Management of Traumatic Wounds to Lower Limbs Resulting From Projectiles of Various Eras

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Doctors will have more lives to answer for in the next world than even we generals
-Napoleon Bonaparte

HISTORY

The past 3 centuries have witnessed magnificent leaps and bounds in medical and surgical advancements at the expense of unfathomable numbers of lives on the battlefields of the world. As technology has advanced the art of killing mankind, the medical profession has had to advance parallel to the former. Bullet projectile technology has evolved from seemingly primitive muzzle-loading, black powder propulsed, low velocity, heavy lead balls to modern smokeless powder propulsed, high velocity, low weight, Spitzer-type bullets (Figure 1).

Advancements in medical knowledge concerning wound sepsis also vastly increased survival projections from sustained limb wounds. Since the first development of combustion driven projectiles, limb and life-threatening wounds have dramatically increased in battlefield scenes. Until the middle of the 20th century, amputation of a full or partial limb has been the standard of care in vascular compromised limbs. The lower extremity wounds of the Korean War marked a significant turning point in traumatic battlefield standards of care with the advent of vascular repair status post-traumatic projectile wounding of limbs. Lower extremity battlefield wounds of the late 20th and early 21st Centuries have progressed from being caused by rifle-fired projectiles to predominantly landmine and improvised explosive devices (IEDs) (Figure 2).

The middle nineteenth century saw many countries engaging in numerous wars including the Crimean War, the US-Mexico War, and the American Civil War. The Crimean War pitted English and French Empires against the Russian Empires. One primary long-arm weapon of the English infantryman was the newly manufactured 1853 Enfield, which fired a 0.577 caliber solid lead ball at velocities approaching 900 feet per second (Figure 3).

On the opposite side of the battlefield was the Russian manufactured Tula Arsenal Model 1845 smoothbore musket, which fired a 0.704 caliber solid lead ball at an unknown velocity presumed to be near, although less than that of the 1853 Enfield musket rifle. At this juncture in time, it was customary to fight your opponent by large scale, full frontal attacks standing shoulder to shoulder to maximize firepower due to the relatively unreliable projectile trajectory from smoothbore muskets. One notable expert from this time period is British surgeon George James Guthrie. Dr. Guthrie did not actually participate in the Crimean War, but he has published many surgical texts on the management of gunshot wounds from his experiences in other wars of the

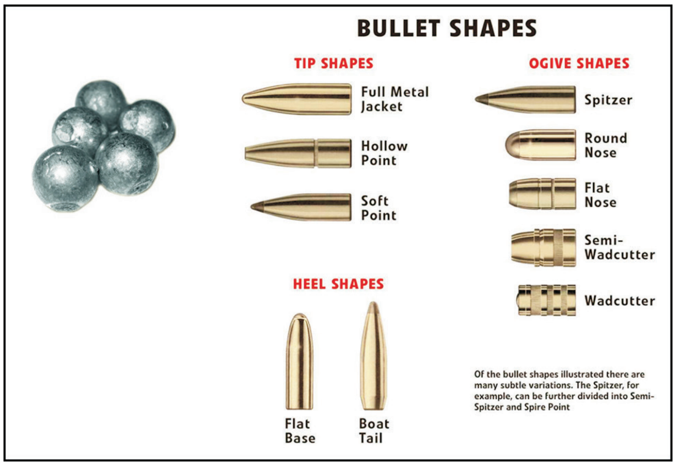

Figure 1. Examples of projectiles ranging from lead musket balls to modern bullet shapes.

Figure 2. Example of ballistic projectile wound to the foot.

era. It was the opinion of Dr. Guthrie that swift amputation should be carried out at the soonest possible moment in order to stave off the potential horrors of death secondary to gangrene. Factors contributing to the necessity for amputation were the nature of the wound created by conical versus round lead ball. Military surgeons noted the osseous deformities caused by conical bullets fired from rifled muskets were significantly more traumatic with more comminution and longitudinal fissuring, quite commonly encompassing the entire shaft into the corresponding joint. Also of importance is the deeper penetration allowed by the conical design compared to that blunt deforming forces of round soft lead. Further penetration up to 4 times deeper compared to traditional round balls were achieved by alteration of the bullet metallurgy (Figure 4).

