Trauma Rounds

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Wound Ballistics

JAMES MALONE, MD:* The case for presentation today is that of a 17-year-old boy who presented to San Francisco General Hospital with a .357 magnum gunshot wound completely through the right upper quadrant of the abdomen at the level of the right costal margin in the midclavicular line. The hole of entrance was dime-sized (1.5 cm) and the hole of exit was quarter-sized (2.5 cm).

The patient was in profound shock upon admission and, after appropriate resuscitation was carried out, laparotomy was done promptly. On operation, massive disruption of the liver with a 10 cm defect in the center of the liver substance between the two lobes was noted. The circulation to the liver was isolated by clamping the portal triad. Debridement of the liver, repair of several large defects in the suprarenal vena cava and right nephrectomy were then carried out and drainage was accomplished through the bed of the 12th rib. The patient's course has been relatively benign and he is about to be discharged now, ten days postinjury.

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F. WILLIAM BLAISDELL, MD:† *I would like to introduce one of our senior surgery residents, Dr. James Wilson. Dr. Wilson received training in small arms while in the Navy and became particularly knowledgeable in the use of the M16 rifle and the .45 automatic pistol. He became interested in the science of ballistics during this period.*

JAMES WILSON, MD:‡ I suggested to Dr. Malone that he present this case because a number of the members of our trauma team, after examining the entrance and exit wounds, were surprised at the extent of the internal damage. In this instance, the liver received the brunt of the injury and literally was exploded by the missile.

I believe that all of us who deal with gunshot wounds must have some understanding of ballistics if we are to manage patients with such injuries properly and if we are to avoid all lethal secondary complications which may result from bullet wounds. Unfortunately, the science of ballistics is a very complex subject that receives little attention in peacetime and usually has rela-

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tively little application in the management of civilian peacetime injuries. The reason for this is that most gunshot injuries we see in civilian situations are wounds from relatively low velocity missiles secondary to the use of handguns.

The mechanism of injury due to low velocity bullets was described as early as 1862 by MacLeod, who based his comments largely on observations made in the field during the Crimean War. In 1848 during Paris street fighting, Hugier observed the bursting effect of high velocity missiles on soft tissue and postulated that this was due to water particle dispersion in the tissues. Kocher then tested this hypothesis experimentally in 1876. In 1894 Horsely confirmed Kocher's studies, theorizing that the extent of damage correlated directly with the amount of fluid in the tissue.

The concept of cavitation was borrowed from hydrodynamics and was first applied to wound ballistics in 1898. Cavitation is the formation of a vacuum as a result of a solid object moving rapidly through a gas or fluid. In 1910 Stevenson described the shearing effect on blood vessels present in high velocity wounds and in 1921 Wilson described the effects of the formation of a temporary cavity on blood vessels, noting that slit-like lesions occurred in areas of the artery distal to the bullet track. Wilson also noted similar lesions in cases of near misses. In 1953, during the Korean conflict, Jahnke and Seeley described microscopic lesions occurring in vessels adjacent to grossly injured segments. These observations helped to explain the high failure rate of primary arterial anastomoses carried out without debridement of adjacent ends.

Interest in wound ballistics has been rekindled with the advent of the revolutionary 5.56 mm (M16) rifle in the late 1950's and with the current use by many police departments (including that of San Francisco) of magnum revolvers. Some state police units and special groups such as S.W.A.T. (Special Weapons And Tactics) units are now also using hollow point bullets and M16 rifles.

The increasing use of these higher speed bullets together with their more destructive characteristics make it imperative that civilian as well as military surgeons understand the basic principles of ballistics. Indeed, military surgeons, by virtue of the nature of the Geneva Convention, will likely treat wounds caused by fully jacketed bullets, while civilian surgeons in a country where hunting is a favorite sport have the greatest likelihood of encountering the most devastating wounds of all—those inflicted by ultra-high-speed hollow point bullets.

Ballistics is the study of projectiles in motion and can be divided into three categories: internal, external and terminal ballistics.

