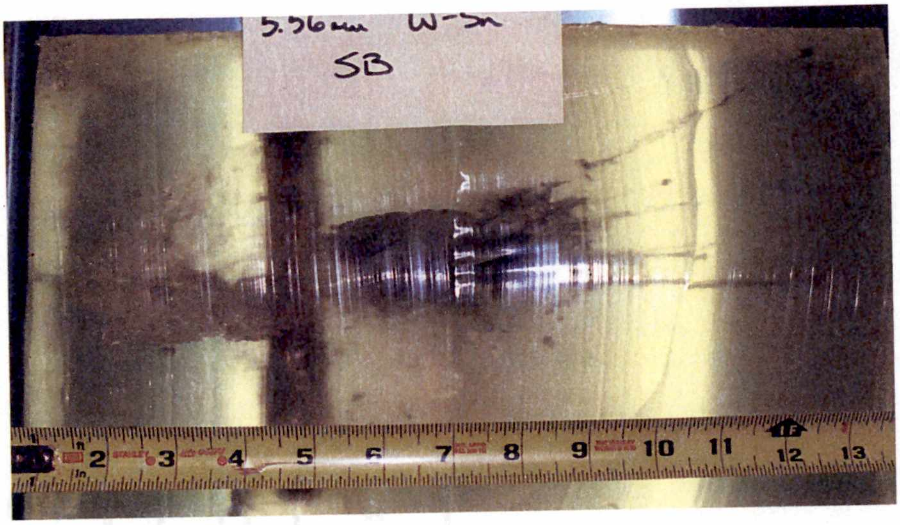

Figure A-47: Third tungsten tin rifle shot against a synthetic bone target.

Figure A-48: Closer view of the synthetic bone from third tungsten tin rifle shot. Note again the comet-like dispersion of bullet fragments past the bone.

Vita

Bryce Anderson began his engineering studies at the University of Tennessee in the Fall semester of 1992. He received his Bachelor's degree in Industrial Engineering from the University of Tennessee, Knoxville in the spring of 1997, and received his Master's degree in Industrial Engineering with a concentration in Human Factors in the fall of 2000. This thesis is presented as partial fulfillment of that degree. Mr. Anderson receives primary funding through the Engineering Fundamentals Division at UT, where he works as a graduate assistant teaching freshman engineering students the intricacies of Matlab and Mechanical Desktop.

Future plans involve the pursuit of Doctoral degree in Industrial Engineering with a focus on accident reconstruction. His pastimes include writing, collecting firearms, and restoring automobiles.