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Ballistic Trauma

A Practical Guide

Fourth Edition

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I would like to dedicate this book to my wife Cristina and my parents Michael and Pauline for their love and support.

To my friends and family—thank you for your support and understanding. To the medics over the world who care for those injured from bullets and blast: your efforts are seldom recognised but you stand against the violence and darkness.
Thank you.

Contents

A Personal Experience

1

Benoît Vivien

1.1 Background

On Thursday, the Twelfth of November 2015, I had been scheduled for a night duty as coordinator physician in the call center of the prehospital emergency department "SAMU de Paris". I knew for several weeks that I had to take part in an important mass casualty exercise the following day, Friday the Thirteenth of November, this was not a concern after a normal night duty. Indeed, since 2 coordinator physicians are on duty in the call center, we usually split the night from midnight to 8:00 AM, so that each of us could have a short sleep of about 3–4 h.

Unfortunately, the activity during the night was very intense, with several road accidents and a building fire in Paris, consecutively each of us only had 2 h of rest. Nevertheless, on Friday the Thirteenth of November, at 8:30 AM, after the daily staff handover and a short shower, I was ready for the planned morning tabletop mass casualty exercise, and the following practical simulation session that afternoon. That morning we opened the crisis room where the tabletop was to take place, and welcomed the physicians who were to be the players for the morning session. The scenario that we had envisaged for Friday Thirteenth, classically considered as an unlucky day in western superstition, was 13 simultaneous terrorist attacks in Paris and its suburbs. After several bombings in Paris in 1995–96, Pr Pierre Carli, chairman of SAMU of Paris, created a specific plan to organize prehospital emergency care for several simultaneous attacks. This plan was called "plan Camembert", since it splits Paris in different sectors like a cheese, prehospital care in each sector being managed by local pre-hospital and in hospital teams independently from other sectors. This plan had been tested several times during tabletop exercises, but never really implemented. However, following the Charlie Hebdo attack in January 2015, and according to confidential information from the authorities, we were advised that

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major terrorist attacks would probably occur in Paris, sooner rather than later. Therefore, we decided to organize the tabletop exercise with 13 different attack locations, a much larger number than the previous maximum of 3.

The players involved were physicians from SAMU of Paris and from other SAMU departments surrounding Paris, as well as representatives from the Fire Department. For the first time, we invited physicians from major trauma centers to take part. Indeed, there is frequently a gap between pre-hospital emergency physicians and in hospital anesthesiologists or intensivists working in trauma centers. Since I had spent the first part of my career in the trauma center Pitié-Salpêtrière (1997–2007), before becoming the deputy chairman of the SAMU of Paris in 2007, I had experience of both environments but this crossover is rare in France. Therefore, for this tabletop exercise, several trauma center physicians were invited to play the role of pre-hospital coordinator physician, a "live my life experience", enabling them to better understand the difficulty of pre-hospital emergency care during a mass casualty event. Finally, due to the high risk situation in Paris, we had invited representatives from the regional health agency and police authorities.

The exercise started at 9:00 AM. According to the scenario defined a few weeks previously, four groups of two terrorists heavily armed with automatic weapons began simultaneously shooting in different areas of Paris and its suburbs. Notifications arrived successively to the crisis room, with a number of victims around 0–10 dead, 0–10 absolute emergencies (AE) and 0–10 relative emergencies (RE), for each one of the 13 sites of terrorist attack. Overall the terrorist attacks lasted about 2 h, with a final count of 66 dead, 74 AU and 48 RE. Applying the principle of the "plan Camembert" adapted to this high number of sites, all of the victims could have been virtually cared for by the different teams, first in the pre-hospital fields, and thereafter in the different trauma centers. However, at the end of the debriefing, one of the emergency physicians involved as a player in the crisis room said and I quote "OK guys, this exercise was interesting, but largely too much… This incredible scenario will never occur in Paris !".

The second part of the day was dedicated to a practical exercise in an old unused building in Necker-Enfants Malades Hospital. The scenario was focused on a mass casualty event due to a terrorist attack occurring in an office building. Victims were simulated using forty-five medical students, while first aid providers were also played by other medical students from our SAMU department. Pre-hospital emergency physicians and nurses had to apply the principles of damage control on site as well as perform triage and categorization using electronic devices allowing traceability of the victims until hospital admission. This practical exercise, lasting 3 h, was considered as very instructive for all of the players, allowing them good working knowledge of the principles of caring for many victims from a mass shooting. After an internal debrief with the other organizers of the mass casualty exercise I went back home at 7:30 PM thinking that my work day was finished, and hoping for a deserved rest after 36 h working in the hospital.

1.2 The Attacks

After having a short dinner, I sat on the couch, and started to watch the football on TV. I'm not usually a fan of football, but tonight the French national team were playing, so it was possibly interesting. However, after 36 h spent in the hospital, I decided to switch channels and watch the continuous news. A few minutes after the first explosion at 9:20 PM near the Stade de France, I saw the alert message on the TV, notifying of an explosion of unknown origin. I found this strange, but was too tired to reflect, and switched the TV back to the football match which rapidly resulted in sleep! However, about 15 min later, my mobile phone and home phone rang simultaneously and I heard the recorded message "This is not an exercise. The mass casualty plan is activated. Please return immediately to the SAMU". I switched the TV back to the continuous news channel and saw with horror the news of 3 successive bombings near Stade de France and simultaneously of several shootings in Paris. I'll always remember the first words I then said to my family "This is exactly what we have played out this morning". I quickly drank two double coffees, and took my car back to the SAMU. During the journey, I made many phone calls to exchange information with colleagues from trauma centers and other SAMU units, some of them having participated in the morning exercise.

After arriving in the crisis room in the SAMU for Paris, I saw the physician who had generated the scenario for the morning exercise and said to him "It's incredible, there have been some leaks !" The investigations since have shown that this was fully unfounded, but this was a really troubling coincidence.

Many physicians, nurses, drivers, providers, phone dispatchers and secretaries came back to the SAMU during the evening, spontaneously or after having received the automatic phone call. We organized the crisis room as for the morning exercise, splitting the room for each of the different events. Simultaneously, we had to manage a fourfold increase in phone calls to the "15", which is the medical emergency number in France. Conversely, the numbers of calls received for current medical emergencies was dramatically reduced, it appeared that people refrained from calling for minor emergencies. However, the world does not stop because of terrorists attacks, for example that night we had to manage three patients presenting with acute coronary syndrome, who were cared for by a Mobile Intensive Care Unit (MICU) team and taken directly to the cath lab.

The high number of staff that came back to the SAMU enabled us to create new MICU teams, who were sent on to the different locations of the terrorists attacks. We also sent a trained emergency physician to each site to perform medical triage and categorization. I should have been one of them, but after just 2 h rest during the previous night, my colleagues refrained me by convincing me that it was not reasonable. So I took the position in the crisis room of supervising the affect of the reinforcement teams.

During the evening the situation after the bombings near Stade de France and the shooting in the terraces and restaurants in Paris was mainly controlled, the Bataclan hostage taking however remained a crucial and uncertain point. Indeed, before the police assault, we had obtained some information suggesting the possibility of approximately one hundred supplementary absolute emergencies. If this situation had occurred, this would have clearly led to saturation of all the trauma centers in Paris. Therefore we had to respond to this possibility early requesting reinforcement from teams on a national scale. I directly called the other SAMU as far up to 500 km from Paris, who were equipped with a helicopter, to ask them first for supplementary pre-hospital teams and to check local availability in their trauma centers to care for AE and RE.

The strategy at this time was to station the maximum number of pre-hospital teams near the Bataclan at the time of the assault, as well as having as many helicopters as possible ready to transfer casualties to trauma centers far from Paris. We finally gained access to 9 SAMU helicopters, each one capable of transporting one patient at a time. Additionally, we obtained 2 military helicopters, each allowing transport of 4–6 patients simultaneously. Unfortunately, after the police assault, the patients that we were supposed to care for had been killed by the terrorists, and the number of new AE and RE patients was relatively limited.

The end of the night was a source of fear and major uncertainty. Our scenario for the exercise during the morning was based on 13 terrorist attacks, while the sad reality of the evening had shown "only" 9 attacks in Paris and its suburbs. We had to face several false alerts of terrorist attacks, mainly due to people seeing military police with weapons in the street of Paris and fearing they were terrorists.

Finally, at 4:00 AM on Saturday, the Fourteenth of November I went back home for a short sleep, having been scheduled for a 24 h duty in the call center beginning at 8:00 AM. Thankfully, some colleagues not involved in the Thirteenth evening shared these duties between them. Given it is usually difficult to find a colleague to cover a Friday, weekend duty, or during national holidays, this spontaneous solidarity was greatly reassuring! The remaining weekend for the SAMU teams was pretty quiet, although we had to face to two other false alerts, one on Saturday and one on Sunday. One of them being very strange and worrying, it was interpreted by some as a trap to test for a potential new terrorist attack against pre-hospital teams.

Unfortunately, the days following this sad Friday, the Thirteenth of November made us realize that many of us, either in our personal or professional field, knew or were closed to one or several victims or there relatives. One of the SAMU of Paris staff a young emergency physician, less than 30 years old, who was working as a GP in our call center was killed on the terrace of the restaurant "Le Petit Cambodge". The English teacher of the daughter of one of the secretaries of the SAMU of Paris lost 5 of her friends during a shooting in a terrace restaurant, and survived only because she was too tired that evening and left early after having a drink with her friends. The girlfriend of the nephew of the wife of a SAMU physician was killed as well as the son of the physician who had helped with the childbirth of another colleague, 42 years ago.

1.3 Summary

Terrorist attacks are unfortunately a tragic event for which we have to be prepared. For emergency teams, regular training is a necessity, both with tabletop and field exercises. The major key points of medical care are the implementation of damage control, and triage and categorization of the victims. Coordination between all the parties involved from first aid providers, firemen and police forces to prehospital emergency and trauma center teams, is the corner stone of the organization. Multi partner exercises, and to greater extent “live my life experience” could contribute to this all with the aim of improving the prognosis of the victims of these dramatic attacks.

Firearms and Bullets

2

Jowan G. Penn-Barwell and Aimee E. Helliker

2.1 Introduction

Weapon development throughout history has focused on overmatch of the enemy's capability by increasing the range and lethality of weapons. This process in the fourteenth Century meant the introduction of early firearms in Europe [1].

The *Firearm,* as defined by the UK Firearms Act 1968 is "a lethal barrelled weapon of any description from which any shot, bullet or other missile can be discharged." Firearms are often referred to as guns by the general public: technically a gun is any machine that converts stored energy to kinetic energy to accelerate a projectile out of a barrel. Therefore the term gun may encompass everything from small handguns to large artillery pieces. This book will use the term firearm to describe guns that using that are carried by hand and use a propellant as a source of stored energy, commonly also referred to as *small arms*.

This chapter provides the clinician with an overview of the terminology specific to the firearms and ammunition field, ammunition types and constructions and types of firearms by introducing firearms and then examining the ammunition used in these weapons.

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2.2 History

The first chemical propellant used in firearms was black powder a mixture of potassium nitrate, sulphur and carbon known as gunpowder. It was first described in China, and knowledge of its composition spread to Europe around the end of the first millennium CE [1]. Firearms were believed to be first used in combat by the English Army in Europe when Edward III deployed Cannon at the Battle of Crećy in 1346 against the French. Interestingly, these firearms were regarded as far less decisive within the battle than the large numbers of longbows, also used for the first time in war on the continent [2]. A well-trained archer with a long bow was significantly more lethal in terms of range and rate of fire than a soldier with a musket. Training an archer however took months whereas a soldier could be taught how to operate a musket in a day.

The capability of firearms dramatically increased over the nineteenth Century with the development of rifling, breech-loading, cartridged ammunition and magazines. Bullets fired from early, un-rifled weapons were initially spherical, and to ensure the maximum mass for a given size, the densest metals were chosen: lead. This had the added advantage of being very soft, this meant that it could conform to the shape of the barrel and when it struck the target it would deform and flatten.

In the late nineteenth Century, smokeless and more powerful explosives e.g. Cordite, replaced black powder as a propellant for rifle ammunition. The higher velocities generated by these propellants meant that soft-lead bullets deformed within the barrel leaving deposits. To combat this, bullets were ‘jacketed’ or coated with a harder metal such as a copper alloy. When full metal jacket rounds were first used by the British Army in action, it was noted that the bullets imparted much less energy and therefore caused far less tissue destruction [3].

In order to achieve the benefits of jacketed rounds with the wounding effect of soft, expanding rounds, the superintendent of the ammunition factory at Dum Dum in India, Capt Bertie-Clay developed a partially jacketed round with an exposed soft-nose which deformed or expanded upon striking the target [4]. However the wounding potential of high-velocity, expanding rifle rounds was regarded as excessive, and their use in warfare inhumane. Ammunition designed to expand in the human body was specifically outlawed by the 1899 Hague convention:

“It is prohibited to use in international armed conflicts, bullets which expand or flatten easily in the human body, such as bullets with a hard envelope which does not entirely cover the core or is pierced with incisions” [5].

Despite latter ratifying this part of the treaty, the initial UK negotiating position at The Hague convention was that this type of ammunition was necessary for use in Africa and India, though accepting that it was inappropriate for use in Europe [6].

The advent of body armour, particularly helmets led to the development military ammunition with increased ability to penetrate. This is typically achieved by the inclusion of a core of a harder metal e.g. steel, within the bullet. This is seen in the design of most modern military ammunition including the standard NATO 5.56 × 45 mm round and the Russian 5.45 × 39 mm used in the AK-74 family of weapons.

2.3 Types of Firearms

Firearms have broadly diverged into three main groups: Handguns, rifles and shotguns. All can be manual, semi or fully automatic operating, however fully automatic handguns and shotguns are rare.

2.3.1 Hanguns

A handgun is a short firearm that can be held with one hand and can be either a *pistol* -where rounds are loaded in a magazine or a *revolver*, a simpler design where a smaller number of rounds are loaded in a revolving drum which also acts as the breech. In UK law there is no definition of handguns but firearms which either have a barrel less than 30 cm in length or is less than 60 cm in length overall are prohibited and are commonly referred to as handguns. Confusingly handguns normally have rifled barrels.

Rifles and shotguns can fire more powerful ammunition than handguns; to control this greater energy transfer they have more substantial breeches and have longer barrels. This extra weight and the more powerful recoil requires them to be held with two hands and typically steadied against the shoulder.

2.3.2 Shotguns

Shotguns have smooth barrels and instead of bullets fire multiple small metal balls known as *shot*. Shotguns are classified according to their internal diameter of their barrel known as *gauge* (US) and *bore* (UK). Bores are numbered according to the size of a lead sphere made from a given fraction of a pound of lead that fits the internal diameter of the barrel. For example a 12-bore shotgun has a barrel diameter that fits a sphere of 1/12th of a pound of lead, and a 20-bore has a barrel diameter that fits a sphere of 1/20th of a pound of lead. Therefore a higher number indicates a narrower barrel.

Shotgun ammunition can vary enormously according to the number and size of shot. Originally shot consisted of lead balls but with environmental concerns in recent years there has been a shift to the use of steel and composites. The size of the shot depends on the target and range, smaller bird and game uses “birdshot” of many small diameter shot with larger game requiring greater energy deposition and therefore using “buckshot” of fewer larger diameter shot.

2.3.3 Rifles

Rifles are long barrelled firearms typically firing higher-energy ammunition than handguns. Their name distinguishes them from their now obsolete predecessors *muskets,* which like shotguns, had smooth barrels. All modern small arms barrels with the exception of shotguns are rifled but the term has remained attached to

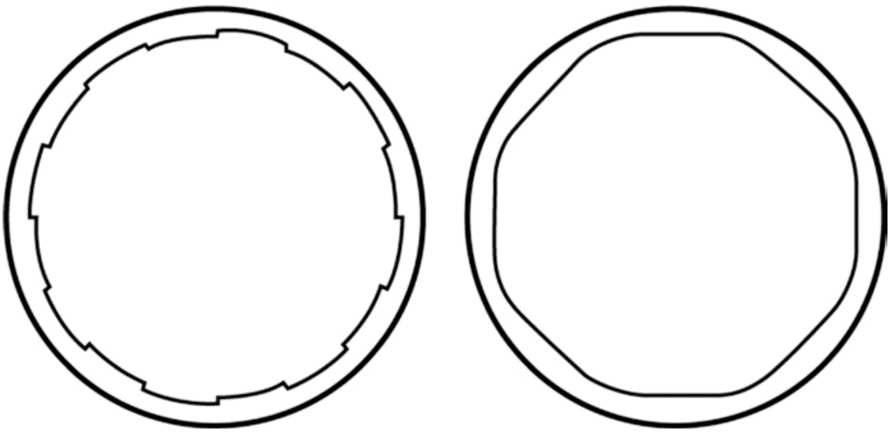

Fig. 2.1 Schematic representing tradition rifling in the cross-section of a barrel on the *left* with sharp edged raised *lands* and *groves* which are the recesses between them; *Polygonal* rifling consisting of subtler 'hills and valleys' is shown on the *right*. Polygonal rifling is used in modern handguns

long-barrelled firearms. The purpose of the rifling being to impart spin to give the projectile gyroscopic stability. In cross-section the rifling appears as a number of lands and grooves (Fig. 2.1), the profile of which may be rectangular or trapezoidal. This rifling results in engraving on projectile, this engraving can be observed and is used within forensic ballistics as described in Chap. 27.

Rifles are an enormously varied family of weapons from crew-served firearms which typically fire ammunition from a *belt* often referred to as *machine guns*, to hunting rifles that require manual loading of individual rounds. An automatic firearm is one which will continue to fire and reload whilst the trigger is squeezed with no further action required from the operator; a semi-automatic firearm will reload itself but only fires when then trigger is released and re-squeezed. Many modern rifles capable of automatic fire have semi-automatic modes and some are limited to semi-automatic function for legal reasons. The term *assault rifle* has no clear definition but in the public consciousness refers to military-style firearms capable of at least semi-automatic action and with large capacity magazines i.e. 30-rounds. Examples of firearms regarded as assault rifles would be the AK and the M-16/AR15 family of weapons.

2.4 Ammunition

Ammunition is defined by the UK Firearms Act 1968 as "ammunition for any firearm and includes grenades, bombs and other like missiles, whether capable of use with a firearm or not…" Conventional ammunition is formed of four component parts, the case, bullet and primer and propellant together are often referred to as a *round*, as shown in Fig. 2.2 below. In the context of firearms, ammunition is a collective term for rounds.

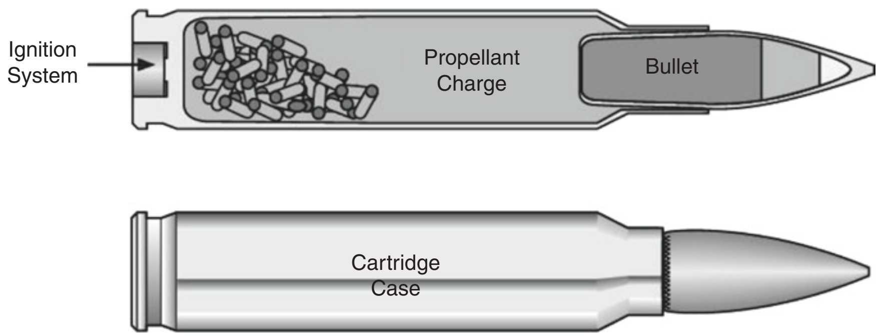

Fig. 2.2 Schematic showing the components of ammunition

The ignition system is commonly a *primer*, a small, impact sensitive explosive which initiates when struck by the firing pin, in turn igniting the propellant within the cartridge. Propellants are combustible materials containing within themselves all the oxygen required for combustion. Propellant mass is measured in grains (gr), one grain is equivalent to 64.8 mg.

The cartridge case provides three functions; waterproof housing to retain the bullet, propellant and primer; protect the propellant from the hot barrel and provide breech obturation during firing i.e. seal the breech and prevent the escape of the propellant gases.

The bullet or projectile seated within the cartridge can take many forms, from a jacketed round through to a steel or lead ball. There are two common descriptions used for the bullet as seen in Fig. 2.3 below: *round nose* typically seen in pistols and revolvers and *spitzer* a typical rifle bullet with a pointed nose and 'boat tail' base round. Spitzer is shortened from the German Spitz Geschossen, translating as pointed projectiles.

When referring to the bullet it is important to note the mass of the projectile as different weights (again quoted in grains) of projectiles can be used. For example the 9 × 19 mm Luger ammunition is commonly available with 115 gr and 124 gr bullets, with different bullet weights for different tasks, a further comparison is shown in Fig. 2.4 of 0.223″ ammunition to highlight the difference.

There are many different constructions of the projectile which will be discussed further in the later sections of this Chapter.

When referring to a round of ammunition it should be referred to as a type and be given as specified by the manufacturer. For example: 7.62 × 54R mm.

- 7.62 refers to the calibre the gun is designed for
- 54 refers to the length of the cartridge case
- R means the case is rimmed
- mm means the dimensions are in mm

Or 0.308 Winchester

- 0.308 is the diameter of the bullet in inches
- Winchester is the designer of the ammunition.

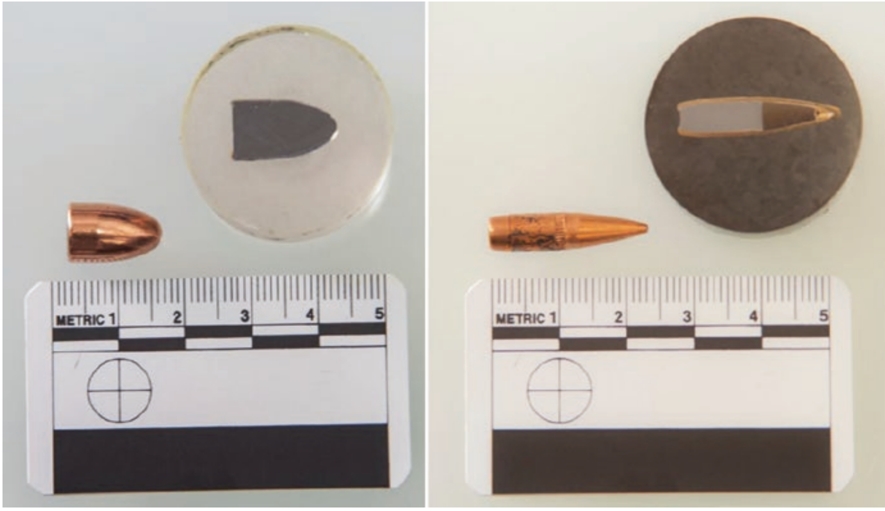

Fig. 2.3 *Left* a round nose bullet, in this case a (9 × 19 mm Luger) and *Right*: Spitzer (5.56 × 45 mm SS109)

Fig. 2.4 Photograph showing two 0.223″ bullets: (*Left*) an 80 Grain Sierra and (*Right*) a 52 grain Speer (HP Boat Tail Match)

It is important not to convert any dimensions from metric to imperial or vice versa. For example 5.56 mm and 0.223″ are equivalent bullet diameters, however firing 5.56 mm × 45 mm NATO in a weapon which is chambered for 0.223 Remington could result in catastrophic failure due to the excessive pressures that would occur due to the difference in dimensions of the throat from the chamber.

Some manufactures use designations such as 'Magnum' to market a higher powered round which gives a higher pressure and therefore greater muzzle velocity of the projectile. An example is 0.44 Magnum which is based on a lengthened 0.44 Special case, the Magnum cartridge is 1/8″ longer than the 0.44 Special and is considerably more powerful.

Ammunition can be fed by hand one round at a time, or be stored in a box attached to the firearm called a *magazine*, usually with a spring-fed mechanism presenting rounds towards the mechanism of the firearm. Alternatively ammunition for some military firearms can be fed into the working parts of the weapon via a *belt*, allowing a sustained high rate of fire.

Calibre is defined as the dimension of the bore of a firearm before the rifling grooves are machined. However the term calibre is used to describe various aspects of firearms and the use is not consistent and does not always correctly define measurements. When referring to the ammunition as a calibre, it is the diameter of the firearm barrel used for the ammunition that is being designated not the diameter of the projectile that is being referred to. For example 5.56 mm × 45 mm NATO ammunition has a projectile diameter of 5.70 mm, however the barrel of a weapon which fires this ammunition is 5.56 mm internal land diameter. The term bore (UK) and gauge (US) is limited to shotguns and some smoothbore weapons. In large calibre guns (for example artillery pieces) the term calibres is often used to describe the barrel length as multiples of the bore diameter.

2.5 Ballistics

Ballistics as a scientific discipline is divided into four areas: *internal ballistics* covers the behaviour of the bullet in the firearm, *intermediate ballistics* covers the area where the projectile leaves the barrel before it enters the free flight covered by *external ballistics* and *terminal ballistics* describes the behaviour of bullets when they strike a target.

Firearms do not directly injure; rather it is the bullet that produces wounds and an understanding of the interaction between bullet and tissues is important to understand and treat these injuries. “The study of wound ballistics requires knowledge of the behaviour of the bullet in flight and the effect it has on the tissues it penetrates.” [7].

The terminal ballistics of projectiles is subject to continuous research and whilst the prediction of the effect of small arms projectiles vs solid targets is more predictable, soft targets such as tissue proves a greater challenge. There are many factors that play a part in the terminal effect, these include the impact velocity of projectile, the angle of attack and the characteristics of the projectile and the target. Terminal ballistics will be discussed in greater detail in Chap. 6.

Bullets are at their fastest when they leave the muzzle; this speed is referred to as the *muzzle velocity*. The kinetic energy of a bullet (KE), and therefore the energy available which can be transferred to the target to cause wounding, is given by the following equation:

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

Where

KE is Kinetic Energy.

m is mass of the projectile.

v is velocity of the projectile.

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.

2.5.1 Drag

From the point of leaving the muzzle the projectile is slowed by the effect of drag as it passes through the air. Drag is complex and consists of two main components: *pressure drag* and *skin friction*. While bullets are in super-sonic flight there is the additional factor of *wave drag*. These components of drag are simplified by combining them into the *drag coefficient,* which differs between projectiles. The *drag force* is the resultant retarding force on the bullet as it travels through a fluid (liquid or gas) and is given by the equation:

$$F_d = \frac{1}{2}\rho v^2 C_d A$$

Where

F_d is the drag force acting to slow the bullet.

C_d is the drag coefficient.

ρ is the mass density of the air the bullet is passing through.

v is the velocity of the projectile.

A is the cross-sectional surface area of the projectile.

It is important to note that again in this equation velocity is squared; therefore *the faster a projectile travels, the greater the effect of drag*.

The drag coefficient is dependent on multiple factors including the shape of the bullet. A more aerodynamic bullet is less effected by drag. The sharpness of a bullet is quantified by the ratio of the calibre to the curve of the front of the bullet and is measured in ogives as shown in Fig. 2.5. Bullets with higher ogives referred to as spitzer style are 'sharper' and less susceptible to drag.

If a bullet is unstable in flight, and tumbles it presents a much greater surface area and will be rapidly slowed by the effect of drag, quickly reducing the KE and therefore the bullets potential to damage tissues. The concept of drag is also relevant in the understanding of the transfer of kinetic energy into the tissues and will be revisited in Chap. 6.

2.5.2 Bullet Flight

Despite the spinning effect conveyed to the bullet by the rifling, it does not travel with perfect stability along the complete axis of its trajectory. There are three main types of instability: *yaw*, *precession* and *nutation*.

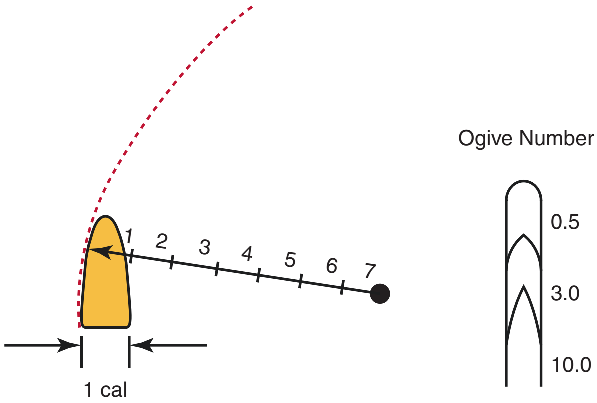

Fig. 2.5 Schematic showing ogive arc calculations on the *left* and typical ogive values on the *right*

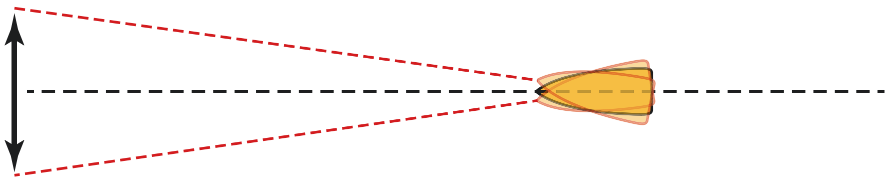

Fig. 2.6 Schematic showing *yaw*, or 'linear wobble.' This has been exaggerated for the purposes of illustration and is usually less then 2°

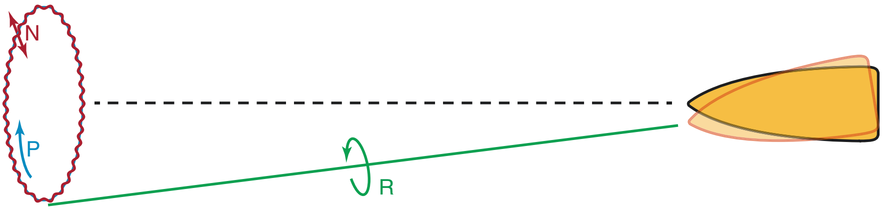

Fig. 2.7 Schematic showing *precession* (P) or rotation of the nose around the axis of flight, along with *nutation* (N), a rocking motion in the axis of rotation. Throughout these movements, the bullet spin (*R*) around its longitudinal axis, conveyed by the rifling of the barrel

Yaw is defined as the linear oscillation of the bullet around the axis of the trajectory and can be thought of as 'wobble' and is illustrated in Fig. 2.6 below.

Precession is the helical rotation or spiralling of the nose of the projectile around the axis of the trajectory. Nutation is the small oscillations of the nose in from the rotational arc of precession as shown in Fig. 2.7 above. Of these types of projectile instability, the most significant is yaw with the precession and nutation decaying with flight [8]. However, during the flight of modern bullets, yaw is negligible and is probably less than 2° at most [9].

2.6 Characteristics of Projectiles

There are many types of projectiles which are used for different purposes for target effect. The most common types are presented below, generally grouped by the target effect commonly experienced against soft targets. Unusual bullet natures such as flechettes (fin stabilised "darts") or duplex/triplex (2/3 bullets in one form) are not considered due to their specialist and scarce nature.

2.6.1 Full Metal Jacket Bullets

Full Metal Jacket (FMJ) is the term used for projectiles which have a jacket which extends around the bullet, covering from tip to base. The base does not have to be fully covered by the jacket, often a small gap is left to allow for the expansion of the bullet when subjected to firing pressures [10]. Most FMJ projectiles have a lead or lead/steel core with projectiles such as armour piercing and tracer are also classed as FMJ.

Ammunition that is designed to penetrate soft body armour is not normally referred to as armour piercing. Armour piercing projectiles are manufactured with a hardened steel or tungsten carbide penetrator core designed to defeat hard body armour or vehicle armour as shown in Fig. 2.8 below. Tracer projectiles have a hollow at the base of which is filled with a small pyrotechnic charge which is ignited upon firing allowing for target indication.

Full metal jacket bullets generally do not fragment on impact with soft tissue, but some deformation of the jacket may occur.

2.6.2 Expanding and Semi Jacketed Bullets

Hollow point (HP) bullets have a hollow in the tip of the lead core and jacket. This is included to cause expansion of the bullet upon impact with the target, causing greater damage to the target. Upon impact with the target the increase in pressure within the hollow results in the deformation of the lead core and jacket to what is often termed a *mushrooming* or *expanding* round. As previously mentioned this ammunition is considered as contravening The Hague Convention, 1899, Declaration IV and is therefore not suitable for use within state on state armed conflict. HP ammunition is used for hunting in order provide a rapid and therefore humane death (and is mandated in some cases) and by some law enforcement and security agencies. Hollow points may be observed with a *plastic tip* see as shown in Fig. 2.9, this tip prevents the projectile from being damaged during handling or feeding into the weapon. Upon impact the tip is forced backwards with the round expanding like a hollow point.

Hollow Point should not be confused with *Match* ammunition used for long-range shooting competitions, also known as *Open Tip Match* (OTM). OTM rounds do not have a depression in the core (see Fig. 2.9). The open tip of the round is due

Fig. 2.8 Photograph showing a Full Metal Jacket Armour Piercing Bullet with a hardened penetrator core visible in cross-section

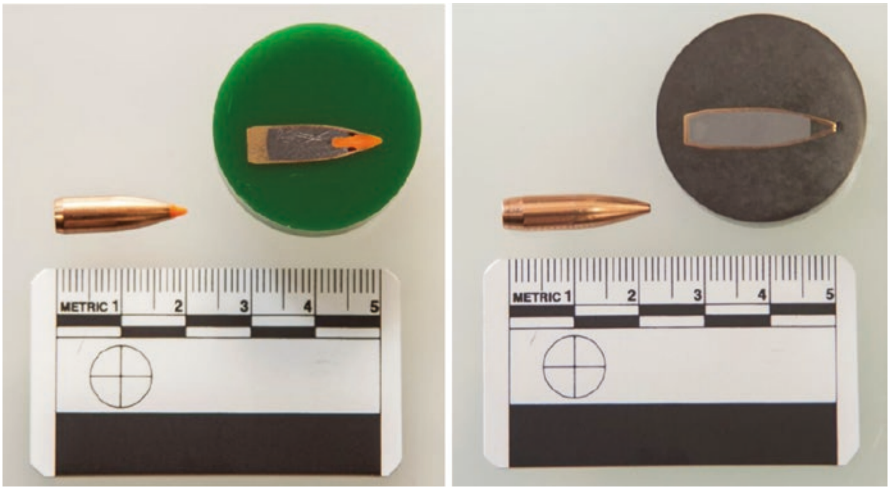

Fig. 2.9 Photographs showing (*Left*) a plastic-tipped hollow point round and (*Right*) an open-tipped match round

Fig. 2.10 Photograph showing a Soft Point Bullet and in cross section

to a consequence of manufacturing where the jacket is swaged onto the bullet from rear to front to achieve a round with consistent ballistics for consistent accurate target shots.

Soft point bullets have no jacket at the tip leaving the core exposed, this makes it a *semi-jacketed* round see Fig. 2.10. These rounds are designed to expand, again with the impact energy resulting in a deformation of the lead core outwards but at a slower rate than the hollow point ammunition. SP rounds are also considered as contravening The Hague Convention, 1899, Declaration IV, but are legally used by UK Police specialist firearms officers as they are less likely to penetrate through one individual and injure a bystander and should more rapidly incapacitate the target.

Ammunition can be modified by filing down the nose and soldiers illegally increasing the wounding potential of their ammunition in this way this has been reported in previous conflicts [11]. Other styles of expanding or semi-jacketed ammunition are available for example where copper is used to fill the hollow instead of the plastic tip or partitioned projectiles.

2.6.3 Fragmenting Bullets

Frangible bullets are designed to disintegrate into small particles upon impact with a surface harder than the bullet with little splashback or ricochet making them

Fig. 2.11 Frangible Bullet shown in cross section

favourable for close-quarter situations for example hostage rescue. The projectiles are made from materials such as sintered tungsten compressed or glued to form the projectile shape (see Fig. 2.11). These then disintegrate on impact with rapid transfer of kinetic energy into the target.

2.7 The Current Threat

Modern military firearms are designed to enable a single soldier to kill and injure a large number of enemy combatants, with an amount of ammunition they can carry themselves. It is therefore logical that those motivated to commit mass shootings against civilians choose military type firearms for this purpose. Table 2.1 lists details of a selection of mass shootings and illustrates a preponderance for perpetrators of these shootings to use firearms designed for military use i.e. variants of the AK and AR-15 family of weapons. Both firearm types use high-velocity, low-mass rounds meaning that a large quantity of ammunition can be carried by the perpetrator. The firearms used in all but the Mumbai, Sousse, Paris and Nairobi attacks listed in Table 2.1 were semi-automatic variants of these rifles illustrating that lethality does not depend on a fully-automatic mechanism.

Table 2.1 A selection of marauding terrorist firearms attacks since 1985

Incident	Year	Assailants	Weapons	Fatalities
Hungerford, UK	1987	1	AK variant, handgun	16
Dumblane, UK	1996	1	Handguns	17
Port Arthur, Australia	1996	1	AR-15 variant	35
Mumbai, India	2008	10	AK variants, explosives	164
Cumbria, UK	2010	1	Shotgun, 0.22 rifle	12
Oslo, Norway			Ruger mini-14	69
Newton, US	2012	1	AR-15 variant	27
Nairobi, Kenya	2013	4	AK variant, explosives	64
San Bernadino, US	2013	2	AR-15 variant	14
Sousse, Tunisia	2015	1	AK-variant	28
Paris, France	2015	9	AK-variant, explosives	130
Orlando, US	2016	1	AR-15 variant	49

It is likely that future mass-shooting incidents will also involve perpetrators using military weaponry and the wounding patterns that these weapons produce is discussed in Chap. 6.

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Fragmenting Munitions

3

John Breeze and Arul Ramasamy

3.1 Introduction

Energised fragments represent a heterogenous range of ballistic projectiles which are produced by an explosive event. Such encounters can occur in both the civilian environment due to terrorism as well as on the battlefield. In current conflicts fragmentation wounds have outnumbered those caused by bullets, with the UK and US experiences in Iraq and Afghanistan finding 74–81% of service personnel being caused by fragments [1, 2]. Bullet wounds tend to be more common in smaller scale conflicts such as the Falklands war or those involving jungle warfare or urban counter insurgency operations [3–5]. Excluding the effects of blast, the lethality of fragmentation weapons is generally far less than bullets, with the exception of artillery shells which produce large fragments at high exit velocities (in the region of 1500–2000 m/s) [6]. Hand grenades in particular are designed to produce a high number of small fragments and often incorporate spheres which are more aerodynamic and thereby increase effective range [7]. The result is to produce many multiply injured survivors that cause a greater burden on healthcare resources and the logistical chain. A large variety of munitions and devices are designed to produce fragments. Such munitions generally either utilise preformed fragments or the explosive force produced within the munition acts to break up the metallic casing (Table 3.1). Personal armour has altered the pattern of distribution of fragmentation injury so that the most common casualty seen on today's battlefield will have multiple extremity, neck, and facial wounds (Chap. 7) [8]. All war wounds are inherently

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Table 3.1 A broad classification of explosive devices producing energised fragments

Type	Method of production	Material	Shape	Mass
Fragmentation grenade including rocket propelled	Preformed	Metallic	Generally spherical or regular	Low
Shell	Preformed	Metallic	Random	Large range from low to high
Mortar	Preformed	Metallic	Generally spherical or regular	Low
Antipersonnel mine	Preformed	Metallic	Generally spherical or regular	Low
Cluster munitions	Preformed	Metallic	Generally spherical or regular	Low
Improvised explosive device	Improvised	Metallic and non-metallic	Random, although often incorporate munitions above	Low

contaminated by organisms through soil, clothing, and skin, and this is potentiated in buried explosive devices such as mines. Bacteria include Clostridia, Streptococcus, Staphylococcus, Proteus, E. Coli, and Enterococcus, although infection is uncommon in small low-velocity wounds of the extremity. In addition, clinicians need to be aware of the presence of fungal infections (e.g. Aspergillus) following fragmentation injury. This is particularly common in incidents where the device has been buried in farmland. These infections result in significant morbidity, requiring multiple surgical debridements and often lead to sequential revision of amputation stumps [9].

3.2 Fragmentation Grenades

Fragmentation grenades can be hand thrown, underslung from a rifle or rocket propelled. The body may be made of hard plastic or steel. Fragments are most commonly produced by notched wire breaking up the plastic or steel outer casing or by depressions within the actual casing which create fragments by the expanding explosive force. The UK currently uses the L109A1 high explosive grenade as its primary device, with a lethal range of 20 m unprotected, and 5 m wearing body armour and helmet (Fig. 3.1) [10]. The M67 is the primary fragmentation hand grenade utilised by both US forces and Canadian forces and produces fragments that have a lethal radius of 5 m and can produce casualties up to 15 m, dispersing fragments as far away as 230 m. Such pre-formed fragments tend to be relatively light (often 0.1–0.4 g) but numerous [11], increasing the probability of a hit in lightly armoured soldiers but with reduced lethality. Under-barrel launchers increase the effective firing range of grenades to 150 m. The ubiquitous M203 single shot 40 mm grenade launcher is capable of firing a wide variety of grenade types including both high explosive and pre-fragmented rounds [10, 12]. The use of flechettes, depleted

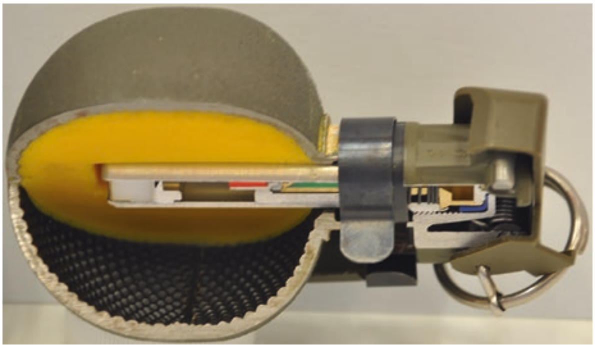

Fig. 3.1 Cross sections of L109A1 fragmentation grenade in which the core (*yellow*) contains an explosive which is ignited by the fuse and propels fragments each formed by dimples in the inner surface of the steel casing. Image courtesy of Dr. Debra Carr

uranium, and tungsten missiles capable of penetrating personal armour may further compound the complexity of wounding with toxicities that have yet to be defined, thus increasing the impact on the medical support system.

3.3 Antipersonnel Land Mines

Anti-personnel mines are a form of land mine and can be classified into blast mines or fragmentation mines. While blast mines are designed to cause severe injury to one person, fragmentation mines are designed to project small fragments across a wider area, and thereby causing a greater number of injuries [13]. Land mines have been deployed in 64 countries around the world and cause over 2000 victims a month with noncombatant far more likely to be injured than soldiers. Although banned by the Ottawa Convention of 1997 and prohibited by International Humanitarian Law, mines continue to be laid across the world. It is estimated that in countries with existing mine fields such as Cambodia, Angola, and Somalia, 1 in every 450 persons undergoes traumatic amputation [14]. Mines can be distributed by a plethora of weapon systems to include aerial delivery and Multiple Launch Rocket Systems (MLRS) that can deliver 8000 bomblets and 100 of mines m a matter of minutes. There are three broad classes of anti-personnel land mines based on mechanism of action (Table 3.2). Static mines are most commonly victim operated by the subject treading on them. Bounding mines can be either command detonated or victim detonated by means of trip wires [15].

The static mine is the most common type throughout the world. Upon contact and detonation, an instantaneous rise in pressure is produced, which along with the products and heated air produce a blast wave or dynamic overpressure. Contact with the body produces stress waves that propagate proximally along with shear waves produced by the blast effect [16]. Traumatic amputation occurs most commonly at the mid-foot or distal tibia [17]. Proximal to the variable level of amputation there is complete stripping of tissue from the bony structures and separation of fascial planes contaminated with soil debris, microorganisms, pieces of the device, footwear, and clothing (Fig. 3.2) [18]. Associated penetrating injury to contralateral limb and perineum are common.

Table 3.2 Broad classification of anti-personnel land mines based on mechanism of action

Type	Description
Static	Implanted in the ground and vary from 5 to 15 cm in diameter, contain 20–200 g of explosive
Bounding	Commonly known as the "Bouncing Betty", these devices have the highest mortality. A small explosive device is propelled 1–2 m above ground then explode, dispersing multiple small preformed fragments
Directional	Typified by the US M18A1 claymore which fires 700 steel spheres, each weighing 0.75 g in a 60° arc, with a range of velocities

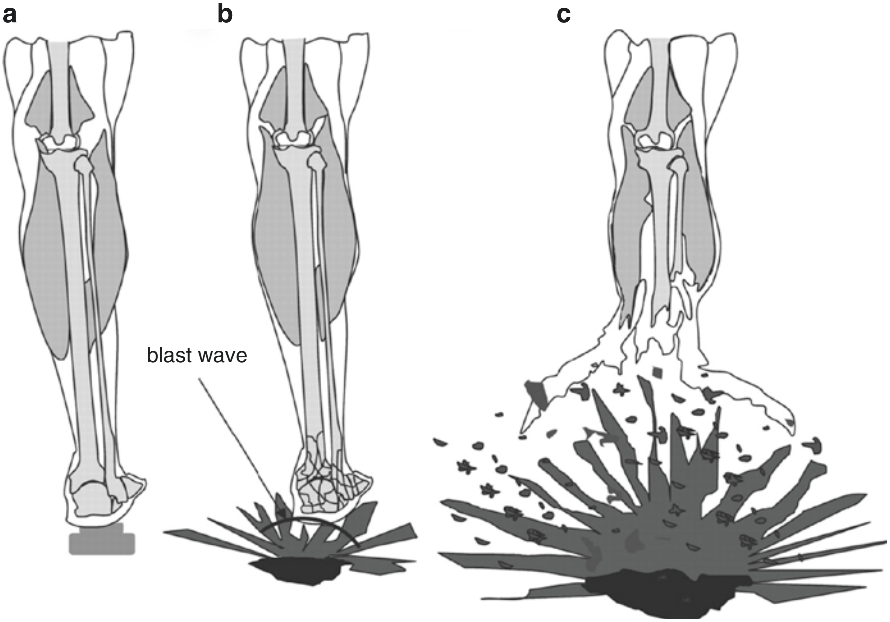

Fig. 3.2 Upon detonation of an anti-personnel mine (**a**), a blast wave is transmitted to the limb causing a brisance effect on the bones (**b**). Some 1–2 ms after detonation, the detonation products reach the limb and place huge stresses on the already damaged bone resulting in multiple fractures and potentially traumatic amputation of the affected limb (**c**). Reproduced with permission from [17]

3.4 Cluster Munitions

Cluster munitions are ordnance that deploy large amounts of explosives over a wide area and can be ground- or air-launched. They are multipurpose weapons with variants that target armoured vehicles, personnel and roads. They can also contain chemical weapons or lay landmines [19]. In general, they consist of a canister, which breaks open to release submunitions over an area known as a "footprint", which can be half up to a square kilometre (Table 3.3).