Despite these technological advances in projectile lethality, the comparatively low velocities allow some fraction of survivability of neurovascular bundles due to their elasticity with non-direct hits. One such example was witnessed by Dr. Guthrie on the battlefield of Toulouse in which a soldier's femoral sheath was penetrated with no compromise of the femoral nerve, artery, or vein. Survivability of life and limb are dependent upon the hemorrhage status of the limb in question. Military surgeons therefore advocate the immediate ligation of questionable vessels at primary medical facilities near the front lines of battle. In the event that ligation is not possible prior to a soldier's receipt into secondary field hospitals, common instruction to litter bearers was to plug the wound with a finger to directly compress the vessel in comparison to simply applying a tourniquet to the affected limb.

In regards to the first half of the American Civil War, little change in warfare techniques and weapons had taken place compared to that of the Crimean War. The British Enfield rifle was in great use by both sides during the 4-year conflict (Figure 5).

After the war, surgeons of the US Army found that projectile fractures to the upper third of the femur resulted in the death of approximately 3 of 4 soldiers regardless of surgical versus conservative management. However, injury to the middle third offered survivability nearing 50% in both conservative and surgical management with surgical management having a slight advantage. Attempts to amputate at the level of the hip proved fatal in all reported cases within a frame of a few days to 3 weeks.

By the close of the nineteenth century, firearm technology had made the jump from muzzle loading to repeating rifles of lower caliber and much higher velocity. The Spanish-American War pitted Spain and Cuba against the US. The American forces were largely equipped with the 30-40 Krag/Jorgensen rifle, which fired a 0.308 caliber bullet at approximately 2,000 feet per second while the Spanish and Cuban forces were primarily equipped with the superior German manufactured 1893 Mauser rifle. The Mauser rifle fired a bullet of slightly smaller diameter, 0.284/7mm caliber at a higher velocity of approximately 2,400 feet per second. The significance of this transformation from heavy lead bullets to smaller, copper jacketed/lead core bullets is that the velocity was double, and in the case of the Mauser, triple that of the black powder-propulsed predecessors (Figure 6).

Figure 3. Lee-Enfiled rifle and cartridge used during the Boer Wars.

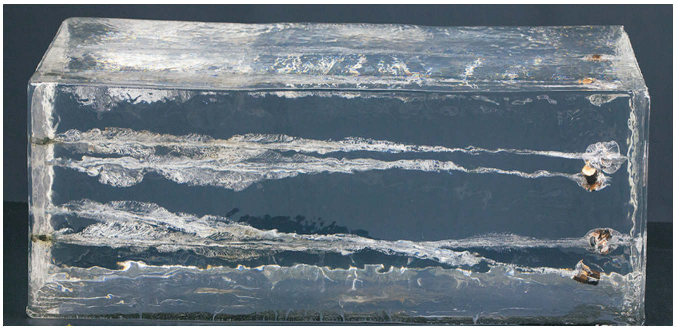

Figure 4. Comparatives of ballistic gel deformations from projectiles of differing mass and velocity.

Figure 5. Enfield rifle used during American Civil War.

It was also just prior to the Spanish-American War that the antiseptic protocols outlined by Lister were incorporated as the standard of care for lacerations and other injuries where microbe seeding was of high potential. Lister advocated the use of warm, diluted carbolic acid to flush wounds at significant risk for infection. To bandage such wounds it was advised to use dry iodoform gauze covered by copious amounts of alembroth wool.

Limb salvage techniques were not advanced beyond what was already standard of care in compromised limbs. The preferred procedure for upper thigh severely comminuted fractures was to amputate at the hip with a survivability of barely ten percent largely attributed to the excessive

Figure 6. Comparatives of flattening between lead conical bullet and a lead bullet surrounded by a brass jacket.

hemorrhage prior to receipt at the field hospital. Contrary to this standard of care, some Russian surgeons theorized that due to the velocity and friction of air during projectile flight, projectiles were essentially sterile from the heat gained by friction and thus created a sterile wound. In these cases, the Russian surgeons did not extract the projectile and simply treated the wounds conservatively resulting in a mere ten percent mortality rate by their records.

