REVIEW

Ballistic Trauma-Considerations for the OrthoPlastic Surgical Team

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Both military and civilian surgeons can encounter ballistic wounds in their practice; these injuries can be complex and challenging. Tissues exert a drag force on the round as it passes through, absorbing Kinetic Energy as tissues are damaged. Tissue damage occurs via three mechanisms: creation of a permanent cavity, temporary cavitation and finally the generation of a shock wave which has negligible clinical relevance.

Assessment of the ballistic wound prior to surgery is necessary to plan the surgical strategy. Surgeons should look for features of high-energy transfer: large wounds, round fragmentation, bone strike, partial or fully retained rounds. Muscle tissue typically tolerates the stretching effect of temporary cavitation well.

After resuscitative life saving surgery, the priorities of orthoplastic reconstructive surgery are: incision, excision, fixation and coverage. Skin incisions are longitudinal along limbs; fascial incisions permits local decompression but consideration should always be given to full fasciotomy and compartment decompression. Ballistic wounds evolve over many hours after injury; tissue can progress to necrosis over time, swell and produce copious exudate. Outside of the head and neck, wounds should never be closed primarily, and patients should be returned to the operating theatre at around 48 hours for re-assessment and further tissue excision if necessary. Fractures should be temporarily stabilised, normally with an external fixator to protect the wound bed. Definitive fixation should only occur at the same surgical episode as definitive coverage or closure.

Introduction

Ballistic wounds are heterogeneous and can be complicated with open fractures, neurovascular injuries and tissue loss [1]. The reconstruction of these injuries is challenging but when performed well enables the patient to rehabilitate and recover [2]. To achieve this goal ballistic extremity wounds should be managed jointly by orthopaedic and plastic surgeons who have an understanding of some of the unique features of these injuries.

Unfortunately it is not just military surgeons who need to anticipate treating these injuries. The on-going conflicts in the Middle-East, Asia and Russia's involvement in Ukraine all generate casualties treated in civilian hospitals. In addition to these armed conflicts are the frequent mass-shootings in the US by perpetrators typically favouring military style weapons and the less frequent marauding terrorist attacks in Europe, Asia and Africa.

This paper aims to review the pathophysics of ballistic wounds and link this 'basic science' to the orthoplastic surgical treatment strategy for the safe management of these injuries.

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Nomenclature and definitions

Discussing ballistics and firearms is complicated by a bewildering nomenclature; terms can by synonymous and ambiguous and there is no logic to the conventions for naming bullet calibres.

A *gun* is machine for transferring chemical energy stored in the form of a propellant into the kinetic energy of a *projectile* or *projectiles*. When a gun is small enough to be carried by an individual, it is termed a *small-arm* or *firearm*.

Firearms can be divided into those small enough to be controlled with one hand termed *handguns*, and those that are operated with both hands whilst steadied against the shoulder. These are either *rifles*, which fire a single projectile or *shotguns* which normally fire multiple small metal balls or *shot*. In most countries, firearms available on the civilian market are restricted to *semi-automatic* fire, i.e. the trigger must be squeezed and fully released to fire a single bullet, as opposed to *automatic* whereby the firearm will continue to fire as long as the trigger is squeezed.

The term *assault rifle* does not have a strict definition but is normally taken to mean a military-style firearm that is typically capable of automatic fire and can be fitted with a *magazine* which can hold 20–30 *rounds*. The two most famous examples of assault rifles are the AR-15 and AK families of weapons.

Bullets or *rounds* are terms frequently applied to both the projectile on its own, or the projectile housed in its casing with the propellant as shown in **Figure 1**. As previously mentioned, the convention for naming bullets is complicated; the diameter of the bullet is known as its *calibre*. Calibre corresponds to the internal diameter of the gun barrel. Confusingly this measurement is frequently given both in millimetres and fractions of an inch. For example, the same calibre round could be described as 5.56 mm or .223.