Table 3.3 Descriptions of a "cluster munition"- derived from [15]

A weapon designed to disperse or release explosive submunitions
Each munition contains greater than ten explosive submunitions
Each explosive submunition generally weighs less than 4 kg
Each explosive submunition is equipped with an electronic self-destruction mechanism or self-deactivating feature

It excludes those designed for air defence or which produce electronic effects

Cluster munitions represent a large proportion of Unexploded Ordnance (UXO) found on the battlefield due to their high failure rates (quoted between 5 and 30%) [20]. When used in areas of civilian and military cohabitation, they, almost guarantee civilian casualties. The military legacy of cluster munitions has been further questioned as a result of US troops being killed post-conflict by their own UXO, not to mention the impediment to mobility when operating in contaminated areas. Indiscriminate use and high failure rates are cited as the two areas of concern giving grounds for humanitarian scrutiny of cluster weapons, and according to research by the Cluster Munitions Coalition (a coalition working to ban cluster munitions internationally), at least 60% of casualties from unexploded cluster munitions are children [20]. There is a lack of accurate mortality and morbidity rates related to cluster munitions. The threat to civilians is certainly far less than from landmines, and it has been suggested that sub-munitions are unlikely to detonate unless handled or thrown. However those most likely to disturb and detonate devices are farmers or children, and there is a growing trend of collecting UXO for scrap metal. The International Committee of the Red Cross observed that those killed or injured by sub-munitions in Kosovo were five times more likely to be under 14 years of age than victims of anti-personnel mines. Such sub-munitions are often brightly coloured (making them attractive to children), lying on the ground and assumed to have failed to explode.

3.5 Artillery

The term artillery encompasses a huge range of weapons capable of producing energised fragmentation. The traditional types (guns, howitzers, and mortars) were sub defined by the trajectory followed by their projectiles. Guns and howitzers not mounted on tanks, ships, or aircraft are often called field artillery. Such pieces are generally dragged behind tractors or trucks or boarded on vehicles for their speedy execution. A gun is a weapon that has a low, or nearly flat, trajectory and fires projectiles in a nearly straight line. A gun's barrel is long in relation to its diameter. A Howitzer has a higher trajectory than a gun with less range than guns, but are capable of firing over the heads of friendly troops or to reach targets protected by hills.

A mortar is a weapon that fires explosive projectiles known as (mortar) bombs at low velocities, short ranges, and high-arcing ballistic trajectories. It is typically muzzle-loading with a short, often smoothbore barrel, enabling a greater rate of fire. The L16A2 81 mm light mortar is the system in current use by both the British and

Australian Army and supersedes the 60 mm mortar. It is a an indirect fire weapon with a maximum range of 5650 m and capable of firing up to 12 rounds per minute [21]. The previous 60 mm high explosive bomb were packed with TNT explosive producing approximately 590 fragments each with an average mass of 1.4 g. A rocket is a self-propelled projectile powered by a rocket motor, that differs from a missile in that it lacks an active guidance system. The UK currently uses the Guided Multiple Launch Rocket System (GMLRS), capable of accurately delivering a 90 kg high explosive warhead up to 70 km and can fire up to 12 rockets in less than 60 s [22].

3.6 Improvised Explosive Devices

An improvised explosive device (IED) is manufactured using easily available materials in order to have a destructive and disruptive effect [23]. IEDs are the most common cause of terrorist explosions in the civilian environment. That are also the most common threat to service personnel worldwide involved in counter-insurgency operations, and are the leading cause of injury and death for soldiers in modern conflicts [13]. IEDs can be manufactured using conventional weapons, or may be completely homemade. An IED consists of a casing, an explosive and a fusing mechanism with or without added material to create a fragmentation effect [24]. The casing of a homemade IED can be made out of diverse commonly available objects including metal cans, glass or polymer bottles and pipes [25]. Fragments impacting personnel may be of random or regular shape, originating from a preformed source (e.g. notched casing, ball bearings), added environmental debris (often referred to as shipyard confetti e.g. nails, ball bearings, screws, washers, bolts etc.) or the environment. In addition human body parts can be incorporated in wounds in suicide bombings (Chap. 5) (Fig. 3.3).

3.7 Retained Ordnance Within a Casualty

Although uncommon, retained live ordnance can occur in military military personnel wounded by explosively propelled devices, particularly from mortars and RPGs [26]. Such devices require a defined number of revolutions or a required distance and time before the missile is armed. There is therefore to potential for the device not to have exploded in such scenarios, particularly if the subject is hit very shortly after firing. A casualty with unexploded ordnance should be transported in the position found so as not to change the missile orientation and should always be grounded to the airframe if evacuated by air. These patients should be isolated and, in a mass casualty situation, should be treated last as the removal of ordnance is time consuming and the surgeon must attend to other casualties before placing his or herself at risk [15]. The basic guidelines for removal of ordnance are outlined in Table 3.4 [27].

Fig. 3.3 An IED cache including pressure plates and explosive material. Downloaded from Defence Imagery. Available from: http://www.defenceimagery.mod.uk/fotoweb/archives/5046-All%20News%20-%20Stock/Purged/ArchPurged/MOD/2012/April/Component%20Parts.jpg

Table 3.4 Removal of unexploded ordnance; adapted from Lein et al. [27]

Notify explosive ordnance disposal
No closed chest massage or defibrillation
Isolate patient from mass casualty situation and protect adjacent area (sandbagged bunker)
Protective equipment for medical personnel
Do not use cautery, power equipment, blood warmers
Avoid vibration, change in temperature, change in missile orientation
Plain radiographs should be undertaken to identify device
No computed tomography, or ultrasound to identify device
Anaesthetist (anaesthesiologist) to leave after induction
Surgeon and explosive ordnance disposal assistant only personnel present during removal
Remove device without changing orientation

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Suicide Bombs

4

Piers Page and Johno Breeze

4.1 Introduction

A suicide bombing is an explosive attack which the perpetrator does not expect to survive. The tactic is one generally associated with religiously-motivated terrorism and has played little role in the campaigns of those groups with secular or purely political aims. Suicide bombs are readily concealed, especially in regions where women are required or choose to wear shape-concealing clothing, and no complex trigger system is required. This means that high-density targets can be attacked with greater ease than by using pre-positioned devices and infiltration of the weapon into the desired attack location is relatively straightforward [1]. Teams perpetrating such attacks can be kept very small, as there is no requirement for escape or evasion by the perpetrator after the incident. For these reasons, it is particularly difficult to establish effective security measures against suicide bombs.

Although the technology in suicide bombs can vary significantly, the majority of attacks conform to the conventionally recognised model of an explosive package, surrounded with pre-formed fragments, worn as a belt or waistcoat. These fragments may be as simple as nails, screws, or nuts on the victim-facing side of the weapon. Suicide bombers who wear the vests are often obliterated by the explosion; the best evidence of their identity is often the head, which may sustain more limited damage because it is separated and thrown clear of the body by the explosion.

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One of the purposes of suicide weapons is to introduce them into a much higher target density environment than that in which a terrorist may be able to plant a larger Improvised Explosive Device (IED). Suicide bombings result in significantly higher number of deaths and casualties at the point of detonation compared to non-suicide bombings [2, 3], in part due to effects which would require a much larger explosive charge in a less densely-packed space. Such an enclosed environment (sometimes termed an ultra-confined space)—a bus or cafe, for example, is a significantly more dangerous place in an explosion than a more open environment, due to the reflection of blast waves within the limited space. Not only will the victims will be struck multiple times by the blast wave, but the peak overpressure of a complex blast wave can be ten times higher than that from which it originated as a result of the summation of reflected and coincident waves. Another implication of the close proximity of suicide bombers to their victims is an increased missile energy—although fragments will have a velocity an order of magnitude less than that of a bullet, those striking victims inches or a few feet away will have had minimal chance for their kinetic energy to decay (as opposed to a roadside IED which may be significantly further away). The energy decay of irregularly shaped fragments is rapid and hence proximity is a key factor in the killing and maiming potential of these weapons. This and the often central position of the weapon in a target area means that the victims closest to the bomber are at risk from not only the energy of the fragments but also the sheer number of them.

4.2 Security and Forensic Issues

Suicide bombings are most commonly encountered in the terrorist or insurgent environment, and so the precautions standard in such a scenario must be taken. Those dealing with the incident in a pre-hospital environment should consider it a non-permissive environment until the incident commander declares otherwise. The potential threats are manifold—although physically linked secondary devices tend to be deployed mainly in remotely detonated devices, the same effect can be achieved by sending a second bomber into a target area flooded with emergency services. Secondary attacks with small arms have also been seen in recent insurgencies. The incorporation of chemical, biological, radiological or nuclear (CBRN) material renders the device more dangerous and the incident higher profile There are few previous pertinent CBRN incidents upon which to make assumptions. Nocera *et al.* described a case of a patient poisoned with aluminium phosphide tablets [4]. This subsequently generated the fumigant gas phosphine when exposed to moisture leading to the evacuation of the hospital staff from the emergency department.

Responders must be conscious of the risk of admitting an unidentified perpetrator into the casualty chain. Apart from any further deliberate acts, a live perpetrator may suggest incomplete or failed detonation of a device and hence indicates a substantial risk to the emergency response. The preservation of evidence must be incorporated into the medical plan for a suicide bombing—agreement with law enforcement agencies before the event on how clothes, fragments, and biological debris are to be collected will facilitate timely, quality care whilst safeguarding the ability to conduct a future investigation. It is also important to plan for the scenario where biological material is required for both forensic and clinical purposes.

4.3 Biological Foreign Body Implantation and Blood Borne Virus Infection

Alongside the immediate injuries, evidence suggests that the long-term health of survivors may be compromised by chronic infection from blood borne diseases contracted either from the environment local to the blast, or from implantation of biological material originating from casualties or the suicide bombers [5]. The survivability of blood-borne viruses (BBV), particularly Hepatitis B virus (HBV) and HIV during and after an explosion is unknown but it is known that the HIV virus remains stable in blood at room temperature, and may persist for a week in dried blood at 4 °C. HBV is 50–100 times more infectious than HIV and can survive outside the body for at least 7 days. During this time, the virus may still cause infection if it enters the body of a person who is not immune. Implanted bone fragments from persons found to be HBV positive have been reported. It is possible that the infection rate is lower than anticipated due to the extreme temperatures at the centre of detonation but biological fragments from victims further away from detonation may not come into contact with such high temperature and pressures. Several reports of implanted human projectiles have been published in the last decade [6, 7] but the actual risk these projectiles pose for transmissible infection is poorly understood.

A major issue in the 7/7 terrorist bombings of the London transport network in 2005 was the unknown BBV infection status of the suicide bombers or victims. In the immediate aftermath of an explosion, viral disease testing might not be appropriate or possible for the deceased. This poses issues to the clinicians who are managing survivors who have been implanted with foreign material. Lack of understanding and limited guidance on ethical considerations regarding biological contamination in mass casualty bombings presents a barrier to delivering high-quality emergency care and so it is essential all potential responders are conversant with the current legal situation.

4.4 Current Guidance and Ethico-Legal Considerations

The background prevalence of infectious hepatitis B infection in the UK population is generally low, but higher in London where there are people from many different areas of birth, some of which are endemic areas. Hepatitis B can be transmitted by blood contact via a wound or, more rarely, via skin abrasions or through mucous membranes [8]. Current guidance has developed from decisions made in aftermath of the 7/7 attacks, effectively recommending PEP for all victims who have sustained penetrating wounds (Table 4.1).

Table 4.1 Risk and implementation categories of post-exposure prophylaxis for those sustaining wounds involving biological material

Category	Wound description	Suggested treatment
1	Directly injured in explosion with major penetrating injuries leading to damaged skin and admitted to hospital	Post exposure management is feasible for in-patients and recommended as routine with the expectation that most patients will receive vaccination
2	Directly injured in explosion with penetrating injuries leading to damaged skin and discharged after receiving treatment in emergency department	Where there are adequate ED records the patient's GP should be contacted and advised to offer post exposure management. Where GP information has not been retained, individuals contacting their GP or other healthcare provider should be offered post exposure management
3	Directly injured in explosion with penetrating injuries leading to damaged skin and did not attend emergency department	It is unlikely to be possible to systematically contact all people within these categories, but where they present to services (emergency or health care) they should be offered post exposure management. Where public messages and statements are made about health for victims, reference should be made to the need to contact family doctors for advice on a number of matters including post traumatic stress, hearing loss as well as BBV risk
4	Indirectly injured (leading to damaged skin) as a result of providing assistance to victims of the explosion (for example cut from fragments of glass or metal on bodies of victims)	
5	Superficial exposure of skin or mucous membranes to blood of victims	Those who contact health care providers should have appropriate risk assessment and post exposure management only if blood exposure to damaged skin or mucous membranes occurred

Derived from [8]

Table 4.2 The prerequisites for consent to medical care in the United Kingdom, derived from [10]

The patient has given consent
Another person authorised to act as the patient's representative has given consent (for example, a child's parent or a person granted power of attorney)
Treatment that is in the best interests of the person is urgently needed, without time to obtain consent

Under common law, a competent adult has the right to refuse medical testing or treatment, even in cases where medical experts believe treatment may offer life-saving benefit. In cases of temporary incapacity, unless there is an urgent clinical need for intervention testing for viral diseases should be postponed until the individual has recovered [9, 10]. According to national guidelines on HIV testing: "If the patient has not appointed an attorney nor left a valid advance statement, HIV testing may be undertaken where this is in the best interests of the patient." If the condition is permanent and a power of attorney has been granted for the person's health and welfare, a decision can be sought. However, the power of attorney may be temporary or time-defined. In order to act within the law, healthcare providers must ensure one of three conditions are met (Table 4.2). In the London 7/7 scenario this allowed testing for HIV, but not prophylaxis, of the unconscious patient.

In victims who are unconscious, deceased or alleged perpetrators, ethical ambiguity over clinical decision-making remains. The decision to commence prophylaxis against BBVs in the unconscious patient or healthcare worker exposed to material from an unconscious or deceased victim or non-compliant perpetrator must be weighed on risk and cannot always be informed by testing of the source of such material [9, 10].

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The Effect of Projectiles on Tissues

5

Jowan G. Penn-Barwell and Tom Stevenson

Key Points

1. Projectiles or rounds affect tissues in casualties by three mechanisms: generation of a shockwave, formation of a temporary cavity and finally the resultant permanent cavity or wound tract.
2. Wounding patterns are idiosyncratic and difficult to predict.
3. Significant tissue damage can sometimes be produced by lower-energy firearms and, paradoxically, minimal wounding can sometimes be seen from higher-energy firearms.
4. Fragmentation of the round and bone-strike are typically associated with greater energy transfer and therefore more severe wounds

> Many of the varieties between one gun-shot wound and another, arise from the difference in the velocity of the body projected; and they are principally the following. If the velocity of the ball is small, then the mischief is less.
>
> —Sir John Hunter, 1794 [1]

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5.1 Introduction

As mentioned in Chap. 2, *terminal ballistics* is the scientific discipline concerned with the interaction between *projectiles* or *rounds* and the objects they impact; when they impact biological tissue this study is called *wound ballistics*. This chapter seeks to distil the multiple, complex and interacting factors that influence gunshot wounding (GSW) into a more coherent but comprehensive and clinical-relevant text.

The behaviour of a round in flight (external ballistics) is predictable enough that a skilled sniper can consistently hit targets at distances of over a kilometre. However, the behaviour of rounds as they pass through tissue becomes idiosyncratic and extremely challenging to predict. Although still governed by Newtonian physics, wound ballistics describes a very complex set of interactions and therefore, there are few reliable rules or patterns to guide the clinician aside from gaining experience of these injuries. This chapter will examine the specifics of these interactions between projectile and tissues rather than detailed techniques of surgical management of such wounds.

Reduced to its fundamental form for the clinical context, wound ballistics concerns the work done by the transfer of kinetic energy (KE) from the round leading to crushing, lacerating, stretching and shearing of the tissues [2]. The KE transferred into tissues is simply the difference between the KE of the round as it strikes the body and that which remains should it exit the tissues. If the round does not exit the tissues, all of its KE will be transferred into the body.

There are three specific mechanisms that will be addressed which allow this transfer of energy to occur: The *shockwave* preceding the round; the *temporary cavity* formed in the wake of the round and finally the *permanent cavity* or *wound tract* left in the tissue [3].

5.2 Shockwave

This is an area of controversy within ballistic literature as the significance of this component is not fully understood [4, 5]. It has long been recognised that when a projectile strikes tissue, a tiny region of very high pressure is generated. This propagates through the tissue slightly faster than the speed of sound in water (1434 ms^{-1}), and therefore *ahead* of the projectile with a duration of 15–25 μs [6]. Whether or not this subsequently has any significant clinical effect on tissues is disputed: some investigators, particularly those examining actual shootings and animal models, believe a significant degree of the observed effect of GSW can be attributed to the shockwave [7, 8]. There is also a belief amongst some investigators that neural tissue might be particularly sensitive to the shockwave [7, 9]. However, others discount the wounding potential of the shockwave and regard it as insignificant or even non-existent when compared to the damage created by the temporary and permanent cavity [10] (Fig. 5.1).

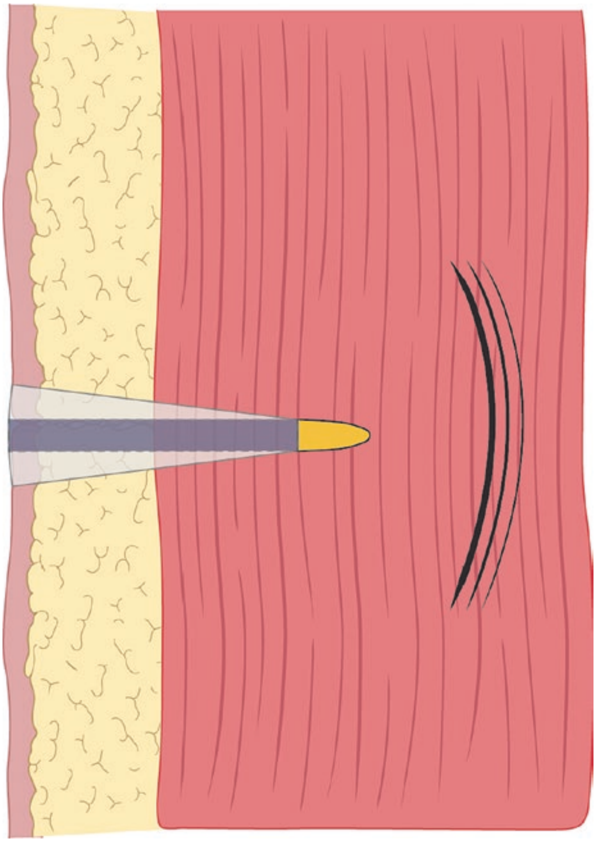

Fig. 5.1 Schematic showing the three components of ballistic wounding: the shockwave preceding the bullet; the temporary cavity expanding radially away from the bullet tract and the permanent cavity directly behind the path of the bullet

5.3 Temporary Cavity

The temporary cavity is the stretching of the tissue radially away from the path of the round, and occurs in its wake as it passes through tissue [11]. When the projectile strikes the tissue it is subjected to a significant increase in retardant forces from the increased drag and is decelerated [12]. This deceleration involves the rapid transfer of KE from the round into the surrounding causing those tissues to radially accelerate away from the path of the round [13]. The process takes place over milliseconds as it must overcome the inertia of the tissues, hence occurs, and continues, after passage of the round. As the tissues accelerate away from the passage of the round, a temporary space or cavity at sub-atmospheric pressure is formed, creating a vacuum which potentially draws air and surface contaminants into the cavity via the entrance (or exit) wound [14, 15]. As the tissues are stretched, those tissues which stretch beyond their capacity to absorb such deformation will tear or fracture [3].

Ultimately, once balance between the radial acceleration of the tissue and the energy the tissue absorbs as it is deformed is reached, the temporary cavity will cease its expansion and collapse back in on itself; it will then expand again, albeit with less available energy. This is visible within modelling as an oscillating or pulsating wave of expansion and collapse which continues over milliseconds until all of the available transferred energy is completely dissipated even when a projectile has left the body [6].

The size of the temporary cavity formed is proportional to the amount of energy delivered. It is important to recognise that cavitation does not occur equally throughout the wound tract: it will be larger wherever the contact surface area of the round is greater, allowing for that greater delivery of KE, such as if the round becomes unstable or fragments as described in greater detail in Sect. 5.6.1 below.

5.4 Permanent Cavity

The round crushes, cuts and shears tissue as it passes through the casualty creating a tract that is typically of a similar size to that of the contact area of the projectile. The permanent cavity is typically a continuation of the trajectory of the projectile though it must be remembered that this trajectory can be deflected by tissue planes, bone strike or otherwise from the instability of the round itself as it traverses the tissues [16]. The entrance wound will usually be predictably minimal in size if the round strikes the body nose first, whereas the exit wound can be more variable; a large exit wound tends to only be present if significant temporary cavitation occurs at the point where the projectile leaves the body [17].

If a round fragments, which can occur either in soft tissue or after bone strike, then each fragment will subsequently continue passage to create a permanent cavity and possibly even a generate a temporary cavity, if the fragments possess enough energy, dramatically increasing the volume of tissue damage in the wound [17, 18].

With regard to the weapon systems and calibres of ammunition available, the number of variables make it difficult for a clinician to predict the injury pattern of a GSW as a casualty arrives; however, lower energy handgun projectiles (e.g. 9 × 19 mm), travelling at lower velocities *typically* only produce a minimal temporary cavity and may not exit the body [17]. GSWs produced by these rounds usually involve damage limited to structures and organs lying in the path of the projectile. Therefore, in 'through and through' injuries, where both entry and exit wounds exist, the structures damaged can be predicted with a fair degree of accuracy where the path of the round is known [19, 20]. However it is important to recognise that higher energy handgun rounds can sometimes form a more significant or clinically relevant temporary cavity: where the round has not been recovered, or the weapon type is unknown, it is perilous to assume that damage from cavitation will not have been caused where the entrance and exit wounds appear minimal as this can mask catastrophic internal tissue injury.

It should also be remembered that paradoxically the higher energy round of a larger calibre (e.g. 7.62 × 39 mm) which passes "through and through" the tissues over a short distance may cause minimal damage; whereas in converse, the lower energy round of a lower calibre (e.g. again, 9 × 19 mm) which does not exit the tissues will dump its entire energy load causing potentially far more devastation to structures by comparison [10].

5.5 Anatomic Injury Patterns

When considering the effect of GSW, it is important to differentiate the anatomic effect and the functional effect of the injury. A high-energy transfer wound to the thigh might involve a relatively large amount of tissue, but if no significant vessels are damaged and the femur is preserved from fracture, the damage may be relatively minimal where, as previously mentioned, muscle tissue is able to tolerate significant deformity and stretch from temporary cavitation without significant injury. Conversely, far less anatomic disruption involving the Central Nervous System (CNS) or the heart and great vessels can be rapidly fatal.

This is evident when one looks at the anatomic distribution of injuries in armed conflict as shown in Table 5.1 below. It is important to remember that military personnel are normally wearing body armour, and therefore will sustain proportionally fewer injuries to their chest and head than unprotected civilian casualties. However, the small proportion of survivors with chest and head injuries relative to those with limb injuries gives some measure of the likely preponderance of extremity injury in a civilian mass-shooting event.

Table 5.1 Anatomic distribution of GSWs in UK military casualties from Afghanistan 2009–2013 [20]

	Fatalities	Survivors	All wounds
Head	(26%)	(6%)	(16%)
Face	(8%)	(7%)	(8%)
Neck	(8%)	(2%)	(5%)
Chest	(31%)	(15%)	(23%)
Abdomen	(12%)	(8%)	(10%)
Spine	(6%)	(6%)	(6%)
Upper limb	(4%)	(22%)	(13%)
Lower limb	(4%)	(34%)	(19%)

5.6 Tissue Injury Patterns

Chapter 2 described how a round is slowed down by the effect of drag, and that this is quantified by the following formula:

$$F_d = \frac{1}{2}\rho v^2 C_d A$$

where F_d is the drag force acting to slow the bullet, C_d is the drag coefficient, ρ is the mass density of the gas or liquid the bullet is passing through, v is the velocity of the projectile, and A is the cross-sectional surface area of the projectile.

The greater the F_d, then the greater the rate of transfer of kinetic energy (KE) is from the round (or fragment) into the tissue. It is important to note that the cross sectional area presented by the round and the density of the tissue it is traversing is proportional to the drag force and therefore the energy transfer [3, 21]. Specific gravity values of different tissues are shown below in Table 5.2. This lead to the conclusion that if the round directly strikes tissue of higher density, it will likely cause more damage e.g. a direct strike to bone will cause more damage than a direct strike to lung tissue.

This helps explain the earlier observation that wound severity is increased with the following factors:

- Tumbling or fragmentation of the round
- Bone Strike

Conversely, if a round traverses a limb without fragmenting or striking a bone then very little energy may be transferred into the tissue. Skeletal muscle is resilient to the stretching seen with temporary cavitation and while some tissue will be crushed in the formation of the permanent cavity, overall the wound may be minor with little tissue necrosis and require only limited surgical intervention [23–25].

Table 5.2 Specific gravity of different tissues along with associated wound severity from high velocity bullets [22]

Tissue	Specific gravity	Severity of wound
Fat	0.8	Moderate
Lung	0.4–0.5	Minimum
Liver	1.01–1.02	Marked
Muscle	1.02–1.04	Marked
Skin	1.09	Marked
Bone (rib)	1.11	Extreme

5.6.1 Tumbling and Fragmentation

As described in Chap. 2, military rounds are designed to resist drag. The effect of the tissue on the round increases drag, however if the round tumbles or fragments, drag is dramatically increased and therefore so is the energy transfer. This explains why temporary cavities are at their greatest at the point in the wound tract where the round tumbles [17] as shown schematically in Fig. 5.2 below.

A gyroscopically stable, high-ogive ("sharper" nose or *Spitzer*) round will pass through tissue for some distance without significant yaw away from its central axis, thus will likely exit the body with much of its kinetic energy retained [26]. Conversely, an unstable, low-ogive ("blunter" nose), expanding or fragmenting round, will strike tissues with an increased contact surface area, allowing transfer of a proportionally larger amount of energy. As the projectile passes through tissue, the torque or spin conferred upon it by the rifling is slowed (for those rounds fired from an appropriately rifled weapon system), further reducing its stability and increasing the opportunity for yaw away from the central axis. The drag coefficient is also increased, and the resultant rapid deceleration also leads to the round being subjected to bending and stressing which can result in fragmentation of the round [3].

Finally, it is worth remembering that many modern rifle rounds are designed such that the centre of mass lies further towards the tail than the nose, so as stability

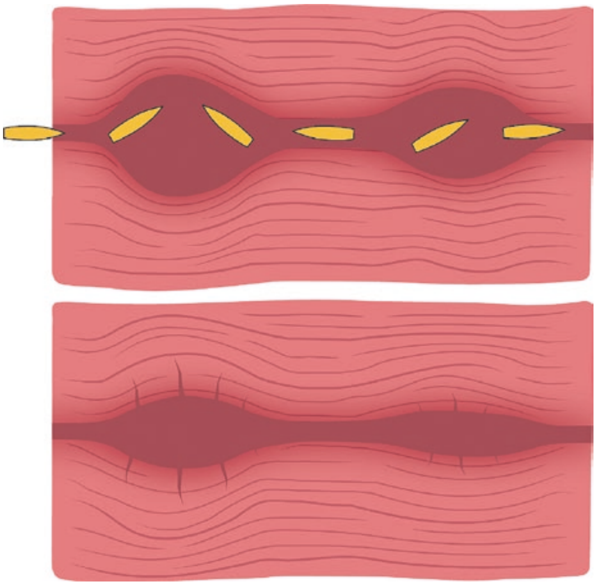

Fig. 5.2 Schematic showing the formation of the temporary cavity in the *upper image*, with maximal cavity formation at point where the projectiles tumble and turn through 180° or even 360° to the direction of travel, and the permanent cavity resulting in the *lower image*

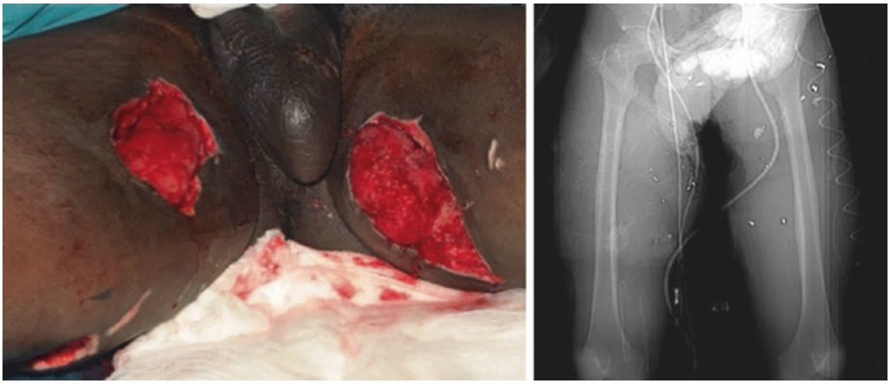

Fig. 5.3 Radiograph and clinical photograph of a casualty injured by a negligent discharge of a 5.56 × 45 mm round at close range. The round has fragmented as shown in the CT scouting image as it traversed across both legs, causing excessive soft tissue damage shown in the clinical photograph taken after the first surgical episode. © 2017 Crown Copyright

is lost once it enters tissues (or even before it enters the body), it can mean the round will reverse its orientation by 180° or even 360° during its forward passage, otherwise known as tumbling [11, 27]. If the penetration distance through tissue is sufficient, or if the projectile strikes tissue of higher density, such as bone, it is likely that the bullet will yaw significantly and may begin to tumble unpredictably, such as when its long axis is at 90° to its trajectory; as previously mentioned, the rate of energy transfer and cavitation is greatest due to the maximal surface area being in contact with tissues.

When the round fragments, there is an overall increased surface area of the projectile in contact with the tissues; as such the components are subject to considerably greater drag so, again, there is greater energy transfer and tissue damage. This is shown in the clinical photograph and radiograph shown in Fig. 5.3 above.

If initial radiographs demonstrate round fragmentation, then it should be assumed that there is significant energy transfer and therefore significant soft tissue damage [28, 29].

5.6.2 Tissue Density

Whilst specific gravities of different tissues were examined earlier, it is now important to consider the clinical implications. The tissue that presents the greatest resistance to the passage of a round is bone. If a round strikes bone, there is normally rapid slowing of the round and therefore energy transfer and tissue damage. A strike to a long bone shaft appears to result in a fracture with significant comminution [22].

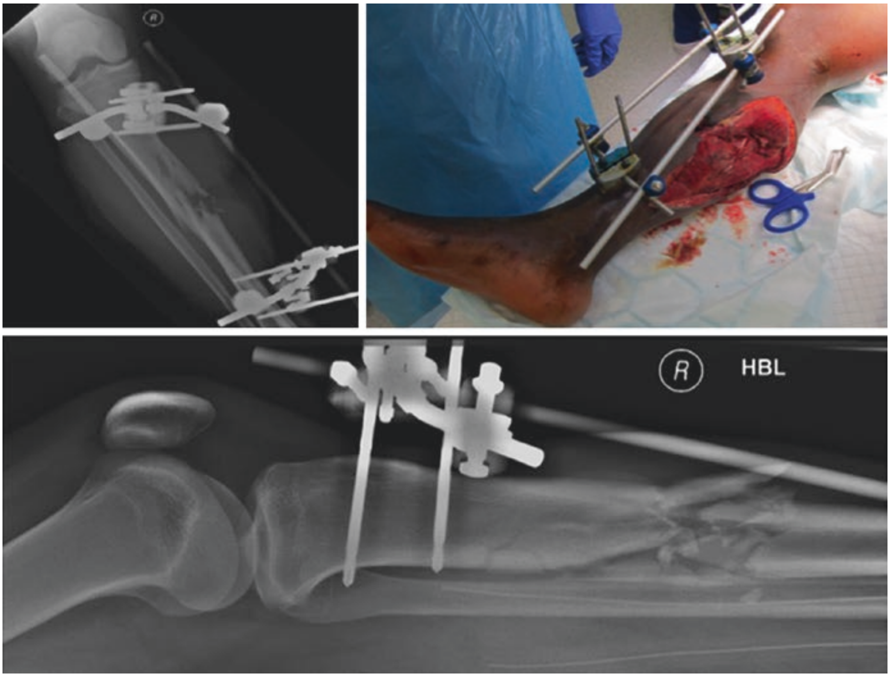

Fig. 5.4 Radiograph and clinical photograph illustrating a gun-shot wound in which the round has struck the tibia causing a multi-fragmentary fracture associated with significant energy transfer and soft-tissue damage as shown in the clinical photograph. This photograph was taken as part of the assessment in the operating theatre prior to the second. © 2017 Crown Copyright

Figure 5.4 above demonstrates the significant energy transfer when a high energy round strikes a long bone.

When lower energy weapons such as handguns are used, there is a higher proportion of incomplete fracture seen [30]. Whilst comminution occurs at a higher rate in high energy GSWs, incomplete fracture can also be seen with higher energy rounds in areas of bone that are more cancellous in nature appear to undergo “drilling” as the round passes through with little apparent damage away from the passage of the round, leaving a ‘drilled-out’ permanent wound tract [22] as shown in Fig. 5.5 below.

When considering tissue of less density, lung tissue is at the opposite end of the tissue density spectrum from bone and therefore offers little drag to rounds as they pass through the lungs. Lung parenchyma is also is an elastic tissue, which can tolerate the stretch that occurs with the formation of a temporary cavity [31] However, if a round strikes a rib as it either enters or exits the chest, there can be significant energy transfer as the round is destabilised, fragments or accelerates splinters of rib bone as shown in Fig. 5.6 below.

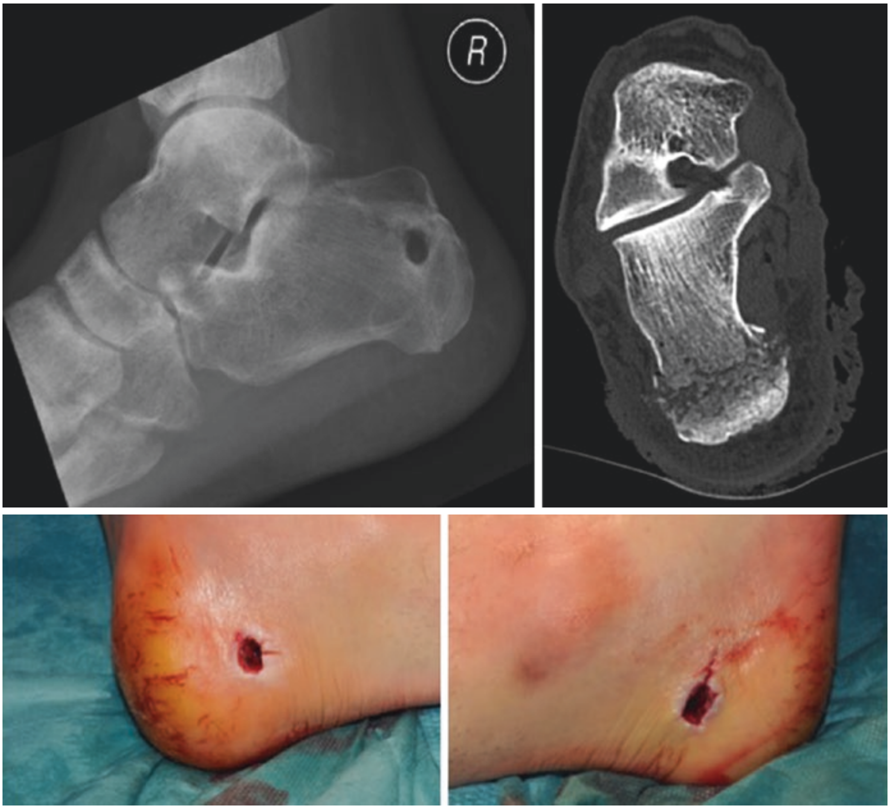

Fig. 5.5 Radiograph, CT image and clinical photographs showing a gun-shot wound to the heel with a low-energy open fracture of the calcaneum. There has been little energy transferred and the wound healed without complication only requiring superficial scrubbing of the entry and exit wounds and irrigation with saline. © 2017 Crown Copyright

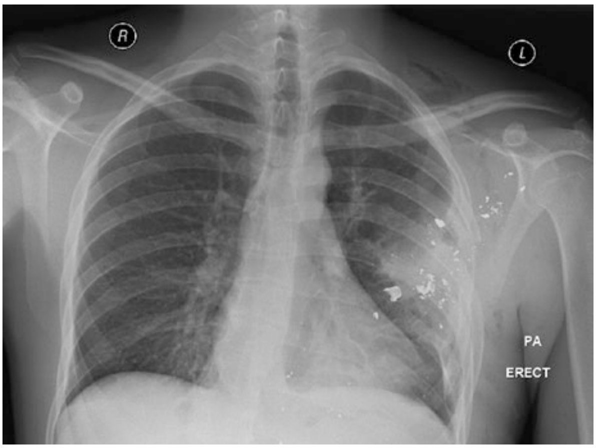

Fig. 5.6 Radiograph of the chest following a gun-shot wound where the round has struck a rib, causing a rib fracture and fragmentation of the round. This has resulted in significant energy transfer resulting in lung contusion. © 2017 Crown Copyright

Conclusion

This chapter has examined the mechanisms by which a projectile transfers energy into the tissue following gunshot and the resultant effect in terms of the wounds that are created. The mechanisms of wounding have been discussed with particular focus on the creation of temporary and permanent cavities.

The typical features of wounds with higher energy transfer and therefore more severe wounds i.e. round fragmentation and bone-strike have been explained with clinical examples.

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Personal Armour Used by UK Armed Forces and UK Police Forces

6

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6.1 Introduction

Personal armour is an overarching term used to describe personal protective equipment that is worn or carried by an individual to stop the penetration of projectiles into the human body (Table 6.1). Personal armour is most commonly used by the Armed Forces and the police, but other users include first responders (such as fire and ambulance personnel) and security professionals. The aim of this chapter is to provide information regarding (a) personal armour materials, (b) how personal armour protects the user, (c) the anatomical structures protected by personal armour and (d) the types of personal armour worn by UK Armed Forces and UK Police Forces. Comments are also made regarding likely behind armour injury and removal of armour.

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Table 6.1 Types of personal armour subdivided by anatomical area protected

Body area	Type of personal armour
Head	Helmet
Face	Visor, glasses, goggles, mandible guard
Neck	Collar, nape protector
Thorax and abdomen	Body armour—'soft' body armour, 'hard' plates
Pelvis	Pelvic protection
Upper arm	Brassards
Thigh	Pelvic protection

There are differences between military and civilian personal armour systems which reflect the threats they are required to mitigate [1, 2]. Body armour typically consists of 'soft' armour and 'hard' armour plates. Soft armour is a waistcoat or tabard style garment covering the torso and contains multiple layers of fabrics manufactured from high-performance fibres and provides resistance to perforation from fragments and low-velocity pistol ammunition. Resistance from stab attacks requires the use of chainmail or laminated fabrics [3]. Resistance to slash attacks from edged weapons typically uses woven or knitted fabrics manufactured from high-performance fibres. If protection from high-velocity rifle ammunition is required then 'hard' armour in the form of plates is provided; these are ceramic-faced/composite backed or 100% composite, depending on threat. Body armour used by the UK Armed Forces is designed to provide protection from fragments and high velocity rifle bullets. In comparison, police officers on routine patrol in the UK need body armour to protect them from edged-weapons (e.g. knives) and low-velocity pistol bullets [4]. In addition police forces require specialist body armour for selected roles such as Authorised Firearms Officers (AFOs) and Specialist Firearms Officers (SFOs) that use similar high-velocity rifle protection to that used by the Armed Forces.

6.2 Personal Armour Materials

The materials used in personal armour are optimised for the threat to be defeated e.g. [1, 2, 5]. In soft body armour, the protective fabric pack is often enclosed in a light- and water-resistant or waterproof cover and then placed in the carrier system. If plates are used in the body armour, these are usually inserted in pockets in the carrier (front and back; sometimes side) [2]. Soft armour designed to provide protection from fragmentation and low-velocity pistol ammunition contains multiple layers of fabrics manufactured from high tenacity fibres which are manufactured into yarns, and which are difficult to cut [2, 3]. These fabric solutions are usually woven para-aramids (e.g. Kevlar® or Twaron®), cross-ply ultra high molecular weight polyethylenes (UHMWPE) (e.g. Dyneema® and Spectra®) or laminated fabrics (usually woven para-aramid). Fragments vary in size, shape and kinetic energy and are usually non-deforming (although may fracture during impact); when they impact the ballistic protective pack, energy is dissipated across the face of the pack, the fibres and yarns within each layer are strained and energy transferred through the fabric layers [6]. The resultant effect is a pyramidal deformation through the pack thickness e.g. [7, 8]. If the tenacity of the fibres/yarns is exceeded then failure occurs. Low-velocity pistol ammunition is defeated by soft armour solutions in a similar manner, however the bullet typically deforms into a mushroom shape (as the bullet core is often a soft metal such as lead); this results in a reduction in kinetic energy density (kinetic energy per unit area) and an associated reduction in pressure applied to the armour [3]. A behind armour blunt trauma (BABT) injury may occur (Sect. 6.6).

Protection from sharp-weapons is provided by the use of chainmail which captures the weapon or laminated fabrics (usually woven para-aramids) which blunt the weapon [3]. For resistance to perforation by spiked weapons (e.g. ice pick, bradawl), laminated solutions are generally used.

Protection from high-velocity rifle bullets is provided by the use of hard plates which are usually ceramic faced /composite backed (ceramics used include alumina, silicon carbide and boron carbide, composites include para-aramid and UHMWPE) [2, 3]. The ceramic is usually harder than the core of the high-velocity rifle bullet threat. On impact the bullet may mushroom and/or fracture; the ceramic fractures into a characteristic conoid pattern. The composite backing will deform with some elastic recovery, but a permanent deformation will remain. A BABT injury may occur (Sect. 6.6).

Helmets and some hard plates are made from composites i.e. fibre (fabric) reinforced polymers e.g. [2, 5]. The fabrics used are para-aramids and UHMWPEs; some older helmets are manufactured from Nylon 6,6 (e.g. the Mk6 military combat helmet; the Mk6A contains nylon 6,6 and para-aramid). The addition of the polymer to the fabric results in a stiffer material which minimises the transient deformation that occurs during the impact event. High-speed video demonstrates that this transient deformation is mostly elastic, a smaller plastic deformation is observed post-testing e.g. [9, 10]. Modelling suggests that the non-perforating acceleration of this deformation is a major energy dissipation mechanism [9, 11]. The major failure mechanism observed in composites providing ballistic protection is delamination; this is directly related to the low interlaminar fracture toughness e.g. [9, 11–14]. Material is compacted near the strike face, with the formation of a plug of composite material travelling ahead of the projectile [11]. The projectile slows during penetration into the composite and delaminations form more readily due to enhanced bending, particularly in thicker sections; the delaminated area increases towards the rear of the composite e.g. [10, 14–17].

6.3 Area of Coverage and Sizing of Personal Armour

6.3.1 Military Body Armour

The area of coverage requirements for UK Armed Forces personal armour identify the anatomical structures that require essential and desirable medical coverage (Table 6.2). The heart, mediastinum, liver and spleen are the structures requiring essential protection [18].

Table 6.2 Definitions of essential and desirable medical coverage for UK military body armour, based upon the assumption of 60 min to surgical care

Coverage	Definition
Essential	Those anatomical structures that if damaged would likely lead to death prior to definitive surgical intervention being available e.g. bleeding from the thorax that cannot be compressed and requires surgical access (thoracotomy) to arrest it. The structures selected are based upon a period of up to 60 min from injury to damage control surgical care.
Desirable	Those anatomical structures potentially responsible for mortality not fitting the requirement for essential coverage as well as those causing morbidity necessitating lifelong medical treatment or that result in significant disability. This includes both physical disability as well as psychological disability e.g. damage to the lower parts of the spinal cord (lumbar or sacral parts) may result in significant loss of function in one or both limbs.

Accurate area of coverage description and correctly sizing body armour to an individual is essential to optimise the coverage and fit that the body armour provides. Body armour that is too small may not provide the essential and desirable medical coverage of the necessary anatomical structures. Body armour that is too large could restrict mobility and encumber the user with additional mass and increased thermophysiological burden as well as gape in areas where coverage and protection is required [19].

Until the VIRTUS system was introduced to the UK Armed Forces in 2015, stature and chest circumference of the individual was used to size all body armour, however VIRTUS sizing regimes now use torso size to more accurately fit body armour. The body armour is fitted from two fingers below the suprasternal notch to the umbilicus (belly button). Male anthropometric landmarks equate to the boundaries of those underlying anatomical structures requiring medical coverage [20]. For example; the superior point on the arch of the aorta corresponds to the suprasternal notch, the lowest point of the liver corresponds to the lower border of the rib cage and the bifurcation of the descending aorta corresponds to the iliac crest (top of the hip bone) (Fig. 6.1).

6.3.2 UK Military Helmets

A helmet has been defined as "item to be worn on the head and intended to absorb the energy of an impact, thus reducing the risk of injury to the head" [21]. Military helmet trim-line is modified in line with User requirements including protection levels, and compatibility and mobility issues e.g. [22–27]. The optimum design of a military helmet from an integration perspective typically considers enclosing the head and then removing sections for vision requirements, a respirator and headset and collar compatibility [1, 28]. With respect to area of coverage, the headforms described by the British Standards Institution have historically defined the area of coverage for UK military helmets [29]. Helmet area of coverage can also be defined by considering the need to protect the essential structures of the brain and brain stem [30].