The early twentieth century played host to the largest war known to man over control of Europe. The Mauser rifle mentioned previously underwent design and cartridge changes to evolve into the infamous K98 Mauser (Karbine-1898) which fired a slightly larger bullet than the first Mauser rifle, this being an 8mm bullet fired at approximately 2,700 feet per second (Figure 7).

Many other rifles were utilized, but this one rifle and caliber met more Allied soldiers than any other infantry weapon of the day. By this time most nations, including those of the Axis Powers, were fielding only full metal jacketed (FMJ) ammunition to reduce the destructive powers embraced by the "mushrooming" effect of the non-encased bullets. The prohibition of non-FMJ was called for and agreed upon by the countries participating in the Hague Convention of 1899. The use of radiographs greatly improved the surgical outcomes of injuries sustained during The Great War (Figure 8).

Foreign bodies were more easily identified and the extent of osseous deformation could be interpreted. Projectile wounds to the lower extremity, especially the knee, were now being treated by debridement of nonviable tissue and

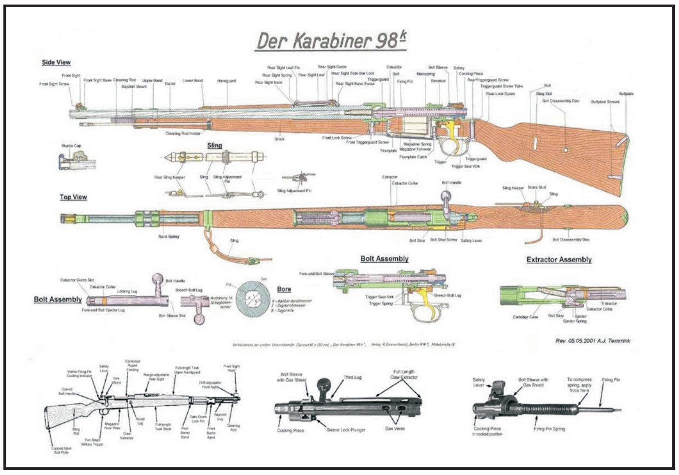

Figure 7. K98 Mauser rifle used during WW I and WW II.

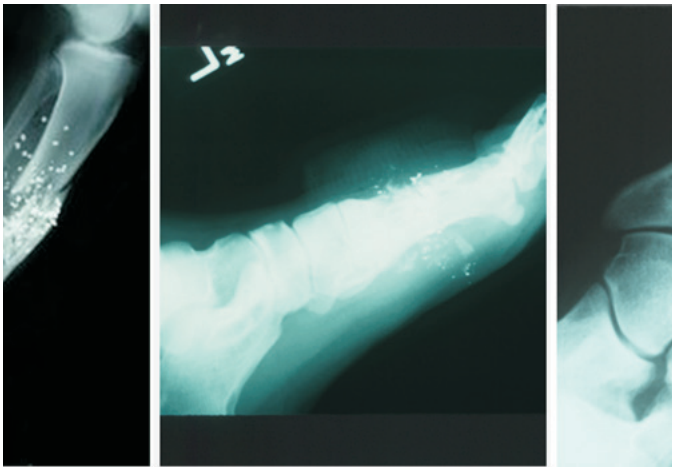

Figure 8. Radiographic imaging showing the effect of high velocity projectiles on bone.

excision of foreign material followed by copious irrigation of either formalin or glycerin. A drain was then placed into the affected joint through a separate incision if sepsis was not to be suspected. The initial wound bed was flushed with more antiseptic via the drain line, and the synovium was then closed primarily if the surgeon was satisfied that the possibility of joint sepsis was minimal. In the event of sepsis or ischemia, immediate amputation was warranted.

Military surgeons emphasized the key factor in life and limb salvage was prompt immobilization of the affected limb to primarily thwart further hemorrhage. The affected extremity was then placed in traction devices at permanent hospital locations. If radiographs showed suitable alignment and if risk of wound infection was minimal, a permanent cast was applied in the corrected position with the knee slightly flexed. One surgeon attempted open reduction and pseudo-delayed primary closure of the femur on 7 soldier patients. Of the 7 undergoing the surgery, 3 died due to sepsis with the surgeon noting that signs of sepsis were evident at the time of surgery. In addition, those 3 mortalities were delayed several days before being given prompt medical and surgical care.