To add to the confusion, different bullet lengths of the same calibre are manufactured. For example bullets of 7.62 mm calibre are manufactured with lengths of 39 mm (AK-47-variant weapons), 51 mm (NATO), and a short 25 mm for handguns. Similarly different dimension of the casing allow different quantities of propellant, even for the same sized bullet. The term 'magnum' implies a variant of ammunition with a greater quantity of propellant in a larger casing. An example of this is the '.357 magnum' round which has the same sized bullet as a '.38 special' but 11.5 grains of propellant compared to 6.7 in the original version.

Energy Transfer

Ballistics is the science of objects in flight; *terminal* or *wound* ballistics refers to the science of the interaction of a round and the object it is striking, in this context, human tissue. Ballistics is governed by the laws of Newtonian physics, and to understand wound ballistics we need to review two equations: *Kinetic Energy*, and *Drag*. However, it is worth noting that while the flight of a round in the air represents a simple system, hence a trained sniper is able to reliably place a round on a target a kilometre away. Wound ballistics however describes the incredibly complex interactions between a round and tissue, which lead to un-predictable wounds and sometimes apparently bizarre behaviour of rounds in tissues. When assessing ballistic wounds, its worth remembering '*bullets don't follow rules*!'

The kinetic energy of a round is given by the following equation:

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

Where
  KE is Kinetic Energy of the round
  m is mass of the round
  v is velocity of the round

It is important to note that the velocity is squared in this equation and therefore increases in velocity have a greater effect on the energy of the bullet than increasing its mass. Kinetic energy can be regarded as the capacity of the round to do *work*, and work in this context is causing tissue damage.

A round in motion is subject to a drag force which slows it down; drag force is given by the following equation:

$$F_d = \tfrac{1}{2} p v^2 C_d A$$

Where
  F_d is the drag force acting to slow the bullet
  C_d is the drag coefficient
  p is the mass density of the medium the bullet is passing through
  v is the velocity of the projectile
  A is the cross-sectional surface area of the projectile

While the projectile is travelling in the air the mass density is very low and hence the drag force is slight. When the bullet is passing through tissue, the mass density is far higher, the drag force greater and therefore the rate at
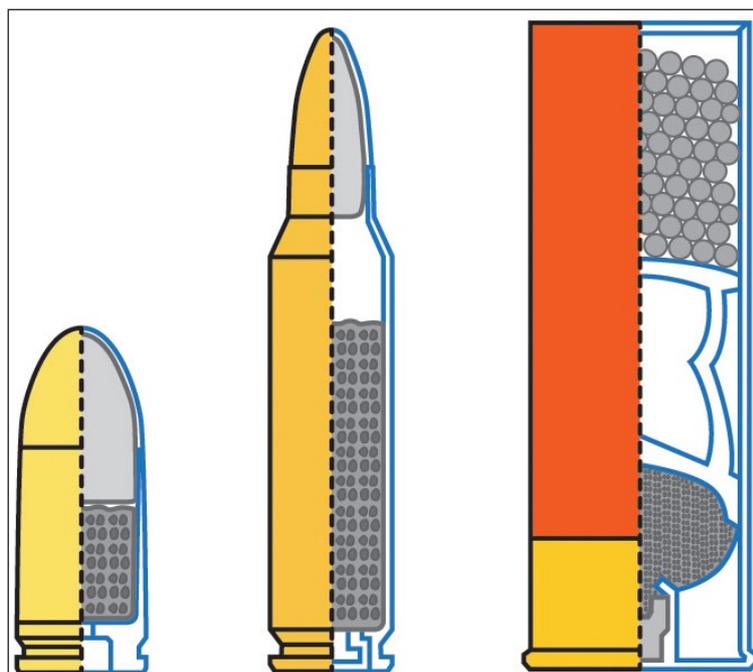

Figure 1: Schematic showing cross-section of different types of ammunition. Left: 9 × 19 mm handgun round; Centre: 5.56 × 45 mm rifle round; Right: shotgun cartridge. Crown Copyright 2018.

which kinetic energy of the round is transferred into the tissues (causing damage), is greater.