Internal Ballistics

Internal ballistics is the study of the passage of the bullet within the gun barrel. The hammer of the gun strikes the fulminate-of-mercury primer which ignites the slower burning powder in the casing, causing the bullet to separate from the casing. The force (or pressure) created by the expanding gas is what propels the bullet. In handguns pressures of up to 40,000 pounds per square inch (PSI) can be reached and in rifles pressures of up to 70,000 PSI may be generated. In view of these facts, it is not difficult to envision how the use of too large a powder charge or of an incorrectly-matched ammunition and handgun combination could cause a weapon to explode, causing serious injury. As a result it is most important that the magnum principles be understood.

A magnum charge simply means that more powder is present in the casing. For example, the only difference between a .38 caliber and a .357 magnum bullet is that the latter shell has more powder in it. As a result of the increased amount of powder, this type of bullet must be fired from a gun designed to withstand the higher pressures generated by it. Consequently, it is apparent that .38 caliber ammunition can be safely fired from a .357 magnum revolver, but not vice versa. Incidentally, for those unfamiliar with the term "caliber," it refers simply to the diameter of the bullet expressed in inches.

Most guns have longitudinal grooving, or rifling, in the barrel. This rifling imparts a spin to the bullet as it exits and this helps to stabilize it in flight. This spin can be greater than 200,000 revolutions per minute.

External Ballistics

As the bullet leaves the barrel, two very important measurable factors come into play: muzzle velocity (or the speed of exit of the bullet) and muzzle energy (determined by the mass and the velocity of the bullet). These measurements, together with the flight characteristics of the bullet, are dealt with in the science of external ballistics.

The efficiency a bullet has in overcoming air resistance in flight can be expressed numerically and is called the ballistics coefficient. It is related to the sectional density and nose shape of the bullet. Additional factors such as drag retardation and rotational energy also come into play, but these lie beyond the scope of this discussion.

In short, the killing power of a projectile is largely determined by the kinetic energy level upon impact. It follows that this killing power will be greater with bullets having higher ballistics coefficients.

One final aspect of external ballistics is important in our present discussion. This has to do with the actual physical flight of a bullet, since the aerodynamic forces acting upon a spin-stabilized bullet can contribute significantly to the wounding power of that bullet. Yaw, the deviation of the bullet's longitudinal axis from the actual line of flight, is a most important factor here because it directly influences the projectile's overturning moment in the target tissue; a bullet will tumble if its overturning moment due to yaw is sufficiently large. Other factors such as precession (or the lateral spinning around the center of mass) and nutation (the rotational movement in circles progressing in a rosette pattern) are also important. All of these influences together help make the wound inflicted by the M16 rifle (the standard military weapon) so devastating.

Terminal Ballistics

Terminal ballistics or wound ballistics is a science which deals with the amount of energy imparted to the tissues by a missile. This is determined primarily by calculation of the striking velocity and by the shape and weight of the bullet, although velocity is by far the most significant factor of these. Three theories have been formulated for quantitating wounding capacity: the *momentum theory,* which states that momentum is equal to the mass of the bullet times velocity; the *power theory,* which says that power is equal to mass times velocity raised to the third power, and the *kinetic energy theory,* which states that kinetic energy equals mass times velocity squared, all divided by two times gravity. The latter theory is now thought to provide the best estimate of wounding capacity and it follows from its application that modest increases in velocity will result in tremendous increases in the kinetic energy of the missile. Recognition of this fact led to the development of the new lightweight but powerful military rifles such as the M16, whose caliber (.223) is quite small.