World War II witnessed another quantum advance in ballistics with resulting magnification of field war wounds. The US primarily fielded the M1 Garand, which offered very accurate semi-automatic fire in an 8-round clip, loaded with a 30-06 caliber round capable of a muzzle velocity of 2800 feet/second and an effective firing range of over 500 yards (~ 460 meters) (Figure 9).

While there were certainly other weapons used, ranging from the Colt .45 ACP hand gun to the M-1 .50 caliber machine gun, the M-1 Garand was the most common infantry weapon deployed by the US during World War II. The effectiveness of this caliber led to a progression of weaponry, which fielded the standard 7.62 mm NATO round, which was actually 308 caliber and fired at about 2,800 feet per second. Dramatic differences were seen between the larger, M1 Garand bullet wounds and the smaller M1 carbine (Figure 10).

Both weapons fired a projectile, which measured about .30 caliber (0.30 of an inch). However, the carbine loaded a shell with much less projectile powder and therefore inflicted less impressive wounds. The use of these 2 weapons continued on in the Korean conflict. By the end of the Korean conflict, ballistics experts realized tactical advantages in greater firepower i.e., weapons that loaded more rounds. The M1 Garand was modified to the M14, which fired a standard NATO 7.62 round, capable of wounding characteristics, which mimicked the M1 Garand. However, both the M1 Garand and the M14 were relatively heavy weapons, with relatively heavy ammunition. Clearly, there were limits on the practical quantity of munitions the average infantry soldier could carry in to combat. To optimize the lethality of a field soldier, and taking notice of the efficacy of tactical assault weapons like the German Strumgewehr and the Russian AK-47 (Figure 11), the US sought development of a weapon that could reduce field load weights and still inflict maximum wounding power. To accomplish this, heavy consideration was given to the formula for Kinetic Energy (KE): KE= ½ MV2 , noting the greater influence of velocity over mass. This led to development of the M16, which fired a new 5.56 mm round (.223 caliber), capable of projecting at 3,110 feet per second, and was adopted as a NATO standard. This smaller projectile offered greater lethality as it transmitted greater energy in a smaller projectile. The projectile in essence mimicked some of the wounding effects of non-FMJ (i.e., "dumb-dumb" bullets with soft lead tips) bullets. The smaller 5.56 mm projectile would tumble within a body mass and track up to 4 shock waves, dragging enormous wounding energy behind the projectile. This resulted in small entry wounds and huge, gaping exit wounds, often not in a linear orientation due to tumbling of the bullet projectile (Figure 12).

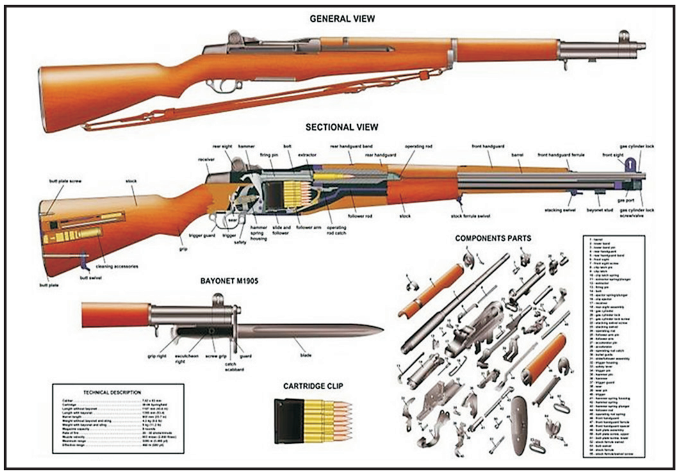

Figure 9. US M-1 Garand used during World War II and Korea.

Figure 10. Examples of 2 commonly used rifles during WW II and Korea, the M-1 Garand and the M-1 Carbine. Both are approximately 30 caliber, but the upper, M-1 Garand causes a much more damaging projectile injury because it has a faster muzzle velocity. However, the lower carbine has the advantage of 20 (later 30) rounds per magazine, compared with 8 rounds per clip of the upper Garand.