Therefore it is worth thinking about wounds in terms of *energy transfer*, described arbitrarily as high or low energy transfer, rather than the type of round or firearm that caused it. If a round travels through the body, it has deposited less Kinetic Energy than if it was completely decelerated and was retained.

Ballistic Wounds

The interaction between a round and tissue is described in three ways, the permanent cavity, the temporary cavity and the shockwave as shown schematically in **Figure 2**.

Permanent Cavity

As a round passes through tissue it shears and tears a path creating a wound tract or permanent cavity in its wake approximately the width of the round. If the round fragments, or strikes and fragments bone, each of these fragments will be accelerated and create their own permanent tract.

Temporary Cavity

This is a complex phenomena whereby the round accelerates tissue radially away from its path creating a 'bubble' in its wake. This 'bubble' stretches and tears tissue and creates a vacuum for milliseconds before collapsing back. The size of the cavity is related to the drag force and is therefore greater if the round has higher velocity, is unstable, or deforming as shown in **Figure 3**.

Tissue like skeletal muscle and lung tissue tolerate stretching relatively well, other tissue like Brain and Liver do not and tear. It is also worth noting that low energy handgun rounds can produce temporary cavities and high-energy rounds can pass through tissue with minimal cavitation.

It is this stretching which can traumatise vessels distant to the permanent cavity and apparent zone of injury which can impact of choice of recipient vessels.

Shockwave

The final form of ballistic wound is the generation of a hydrostatic shockwave, which is a controversial topic and of little relevance to the orthoplastic reconstructive surgical team [3, 4]. However, this phenomena can rarely cause neuropraxia in nerves distant to the permanent and temporary cavities [5].

Assessment of Ballistic Wounds

After life-threatening injuries have been addressed, the ballistic wound should be assessed and planning for skeletal stabilisation and soft-tissue reconstruction begun [6]. The objectives of the assessment are to:

i.   Determine the likely extent of energy transfer and therefore wound severity and zone of injury.
ii. Establish and document any neurovascular damage.
iii. Characterise fractures.

Pre-operative assessment

The circumstances of shooting instances are often confused and the patient might provide little useful history. It is worth trying to establish whether they were shot with a long (rifle) or short (handgun) weapon, with shotgun wounds being obviously characteristic.

Clinical examination should establish perfusion and innervation distal to the wound. When assessing wounds avoid assuming that entrance wounds are small and exit large, although this is usually true, it is not always. Medical notes can be involved in legal proceedings and inaccurately assigning the direction of fire can have significant implications.
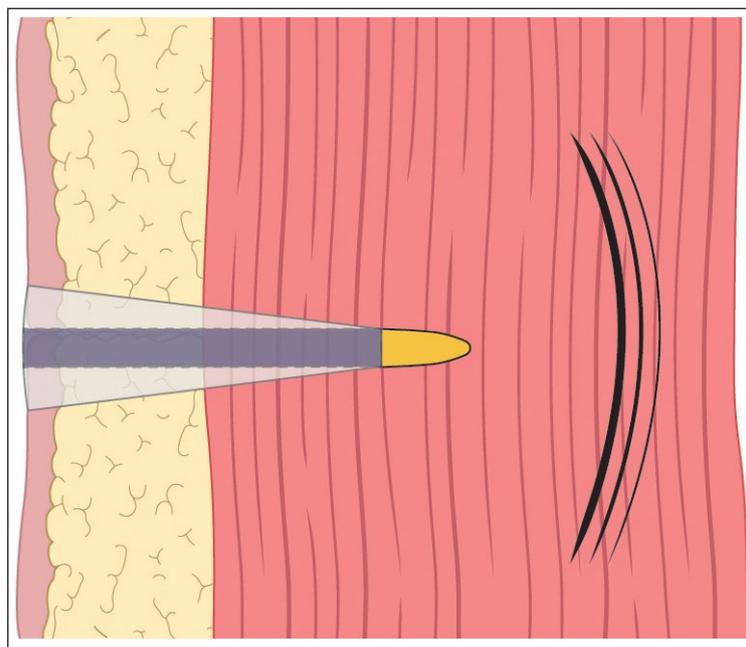

