High velocity gunshot injuries to the extremities: management on and off the battlefield

Jowan G. Penn-Barwell¹ · Kate V. Brown¹ · C. Anton Fries¹

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Abstract The gunshot wounds sustained on the battlefield caused by military ammunition can be different in nature to those usually encountered in the civilian setting. The main difference is that military ammunition has typically higher velocity with therefore greater kinetic energy and consequently potential to destroy tissue. The surgical priorities in the management of gunshot wounds are hemorrhage control, preventing infection, and reconstruction. The extent to which a gunshot wound needs to be surgically explored can be difficult to determine and depends on the likely amount of tissue destruction and the delay between wounding and initial surgical treatment. Factors associated with greater energy transfer, e.g., bullet fragmentation and bony fractures, are predictors of increased wound severity and therefore a requirement for more surgical exploration and likely debridement. Gunshot wounds should never be closed primarily; the full range of reconstruction from secondary intention to free tissue transfer may be required.

Keywords Ballistic · Combat · War · Gunshot wounds · Injuries · Gun

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✉ Jowan G. Penn-Barwell
jowanpb@me.com

¹ Academic Department of Military Surgery and Trauma, Royal Centre for Defence Medicine (RCDM), ICT Research Park, Vincent Drive, Edgbaston, Birmingham B15 2SQ, UK

Introduction

Approximately 70 % of battlefield wounds sustained in conflict since the Second World War are due to explosive munitions [1•]. However, gunshot injuries are more frequently encountered during the early phases of conflicts, known as “theatre entry operations” [2].

The majority of battlefield injuries affect the extremities; therefore, orthopedic surgeons often have the primary responsibility for the management of casualties with gunshot wounds (GSWs).

This paper will review the current best practice for surgical treatment of combat gunshot injuries in light of recent clinical experience, scientific research, and historical expertise. In order to fully understand clinical considerations, the ballistics of wounding will first be reviewed.

Energy transfer into extremity wounds

The amount of work or damage inflicted on tissues depends on the amount of kinetic energy possessed by the bullet when it strikes the body and the amount possessed when, and if, it exits the body. Kinetic energy (KE) is given by the following equation:

$$KE = \frac{mv^2}{2}$$

Where
 m = mass
 v = velocity

Modern military ammunition, i.e., the 5.56×45 mm SS109 and M855 rounds used by NATO forces and

the 5.45×39 mm 7 N6 used in the AK-74, are all high velocity with relatively low mass, allowing soldiers to carry more rounds for the same weight while still potentially possessing a large KE. Table 1 illustrates the differences in KE between handgun and common military ammunition.

Since the mass of the bullet is a constant, its deceleration as it travels through the body dictates the amount of KE transferred.

Two principle factors affect the rate at which a bullet is decelerated:

- (i) The type of tissue the bullet is passing through
- (ii) The surface area of the bullet presented to the tissue

In simple terms, the bullet will transfer the least energy if it does not deform, fragment, tumble, or strike bone. Tumbling, fragmentation, or deformation (sometime called “expansion” due to the increase in the surface area presented by the bullet) increases the drag on the bullet, slowing it, and increasing the transfer of energy. A similar effect occurs when the bullet strikes bone after traversing soft tissue.

The wounding effect of bullets can be divided into two types (see Fig. 1):

1. A permanent cavity

The formation of a wound tract by the direct cutting and shearing effect of the bullet forcing its way through tissue, i.e., the same wound that would be produced by a spear or arrow of the same diameter travelling through the body.

2. A temporary cavity or cavitation

This results from the turbulent flow created in the wake of the bullet and produces an expanding bubble of low-pressure vapor that rapidly collapses back on itself [3]. Cavitation occurs in the wake of most bullets but is greater with more turbulence around the bullet—i.e., if it is fragmenting, tumbling, or deforming or is travelling faster. These features are more commonly seen in large game or military ammunition, and therefore, wounds involving cavitation are seen more commonly in battlefield injuries than those encountered in the civilian setting.