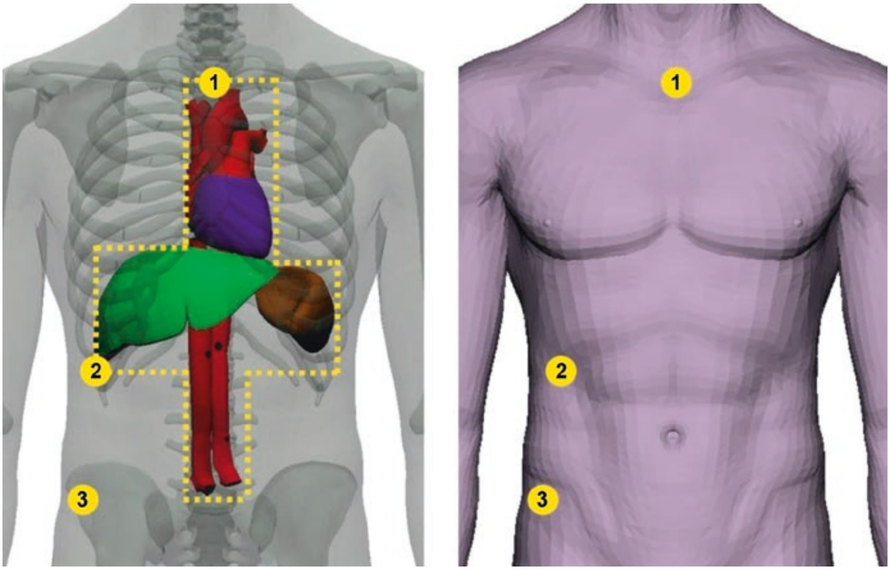

Fig. 6.1 Anatomical structures and anthropometric landmarks. *Left*: anatomical structures requiring essential coverage for the UK Armed Forces future body armour systems 1 = superior point on the arch of the aorta, 2 = lower border of liver and 3 = bifurcation of the descending aorta. *Right*: external anthropometric landmarks that correspond to the internal anatomical landmarks described in the left image 1 = suprasternal notch, 2 = lower border of rib cage and 3 = iliac crest

6.3.3 Police Body Armour

Most UK police forces now supply body armour that is measured for the individual. Manufacturers have a size roll from which they provide the closest fit to the individual based on a series of measurements which the manufacturer requests. Anthropometric landmarks have been used as a guide for fitting police officers with their body armour. The typical guide was two fingers widths down from suprasternal notch and two finger widths up from the belly button. The design of the armour is recommended to provide coverage to the heart and great valves (superior and inferior vena cavae, pulmonary arteries and veins, and aorta), liver and spleen [31].

6.4 Military Personal Armour Systems

6.4.1 Enhanced Combat Body Armour (ECBA)

ECBA was originally introduced in 1991 as Combat Body Armour Internal Security (CBA IS) and is a waistcoat-style front opening garment that covers the torso (Fig. 6.2) [2]. Hard armour plates cover the heart and great vessels at the top of the heart, based on the assumption that definitive surgical care was available within

Fig. 6.2 Enhanced Combat Body Armour (ECBA); (**a**) cover, (**b**) soft armour filler, (**c**) and front and rear hard armour plates

20 min. The total mass of ECBA is less than 5 kg for a medium size, of which each ECBA plate accounts of 1.1 kg.

6.4.2 OSPREY

The modular OSPREY body armour system was introduced in 2005 as an Urgent Operational Requirement (UOR) to UK Armed Forces personnel deployed in Iraq and Afghanistan [2, 32]. OSPREY soft armour is a tabard-style garment providing coverage to the torso, with removable neck and upper arm protection (Fig. 6.3). OSPREY plates cover over twice the area of an ECBA plate reflecting that medical attention would likely be further away. The OSPREY plates provide a higher level of ballistic performance compared to ECBA plates and an enhanced multi-hit capability; they weigh approximately 3 kg each. The OSPREY system was the first UK modular body armour system, enabling the level of protection to be tailored to the threat and the individual's role; for example wearing collars and brassards increases the area of coverage and hence the level of protection, but also the total mass. ECBA plates can also be used instead of OSPREY plates when there is a reduction in the threat level or as side plates when there is an increase in the threat level. The complete OSPREY system weighs approximately 15 kg.

6.4.3 VIRTUS

The VIRTUS personal armour and load carriage system was delivered to high-readiness UK Armed Forces personnel in November 2015 [2] (Fig. 6.4). VIRTUS was designed, procured and tested as a system with the primary aims to be a scalable system improving integration and interoperability, and reducing mass and bulk. VIRTUS soft armour retains the same level of protection as but is lighter than OSPREY; for the first iteration VIRTUS retains the OSPREY plates. The level of

Fig. 6.3 OSPREY personal armour system; (**a**) OSPREY with arm brassards and collar, (**b**) Front and rear soft armour, (**c**) OSPREY plates, (**d**) ECBA plates used as side plates

Fig. 6.4 VIRTUS body armour with detachable arm brassards and neck collar

protection can be scaled up or down to match the threat by adding or removing soft armour and/or hard plates. When the complete ensemble is worn, VIRTUS is 4.7 kg lighter than OSPREY and the mass is likely to reduce further when new plates are introduced.

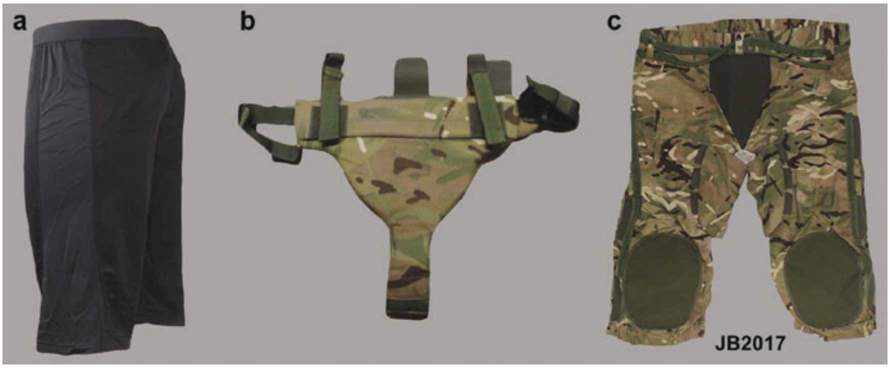

Fig. 6.5 Pelvic protection system. (**a**) Tier 1, (**b**) Tier 2, (**c**) Tier 3

6.4.4 Pelvic Protection

Protection of the pelvis and thigh from explosively propelled debris and fragmentation was introduced in 2010 as an Urgent Operational Requirement for UK Armed Forces personnel serving in Afghanistan [33]. The Pelvic Protection System (PPS) comprises of three garments providing an incremental increase in coverage and level of protection. Tier 1 was designed as a next-to-skin garment to be worn on a daily basis, with human factors acceptance being the primary driver rather than the protection level (Fig. 6.5a). Tier 1 provides protection against the dirt, dust, grit and debris emanating primarily from the soil/substrate in which explosive devices are buried. Tier 1 is available in male and female variants and a number of sizes. Tier 2 is available in three sizes and provides the same level of protection as the OSPREY body armour vest from fragments (Fig. 6.5b). Tier 2 is worn over the combat trousers and protects the groin and buttocks area and some of the inner thigh, and is stowed on rear (on the belt) when not in use. Tier 3 is a longer garment that is worn over the combat trousers. Tier 3 is worn in situations of increased threat and provides enhanced protection to the thigh, abdomen and femoral artery. Tier 3 is worn in conjunction with Tier 2, for short duration and high-risk activities (e.g. Counter-IED) (Fig. 6.5c).

6.4.5 Military Combat Helmets

The primary requirement for combat helmets for the UK Armed Forces is to provide fragmentation protection as well as a level of protection against non-ballistic impact. Prior to the introduction of helmets with composite shells in the mid-1970s, UK military helmets for the Armed Forces were metallic. Modern military helmets typically comprise a composite shell, a foam liner, a suspension system and a retention system.

The Mk6 general service combat helmet was introduced in the mid-1980s and comprised of a nylon 6,6 composite shell with a high-density closed-cell polyethylene foam liner [34, 35]. In 2006, the Mk6A combat helmet was introduced into operations in Iraq [32]. The Mk6A combat helmet retained the same non-ballistic-impact protection and was the same shape as the as the Mk6, but had a 40% increase in the level of fragmentation protection compared to the Mk6; the helmet shell was a hybrid composite of para-aramid and nylon 6,6. The Mk6A also introduced a new improved 4-point chinstrap, compared to the 3-point chinstrap of the Mk6. In 2010, the Mk7 combat helmet was introduced to combat operations in Afghanistan; this helmet has a different shape to the Mk6 and Mk6A, and is thinner and lighter [2]. The Mk7 shell is manufactured from para-aramid composite and provides an increased level of fragmentation protection compared to the Mk6 and Mk6A, whilst retaining the same level of non-ballistic impact protection. The simplest way to tell these helmets apart is by the shell colours, as the Mk6 combat helmet is olive drab (green), the Mk6A is black, and the shell of the Mk7 combat helmet is sand.

The VIRTUS helmet was introduced in 2015; it is manufactured from ultra high molecular weight polyethylene (UHMWPE) (Fig. 6.6) [2]. This helmet is lighter and a different shape compared to the Mk6, Mk6A and Mk7 combat helmets; it is optimised for anatomical coverage. The VIRTUS helmet has a higher level of fragmentation protection and non-ballistic impact protection compared to the Mk7 helmet; it also includes a nape guard so that flexibility and interoperability is maintained while retaining fragmentation protection. A visor and/or mandible guard can be fitted to the VIRTUS helmet for certain tactical scenarios. These components can be used individually or together as an integrated system providing complete coverage

Fig. 6.6 The VIRTUS helmet system comprising helmet, visor, multifunctional front mount, mini rail and mandible guard

of the head and face. The VIRTUS helmet also features an integrated permanent universal mount for night vision capability and a scalable counterweight that can be attached to the rear of the helmet for when the night vision system is in place.

6.4.6 Eye Protection

There is a requirement for UK Armed Forces personal armour to protect vision and prevent potential ingress of fragments into the brain via the eye and reduce facial disfigurement. Protection of the eyes from fragments is provided by low impact ballistic protective spectacles and medium impact ballistic protective goggles (Fig. 6.7) [2].

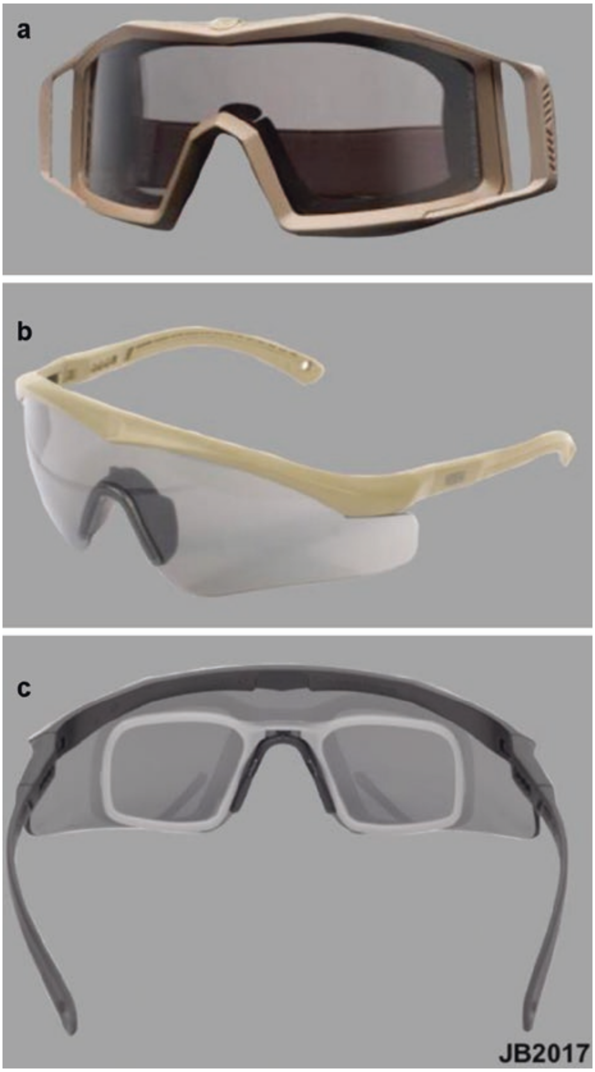

Fig. 6.7 Protective eyewear; (**a**) Medium impact ballistic protective goggles, (**b**) Low impact ballistic protective spectacle, (**c**) Prescription inserts are available with both sets of eyewear

Prescription inserts are available with both sets of eyewear. The VIRTUS system provides progressive coverage of the face using ballistic protective eyewear (spectacles, goggles) or a visor, both of which may be worn in conjunction with a mandible guard.

6.5 UK Police Armour Systems

6.5.1 Police Body Armour

The main purpose of body armour developed for the police is to reduce the risk of a life changing or life ending injury from sharp-weapon and ballistic threats. UK police body armour is not designed to provide protection from fragmentation threats. Within the UK, body armour that is designed for police use is available in various protection levels. These levels are defined in the standards developed by the Home Office on behalf of the National Police Chiefs Council (NPCC) [4]. The standards are developed around the threats faced by the police in the UK, and take into consideration the balance between protection and functionality. These standards enable manufacturers to develop solutions which can then be approved before being procured by the police. Police forces in the UK can purchase body armour from any supplier that meets their risk assessment and ergonomics requirements, and it is recommended that their armour is certified to UK Home Office police body armour testing standards.

Within the UK, the primary threat currently faced by the police is from sharp-weapons. Typically, a routine patrol police officer will be issued with dual purpose body armour that is designed to provide protection from low-velocity pistol bullets and sharp-weapons (Fig. 6.8a). Typically, these body armours have an areal density[1] of between 5 and 7.5 kg m^{-2}. Although the majority of police officers in the UK are routine patrol, all police forces have a number of firearms officers. These officers are provided with a higher level of protection due to the nature of the threat they are trained to respond to. Typically, these officers will be issued with a soft armour to provide protection against low-velocity pistol bullets with hard plates to provide protection from rifle bullets, such as 7.62 × 51 NATO ball and 7.62 × 39 mild steel core (Fig. 6.8b). Typically, the soft armour has an areal density of 7–8 kg m^{-2}; the hard plates vary depending on the level of protection required, but the areal density typically varies between 15 and 35 kg m^{-2}. Some police forces supply firearms officers with armour that has the addition of sharp-weapon protection to the ballistic protection. This typically results in soft armour solutions with an areal density of >8 kg m^{-2}. As with military body armour, this higher level of police body armour may also have additional protective panels such as neck, groin and shoulder guards. For certain roles, the use of low level covert armour solutions that provide either low-velocity pistol protection or sharp-weapon only protection may be used (Fig. 6.8c).

[1] Areal density is the equivalent mass per square metre (kg m^{-2}).

Fig. 6.8 Typical police body armour worn in the UK (Images are copyright Cooneen Group), (**a**) Routine Patrol, (**b**) Authorised Firearms Officers, (**c**) Covert

It is anticipated that if a police officer is subjected to a non perforating ballistic impact to body armour there may be a level of behind armour blunt trauma (BABT) (Sect. 6.6). The armours when certified are tested to be within predefined limits of back face signature (BFS) when measured on Roma Plastilina No 1 [4]. Whilst this is not a biofidelic testing medium and does not represent a human torso, it does provide an indication of the material performance and has been used for over 30 years with a number of documented 'saves' [36, 37]. For sharp-weapon resistant armour, the test blade can perforate the rear of the armour to a maximum length of 8 mm. It may be possible that the skin of the users will be penetrated, however studies have shown that at 8 mm the probability of striking a vital organ is very low [38].

6.5.2 Police Helmets

Within the police service there are predominantly three styles of helmet; Custodian Helmet, Public Order Helmet and a Ballistic Protective Helmet. Although there are specialist helmets for other roles such as maritime, working at heights and mounted officers, these are usually commercial off the shelf (COTS) solutions with police markings. The Custodian Helmet is the standard routine patrol helmet which has been in use by the police service within the UK for a number of years, traditionally made from cork, the helmet itself provides very little protective properties (Fig. 6.9a). The Public Order Helmet (Fig. 6.9b) is designed for use in situations of severe public disorder and is primarily designed to protect the police officer from a severe non-ballistic impact to the head. Public Order Helmets are tested and certified by the Home Office on behalf of the NPCC in accordance with the 2004 protective headwear standard [39]. In addition to providing impact protection to the head and face, the helmet and its visor are also designed to be resistant to the effects of burning liquids, fluid ingress and chemicals. These helmets

Fig. 6.9 Example of UK Police Helmets; (**a**) Custodian Helmet, (**b**) Public Order Helmet (image courtesy of MLA Ltd.—Merlin Public Order Helmet)

typically weigh around 1.75 kg and incorporate a neck guard to help provide coverage between the top of the flame retardant overalls and the helmet edge. The helmets also have a full face visor to enable the officer to have as wider range of vision as possible.

The requirement for ballistic protective helmets within the police service is limited to firearms officers within forces (or those working closely with them). The primary requirement is to provide low-velocity pistol ammunition protection equivalent to that provided by the soft armour issued to a firearms officer. The design and style of these helmets has traditionally been very similar to that used in the military, however some variation in that design has been seen in the last few years.

6.6 Behind Armour Blunt Trauma (BABT)

Behind armour blunt trauma (BABT) has been defined as "…the non-penetrating injury resulting from the rapid deformation of armours covering the body." [40]. BABT also includes pencilling; a narrow, tapered, deep deformation of the soft body armour into the torso [41, 42]. As a result of a ballistic impact onto body armour, stress waves are generated and propagate through the body armour and the underlying tissues (including those not in direct contact with the armour); they may be transmitted and/or reflected by the armour components and/or various tissues depending on the speed of sound in the material e.g. [43–46]. The applied shear stresses may result in tearing of tissue [40, 47–49]. Typical injuries include skin contusion, laceration and penetration; rib fracture; and contusions to lungs, kidneys, spleen and (rarely) the heart e.g. [36, 40, 47, 49–55]. There is no evidence for fatalities due to BABT when personnel (military or police) are attacked by a threat for which the body armour they were wearing was designed [37]. However, an enhanced risk due to BABT might emerge as body armour design continues to be optimised resulting in thinner, lighter and more compliant armours.

6.7 Removal of Personal Armour to Treat Injuries

The comprehensive assessment of an injured person requires the removal of personal armour [56]. This can be challenging due to the need to immobilise the spine with the casualty maintaining a supine position until safely extracted. Soft body armour comprised of multiple layers of para-aramid and/or UHMWPE fabrics cannot be cut from a casualty with the standard heavy-duty scissors that are carried by emergency clinicians. Advice provided to clinicians to remove body armour includes cutting the side webbing straps of the ECBA as this does not involve directly cutting the armour material. OSPREY can be removed using the fasteners at the shoulders; the VIRTUS body armour has a quick release mechanism at the front of the soft body armour. Clinicians should be trained to remove body armour in the most effective manner. Any bullets and/or fragments contained within the body armour and helmets as well as those removed during surgical intervention should be retained as they may potentially be forensic evidence.

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Triage

7

Ed Barnard and Jamie Vassallo

7.1 Introduction

In 2015 and 2016 there were 48 terrorist incidents resulting in 320 deaths and 1227 further casualties in Western Europe alone. The three largest of these incidents were Marauding Terrorist Firearms Attacks (MTFA), accounting for 82% of the total casualties in this period (258 deaths and 1011 casualties) with a median total number of casualties per incident of over 400. Prioritising medical care in the aftermath of these attacks, whilst being aware of tactical constraints, is essential in order to provide an optimal health response.

The health response to an MTFA has historically involved principles explained in the Major Incident Medical Management and Support (MIMMS) training manual [1]. The first casualty contact action in MIMMS is to identify the medical treatment priority of all patients, and in order to do so rapidly mandates that no treatment takes place until this phase is completed. This process is known as triage—a word derived from French '*trier*' that literally means 'to sort', and has its origins in coffee bean selection and latterly to describe a process of prioritising casualties on the basis of their clinical acuity for medical treatment.

The London bombings on 7th July 2005 identified several key lessons for the pre-hospital health response to an MTFA. In response to the Coroner's inquest a

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review of the triage system took place, resulting in changes to the MIMMS paradigm: primarily the requirement to undertake immediately life-saving interventions alongside the triage process and the use of a 'two clinician' triage system.

Triage systems need to be simple, and rapid, with reproducible results, whilst also allowing for a defined and limited number of immediate lifesaving interventions. This chapter will outline these processes.

7.2 History of Triage

The concept of medical triage was developed by Baron Dominique-Jean Larrey, Chief Surgeon of Napolean's Imperial Guard (1766–1842) [2]. Larrey's priority was to maintain fighting effectiveness, and therefore those with minor injuries received treatment first (to allow them to return to the battlefield), followed by the most severely injured.

The next major advancement in triage is attributed to British Naval Surgeon John Wilson (1834–1885), who declared that surgeons should concentrate their efforts on those with an immediate need for treatment and in whom intervention was likely to be successful, whilst deferring the care of those with minor wounds, and those whose wounds were probably fatal.

The term 'triage' was in widespread use during the First World War. A military war manual at the time observed: '*It is often physically impossible to give speedy and thorough treatment to all patients. A single case, even if it urgently requires attention,—if this will absorb a long time,—may have to wait, for in that same time a dozen others, almost equally exigent, but requiring less time, might be cared for. The greatest good of the greatest number must be the rule*' [3].

The treatment priorities of triage have necessarily changed over time, but the underlying principle to give the right patient the right care at the right time remains extant.

7.2.1 Modern Day Triage

The MIMMS practical course and accompanying manual were written in the aftermath of the Musgrave Park Hospital bombing in 1991, and in recognition that healthcare professionals were inadequately prepared for a major incident. The backbone of MIMMS is the now well-known mnemonic 'CSCATTT'—a standard, systematic sequence of actions: Command, Safety, Communications, Assessment, Triage, Treatment, Transport [1]. Since its inception in 1994 the principles of MIMMS have been taught to a large number of healthcare professionals in the UK and overseas, and influenced major incident policy.

More recently adaptations to the system of triage have been made in response to the attacks in London in July 2005—these include recommendations for a two-person triage team to allow lifesaving intervention (application of tourniquets to control catastrophic haemorrhage) to be undertaken alongside assigning triage categories. The requirement for adequate supplies of immediate life-saving equipment was further highlighted following the Paris MTFA in November 2015: '*the demand for tourniquets was so high that the mobile teams came back without their belts*' [4].

The United Kingdom's National Ambulance Resilience Unit (NARU) was formed in 2011 to help strengthen national resilience and to improve patient outcomes in challenging pre-hospital environments, including the health response to MTFAs. NARU now provides national level guidance for the command and control, and management of incidents involving a large number of casualties [5].

Today there are numerous different triage systems in place around the world—this is likely to reflect both evolution in response to specific incidents, and the recognition that one triage system may not be applicable to all types of major incident.

7.3 Principles of Triage

7.3.1 Triage: When?

Triage takes place day-to-day in most healthcare systems. In the UK this typically starts with the Ambulance Service call taker using a pre-defined set of questions to initiate the most suitable response. In order that the seriously unwell and injured are dealt with expediently and appropriately this system must be rapid, reliable, and reproducible. This sorting process (triage) continues at every step of the casualty's journey in order that they receive the right healthcare, at the right facility, and at the right time—these are the fundamental principles of triage (Box 7.1).

Box 7.1 Fundamental principles of triage

- Triage is a routine process in healthcare
- It should be rapid, reliable, and reproducible (irrespective of the provider delivering it)
- Effective triage results in the right patient receiving the correct healthcare at the most appropriate facility, at the right time.

In a major incident this process is even more important, as by definition it is a situation in which the number, type, or location of live casualties requires extraordinary resources. Therefore for optimal outcomes there must be a system in place that makes the best use of available resources.

The physiological state of casualties changes over time in response to both injury and interventions, triage must therefore be regularly repeated. In the major incident setting triage will occur numerous times; on first contact, before moving the casualty, in a casualty clearing station, prior to evacuation to hospital, and again on arrival at hospital.

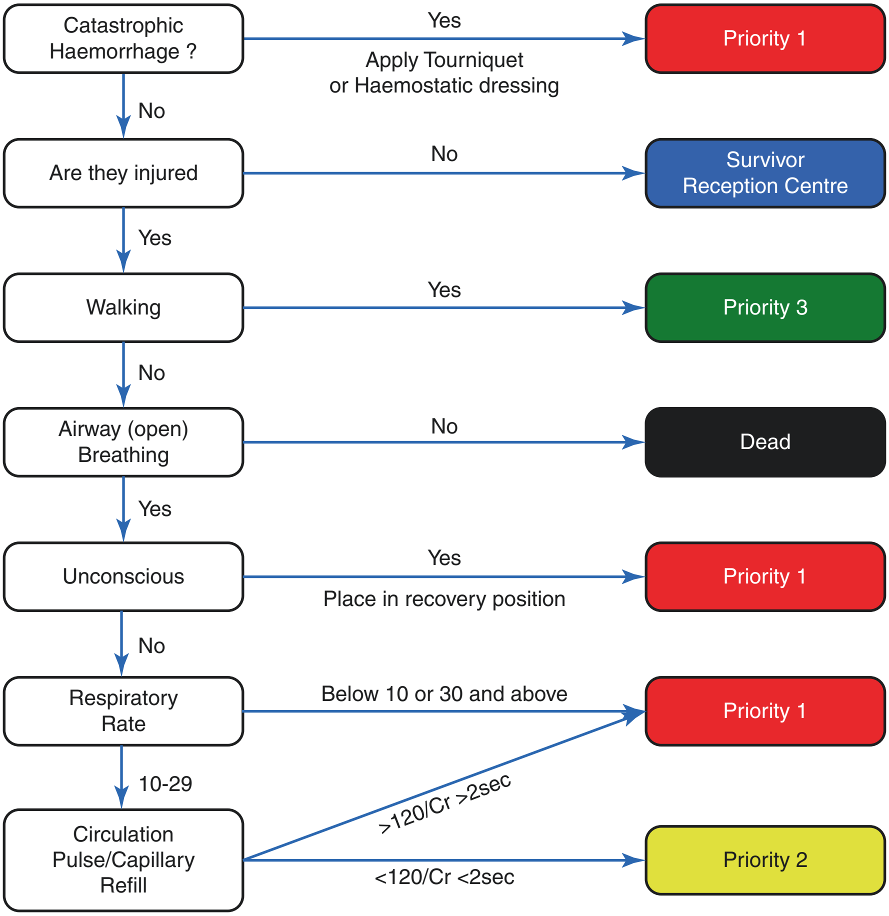

Fig. 7.1 Triage sieve-based on National Ambulance Resilience Unit Triage card

It is unrealistic to expect healthcare providers to do something in a major incident that they do not do regularly. Deliberate practice of triage should be supported by routine use (for example at any incident with a greater number of casualties than providers), and through major incident exercises. In recognition of this principle NARU have modified the UK civilian triage system to follow the day-to-day patient assessment paradigm of <C>ABC (Fig. 7.1).

7.3.2 Triage: Who?

Large-scale incidents, including MTFAs, have repeatedly shown to be disorganised, and it is likely that the first medical responders will be drawn into providing care to casualties that they first encounter (rather than initiating systematic triage). As soon as effective command, safety, communications, and scene assessment have taken place an effective triage system should be implemented. NARU guidance dictates the use of two-person triage teams to rapidly; triage casualties, apply triage labels, keep a casualty record, and perform a limited number of lifesaving interventions.

An underlying principle of triage is that it must be rapid, simple, and reproducible. A triage system should allow any pre-hospital provider to undertake primary triage; with appropriate training this could be extended to Fire and Rescue Service, Police, and military personnel.

Subsequent pre-hospital triage is likely to be undertaken by designated personnel, for example a Triage Officer. Utilising these specifically trained personnel may allow a more detailed casualty assessment, for example by including anatomical injury and mechanism of injury in decision-making. These more complex triage processes aim to increase sensitivity and specificity, and therefore reduce over and under-triage, in order to better categorise patients. However, this secondary triage is more time-consuming, and requires a higher level of clinical experience, it is therefore not suitable for the initial clinical assessment.

On arrival to hospital senior medical staff will use a combination of physiology, anatomical injury, and clinical acumen to further prioritise patients for medical treatment. The differentiation of primary triage and secondary triage is explicit in some systems, and in the UK is described using the 'Triage Sieve' and 'Triage Sort' respectively; these are further explained in the next section.

7.3.3 Triage Outcomes

The purpose of triage is to categorise casualties on the basis of their clinical acuity. Traditionally, irrespective of the system used, casualties are allocated to one of three categories corresponding to their urgency, this is summarised in Table 7.1.

The priority 4 or expectant category exists for casualties who, even with maximal medical attention are unlikely to survive. This category is implemented at the discretion of the overall operational "gold" commander and is reserved for exceptional situations.

Existing UK doctrine states priority one (immediate) patients require life-saving interventions immediately (for example decompression of a tension pneumothorax), priority two (urgent) patients require intervention within 4–6 h, and that priority three (delayed) patients can receive intervention after this time.

Historically triage systems have been validated against injury scores, aiming to predict those sustaining major trauma and convey them to the most appropriate hospital. However, it is well recognised that the injury severity score and need for

Table 7.1 NATO and UK triage priorities

Description	T	Colour
Immediate	1	Red
Urgent	2	Yellow
Delayed	3	Green
Dead	Dead	White
Expectant	4	Blue

life-saving intervention do not correlate, and within a MTFA or major incident setting the latter (the need for intervention) is the more appropriate measure [6, 7].

Although it is recognized internationally that the priority one (immediate) casualty is one whom requires a life-saving intervention, the definition of 'life-saving intervention' has only recently been defined. Expert consensus defined these as being interventions required within 1 h (Box 7.2) [8]. Whilst consensus exists for the priority one casualty, there is currently no good understanding of the timing requirements for the less urgent clinical categories, priorities two and three.

Box 7.2 Consensus definition of Priority One defining life-saving intervention (adapted from Ref. [8])

1	Intubation for actual or impending airway obstruction.
2	Surgical airway for actual or impending airway obstruction.
3	Thoracostomy (needle/finger/tube).
4	Application of a chest seal (commercial/improvised).
5	Positive pressure ventilation for ventilatory inadequacy.
6	Application of a tourniquet for haemorrhage control.
7	Use of haemostatic agents for haemorrhage control.
8	Insertion of an intra-osseous device for resuscitation purposes.
9	Receiving uncross-matched blood.
10	Receiving ≥4 units of blood/blood products.
11	Administration of tranexamic acid.
12	Laparotomy for trauma.
13	Thoracotomy or pericardial window for trauma.
14	Surgery to gain proximal vascular control.
15	Interventional radiology for haemorrhage control.
16	Application of a pelvic binder.
17	ALS/ALS for a patient in a peri-arrest/cardiac arrest situation.
18	Neurosurgery for the evacuation of an intra-cranial haematoma.
19	Craniotomy/Burr hole insertion.
20	Spinal nursing for a C1-3 fracture.
21	Administration of a seizure-terminating medication.
22	Active/passive rewarming for initial core temp <32 °C.
23	Correction of low blood glucose.
24	Administration of chemical antidotes.

7.4 Current Triage Systems

7.4.1 Primary Triage

There are multiple different triage systems in use internationally:

The UK currently employs the New Triage Sieve, commissioned by the National Ambulance Service Medical Directors Group in 2013 and delivered by the National

Table 7.2 A comparison of triage systems

Method	First assessment	Second assessment	Third assessment	Fourth assessment	Fifth assessment
START	Walking?	Breathing? Rate > 29	Palpable Pulse?	Obeys commands?	Catastrophic haemorrhage
Care-flight	Walking?	Obeys commands?	Breathing? Palpable radial pulse?	–	–
New Triage Sieve	Catastrophic haemorrhage? *(apply tourniquet)*	Walking?	Unconscious?	Breathing? Rate <10/>30	Heart rate>120, or capillary refill >2
UK Military Sieve	Walking?	Catastrophic haemorrhage? *(apply tourniquet)*	Breathing? Rate <10/>30	Heart rate >120	Unconscious?
Modified Physiological Triage Tool	Walking?	Breathing rate <12/>22	Heart rate ≧ 100	Glasgow coma scale < 14	–

Ambulance Resilience Unit (Fig. 7.1). The New Triage Sieve is an adaptation of the MIMMS triage sieve, and uses rapidly identifiable casualty characteristics and physiology to allocate priorities. The first action is to apply a tourniquet to catastrophic haemorrhage, this automatically makes a casualty P1. This is followed by identifying those with no injuries, signposted to a survivor reception centre and assigning the walking wounded P3 status. Subsequent assessment of airway, consciousness, respiratory rate, and circulation sieves casualties into dead, T1, and T2 categories. This system recognises that clinicians use the <C>ABC paradigm day-to-day, which starts with 'catastrophic haemorrhage' and therefore should use the same system during a major incident. This is in contrast to the UK military sieve, which starts by differentiating walking casualties as injured or not injured, followed by a similar assessment to that of the New Triage Sieve (Table 7.2).

The 'Simple Triage And Rapid Treatment' (START) triage system was developed in the US in 1983 and is designed for use by rescuers with basic first aid skills. START allocates priority categories, immediate, delayed, minor and dead, in a similar method to the UK military sieve—starting with identifying walking casualties. START includes an assessment of catastrophic haemorrhage, airway, breathing, circulation, and mental status—those that cannot obey commands are priority one 'immediate' (Table 7.2).

In 2001 the Care Flight triage system was introduced with the intent of standardising the initial health response to a major incident in Australia. This system is notably different to UK systems and START in that it does not require any physiological monitoring. Care Flight triage starts with assigning the walking casualties a delayed priority, followed by assessment of ability to obey commands, breathing, and radial pulse presence. The simplicity of this system means it is rapid, and suitable for casualties of all ages (Table 7.2).

A number of studies looking at triage tool performance both within a trauma registry and retrospectively following a major incident, have demonstrated that existing triage tools have poor performance at identifying those in need of a life-saving intervention [9, 10]. Within a civilian trauma registry dataset, all triage tools demonstrated poor sensitivity, corresponding to an inappropriately high rate of under-triage and thus failing to identify those in need of life-saving intervention. However, despite low sensitivity, all triage tools had in excess of 90% specificity, yielding a very low rate of over-triage [11].

7.4.2 Secondary Triage

Triage is a dynamic process, and as previously stated should be repeated at each stage of the casualty's transition from scene to hospital. This process serves not only to alert the healthcare provider to subsequent deterioration, but also to assess any response from treatments already given.

Within both the UK military and civilian setting, a formal secondary triage assessment, using the Triage Sort is undertaken, again allocating the casualty to one of three categories. Existing major incident doctrine suggests that secondary triage should be performed when the situation permits.

Based on the Revised Trauma Triage Score, the Triage Sort uses a ranking system to provide an additional assessment of the casualty's physiology. Unlike the Triage Sieve, this includes a systolic blood pressure measurement and an assessment of conscious level using the Glasgow Coma Scale (Fig. 7.2).

Whilst the aim of the Triage Sort is to further refine the triage decision, evidence from military studies suggest that it is no better than existing primary triage methods at predicting the priority one 'immediate' casualty [12].

The use of senior clinicians' gestalt can be considered an additional form of secondary triage; not only has it been used in the past, but in addition, features as the final step in the Triage Sort. Methodologically however, it is not a protocolled assessment and is not only dependent on the resources available at the incident, but also the experiences of the clinician involved. Whilst difficult to quantify what is essentially a qualitative process, Israeli experience of senior clinician gestalt demonstrated only 50% sensitivity for predicting severe injury [13].

7.4.3 Casualty Labeling

Once a casualty has had a triage category assigned, there is a need to both differentiate their category from others and to identify that they have been triaged. The labeling system used needs to be dynamic to changes in the casualty's condition, be easily attached to the casualty, weather-proof, and ideally allow unique numbering as well as an area for concise medical notes.

The cruciform card and the Smart Tag system (commonly used in UK civilian and military settings respectively) both allow re-folding of the same card to change

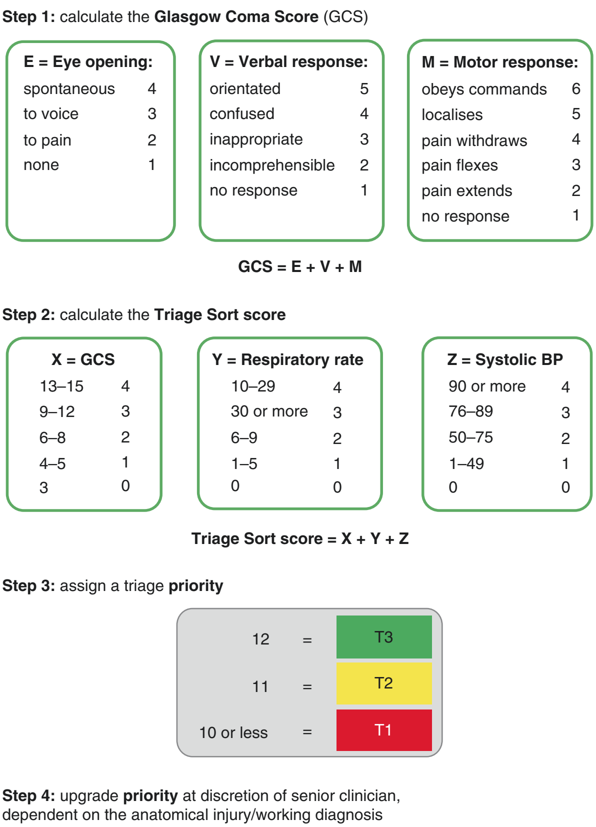

Fig. 7.2 Triage Sort—clinical guidelines for operations (Joint Services Publication 999 October 2012, crown copyright)

a triage category, while also including space for brief medical notes as well as a unique numbering system.

Not all methods of triage labeling include a label for the priority four, expectant category. If the expectant category has been authorized by the senior Gold command, those performing triage must be aware of their local procedure of how to identify such casualties.

7.5 Triage Systems Research

There is increasing evidence to demonstrate that existing triage tools have poor performance at predicting those in need of a life-saving intervention, the priority one (immediate) patient [9, 14]. The development of an effective triage method is therefore an important research priority in improving trauma care during a major incident.

In an ideal setting, like any diagnostic test, the triage method utilised will have both 100% sensitivity and specificity. However in practice, the optimal performance of a triage tool lies in the balance between sensitivity and specificity, correlating with rates of over and under-triage. Whilst an over-triage rate of 65% was tolerated following the London 7/7 bombings [15], this level of over-triage may well overwhelm a more rural setting with fewer healthcare facilities immediately available.

Guidance currently exists for measuring the performance of field triage, a process that utilises a combination of anatomical, mechanism, physiological and clinician gestalt assessments. For the field triage process, both the American College of Surgeons (ACS) and the Centers for Disease Control (CDC) suggest that tolerable thresholds are a rate of 5% under-triage and 35% over-triage. For the major incident setting, the ACS simply state that both under and over-triage should be kept to a minimum [16, 17].

The New Triage Sieve adopted by the UK follows the <C>ABC paradigm (Fig. 7.1). A review of patients presenting to the Royal London Hospital following the 7/7 London bombings demonstrated only three patients with injuries that would be consistent with requiring tourniquet application [18]. Although it was noted at the coroners inquest that make shift tourniquets were used by police who enter the scenes in the early phases [19]. In comparison, the experience from the 2015 Paris MTFA clearly supports this addition to the New Triage Sieve [4]. The likely requirement for controlling catastrophic haemorrhage will be dependent on the mechanism of the major incident (e.g. London 7/7 vs Paris MTFA) and the injuries sustained. It is unlikely to be required in all major incidents, but the concept of a simple life-saving intervention (if required) incorporated within a triage algorithm is sensible and is unlikely to grossly delay the triage process.

Work within the UK military has been undertaken to identify the optimum physiological thresholds for identifying those in need of life-saving intervention [20]. Derived specifically for this purpose, the physiological parameters within the Modified Physiological Triage Tool (MPTT) have been optimised to predict the need for life-saving intervention. Within both a military and civilian environment this has the greatest sensitivity at identifying the priority one patient. However this comes at the expense of a high rate of over-triage, although within a civilian setting this was found to be comparable to that observed following 7/7.

An initially high level of over-triage should be accepted at a major incident, as without this, large numbers of genuine priority one patients are likely to be missed. Once the casualty has been removed from the ‘front line’ of the incident, to a more permissive area, a secondary triage process, which yields a reduced rate of over-triage can be undertaken in order to refine the casualty’s category.

The existing method of secondary triage, the Triage Sort, performs poorly in this role, further research is required to optimize the secondary triage process. Early military studies have shown that the use of the Shock Index (HR/SBP) shows improved performance over the Triage Sort at predicting the need for life-saving intervention [12]. From UK civilian studies it is observed that the groups most frequently under-triaged are those sustaining injuries to the thoracic region. By using a combination of physiological and anatomical assessments, similar to that observed in the field triage process, it is likely that the secondary triage process can be improved considerably.

Providing a modified two-tiered triage approach like this to a major incident will reduce the overall over-triage rate of an incident and reduce the critical mortality that has previously been associated with over-triage.

7.6 Summary

The concept of triage in clinical practice arose from the contingencies and demands of armed conflict. In modern times triage is practiced routinely in most healthcare settings, and exceptionally in response to major incidents and MTFAs. If simple and effective to use, regularly exercised and widely understood, triage systems ensure the optimal care of a group of casualties in times of limited resources. Triage systems should continue to be developed in response to evolving threats in order to fulfill the underlying principle—to give the right patient the right care, at the right time, and in the right place.

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Prehospital Management of Ballistic Injury

8

Ravi Chauhan and Damian Keene

8.1 Introduction

The pre-hospital care of the ballistic casualties can be considered as having two key intertwining parts; management of the casualty and management of the scene. Managing the casualty is based upon a reproducible systematic approach to treatment, tailored to the level of tactical threat. Whilst care of injured casualties is always the first priority of health care providers, the tactical situation takes primacy over the medical needs of the casualties. It is important to understand that pre-hospital environments are extremely dynamic. Understanding the tactical threat at all times is key to determining the degree of care that can be delivered at any stage.

8.2 Scene Management

8.2.1 Initial Approach and Communication

Scene management at a major incident can be extremely complex. Following a hospital bombing in Belfast in 1991, the concept of "Major Incident Medical Management and Support" (MIMMS) was developed [1]. At that time, it was recognized that medical responders had no standardized approach to a major incident. MIMMS gave a

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Fig. 8.1 Initial MIMMS approach to scene management [1]

Command and Control

Safety

Communication

Assessment

Triage

Treatment

Fig. 8.2 THREAT acronym for mass shooting scene management [3]

Threat suppression

Hemorrhage control

Rapid
Extrication to safety

Assessment by medical providers

Transport to definitive care

framework to base major incident management upon (Fig. 8.1). Whilst MIMMS is the NATO standard for major incident management on military operations, it is only used by the ambulance service within UK civilian practice. Further learning from terrorist incidents has identified that delays in casualty treatment and evacuation have occurred due to poor communication between emergency services with each working effectively in isolation [2–4]. In the UK this has led to implementation of the Joint Emergency Services Interoperability Programme (JESIP). This involves fire, police and ambulance services training alongside each to improve on scene communication and to better understand each other's capability.

A similar programme has been developed in the US; a concept called 3 Echo, "Enter, Evaluate and Evacuate" which looks at a streamlined method for extraction and administration of life-saving haemorrhage control to marauding terrorist fire arms (MTFA) attacks [5]. The main principles of this framework are improved communication between services, a shared goal of early identification of casualties by the first wave of law enforcement and establishing safety corridors for evacuation. Instead of clearing large geographical areas such as an entire school, corridors of safety are established as a means of early access too and evacuation of casualties even before the attack has ended.

In 2013 a US Consensus group was tasked with identifying ways to improve outcome specifically in active shooter incidents. The acronym THREAT was created to highlight the key messages and actions on pre-hospital mass shootings (Fig. 8.2) [3].

Irrespective of the existence of different approaches it is vital that only one approach is used at a single incident to ensure a coordinated and rapid response. All systems have been developed with the same key themes following on from reviews of previous incidents; these themes will be discussed below.

8.2.2 Command and Control

Classically major incidents have been laid down in a layered system (Fig. 8.3). The area of immediate danger around the incident is the first area cordoned off. This is known as the inner cordon and provides a line between the area of danger immediate to the incident and an area of safety outside it. This cordon allows command and control of the immediate scene, with casualties leaving and emergency personnel entering via one point. An outer cordon is then established that gives emergency personnel an area to operate within to conduct assessment, treatment and transport of casualties, this normally occurs at a casualty clearing station. This is a fixed facility that has multiple medical personnel and can allow the conduct of more advanced interventions such as rapid sequence induction of anaesthesia.

8.2.2.1 Is Marauding Terrorist Fire Arms (MTFA) Attack Just Another Major Incident?

Management of an MTFA incident has many basic themes in common with other major incidents. Nonetheless, they have some unique differences that make implementing a major incident plan difficult and treatment of casualties challenging.

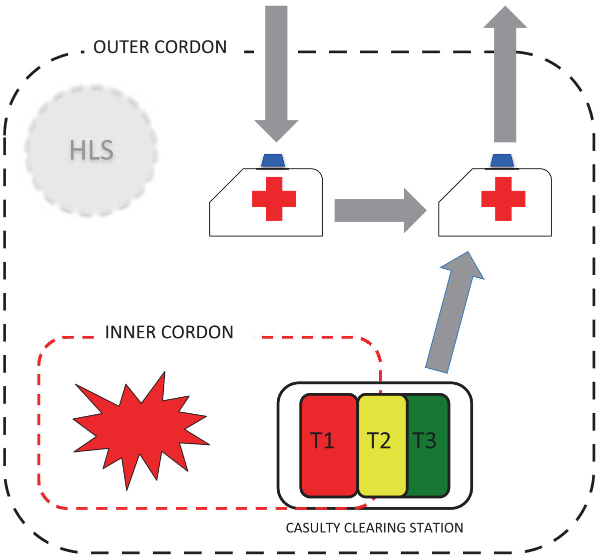

Fig. 8.3 MIMMS scene layout

The Utøya Island shooting in 2011 highlighted the delays that can occur if medical personnel wait for the risk at scene to be completely eliminated. Limited inter-agency communication and a persisting threat by the shooter resulted in emergency medical staff unable to get onto the island and access casualties for 2 h and 7 min [4]. Once secured, casualty management followed the MIMMS principles. The island provided a natural cordon allowing the setting up of a casualty clearing station in a place of safety although this was subsequently relocated to allow better helicopter access for evacuation.