Figure 2: Schematic showing the three components of a ballistic wound: the permanent wound the formation of the temporary cavity and the hydrostatic 'shock wave' ahead of the round. Crown Copyright 2018.
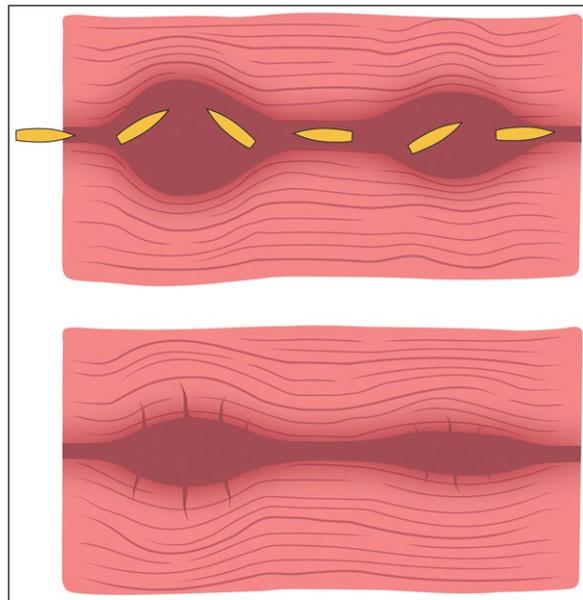
Figure 3: Schematic the creation of a temporary cavity and its maximum size at points when the round is tumbling. Crown Copyright 2018.

The presence of a single wound indicates a retained round which is predictive of higher-energy transfer [7], but look for occult wounds around the groin, and axilla which can be very subtle and hidden in skin folds.

The injured limb should be imaged with orthogonal plain radiographs with and without radiopaque markers placed over the wounds to aid estimation of likely permanent tracts and therefore plan surgical approaches.

The presence of bone strike, bony fracture and round fragmentation are particular associated with high-energy transfer and greater tissue damage [7]. These features indicate that more aggressive exploration and surgical excision may be appropriate. Conversely their absence indicates a low energy transfer wound with less tissue damage and the potential for more conservative management.

Intra-operative assessment

The intra-operative assessment involved exploration of neurovascular structures potentially in the zone of injury. This is always best performed starting in normal anatomy and tracing structures into the zone of injury. Nerves and vessels are normally resilient to the stretching of the temporary cavity formation, in the event of transection, direct repair is likely to be challenging however due to damage to the structure adjacent to the point of transection. If nerve or vessel grafting is performed, this must occur at the level that the structure is un-injured.

Surgical Priorities

Quality orthoplastic reconstruction sets a patient on the pathway of rehabilitation and recovery with the potential for enormous benefits for the rest of their life. However, reconstruction can only occur after successful resuscitation which itself can necessitate resuscitative surgery.

The details of resuscitative surgery are beyond the scope of this paper, but may well involve thoraco-laparotomies in order to gain proximal vascular control of major haemorrhage and address intestinal penetration. Major vessels can be shunted temporarily prior to definitive graft reconstruction.

Once a patient has had their life-threatening injuries addressed, the priorities of the orthoplastic surgical team are incision, excision, stabilisation, fixation and coverage.

The term debridement was first used by French surgeons to describe wound incision and decompression-literally to 'unbridle'. During the First World War however it was adopted by British, Canadian and US surgeons at the intra-allied Surgical conference in 1917 and taken to mean the process of excision [8]. In this paper, the terms incision and excision are used to avoid confusion.