Fig. 1 Schematic showing formation of tract of permanent cavity and temporary cavity with tensile damage to tissue due to the effect of stretching of tissue due to cavitation. © Surg Lt Cdr J Penn-Barwell

Effect of GSW on extremity tissues

It is important to distinguish between anatomic and functional effect of GSWs. The anatomic effect of bullet traversing the body and creating a permanent cavity will be similar in the thigh or the head, but the functional effect may be negligible in the former and almost certainly fatal in the latter. In the head and torso, there are organs and structures in which almost any anatomic disruption will result in death, e.g., the CNS, heart, and great vessels, whereas structures in the extremities are typically more tolerant of gunshot injuries.

Skin and muscle

These tissues are relatively elastic and therefore tolerate the temporary stretching effect of cavitation relatively well with limited tissue necrosis. Functionally, injuries to these tissues are also well tolerated.

Neurovascular structures

Nerves and vessels are often relatively fixed anatomically and therefore are vulnerable to the temporary distorting effect of cavitation. They can remain macroscopically intact away from the permanent cavity; however, intimal damage in vessels and axonal damage in nerves can result in functional failure even some distance from the path of the bullet [4•, 5].

Table 1 Comparison of two common military rifle bullets with the ubiquitous 9×19 mm handgun round [32–34]

Ammunition	Weapon	Mass (g)	Muzzle velocity (ms ⁻¹)	KE (KJ)
SS109	M-16 family, SA-80	4	940	1.7
7 N6	AK-74	3.4	900	1.4
9-mm NATO	Handgun	8	350	0.5

Bone

The unique strength of this tissue means that it exerts a significant retarding effect on projectiles that strike it. This results in considerable energy transfer, often with extensive fragmentation of both bone and bullet. There follows the potential for these fragments to be accelerated as secondary missiles [6, 7].

Surgical management

The treatment of battlefield gunshot extremity wounds involves a hierarchy of surgical priorities:

- i) Control of hemorrhage
- ii) Prevention and treatment of infection
- iii) Reconstruction

Geographically and chronologically, these priorities are addressed in three distinct phases—immediate care, damage control, and definitive surgery (Table 2). Damage control surgery is usually performed in a constrained environment, close to the point of wounding and very rapidly after injury. It aims to control hemorrhage and reducing contamination. Definitive surgery is a series of staged procedures away from the battlefield and in a more resourced setting. It is focused on treating or preventing infection and reconstructive procedures.

Hemorrhage control

Battlefield GSWs can cause exsanguinating hemorrhage by transecting major vessels. On the battlefield, the “C” of circulation is addressed prior to the airway in the military evolution of the Advanced Trauma Life Support paradigm [8]. In practice, this is a combination of direct pressure dressings and, if necessary, a proximal tourniquet. Junctional injuries, i.e., those involving the groin and axilla, continue to represent a challenge, and a variety of hemostatic dressings have been developed to assist the arrest of bleeding in these injuries

[9]. Currently, a gauze impregnated with *Kaolin* (aluminum silicate) impregnated gauze is issued to US and UK soldiers and medics [10]. As soon as possible, damage control resuscitation should be initiated with 1:1:1 ratio of packed red cells, fresh frozen plasma, and platelets [11, 12].

Vascular injuries need careful assessment as there is a high rate of occult vascular damage in battlefield GSWs [13]. It may not be possible to assess the ankle-brachial index due to concurrent injuries, and initial assessment of a suspected vascular injury will likely involve contrast CT and/or surgical exploration with arteriography to demonstrate occult intimal damage [14].

In the damage control phase of forward surgery, a temporary shunt can be used to perfuse extremities before definitive formal interposition vascular grafting [15]. Vascular injury and repair mandates distal myofascial compartment decompression.

Prevention and treatment of infection

Battlefield GSWs are contaminated with bacteria and small quantities of clothing. Contamination can also be sucked back into the tract from the exit wound as the cavitation collapses.

Antibiotics with activity against gram-positive species should be administered systemically as soon as possible as delay has been shown to result in subsequent infection [16, 17].