In Paris, a number of mobile gunman created multiple zones of casualties (not disregarding the suicide bombers), each zone potentially overlapping and each a major incident in its own right (Fig. 8.4) [6]. Dynamic incidents such as this can cause difficulty in setting up true inner and outer cordons. In this kind of instance setting up a casualty clearing station will not be possible as its safety can be compromised. Having a fixed point in an MTFA were the incident is not geographically constrained may prove ineffective. In this instance a casualty clearing point, a location for rescuers and evacuation assets to rendezvous, can be used for rapid casualty evacuation with treatment on route to hospital.

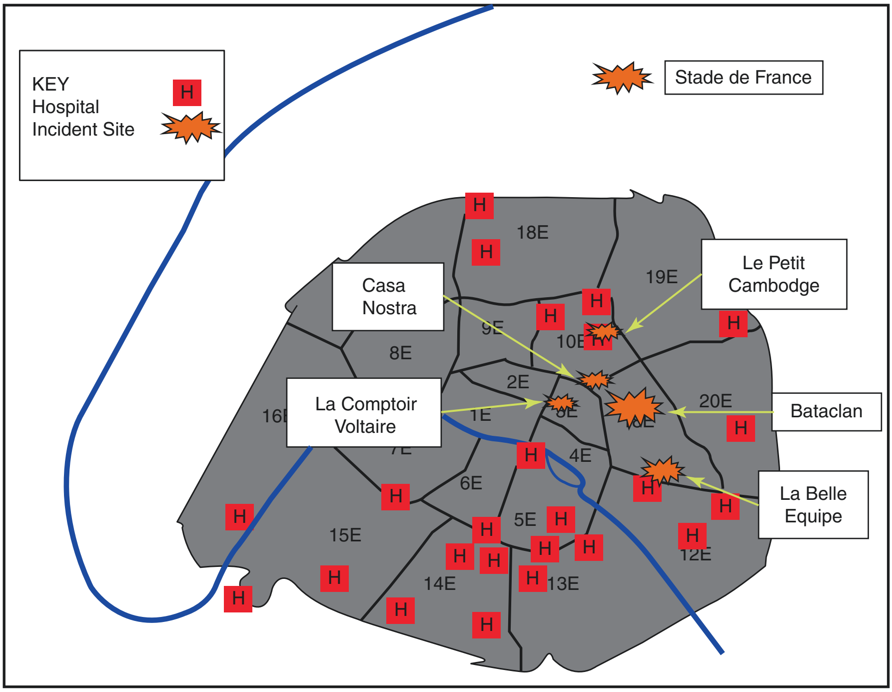

Fig. 8.4 Location of multiple simultaneous incidents from the 2105 Paris attack [6]

8.2.3 Safety

The first rule of any pre-hospital incident is safety. This includes all emergency services personnel, the casualty, and the scene. In the initial phases it may not be possible to differentiate an MTFA from an isolated firearms incident. Emergency services personnel need to be vigilant without being overly cautious about entering the scene due to any residual risk.

Following the Cumbria (UK) shootings in 2010, an official government report found significant delays in reaching casualties, as medical personnel did not approach the scene due to the threat from the gunman whose location remained unknown [7]. It concluded that “During an incident such as this, it is very unlikely that the police will be in a position to guarantee that the scene is safe; it would be reasonable for the public to expect the ambulance service to attend scenes where there is a residual risk” [7]. Similar conclusions have been reached in the US following MTFA incidents [4].

This has led internationally to the development of Tactical Emergency Medical Support (TEMS) [2]. In the UK they are termed Hazardous Area Response and Incident teams (HART). These are unarmed medical personal with tactical training/awareness wearing appropriate PPE to enter areas still under attack or in the close vicinity [2].

8.2.4 Assessment

Rapid initial scene assessment is vital to ensuring a timely emergency response. This information needs to be communicated in a clear and logical way to avoid error especially in what is likely to be a very stressful situation. In the UK the mnemonic METHANE is used both as a guide to gather necessary information, and then to distribute it (Fig. 8.5). This communication tool can be used repeatedly to update the information already provided. Not all information needs to be available prior to sending a METHANE report, in the initial instance it may simply be a location and casualty estimate that is sent in order to initiate a rapid response from the emergency services.

M - My name/call sign/reference. Major incident standby or declared

E - Exact location–grid reference if possible

T - type of incident–chemical, transport, radiation

H - Hazards

A - Access/egress

N - No of casualties and severity

E - Emergency services on scene or required

Fig. 8.5 METHANE mnemonic

8.2.5 Triage

The aims of triage are to prioritise the needs of a large number of casualties for treatment and evacuation to maximise patient survival. The commonest form of triage involves a physiological system assessing vital signs in a stepwise manner to give a triage category. It has been identified in MTFA/ballistic incidents the rates of over triage are as high as 67% but also that seriously injured casualties can easily be missed [2]. There is anecdotal evidence from the attack at Utøya Island in Norway that allowing a more 'loose' triage system based on senior clinician assessment may overcome some of these issues [4].

The UK has now adopted the National Ambulance Resilience Unit (NARU) triage approach based on that of the UK defence medical services. This takes into account the early recognition and treatment of catastrophic haemorrhage which is the commonest cause of preventable battle field death [8]. The details of triage are covered in further detail in Chap. 17.

8.3 Medical Management

Medical teams who attend incidents of ballistic trauma may find themselves providing care in a tactically hostile environment. In an MTFA a direct threat may still be present as medical personnel reach the first casualties, this is classed as a non-permissive environment (hot zone). As the threat reduces, either by moving the casualty or removing the threat, the environment is classed as semi permissive (warm zone). Care within these settings is described by the British Military as Care Under Fire (CUF) and Tactical Field Care (TFC) respectively [9]. Once the threat is completely removed the scene is deemed permissive and normal scene management can apply.

These environments are not discreet but are part of a spectrum. Medical care can be delivered at any point on the spectrum but is far more limited in the non-permissive environment. Care at each stage is based on the same <C>ABC approach, Catastrophic haemorrhage, airway, breathing, and circulation with increasingly advanced interventions and support performed the more permissive the environment. It is important to note that environments do not always become increasingly permissive and that even in semi-permissive areas an increased level of threat can arise at any time.

8.3.1 The Non-permissive Environment

8.3.1.1 Care Under Fire (CUF)

A non-permissive environment implies that either the medic or the casualty is under a direct threat. The risks range from being under direct fire or within range of possible explosive devices. It is not a place in which to deliver medical care. UK military treatment at this stage is initially limited to control of catastrophic haemorrhage and addressing airway obstruction. The use of tourniquets to control haemorrhage from the limbs and the prone position to improve airway opening and allow postural drainage of any blood can both be rapidly applied and are self-sustaining. The primary role of those delivering care at this stage is likely to be overcoming the attackers or rapid casualty evacuation. The need for this approach in civilian MTFA incidents is well recognised [3]. All emergency services personnel should be capable of controlling external haemorrhage [2, 3].

8.3.1.2 Buddy-Buddy or Self-Aid

In military systems, there is one step prior to CUF it is delivered by the casualty themselves if able (self-aid), or a fellow soldier (buddy-buddy aid). This has been identified as one of the key interventions that has likely lead to improved military casualty survival [10]. There is growing consensus that members of the public should be trained to assist in these rare occurrences [11]. Within the UK the '*citizenaid*' programme has been developed to educate members of the public in ways to 'self-help' in an MTFA. This includes advice on improvised tourniquet use and haemorrhage control [12].

8.3.2 The Semi-Permissive Environment: Tactical Field Care

As the threat decreases the environment is deemed to become semi-permissive, allowing more involved medical care to be undertaken or tactical field care (TFC). It is performed once the immediate threat is removed: this may be by suppressing the attackers or evacuation to cover; thus, providing a semi-permissive environment. This is not a fully permissive environment and care is still limited to that required to ensure safe onward evacuation.

The line between CUF and TFC is not distinct, they are, in fact, the two ends of a continuous spectrum that involves the delivery of clinical care with continuous tactical risk assessment.

Tactical field care involves a rapid assessment following the <C>ABC approach with each part addressed in turn, this is known as 'vertical resuscitation'. A systematic approach is employed to reduce the risk of becoming distracted by overt injuries and ensures time-critical injuries are identified first. Other life threatening injuries such as open or tension pneumothorax can be identified and treated at this stage. In an MTFA this may not occur until loaded onto an ambulance for evacuation.

8.3.3 The Permissive Environment

A permissive environment is a safe environment. There will be access to the full range of equipment and resources available in the pre-hospital setting. This includes advanced analgesia and Rapid Sequence Induction (RSI) of anaesthesia. This is most likely to be a fixed location such as a casualty clearing station. Despite the availability of such interventions casualty evacuation should not be delayed. In the attack on Utøya island only two casualties received RSI despite a relatively long evacuation time [4].

8.4 Key Medical Interventions

8.4.1 <C>ABC

It was recognized that haemorrhage was the commonest preventable cause of death amongst military casualties with ballistic injury. This lead to a paradigm shift in treatment priorities with catastrophic hemorrhage taking precedence over airway [13]. This approach has now been adopted for the management of all trauma victims. Care at any point is based on the <C>ABC approach but with increasingly advanced interventions and decision-making becoming available further down the chain.

8.4.2 Haemorrhage Control

This is an area of pre-hospital care that has undergone considerable research and innovation. Haemostatic agents have been developed that aim to stem blood-flow through the accelerated promotion of clotting. The development of these agents has its origins in the second Gulf War during which time there were a high number of soldiers that died from uncompressible massive external hemorrhage [14]. Although a number of commercial products are available they can be broadly divided into factor concentrators, mucoadhesive agents and procoagulant supplimentors. CELOX™ is one of many available topical hemostatic dressings that have been developed as a consequence of the recent conflicts. It contains chitosan, a structural element of shell-fish exoskeleton that increases the speed of clot formation. This is particularly useful in control of junctional bleeding where tourniquets application is not possible.

A study in 2013 compared some products and standard, unmediated, gauze bandage, showing that that standard gauze was faster to pack with no difference in haemostatic success or blood loss [15]. Since then there has been significant further development of these agents with consensus supporting their use [3].

In a semi-permissive environment, hemorrhage control follows a step-wise approach (Fig. 8.6). Ultimately all medical treatment will be dictated by the tactical situation. Even though an injury may be amenable to direct pressure if the tactical situation requires, a tourniquet may be applied as it is most likely to guarantee rapid control of bleeding [16].

In order for this approach to be successful, the haemorrhage needs to be amenable to compression. Chest injuries and abdominal injuries as well as some junctional injuries (groin and axilla) may not be controllable in this manner. These casualties require rapid recognition and evacuation to a surgical facility to allow surgical control [17].

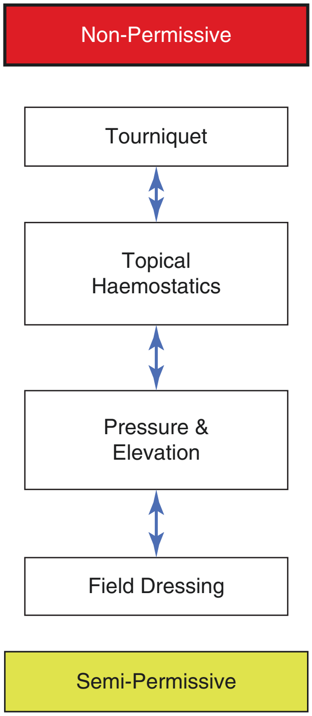

Fig. 8.6 Haemostasis ladder—steps can then be 'reversed' as the tactical situation permits

8.4.3 Cervical Spine Control

Cervical spine immobilization is employed in the management of the blunt trauma casualty where clinical signs, symptoms, or the mechanism of injury lead one to suspect biomechanical instability in the cervical spine. The concern is that further movement will cause or aggravate a spinal cord injury however this concept is being increasingly challenged [18].

In penetrating trauma, this approach has been reviewed and practice changed. The faculty of Prehospital care (UK) consensus statement regarding spinal immobilisation advocates that penetrating trauma to the spine does not require immobilisation in the absence of overt neurological signs [19].

Where a penetrating injury has occurred alongside a blunt injury, for example the casualty shot in the neck and falls off a roof, then immobilisation may be necessary. In the context of an MTFA it is highly likely that spinal immobilisation would be inappropriate, it will reduce the mobility of the casualty and rescuers as well as use significant human resources.

8.5 Preparation

A systematic review by Turner et al. unambiguously linked disaster preparedness to a successful response [2]. A lack of familiarity and unpreparedness predisposes to confusion and delay. MTFA incidents in Minneapolis (2012) and Paris (2015) demonstrated how inter-agency training can lead to efficiency of both response and treatment. In Minneapolis the 3 Echo protocol training resulted in triage and evacuation of patients with reported unprecedented efficiency [5]. The Multi-disciplinary exercise that was conducted annually and on the morning of the Paris attack was key in the successful management and evacuation of patients [6]. Both incidents have clearly demonstrated the critical nature of inter-agency preparation and training.

Preparation focuses on both challenging the infrastructure within single agencies as well as multi-agency working. The aim should be to facilitate good communication alongside effective command and control to improve casualty outcome in unpredictable environments. The UK the Joint Emergency Service Interoperability programme (JESIP) exists to improve the way in which emergency services work together in when responding to a multi-agency incident by providing regular training on the principles of scene management [20]. Classroom based training is not adequate; regular inter agency simulated exercises are fundamental in ensuring a successful response [2, 6].

The introduction of Citizenaid in the UK has given members of the public some insight into such incidents and has empowered them with some skills that may prove lifesaving in a multi casualty setting [12].

8.6 Developments

Many of the developments in the field of pre-hospital care have been driven by combat experience in theatres of operations around the world. The focus of these developments has been wide ranging, however of particular use to pre-hospital practitioners has been the introduction of technologies and equipment that focus on treating the <C>ABC of the injured ballistic casualty.

A recent review of the cause of death in US active shooter events demonstrated that extremity injury with catastrophic hemorrhage is less common in civilian ballistic incidents [21]. The commonest cause of preventable death was deemed to be from isolated chest injury without significant bleeding, most likely due to the absence of body armour in the civilian environment. Despite the reduced number there are still casualties who benefit from tourniquet application [2, 6, 21]. This serves to highlight that, whilst learning from military incidents has led to some key changes, civilian injury patterns are not identical. Focus should move now towards studying these unfortunate events in order to better guide future treatment and management.

8.7 Summary

MTFA incidents whilst rare, continue to occur. In order to improve outcome a system needs to have pre-planned and practiced procedures in place. Early management of catastrophic haemorrhage is still the cornerstone of initial treatment in ballistic injury, empowering the public and all emergency service personnel to undertake basic techniques to stop compressible bleeding will hopefully lead to increased survival in the future.

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Emergency Department Management

9

Jason Smith

9.1 Introduction

The Emergency Department management of patients with ballistic trauma should include rapid assessment and life-saving intervention, followed by appropriate investigation and referral for definitive management depending on the haemodynamic status of the patient.

9.2 Preparation

Prior notification of the imminent arrival of a trauma patient is vital if an adequate and prepared response is to be initiated. Equipment should be prepared, personnel amassed and briefed, and theater and blood bank notified of the imminent arrival of the patient. Ballistic trauma should prompt the activation of a multi-disciplinary trauma team, the typical composition of which is described in Fig. 9.1. If the pre-hospital notification suggests a patient with life-threatening haemorrhage, additional personnel specifically tasked with the delivery of massive transfusion of blood and blood products through a rapid infusion device should be assembled. The team in attendance should be dressed in the appropriate protective equipment (including lead aprons). Equipment preparation should include the means to perform rapid sequence induction of anesthesia and intubation, chest decompression, and vascular access. Radiography should be present and prepared to perform a chest X-ray during the first few minutes of assessment (pre-loading X-ray plates if necessary).

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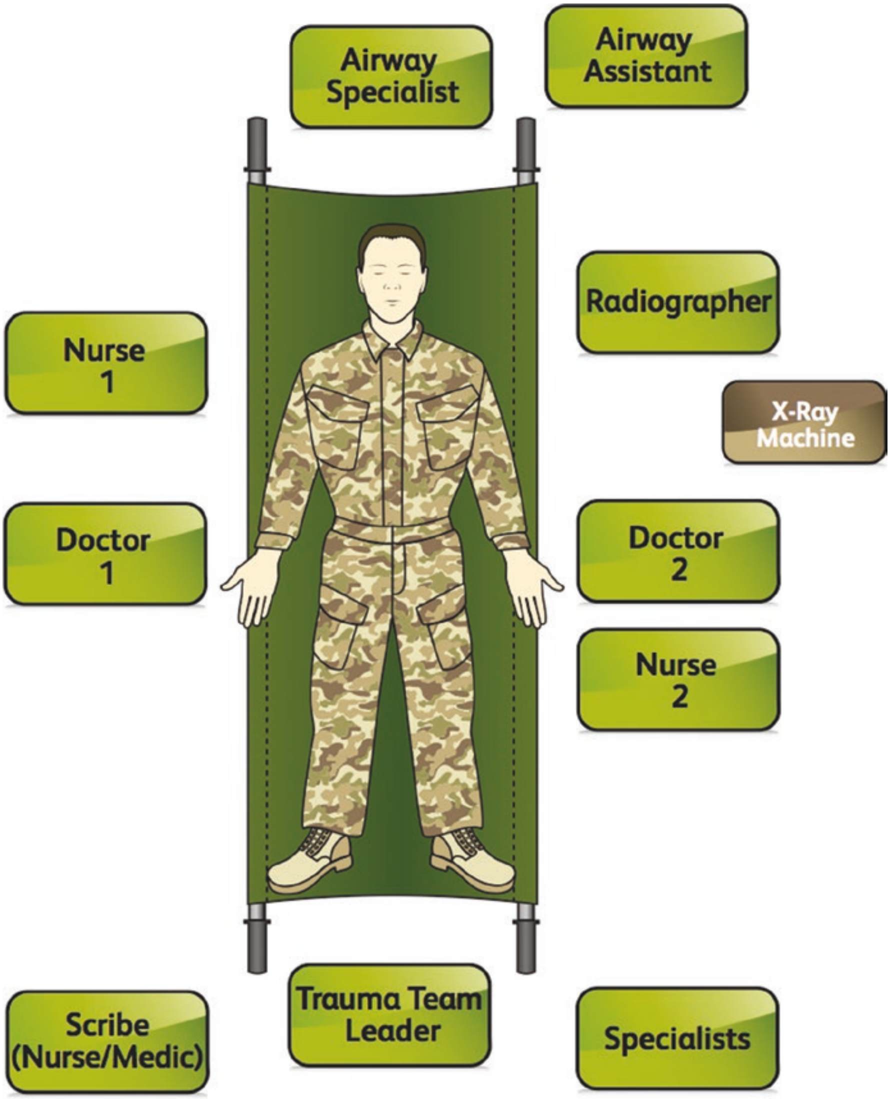

Fig. 9.1 A trauma team—layout of seven personnel around a resus bay (team leader, airway plus one, procedures plus one, survey, scribe) (Reprinted with permission from Hodgetts and Mahoney 2008)

9.3 Arrival

As the patient arrives in the resuscitation room, the trauma team leader should be easily identifiable. The whole trauma team needs to listen in to a brief handover from the pre-hospital team, prior to transfer from the ambulance stretcher to the resuscitation trolley. This occurs most easily if there is silence other than the person giving the handover. The handover should give a brief summary of events in an easily digestable format, such as the ATMIST handover (Table 9.1).

The only exception to this is if there is immediate life threatening instability such as ongoing cardio-pulmonary resuscitation or the requirement for definitive airway management. In this instance the patient is immediately transferred, the handover is then given whilst clinical treatment to address the immediate problems is commenced.

The patient then needs to be transferred from stretcher to trolley. This is followed by a primary survey including assessment and treatment of catastrophic hemorrhage, airway, breathing, circulation, and disability (Table 9.2).

In ballistic trauma the back of the patient must be examined early as part of the primary survey. It may be appropriate to examine the patients back during initial transfer to the ED trolley if a roll is performed as part of the transfer. If the patient is already on a scoop or vacuum mattress as part of their pre-hospital management examination of the back must not be forgotten.

Table 9.1 ATMIST handover

A	Age
T	Time of injury
M	Mechanism of injury
I	Injuries sustained
S	Signs—vital signs including pulse, respiratory rate, blood pressure and Glasgow coma score
T	Treatment—pre-hospital treatment administered

Table 9.2 Primary survey

<C>	Catastrophic hemorrhage (control of exsanguinating hemorrhage)
A	Airway (low probability of cervical spine injury with GSW)
B	Breathing (give high flow oxygen)
C	Circulation (with control of hemorrhage and circulatory access)
D	Disability
E	Exposure and control of environment

9.4 The Primary Survey: <C> ABCDE

Traditional trauma courses teach a vertical and sequential approach to assessing the trauma patient, starting with catastrophic haemorrhage, moving on to airway, breathing and then circulation. In reality, in the presence of a trauma team, this primary survey should happen horizontally or simultaneously, with the airway clinician at the head end assessing and managing the airway and administering oxygen, while the primary survey clinician assesses breathing, an assistant attaches monitoring, and intravenous access is gained by the individual nominated to undertake procedures. The radiographer should be moving in to perform a chest X-ray, and the team leader and surgeon making an initial assessment of whether or not immediate surgery is indicated. The operating theater staff need an update at this stage as to whether they need to prepare for the imminent arrival of a trauma patient.

Key questions during the primary survey are:

- Is there uncontrolled external hemorrhage?
- Does the patient require a definitive airway?
- Does the chest need to be decompressed?
- Does the patient have cardiovascular instability?

9.4.1 Is There Uncontrolled External Hemorrhage?

In the presence of continuing external haemorrhage, attention needs to be directed at controlling this by pressure and elevation, use of a tourniquet, sutures, or novel haemostatic agents. If control is not possible early surgical intervention is likely to be required the speed of which will be dictated by the patients physiological stability.

9.4.2 Does the Patient Require a Definitive Airway?

In the presence of airway obstruction, it may be necessary to secure a definitive airway. Indications for this are listed in Table 9.3. This is usually performed by rapid sequence induction (RSI) of anesthesia and intubation. In the presence of complicating factors such as an airway burn, or expanding neck haematoma, the use

Table 9.3 Common indications for tracheal intubation in ballistic trauma

Airway obstruction (absolute or impending)
Facial trauma
Expanding neck haematoma
Airway burn injury
Reduced conscious level including agitation
Requirement for anesthesia
Requirement for ventilation

of fibreoptic instruments, videolaryngoscopy or a surgical airway may be necessary. In the case of ballistic neck injury with bleeding into the oropharynx the use of videolaryngoscopy or fibreoptic scopes cannot be relied upon as the view may be obscured by blood.

Significant care needs to be taken when anaesthetising cardiovascularly unstable patients. The delivery of anaesthetic drugs combined with the increase in thoracic pressure from positive pressure ventilation can result in precipitous falls in blood pressure and cardiac arrest in hypovolemic patients. Fluid resuscitation should be commenced prior to RSI unless the airway is threatened by direct neck injury or airway obstruction. In this instance fluid resuscitation should occur simultaneously.

9.4.3 Does the Chest Need to Be Decompressed?

When assessing breathing, attention should be paid to symmetry, expansion, air entry, and external evidence of injury. Half of the chest is obscured in the supine trauma patient, as described earlier a log roll is essential to detect injury on the back in penetrating trauma. Physiological parameters including respiratory rate, pulse, blood pressure and oxygen saturation should be measured. In the presence of asymmetrical chest movement, reduced air entry and abnormal physiology, the patient may require urgent chest decompression for treatment of a tension pneumothorax. The classical signs of a tension pneumothorax (deviation of the trachea, engorged neck veins, hyper-resonance) are often not present in the spontaneously ventilating patient.

Decompression can be performed with a needle or cannula, placed into the second intercostal space in the mid-clavicular line, although this method is unreliable and often fails to resolve the problem. Definitive chest decompression by thoracostomy (making the hole through which an intercostal drain is inserted) is often necessary to relieve pressure. In a ventilated patient open thoracostomies can rapidly be performed if chest drains are not immediately available. This allows rapid reduction of the intrathoracic pressure particularly if the patient is haemodynamically compromised. Both are safe procedures if performed in the fourth or fifth intercostal space, just anterior to the mid-axillary line.

9.4.4 Is the Patient Shocked?

The next question is whether the patient is displaying signs of hemorrhagic shock. In the presence of shock from ballistic injury, the cause is almost always hemorrhage, and control of hemorrhage is therefore the immediate priority. In the meantime, vital organ perfusion should be maintained, although the absolute level of blood pressure (or other physiological target) that should be maintained is still the matter of some debate. A practical solution is to maintain consciousness, although some would advocate titrating intravenous fluid to the presence of a radial pulse or a systolic blood pressure of 80 mm Hg.

With regard to which fluid to use, there has been a move to the early use of blood and blood products in severely injured ballistic casualties. This should be given initially in a ratio of 1:1:1 (plasma, platelets and packed red blood cells) but can be tailored to individual requirements if near patient coagulopathy testing such as rotational thromboelastometry is available and bleeding is controlled, However, hemorrhage control must be the absolute priority.

9.5 Initial Investigations

In time-critical patients, only those investigations that will immediately alter management should be performed. Typically, for penetrating torso trauma, this will include a chest X-ray, collection of blood for cross-matching, and little else.

At the same time as blood is drawn, however, an initial venous blood gas will give useful information regarding blood pH, serum lactate, and base deficit, and blood should also be sent for a baseline full blood count, clotting profile, and electrolyte screen.

The role of focused assessment with sonography for trauma (FAST) in penetrating torso trauma is less convincing than in blunt trauma. The same principles apply, in that if there is free intra-peritoneal blood, and the patient is shocked, they will require surgery. FAST can be used to triage the body cavities for surgery.

9.6 Secondary Survey

It is particularly important in penetrating trauma that a full and thorough secondary survey is performed to identify wounds that may be entry or exit wounds. This includes a log roll to examine the back, and careful examination of the scalp, axillae, and perineum. Small wounds may be hidden among hair so dried blood needs to be cleaned off and the underlying structures examined.

9.7 Decision Making

Patients with ballistic trauma fall into two groups. They are either physiologically normal or abnormal. The abnormal group can be further subdivided into those in whom critical organ perfusion can be maintained, and those in whom it cannot. This final group need urgent surgery to control hemorrhage or they will die. This should not be delayed further and such patients should be transferred to the operating theater within a few minutes of arrival in hospital (Fig. 9.2).

At the other end of the spectrum is the patient with anatomical evidence of injury but no physiological disturbance. This patient can undergo further investigation in the form of X-rays, contrast-enhanced computed tomography (CT), or angiography as necessary. Somewhere between these lies the group of patients who respond to initial resuscitation, but have had at some time evidence of physiological disturbance.

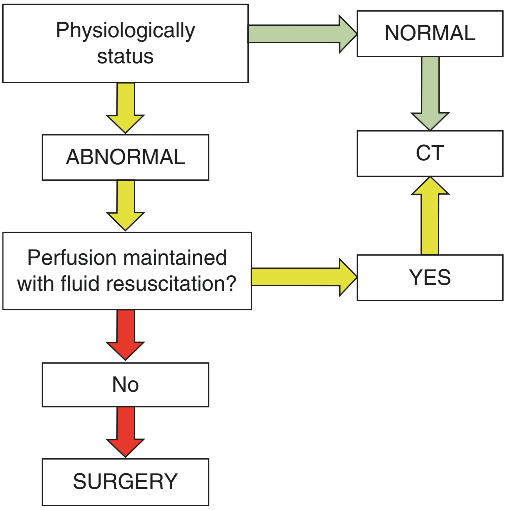

Fig. 9.2 Destination decision making in ballistic trauma

These patients will often require surgery, but there may be time to perform limited investigations such as CT or angiography to better inform the surgeon.

The decision as to the disposal of the patient and the time-critical nature of their condition needs to be made at a senior level, with appropriate senior surgical expertise to support it.

9.8 Handover

Adequate verbal and written handover of the key points are vital for seamless care of the trauma patient. In UK hospitals, the team leader in the resuscitation room will normally be an emergency physician, who will hand over responsibility to in-hospital clinicians as the patient leaves the emergency department. A clear delineation of responsibilities should be in place so there is no confusion. In an ideal world, trauma patients would be admitted under a named trauma surgeon who will oversee care and recruit the expertise of other specialties as necessary. Documentation should be clear and standardized to minimize confusion.

9.9 Considerations with Multiple Patients

As with a single patient preparation is the first key step. It is vital that every trauma hospital has a major incident plan that can be enacted in the event of a major incident (MI). The important factors that need to be addressed early are those of staff and resource availability. The main differences of a ballistic over other MIs will be the higher number of high priority casualties requiring volume resuscitation and early surgery. Access to both are likely to be limited especially in the early phases of an incident.

To overcome this triage of casualties entering the ED and early identification of those requiring urgent surgery is essential. It is unlikely that capacity will exist to take all those requiring surgery to theatre immediately. Prioritization by senior clinicians is essential.

O negative blood stocks are limited, the early use of O positive blood will be necessary in suitable recipients and an early switch to type specific blood. Both will help to minimize depletion of O negative stock. Early group and saves should ideally be one for all patients. Without a robust planned approach to patient labeling there will be an increased risk of ABO incapability reaction due to administrative error.

9.10 Summary

The management of the ballistic trauma patient requires a systematic approach to patient treatment and assessment. Pre-established systems need to be in place to allow urgent access to resuscitation and surgery to improve outcome in this severely injured group.

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Radiology and Ballistic Trauma

10

David Gay and Iain Gibb

10.1 Introduction

Imaging is now at the forefront of trauma care. The days of a limited CT sometimes hours after injury have been replaced by rapid imaging involving plain film, ultrasound and CT. There is now increasing evidence pertaining to trauma imaging with a proven reduction in mortality with the use of rapid CT [1].

This chapter aims to describe the uses of imaging in ballistic trauma which have been learned from years of civilian and military trauma experience.

The first part of the chapter is focused on the injured patient. The second part will describe the imaging strategies that will be necessary in a mass casualty situation.

This chapter will focus on:

- Describing a trauma imaging algorithm
- The CT traumagram protocol
- The uses of different imaging modalities in trauma
- Injury patterns and examples

10.2 Trauma Imaging Algorithm

When an injured patient arrives in the ED having been subject to ballistic trauma the focus is on rapid assessment allowing rapid treatment. The role of imaging is to identify life or limb threatening injuries and identify sources of bleeding. In a modern ED there should be access to plain film, ultrasound and CT. Plain film and

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ultrasound should be available at the bedside and CT should be as close to ED as possible.

The initial assessment of the patient involves concurrent activity. A radiographer should be prepared for a plain chest and pelvic X ray whilst the primary survey is conducted, lines are inserted, bloods are taken and the patient is potentially intubated. A chest X-ray early in this period can help rule out potential impending fatal thoracic injury.

What happens next depends on the stability of the patient. If the patient is stable and a CT is nearby a CT traumagram should be considered as soon as possible. If the patient is very unstable and is going to the operating room, an ultrasound of the chest and abdomen can be performed. This will identify significant free fluid in the chest, abdomen or pelvis.

Ultrasound can be accurate at detecting pneumothorax, haemothorax and abdominal fluid but it is very operator dependent. The role of ultrasound in trauma will be discussed in detail further on.

It is the view of the authors that ultrasound should never delay the CT examination as long as CT is readily available and the patient is stable enough for the transfer. This has been incorporated into the latest NICE guidance for trauma [2]. This states that ultrasound should not be performed if imaging with CT is readily available.

The trauma imaging algorithm is presented as Fig. 10.1. It should be noted that the ultrasound scan does not change the patient pathway. In the authors' experience as well as providing prompt FAST assessment for the ED clinicians one of the main

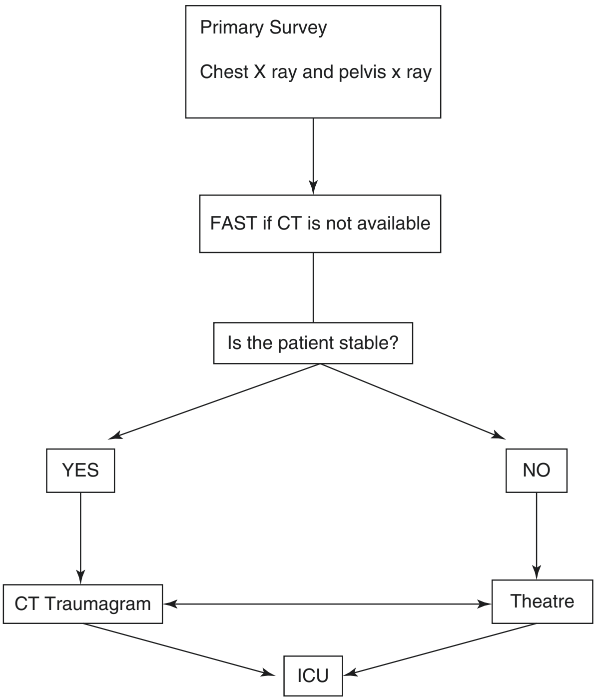

Fig. 10.1 Trauma algorithm. Note that the *arrow* between CT and theatre is a *double arrow* as some patients are scanned post or peri-operatively

benefits of performing ultrasound during the resuscitation phase is having a radiologist present in the ED to assist with further imaging and clinical decision making.

If a patient presents to a facility without CT then having a suitably experienced ultrasound operator is desirable. A radiologist or fully trained sonographer can image the abdominal viscera, the heart, the eyes and the pelvis. Sequential ultrasound can be of benefit looking for the progression of free fluid. Ultrasound of the optic nerve has been found to be accurate at detecting a raising intracranial pressure which could be lifesaving if a CT scan is not possible.

10.3 CT Traumagram

At the start of the Iraq war in 2003 CT imaging in trauma was essentially the same protocol as a staging scan for cancer. A non-contrast head scan was performed followed by an arterial phase scan of the chest. Then the patient was repositioned and a portal venous scan of the abdomen and pelvis was performed.

This protocol was slow as repositioning and different phases were time consuming. The contrast administration meant that arterial bleeding would be readily identified in the chest but not necessarily evident in the abdomen or pelvis.

With the advent of faster scanners with more slices and more advanced contrast injection systems a new protocol for trauma has evolved which has been used extensively in the military, both US and UK but has also been adopted in civilian trauma practice [3]. A non-contrast head scan is performed. This is then followed by a single scan from the base of skull to the pelvis, or the feet if there is lower limb trauma. This scan can be performed with a breath hold of 10–15 s. The key to this scan is the contrast timings. A dual phase scan is performed by injecting contrast at a slow rate for a number of seconds then the rate is increased just before the scan. This means that when the images are acquired the fast bolus of contrast is in the arterial system and the slow bolus of contrast is in the venous system. So for the same volume of contrast in less time the scan will identify arterial, portovenous and venous bleeding as well as enhancing the visceral organs to identify injury. This protocol is used to produce 3D vascular reconstructions to allow the surgeons to formulate plans rapidly pre-operatively when dealing with complex vascular injuries. An overview of this contrast protocol is shown in Fig. 10.2. This technique also reduces dose by avoiding repeat scans of anatomical areas to show the different phases of vascular enhancement.

This is a simple dual phase technique which is easy for less experienced radiographers to manage effectively and consistently. There was an initial learning experience for radiologists as the appearance of the spleen can appear heterogeneous on some studies. This should not be mistaken for visceral injury. Figure 10.3 demonstrates this appearance of the spleen.

A large multicentre study has recently looked at the timing of CT [4]. Injured patients (not just ballistic trauma) were split into conventional trauma imaging as described above or a CT before any plain film and before conventional trauma imaging. The findings showed no difference in hospital mortality.

	Head	Circle of willis to feet
Patient position	Head first	Head first
	Supine	Supine
Contrast	N/A	Omnipaque 300
Volume (mls)	90	50
Flow Rate (mls/sec)	1.6	3.5
Scan parameters		
Start location	Vertex	COW
End location	Base of skull	Pelvis/feet
Scan start delay (secs)	N/A	70
Scan type	Helical full	Helical full
Helical collimation	0.625	0.625
Scan FOV	Head	Large Body
Detector coverage (mm)	20	40
Rotation time (secs)	0.5	0.5
Pitch	0.531:1	1.375:1
Speed (mm/rotation)	10.62	55.00

Fig. 10.2 Contrast and scan parameters for a CT Traumagram

Kv	140	140
mA	300	80 - 610
Auto/Smart mA	No	Yes
Slice thickness (mm)	5	5
Recon algorithm	Soft	Standard
WW/WL	100/40	400/40
Additional recons		
Recon algorithm	Bone plus	Soft
	Bone plus	Standard
Thickness (mm)	1.25	1.25
	1.25	1.25
WW/WL	2000/500	100/40
	2000/500	400/40

CONTRAST VOLUMES AND RATES FOR PAEDIATRICS

Fig. 10.2 (continued)

Child Weight (Kg)	Contrast Volume	Venous Phase Volume	Venous Phase Rate	Arterial Phase Volume	Arterial Phase Rate
5	10	7	0.2	3	0.4
10	20	14	0.3	6	0.6
15	30	20	0.4	10	0.8
20	40	26	0.5	14	1.0
25	50	33	0.6	17	1.3
30	60	40	0.7	20	1.6
35	70	47	0.8	23	1.8
40	80	53	0.9	26	2.1
45	90	60	1.0	30	2.2
50	100	66	1.2	34	2.4
55	110	73	1.3	37	2.6
60	120	80	1.4	40	2.8
70	140	94	1.6	46	3.3

Fig. 10.2 (continued)

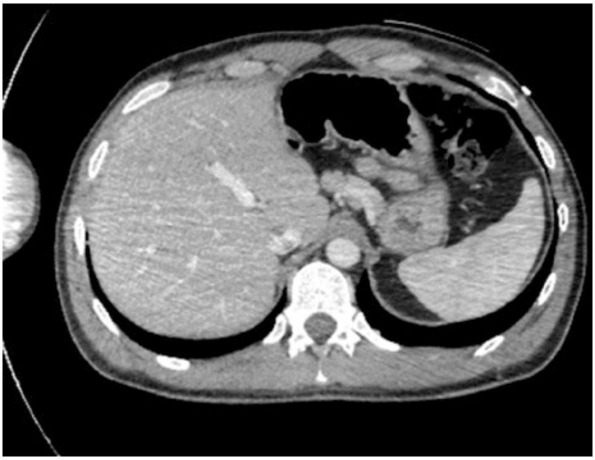

Fig. 10.3 A normal traumagram. Contrast is seen in the aorta and portal system with a slightly patchy enhancement pattern of the spleen

10.4 Use of Imaging Modalities in Trauma

10.4.1 Plain Film in the ED

Plain film of the chest is an essential part of the initial assessment. To rule out or in a large haemothorax or pneumothorax can lead to a life saving procedure before further assessment with CT or an urgent theatre transfer. Digital radiography (DR) X ray equipment can produce an almost instant image on a screen at the bedside (Fig. 10.4). ED staff can then assess the chest image for gross pathology without having to wait for a formal report. In an established ED the X ray equipment can be ceiling mounted to allow positioning at different resuscitation bays. In a field setting mobile DR equipment is now more lightweight with new versions having a battery power source allowing them to be carried in a backpack. The plain film is also useful in ED for tube and line positioning prior to moving the patient but with the advent of novel devices such as sternal buttons and intraosseous needles clinicians need to be aware of the appearances of these new devices to avoid misinterpretation of a sternal button for a ballistic fragment (Fig. 10.5).

Fig. 10.4 A mobile digital X ray

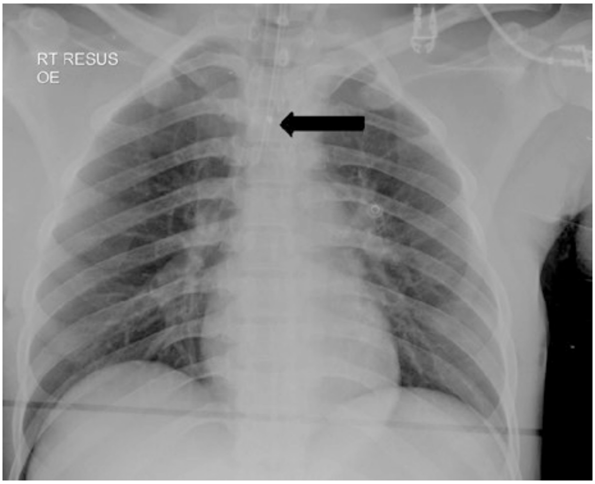

Fig. 10.5 Portable digital chest radiograph demonstrates an IO device in the sternum (*black* arrow)

What is more controversial is the need for a pelvic film. In major trauma it has long been part of the ED X ray series. It could be argued that if a patient is imminently going to have a CT scan the pelvic X ray is futile. There is no level 1 evidence to support either argument. In ballistic trauma a pelvic X ray should not slow the time to CT. In the event of ballistic injury pelvic instability is unlikely however the patient may arrive with a pelvic binder in situ. At this point clinical assessment is warranted and imaging following binder loosening or removal is recommended. This does not need to be a plain film but may be by CT if this is already planned or fluoroscopy.

10.4.1.1 Ultrasound in Trauma

Ultrasound is a versatile, mobile modality that has the advantage of not producing ionising radiation. In a trauma setting ultrasound can be used to assess for pneumothorax, haemothorax, cardiac activity, haemopericardium, visceral abdominal injury, IVC filling and free fluid. The disadvantage of ultrasound is that the results are heavily operator dependent. Only practitioners that are properly trained and regularly use ultrasound as part of their regular practice should perform ultrasound in a trauma setting.

The commonly used algorithm for ultrasound in trauma is the Focused Assessment Sonography in Trauma or FAST. This describes a four part assessment of the heart and pericardium, the right and left sides of the abdomen and the pelvis. The principle of FAST is detection of free fluid.

An unpublished audit by one of the authors compared FAST with operative findings or CT findings. One hundred and sixty seven patients were scanned that went on to CT or laparotomy. There were 24 true positives, one false positive, 154 true negatives and eight false negatives. This resulted in sensitivity of 95.3%, specificity of 99.4, and 94.7% accuracy for the detection of free fluid.

FAST need not be used if there is rapid access to CT. This is part of the latest trauma guidance from the National Institute for Clinical Excellence [2]. However in a remote setting without CT ultrasound may be the only imaging modality which is portable and can image the viscera. However ultrasound should be performed by trained, competent operators who regularly perform ultrasound whilst recognising there is suboptimal sensitivity even in experienced operator's hands [5].

Ultrasound has a reasonable accuracy for detecting pneumothorax by detecting the lack of moving pleura beneath the chest wall [6]. If CT is not available this could be used to detect a small pneumothorax not seen on the CXR. If CT is available and the patient is stable CT will be more accurate at detecting pneumothoraces.

10.4.1.2 Orbital Ultrasound

Ultrasound of the orbit is easy to do and more importantly easy to learn. Studies have proven that non sonographers can learn the technique very quickly [7]. There are two main uses for performing orbital ultrasound: foreign body detection and assessing rising intracranial pressure.

In ballistic trauma patients can be subjected to small fragments of ammunition, dirt, clothing or even biological tissue from other casualties. The eye is very sensitive to foreign body ingress and sight can be threatened with even small fragments. Assessing the eye involves acuity and visual fields but some departments cannot proceed to a slit lamp assessment. Ultrasound can detect small foreign bodies, lens dislocation, retinal haemorrhage and retinal detachment. Figure 10.6

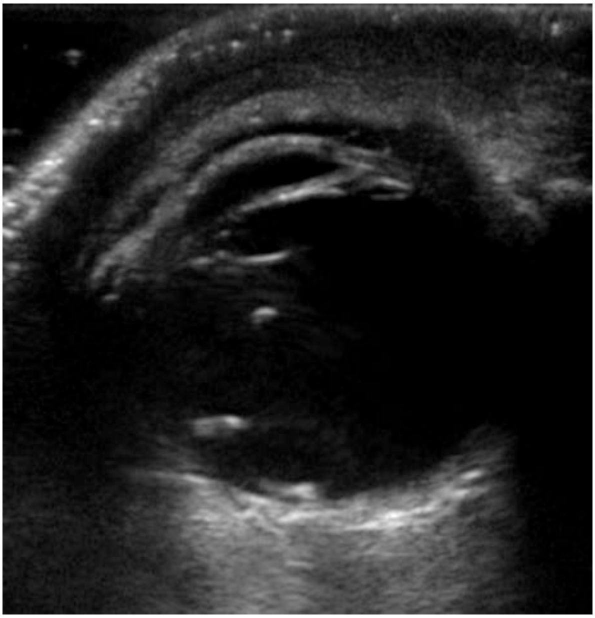

Fig. 10.6 Orbital ultrasound demonstrated multiple foreign bodies in the posterior chamber

Fig. 10.7 Optic nerve measurement

shows orbital ultrasound demonstrating multiple foreign bodies in the posterior chamber. A study performed during a military deployment with high numbers of eye injures found ultrasound to be more sensitive that CT at detecting foreign bodies [8].

Ultrasound of the orbit can readily see the optic nerve (Fig. 10.7). The nerve is covered in all three meningeal layers and is a direct link to the CSF. Any raised intracranial pressure can result in the diameter of the optic nerve increasing [9]. Studies have shown the measurement of the nerve has good inter and intra-observer variability [10]. There is also a normal range for the size of a normal optic nerve from 4 to 5.9 mm [10]. The main utility of this test is in a setting where access to a neurosurgeon or intracranial pressure monitoring is limited.

10.4.2 The Role of MRI in Ballistic Trauma

MRI has a very limited role in trauma imaging. The nature of ballistic injuries often results in metallic fragments being deposited in the patient. An MRI would either rip the fragment out of the patient or heat it up to make the scan unbearable for the patient.

If there are no retained metal fragments MRI is principally used for imaging the brain and spine. If a spinal cord injury is suspected MRI is more sensitive than CT for assessing the cord and nerve roots.