A fundamental principal of managing ballistic wounds is the understanding that they evolve over time; tissues swelling necrosis can progress for many hours after the initial trauma. Primary closure of ballistic wounds almost inevitably results in infection as swelling tissue is constrained and exudate trapped. It is impossible to sterilise a ballistic wound, rendering it free from the presence of any bacteria. The initial aim of orthoplastic surgical management is to create an healthy wound which can eradicate this inevitable bacterial contamination. Infection when it does occur is typically caused by gram-positive staphylococcal species which complicate other traumatic and surgical wounds [9].

Incision

The aims of wound incision are to allow intra-operative assessment and exploration of the wound and to permit decompression and drainage.

Wounds should be extended longitudinally and in a direction permitting conversion to a formal fasciotomy if required. Few wounds will ever need to be laid open, i.e. the wounds connected with a single incision as this can cause significant unnecessary tissue damage and loss of fuction. In the event of high-energy wounds, the

incision should extend sufficiently to allow the wound to be explored from outside the zone of injury.

Traumatised muscle tissue will swell, so fascia should be incised to beyond the zone of injury to allow for this and aid drainage of exudate. Consideration should be given to a full fasciotomy if the wound is judged to involve high-energy transfer.

Excision

The aim of tissue excision is to remove contamination and necrotic tissue leaving a healthy wound bed for infection-free reconstruction.

Skin is elastic and tolerates stretching well, rarely needing excision [10]. The wound should be explored from outside the zone of injury both to avoid accidental damage to neurovascular structures in disrupted anatomy and to allow comparison between barely damaged, vulnerable-but-viable, and necrotic tissue [11]. These are analogous to Jackson's burn model which described zones of hyperaemia, stasis and necrosis [12].

All necrotic tissue should be excised, vulnerable but viable tissue can be left in situ, but consideration should be given to excision of greater proportion of 'borderline' tissue in cases of multiple wounds or a physiologically unstable patient. Bone fragments should be subject to the 'tug-test' and those without attachment excised.

The permanent wound tract can be 'flossed' by passing saline soaked gauze through the tract, this will dislodge loose, necrotic tissue while avoiding the destruction of 'laying open' tracts [13].

After adequate excision of the wound has been performed it should be irrigated to remove any residual contamination and necrotic material. This is performed using warmed sterile saline; antiseptic solutions have the potential to tip viable-but-vulnerable tissue into necrosis [14, 15].

After the necrotic tissue has been excised from the ballistic wound then it should be dressed and not closed primarily. The exception to this are wounds to the head and face, wounds here are rarely complicated by infection due to the privileged vascular supply.

Topical Negative Pressure (TNP) dressings have been shown to be very effective for dressing ballistic wounds [16]. This is believed to be because TNP removes exudate and in theory promotes blood flow to the wound bed. Complex wounds with large amounts of tissue loss can be dressed with a loose gauze ribbon e.g. Kerlix™ in preference to open cell foam/sponge TNP dressing.

An alternative to TNP dressings is fluffed-gauze laid into the wound and covered with an absorbent dressing-the aim should be to promote drainage without constricting the wound.

Stabilisation

Movement of fractures within the wound increases the susceptibility to infection [17] but definitive fixation is not possible until the wound has been closed or covered definitively normally at the second surgical episode at the earliest.

Normally temporary stablisation should be performed with application of an external fixator with pins placed outside of the zone of injury. However temporary plate fixation performed through the wound can be an appropriate method of temporary stabilisation, prior to revision to definitive fixation as shown in **Figure 4**.

Fixation and coverage

Definitive surgical fixation should only be performed at the time that the wound can be closed or covered. Open wounds will inevitably be colonised with bacteria and implanting definitive fixation implants in this environment risks deep colonisation and almost inevitable infection.