Figure 11. Comparative of the German Strumgewehr on the top and the similar Russian AK-47 on the bottom.

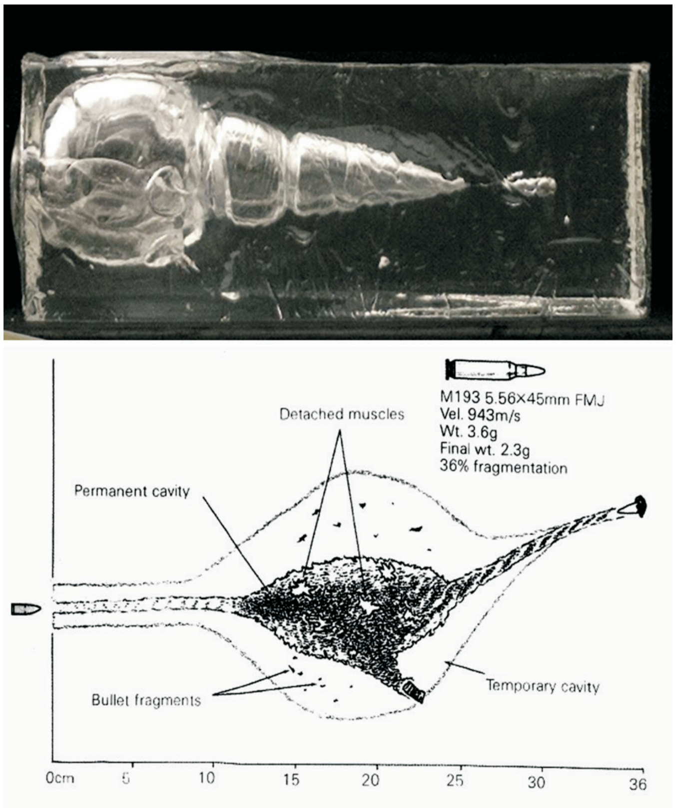

Figure 12. Examples of shock waves that follow high velocity projectiles in ballistic gel and the tendency for small weight projectiles to fragment and tumble.

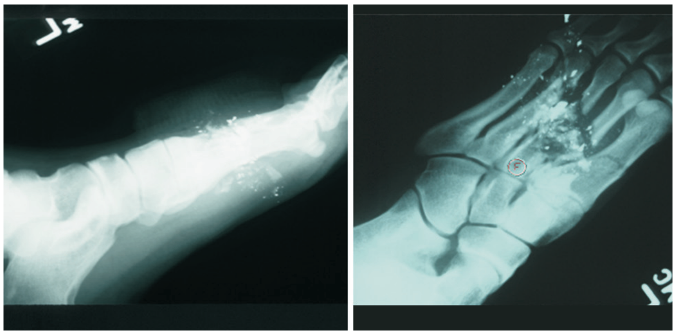

Figure 13. Radiographs of high-velocity projectile injury to the left foot.

Figure 14. Initial debridement with stripping of fascia, removal of superficial fragments and evaluation of metatarsal parabola.

Beginning in World War II and significantly refined during the Korean conflict, evacuation of troops from "hot zones" to field hospitals or US Navy medical vessels drastically improved the survivability of soldiers and probability of saving effected limbs. Limb saving techniques implemented during the Korean War, such as direct repair of compromised vessels and/or use of patch-grafting for revascularization, combated ischemia that would ultimately lead to either a below-knee amputation or in some cases an above-knee amputation. Lieutenant Commander Gorman of the US Navy Reserves reported that all surgical patients with compromised popliteal arteries automatically received fasciotomies to prevent further ischemic damages due to edema. At the field level, protocols were developed to initiate aggressive local debridement of devitalized tissue, following the edicts of early 20th Century surgeon Thomas Hunt:

"Of the Bone, leave it alone, Of the Skin, slice it thin, Of the Fascia, Slash ya."

This was followed by delayed primary closure and high dose "war wound" IV antibiotic regimen. Skeletal structures, which are structurally compromised, should be restored to relative positions of function via linear or hybrid external fixation, which is followed at higher tiered medical facilities with possible internal or more sophisticated external fixation modalities.