Upon evaluating the impact kinetic energy of a missile, we see that both mass and velocity play important roles in determining the actual wounding capacity. Taking mass first, it is obvious that increases in mass will increase the impact energy. The .45 caliber automatic pistol, which has been standard issue of the United States armed services since 1911, was developed with precisely this principle in mind. At that time, the velocity factor of the equation was unalterable—powder and chamber steel had not yet advanced enough to enter the magnum era. Ballistics experts examined the ability of the then-standard .38 special revolver (used before the .45) to wound enemy personnel and found that even when solidly hit, an enemy might not be immobilized. Therefore, it was concluded that by increasing the mass of the bullet to the 240-grain weight of the .45 missile, the desired wounding effect could be achieved. A present-day comparison of bullets shows the importance of mass differences between the .357 magnum and the .44 magnum. Both travel at approximately the same velocity—about 1,500 ft per second. But the .357 bullet weighs 158 grains while the .44 bullet weighs 240 grains. This mass difference accounts for the diverse muzzle energy values for these two missiles—845 ft-lb and 1,150 ft-lb respectively.

The amount of energy imparted to the tissue may be estimated as the kinetic energy upon impact minus the kinetic energy upon exit. It is here that actual bullet design becomes important and the great difference between battlefield and civilian wounds is readily seen. Ideally, a bullet should dissipate all of its energy to the tissue with no residual exit energy. The severity of a wound, then, is directly related to the amount of kinetic energy absorbed by the tissue from the bullet. The level of energy absorption at a tissue depth of 15 cm in humans is used as the index of wounding capacity, as this is the depth at which most vital structures lie. Therefore, missiles which disintegrate upon impact or which have great penetrating ability such as those designed for elephant hunting are inappropriate for military use, as these types of bullets would pass right through the target object without releasing any significant amounts of energy.

Types of Bullets

Bullets are divided into three basic types: lead, semijacketed (hollow point or soft point) and fully-jacketed. The lead bullets utilize maximum mass while maintaining minimum air resistance. When equipped with a magnum charge of powder, they are the standard issue cartridge used by the San Francisco Police Department—the .357 magnum lead bullet. This type of bullet will impart most of its energy to whatever it strikes since it becomes deformed after impact and therefore the danger of innocent bystanders being injured by bullets passing through the target object is minimal. However, due to the low melting point of lead, these bullets cannot be propelled beyond a velocity of about 2,000 feet per second (FPS).

Therefore, for higher speed missiles, one must use jacketed bullets. These usually have a lead core with a copper-nickel jacket although steel is sometimes used when high penetration is desired, as when automobiles or armored vehicles are likely targets. Semijacketed bullets with lead noses or hollow points are designed to mushroom after initial penetration, thereby dissipating more energy to the tissues. With the use of an expanding bullet—that is, a hollow point—the advancing frontal area of the bullet after impact can achieve impact values ten times greater than those of a fully-jacketed bullet.

In some states, police use hollow points to achieve greater immobilizing ability. These are usually used in conjunction with a magnum load, since it has been shown by Dimaio and others that standard loads like that of the .38 special do not generate enough velocity (or kinetic energy) to enable the hollow point to wound any more effectively than the more conventionally designed bullets.

Fully-jacketed bullets are mandatory ammunition for military use as designated by the Geneva Convention. With the use of these bullets, the penetration (especially with high velocity weapons such as the American M14 and the Russian AK47) becomes much greater with less damage to the tissue, since less kinetic energy is absorbed. An exception to this is in the case of the M16 at higher velocities; so-called "lead splatter" will occur—that is, even though the missile is fully jacketed, its velocity is so great that it may disintegrate in its course through the body.