The decisions regarding surgical treatment of GSW can be complex due to the heterogeneous nature of these injuries. Assessment of extremity GSW requires at a minimum careful neurovascular examination and orthogonal radiographs with radio-opaque markers over wounds.

Radiographs and clinical examination allow a reasonable assessment of energy transfer and therefore likely wound severity. Evidence of bone strike, bone fracture, and bullet fragmentation is indicative of greater energy transfer and therefore a likelihood of greater tissue damage requiring more extensive surgical exploration to ensure all excised necrotic tissue [18, 19]. The judgment of injury severity requires a degree of “art”

Table 2 Surgical treatment priorities

Phase	Hemorrhage control	Infection control	Reconstruction
Immediate care	<ul style="list-style-type: none"> • Direct pressure dressings • Tourniquets • Hemostatic dressings 	<ul style="list-style-type: none"> • Systemic antibiotics 	
Early damage control	<ul style="list-style-type: none"> • Vessel ligation or shunting 	<ul style="list-style-type: none"> • Wound extension and exploration • Excision of necrotic tissue • Irrigation • Fracture stabilization 	
Delayed definitive surgery	<ul style="list-style-type: none"> • Interposition grafting 	<ul style="list-style-type: none"> • Repeat exploration and irrigation 	<ul style="list-style-type: none"> • Fracture fixation • Soft tissue closure and coverage

rather than just application of science and surgeons inexperienced with assessing these wounds should err of the side of incision and exploration.

A caveat to this is in the management of gunshot wounds affecting vital functional structures; for example in the hands and face, a more conservative excision is possible for three reasons; firstly, the excellent vascularity and healing potential of these areas enable tissues which may appear of questionable viability at “first look” to recover; secondly, these smaller body areas will drive a reduced systemic response by virtue of their relatively small volume of body composition, and thirdly, even small amounts of preserved tissue, for example in thumb length or eyelid, may have very significant effect on eventual functional outcome.

In complex injuries with any suspicion of extensive tissue destruction, wounds should be extended and all myofascial compartments involved thoroughly decompressed. The wound should be gently lavaged with several liters of saline delivered at low pressure [20]. Damp ribbon gauze can be passed along tracts with a blunt clip and used to gently “floss” any loose, necrotic tissue from the wound.

Complex wounds should be dressed with topical negative pressure (TNP) dressings to assist gentle drainage [21]. These have the advantage of providing a secure and controlled wound environment that facilitates evacuation of the casualty through the military chain of care. There is however a logistic burden conferred with respect to consumable items, and the provision of charged suction units is a constraint in austere military environments.

If TNP dressings are not available, the wound is gently packed with fluffed gauze. There is no evidence of superiority of any other dressings [22]. Wounds should be re-explored in 48 h for repeated debridement, lavage, and possible delayed primary closure. There is some evidence that wounds can be safely left for longer periods if covered with TNP [23]. In cases of delayed presentation, a third or fourth assessment in the operating room might be required prior to closure.

Timing of further wound excision is a matter of clinical judgment based on the physiological state of the patient. However, in the military setting, logistic constraints of the evacuation process are also taken into consideration. It is advantageous to reduce the numbers of dressing changes and excisions in an unstable patient requiring vital organ support where the wounds are considered to be clean; however, if wound infection or the presence of additional necrotic tissue is thought to be driving this deterioration, then further debridement and irrigation is mandated.

Bone fractures should be stabilized temporarily with an external fixator to reduce movement in the wound bed. This serves several purposes including reducing pain, preventing further injury to surrounding tissues, and reducing bacterial infection. External fixation is safe in the military environment [24] and is preferred to plaster casting as it provides greater

stability to the wound and can be left in situ during subsequent surgical procedures.

An injury with small entrance and exit wounds, no neurovascular compromise, and no evidence of fracture or bullet fragmentation on radiographs can be regarded as a simple through-and-through wound. It is likely in these injuries that there is a small amount of necrotic tissue in the permanent tract only and they can safely be managed minimally with irrigation, dressings, and prophylactic oral antibiotics [25, 26, 27]. Consideration should be given to temporarily restricting use of the limb by plaster cast in order to protect the healing tissues.