10.5 Injury Patterns and Examples

10.5.1 Junctional Injuries

The neck, axilla and groin are known as the junctional zones. These are very difficult areas to assess clinically and more difficult to operate on especially to control haemorrhage. CT has proven very useful at detecting life and limb threatening injuries to these areas. Accurate diagnosis often with triplanar reconstruction can help the surgeon plan an approach and plan surgery. See Figs. 10.8 and 10.9.

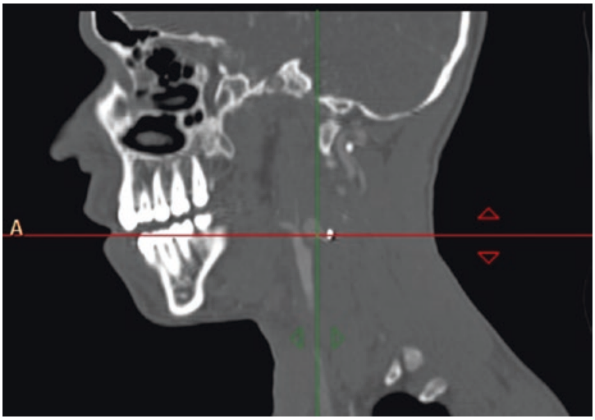

Fig. 10.8 A metallic fragment has resulted in a carotid pseudoanuerysm (confluence of *green* and *red lines*)

Fig. 10.9 Groin injury. A metallic fragment is just superficial to the uninjured external iliac vessels (*arrow*)

10.5.2 Foreign Bodies

Foreign bodies and the tract they have taken can be an important part of imaging ballistic injuries. The appearance of the IO device has already been described. In blast injuries the foreign body may be part of the patient's own anatomy or clothing (Fig. 10.10). Other organic or non-organic matter can be blown into the patient.

10.5.3 When Not to Operate

One of the most important decisions in trauma management is when not to operate. Will the procedure be more harmful to the patient than a period of observation? CT heavily influences this decision by being able to rule out active extravasation. The dual phase traumagram has improved the ability to detect arterial and venous haemorrhage.

If a trauma CT has ruled out active extravasation then either serial ultrasound or repeat CT can detect any increase in the amount of free fluid or haemorrhage.

Two case studies are detailed below (Figs. 10.11 and 10.12) where the CT findings together with the stability of the patient resulted in a decision being made not to intervene. Both patients were observed and neither required an operative procedure.

10.5.4 Pregnancy

The benefits and risks of CT and the associated high dose of ionising radiation with CT must be carefully considered in pregnant patients. Reducing the risks to the foetus by selective CT imaging or adjusting CT technique should be considered [11]. In ballistic trauma more harm will come to mother and child if CT is avoided or delayed particularly if the life of the mother is at risk.

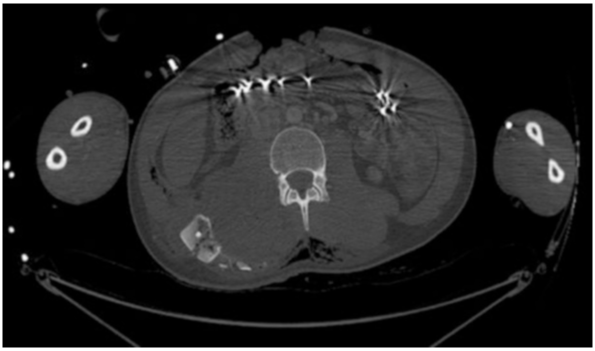

Fig. 10.10 A postoperative CT traumagram demonstrates the patient's talus in the peri-lumbar region

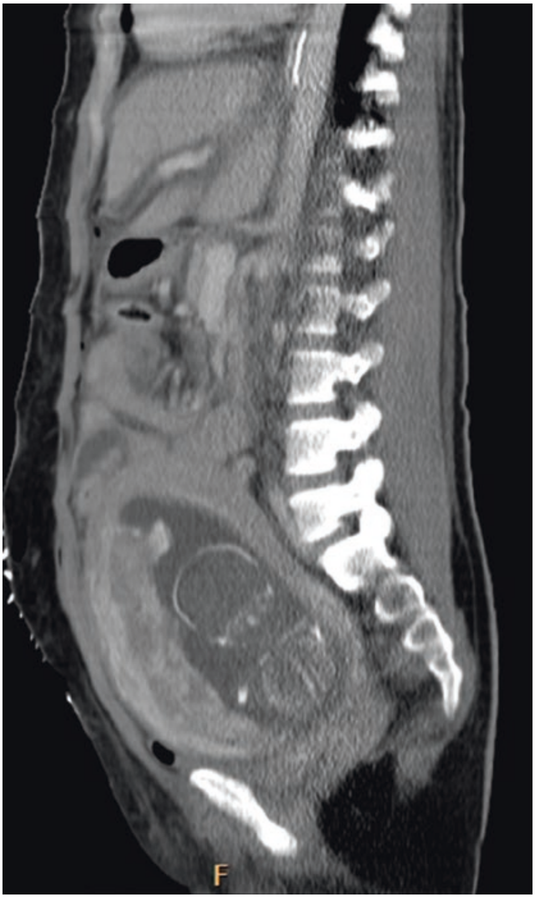

Fig. 10.11 Demonstrates a pregnant patient and foetus after ballistic abdominal injury. There is a small amount of fluid surrounding the liver but no active haemorrhage. No operative intervention was necessary and the patient discharged after a period of observation

Fig. 10.12 Demonstrates a metallic fragment in the posterior liver with a tract along the left lobe. No active haemorrhage was seen and no intervention was carried out due to the risk of bleeding if any tamponade was relieved

10.5.5 Paediatrics

Children's anatomy, their proportions and the relative elasticity of tissues, particularly in bone, differ from that of adults and for this reason must be considered separately. The NICE and RCR guidance for imaging children after trauma states that CT should be avoided unless there is serious injury especially of the chest as children rarely suffer from chest trauma [12]. However in ballistic trauma CT should be used to delineate injuries as there is no real alternative. What should be borne in mind is how much of the body to image. Consideration should be given for restricting the coverage of the traumagram on a case by case basis.

10.6 Imaging Multiple Casualties

A mass casualty scenario is defined by a number of casualties that overwhelm the accepting medical facility. In a small hospital this may be as low as two or three injured patients. The following is aimed at a situation involving many injured patients such as a Marauding Terrorist Firearms Attacks as seen in recent years in Mumbai and Paris. Considering how your department will function prior to such an event is the first step in being able to cope effectively with the situation [13].

Any large trauma centre should have a well rehearsed plan for such a situation. This should involve multiple agencies as well as all relevant departments within the hospital. Such a plan should be regularly rehearsed with table top and moulaged scenarios [13].

In the event of a major incident it is essential that each department such as ED, surgery, radiology and intensive care has a senior clinician who will coordinate personnel and equipment without being directly involved in clinical care. In radiology, inpatient and outpatient scanners may need to be emptied to accept casualties. Radiographers need to be briefed ideally before the first patient arrives. Reporting radiologists need to be stood up or, if the event is out of hours, called in to assist. A mixture of consultants and senior trainees should be used [13].

As the patients arrive a form of triage will be performed in the ED. FAST has a crucial role in this scenario to rapidly assess multiple patients for free fluid which adds objectivity and confidence to the triage. A radiology presence in the ED is essential for good communication. The senior clinicians coordinating the response should establish a priority list of patients for theatre or CT but this priority list will be fluid depending on the changing clinical conditions of patients. Good communication between these clinicians is essential to ensure priorities continue to be addressed. It is very easy in a busy stressful situation for staff to confuse patients even when using pseudonyms. Training and rehearsal in small teams will help avoid confusion, help develop local policies and build a team ethos which has benefits in day-to-day practice.

As patients are scanned rapid provisional reports should be given to the team looking after the patient with a full report issued as soon as possible. The coordinating radiologist should be aware of the findings. It may become apparent that CT results mean that a patient moves up or down the list for theatre. The coordinating radiologist should also maintain good communications with their ED, surgical and ITU colleagues. Only when every patient has been scanned and reported should personnel be stood down.

A hot debrief followed by a lessons learnt process is also vital for the development of a good service.

Occasionally an incident will be so large that patients may go to different facilities. It may also be possible for regional reporting with neighbouring hospitals on the same PACS assisting each other reporting trauma scans [13].

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Damage Control Resuscitation

11

Damian Keene

11.1 Introduction

The most common cause of death from all causes of trauma is haemorrhage. Within the UK it accounts 40% of all deaths from trauma and for 80% of deaths in the operating theatre [1]. It remains the leading preventable cause of trauma-related death and the most frequent reason for death within the first hour of injury [2]. A similar picture has been seen in the recent conflicts in Iraq and Afghanistan with the majority of deaths from ballistic and blast injury occurring within the first hour [3]. The most common preventable cause of death being from exsanguination due to uncontrollable haemorrhage [4].

In 2003 Brohi et al. demonstrated that traumatic injury leads to coagulopathy as part of the primary physiological response to trauma. Known as acute trauma coagulopathy (ATC) it results from the injury process itself and its severity is directly related to the severity of injury [5]. Our increased understanding of the physiology of trauma haemorrhage has been fundamental to the development of the current approach to its management. This is encompassed by the concept of damage control resuscitation (DCR). DCR describes a multi-faceted approach aimed at reducing mortality from trauma. The concept has evolved rapidly over the last decade based on military experience in Iraq and Afghanistan, leading to significant improvement in casualty survival from ballistic injury [6, 7]. It encompasses three main resuscitative strategies; permissive hypotension, haemostatic resuscitation and damage control surgery (DCS).

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11.2 History of DCR

In 1983 Stone et al. described the concept of truncated exploratory laparotomy. Surgery was stopped with the onset of clinically apparent coagulopathy [8]. This approach was further developed by Rotondo et al. in 1993 with the concept of 'damage control.' They described deliberately short and rapid surgical control of haemorrhage, damage control surgery DCS, followed by resuscitation aimed at correcting hypothermia, correcting coagulopathy and re-establishing normal cardiovascular parameters. A further definitive period of surgery then followed. This was opposed to waiting for the onset of clinical coagulopathy before termination of surgery. This approach demonstrated improved outcomes in the most severely injured [9]. Johnston et al. expanded the remit of damage control in 2001 suggesting both short pre-hospital times and early emergency department warming and volume resuscitation may be responsible for improved survival in their trauma network [10].

The onset of conflict in Iraq and Afghanistan further developed the concept of damage control; the severity and complexity of the casualties driving efforts to improve their management subsequently leading to significant reductions in mortality [6, 7]. Over this period, the multiple stages and interventions of trauma resuscitation have been unified under one concept, damage control resuscitation (DCR). The three key facets of DCR are [11, 12];

1. Haemostatic resuscitation (HR)
2. Permissive hypotension (PH)
3. Damage control surgery (DCS)

These are undertaken in parallel rather than sequentially as previously described (Fig. 11.1).

The UK military definition of DCR encompasses all care from point of injury through to post-surgical care on the Intensive Care Unit. The overall aim being 'to minimise blood loss, maximise tissue oxygenation and to optimise outcome' [11]. This has pushed the point of initiation of DCR even closer to the point of injury with

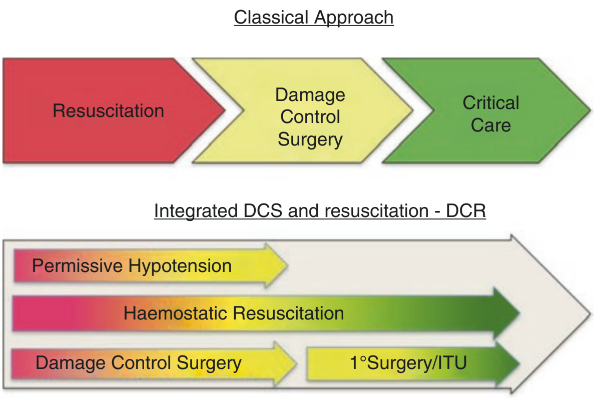

Fig. 11.1 Key aspects and timings of DCR

the advent of 'self or buddy aid.' This entails early use of tourniquets and haemostatic dressings at the point of wounding by the casualties themselves or fellow soldiers [13–15]. With the increased occurrence of MTFA incidents there is an increasing drive to educate and empower the public in the concept of self or buddy aid [16]. This is now being pushed forward to UK civilians as the 'citizenaid' programme [17].

11.3 Physiology of Trauma

11.3.1 The Lethal Triad

The lethal triad of hypothermia, coagulopathy and acidosis was first described in 1982 and is associated with increased mortality in trauma [18]. Shock due to blood loss leads to tissue hypoperfusion resulting in anaerobic metabolism and the generation of a metabolic acidosis. Prolonged acidosis, pH <7.1, is associated with multiple negative effects on coagulation including reduced fibrinogen levels, thrombin generation and platelet count [19].

Poor tissue perfusion leads to hypothermia, this is compounded by removal of casualties clothes to find injury and the administration of cold fluids. Hypothermia results in reduced platelet function and coagulation enzyme activity. Its presence is an independent predictor of mortality [20, 21].

Coagulopathy is not only a product of hypothermia and acidosis, clotting factors are consumed and lost due to clot formation. The administration of crystalloid fluids can worsen it further due to haemodilution [22]. The coagulopathy leads to further blood-loss and hypothermia leading to a vicious cycle of worsening physiology that if allowed to continue will result in death [18].

11.3.2 Acute Trauma Coagulopathy

In the last decade it has been shown that coagulopathy will develop independently of the lethal triad as part of the primary physiological response to traumatic injury [5]. In 2003 Brohi et al. demonstrated that coagulopathy was present in up to one-third of trauma patients (Injury Severity Score >15) presenting to emergency department even before the administration of fluids, its severity was directly related to the degree of tissue damage and duration of shock. This has led to the concept of Acute Traumatic Coagulopathy (ATC) [5]. Patients with ATC have significantly higher mortality and are at greater risk of multi-organ failure [5, 23].

The exact pathophysiology of ATC is yet to be fully understood, it is likely there are a number of interplaying processes. Both pro-coagulant and anti-coagulant processes appear to be enhanced but with the balance tipping toward anticoagulation by increased fibrinolysis. This is the rationale for tranexamic acid (TXA) administration which has been shown to reduce mortality from trauma haemorrhage [24].

Activated protein C (APC) levels are raised in patients with ATC with tissue hypoperfusion implicated as the initiating factor [23, 25]. APC is an anticoagulant protein that exerts its effects by inhibition of plasminogen activator inhibitor (PAI) resulting in fibrinolysis. It also combines with Protein S on endothelial cells resulting in inactivation of FVa and FVIIIa thereby reducing thrombin formation [23]. APC levels have been shown to be elevated and both FVa and VIIa levels reduced in casualties with ATC [26]. A recent study has shown that whilst FVa and FVIIIa are reduced they are not reduced enough to explain the degree of coagulopathy suggesting that APC induced fibrinolysis is the predominant effect [23].

Hypoperfusion results in hypoxia as well as epinephrine and vasopressin release which activates tissue plasminogen activator (t-PA), also inhibiting PAI thereby promoting fibrinolysis [27].

Platelets are a key contributor to both clot initiation and final clot strength [28]. Whilst platelet counts are typically normal, significant dysfunction has been demonstrated on admission even after minor injury [29–31]. It has been postulated that this occurs due to massive ADP release from tissue trauma resulting in exhaustion of the ADP receptor mediated response pathways [29]. The role of platelet dysfunction is supported by recent findings that platelet administration is associated with improved mortality and decreased transfusion requirements in major trauma [32].

11.4 Components of Damage Control Resuscitation

The aim of DCR is to optimise the physiological status of the patient at all stages, in particular with regards to coagulopathy, with the aim of stopping or preferably reversing the physiological deterioration of the casualty.

11.4.1 Permissive Hypotension (PH)

The aim of PH is to maintain perfusion of vital organs without causing clot disruption, due to raising blood pressure, and to minimize the administration of crystalloid fluids. Crystalloid fluids contain electrolytes similar to that of the plasma but no clotting factors, platelets or red blood cells.

Whilst bleeding is uncontrolled, 250 ml fluid boluses are given to achieve a target systolic blood pressure of 80–90 mmHg, approximately 80% of the normal value in a young adult [33]. A radial pulse can be used as a surrogate until a blood pressure is available however, whilst absence of a radial pulse signifies significant shock its presence does not guarantee a blood pressure of 80 mmHg [34, 35]. If there is no head injury, fluid can be titrated to maintain consciousness as this is a direct marker of end organ perfusion.

Permissive hypotension should be thought of as a state of ‘controlled’ shock where a significant proportion of the bodies’ tissues will deliberately be inadequately perfused, resulting in ongoing acidosis. It is vital that as soon as bleeding is controlled, a normal blood pressure is targeted to reverse the acidosis [36]. Not all bleeding will require surgical control; application of a tourniquets or a pelvic binder may initially be adequate.

PH is contraindicated in patients with head injuries. Hypotension in this group is associated with increased mortality, recent studies have suggested that the threshold for intervention in this cohort should be increased to a systolic blood pressure of 110 mmHg [37, 38].

Evidence for improved mortality from PH is still lacking. Improved mortality in penetrating trauma has been demonstrated, however this was in a system of no fluid versus fluid, rather than fluid titrated to a target blood pressure [39]. Evidence from animal studies shows that in blast injury hypotension can be maintained for up to 60 min but past this point the oxygen debt of the tissues may be impossible to overcome even with aggressive DCR [40–42].

11.4.2 Haemostatic Resuscitation (HR)

The aim of HR is to restore normal patient physiology by reversing the effects of the lethal triad and ATC. Rapid control of blood loss is vital if this is to be achieved [43, 44]. Whilst bleeding is ongoing even aggressive HR will at best only halt the coagulopathy and not reverse it [44]. This highlights the importance of parallel HR and control of bleeding.

Improved mortality from the use of high ratio Packed Red Blood Cell (PRBC) and Fresh Frozen Plasma (FFP) resuscitation, at a ratio of 1:1, was first demonstrated in 2007 based on casualties treated at a US combat support hospital [45]. Multiple subsequent retrospective studies in civilian hospitals have supported this initial finding [46]. The exact ratio that confers improved survival has been questioned with one retrospective study showing no benefit of 1:1 ratio (PRBC:FFP) administration over a ratio of 2:1. Subsequently the PROPPR prospective randomised control trial compared 1:1:1 or 1:2:1 (FFP:PRC:Plts) in resuscitation of trauma haemorrhage. There was no difference in the 24 h or 30 day mortality with each ratio but haemostasis was achieved in more patients in the 1:1:1 group [47]. A recent prospective cohort study demonstrated that not only did a high ratio of FFP to PRBC improve survival, a high ratio of platelets to PRBC (of 1:1 or greater) was associated with improved survival and reduced transfusion rates [32].

Heamostatic resuscitation itself can be considered as consisting of two phases: resuscitation before and after control of bleeding.

11.4.2.1 Massive Transfusion Protocols

The logistical challenges in undertaking massive transfusions are significant even in single casualties, with the complexities rising significantly with increased casualty load [48]. The rapid restoration of blood volume in severely shocked trauma patients can require significant volumes of blood products, with one UK study of military casualties having a median administration of 27 units of PRBC and FFP [43]. In order to achieve adequate volume and composition of blood products massive transfusion protocols are used (Fig. 11.2) [48].

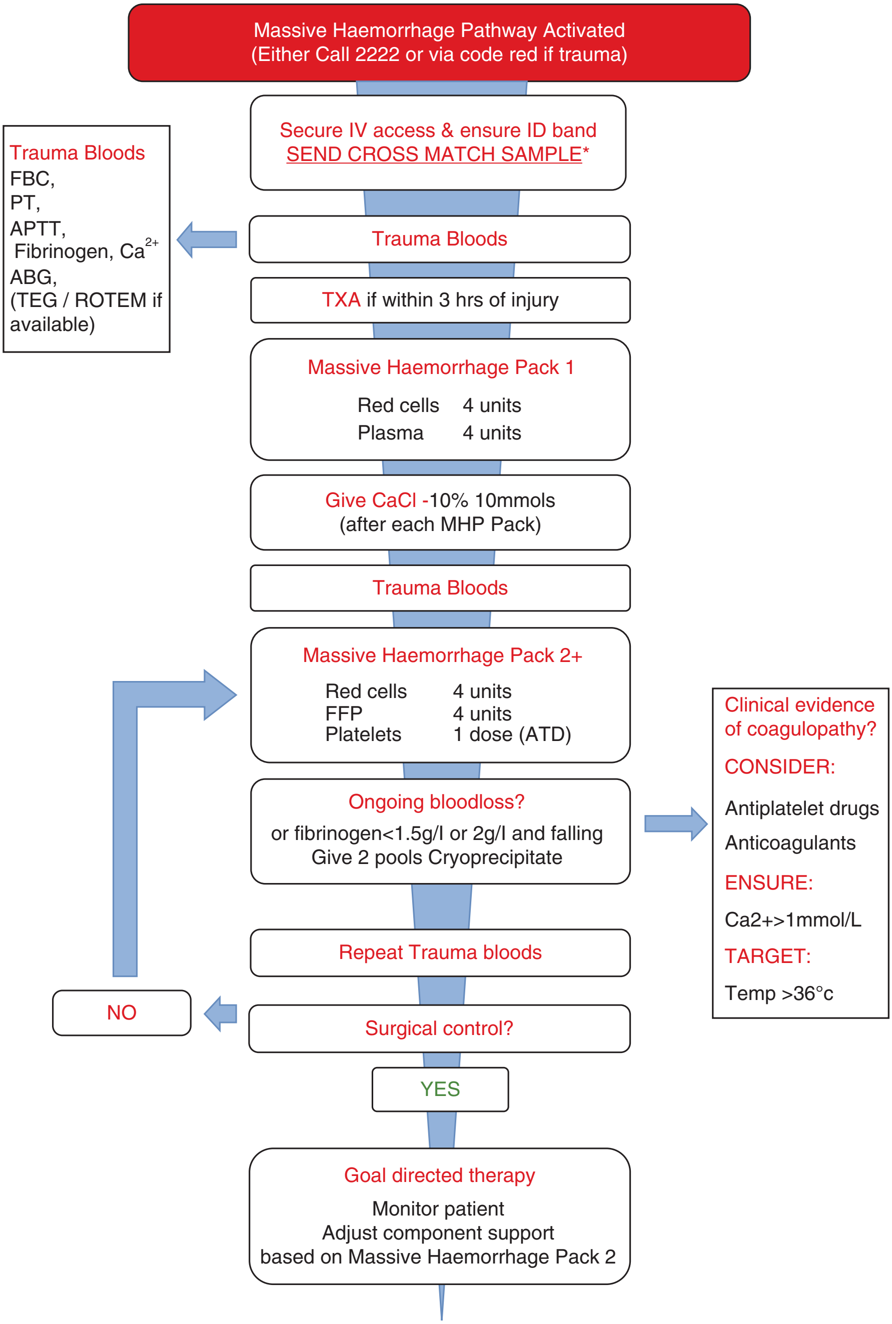

Fig. 11.2 Example of a massive transfusion protocol—based on Queen Elizabeth Hospitals Birmingham (UK) massive haemorrhage protocol Standard operating procedure Nov 2016

Once the recognition or expectation of a massive transfusion is present, one call to a dedicated phone line can be made to trigger the protocol. Blood boxes containing pre-defined blood products are released until the protocol is terminated by the treating clinicians. This allows rapid administration of fixed ratios of Fresh Frozen Plasma (FFP), Packed Red Blood Cells (PRBC) and platelets. Whilst bleeding is uncontrolled fixed ratio transfusion is recommended.

Use of laboratory coagulation studies in this phase is likely to be unhelpful as these tests require time to send, analyse and return, taking up to 60 min to provide results [49]. In this time the patient's blood volume may have been replaced several times, making the results historic [50].

11.4.2.2 Targeted Resuscitation

Once bleeding is controlled a more tailored approach is employed to both the volume and the type of blood products administered. Efforts are made to reduce the sympathetic drive of the casualty using opiates. Any resulting drop in blood pressure is then corrected with PRBC and FFP (1:1) with the aim of restoring the patients normal blood volume. The degree of metabolic acidosis is used as a marker of adequate resuscitation, the target being normalization of the base excess and improving lactate [51]. This is tested at least every 30 min, more frequently if the casualty is unstable. The aim of this process is to restore their physiological reserve allowing them to tolerate further blood loss that may occur during surgical debridement that they would not have tolerated initially.

Standard vital signs are poor markers of adequate resuscitation [52]. Anecdotally once initial surgical control is gained, the patient may be normo or hypertensive due to a high sympathetic tone. They will still be significantly acidotic and volume deplete. If surgical control were to be lost prior to adequate volume resuscitation and correction of their acidosis, rapid deterioration or death may result. At this point a pause in surgery allowing time to 'catch up' maybe necessary with surgery continuing once physiological stability is improved. This approach requires close communication between the anaesthetic and surgical teams [53].

Correction of coagulopathy at this stage can be guided by coagulation studies which are available in most hospital laboratories. The standard tests of coagulation are platelet count, fibrinogen levels, prothrombin time (PT) and activated partial thromboplastin time (aPTT) (Fig. 11.3) [51, 54]. Their use as a guide to product

	Target	Treatment
INR and aPTT	< 1.5 of normal	If high give FFP 30ml/kg
Fibrinogen	1.5 – 2 g/L	Replace with cryoprecipitate
Platelet count	75 x10^9/L (100 if ongoing bleeding OR head injury)	Replace with 1 ATD

Fig. 11.3 Normal laboratory test treatment targets [55]

replacement is not without limitations. None look at whole blood clotting or take platelet function into account. PT and aPTT are measures mainly of clot initiation, patients can still be coagulopathic even with normal aPTT and PT values [55]. As previously stated test turnaround time can be prolonged leading to delays in treatment of any underlying coagulopathy [49].

Point-of-care coagulation monitoring using viscoelastic tests can provide meaningful results with in 10 min [56]. Their use is proving successful in targeting product replacement and has demonstrated a reduction in blood product administration but no reduction in mortality [57].

When using tests to guide resuscitation it is important to understand the difference between treatment targets versus triggers. A target is the minimal acceptable level that a value is allowed to reach, for example fibrinogen should be >1.5 g/dl [55]. If 1.5 g/dl is used as a treatment trigger the level would fall below acceptable minimal standards before correction as test turnaround is never instantaneous and there will likely be a delay before blood products are available. Falling levels need to be anticipated and acted upon before they reach minimal targets. Treatment triggers mean that early delivery can be considered based on the clinical situation and direction to maintain levels above the suggested minimal targets. The faster the test to intervention time the smaller the margin between target and trigger required.

11.4.3 Tranexamic Acid

Part of the coagulopathy in trauma is caused by fibrinolysis. To prevent this Tranexamic acid (TXA) should be given as early as possible, preferably in the prehospital phase. It must be given as soon as possible with in 3 h of injury, after this period it is associated with an increase in mortality [25]. Retrospective UK Military data showed that the survival effect was more pronounced in those receiving a massive transfusion [58]. Whilst Crash-2 showed a net increase in survival it did not identify which patients had ATC, the perceived target of action. Current studies are underway to assess if a particular cohort of patients can be identified that will gain maximal benefit from this therapy (PATCH 2) [59].

11.4.4 Hypothermia

As previously stated hypothermia is associated with increased mortality [20]. Once heat is lost rewarming can take significant periods of time to achieve. The best strategy here is prevention, limiting casualty exposure, warming intravenous fluids and methods to reduce evaporative losses [60]. If warming is required under casualty heating systems may provide the best option if surgical access is required to most of the casualty. Forced air warming devices can be used if the casualty is being operated on in limited body areas. It is vital to remember that blood can pool under the casualty on the operating table this will lead to further cooling or difficulty warming.

11.4.5 Managing Electrolytes: Hypocalcaemia and Hyperkalaemia

Acute hypocalcaemia is a common complication of massive transfusion, calcium is bound by the citrate in transfused FFP reducing the ionized plasma levels [51]. Hypocalcaemia increases coagulopathy by reducing the function of the clotting cascade and platelets. Myocardial contractility and systemic vascular resistance are also reduced. Low ionized calcium levels are associated with increased mortality and need for massive transfusion [61].

During uncontrolled bleeding and the use of MTP calcium should be replaced at set intervals, more if the ionised calcium is still reduced. 10 ml of 10% Calcium Chloride or equivalent should be administered with every 4 FFP and 4 PRBC. Once bleeding is controlled regular arterial blood gases should guide calcium replacement.

Potassium concentrations in PRBCs can be over 60 mmol/L depending on the age of stored blood [62]. Whilst efforts to reduce potassium levels through washing and irradiation appear to have reduced the occurrence of hyperkalaemia in standard transfusions, it can still occur with the administration of large volumes of PRBC [62, 63]. Potassium levels must be closely monitored and hyperkalaemia treated with a glucose and insulin infusion.

11.4.6 Anticoagulants

In developed countries many victims of trauma are increasingly elderly patients with significant comorbidities requiring anticoagulation. Many of these patients are now taking Novel Oral Anticoagulants (NOAC) which are less detectable with standard laboratory tests, TEG/ROTEM may prove more useful in this group although clinical experience is still limited [64–66]. If, despite normal testing, the patient is clinically coagulopathic preceding use of a NOAC must be considered. The drugs are currently difficult to reverse but agents are starting to be approved for clinical use. Expert advice from a Haematologist is advised.

11.4.7 Factor Concentrates and Fresh Whole Blood

Whilst UK and US practice involves the use of FFP and cryoprecipitate for resuscitation European systems utilise factor concentrates such as prothrombin complex concentrate and fibrinogen concentrate to achieve similar goals [67]. This approach has been shown to reduce the need for allogenic blood transfusion and has the advantage of not requiring a cold chain for storage [68, 69].

Despite modern DCR techniques some casualties will continue to have a worsening coagulopathy. This may in part be due to the decreased red cell function and reduced levels of functioning clotting factors in stored blood products [70].

Fresh whole blood (FWB) overcomes these problems and has been used safely on recent military operations. It has shown a larger reduction in coagulopathy compared to component therapy [71]. Multiple retrospective analyses of mortality have however shown conflicting effects although none have shown harm [71–73]. There is now increasing interest in the use of both FWB and stored whole blood for resuscitation in trauma. This is likely to be an area of significant research in the immediate future [74].

11.4.8 Damage Control Surgery

DCS comprises of a range of surgical interventions targeted at halting deterioration of the patient's physiological condition rather than attempting definitive restoration of function. DCS allows rapid control of bleeding without which normal physiology in particular correction of coagulopathy cannot be achieved even with advanced fluid resuscitation techniques [44, 45]. This is discussed further in Chap. 13.

11.5 Considerations with Multiple Ballistic Casualties

DCR in severely injured hypovolemic casualties requires significant resources in terms of personnel, operating space and number of blood products [75, 76]. In the 2015 Paris terror attacks there were 76 high priority casualties that required emergency surgery or embolization to control bleeding [77]. Planning for the London Olympics estimated requirements of 10 units of PRBC, 6 Units FFP and 1 pool of platelets per T1 or high priority case [74].

An MTFA incident within the UK is likely to place significant pressure on blood stocks, particular group O [76]. Early use of group O positive blood in all males as well as females over 50 years will help to protect O neg. stocks. An earlier switch to group specific blood can be considered but this may well increase the risk of ABO incompatibility [74].

The use of pre-screened fresh whole blood donor panels may provide a means to meet surges in demand. This system is currently being implemented in Norway to increase blood supplies in times of emergency [74].

The large number of casualties requiring rapid access to surgery can provide significant pressures on theatre capability. Planning and preparation is key to being able to rapidly gain additional staff and generate increased theatre capacity.

Conclusion

Addressing all aspects of abnormal physiology as close to the point of injury as possible is vital for successful damage control resuscitation. Good organisation with the early involvement of senior clinicians and well-rehearsed teams are key to delivery, especially in the event of multiple casualties. Use of this approach is now well shown to improve outcome in severe ballistic injury [6].

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Anaesthesia and Analgesia

12

Mark Davies and Jeyasankar Jeyanathan

12.1 Introduction

Ballistic Trauma presents complex and potentially hazardous challenges during the perioperative period. This requires the anaesthetist in conjunction with the rest of the trauma team to provide early and aggressive care in order to initially stabilise and later restore normal physiology. The lethal triad of acidosis, hypothermia and coagulopathy can significantly influence and worsen an already perilous clinical picture. The concepts of damage control resuscitation (DCR) address the thorough and careful integration of both anaesthesia and surgery to effectively deal with this lethal triad [1]. The delivery of anaesthesia in ballistic trauma is a careful combination of tailored resuscitation, analgesia and sedation. The various aspects of DCR and damage control surgery (DCS) are described in detail in separate chapters. This chapter will therefore concentrate on anaesthetic elements, with an emphasis on airway management, induction and maintenance of anaesthesia and a dedicated section focussing on analgesia.

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12.2 The Anaesthetist in the Trauma Team and Human Factors

On arrival of a casualty with ballistic trauma, modern major trauma management features the assembly and deployment of a skilled multidisciplinary trauma team, led by a designated trauma team leader (TTL). Frequently the initial resuscitation efforts are in the emergency department (ED) but may be rapidly shifted to the operating theatre and subsequently to intensive care. Imaging of the patient may feature very early on, including a full trauma series of CT based radiology. If however the casualty has injury patterns causing haemodynamic instability, particularly if refractive to blood product resuscitation, then emergency DCS alongside DCR will be necessary. The anaesthetist is key in stabilising and supporting the casualty through all of these management routes, and furthermore is integral in clinical decision making in collaboration with the other disciplines present. It is evident then, that the anaesthetist is closely involved in assessment and resuscitation, but also plays an ongoing and crucial role, both in the transition stages, and in continued care as the patient journeys from ED through radiology, or theatres and critical care.

Ballistic Trauma can cause obvious and massive injuries, but as with all trauma it is vitally important to look for other injuries which may be subtle but could be of more significance. Overt injuries such as a traumatic amputation, or a very distressed patient can easily distract from the early detection and prompt intervention of significant injuries, for example gunshot wounds penetrating the thorax. The anaesthetist, as an integral member of an organised trauma team, may in such situations be asked to engage with the delivery of early analgesia, sedation or formal anaesthesia with intubation and ventilation. They should also endeavour to encourage and help facilitate a systematic, rapid, yet thorough trauma survey incorporating horizontal concurrent activity from the entire trauma team to avoid overlooking such crucial injuries. Clear communication during this course is important, and it is essential that information should be fed to and through the TTL. From all of this it is clear that many elements of human factors form a crucial part in the organisation and delivery of trauma team care in ballistic injured casualties.

There is a separate chapter on human factors and therefore this will not be explored further here.

The remainder of this chapter will focus on

- Airway intervention
- Induction and Maintenance of Anaesthesia
- The role of Regional Anaesthesia
- Analgesia

12.3 Airway Intervention

The management of the airway in ballistic trauma patients, in particular the securing of a definitive airway, is an important early tool of the resuscitative efforts delivered by the anaesthetic team. Rapid sequence induction of anaesthesia (RSI) is a formalised and familiar method of intubating the trachea. The indications for RSI in the trauma casualty include:

- A lowered conscious state or unconscious (Glasgow coma scale (GCS) <8)
- Ventilatory failure
- Impending or actual airway compromise
- Injured patients who are unmanageable or severely agitated such that deemed a significant harmful risk to themselves or others.
- Humane reasons such as uncontrolled pain.

The RSI may feature very early on in the resuscitation phase. The TTL and anaesthetist must declare the intent and reasons in order to make the team aware of this important but potentially hazardous manoeuvre. In the National Audit Project (NAP 4) carried out in 2011 by the Royal College of Anaesthetists UK, it was identified that human factors had contributed to 40% of the adverse outcomes reported [2]. It was further proposed that a predetermined "Airway Strategy" comprised of a set of sequential airway management plans were put in place prior to commencing [2, 3]. As such, human factors, including the handover of leadership from the TTL to the anaesthetist during the RSI period, along with preparation, situational awareness and clear communication across the trauma team, are required for safe airway management [4].

The difficult airway society (DAS) recently published guidance on management of the unanticipated difficult airway. The algorithm of safe practice recommends planned and prepared drugs, personnel and environment to assist airway management. The protocol is made up of the following four steps:

- The best attempt at tracheal intubation be it with direct laryngoscopy or video laryngoscopy,
- Failing this, placement of a supraglottic airway device to maintain oxygenation
- If this is not adequate then a final attempt at mask ventilation
- If intubation and ventilation are now not successful by any modality progress swiftly to surgical cricothyroidotomy [5].

The preparation for RSI should clearly identify where all necessary equipment is, including the preparation for surgical cricothyroidotomy. This preparation for a surgical airway should include identification of the individual who will be carrying this out, which may be the surgeon in the trauma team, with the presumed target area identified and marked on the neck prior to RSI [6]. This is particularly necessary if a difficult airway is predicted in advance. It is good practice to clearly list and declare the airway strategy to the team prior to commencing the RSI.

The airway management of patients with ballistic trauma will need careful consideration factoring in the potential injuries sustained pertinent to the anatomical territories that may be involved.

- Ballistic facial Injury
- Ballistic neck Injury
  - Three zones

Ballistic injury to the face has a number of airway management options including RSI [7], surgical airway [7] or fibre-optic intubation techniques [8, 9]. In the severely traumatised facial injury RSI and oral intubation is still often deemed to be the most useful and familiar method. This is usually because the structures for intubation may be openly visible and placing an oral endotracheal tube safely may ironically be made easier as a result of the injury [8, 10].

If the neck has suffered ballistic penetrating injury, then airway management may require vast modification. The techniques described for airway management should firstly take into consideration the area of the neck involved. The anatomical classification into three zones helps to determine an airway strategy for what would be deemed as the "anticipated" difficult airway.

The zones are described as:

Zone I—area between the sternal notch along the clavicles and superiorly to the cricoid cartilage.
Zone II—area between the cricoid cartilage and the angle of the mandible.
Zone III—area between the angle of the mandible and superiorly the base of skull.

Casualties presenting with haemodynamic or airway instability will inevitably influence the level of urgency required prior to intervention. If the situation is deemed to be an emergency unnecessary delays to facilitate imaging or endoscopic surveillance should be avoided. Conversely, if the patient is stable, then the investigation of choice, and moreover the safest course of action, is to proceed to CT-angiography in order to determine the full extent of injuries and any attendant hazards related to planned airway intervention [11].

The Zones include the following key anatomical structures:

Zone I
Trachea, thyroid, oesophagus, spinal cord and the apices of the lungs.
Vascular structures—common carotid artery, vertebral artery, subclavian artery, the key vessels of the upper mediastinum.
Zone II
Trachea, pharynx, oesophagus, vagus nerve, recurrent laryngeal nerve and the spinal cord.
Vascular structures—common carotid artery, vertebral artery, internal jugular vein.
Zone III
Cranial nerves—IX-XI and the spinal cord.
The floor of the mouth.
Vascular structures—internal and external carotid arteries, vertebral arteries, jugular veins.

Given these crucial territories an airway management strategy for penetrating airway injury by zones was proposed by Mercer and Breeze [12] which included the following suggestions:

Zone I
Intubation directly through any obvious large airway defect.

Surgical cricothyroidotomy.
Emergency surgical thoracotomy.
Zone II
In proximity to the larynx:
Injuries distal to the larynx—Fibreoptic intubation or surgical cricothyroidotomy.
Injuries proximal to the larynx—RSI with oral intubation.
Zone III
RSI with oral intubation.
Surgical cricothyroidotomy [12].

It should be noted that there are a number of newer airway devices which are not individually mentioned but are incorporated under the banner of RSI and oral intubation. Whilst direct laryngoscopy remains the most familiar technique, the role of video-laryngoscopy has become a frequented airway strategy. A few examples are the GlideScope (Verathon, Bothwell, WA) the Airtraq (Prodol Meditec, Getxgo, Spain) and the C-Mac (Karl Storz, Tuttingen, Germany).

Awake fibre optic intubation allows oral and intraluminal visualisation during the intubation process. Thus if any tracheal injury is seen, the endotracheal tube can then be carefully sited distally to the injury. The surgical team as a whole must be prepared and briefed prior to undertaking this procedure.

Blind nasal intubation should not be undertaken in the trauma population particularly with penetrating facial or neck injury, This is particularly pertinent as other associated injuries, for example base of skull fractures, cannot be ruled out and the combination of worsening injuries make this a dangerous undertaking.

In conclusion, the clinical picture should be interpreted in the light of all the expertise available, be that anaesthetic, surgical, radiological and others. This combined with advanced imaging and other results will determine the urgency required in securing the airway. Importantly, in all situations, a final airway strategy should be formulated early using the techniques described above.

12.4 Induction and Maintenance of Anaesthesia

Induction of anaesthesia for ballistic trauma usually includes an induction agent, a muscle relaxant and a short acting opioid.

A typical example of drugs used for anaesthetic induction might be:

Opioid analgesia—fentanyl 1–3 μg/kg ➔ *Caution with either a reduction or omission of dose in the hypovolaemic, shocked patient*
Induction agent—ketamine 1–2 mg/kg ➔ *Again Caution with either a reduction or omission of dose in the hypovolaemic, shocked patient*
Muscle relaxant—rocuronium 1 mg/kg

Induction of anaesthesia in the shocked, hypovolaemic patient may cause severe cardiovascular instability, and as such, the agents used and doses, may differ significantly as deemed appropriate by the anaesthetist. For example a recipe is given below for induction of anaesthesia in the shocked trauma patient which has been successfully used even in the prehospital arena is the reduced dose trauma induction [13]:

Opioid analgesia—fentanyl 1 μg/kg
Induction agent—ketamine 1 mg/kg
Muscle relaxant—rocuronium 1 mg/kg

Alternative drugs which may be used include:

Opioids—alfentanil, remifentanil and morphine
Induction agent—propofol
Muscle relaxant—suxamethonium.

Broadly speaking, maintenance of anaesthesia is achieved by one of two methods:

– Intravenous anaesthesia. The shocked patient can have maintenance with boluses of ketamine until surgical haemorrhage control (be it proximal control, repair of vascular injury and suitable stability with DCS) is obtained. After this point fentanyl can be cautiously titrated. Given that fentanyl can have significant cardiovascular sequelae in large bolus doses, the gradual building of intravenous fentanyl needs to be done with vigilance. Having factored this, fentanyl could in certain casualties be built up to a maximum of 10 μg/kg titrated for analgesia and also to aid vasodilation of the distal vascular tree and microcirculation, which is likely to have become severely vasoconstricted in the acute phase of profound hypovolaemic shock. The completely haemodynamically stable patient may be managed with agents such as propofol and remifentanil in a total intravenous anaesthetic form
– Inhalation of volatile anaesthetic gases. Volatile gases cause vasodilatation which with associated hypotension may compound haemodynamic and cardiovascular instability hence judicious use is required with this method.

Often a combination of the two methods is employed, utilising a low concentration of volatile agent, supplemented with frequent small boluses of ketamine (25 mg), changing to aliquots of 75–150 μg of fentanyl when surgical control of haemostasis is achieved. A small dose of benzodiazepine such as midazolam may also be used in order to reduce the likelihood of accidental awareness under anaesthesia, and the dysphoria sometimes seen with ketamine.

12.5 Regional Anaesthesia

Regional anaesthetic (RA) techniques are an important tool in delivery of multimodal analgesia. In surgical intervention on an isolated region, there is potential to use RA as the sole anaesthetic technique. It also has benefits in obtunding the sympathetic response to trauma. The idea of bathing nerves with targeted local anaesthetic has been made accurate and more refined with ultrasound guidance.

Regional techniques may allow a reduction in opioid requirement, and consequent side-effects. The likelihood of faster post-operative recovery, shorter intensive care stays [14] and potential to reduce the incidence of chronic pain syndromes following complex trauma make regional techniques a very attractive consideration in ballistic trauma [15].

Epidural analgesia should also be considered for ballistic trauma patterns involving lower limbs or abdominal injuries, if the facilities are safely in place. It can offer profound pain relief with the added benefit of obtunding the autonomic stress response. Epidurals are not without potential complications however, and require meticulous aseptic technique and careful post-insertion monitoring. Complications include haematoma, with potential for cord compression, central neurological infection, nerve damage, dural puncture and hypotension. Following insertion, ongoing management of the epidural is extremely important and requires properly trained staff to facilitate this.

Peripheral nerve blocks provide the opportunity for a wide range of techniques to deliver analgesia for a variety of extremity injuries. These techniques are associated with fewer complications and contraindications compared to epidural anaesthesia. Regional techniques may be delivered as a "single shot" or via continuous peripheral nerve block infusions. It is possible to block multiple sites simultaneously, for example to provide post-operative analgesia via a brachial plexus infraclavicular block for an upper limb ballistic injury, combined with a femoral, sciatic nerve block for lower limb injury, as long as safe local anaesthetic dose levels are not exceeded.

The risk of nerve damage is small but not impossible, so careful mapping of pre-existing neurological deficit is essential. The potential risk for complications of nerve blockade must be discussed with the patient and surgical team, as well as the intended benefits, in advance of the procedure. Lower limb blocks for severe ballistic injury associated with fractures and at risk of compartment syndrome should be considered for elective fasciotomy.

The risk profile arising from nerve blockade, be it peripheral or neuraxial, performed in the presence of coagulopathy must be carefully weighed up. Buckenmaier et al. made some recommendations for the placement of epidural catheters or deep blocks with catheter placement [16]:

- APTTR <1.5
- INR <1.5
- Platelets >80 × 10^9/L

As with epidurals, bleeding, infection and failure of the block are potential complications. Marked cardiovascular and neurological changes are markers of local anaesthetic toxicity, hence assessment must be made during, and in the immediate hours after the block. If one is to avoid these potentially dangerous complications it is vitally important to stay within the safe maximum doses of the commonly utilised local anaesthetic drugs:

Lidocaine has a maximum dose of 3 mg/kg, however when used with adrenaline the dose is increased to 7 mg/kg. Lidocaine has a rapid onset time of between 2 and 15 min.

Bupivacaine has a maximum dose of 2 mg/kg with a slower onset time of 10–25 min. It is extremely important to note that Adrenaline does not increase the safe, maximum dose of Bupivacaine.

Regional blocks that can be performed in ballistic trauma include:

- Interscalene brachial plexus block
- Supraclavicular brachial plexus block
- Infraclavicular brachial plexus block
- Axillary brachial plexus block
- Femoral nerve block
- Sciatic nerve block
- Popliteal nerve block

The surgical team may perform local anaesthetic infiltration under direct vision, for example via simple wound incision infiltration, or more formally a rectal sheath block or paravertebral block.