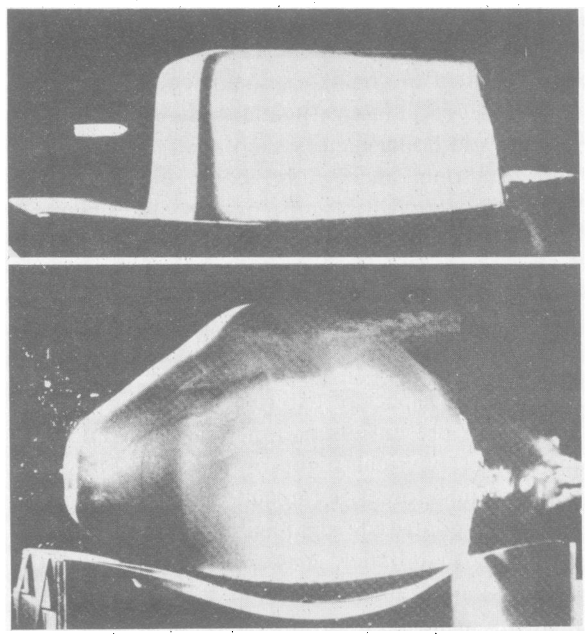

Figure 1.—High Velocity Injury. **Top,** Bullet is shown approaching a suspended gelatin block, **Bottom,** Bullet has emerged from the right of the gelatin block. The tremendous explosive or cavitation effect is exemplified by the simulated tissue. (Reproduced by permission of author and publisher from Amato JJ, Billy LJ, Lawson NS, Rich NM: Am J Surg 127:454, 1974)

Bullet Velocity

Now we come to the most important part of the kinetic energy equation—velocity. Bullet velocity is probably best classified as low (if less than 1,000 ft per second), medium (if in the 1,000 to 2,000 range) and high (if the velocity is greater than 2,000 ft per second). The muzzle velocity of a given weapon is determined by the weight of the bullet and the powder charge, while impact velocity will be determined, of course, by these factors together with the range or distance of the target from the weapon.

Low velocity wounds do little damage other than in the direct pathway of the bullet, for only a small temporary cavity is formed. In fact, as was noted by MacLeod in 1862, blood vessels can actually be pushed aside by low velocity missiles.

Medium and high velocity wounds may be grouped together for purposes of this discussion. Medium velocity bullets such as the .357 magnum and the .44 magnum create larger temporary cavities and a greater blast effect than do the low velocity bullets like the .22 or .38—but not nearly to the extent as that seen with high velocity weapons such as the M16 or the .30-06.

A high velocity bullet releases energy upon impact, which creates a temporary cavity (Figure 1). This phenomenon is known as tail splash and the energy released is transmitted to tissue particles with rapid acceleration, both in a forward direction and laterally. Consequently, these particles then push forward and expand the cavity laterally to up to 30 times the size of the entering bullet and pressures of up to 3,000 pounds per square inch can be reached during the few milliseconds of cavity formation. The cavity begins to form 1 to 2 msec after impact and the missile undergoes several pulsations of decreasing amplitude before it comes to rest, resulting in the permanent track—the only damage apparent to the surgeon at the time of debridement of the wound. As mentioned earlier, the type of tissue and the pathway of the bullet are also important factors. Indeed, the pattern of injury is largely determined by the density, elasticity and cohesiveness of the tissues penetrated.

The high elasticity of lung tissue helps to protect it from the damage accompanying creation of the temporary cavity; the cavity in lung tissue is much smaller than that seen in muscle, liver or bone tissues. But this is not to say that no damage is done. The shock wave alone from higher velocity bullets such as the M16 causes massive destruction of cellular integrity.

Muscle and liver are two types of tissue with very similar densities and the energy absorbed per cubic centimeter of tissue for both muscle and liver tissue is essentially the same. Both exhibit tail splashing when penetrated, but only a small area of destruction surrounding the temporary cavity will ultimately be seen with muscle wounding even though initial tissue displacement might be extensive. Since liver tissue has less cohesiveness than muscle tissue, the formation of the entire temporary cavity will result in obvious external damage, manifest by gross disruption, as occurred in the case just presented. Therefore, the permanent cavity will approximate the size of the temporary cavity. The spleen has this same characteristic.

Some debate has ensued over the existence of a temporary cavity in instances of high velocity bone injuries. However, some cavitation is probably the case. As is obvious, when bone is struck the boney fragments themselves become missiles, producing even more damage. As you might imagine, even large bones may be fractured though not directly struck by a high velocity bullet.