CASE REPORT

A 19-year-old presented with a high velocity gunshot wound of the left foot, resulting in multiple bullet fragmentation and comminutions of the midfoot involving the first, second, third, fourth, and fifth metatarsals. The third and fourth metatarsals were for the most part, disintegrated within the midfoot (Figures 13, 14).

The patient was evacuated to an initial medical facility within 4 hours of the gunshot. He was treated by copious irrigation and starting on intravenous antibiotics. The superficial bullet shrapnel fragments were removed and the entrance wound was expanded and explored within the limits of the track of the bullet projectile. Deep fragments, which might place vital structures at risk, were left alone.

Thereafter, the primary wound was left open and packed within the framework of an external fixator. The fixator was placed to preserve length and positions of function of rays 1-5 of the forefoot. Fractures of the first and fifth metatarsals were clean fractures, due to expanding shockwaves from the primary bullet track. These were fixated with 3 or more Shantz screws. The middle 3 rays were pulverized by the force of the high velocity projectile. The heads of each of these was preserved. Shantz screws were used to retain length of the respective rays within the framework of the forefoot. The patient was evacuated to a higher tiered facility and observed for 6 weeks, giving the first and fifth metatarsals time to heal (Figure 15).

After 2 months, the external frame was removed. The fourth metatarsal had "glump healed" with enough bone fragments to maintain its length. However, the third and second metatarsals had no substance between the head and the base of the respective second and third rays. Therefore, a segment of fibula was harvested to match the length of space between the second and third metatarsal heads and bases (Figure 16). These segments were grafted to the respective metatarsals to restore the second and third ray lengths and a normal metatarsal parabola (Figure 17).

The patient was kept nonweight-bearing for 2 months with another month of limited weight-bearing in a reverse wedge shoe. Thereafter, he healed uneventfully. There was no shortening of the toes and he was able to wear regular shoes without difficulty. In conclusion, by understanding the physics of ballistic tissue damage, the trauma surgeon will be better able to optimize outcomes and restore function in lower extremity projectile injuries.

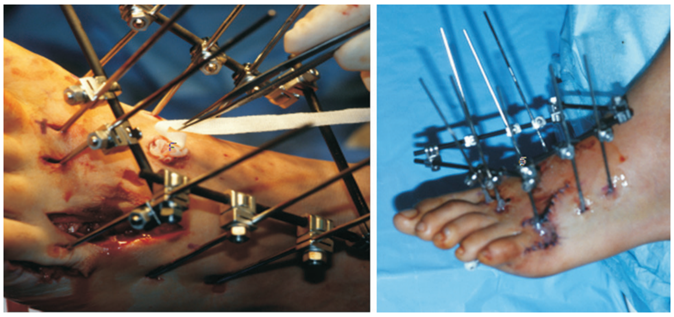

Figure 15. Application of external fixator and packing of wound for DPC.

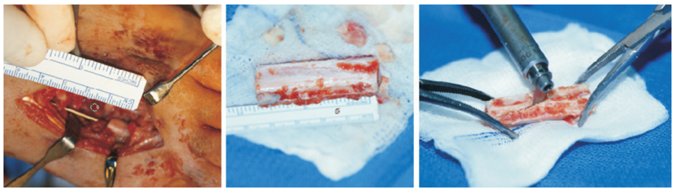

Figure 16. Measuring filler struts and harvesting from fibula.

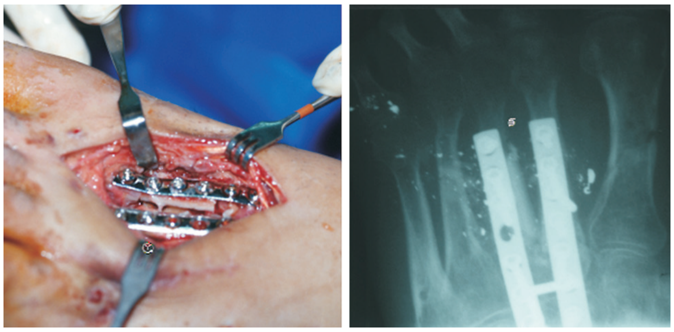

Figure 17. Placement of internal fixation to maintain metatarsal strut autografts.

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