The ability to treat GSWs in a relatively conservative manner is a luxury only available to surgeons whose patients are rapidly delivered to them from the battlefield. However, the surgical practice in the pre-antibiotic era of the Second World War was to manage simple soft tissue wounds conservatively [28], and this is supported by subsequent experimental studies [26, 27]. For those surgeons treating casualties wounded many hours or even days previously, a more radical exploration of the wound is appropriate to eradicate infection [29].

Reconstruction

This phase can only commence when the wound is healthy and free from signs of infection.

Fixation of fractures from gunshot injuries can be approached in a similar manner to those from other mechanisms. Though it is sometime easier to use plates for fixation in instances where the surgical extension of the wound has essentially prepared the dissection necessary for the procedure. It has been noted anecdotally that ballistic fractures are very slow to heal, and this should be borne in mind when considering possibility of non-union.

No matter how innocuous wounds appear, they should never be closed primarily at the first surgical episode. Delayed primary closure or healing by secondary intention is the mainstay of soft tissue reconstruction following GSW.

For more extensive tissue loss that requires wounds to be covered rather than just closed, the reconstructive ladder is applied. Where soft tissue coverage of vital structures or fractures can be achieved, split skin grafting may be all that is required. In recent conflicts, some success has been achieved in using dermal scaffolds to produce a more durable and robust dermal layer that can receive a split skin graft; this is particularly advantageous in the load bearing areas for prostheses. Local flaps near the zone of ballistic injury may rely on a recipient tissue bed that is within the zone of trauma and flaps must be designed in such a way as to rely on such tissue for their vascular supply. If this is unavoidable, free tissue transfer may be the only solution; however, great care must be taken to place the microvascular anastomosis outwith the zone of trauma.

The timing of free tissue transfer in trauma reconstruction is also a challenge to flap viability, and it is the case that free tissue transfer within the first 72 h after injury offers the best chance of success due to the inflammatory response and tissue edema and compliance being optimized; the “subacute” 72 h to 3-week time window is best avoided; however, in the case of military trauma, it is frequently not possible for the patient to be either physiologically well enough or in a location permissive enough for microsurgery to be performed [30, 31]. Delaying soft tissue coverage beyond this 3-week window where vital structures or fractures are exposed is rarely possible, and hence, free tissue transfer must often be performed in a suboptimal wound environment.

In the choice of donor tissue, consideration must be given to donor site morbidity, especially in multiply injured patients. Latissimus dorsi and rectus flaps can further limit the ability of an injured patient to ambulate in the future as these are trunk stabilizing muscles. Preference is given to flaps with reduced donor morbidity including perforator flaps such as the antero-lateral thigh or scapula flaps or muscle flaps such as the gracilis.

In the case of delayed reconstruction, where severely injured patients have received split skin grafts in the first instance to achieve early wound closure and physiological stability, success has been achieved by removing scar tissue from structures such as nerves and tendons and replacing the skin grafts with vascularized free tissue. This has enabled functional recovery and treated neuropathic pain. It has been a universally observed phenomenon that in such cases, a delayed SIRS type response has occurred causing local tissue edema; it is suggested that this may be due to extended periods on intensive care at the time of injury or due to the receipt of large volumes of blood products. It has become standard practice in these cases to delay the final inset of the flap until after this edema has subsided following the microsurgical case.

Conclusion

Gunshot wounds sustained on the battlefield are a heterogeneous group of injuries, and they should not be regarded as all requiring radical tissue debridement. The features predictive of greater energy transfer are easily understood with a basic appreciation of terminal ballistics. The surgical priorities of hemorrhage control and prevention of infection start from the point of wounding. Later bony and soft tissue reconstruction can reduce the burden of residual injury.

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Compliance with Ethics Guidelines

Conflict of Interest None of the authors have any conflicts of interest with the subject of this work.

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