DR. BLAISDELL: *Dr. Wilson, would you mind spending a moment describing the particular principles of ballistics involved in vascular injuries?*

DR. WILSON: Vascular injuries are a special category. Damage to areas of vessels remote from the actual track often occurs. In one experiment a steel sphere fired at 3,000 feet per second into a femoral artery suspended in gelatin produced a shearing injury for several inches along either side of the direct path of injury. In similar studies, the artery suspended in gelatin was severely damaged by cavitation even when an M16 bullet passed several inches away. The lesions produced secondary to cavity formation add to the total destruction of tissue in the direct path of the bullet. These vascular injuries consist of loss of endothelium, microthrombus formation, breaks in the internal elastic membrane and outward herniation of the media.

DR. BLAISDELL: *I have found it helpful to envision vascular injuries as the artery being forcibly stretched to several times its normal length in the area of injury. The adventitia or outer coat of the artery is the toughest and most durable part, and the intima (inner coat) the least. This "stretch injury" results in a transection of the intima and a variable portion of the media, and the shearing effect causes the intima to roll up like a windowshade in both directions from the center of the injury. This leaves denuded vessel walls with variable degrees of intimal obstruction on both sides of the injury.*

DR. MALONE: Dr. Wilson, as you know, we do not carry out much debridement of missile tracks associated with most handgun injuries that we treat. Would you comment on the principles of debridement? How radical should this be?

DR. WILSON: As I indicated, low velocity missile injuries such as those associated with .22 or .38 caliber handguns produce an injury much like a simple stab wound. The police magnum pistols, however, produce a much more extensive soft tissue injury, and debridement of the missile track back to viable bleeding tissue should be done. In high velocity rifle injuries, survival following truncal injuries is rare. Injured extremities require extensive debridement and often amputation.

DR. BLAISDELL: *I agree entirely with Dr. Wilson's comments. Frequently, however, the nature of* *the injury is such that the surgeon may have difficulty carrying out adequate debridement. This includes problems over areas such as vital organs, mesentery, retroperitoneum and pelvis. At the initial operation, all grossly nonviable tissue should be removed. Then reoperation should be carried out within 12 to 24 hours to reassess the tissue damage and to complete the debridement of any tissue which has become nonviable. This should be repeated as often as necessary until all nonviable tissue is removed. In some instances, Marlex® mesh may be necessary to close abdominal wall defects so created.*

Dr. Wilson, do you have any closing comments?

DR. WILSON: It is clear that high velocity wounds can cause extensive damage beyond that which is immediately apparent in an emergency room or operating theatre. Just as it is important to know the mechanisms of a burn injury, it similarly is extremely helpful to know, if possible, the caliber and type of bullet used to inflict the injury.

In most criminal trauma cases, the exact nature of the weapon used to inflict the injury will not be known. However, an attempt has been made here to give you the knowledge to make an educated guess as to the potential of the wound you will treat.

Two Opinions on the Diagnosis of Chronic Hepatitis

When should you suspect chronicity in a patient treated for acute hepatitis?

DR. BOYER: "I think if a patient has evidence of abnormality of liver function for more than three months, one should find out what kind of hepatic abnormality you are dealing with. Now, of course, you want to exclude the more common causes, such as alcohol abuse and biliary tract disease, but in many of these patients, that is the point at which we would advise the patient to come in for a liver biopsy to settle the issue if we cannot exclude chronic hepatitis on clinical grounds. So I use a definition of about three months, which is really based on what we know about the normal time course for acute viral hepatitis to resolve. And most cases, of course, will be resolved within that time limit."

DR. REYNOLDS: "Well, I wouldn't disagree with trying to find out at somewhere around the three-month level, all circumstances permitting, but having seen a number of patients in whom the condition dragged on as long as nine months and then seemed to resolve totally, I would like to extend that period of time considerably before I would be very confident of chronic disease—extend it months, and maybe a year."

DR. BOYER: "I didn't mean to imply that these patients all have chronic disease. I think many of them will turn out not to have chronic disease."

DR. REYNOLDS: "There's nothing wrong with trying to find out at three months, I agree. And particularly if the antigen remains positive for more than about 10 to 12 weeks. This is very suggestive that things are not going to heal up completely."

—JAMES L. BOYER, MD, *Chicago*
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