Figure 4: An external fixator stabilising a tibia fracture caused by a high-energy round. The fracture caused high-energy transfer and produced a severe wound with large soft tissue loss. Extensive fragmentation is likely to be associated with increased rates of deep infection and non-union. Photograph has been taken prior to second excision. Crown Copyright 2018.

Ballistic fractures frequently heal very slowly and therefore definitive fixation should be suitably robust and intended to load-bear for longer than conventional fractures.

Wounds can be primarily closed at the second or subsequent surgical episodes, this can be performed loosely to allow some on-going wound drainage.

Small wounds the size of a permanent cavity can be left to heal from primary intention. In 'through-and-through' wounds, it is not uncommon to have one small wound and one larger one-presumed to be the entrance and exit wounds respectively. In this instance the larger wound might need some form of closure or coverage while the smaller wound can be left to granulate.

Larger areas of skin loss but with a healthy muscular wound bed underneath can be covered with split skin graft as would be performed for a similar defect of another cause. Use of TNP dressing can help generate a healthy bed of granulation tissue that will accept a split-skin graft. As always, it is preferable to apply split or full thickness skin graphs to healthy muscle. A greater failure rate will occur if recipient wound beds are damaged, scarred or is poor quality granulation tissue.

In the event of larger soft tissue and skin loss, more complex reconstructive techniques including vascularised composite tissue transfer may be required. As previously stated micro-anastomosis should be sited outside of the zone of the temporary cavity to avoid the potential for intimal damage in recipient vessels leading to early graft failure. When planning free tissue transfer, the resource demands in terms of equipment (microscopes), surgical time and nursing support should be considered. In resource-constrained environments, free-tissue transfer may not be an appropriate strategy due to the consumption of resources for the care of a single patient.

An additional consideration when contemplating free-tissue transfer is donor-site morbidity. In amputee patients, the Rectus-abdominus and Latissimus-dorsi flaps may compromise rehabilitation and future mobility which will depend more on truncal and upper limb strength.

An alternative to free tissue transfer is local rotational flaps with split skin grafts as required [18].

Non-operative management

Not all ballistic wounds need surgical treatment. Ballistic wounds that can be managed without surgery are those with only minimal haemorrhage, and without features of high-energy transfer-i.e. a 'through-and-through wound' with no significant soft tissue damage, no bone strike, no round fragmentation. These wounds (more typically from handgun injuries) will involve minimal energy transfer and therefore little tissue damage [7] An example of this is shown in **Figure 5** below.

Non-operative management of a ballistic wound involves non-restrictive, absorbable dressings to permit wound drainage, oral antibiotics for 48 hrs and consideration to splintage to prevent excessive movement of the injured limb. Wounds should be followed-up closely to watch for the development infection [19].

Challenges and pitfalls

Ballistic injuries are heterogeneous and few surgeons deal with them frequently, the following are potential difficulties and mistakes that can occur.

Wound evolution

As previously stated, ballistic injuries evolve. A common mistake is for the surgeon to perform primary closure after wound excision. Even if the wound bed looks clean and healthy after initial excision, further tissue necrosis, tissue swelling and is likely to occur, with deep infection the likely result. This is a lesson that has been learnt and re-learnt over the course of several generations of military surgeons [20].
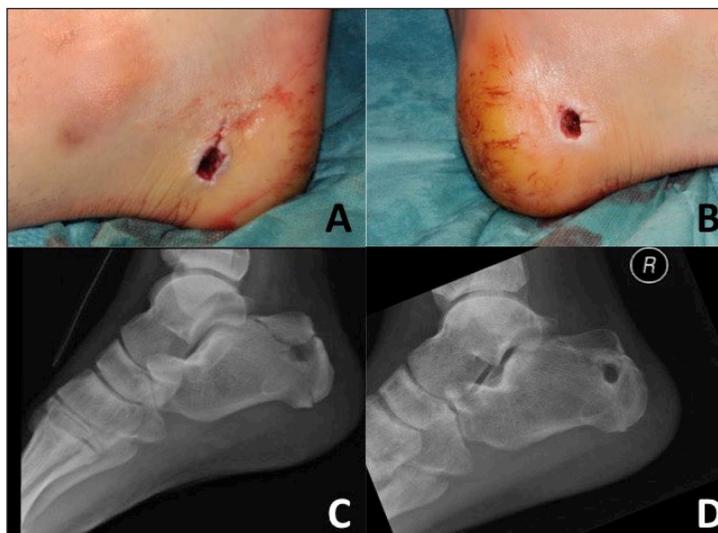