All of these blocks may be enhanced by placement of a catheter and use of an infusion device to deliver continuous peripheral nerve blocks, in order to provide ongoing analgesia.

12.6 Analgesia for Ballistic Trauma

> We must all die. But that I can save him from days of torture, that is what I feel as my great and ever new privilege. Pain is a more terrible lord of mankind than even death itself. Albert Schweitzer [17]

This section on analgesia will cover the following points:

- Importance of good pain relief;
- Recognition, assessment and treatment of pain;
- Some commonly used drugs;
- Summary

Pain is a ubiquitous experience, and affects all of us at some point. Casualties who sustain ballistic injury will inevitably experience pain to a greater or lesser degree. Timely and effective treatment of pain is beneficial for a variety of reasons. Not the least of these considerations are simple humanitarian ones; if we can treat pain and reduce suffering, we should. However, there are also other, more compelling and measurable reasons, including a tangible reduction in complications in the cardiovascular, respiratory and endocrine systems [18, 19], as well as a suggestion that good, early pain relief appears to offer a degree of protection from post-traumatic stress disorder (PTSD) [20].

12.6.1 What Is Pain?

Pain is something that we all experience during our lifetimes, usually in response to noxious stimuli. The very great majority of us see this pain decrease and disappear over time, but a small proportion go on to develop persistent pain problems. Traditionally it was believed that our perception of pain was simply down to a Cartesian type reflex [21]. However, we now know, that whatever pain is, it is not simply a straightforward stimulus-response reflex, and that there are multiple ascending and descending influences on pain perception. It can be said that while animals may feel pain, humans experience pain, in the light of their personal circumstances, and their emotions. Given then, that humans are rational, emotional beings, it is apposite to explain pain in such terms. See Figs. 12.1 and 12.2.

The most commonly quoted and accepted definition of what pain is, has been ratified by the International Association for the Study of pain (IASP) and is as follows;

> Pain is an unpleasant sensory or emotional experience, associated with actual or potential tissue damage, or described in terms of such damage [22].

It is possible, when considering a book dedicated to treatment of ballistic trauma, that one may feel that the above definition is unnecessary, untrue, and that of course, all the pain caused in this way is due to actual, physical damage. This is understandable, however it is certain that pain perception is much more than a simple response

Fig. 12.1 Traditional cartesian model showing a simple stimulus response reflex. With permission from the artist Dr. Rachel Murray

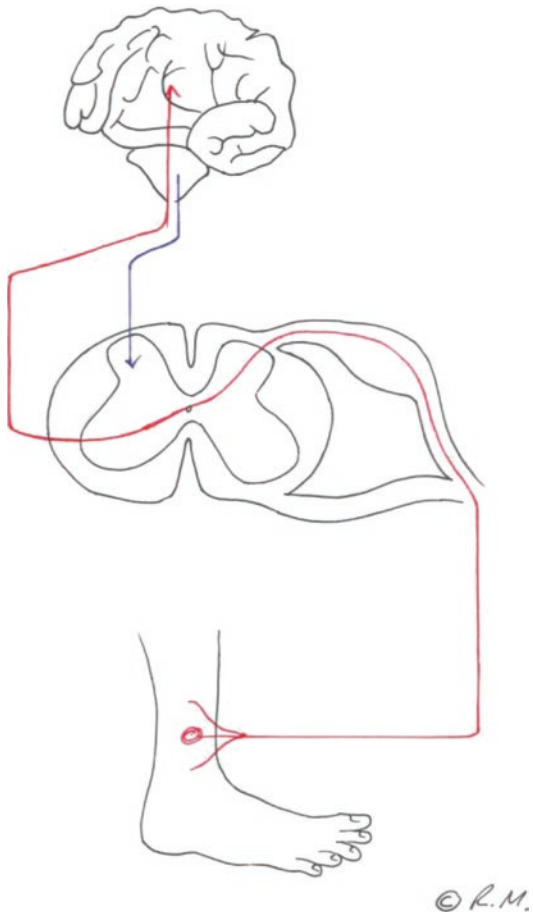

Fig. 12.2 Modern view of a pain sensory reflex. It is now known that pain responses are subject to central, ascending and descending neuromodulation at various points along the pathway, which may go some way to explaining individuals' differing response to similar stimuli. With permission from the artist Dr. Rachel Murray

to noxious stimuli alone. Furthermore, ascribing pain as simply a response to tissue damage, risks falling into the trap of overestimating, or underestimating pain in individuals presenting with similar injuries, and therefore, potentially failing both groups.

12.6.2 Types of Pain

Pain is traditionally divided into acute pain and chronic pain, and also, into nociceptive and neuropathic pain.

The terms acute, and chronic, are indicative of the chronicity of pain, i.e. the amount of time pain has been present, and have nothing to do with the nature or intensity of pain. Persistent pain is a newer term starting to gain purchase, and is probably more useful than the term chronic.

Acute pain is that which arises early, following a physical insult. Clear examples would be post-operative pain or pain as a result of ballistics injury. Given time and with appropriate management including analgesia, this pain will reduce and resolve completely in the majority of individuals.

Chronic pain is the term used to describe the pain which persists after one may reasonably have expected it to resolve. There is no hard and fast definition for this time period, but pragmatically most agree that pain persisting after 3 months fits this description [18]. The reasons why some individuals will go on to develop chronic pain are complex, and are not fully understood. The evidence base for the use of anti-neuropathic medications for acute injuries likely to involve nerve damage is not strong. However, there is much work ongoing to explore this subject. Until stronger evidence is obtained, the consensus is that use of anti-neuropathic medication in the early phase is *likely* to be of benefit in preventing development of chronic neuropathic pain conditions in some individuals, and at the very least it has an opioid sparing effect in the acute period.

Pain may be further subdivided into nociceptive and neuropathic pain.

Nociceptive pain is fairly well understood in terms of the receptors and pathways involved in its transmission. (See Fig. 12.2). Responses are mediated via a variety of receptors mediating pressure, or thermal and chemical stimuli, to name a few. There is a wide dynamic range of response, and the response generally corresponds well to the intensity of the stimulus.

Neuropathic pain is less well understood, and arises as a result of damage to the nervous system. The response is not dependent on intensity of stimulus, and is often persistent even when the original insult is no longer present. Descriptors of neuropathic pain include causalgia or burning pain, lancinating or stabbing pain, altered sensations or paraesthesia, and hypersensitivity. It is beyond the scope of this chapter to delve further into the nature and treatment of chronic pain.

12.6.3 The Importance of Good Pain Relief

Marauding Terrorist Firearms Attacks (MTFA) have been seen with increasing frequency worldwide in recent years. The numbers of casualties have been higher than that normally faced by civilian medical facilities. No matter how overwhelming these incidents maybe, casualties should receive high-quality, pain relief tailored to their needs, for a multitude of reasons.

In more recent years, the issue of pain relief as a 'human right' has taken root [7], following directly from the foundation covenants of the United Nations' Universal Declaration of Human rights, and leading to the Declaration of Montreal. The first International Pain Summit in 2010 stated that access to pain management is a fundamental human right [23].

There are important ethical and humanitarian considerations in delivery of effective analgesia, as well as more tangible benefits to be gained from timely and effective pain relief.

These negative effects may impact deleteriously on physical and social function, sleep and health-related quality of life. Importantly unresolved pain may well predispose to later development of chronic pain conditions. In the shorter term, pain which is not addressed effectively will impede rehabilitation and early normalisation of function following a traumatic insult. In addition, and not least, unresolved acute pain may well predispose to higher rates of PTSD in some individuals, and there is some suggestion that addressing pain early and effectively, can provide a degree of protection against this [18–20, 24].

12.6.4 Recognition, Assessment and Treatment of Pain

> Those who do not feel pain seldom think that it is felt
>
> —Dr. Samuel Johnson 1709–1784

In recent years there has been a move to treat pain as a kind of fifth vital sign, along with heart rate, blood pressure, respiration rate and temperature. The important focus in this approach is to be proactive in seeking and assessing pain and treating it effectively where it exists. Poor pain assessment by physicians has been identified time and again as the single most important barrier to adequate pain management [25].

There are many pain rating scales in use, and these may be more or less useful in certain circumstances.

Numerical rating scales (NRS) can be excellent research tools in assessing pain in controlled environments, but are of less utility in clinical practice. Rating pain on a scale of zero to ten, using a 100 mm line, with zero being no pain, and ten being the worst pain imaginable, gives laboratory investigators accurate measurements of perceived pain in the research set up. However, in practice it is far less useful at the bedside, or when assessing casualties presenting with injuries. What is needed in these cases, is a simple system which is easily understood by both the casualty, and the health provider.

One such system is that favoured by the United Kingdom Armed Forces Medical Services. The system used, utilises a zero to three scale (0–3), with a score of zero equating to no pain, one equating to mild pain, two to moderate pain, and three equating to severe pain. This system has proven to be a simple and effective tool in helping to identify pain, and to treat it accordingly.

The single most important point here is that an individual's pain is not a static state, and having made the effort to recognise an individual's pain, assess it and treat it, reassessment at regular intervals is essential to ensure that any ongoing need for analgesia continues to be met.

In some situations, there will be cases where the 0–3 scale is inadequate. This may be due to language difficulties, gauging pain across different cultures, or in treating paediatric patients. In these cases, one may have to use other pain scales, such as paediatric "*Oucher*" scales or *Faces Pain Scales* (FPS). Importantly whatever method is used to assess pain and ongoing requirements for analgesia, a consistent and systematic approach by all members of the healthcare team is essential.

It is also salient to point out, that whatever the situation, and the assessment tools utilised, one must always use clinical judgement and personal experience as the failsafe option to guide treatment.

Treatment of pain can only be adequately performed after recognition and assessment. Proper pain assessment is the bedrock of proper pain treatment, and will guide the clinician or healthcare provider in provision of effective and personalised pain relief.

Treatment may be subdivided in to non-medical and medical options.

Non-medical treatment options are generally under appreciated and underutilized especially in modern medical systems, but there is little doubt that an empathetic approach and simple reassurance will have significant positive effects on the casualty and those around them.

Removal of the cause of the pain, and removal of the casualty from a place of danger will also help. Simple measures such as splinting of fractures, application of dressings to wounds, or protection of burned areas are invaluable and should never be underestimated in their utility.

From a medical point of view, the treatment given will be dependent on the expertise and experience of the healthcare provider attending.

In the United Kingdom, most ambulances carry cylinders of 50/50 nitrous oxide and oxygen known as Entonox. Entonox may be used where rapid analgesia, and a tolerable amount of sedation without loss of consciousness, is desirable, and is extremely useful in procedures such as splinting fractured limbs or allowing applications of dressings. The agent is very fast-acting but also has a very fast offset.

When longer term analgesia is required, the gold standard for pain relief has traditionally been Morphine and its analogues, either naturally occurring or synthetic.

However, not all casualties will require opioids, and it is advisable to adopt a multi-modal analgesic approach, based upon the World Health Organisation (WHO) "pain ladder".

Traditionally the WHO pain ladder was designed for use in cancer pain, and escalated the level of analgesia as pain became more problematic. In acute pain situations however, the ladder is effectively turned on its head, so that in the initial stages all of the analgesic options may be deployed, and tailored downwards later as pain is controlled and becomes less problematic. In effect a "reverse pain ladder" concept is employed (Tables 12.1).

Some casualties with less severe injuries may be adequately dealt with by the use of drugs on the bottom rungs of the ladder, such as Paracetamol, NSAIDs and the so-called weaker opioids.

Use of opioid medication in acute trauma is often under used because of unwarranted fears of side effects and development of addiction. This is nothing new. As far back as the American Civil War, physicians saw opioid use as problematic, and use of opioid medication became known as the 'Soldiers' Disease'. Since then use of opioid medication has consistently been stigmatised. The authors have derived the following table which sets to aid understanding of the issues involved, and the terminology and definitions used (Table 12.2).

Table 12.1 Pain ladder and drugs used

Pain score numerical 0–10	Numerical 0–3	Verbal	Analgesics used		
10	3	Severe			Strong opioid
9					
8					
7					
6	2	Moderate		NSAID and/or weak opioid	NSAID and/or weak opioid
5					
4					
3	1	Mild	Paracetamol	Paracetamol	Paracetamol
2					
1					
0	0	No pain			

Table 12.2 Terms used in describing opioid use

Terms relating to use of opioid medication in acute pain
Dependence—This term indicates the potential to develop withdrawal symptoms if the dose of a drug is reduced or ceased. Dependence is a phenomenon associated with many different drugs, and is not exclusive to opioids. A good example is the practice of slowly tapering doses of steroid medications
Tolerance—This occurs when a given dose of a drug is observed to have a reduction in effect. When using opioids, patients are frequently seen to become tolerant quickly to effects such as nausea and sedation. The effect is much less marked with the side-effects of constipation. Tolerance may also be seen with analgesic effects, although slowly, and this is sometimes misinterpreted as drug-seeking behaviour, when dose escalations are sought
Addiction—is the compulsive use of a substance, or preoccupation with obtaining it, in the face of evidence suggesting further use may be harmful at worst, or useless at best. Health care providers consistently overestimate the prevalence of addiction in treatment of acute pain following traumatic injury, and whilst there is no denying that it may exist, the figures are universally cited as lying in the low single digits
Pseudo-Addiction—This is an important definition, and refers to a health care provider's impression that individuals are seeking opioids due to addiction, when in fact they are seeking them for the relief of untreated pain. Effective use of multimodal pain plans, and regular reassessment of an individual's pain scores will help to reduce the reliance on opioid medications and allow appropriate tapering of drug doses at the correct time

12.7 Commonly Used Drugs

This section is not meant to be exhaustive, and no responsibility can be taken for doses suggested as these will differ from unit to unit, and country to country. Health care providers should always consult their own local and national guidelines, and if in doubt seek further advice. The maxim that one can always give more of a drug, but once given, cannot be taken back, is extremely apt here.

12.7.1 Morphine

Morphine is traditionally held to be the *gold standard* analgesic agent, in that it is against Morphine that the effects of other analgesic drugs have been measured. Morphine can be delivered via a variety of routes, including oral, subcutaneous, intravenous, intramuscular and intraosseous (PO, SC, IV, IM, IO). It is extremely important to note that the bioavailability of the drug is very different via different routes, and that dose adjustments must be made accordingly. In acute pain from trauma, the most effective route of delivery will be either IV or IO. IM administration may be unpredictable in terms of absorption, and speed of onset, and the oral route should be avoided at this time if possible. Oral bioavailability is around one third of that via the IV/IO or IM routes. The subcutaneous route is unsuitable for acute pain management due to the drug's low lipid solubility, and unpredictable absorption.

Morphine will cause analgesia and sedation in sufficient doses, but there are several undesirable side-effects which the health care provider should be aware of. The commonest of these include nausea, vomiting, pruritus and dysphoria. Morphine and its analogues may also be associated with respiratory depression in some individuals, and thus appropriate monitoring of vital signs, most notably respiratory rate and oxygen saturation (SpO2), is essential following administration. There are many different opioid formulations available for use in the acute phase, and these can be seen in the table below, and the commoner formulations are described below. See Table 12.3 for commonly used drugs in acute pain with some recommended doses.

12.7.2 Fentanyl

Fentanyl is a synthetic opioid available in a variety of formulations. It has negligible oral bioavailability, and is therefore administered via the IV, transdermal or transmucosal routes. It may also be taken sublingually or via the buccal route. Fentanyl is a highly lipid soluble drug, which accounts for its rapid onset when given via the IV route. It is very much more potent than morphine, but has a considerably shorter effect and offset. It is possible to use Fentanyl intravenously in the acute phase, but for a longer lasting effect consideration should be given to delivery via a different route.

UK Defence Medical Services now issue individual service personnel with oral transmucosal fentanyl citrate lozenges (OTFC) for immediate treatment of acute pain. These are available in a range of doses—the UK DMS currently use 400 or 800 µg preparations, and the casualty has to rub the lozenge over the oral mucosa in order to aid absorption. The preparation is fast-acting, and allows the casualty to 'manage' their own analgesic needs. If their pain is subsiding, they stop rubbing. If they have pain they continue. The preparation is well tolerated, and easy to use. Obviously if there is significant oral or maxillo-facial injury, or if the casualty is unable to use the lozenge for another reason, other options are required.

Table 12.3 Commonly used drugs in acute pain

Drug	Preferred route of administration in acute pain	Other routes	Effects	Dose
Morphine	IV	IM, IO, PO, SC	Analgesia, Sedation, Dysphoria, Nausea, Respiratory depression	No clear maximum. 0.05–0.1 mg/kg starting dose, followed by 2 mg at 5 min intervals, until pain relief achieved
Fentanyl	IV or transmucosal	IO, SL, Buccal	Analgesia, Sedation, Nausea, Respiratory depression	IV given 0.5 μg/kg, and then 20 mpg boluses at 5 min intervals until analgesia achieved OTFC supplied as 400 or 800 μg lozenges. May be repeated. Further doses under medical supervision
Ketamine	IV	IO, IM	Analgesia, Dissociation, Sympathomimetic effects, Psychomimetic effects, Salivation—especially in those of African descent	IV 0.25–0.5 mg/kg bolus for pain relief, titrated for effect and repeated as required under medical supervision
Entonox	Inhaled		Analgesia, Dysphoria, Nausea	50:50 mixture of nitrous oxide and oxygen. Self regulated by patient Not for use if pneumothorax suspected, abdominal distention or suspected bowel obstruction
Methoxyflurane	Inhaled		Analgesia, Dysphoria, Sedation, Hypotension, Respiratory depression, Hepatotoxicity risk with frequent repeated doses	Two 3 mL doses. Do not use on consecutive days, do not exceed more than 15 mL per week Contraindicated in history of malignant hyperthermia

Table 12.3 (continued)

Drug	Preferred route of administration in acute pain	Other routes	Effects	Dose
Diamorphine	IV or Intranasal (IN)	IO, IM	Analgesia, Sedation, Nausea, Respiratory depression	0.025–0.05 mg/kg IV, followed by 1 mg IV at 5 min intervals until clinical effect achieved IN licensed for use in children and adolescents, 720 µg/spray to 1600 µg/spray according to weight and manufacturers instructions
Tramadol	IV	IM, PO bioavailability same for all routes so dose is the same	Analgesia, Sedation, Nausea	25–100 mg up to four times daily. Monitoring is required if used concomitantly with other opioids
Codeine	IV	PO	Analgesia, Sedation, Nausea, Constipation, Antitussive, Antidiarrhoeal	15–60 mg up to four times daily. Monitoring is required if used concomitantly with other opioids
NSAID	IV	IM, PR, PO	Analgesia, Anti-pyretic effect, Gastric irritation, Inhibition of platelet function, potential inhibition of renal flow in hypotension or hypovolaemia	There are many different NSAIDs available with varying side effect profiles. It is beyond the scope of this text to list them all. NSAIDs are valuable adjuncts in acute pain, and aid in reduction of opioid requirements
Paracetamol	IV	PO, PR	Analgesia, Anti-pyretic effects Medication overuse headache in long term use	Adult dose is 1 g up to four times daily. Paediatric dose and those under 50 kg weight—20 mg/kg loading dose, and 15 mg/kg up to four times daily. Do not exceed 90 mg/kg per 24 h

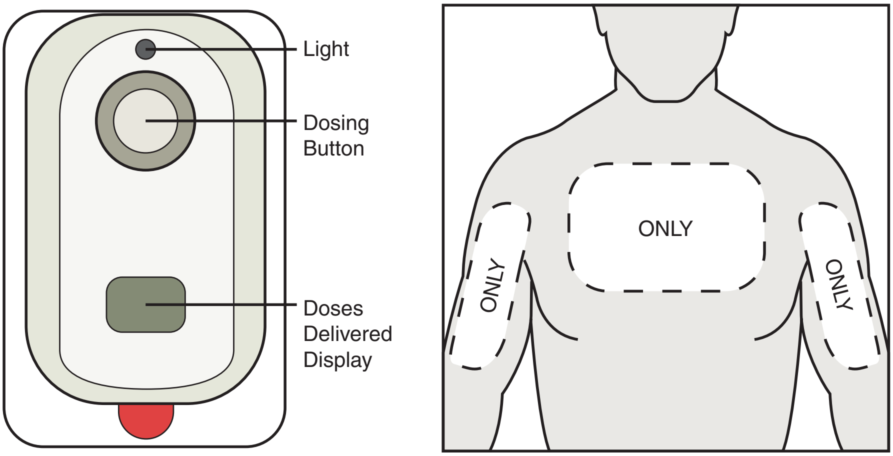

Fig. 12.3 IONSYS Iontophoretic PCA Patch, 40 µg per dose transdermal system. Fentanyl 40 µg per dose transdermal system, maximum of 80 doses (3.2 mg/24 h). With permission from inventive Health Commercial on behalf of The Medicines Company

In the longer term, Fentanyl may be used for ongoing acute pain management via intravenous patient controlled analgesic devices (IVPCA), or via transdermal patches.

A new development is the iontophoretic PCA patch. The advantage of this system lies in the fact that it is a cordless system, which does not require a programmable IV pump, and which can deliver up to eighty 40 µg doses over a 24 h period. At present it is licensed for hospital use only. See Fig. 12.3.

12.7.3 Ketamine

Ketamine is an anaesthetic agent which at lower doses has potent analgesic effects, and has been used widely by UK Armed Forces Medical Services for many years and during many conflicts. It is an extremely versatile and useful drug when used correctly, but in common with every other agent it does have some undesirable side effects. Ketamine is in use across the world as an anaesthetic and analgesic agent, especially in less-developed countries. It is cheap, easy to administer, and does not require expensive or complicated equipment for its use.

Ketamine may be administered via the IM, IV or IO routes. It has a sympathomimetic effect and may give rise to an increase in blood pressure and heart rate following administration. This property makes it useful as an anaesthetic agent in casualties at risk of shock or hypovolaemia.

Although Ketamine has great utility as an effective analgesic agent in the acute phase, it is relatively short-acting, and consideration needs to be given to longer lasting formulations later on. One of the main undesirable side effects of Ketamine

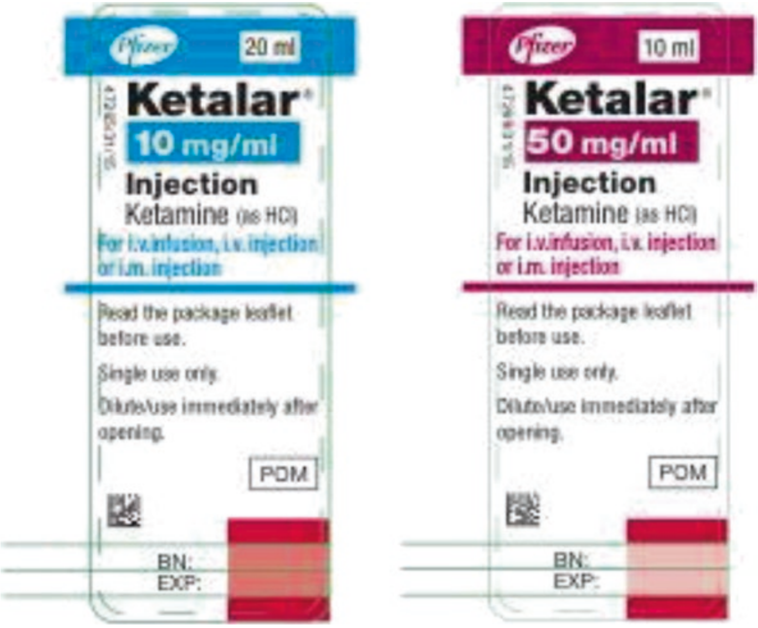

Fig. 12.4 Depicting Ketalar—ketamine as 10 and 50 mg/mL presentations. With permission from Pfizer

is the potential for associated psychomimetic effects such as agitation and hallucination. These can be very adequately dealt with by the co-administration of a very small dose of benzodiazepine, and ongoing care in a calm, quiet environment. Of great importance is that Ketamine is supplied in several different strengths in strikingly similar packaging. It is vital to ensure that this is taken into account when preparing this drug. See Fig. 12.4.

12.7.4 Entonox® BOC

Entonox is routinely carried by most UK ambulance services. Entonox is a ready-to-use medical gas, which is a mixture of 50% nitrous oxide and 50% oxygen that provides rapid, safe and effective short-term pain relief. The gas is inhaled via a purpose-designed mouthpiece with a demand valve. Thus the amount of gas delivered depends entirely on the casualty's need, as it only delivers agent when actively inhaled from the mouthpiece. It is extremely fast-acting and also has a fast offset. For rapid, short-acting pain relief in moderate to severe pain it can be extremely useful. It is especially well suited to aiding in procedures such as fracture splinting or dressing changes. Entonox has an excellent safety profile, and has been safely used for decades, including in the obstetric population. The main side effect in short-term administration is nausea. Although excellent for short procedures, or for

Fig. 12.5 Penthrox (Methoxyflurane) inhaler. With permission of Galen Limited

short-term pain relief, Entonox is not suitable for ongoing treatment of acute pain, or for chronic pain and break-through pain.

12.7.5 Methoxyflurane

Methoxyflurane is an inhaled anaesthetic agent, which when used in low dose is reported to give good pain relief in moderate to severe pain. It is known colloquially as the "green whistle" and has been used in Australia and New Zealand, and by their military medical services for many years. Due to potential for side-effects, its use is strictly limited to short-term, acute pain relief, and it is not suitable for use in relief of chronic pain or break-through pain. It has very recently been introduced to the UK and several ambulance services have taken up its use already. Ease of use, and relatively rapid onset to pain relief following six to ten breaths, may well lead to its increased uptake in the future. See Fig. 12.5.

12.7.6 Diamorphine

Diamorphine has been used extensively in the past, especially for pain in palliative care and pain of cardiac origin, but in recent years its use has been severely limited by global supply issues. Due to its chemical composition, Diamorphine has roughly twice the potency of Morphine. Diamorphine has a potent analgesic effect, as well as a degree of sedation and anxiolysis.

More recently Diamorphine use, other than by the intravenous route, has become more common. In paediatric analgesia, intranasal Diamorphine has long been used successfully to deliver rapid onset of good quality analgesia. Specific preparations are now available for this purpose in children, and there is more evidence that this method of the drug's delivery is safe and effective in adults too. [26] See Fig. 12.6.

12.7.7 Tramadol

Tramadol is described as a 'weak' opioid, and has similar effects to morphine. It has a unique mode of action via a weak effect at opioid receptors and inhibition of nor-adrenaline reuptake, as well as potentiating serotonin release, through which it is

Fig. 12.6 Intranasal diamorphine—Ayendi dispensers. Note differing doses, and volumes, specific to body weight. With permission from Wockhardt UK

believed to cause descending inhibition of nociception. Oral bioavailability is very high, with administration approaching the same bioavailability as IV with repeated doses. It is said to cause less cardiovascular and respiratory depression than Morphine, but shares the common side effects of nausea, sedation and drowsiness. It is contraindicated in patients taking monoamine oxidase inhibitors, or with a history of epilepsy.

12.7.8 Codeine

Codeine is also described as a 'weak' opioid, with about one sixth of the potency of Morphine. Codeine is a natural opioid, and is one of the principal opium alkaloids. It can be argued that Codeine is a pro-drug of Morphine, its metabolites being morphine-glucuronides. Codeine metabolism to Morphine depends on isoforms of cytochrome P450, and approximately 15% of the UK population are poor metabolisers of Codeine, and as such, true non-responders to the drug. Conversely, there are others who are 'fast' metabolisers, in whom one may see an excessive response. Codeine is no longer recommended in pain in paediatric patients. Codeine is much less sedative than Morphine, and less likely to cause respiratory depression. Nausea and constipation are seen often, and this latter, common side effect is often used to good effect in antidiarrhoeal preparations.

12.7.9 Non-Steroidal Anti-Inflammatory Drugs (NSAID)

NSAID are a very useful adjunct in treating acute pain. Although predominantly used for mild to moderate pain, they are key in helping to reduce opioid requirements, and as part of a balanced multi-modal analgesic regime. There are many NSAID in use and it is beyond the scope of this text to describe them all. NSAID work by inhibiting the action of the cyclooxygenase system (COX) and as well as producing pain relief and having good antipyretic effects, they have several other significant effects. The main issues are adverse effects on the gut via gastric irritation, interference with coagulation via platelet inhibition, a risk of severe asthma attacks in around 20% of asthmatics, as well as a potential for inhibition of renal function via their effects on renal prostaglandins. This last effect is especially important to consider if administering these drugs in hypotensive or hypovolaemic casualties, in whom renal function may already be compromised. Finally there has been some work suggesting that NSAID may delay long term fracture repair.

12.7.10 Paracetamol

Paracetamol is used in mild to moderate pain. Its exact method of action is not known, but it has analgesic and antipyretic effects. When used with other analgesics, it is said to display synergistic properties, with greater pain relief seen than with using the drugs alone. Due to the fact that it is easily obtainable without prescription, it is often undervalued, but its concomitant use as part of a balanced multimodal analgesic regime will aid in reducing opioid requirement.

12.8 Unconventional Analgesics in Suspected Nerve Injuries

This section will briefly look at the use of medications which are thought to be of use in reducing the later development of persistent or neuropathic pain.

Neuropathic pain is that occurring due to damage or disruption involving nerves. Neuropathic pain guidelines suggest the use of anti-neuropathic medications such as Tricyclic Anti-Depressants (TCADs) and the Gabapentinoids such as Pregabalin and Gabapentin.

The experience of the UK Military Medical Services has been to start treatment against neuropathic pain at an early stage, and where significant nerve injury is suspected, most casualties will be commenced on significant doses of TCAD, usually Amitryptiline, and Pregabalin. It is suggested that anti-neuropathic agents reduce opioid requirements, but the evidence for this remains unproven. At the very least, these agents aid sleep in what is often an extremely distressing and traumatic time for the patients, in terms of physical, physiological and psychological upset.

12.8.1 Amitryptiline

Amitryptilline is the most well-known TCAD, and is the usual first choice drug when selecting from this family. It is used in doses far lower than those seen when it used for depression. One of the barriers to its use is the stigma attached to taking anti-depressant medication, for a condition which is entirely different. For this reason it is very important to educate the patient on the rationale for this medication choice. Initially TCADs are very sedating, and will be associated with a degree of hangover, or mental fogging the day after. In time this, and the nausea which sometimes accompanies its use, will dissipate. As well as aiding sleep, and improving quality of sleep, TCADs can also aid with pain, and muscle spasm associated with pain. Dry mouth is a quoted side effect. Within the TCAD family, there are several other choices, which may suit individuals better, and which in the longer term are said to be better tolerated due to decreased prevalence of side effects.

12.8.2 Gabapentinoids

Gabapentinoids such as *Pregabalin* and *Gabapentin* are used for treatment of neuropathic pain, and it is intuitive that their use in casualties with nerve injuries will help to reduce the incidence of ongoing, persistent nerve pain. Again this has yet to be established by good clinical studies, but in the meantime, their use aids in reducing the opioid requirement, and like TCADs, will aid sleep. UK military casualties are routinely commenced on Pregabalin. This has the advantage of being a twice daily regimen versus Gabapentin's three times daily, and it also has a narrower dose range, potentially making it easier to tailor dose to need. Common side effects with the gabapentinoids include sedation, and nausea. Some patients also report weight gain.

12.9 Summary

Pain management has made huge leaps forward in recent years. It is now widely and rightly acknowledged that good, effective and timely pain relief is the correct thing to do. Furthermore the casualty has a moral right to receive good pain relief where facilities exist for its provision. It has been shown that not only is pain relief desirable from a humanitarian point of view, but it also has many benefits to the patient, both in terms of physiological benefits and meaningful rehabilitation in the shorter term, and in reduction of later psychological sequelae such as PTSD.

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13 Damage Control Surgery and Ballistic Injury to the Trunk

David O'Reilly

The first part of this chapter discusses Damage Control Surgery (DCS), which is the modern approach to the surgical management of seriously injured patients with deranged physiology. DCS was developed for the management of abdominal injuries so this fits naturally with the second part of the chapter, which discusses the presentation and management of specific ballistic injuries to the trunk. Vascular injuries (including junctional trauma) are discussed in Chap. 19, while genitourinary injuries are discussed in Chap. 20.

13.1 Development of Damage Control Surgery

The term "Damage Control Surgery" was coined in 1993 by Rotondo et al. [1] in an influential paper on the management of patients with severe penetrating abdominal injury. The term derives from naval practice in dealing with a damaged vessel: immediate threats to the ship, such as a rupture in the hull are dealt with quickly using the materiel that is to hand; the resulting repair is likely to be only temporary but allows the ship to stay afloat and to operate (or, in the context of combat, to fight); definitive repair is delayed until it can be achieved safely.

That speedy and judicious surgical intervention is crucial to the outcome of injured patients is no novelty: in 1812, Larrey (Napoleon's surgeon) wrote concerning amputation after gunshot wound that "The first 24 hours is the only period during which the system remains tranquil, and we should hasten during this time, as in all dangerous diseases, to adopt the necessary remedy." [2] The period considered

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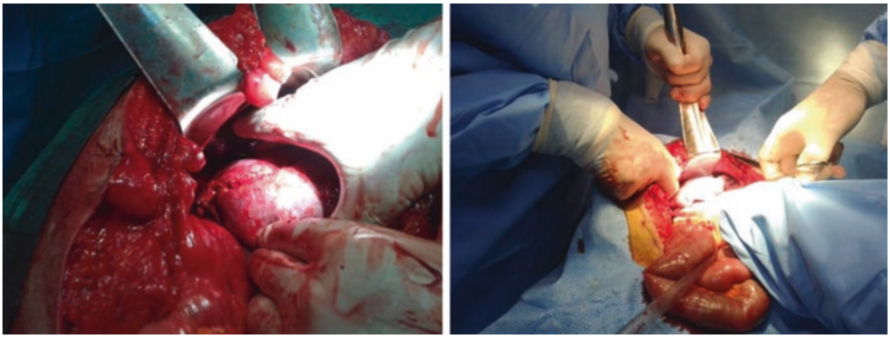

Fig. 13.1 A substantial liver injury due to ballistic injury. Both images are taken from the foot of the operating table; the retractors are being pulled towards the right shoulder. Bleeding was effectively controlled with packing

critical has shortened since then, through Cowley's "Golden Hour" to the "platinum ten minutes", (although little evidence supports these specific cut offs) [3]. However, the key insight of DCS is that **the anatomy and physiology of an injury can in fact be competing priorities, and that the latter should trump the former**. Before DCS, standard practice was the immediate repair of all injuries (i.e. fixing the anatomy), without adequate regard for the patient's physiology.

The management of liver injuries has been crucial to the development of DCS. In 1908, Pringle described controlling hepatic bleeding using digital occlusion of the portal triad. This is, of course, a manoeuvre that can only be maintained for a short time. Pringle advocated deep sutures to permanently arrest bleeding, with packing as an adjunct. Packing was advocated by other surgeons in the early twentieth century but fell out of fashion during the Second World War due to poor outcomes [4] (see Fig. 13.1). These were seen in the context of mandatory exploration of all suspected liver injuries without the benefit of modern critical care and with packs left in situ for long periods, making removal traumatic. Hepatic suture, selective ligation of the hepatic artery [5, 6] or formal liver resection [7, 8] were advocated.

In time, it became apparent that such major interventions were not appropriate in the most severely injured patients (who most needed effective haemostasis) because of these patients' physiological state. Packing of liver injuries was described again in the 1970s [9, 10] and this set the stage for the introduction of DCS.

A series of papers (beginning with that of Stone et al.) [1, 11, 12] then tackled the problem of severely injured patients with coagulopathy, demonstrating that early termination of laparotomy by ligation of vascular injury, stapling (or tying) of injured bowel and packing of other haemorrhage led to improved outcome. The physiological derangement was characterised by Burch as the "lethal triad": coagulopathy, acidosis and hypothermia [13]. While the understanding of trauma physiology has progressed, these three mutually exacerbating abnormalities remain important markers of the need for DCS. The practice spread in American trauma centres before becoming established as the standard of surgical practice by the turn of the century [14].

Subsequently the damage control approach was extended to the management of serve injuries in other parts of the body. Shunts became an increasingly important part of the management of vascular injury. The concept of damage control orthopaedics was developed, recognising that definitive management of multiple fracture, particularly involving intramedullary nailing, can greatly add to the inflammatory insult, with consequent worsening of adult respiratory distress syndrome and multi-organ failure [15, 16]. Registry data demonstrates an increased use of initial external fixation in multiply injured patients, with later delayed definitive care [17].

However, DCS in its mature form is best understood as one component of the modern approach to the management of severely injured patients: damage control resuscitation (DCR). DCR is discussed in detail in Chap. 11. In brief, in the period since the turn of the century there has been a much greater appreciation of the nature and extent of physiological derangement early after trauma, in particular the development of coagulopathy [18–20]. This has occurred in parallel with a developing appreciation of the effects of resuscitation practice, particularly the use of hypotensive resuscitation [21], limited use of crystalloid fluid and the aggressive use of blood products with a high ratio of plasma to red blood cells [22, 23].

These developments have led to a change in the use of the damage control approach to trauma surgery. Classically, DCS was described as consisting of three (later four or five) stages [24]:

- Stage 0: Rapid transport to definitive care and recognition of need for DCS (added later)
- Stage 1: Rapid control of haemorrhage and contamination (abbreviated laparotomy)
- Stage 2: Resuscitation (restoration of physiology in the intensive care setting)
- Stage 3: Return for completion of operative repairs
- Stage 4: Definitive abdominal closure (also added later to acknowledge that fascial closure may not occur at the time of definitive injury management).

Thus emphasis on the restoration of physiology was reserved until after the initial operation, as demonstrated in Fig. 13.2.

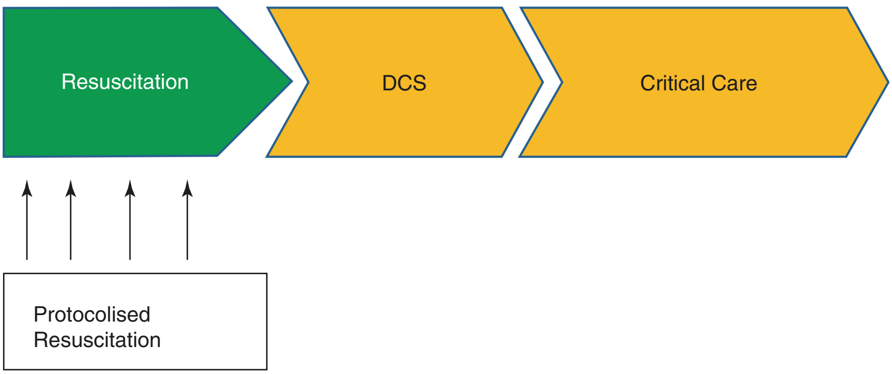

Fig. 13.2 Traditional paradigm of DCS. Modified from Midwinter [25]

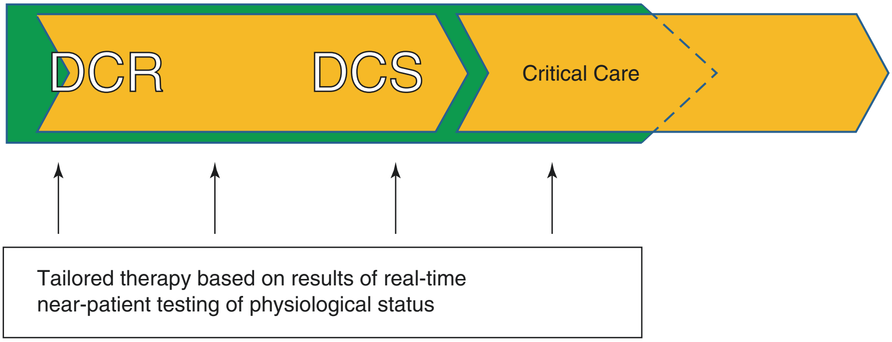

Fig. 13.3 DCS as an integral component of DCR. Modified from Midwinter [25]

By contrast, under the DCR approach, the management of the patient's physiology is central from the beginning and DCS takes place in parallel with resuscitation, as shown in Fig. 13.3.

Indeed, military experience has shown that DCR can be initiated in the prehospital setting, delivering a healthier patient to the surgeon [26, 27], and then continued during surgery, thereby restoring the patient's physiology before surgery is completed [28]. This raises the possibility of proceeding to definitive repair at this stage in a subgroup of patients who otherwise would have required time on ITU before returning to theatre. As discussed later, decision making in DCS has always required close liaison between the surgeon and the anaesthetist but this is doubly true now that an initial decision to employ damage control techniques can lead on, in combination with the other elements of DCR, to the patient becoming fit for immediate definitive repair.

13.2 Techniques in Damage Control Surgery

The operative techniques that are employed in DCS can be thought of in three overlapping categories: resuscitative, abbreviating and definitive. Resuscitative interventions are those intended to immediately improve the patient's physiology or stop exsanguinating bleeding. The effects of these techniques may preclude their being employed for more than short periods. Cross clamping of the descending aorta, the lung twist and Pringle's manoeuvre are examples of this. Abbreviating measures are those that allow surgery to be safely terminated more quickly than would be the case using the *standard* definitive management. Definitive measures are those which are intended to conclusively manage an injury and may be employed during initial surgery or may supersede abbreviating techniques used previously. (Definitive management may nonetheless require more than one intervention, for example wound debridement with a planned relook operation.) Arterial shunting is an abbreviating technique whilst arterial ligation is both abbreviating and definitive. Packing of the liver falls into all three categories:

- it can be employed as a resuscitative measure at the start of a laparotomy, arresting bleeding and facilitating resuscitation before surgery continues,

- it can be used to abbreviate the operation, perhaps facilitating transfer to the care of a specialist and
- it can be the definitive management of an injury (perhaps in combination with angioembolization).

By choosing techniques from these categories the surgeon can achieve three goals, which have the following order of priority:

1. Supporting the patient's physiology, arresting haemorrhage and removing contamination,
2. Preventing the operation adding *unduly* to the physiological stress on the patient,
3. Achieving definitive repair.

Understanding the patient's physiological status and burden of injury and appreciating how these will interact is therefore crucial to the selection of surgical techniques.

13.3 Indications for DCS

Wherever possible the need to employ DCS should be identified by the treating team before surgery begins and before the patient enters a downward physiological spiral. This will allow surgery to be expedited and then abbreviated; in combination with appropriate resuscitation, this may prevent the lethal triad from ever developing. However, severely injured patients often present with serious physiological problems. About 30% of trauma patients develop an endogenous coagulopathy that will be present at hospital admission [18, 29]. These patients are shocked and severely injured and they have a high mortality [30].

Rotondo and Zonies laid out indications for DCS in 1997, using the useful headings of conditions, complexes and critical factors, as shown in Table 13.1 [24]. Despite advances in the understanding of trauma physiology, this list remains sound.

Table 13.1 Key factors in patient selection for damage control

Conditions	High-energy blunt torso trauma
	Multiple torso penetrations
	Haemodynamic instability
	Presenting coagulopathy and/or hypothermia
Complexes	Major abdominal vascular injury with multiple visceral injuries
	Multifocal or multicavitary exsanguination with concomitant visceral injuries
	Multiregional injury with competing priorities
Critical factors	Severe metabolic acidosis (pH <7.3)
	Hypothermia (<35 °C)
	Resuscitation and operating time >90 min
	Coagulopathy as evidenced by development of non-mechanical bleeding
	Massive transfusion (>10 u packed red blood cells)

It should be extended to encompass indications for damage control surgery outside the trunk, such as multiple long bone and pelvic fractures, or combined orthopaedic and neurosurgical injuries as indications for the use of damage control orthopaedics. At the time of its writing coagulopathy was identified by laboratory tests or seen clinically. In current practice, near patient testing, such as thromboelastography, can quickly identify significant coagulopathy before it develops into severe non-surgical bleeding [31].

As mentioned above, effective DCR may restore a patient's physiology, such that the surgeon may wish to proceed on to definitive repair without first sending the patient to intensive care. If successful, such a strategy could spare the patient a second procedure and avoid the need for measures such as temporary abdominal closure and a period of intubation and ventilation. There is as yet only limited data to support this approach. As such, it should be employed only sparingly and by experienced clinical teams.

The need for DCS may be recognised before surgery or the patient may deteriorate during the operation. In the former case the surgeon's success will depend on the adequacy of resuscitation carried out by colleagues. In the latter case, the surgeon cannot make a proper assessment of the patient's condition without knowing what resuscitation has been given and how the patient has responded. For these reasons, communication is absolutely crucial to successful DCS.

13.4 Communication During DCS

The importance of good communication within an operating team is well recognised [32]. The enhanced communication engendered by the WHO surgical safety checklist may be more important to its demonstrated efficacy than any one of the individual items on the list [33, 34]. In severe trauma the patient is unstable and the pace of events is very fast. Critical decisions must be made and then reconsidered repeatedly. At the same time, every member of the team has technically complex tasks to complete. This raises the danger that individuals will become task-focused as they pour everything they have into the attempt to save the patient. They may therefore lose situational awareness [35]. Informal conversation between surgeon and anaesthetist ("How's he doing?") does not ensure that the full picture is communicated in a consistent and timely fashion. Trauma teams, whether in the ED or the operating theatre, often assemble at short notice and are unfamiliar with one another.

For all these reasons, it is necessary to employ a communication strategy that is quick and simple, iterative, formalised and transferable. The UK Defence Medical Services have developed just such a framework [36]. As part of a broader commitment to engaging with the importance of human factors [37], particularly through training [38], this has contributed to the remarkable improvement in injury outcomes seen in recent conflict [39].

The strategy has three components. The first stage, the "Command Huddle", recognises that DCS decision making begins in the resuscitation bay. The second stage, the "Snap Brief", allows the quick transfer of relevant information from the reception/resuscitation team to the team in theatre. The third stage consists of regularly repeated "Sit Reps": discussions between surgical and anaesthetic teams about the patient's progress. During each, the following information needs to be communicated:

1. Futility or otherwise of resuscitation of the patient. An early decision about this must be made in order to optimise resource allocation
2. Surgery:
   a. Surgical plan and priorities (where DCS is required, this should be articulated clearly to ensure all of the team are aware)
   b. Anticipated duration of procedure
3. Transfusion:
   a. Amount and type of blood products transfused so far
   b. Rate of transfusion
   c. Other products such as whole blood or cryoprecipitate requested
4. Coagulation:
   a. Coagulopathy (e.g. result of ROTEM®)
   b. Coagulation adjuncts used (tranexamic acid, recombinant Factor VIIa)
5. Physiology:
   a. The Base Excess (a sensitive guide in resuscitation)
   b. Patient's temperature

The **Command Huddle** occurs early in the patient's care, usually after the primary survey and (if appropriate) initial fluid therapy. The trauma team leader directs a discussion between the senior surgeons in the relevant specialties and the anaesthetist. In the military context, all of these individuals will be consultants. This may not be true in the civilian setting, especially in units that do not see high volumes of trauma. This only enhances the importance of the discussion: by establishing a shared understanding of the patient's priorities it can give weight to what might otherwise be the decision of a junior member of the team. Two decisions need to be made. The first is whether it is appropriate to continue with resuscitation and treatment. This includes an assessment of whether there is a reasonable prospect of the patient surviving with adequate function (e.g. it may not be appropriate to treat a patient with a large penetrating brain injury and persistent shock). It may also be appropriate to consider the available resources and the needs of other patients, be they present or expected. These considerations are routine in military practice and will arise for civilian practitioners during mass casualty events. The second decision is whether the patient's injuries and physiology require immediate surgery, further investigation (usually CT) or further resuscitation and observation (whether on ITU or the ward). The necessary timing of these forms of disposal is crucial: a shocked patient and a stable one with eviscerated bowel both need surgery but the urgency is very different.

The **Snap Brief** allows the surgeons, anaesthetists and operating department staff to quickly form a team operating from a shared understanding of the patient's injuries and physiology. The surgeon gives the clinical and imaging findings and states the operative plan. The anaesthetist details the transfusion, coagulation and physiological parameters. The start time should then be recorded and surgery can begin.

During surgery the lead anaesthetist should initiate a **Sit Rep** every 10 min. The duration of surgery so far and the transfusion, coagulation and physiological parameters should be stated. The surgeon then details operative findings and progress and states the surgical plan.

13.5 Outcomes of Damage Control Surgery

No randomised trials have been conducted to demonstrate the superiority of the DCS approach [40]. Non-randomised studies all suffer from bias due to difficulty balancing physiological and anatomical factors between the intervention and control groups and confounding changes in other aspects of care. Since DCS in now part of DCR, one must look at some of the older studies to understand the efficacy of DCS in isolation. In 2000, Shapiro et al. published a collective review of 1001 patients managed with DCS [14]. The mortality was 50% which compares very favourably with earlier outcomes for patients with the "triad of death", where mortality was greater than 90% [41].

13.6 Assessment and Management of Thoracic Injuries

13.6.1 Indication for Immediate Thoracotomy

During the initial assessment of a patient with ballistic injury to the chest, the first task for the surgeon is to differentiate between patients who require immediate (emergency room) thoracotomy, those who require thoracotomy but can safely be transported to the operating theatre and those who can be initially managed and investigated in the resuscitation bay. Patients in cardiac arrest or who are in danger of losing cardiac output should have immediate surgery [42] after intubation and bilateral finger thoracocentesis. Some controversy exists about the contraindications to immediate thoracotomy: concomitant head injury, multisystem trauma or more than 15 min of cardiopulmonary resuscitation are sensible restriction that are well supported by the literature [43]. Asystole without pericardial tamponade (assessed by focused assessment with sonography for trauma [FAST]) also indicates futility [44]. Because penetrating injury generates a preponderance of injuries that are readily corrected, survival after ED thoracotomy is better than in blunt trauma [43–45]. However, this is less true of ballistic injury than of stabbings.

13.6.2 Tension Pneumothorax

However, the vast majority of patients will complete primary survey with CXR and, usually, FAST. Tension pneumothorax should be excluded in any haemodynamically unstable patient with chest trauma [46]. This is far more common in patients who have been intubated and ventilated than in awake patients. In the former case, positive pressure ventilation pushes air into the pleural space, whereas in the latter the normally low levels of negative inspiratory pressure tend not to entrain large volumes unless there is injury to a major airway or a sucking chest wound. In awake patients, respiratory compromise will usually manifest well before the embarrassment of venous return and cardiac filling. In ventilated patients, evidence of cardiovascular compromise occurs earlier. Classical signs of tension pneumothorax (tracheal deviation, engorged neck veins, hypertympanic and hyperinflated hemithorax) are late developments. Needle thoracocentesis can be effective for the relief of tension pneumothorax but can easily fail in obese or muscular patients (soldiers being a particular example of the latter) or when the needle becomes kinked or blocked. It is therefore a prehospital intervention. Finger thoracocentesis by incision and dissection in the fourth intercostal space in the mid-axillary line allows the finger to be inserted to decompress the pleural space and is extendible to achieve thoracotomy when appropriate. If an intercostal drain cannot be placed immediately, the finger may be reinserted whenever there is suspicion of recollection of gas.

Ballistic injury can cause an open pneumothorax with a sucking chest wound. If the thoracic wall defect provides less resistance to the flow of air than the trachea, then air will be preferentially entrained via the defect into the pleural space during inspiration. A large pneumothorax with features of tension may ensue. Management of such a wound is by an occlusive dressing and chest drainage (and subsequent appropriate closure of the defect). Where this is not achievable (in the prehospital environment, for example) a dressing that is sealed at three edges but open at the other or which incorporates a valve (such as the Asherman Seal) may be used. In theory these should allow the egress of air while occluding the wound during inspiration. Results are variable.

13.6.3 Haemothorax and Simple Pneumothorax

Intercostal drains are also indicated in patients with significant haemothorax or non-tension pneumothorax. These will often coexist and dual drainage (an anterior drain directed to the apex for air and a posterior [back] drain for blood at the base) is then needed.

The drainage of haemothoraces is both therapeutic and investigative. While a small haemothorax will not compromise the ventilation acutely, a restrictive defect due to fibrothorax can develop once the clotted blood begins to organise. These patients can go on to require open decortication of the lung. Empyema is also a common (16%) complication of retained haemothorax [47]. Therefore only very small (<200 ml) haemothoraces should be treated conservatively. Equally, significant retained haemothoraces diagnosed later in the patient's management, often after incomplete drainage, should be evacuated. Video-assisted thoracoscopic surgery is the usual means of achieving this.

Simple pneumothoraces should be drained in most cases. Small pneumothoraces in well patients, particularly occult pneumothoraces that are only detectable on cross-sectional imaging (more common in blunt than penetrating trauma), can also be managed conservatively, although they will often require a period of monitoring [48]. However, in a ventilated patient they should be drained to prevent the development of tension.

The selection of patients for operating room thoracotomy is driven by the haemodynamic response to initial resuscitation including thoracocentesis, intercostal drain output and imaging. Criteria for operative intervention vary [42, 47] and often concentrate on the output of blood from the chest drain. Initial drainage of more than 1500 ml or 200 ml per hour for more than 4 h are typical. However, a clotted haemothorax may not produce much output and cardiac tamponade will not be detected at all. Transient or absent response to resuscitation and thoracocentesis is therefore an indication for surgical exploration. In a sufficiently stable patient, CT may resolve diagnostic doubt. Rarely, a relatively stable patient may have persistent haemorrhage with arterial extravasation on imaging. Catheter embolization is an option in such cases. Thoracotomy is also indicated for persistent air leak.

13.6.4 Cardiac Injury

Cardiac injury after ballistic injury has features distinct from those usually seen after a stabbing. A low velocity bullet or fragment injuring the heart will typically cause a disruptive injury to more than one cardiac structure, e.g. by traversing the right ventricle, intraventricular septum and left ventricle. The potential for the cardiac injury to be incompatible with adequate cardiac function is therefore greater than in the case of, say, linear penetration of the right ventricular wall due to a stabbing. The latter injury may be compatible with life if cardiac tamponade is relieved; the former may not be. Hence operative mortality for cardiac gunshot wounds is 81% [49]. However, survival after ventricular penetration, with the bullet lodged in the cardiac muscle, retained in the heart or embolized, is well described [50, 51]. Low-energy transfer projectiles can cause salvageable cardiac injuries, particularly if they pass tangentially.

As with tension pneumothorax, the classical signs of pericardial tamponade (muffled heart sounds, engorged neck veins, Kussmaul's sign) develop late or are difficult to detect. Cardiac injury should therefore be suspected in any patient with compromised circulation and wounds that suggest the projectile may have traversed the heart. FAST is an excellent means of detecting pericardial fluid. Needle pericardiocentesis is a poor diagnostic tool ("a needle with a clot at each end"). There is a limited role for using a subxyphoid window (extraperitoneal dissection through a short midline incision below the xyphisternum to allow the pericardium to be opened and its contents assessed from below) as a diagnostic manoeuvre where no ultrasound is available. It should be reserved for when the suspicion of tamponade is low and the surgeon wishes to avoid the morbidity of a thoracotomy. While tamponade may be relieved briefly by this route, it does not allow repair and the surgeon should proceed to thoracotomy or sternotomy. The author has experience of one patient who had a low volume haemopericardium and developed tamponade several days later as the collection of blood began to break down and grow in size due to the action of osmosis (a phenomenon more familiar after subdural haemorrhage). This was effectively managed via a subxyphoid window. A window in the pericardium is a useful way of assessing the heart in a patient who becomes unstable during laparotomy. Electrocardiography and trans-thoracic or trans-oesophageal echocardiography are useful for the detection of injuries affecting the blood supply, conduction apparatus and valves of the heart in injured patients with evidence of cardiac insufficiency without tamponade.

13.6.5 Posterior Mediastinum

Injury to the aorta and great vessels is covered in Chap. n. Injury to the oesophagus should be suspected in patients with a transmediastinal ballistic injury. Clinical signs of oesophageal injury (haematemesis, dysphagia, stridor and epigastric tenderness) may be masked or delayed. CXR may show non-specific findings including left pleural effusion (likely to be taken for a haemothorax) and pneumomediastinum. The suspicion of oesophageal injury will often be raised by the path of a projectile as defined by CT [52, 53]. Adjacent air bubbles or bullet/bone fragments are suggestive while thickening or discontinuity of the oesophageal wall are diagnostic. In a stable patient, suspicion of oesophageal injury should prompt further investigation. In awake patients, a contrast oesophagogram using water-soluble contrast should be performed. Where clinical suspicion is high, a further study using barium is often recommended, and there is evidence that this increases the sensitivity in the detection of postoperative oesophageal leaks [54]. It is not clear whether the change of contrast agent provides the benefit or simply the repetition of the test. CT with oesophageal contrast may be used instead. Extravasated barium must be washed out to prevent mediastinitis so should not be used if immediate surgery is not possible. Oesophagoscopy can visualise injuries that are not revealed by contrast studies (the mucosal defect may be small or non-existent). It does not give good views of the oropharynx so is less useful in neck injuries. In intubated patients in can be more difficult to obtain contrast images but this can be done drawing the NG tube into the oesophagus and while injecting contrast [52]. Where resources such as CT and endoscopy are not available, it may be appropriate to exclude oesophageal injury operatively: the consequences of a missed injury are far worse than those of a negative thoracotomy [55].

Injury to the thoracic duct will present as chylothorax, haemochylothorax or at surgery for other reasons. Pleural fluid triglycerides above 1.24 mmol/l are diagnostic; levels above 0.56 mmol/l require lipoprotein analysis to detect chylomicrons; below this chylothorax is unlikely [56]. Chyle leak can result in severe nutritional and fluid losses. If losses are less than 1.5 l/day then conservative management may be appropriate with reduction of chyle flow by excluding lipids other than medium chain fatty acids from enteral feeding. At surgery, injecting cream with methylene blue into the stomach may help identify the thoracic duct. Mass ligation of the tissue between the descending aorta and the azygous vein is the definitive manoeuvre.

13.7 Operative Management of Chest Injury

Anterolateral thoracotomy, extendible to bilateral "clamshell" thoracotomy (Fig. 13.4), is the default incision for the management of ballistic chest trauma. Sternotomy is to be preferred for treating injury to the aortic arch and its branches although it may not

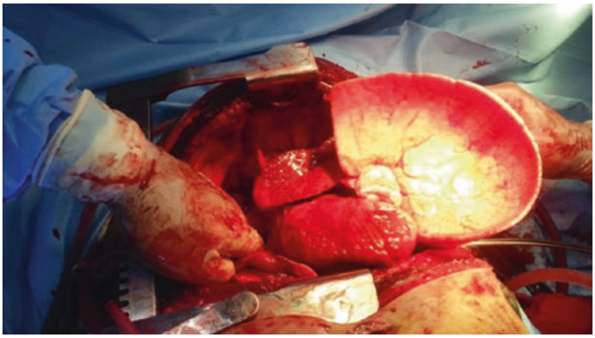

Fig. 13.4 A clamshell thoracotomy. The image was taken from the foot of the operating table. The pericardium has been opened widely to expose the heart. The right lung is retracted by the surgeon's hand. The left lung, ventilated with positive pressure and unrestricted by the abdominal wall, has hyperinflated; excessive expansion of the lungs should be avoided

give superior access to the left subclavian artery. Sternotomy provides excellent exposure of the heart and, unlike clamshell thoracotomy, preserves the internal thoracic arteries for use in the (rare) revascularisation of coronary arterial injury. However, it provides limited access to the pleural cavities and a sick trauma patient will not easily tolerate the additional manipulation of heart and lungs that this may necessitate (especially on the left). It provides poor access to the posterior mediastinum and the intercostals. Other conduits for revascularisation can be used. Sternotomy should therefore be reserved for the unusual situation where there is no doubt about the location of all injuries and it is the best approach. Posterolateral thoracotomy also has a role for some well-defined injuries located posteriorly. Some surgeons prefer to place an ipsilateral wedge under the patient to improve exposure. The disadvantage arises if the zone of injury in fact crosses the midline. Positive pressure ventilation must be established before thoracotomy abolishes the negative inspiratory pressure.

The great majority of salvageable operative injuries in the chest can be dealt with, at least initially, using a very limited set of instruments: a knife and heavy scissors (or other means of dividing the sternum), one or two Finochietto retractors (one is needed for anterolateral thoracotomy; in a clamshell an assistant can provide decent exposure without either of them), Roberts or similar clips, 2-0 polypropylene sutures with forceps and needle holders, and swabs and suction. Quick access to these in the ED (or the prehospital environment) will allow decompression of pericardial tamponade, manual or suture control of cardiac and pulmonary haemorrhage, use of the lung twist and compression of bleeding from other sources, such as the intercostals. With a little more equipment the aorta can be occluded by a clamp or other means. Depending on the situation and available resources, the patient can then be transported to the operating theatre for definitive surgery.

Open cardiac massage can be performed if the patient has no output after the pericardium has been opened and any injury to the heart is closed. The heart should be milked between two flat hands from the apex towards the outflow tracts. The apex must not be raised as this will reduce "diastolic" filling. Adequate compressions combined with proper ventilation can be demonstrated by observing a rise in expired CO_2. Attention should be paid to the physiological consequences of cardiac arrest; in particular by administering insulin to counteract hyperkalaemia. The intention is to supplement cardiac output, particularly allowing the myocardium to be perfused. If the muscle is does not fibrillate or attempt to contract, particularly if it feels firm, or if there is no filling after rapid resuscitation, this will be futile.

A description of the surgical techniques to be used during trauma thoracotomy is beyond the scope of this chapter. The pericardium should be opened in every case. Salvageable cardiac injuries are amenable to direct suture repair. Bleeding from the lungs can be controlled by non-anatomical resection or tractotomy. More central bleeding may require a lung twist or even a pneumonectomy. These increase the vascular resistance faced by the right side of the heart, leading to heart failure and physiological collapse. Mortality is 50% or more [57]. Oesophageal injuries can occasionally be repaired but drainage and later reconstruction is often appropriate. After a clam shell thoracotomy, the chest should be closed with five drains: two for each hemithorax and one for the pericardium. The latter should not be closed, but also not left so widely open that the heart can twist around the vessels and sublux into the right chest.

13.8 Assessment of Ballistic Injury to the Abdomen

13.8.1 The Unstable Patient

Fluid resuscitation of patients with ballistic trauma prior to reaching hospital should be minimised [21]. Where the patient is exsanguinating, boluses of fluid can be given, titrated to maintain consciousness and/or a radial pulse. Ideally, blood products should be used [27]. Once the patient reaches a surgical facility, they should be assessed rapidly. **Patients with haemodynamic instability or signs of peritonitis after ballistic injury to the abdomen require immediate laparotomy.** Where there is only modest hypotension or no overt shock (i.e. there may be mild tachycardia and a narrowed pulse pressure), a fluid bolus can be administered to assess the patient's response. This is only appropriate if non-operative management is to be considered (see below). In all other cases, resuscitation should be minimised until the source of bleeding has been controlled.

Except where the CT scanner is an integrated part of the trauma bay and the scan can therefore be performed without delay to the patient's surgery, there is no indication for scanning the patient: the laparotomy allows definitive investigation of all abdominal injuries. FAST scan can be useful for prioritising between abdominal and thoracic surgery if either region could be the site of major bleeding (see Chap. 10 imaging).

13.8.2 The Stable Patient

The management of the haemodynamically normal patient (without peritoneal signs) after ballistic injury is more controversial. Non-therapeutic laparotomy can be associated with morbidity, although the rate of reported complication rate varies from 12 to 41% [58–60]. **Peritoneal signs mandate laparotomy.** Selective non-operative management (SNOM) of ballistic injury is less widely accepted than in the case of stabbings. Nonetheless, successful use of this approach has been described by a number of centres. No surgeon would be criticised for performing a laparotomy on a patient with ballistic abdominal injury and this must always be regarded as the standard approach.

After a high energy-transfer ballistic injury, there will be extensive soft tissue damage to the abdominal wall such that a laparotomy is indicated even for a tangential injury. The question of SNOM arises in low energy-transfer injury. Fragmentation injury that does not penetrate the abdominal wall on CT should be treated by local debridement alone [61]. Where a bullet or fragment has penetrated the peritoneum, SNOM may be appropriate if all of the following criteria can be satisfied:

- The patient is haemodynamically stable, with no peritoneal signs and no evisceration of bowel.
- The patient is awake and alert, able to communicate and does not have significant distracting injuries or other problems which could mask abdominal signs.
- The patient has had a high quality CT scan which shows no evidence of an injury requiring intra-abdominal surgery.
- The surgeon should be mindful that a retroperitoneal injury seen on CT could fail to generate significant peritoneal signs, even when the bowel is penetrated. A wound tract close to a retroperitoneal hollow viscus should prompt the consideration of surgery.
- Facilities and staff are available for the serial examination of the patient with monitoring and for a prompt move to the operating theatre if an indication for surgery develops.
- The treating unit and staff are experienced in the management of ballistic injury.

An exception to this rule may arise in the context of a major incident: patients meeting the other criteria may be triaged to receive SNOM due to the higher priority of other patients. If, after a period of SNOM, they remain stable etc., it may not be appropriate to operate even though the resources to do so are now available.

The requirement for CT, monitoring and prompt theatre access mean that SNOM is not normally possible in austere environments and is problematic where the patient will be evacuated [61]. Patients who fail SNOM after ballistic trauma almost always develop signs within 24 h [62–68]. Those who proceed past this point can be discharged soon thereafter: a median length of stay of 4 days for successful SNOM was reported in one of the largest series [68].

Angioembolization is frequently employed as part of SNOM. If it is unavailable, then extravasation of contrast on CT becomes a contraindication to SNOM. Technical efficacy is greater than 90% [69]. However, as many as 15% may develop partial hepatic necrosis after embolization of the liver. About a fifth of patients will fail SNOM of a gunshot wound [68]. These patients have a higher mortality (2.7%) than those who do not undergo surgery (0.7%) and all those sustaining gunshot wounds (1.8%).

13.9 Operative Management of Abdominal Injury

13.9.1 Laparoscopy

Many enthusiasts have advocated for the role of laparoscopy in penetrating abdominal injury. However, published series have been of poor quality [70], and suffer from publication bias. In any case, the unpredictable path of a bullet through the abdominal cavity combined with the limited access that laparoscopy gives to some areas (the lesser sac, the retroperitoneum) means that its role will always be more limited even than in the management of stabbings. Laparoscopy may have a role as a diagnostic modality to help avoid non-therapeutic laparotomy. However, whether it is useful depends upon the surgeon's general approach to ballistic abdominal injury as a whole:

- If the patient is haemodynamically unstable or has peritoneal signs, laparotomy is mandatory.
- If not, and the surgeon practices SNOM, then there is no role for laparoscopy.
- While an early laparoscopy may reveal a hard indication for laparotomy (e.g. free bowel contents), it is more likely to show a soft indication (e.g. small volume free blood) that will then drive a laparotomy that could perhaps have been avoided.
- If the surgeon does not practice SNOM but suspects that the injury has not penetrated the abdomen and CT cannot resolve the issue, there may be a role for laparoscopy. Laparotomy may be avoided if the peritoneum is intact.

Laparoscopy (or thoracoscopy) is well indicated after successful non-operative management of a penetrating thoracoabdominal injury with possible diaphragmatic injury [71]. The diaphragm can be assessed and often repaired in this way [72].

13.9.2 Laparotomy

Again, it is not intended to give detailed operative instructions here. Given the unpredictable passage of the missile(s), the surgeon should be ready to move from the abdomen to adjacent areas (the chest, the groins). A full midline laparotomy is required. Packing is not always required: it may be possible to directly address the point of bleeding. All the viscera should be examined in every case of laparotomy for ballistic injury: this requires opening of the lesser sac, kocherisation and mobilisation of the ascending and descending colon. The great vessels and kidneys are discussed in Chaps. 20 and 21. Access to these and to the pancreas and root of the mesentery may require visceral rotation (see Fig. 13.5). Retroperitoneal bleeding, including non-expanding haematomata, requires exploration. The key is, when possible, to first prepare for the possible consequences of releasing tamponade by establishing vascular control outside the zone of injury.

Bleeding from the liver can be temporized by packing and/or the Pringle manoeuvre. If packing controls bleeding that cannot be stopped with simple manoeuvres (diathermy, direct suture) and bleeding resumes when the packs are removed, they should be replaced and the operation should be abbreviated. Angioembolization is a

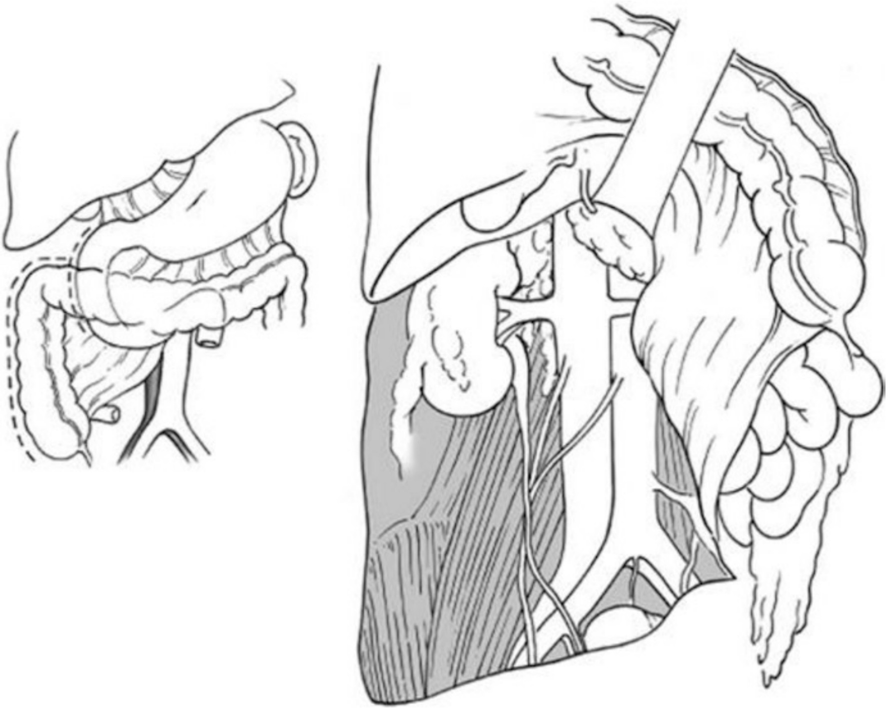

Fig. 13.5 Right medial visceral rotation (Cattell-Braasch manoeuvre). The duodenum is mobilised (as in Kocher's manoeuvre) and the dissection is extended to allow reflection of the right colon, continuing up the root of the small bowel mesentery to the ligament of Trietze. Left medial rotation (Mattox manoeuvre) allows access to the right renal hilum and upper abdominal aorta [Image from Penetrating Trauma: A Practical Guide, Fig. 52.3] [73]

useful adjunct. Definitive management includes packing, non-anatomical resection, hepatotomy with direct clipping or other control of bleeding. Balloon tamponade of a through-and-through injury is highly effective. Retrohepatic bleeding is extremely difficult to control; a haematoma here should be left intact. Whether managed operatively or conservatively, high-grade liver injury is associated with bile leaks, which occur in 35% of patients [74]. Biliary decompression by endoscopic retrograde or percutaneous cholangiography is usually sufficient management. Operative decompression with a T-tube or cholecystostomy may be necessary in austere environments. Resection is rarely needed.

Splenic injuries can be managed by splenorraphy if isolated and minor; this is of greater importance in young patients. However, a repaired spleen must be carefully monitored, just as for SNOM of splenic injury, and thus this approach is not suitable in all circumstances. Splenorraphy is not appropriate after failed SNOM.

Pancreatic injuries should be managed by resection of injuries to the body and tail and drainage of those to the pancreatic head. However, ballistic injury to the head is often so destructive as to require resection. It is also likely to be associated with injury to the portal vein or IVC and their tributaries, which are associated with a sevenfold increase in operative mortality [75]. Combined duodenal injury can be managed by pancreaticoduodenectomy or primary repair with drainage. In the latter case, the duodenum should also be internally drained (closure over a Foley catheter is effective). Pyloric exclusion can be used if there is thought to be a high risk of duodenal fistula. The pylorus is sutured closed and bypassed by gastrojejunostomy; after a period the pylorus normally cuts through the sutures and restores anatomical flow. However, there is no evidence that it improves outcome [76].

Low energy-transfer injury to the bowel may be suitable for direct repair. Multiple injuries, as after fragmentation or shotgun injury, are best managed in this way so as to avoid the loss of too much bowel. However, repair requires healthy bowel in a healthy patient. Bowel is therefore often resected but left without anastomosis (the ends stapled or tied), which is completed at subsequent surgery. If a stoma is certain to be needed, it may be advantageous to fashion it at the index procedure. Oedema of the mesentery and abdominal wall may make this more difficult later. Suspected rectal injuries should be defunctioned but there is no requirement for washout and presacral drainage, as was formerly recommended.

13.9.3 Re-Look Laparotomy

Except where there is ongoing bleeding or abdominal soiling, re-look laparotomy should be delayed until 24–48 h have passed. Packs should be soaked and removed carefully, beginning with those least likely to be intimately related to clot. Every attempt should be made to achieve definitive repair of all injuries at the first re-look laparotomy and to achieve fascial closure. Occasionally re-packing is necessary. The surgeon should then consider whether it is likely that a further delay before a second re-look is likely to result in definitive control. It may be that specialist intervention will be required; if necessary the patient should be transferred to an appropriate centre.

13.10 Temporary Abdominal Closure and Definitive Repair

Laparostomy may be required to facilitate DCS or for the treatment or relief of abdominal compartment syndrome. Happily, the move to DCR has been associated with a decrease in the incidence of abdominal compartment syndrome, probably due to decreased fluid resuscitation and diminution of inflammatory response [77].

Several factors should be born in mind for temporary abdominal closure:

- The bowel needs to be contained, protected from trauma, kept warm and not allowed to dry out.
- Swelling of the abdominal viscera can progress postoperatively.
- Abdominal fluid must be managed.
- Over time it becomes increasingly difficult to re-appose the recti due to contraction of the lateral abdominal musculature.
- At the same time, the abdominal contents becomes adherent to the peritoneum, making re-exploration more challenging and closure more difficult.

Ideally, a technique of temporary abdominal closure would address all of these issues by protecting the bowel, increasing the abdominal domain, collecting abdominal fluid, holding the recti near to their anatomical position and forming a barrier behind the abdominal wall while not itself adhering to the bowel. A number of techniques have been described which variably meet these requirements, while also differing in ease of application and cost.

The simplest technique is to use an opened intravenous fluid bar (Bogotá bag) sutured to the fascia. Fluid is managed via drains and either pads or a wound manager. The bag can be incised to access the abdomen and then closed with the removal of redundant material in order to bring the recti together if closure is not immediately possible. Silastic sheets achieve a similar effect at greater expense. Proprietary negative pressure dressings (e.g. Abthera [KCI Acelity, San Antonio TX, USA]) maintain tension on the fascia while placing an inert barrier between the abdominal contents and the wall. Fluid is carried away by the suction system. It is suggested that these systems reduce bowel oedema, thereby assisting with closure. Vacuum packs (such as the "OpSite sandwich") can be improvised at reduced cost: a perforated plastic sheet is placed behind the abdominal wall and suction is applied to drains placed within gauze packs that fill the laparostomy defect. See Fig. 13.6.

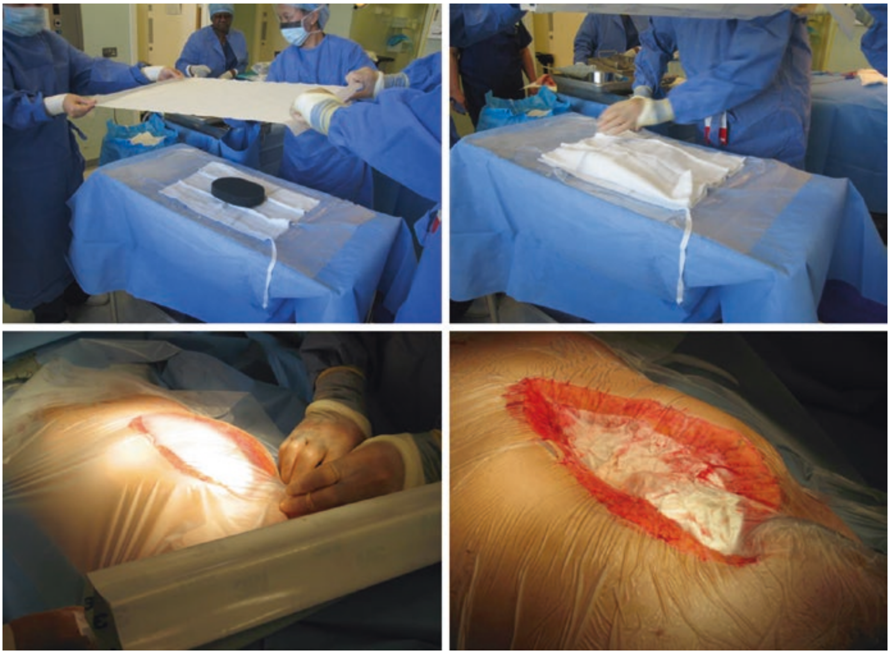

Fig. 13.6 An improvised vacuum pack for temporary abdominal closure. A large gauze swab is placed on the adhesive side of a clear plastic film dressing. In this case, a black sponge has been added before a second film and swab are placed over the whole. Incisions are made in the films to allow passage of fluid. After placement behind the abdominal wall with loose gauze and suction tubes in the wound, further film dressings are used to seal the arrangement

Systematic reviews [78, 79] indicate that all these techniques are associated with fistula formation (probably 5–10% of patients) and abscesses (a similar proportion). Patients managed this way have a mortality of 15–33%, but this probably relates to the underlying severity of injury. Abdominal closure is eventually achieved in 13% of patients who simply have wound packing against about a third of those managed with a Bogotá bag and one half to two thirds of those managed with proprietary or improvised negative pressure systems. The only randomised trial in this area was too small to demonstrate differences in outcomes [80].

Fascial closure should be attempted at each relook laparotomy (unless inappropriate) and every effort should be made to achieve it by the end of the first week as it is rarely possible thereafter [81]. Progressive tension on the fascia can increase closure rates: dynamic tension sutures and the Whittman patch are associated with closure rates of over 80% [78, 79]. Closure can be assisted by component separation, in which the external oblique aponeuroses are divided lateral to each linea semilunaris (the rectus sheaths may also be mobilised) [82]. Component separation can also be used to assist later reconstruction or even to achieve primary closure at the index laparotomy if laparostomy is undesirable but compartment syndrome is a concern (e.g. in austere settings).

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Management of Ballistic Trauma to the Head

14

Stuart A.G. Roberts

Key Points

1. Projectiles or rounds affect tissues in casualties by three mechanisms: generation of a shockwave, formation of a temporary cavity and finally the resultant permanent cavity or wound tract.
2. Wounding patterns are idiosyncratic and difficult to predict.
3. Significant tissue damage can sometimes be produced by lower-energy firearms and, paradoxically, minimal wounding can sometimes be seen from higher-energy firearms.
4. Fragmentation of the round and bone-strike are typically associated with greater energy transfer and therefore more severe wounds.

14.1 Introduction and Historical Background

Penetrating head injuries (PHI) have been a feature of conflicts for centuries with museum specimens showing a variety of injuries, from square-shaped pterional entry points from war-hammers, to signs of healed linear and depressed skull fractures bearing the impression of arrows, swords and pole-axes [1]. PHI remained a significant cause of death through the great conflicts of the twentieth century and more recent conflicts in Iraq and Afghanistan [2]. Between 2000 and 2012 in global conflicts, the US Defense and Veterans Brain Injury Centre reported that American service members sustained a total of 255,852 TBIs with 6472 incidences of PHI [3].

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Mechanisms of PHI are either from explosive munitions producing low-level blast fragmentation injuries or bullets (termed rounds in a military context). Frequency of injury is comparable across the Falklands, US-Vietnam and US-Korea conflicts where 70% of injuries were from blast and 30% from gunshot wounds (GSW) [4]. Between 2003 and 2011 the most common mechanism of traumatic brain injury (TBI), both blunt and PHI, was blast (67.5%) followed by GSW [5].

Blast is rare in the civilian setting outside of the Middle East, and GSW although relatively common in the US is currently rare is Europe. Civilian GSW traditionally resulted from low-velocity rounds fired at close range, typically from handguns or shotguns [6, 7]. This accounts for a significant proportion of civilian injuries in the form of homicides, suicides and accidents with an estimated 10.4 deaths per 100,000 each year in the US [8]. However, recent terror attacks with explosive devices or mass shootings have introduced a new pattern of injuries into the civilian sector. Because of large numbers of casualties with PHI treated during wartime, advances and refinements from the military experience have permeated into civilian practice.

In eighteenth and nineteenth century conflicts, PHI was considered irrecoverable and casualties underwent little, if any, formal intervention by surgeons. There was little advancement in surgical methods, which was largely at the discretion of the operator. Eighteenth century surgeons such as François Quesnay and Percivall Pott favoured immediate surgery, whereas Pierre-Joseph Desault favoured no intervention at all. Napoleon's surgeon and early innovator in battlefield surgery, Dominique Jean Larrey, performed surgery for depressed skull fractures and haematomas, but would not operate on brain parenchyma at all [9].

Professor John C. Warren transformed surgery forever with the first use of general anaesthesia. This came just in time for war in the Crimea (1853–1856), where military field hospitals readily embraced anaesthesia. The Crimea also marked the first time that surgeons began to systematically report results. McLeod noted that 10% of all GSW involved the head with an associated mortality rate of 100%. He recorded: "*Of 19 cases in which the skull was perforated, all died.*" [10]. In World War I there was a high rate of infectious complications and Keen wrote in 1918:

> the soils of Belgium and France have been cultivated for over twenty centuries, since even before the days of Caesar's Gallic Wars. The fields have been roamed by cattle, horses, swine and other animals including man; the soil has been manured thousands of times, and so is deeply impregnated with faecal bacteria in addition to ordinary pyogenic bacteria … it was no wonder that infection from pyogenic organisms and the bacteria of tetanus and gas gangrene ran riot [11].

It was into this quagmire that a young Harvey Cushing arrived and his legacy remains today. His case reports advocate complete shaving of the area of operation, broad based skin flaps, *en bloc* bone removal with suction, careful dural closure and two-layer skin closure without drains, believing elimination of dead space was key [12]. Finally, he advocated thorough debridement and saline irrigation, rather than previously advocated antiseptic solutions. Through reducing infection and secondary complications, Cushing reduced mortality from PHI from over 58% to 28% [13]. After the war, Cushing presented at the American College of Surgeons, where William Mayo commented: "*Gentleman, we have this day witnessed the birth of a new specialty, neurosurgery*" [14].

Prior to the Second World War (WWII), the expectation was that outcomes would be better. Neurosurgical training was now established and antibacterial treatments more widespread and effective. Cushing's work was revisited as the minimum standard expected [15]. WWII saw the introduction of the Mobile Neurosurgical Unit (MNSU) which took inspiration from the teachings of Cushing [16]. The first neurosurgical operation was to be definitive with subsequent operations considered to carry greater risk of complications. Preceding modern military resuscitation strategies such as Battlefield Advanced Trauma Life Support (BATLS), there was little place for first-aid neurosurgery in the field, aside from control of catastrophic haemorrhage [17]. Through definitive surgery, the incidence of infection, intracerebral abscess and meningitis was reduced from 25% to 5%, with 90% of wounds healing by primary intention [18].

In addition, using an MNSU, Howard Florey conducted one of the most important trials in twentieth century surgery. Despite impurity of early samples, the first large-scale trial of penicillin was performed in five hospitals at Tripoli and Sousse in 1943. Because of this trial, MNSUs used penicillin in mainland Italy, where its value became apparent in the treatment of infected wounds, pyogenic meningitis and prophylaxis of brain abscess. Consequently, MNSUs developed an antibiotic regimen that became the standard treatment. The strength of Florey's results proved beyond doubt the significance of penicillin and, although initially classified, facilitated international support for mass production and distribution of the drug [19, 20].

MNSUs dealt with over 20,000 casualties. Eighty percent of head injuries in all theatres were treated by a MNSU, demonstrating the overwhelming success of the concept. Around 90% of those with scalp wounds and simple skull fractures returned to their units and 70% of those with PHI returned to employment [21].

The success of the MNSUs had far reaching significance. Retired United States Army Medical Corps (USAMC) neurosurgeon Michael Carey described the impact of the MNSUs writing:

> So successful was the British MNSU concept that it was adopted by the Canadian Army during World War II and borrowed by Colonel Arnold Meirowski for the American Army in Korea. The American Army neurosurgical detachments and their overall configurations used in Vietnam, Desert Storm and maintained to this day, are direct descendants of the British MNSUs in World War II [18].

By the 1980s CT capabilities became available during the Israeli-Lebanese conflict and it was here that less aggressive management and minimal brain debridement demonstrated improved seizure outcomes following PHI [22]. In recent conflicts, the UK DMS demonstrated a deliberate approach to continuous stepwise performance improvement which has also been shown to improve outcomes [4]. Such important experiences are instrumental in the evolution of the modern surgical management of PHI.

14.2 Ballistics-Neurosurgical Considerations

The ballistics of wounding has been discussed in Chap. 5, however there are some unique anatomic considerations that apply to the head that must be examined in order to understand ballistic PHI.

Firstly, by definition, there is always bone strike in PHI, leading to not only the likely destabilisation of the round, but also the likely generation of secondary projectiles in the form of skull fragments. This effects means that there will likely be complex permanent cavities/wound tracts formed by both the round and skull fragments [23]. The destabilised round is also more prone to generating a temporary cavity if it starts to tumble.

Secondly, brain parenchyma is extremely intolerant to the stretching effect of temporary cavitation [24] as described in Chap. 5. Given the enclosed nature of the skull, the formation of a temporary cavity can result in shearing of neurons and may result in extra-axial hematomas, or parenchymal contusions [25]. For this reason, higher velocity PHI should be considered a diffuse in addition to focal injury.

Finally, the shock wave generated by higher velocity projectiles which although negligible in other anatomic regions, can have a profound effect on neural tissue [26, 27].

Conflicts in Iraq and Afghanistan have introduced the improvised explosive device (IED) into the lexicon as discussed in greater detail in Chaps. 4 and 5. The evolution of IEDs in modern, low-intensity, urban conflict employed against both military and civilian targets have become a major cause of PHI [2, 28]. Blast produces unique and complex TBI of which PHI can be a component. Commonly, components of the device (e.g. fragments of the weapon or intentionally placed shrapnel such as ball bearings) and debris from the surrounding environment carried by the wind are driven into personnel, causing PHI. In urban environments, this is commonly glass [29]. Regardless, the kinetic energy of the projectile will determine degree of penetration and severity of injury.

14.3 Injury Classification

Since WWI, PHIs have been classified to correlate type of injury with prognosis. It was patients treated in WWI, during the Third Battle of Ypres (Passchendaele), that formed the basis for Harvey Cushing's case reports. Cushing standardized intracranial injuries into nine categories with separate mortality rates which are explained in Table 14.1 [1]. His original classification of nine different injury patterns was refined by Matson in WWII to four categories.

Traditional military teaching correlates outcomes from PHI with coma scores [30]. This can either be an AVPU (alert; verbal; pain; unresponsive) assessment or more detailed Glasgow Coma Scale (GCS), and correlation between the two scoring systems has been demonstrated [31, 32]. Outcomes following PHI have been correlated with GCS and AVPU although this does not take into account differences in energy transmission and tissue interaction between GSWs and blast fragmentation [33].

Table 14.1 Cushing's tabulation of intracranial injuries based upon his case reports, standardised into nine categories with mortality rates

Grade	Description	Cases	Deaths	Mortality
I	Scalp wounds with intact cranium	22	1	4.5%
II	Skull fractures with intact dura	54	5	9.2%
III	Skull fractures, dura lacerated	18	2	11.8%
IV	Gutter wounds with indriven fragments, often extrusion of brain (local contusions, fungal abscess and encephalitis)	25	6	24%
V	Penetrating wounds with lodged projectile and bone fragments (extrusion and abscess common)	41	15	36.6%
VI	Penetrating wounds entering ventricles (a) bone or (b) projectiles (CSF leak, ventriculitis common)	(a) 14, (b) 16	(a) 6, (b) 16	(a) 42.8%, (b) 100%
VII	Craniofacial track involving (a) orbitonasal and (b) auropetrosal	15	11	73.3%
VIII	Perforating wounds with severe cerebral injury (haemorrhage and compression)	5	4	80%
IX	Craniocerebral injury with diffuse skull fractures (widespread contusions and compression)	10	5	50%

Increasingly considering medical advances, patients with PHI, particularly from low velocity blast fragmentation survive to discharge and many injuries traditionally thought un-survivable result in unexpected survivors [34, 35]. Military patients are normally younger than civilian cohorts and observational studies such as IMPACT have highlighted increasing age as being strongly related to poorer outcomes [36]. The high survival rate suggests that Injury Severity Scores (ISS) of 75 should no longer be considered as "un-survivable". With the introduction of advanced trauma networks and an increase in physician-delivered pre-hospital care we can expect outcomes to improve further in civilian practice. Attempts at measuring disability, functional recovery, or patient-reported quality of life have been made to inform prognostication but has inherent challenges, and no major trauma registry has successfully incorporated this [37]. This suggests that existing classification systems are suboptimal for prognostication in PHI and that new bespoke classifications are required.

More recently, there has been a drive to develop a single TBI severity classification system based on commonly used TBI severity measures and indicators. One example of this is the Mayo classification [38]. In this instance, mild traumatic brain injury (mTBI) is characterised by the presence of any of the following;

1. absence of a low GCS or loss of consciousness,
2. a short duration of post-traumatic amnesia (PTA) and
3. a lack of neuroimaging evidence of significant structural brain damage.

TBI is classified as moderate-severe by the presence of any of the following;

1. if death results,
2. there is loss of consciousness for greater than 30 min,

3. post-traumatic amnesia lasts for greater than 24 h,
4. worst GCS is less than 13 in the first 24 h or
5. one of the following is present: intracerebral haematoma; subdural haematoma; extradural haematoma; cerebral contusions; penetrating dural injury; subarachnoid haemorrhage and brain-stem injury [38].

Currently, a PHI is described as a tangential wound, a penetrating wound, or a perforating wound [39].

14.3.1 Tangential Wounds

A tangential wound as shown in Fig. 14.1 occurs when a projectile strikes the head at an oblique angle and commonly results in scalp lacerations, skull fractures, and cerebral contusions. Projectiles may traverse the subgaleal space and exit or remain lodged in the scalp. The presence of a haematoma, depressed skull fracture, or cerebrospinal fluid (CSF) leak may necessitate surgical intervention. Otherwise, local wound care may be applied. These injuries generally carry a better prognosis with less severe neurological deficits, but they may present with seizures or focal deficit depending on location and extent of injury.

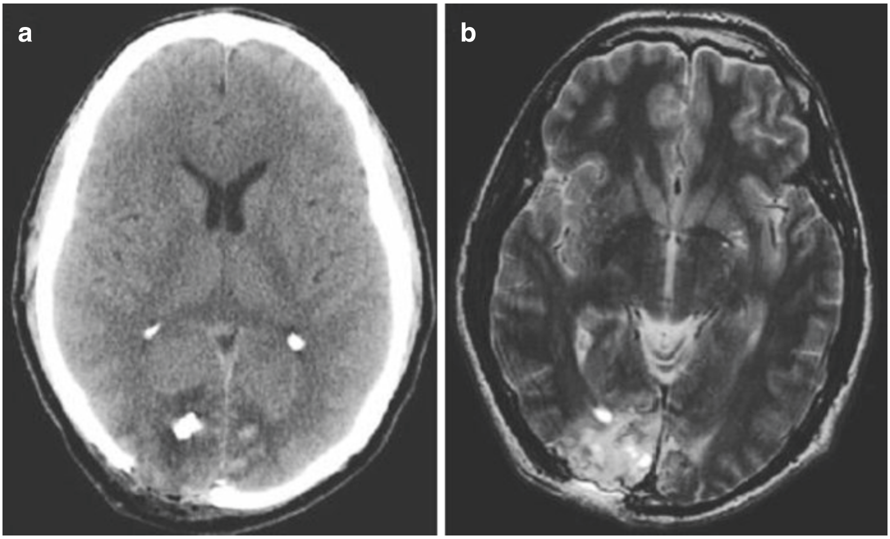

Fig. 14.1 Tangenital intracranial injury. (**a**) CT of tangential wound to right occipital region from a 7.62 × 39 mm round while wearing military helmet. The wound was emergently debrided at nearby field hospital. Note the in-driven bone fragments. (**b**) MRI of same patient revealing underlying contusion after CT confirmation of no residual metal fragments

14.3.2 Penetrating Wound

As discussed previously, the velocity of the projectile is the main determinant of its energy. If the projectile has enough energy to penetrate the brain parenchyma but not exit the cranial vault it is referred to as penetrating. Energy absorbed by the skull often results in fragments of bone acting as secondary projectiles within the brain. Contusions, lacerations, or haematomas may be caused by these injuries as shown in Fig. 14.2 below.