Figure 5: A non-operatively managed ballistic wound. Images **A** and **B** show the permanent tract skin wounds and **C** shows an un-complicated fracture. Even with the fracture, the injury was judged to be low-energy transfer and **D** shows the fracture united at 3-months post injury. Crown Copyright 2018.

Vascularised Composite Allograft

As stated above, the use of recipient vessels within the zone of injury from the temporary cavity can mean relying on vessels that have recently been stretched and traumatised.

Excessive incision

The International Committee of the Red Cross (ICRC) textbook argues that ballistic wound tract from 'military' weapons should be laid open if there is evidence of a temporary cavity formation. This is based on experience from ICRC hospitals treating injured refugees from the Russian-Afghan war. Presentation, surgery and antibiotics were often delayed for days after injury, a different context to the one that most orthoplastic teams will treat patients with ballistic wounds.

The generation of surgeons with the most experience of ballistic wounds were those who practiced (largely before antibiotics) in both the First and Second World Wars. One of these, General Ogilvie argued that laying open wound tracts in simple through-and-through was a 'cardinal sin' of war surgery [10].

There is experimental data to support this more measured approach. Two military surgeons conducted animal experiments after their experience of treating ballistic wounds on the battlefield-Fackler after the Vietnam War [21] and Watts after the Korean War [22]. Both studies demonstrated the safe, conservative management of through-and-through ballistic wounds to the extremities.

Nerve reconstruction

Neurological deficit from damage to peripheral nerves can have devastating affect on patient outcomes. These are challenging injuries; large wound surface area can lead to considerable scar-tissue incarcerating intact but damaged nerves and making delayed repair very challenging.

Unanswered questions for future research

The initial treatment of ballistic wounds has changed little since the First World War. A surgeon will look at tissue and excise that which they think is not viable, then bring the patient back to the operating theatre around 2-days later and repeat the process until the wound is clean and healthy.

We know little about why some tissue, which appears healthy at the time of the first surgery, will progress to necrosis. We do not know if it might be possible to mitigate this process and prevent some tissue from undergoing necrosis. Alternatively, it might be possible to identify tissue that will inevitably succumb and excise it during the first surgery.

Conclusion

The on-going conflicts in the Middle-East, Asia and Ukraine, and regular mass shootings in the US and occasionally Europe, mean that orthoplastic surgical team across the world need to anticipate treating these injuries.

Ballistic injuries behave differently to those normally requiring orthoplastic reconstructive surgery and require a different strategy to their management. However the surgical tactics and techniques are no different those normally used in limb reconstruction, they just need to be applied with an understanding of the unique pathophysiology underlying these wounds.

Key Points

1. Treat the patient and the wound, not the bullet or the firearm.
2. High-energy weapons can produce low energy transfer wounds and vice versa.
3. High energy-transfer wounds evolve over several days with swelling, further tissue necrosis and exudate.
4. Ballistic fractures will frequently be slow to heal; skeletal fixation must be robust enough to protect healing fractures over the course of a delayed union.
5. Vessels distant from the permanent wound cavity may be traumatised and can represent an anastomotic risk for vascularised tissue grafting.
6. A surgeon can do more damage than a bullet with too aggressive or insufficient excision of the wound.
7. Bullets frequently ignore the rules of ballistics!

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Competing Interests

The author has no competing interests to declare.

Guarantor

Jowan Penn-Barwell takes responsibility for the integrity of this work.

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