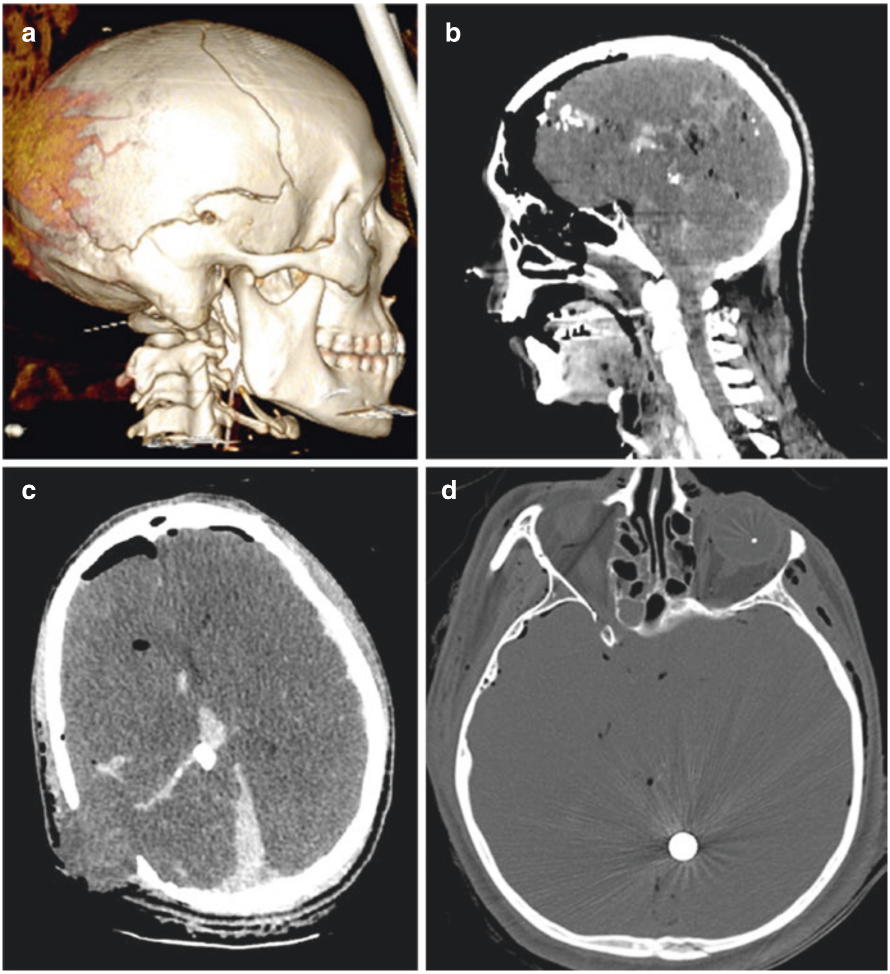

Fig. 14.2 Penetrating intracranial injuries. (**a**) Gunshot entrance wound without and exit. (**b**) Tract from a GSW to the head showing no exit wound. (**c**) Penetrating injury following a blast, with swollen and herniating brain. (**d**) Penetrating injury from a ball bearing with internal ricochet

Depending on the energy imparted, projectiles may produce unusual tracts that may be detected on CT, but missed on plain films. Projectiles can ricochet from the inner table opposite of its entry, creating new tracts within the parenchyma. Projectiles may also change directions on contact with the dura following penetration of the outer and inner tables of the skull; known as careening. The projectile then travels along the inner table of the skull, with the potential to damage the venous sinuses.

14.3.3 Perforating Wound

The most destructive pattern of injury is the perforating wound as shown in Fig. 14.3, which is defined by an entry and exit wound with a tract through brain parenchyma. This injury requires a higher-velocity projectile than with a penetrating injury, and

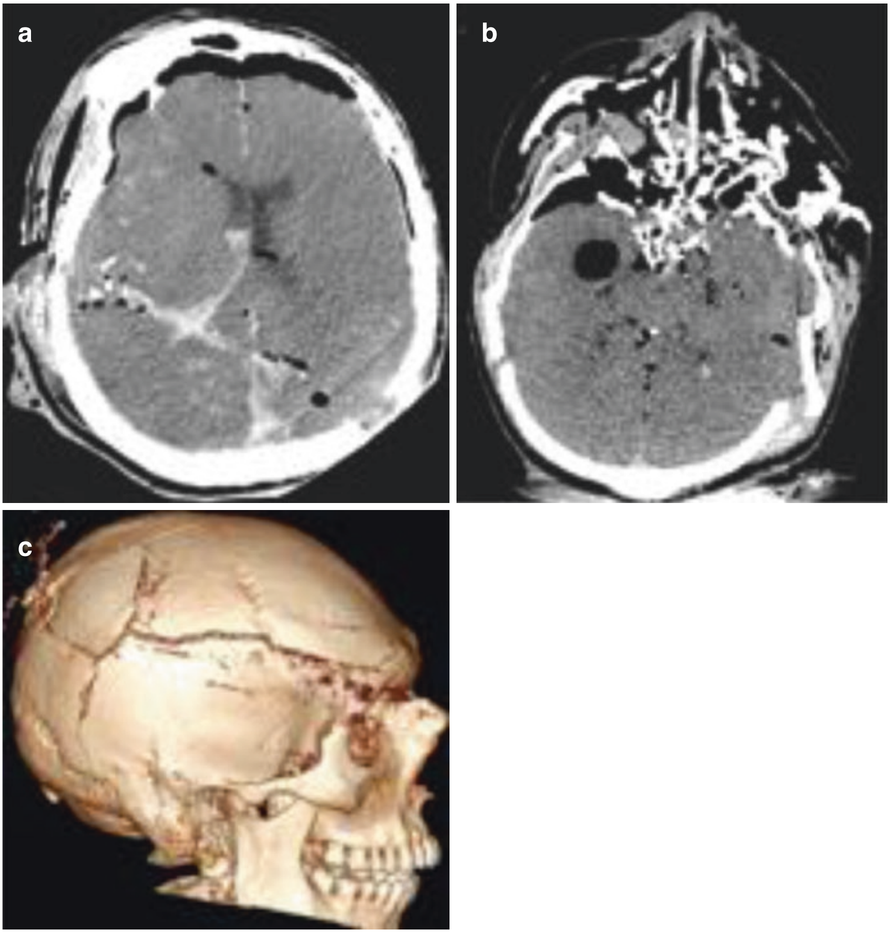

Fig. 14.3 Perforating intracranial injury. (**a**) Axial CT of a perforating GSW with transventricular tract. (**b**) Example of retained cavity following GSW. (**c**) Fractures to the calvarium resulting from cavitation

thus imparts a higher amount of kinetic energy to the tissue. Local and distant structures are damaged from the cavitation effect the projectile imparts, resulting in multiple fractures, contusions, and hematomas.

14.4 Initial Resuscitation and Management

The adoption of the Major Trauma Networks (MTNs) in the United Kingdom in April 2012 [40] has meant that casualties with severe TBI are transported directly to an Major Trauma Centre (MTC), providing journey time does not exceed 45 min. All MTCs provide a 24-h consultant-led trauma team, immediate access to CT scanning, and a dedicated operating theatre for trauma. This has resulted in increased pre-hospital physician presence and increased frequency of pre-hospital intubation for at-risk trauma patients [41].

Since introduction of MTNs, all indicators of the quality of care improved, fewer patients required inter-hospital transfer and a greater proportion were discharged with improved outcomes. PHI was shown to be a major driver of mortality. In the UK, the National Institute of Health and Care Excellence (NICE) based a recommendation on this finding in the 2007 updated head injury guidance. A halving in TBI case fatality has been associated with increasing transfer to neurosurgical units over the 2003–2009 period, although NICE's other recommendations around access to early CT imaging may have also contributed to improved outcomes [42].

The use of a helicopter permits faster transport from the scene or outlying hospital to a neurosurgical center for early intervention in most major cities in Europe and the United States [43, 44]. Deployment of pre-hospital physicians allows interventions such as burr-holes to be undertaken at the scene [45]. Despite this, data from the Collaborative European NeuroTrauma Effectiveness Research in Traumatic Brain Injury (CENTER-TBI) study shows that among high-volume, specialised neurotrauma centers there remains substantial variation in structures and processes of care [46].

A combat situation provides a different environment for management of PHI, and is organized according to "Role" or "Echelon", used by NATO to describe stratification of tiers in which medical support is organised on a progressive basis; conducting treatment, evacuation, resupply, and functions essential to maintain health of the force and fitness to fight [47]. Initial Role 1 medical support is integrated within a battalion-sized unit of approximately 500–1000 troops and includes capabilities for providing first aid and immediate lifesaving measures [17, 48].

Role 2 is the furthest forward surgical team and is normally provided at larger unit level and can only provide life and limb saving damage-control resuscitation and surgery. Role 3 is normally provided at Division level and are regarded as 'Field-hospitals' or maritime 'Hospital Ships'. This is the first unit that would have specialist diagnostic resources specifically CT, and limited, if any neurosurgical capabilities [49]. Military neurosurgeons are deployed where most beneficial and depending on the theater of operations, neurosurgical support may be located at a variety of echelons.

Subsequently, casualties are transferred to home nation hospitals (Role 4) likely via a prolonged flight. During aeromedical evacuation, casualties will be under the care of specialist aeromedical teams but there is unlikely to be specialist neurosurgical expertise during the flight. Timing of surgery and decision to evacuate is important as there is increasing evidence that hypobaria during aeromedical evacuation can be detrimental to neurological recovery [50, 51]. Therefore aeromedical evacuation may have to be delayed for a patient to stabilise in order to reduce the risk of neurosurgical intervention arising during transport.

In either a civilian or combat environment, patients with a PHI often experience a period of apnoea and hypotension, both of which are shown to worsen prognosis [52, 53]. Early intubation and appropriate fluid resuscitation may reduce secondary complications from these events. There has been a significant improvement in the understanding of resuscitation with blood products over the last 15-years. The traditional concept of restoring a casualty's haemoglobin concentration by administering packed red blood cells (pRBCs) has been augmented by the administration of pRBCs and FFP at approximately a 1:1 ratio with early platelet administration [54]. This strategy was improved by massive transfusions being guided through real-time, near patient thromboelastography (TEG), introduced from 2009 which has supplanted traditional measures of 'clotting', allowing tailored correction of coagulopathy as part of resuscitation [55]. Additionally, the use of tranexamic acid (TXA) has been shown to improve survival following in both civilian and military studies and is now routinely administered pre-hospital within the military trauma system [56, 57]. The CRASH-3 trial will specifically evaluate the effect of TXA in TBI.

A challenge to early intubation in the field can be cervical immobilization. A recent review of the incidence of spine injury in patients with in 172 patients with isolated PHI found 5.6% had unstable cervical fractures without initial neurologic deficit [58].

However, as in any trauma, Advanced Trauma Life Support/Battlefield Advanced Trauma Life Support (ATLS/BATLS) guidelines should be followed, with a focus on preventing hypoxia and hypotension both of which significantly impact on survival and outcome following PHI.

A brief history from medics, family members, or paramedics should always be taken to include the mechanism of injury, neurological examination at the scene, periods of hypoxia or hypotension, and known past medical history or allergies (as part of an AMPLE assessment). During the primary and secondary survey, the patient is inspected thoroughly for entry and exit wounds, which should also include the oral cavity. A temporary clean, bulky dressing is applied to the wounds. A brief neurological exam is performed, remembering that the patient should be fully resuscitated before determining a prognosis.

The patient's Glasgow Coma Scale (GCS) score, the presence of hypotension or hypoxia, and any use of pharmacological agents should be noted. As mentioned previously, traditional military teaching correlates outcomes from PHI with coma scores as shown in Table 14.2 below, although there is increasing evidence that this relationship might be more complicated than previously thought [30].

Table 14.2 Correlation between initial level of consciousness and mortality [30]

Level of consciousness	Percentage mortality	Approximates to
Alert	12	A
Drowsy	33	V
Reaction to pain	79	P
Coma	100	U

If the patient has a GCS score of less than 8 or cannot otherwise protect their airway, intubation for adequate airway protection, oxygenation, and ventilation should be considered. Brainstem reflexes and pupillary exam, to include size, symmetry, and reactivity, are noted. Evaluation for CSF leak is performed at this point, including inspection of the tympanic membranes and nares. Antiepileptic agents and broad-spectrum antibiotics should be administered in accordance with local policies.

14.5 Neuroimaging

Neuroimaging in PHI is vital for prognostication and surgical decision making [25]. With the increasing tempo of military conflicts in the last decade, much has been learned about imaging battlefield casualties in acute settings, including availability of Multidetector CT (MDCT) in theatre. Regardless of location, in PHI imaging ought to be used in order to assess as best as possible: entry and exit sites; intracranial fragments; projectile tracks and relationships to both blood vessels and skull-base structures; intracranial air; opening of the ventricles; basal ganglia and brain stem injury; projectile tracks crossing the midline; effacement of the basal cisterns; brain herniation and mass effect [59].

Traditionally, imaging of the cranium relied on skull radiographs. This can provide a quick impression on the nature of the injury and evaluate for the presence of intracranial fragments and air, especially in circumstances where CT is unavailable. The true trajectory of fragments may be misleading in the presence of ricochet or careening fragments as shown in Fig. 14.4 [60]. If rapid access to a CT scanner is possible, plain films are not required. Non-contrast CT with bone windows allow for precise localization of bone and projectile fragments, identification of the trajectory, and characterisation of brain injury. The presence of mass effect and classification of hematomas, either epidural, subdural, parenchymal, or intra-ventricular, can be performed [59].

In resource constrained healthcare systems there may be no CT access available; alternatively in a mass-casualty event there imaging facilities may be overwhelmed. Patients with PHI who are managed expectantly without CT imaging will be expected to have poorer outcomes. Access to CT in future conflict is also not guaranteed. In resource-poor environments lacking CT, studies have shown that clinical criteria may be used to select those who could benefit from surgery [61].

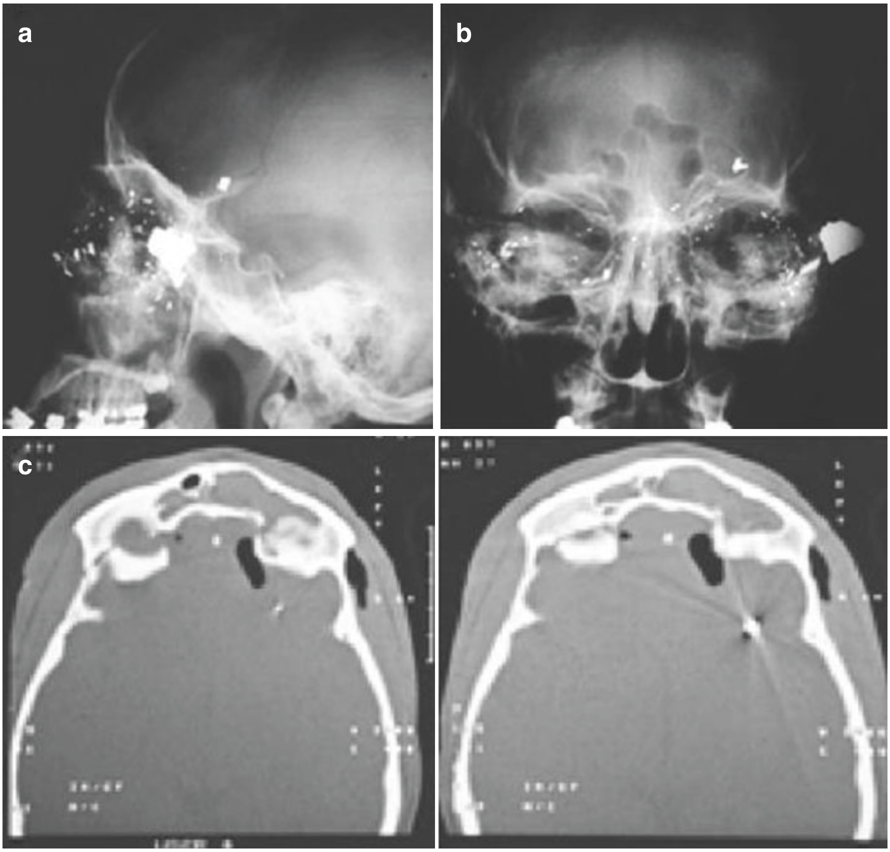

Fig. 14.4 Lateral (**a**) and Anterior-Posterior (**b**) skull X-rays of GSW provides some information on retained fragments, presumed tract of injury, and involved structures. (**c**) CT scan demonstrates much better anatomic information in the same injury

There has also been some success with handheld scanners, such as Near InfraRed devices for detection of intracranial haematomas in austere environments. There are ongoing trials in military and civilian settings [62, 63].

PHI is also associated with intracranial vascular injury and angiography is recommended. Studies following the Iran–Iraq war showed a four to ten times increased risk of traumatic aneurysm development in patients with facio-orbito or pterional entry, intracranial hematoma, or projectile trajectories that crossed dural compartments [64]. Further studies documented 15 cases of traumatic aneurysms from the Lebanese conflict: 14 from blast fragmentation and one from a bullet. Angiograms were recommended for all patients with retained fragments, no associated exit wound, and an intracranial hematoma in the distal portion of the trajectory [65]. Other high-risk injuries included projectile trajectories through or near the Sylvian fissure, supraclinoid carotid artery, basilar cisterns, or major venous sinuses.

In series from the US involvement in Afghanistan there were 64 vascular injuries detected following 162 penetrating craniocervical injuries (34% prevalence) as shown in Fig. 14.5 below. Common vascular injuries were traumatic intracranial aneurysms (TICAs), traumatic extracalvarial aneurysms (TECAs), arterial dissections, and arteriovenous fistulae [66]. Recommendations were that neurosurgeons and critical care specialists maintain high degree of suspicion for these injuries, and investigations could include mandatory digital subtraction angiography (DSA) performed in all patients following PHI.

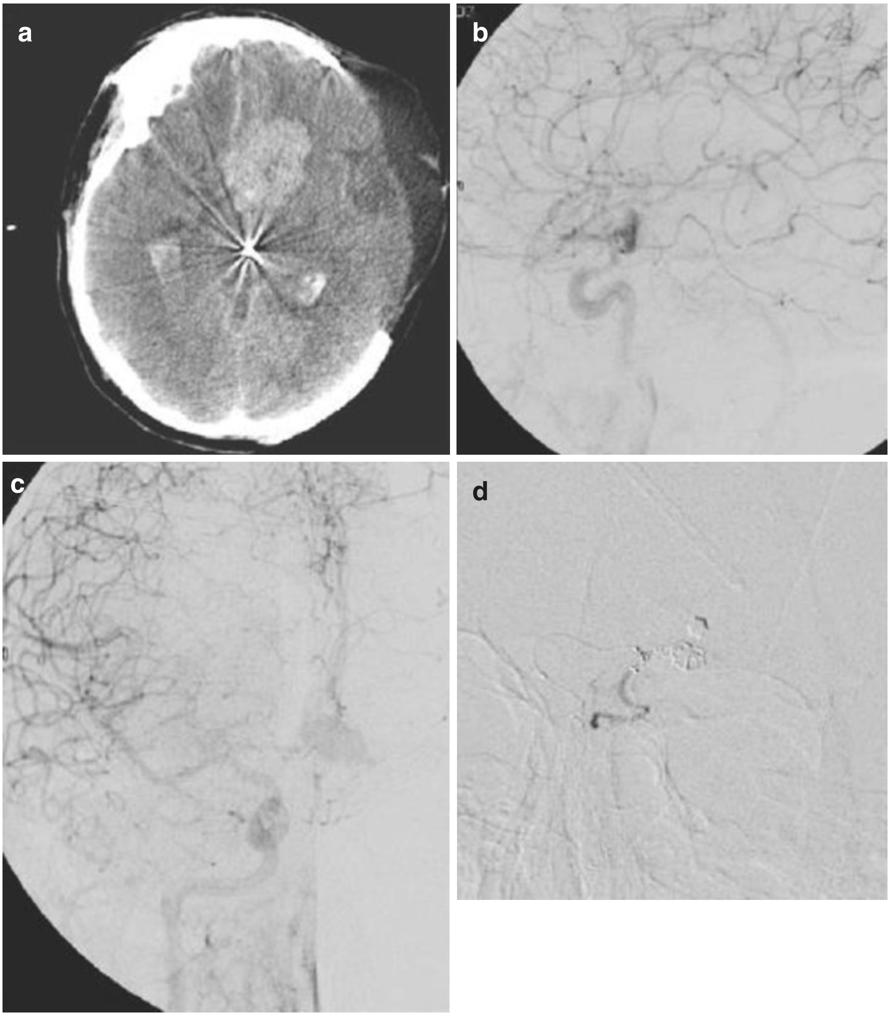

Fig. 14.5 (**a**) CT showing delayed hematoma in patient involved in a shrapnel injury to base of skull and orbit. (**b**) Lateral and (**c**) AP angiogram revealing pseudoaneurysm of anterior cerebral artery. (**d**) Psuedoaneurysm was treated by endovascular coiling. The patient's initial angiogram after injury was negative

Magnetic resonance imaging (MRI) currently is not recommended in the acute management of PHI [59]. Retained ferromagnetic fragments produce artifact, distortion, and can rotate from the magnetic torque [67–69]. Magnetic resonance imaging may be beneficial in certain cases where the projectile is not retained or is known to contain no metallic elements.

14.6 Preoperative Treatment

Although raised intracranial pressure (ICP) is common following PHI there is not extensive evidence of management, possibly due to occurrence in austere environments [70, 71]. Data from TBI suggests that maintenance ICP less than 20 mmHg has a more favorable prognosis than those with uncontrolled intracranial hypertension [70]. Prevention of secondary brain injury following uncontrolled cerebral oedema is the focus of medical management with the objective being lowering of ICP to facilitate cerebral perfusion and oxygenation [72]. When ICP becomes refractory to medical management irreversible secondary brain injury likely has occurred [73].

ICP monitoring should ideally be initiated when the clinician is unable to assess a patient's neurological exam, commonly at a GCS score of less than or equal to 8. There are various means to monitor ICP, the most common being intraventricular catheters and intraparenchymal monitors. Intraventricular catheters offer the therapeutic advantage of CSF drainage for treatment of elevated ICP. In civilian settings, with TBI guidelines and access to MTNs routine intracranial pressure monitor use has increased following PHI, with a US study suggesting increase from 32.4% in 1991 and 50.8% in 2000 to 77.4% in 2007 [74]. However, ICP monitoring may not be available in austere environments. Deployed neurosurgeons may not have neurointensive care facilities. Currently, deployed UK military facilities do not have ICP monitoring routinely [35].

Pre-operative PHI Management:
Nurse in bed with head-up tilt of 30–45°, head in mid-line and light sedation.

Keep mean arterial blood pressure >90 mmHg.
Monitor cerebral perfusion pressure and keep >60 mmHg.
No steroids or hypothermia.
No prolonged hyperventilation.
Treat seizures with phenytoin or similar anti-epileptic as per local policies.

In the absence of ICP monitoring, treatment should be commenced if patients demonstrate clinical evidence of herniation or progressive neurological decline. General treatment measures include elevation of the head of bed to 30–45°, keeping the head midline to avoid venous outflow constriction, light sedation, and avoiding hypotension, hypoxemia, or hypercarbia [70].

Arterial blood pressure < 90 mmHg should be avoided and cerebral perfusion pressure (CPP) should be kept >60 mmHg [75]. Elevated ICP affects the CPP through the relationship: CPP = MAP − ICP. More aggressive treatment measures include increased sedation, CSF drainage, and administration of osmotic agents such as hypertonic saline or mannitol (0.25–1.00 g/kg body weight) although no large clinical trial has been performed to directly compare the two agents [70]. Hyperventilation reduces ICP through cerebral vasoconstriction, and therefore carries the risk of hypoperfusion from decreased cerebral blood flow. It would appear to be clear that hyperventilation should only be considered in patients with raised ICP, in a tailored way and under specific monitoring which may not be available in austere environments [76]. Prolonged prophylactic hyperventilation with $PaCO_2$ of <25 mmHg is not recommended [77]. Furthermore, in a recent large multicenter trial of therapeutic hypothermia for TBI in patients with an intracranial pressure of more than 20 mmHg, therapeutic hypothermia plus standard care to reduce intracranial pressure did not result in outcomes better than those with standard care alone [78]. There is no indication for steroids in PHI.

Seizures are common after PHI, and around 30–50% of patients will develop seizures [79]. Four to 10% of these will occur within 7 days of the trauma while 80% occur within the first 2 years, however 18% may not have a seizure until more than 5 years following injury [80, 81]. Longitudinal data from the US campaign in Vietnam indicated that after 15 years of follow up, nearly 50% of PHI patients stopped having seizures [80]. Studies of PHI recommend antiepileptic drugs during the first week as seizure prophylaxis although use beyond the first 7 days is not recommended in less serious trauma [79, 82]. There is insufficient evidence to recommend levetiracetam compared with phenytoin currently although trials are ongoing.

14.6.1 Infection in PHI

PHI wounds are considered contaminated, both superficially and deep. Prior to antibiotic use, WWI infection rate for PHI was 59% [83]. Over 100 years later, there remains insufficient data to recommend a standard regimen of prophylactic antibiotics for PHI [84]. Historical data show atypical organisms have been isolated following wartime TBI; with *Acinetobacter spp.* more commonly reported than civilian literature [84]. A study of organisms isolated following infected PHI from the Iran-Iraq conflict reported predominance of *Acinetobacter, Staphylococcus, and Streptococcus* from wound swabs in addition to *Escherichia coli, Klebsiella* and *Enterobacter* from bone fragments [85]. This has been replicated in recent conflicts and it is suggested that broad spectrum antibiotics with coverage for *Acinetobacter, Staphylococcus, and Streptococcus* be commenced early [35]. Cepahlosporins such as cefuroxime have been suggested in addition to metronidazole or vancomycin, commonly maintained for 7–14 days [86].

14.7 Surgical Management

The foundation for surgical management of PHI is found in work performed by Cushing during WWI: craniectomy, thorough debridement of devitalized scalp, bone, brain, metal and bony fragments, and meticulous closure [1]. This approach has remained relatively unchanged through recent conflicts. Data from recent conflict suggest CT capabilities permit less vigorous removal of bone and metallic fragments or repeat craniotomies solely for removal of additional fragments. Debridement should be conservative and confined to nonviable brain tissue, with removal of readily accessible fragments [22, 87].

Treating GSWs with local wound care and closure in patients whose scalp is not devitalized and have no significant intracranial pathologic findings remains a recognized treatment option [87]. A subset of PHI patients from the Lebanese conflict showed good outcomes with simple wound closure and a 3-day course of IV antibiotics [88]. Patients met the following criteria: initial GCS score greater than 10, presented within 6 h of injury, entry wound less than 2 cm, no exit wound, trajectory not through the proximal Sylvain fissure, and no significant intracranial hematoma. These criteria attempted to eliminate patients whose injury would produce a significant amount of devitalized tissue.

Early identification and evacuation of haematomas is important in effecting outcomes of PHI. Rapid evacuation of haematomas causing significant mass effect remains standard practice. Decompressive craniectomy is a mainstay of damage-control neurosurgery [89]. It is also performed semi-prophylactically in situations where military neurosurgeons believe it is likely the casualty will develop intracranial hypertension during evacuation [22]. Surgical timing and decision to evacuate are important as there is evidence that hypobaria during aeromedical evacuation may be detrimental to neurological recovery [50, 51]. US military data from PHI suggest outcomes are better if surgery was performed early, preventing swelling during aeromedical transportation [90]. This differs from civilian settings, where decompressive craniectomy is a life-saving procedure performed for refractory raised ICP.

Civilian studies have attempted to define whether decompression should be a first-line treatment for TBI. RESCUEicp (Randomized Evaluation of Surgery with Craniectomy for Uncontrollable Elevation of intracranial pressure) showed that at 6 months, decompressive craniectomy in patients with traumatic brain injury and refractory intracranial hypertension resulted in lower mortality and higher rates of vegetative state, lower severe disability, and upper severe disability. Rates of moderate disability and good recovery were similar in the two groups [91].

In UK military series, decompressive craniectomy for PHI was often performed via inverted question-mark fronto-temporo-parietal incisions [35]. More common in US series is Kempke's incision [22]. This spares the posterior auricular and occipital arteries, involving a coronal incision immediately anterior to the pinna to the midline with a second incision perpendicular to it running above the midline frontally to occipital. This may be more suited to complex PHI as vascular preservation enhances soft tissue health. This could aid the multi-disciplinary reconstructive approach to these complex injuries. When performed, decompressive craniectomy should not be less than 12 × 15 cm [77].

In a military cohort with penetrating injury, there is high risk of contamination that predetermines unsuitability for bone flap retention [35]. Large studies suggest higher complications if surgery was performed for trauma, sinus injury or CSF leakage [92]. Bone flaps can be resorbed from within their abdominal pouch if left in for more than 3 months; therefore, this may not be suited to casualties where protracted recovery is anticipated [93]. In battlefield polytrauma, the injured abdomen may be unsuitable for implantation of a bone flap. It would seem appropriate that retention of the bone flap is only considered in isolated closed, non-contaminated head injury.

Air sinus injuries present increased risk for CSF leak, especially with orbitalfacial wounds. Historically, there is a 15% incidence of air sinus injury in military PHI [94]. Delayed repair increases the risk of post-traumatic infection and CSF fistulae. Management may include craniotomy and anterior fossa reconstruction, cranialisation of the frontal sinus, and meticulous dural closure. For temporal bone injuries, a mastoidectomy or middle ear exploration with Eustachian tube packing may be required.

A study of 110 projectile head injury victims during the Iran–Iraq conflict suggested survivors had wide bony decompression, excision of wound tracts and meticulous dural closure including the use of temporalis fascia, fascia lata, or graft material [95]. Reports from the Vietnam conflict suggested 50% of CSF leaks were located at the wound site. Mortality for these patients was 22.8% versus 5.1% for those without a CSF leak. CSF leak is the variable most highly correlated with intracranial infection in PHI. In the Vietnam cohort, 44% of fistulas closed spontaneously. However, if CSF leak is persistent or delayed, treatment with CSF diversion or direct surgical repair should be considered [87]. Duraplasty is controversial, yet studies suggest duraplasty with autologous or synthetic grafts result in lower incidence of CSF leakage [96]. While overlay does not constitute meticulous closure; it follows recommendations from recent US case series and befits principles of damage control surgery [90].

Surgical Treatment of PHI:

Fronto-temporo-parietal “question mark” or “T-bar” incision to preserve scalp blood supply.

Large craniectomy (greater than 12 × 15 cm) to prevent brain strangulation over bone edges.

Excision of necrotic of irretrievably contaminated brain tissue.

Adequate brainstem decompression

Use of dural onlay substitutes for dural closure.

Avoidance of bone flap retention.

14.8 Postoperative Care

Postoperatively, patients should ideally be monitored in an intensive-care setting. If available, ICP should be monitored with a target ICP of less than 20 and a recommended CPP value for survival and favourable outcomes of between 60 and 70 mmHg [77]. Attempts to maintain CPP with fluids and pressors should be undertaken with caution due to the risk of adult respiratory failure.

Elevation in ICP or deterioration in neurologic status warrants emergency CT of the head to identify a new mass lesion, typically an evolving contusion, oedema or a post-operative haematoma. Persistently raised ICP > 22 mmHg is associated with increased mortality [77]. A new hemorrhage after surgery should raise the suspicion of underlying vascular injury or coagulopathy. In certain cases, typically young patients with non-dominant hemisphere lesions, decompressive craniectomy, and duroplasty may be considered with refractory increased intracranial pressure.

Post-traumatic hydrocephalus can occur, with incidence ranging from 0.7% to 29%. Commonly treated by ventriculostomy, series suggest CSF diversion rate of around 3.65% [97]. In patients with an EVD, inability to wean over 7–14 days with persistent high CSF outflow at normal pressure is a good indication the patient will require permanent CSF diversion. If imaging reveals hydrocephalus, including an enlarged fourth ventricle with no focal mass effect, lumbar puncture can be considered to record an opening pressure and offer temporary relief. Final timing for definitive CSF diversion is determined by the presence of other injuries, nutritional status, and infectious complications.

Pyrexia, elevated white cell count, and meningeal signs may indicate postoperative meningitis. In the presence of an EVD, CSF should be sent for analysis. In addition to evaluating the EVD, examination for CSF leak should be performed. Not all CSF leaks are present on admission. Following Vietnam, 72% of CSF leaks appeared within the first 2 weeks of injury [80]. While antibiotics should not be used routinely for CSF leak, there is increasing prophylactic use of pneumococcal vaccination, although without widespread evidence [98].

Coagulation should be re-evaluated as PHI is a known cause of coagulopathy. Brain parenchyma contains thromboplastin that can activate the extrinsic coagulation cascade. If high levels are released, the patient may develop a disseminated intravascular coagulation (DIC). As coagulopathy is proportional to the amount of thromboplastin released from injured parenchyma, presence of DIC represents significant parenchymal injury and may suggest poor prognosis [33].

Antiepileptic medication and antibiotics should all be considered, and their use is discussed previously.

14.9 Prognosis

In comparing outcomes, PHI patients fare worse than non-penetrating TBI, with overall mortality of 88% compared to 32.5% [99]. Typically, death occurs soon after injury, with 70% occurring within the first 24 h [100]. An accurate assessment of prognosis for each patient is essential to determine the appropriateness of treatment, especially in a military or resource-constrained environment.

Various factors are thought to contribute towards outcomes in PHI. Older patients typically have higher mortality. In limited studies evaluating age and prognosis, age greater than 50 years is associated with increased mortality. Whilst PHI in military patients will be younger [35, 99] this is not likely to be the case in the event of a terrorist attack.

In civilian populations, GSW remains the most common type of PHI, with a majority being suicide attempts, associated with a higher mortality. It is unclear if the poor outcome in PHI from unsuccessful suicide attempts is based on injury patterns or limited resuscitation based on a presumption of worse outcome [101].

This is different in the PHI seen from combat injuries. A UK study was the first to highlight and define the significant difference in survival to hospital discharge following PHI caused by blast fragment compared to GSW, attributable to different injury severity [102]. The high velocity associated with military bullet wounds typically causes devastating intracranial wounds. One series reported a mortality with this wound to be 82% higher than with fragmentation wounds [103]. There is not a correlation between outcome and caliber of weapon, likely because the energy imparted to the tissue also is related to the velocity, which can be variable.

GCS is one of the strongest predictors of mortality and outcome [99]. In civilian settings, most patients present with a GCS of 3–5. These patients have the highest rate of mortality and poor outcome. In military series, most patients who present following PHI, with a GCS > 5 survive to discharge [102]. Increasingly ISS/GCS at point of injury does not reflect eventual outcome and evidence increasingly suggests it not be used to prognosticate and alter treatment pathways, as there is poor correlation with long-term outcome.

Neurorehabilitation should always be considered because survival, return to independence and full employment are very likely [104]. A UK study of military PHI with ISS 75 showed all casualties had a GOS score greater than 3 [35]. This is broadly similar to US data; who reported 84% of casualties with follow-up data achieving a GOS score greater than 3 at 1–2 years [90]. High survival rate from "unsurvivable injuries" supports on-going work to develop, evolve and adapt military specific trauma scoring systems.

Systemic insults after a PHI can worsen the patient's outcome. Periods of hypotension, respiratory distress, and coagulopathy all are associated with increased mortality [99]. Impact Brain Apnoea (IBA), a phenomenon of apnoea following PHI may be a significant and preventable contributor to death attributed to primary injury, and simple interventions could improve outcomes [105].

An abnormal pupillary exam is common and may result from orbital trauma, medications, cerebral herniation, or brainstem injury. Patients presenting with unequal or fixed and dilated pupils have an increased mortality. There is little data that exists on the prognostic value of ICP, yet what is available suggests elevated ICP within the first 72 h correlates with higher mortality [99].

As previously discussed, CT scan is the diagnostic modality of choice. Three prognostic indicators can be determined from the patient's initial scan: projectile tract, evidence of increased ICP, and the presence of haemorrhage or mass lesion. Projectile trajectories associated with increased mortality include bi-hemispheric lesions, multilobar lesions, and those that involve the ventricular system. In low-velocity GSW, fatal outcome and low GCS were associated with a 'tram-track' sign on imaging. Passage through the supra-dorsum sellar transventricular zone (zona fatalis) were always associated with fatal outcomes [106]. One exception may be a bi-frontal injury. Basilar cistern effacement on CT, indicative of elevated ICP, is associated with increased mortality. Midline shift alone, however, is not. The presence of large contusions and/or subarachnoid haemorrhage is associated with increased mortality. A stronger correlation, however, exists between increased mortality and the presence of intraventricular hemorrhage [99].

Understanding these prognostic indicators is important for those who might be managing PHI in a mass casualty event where teams must decide who would most benefit from surgery and aggressive management. In civilian GSW, no patient with a post-resuscitation GCS of 3–5 and only 20% of those with GCS of 6–8 had a satisfactory outcome, defined as either good or moderately impaired GOS [43]. More recent work shows 66–90% of civilian GSW casualties die before reaching hospital. Of those who are admitted to hospital, up to 51% survive [107].

Conclusion

PHI, from blast and GSW is common both as isolated injuries and as a component of multi-system poly-trauma and will be encountered from urban environments to war zones. Recent urban terrorist events highlight the importance of basic understanding of PHI for all, from pre-hospital care providers, doctors and nurses working in the emergency room, as well as military surgeons and medical and nursing staff on deployment in regions of conflict. Multidisciplinary specialist management is likely required for optimal outcomes for these complex injuries.

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Penetrating Ballistic Spinal Injury

15

Stuart Harrisson

15.1 Introduction

Penetrating spinal injuries can be classified in to either ballistic (or missile) injuries or non-ballistic injuries (i.e. stab injuries). Civilian experience of penetrating spinal cord injuries varies from country to country, generally dependant on exposure to firearms within the population. Countries without guns will have some stab injuries but the incidence tends to be far lower. Military experience of penetrating spinal injuries is different from civilian experience, because although there will be exposure to gunshot injuries there will also be exposure to blast fragmentation injury. Cases of terrorist bombings may also expose non-military surgeons to similar injury patterns.

Penetrating injuries of the spine have posed a challenge to surgeons for over 100 years, and the management of penetrating spinal cord injuries remains controversial. For surgeons, the primary question has been "is decompressive surgery of any benefit? Is there likely to be a greater chance of neurological recovery if the neural components are decompressed?" As will be discussed the recent experience from Afghanistan and Iraq has led to this being reflected on again in modern conflicts, with a revaluation the limited evidence available. This chapter sets out to define ballistic penetrating injuries to the spine, reviewing the previous literature, the relevant anatomy, injury patterns, prognosis, assessment and management.

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15.2 Historical Perspective and Epidemiology

Care should be taken when comparing data regarding penetrating spinal injuries. In most civilian series, the injuries are caused by low velocity gunshot wounds (GSW), whilst military injuries tend to be mainly of explosive fragments or a higher velocity gunshot wounds [1]. Whilst these injuries are no longer attributed with the same mortality as previously, they are devastating injuries as the patient is often left with a significant disability, governed by the level of paralysis and incontinence.

15.2.1 Civilian Data

Depending on the data reviewed penetrating injuries are the second or third most common cause of Spinal Cord Injury (SCI) within the USA, causing about 15% of SCI [2–4]. In civilian cases, penetrating ballistic injuries, which are mainly gunshot wounds, are most common in the thoracic spine. If they involve the cervical spine then about 70% will be complete injury whilst in the lumbosacral spine 70% will be incomplete [5]. They are more common in young males, and often involve alcohol or illicit drug consumption [2]. About a quarter are associated with other injuries. Whilst this chapter concentrated on ballistic data it should be noted that stabbing injuries have similar poor outcomes [2].

15.2.2 Military Data

Historically, the prognosis in penetrating spinal injuries was very poor. Matson states in his famous text published in 1948 that "this has always been a difficult and discouraging group of cases to treat and perhaps for this reason they have been neglected" [6]. During the American civil war, there are records of 650 battle related spinal injuries with an associated mortality of greater than 50% [7]. In nineteenth century conflicts the mortality of ballistic spinal injuries is quoted as being around 50% [1]. In the First World War the mortality was reported as being greater than 70%, with urinary sepsis being the main cause of death. Surgery was used in some cases, but with a high operative mortality of 62% [8]. Reports after the war suggested that surgical intervention was used only in those cases were there was an incomplete injury, and then a subsequent deterioration; these were relatively rare cases [1]. Laminectomy was the only surgical procedure.

By World War Two, a more aggressive approach to treating these injuries was being used, with a greater range of surgical indications (including aggressive debridement, canal decompression, intra-dural exploration of virtually all patients—including those with complete injuries), with the subsequent effect of far more surgical interventions in a wider variety of cases. Non-operative mortality remained high at 62% with operative mortality between 5 and 12% [2, 6, 9]. Mixed results were reported, with between 40 and 60% improvements being quoted in some series [1]. Maximal intervention was provided with often no effect.

By the Korean war the operative mortality had dropped to 1%. Aggressive surgical decompression was undertaken at an early stage, with patients having laminectomy as soon as possible unless they required other lifesaving surgery. Whilst 48% of patients were reported to show improvements, and most interestingly this was seen in patients with cervical injuries, these results could not be matched in civilian series and appear to have been reviewed sceptically [1]. By Vietnam, despite the improved evacuation times, no significant improvements were being seen despite this aggressive surgery. Guidelines moved again from routinely performing surgery, towards only offering interventions in those patients with developing neurological deficit. This approach was backed up by similar approaches in later conflicts such as the Iran-Iraq war, the Lebanese civil war and in Croatia. All demonstrated no significant improvements in neurological outcomes in patients with penetrating spinal cord injury who underwent decompressive surgery [10–12].

15.2.3 The Twenty-First Century

The casualties in the recent conflicts in Afghanistan and Iraq have been recorded in the greatest detail of any conflict to date, with trauma registry's and better medical note-taking allowing cases to be identified and outcomes more accurately measured. Care should always be taken though when using military combat casualties' data, as comparisons between different series of data can be fraught [13].

A retrospective analysis of American injuries between 2005 and 2009 found spinal injuries present in 11% of the reported 8500 combat injuries [14]. these injuries were fractures, but 9% had a spinal cord injury. The most common cause of injury was explosive blast, but it should be noted this series was not looking exclusively at penetrating injuries. Differences between operational theatres were noted, with Iraq having significantly more GSW compared with Afghanistan. 3.3% of those with spinal injuries died subsequently of their injuries. The group calculated a combat incidence of 4.0 per 10,000 for spinal fractures and 0.4 per 10,000 for SCI and concluded noting that spinal trauma in modern conflicts exceeded previous reported rates. Amongst the 5424 deaths in Afghanistan and Iraq [15] there were 2089 cases which had some form of spinal trauma [15]. 40% of these fatalities had a spinal cord injury.

Blair et al. tried to follow a cohort of spinally injured patients between 2001 and 2009 through their surgical management [16]. Their retrospective analysis of American patients from the evacuated patient trauma registry showed that 5.45% of patients (n = 598) had a spinal injury, of which 17% were spinal cord injuries. Many the injures were called by explosions, but injury by GSW was 3.78 times more likely to cause a SCI, and if you had a spinal injury associated with a GSW there was a 53% incidence of spinal cord injury. Of the SCI 45% were complete injuries. Just over half the SCI patients (n = 59) had American Spinal Injury Association (ASIA) recordings at follow up and were therefore further analysed. About half of the ASIA grades improved with only one having a neurological deterioration (who had surgery). In total, 40 cases had surgical intervention—of which 22 improved and 18 showed no change, and the one case of deterioration. In the non-surgical patients 8 improved with no surgery, and 10 showed no change. Blair et al. also looked at the breakdown of penetrating and non-penetrating injuries, finding that 28% of injuries were penetrating [17]. Of the 104 SCI cases, 63 were due to penetrating injuries. They noted that penetrating injuries had a significantly high level of SCI compared to blunt (as would be expected) and associated higher incidence of operative intervention and neurological deficit. They found that penetrating injuries were most common in the lumbar region, which they felt may be due to the increased use of body armour. Whilst again they noted that explosions were the most common cause of spinal injuries, only 32% of these injured patients had a penetrating element.

There has been limited publication of analysis of the UK military trauma registries with regards to spinal injuries. During Iraq and Afghanistan, 43% of cervical ballistic wounds are known to have had spine or spinal cord injury [18]. A retrospective analysis of penetrating cervical spinal trauma addressed the question of neck immobilisation after penetrating neck injuries [19]. It reported that only 3% of unstable spinal injuries survived to hospital and therefore very few would benefit from cervical immobilisation, especially as there was risk of delaying, or affecting treatment of other injuries, with a collar in place.

15.3 Anatomy and Pathophysiological Considerations

The spine can often be considered in two sections, the osseous part (composed of the vertebrae) and the neural elements. The osseous spine has two primary functions; to provide skeletal stability (linking the pelvis and head) and protect the spinal cord and other neural elements, transmitting neural connections from brain to peripheries. There are seven cervical vertebrae, twelve thoracic, five lumbar and then the sacrum and coccyx. The vertebrae articulate with adjacent levels (except in the high cervical region) by means of the intervertebral disc anteriorly (or ventrally). Posteriorly (or dorsally) there are bilateral paired facet joints to support the structure.

The spinal cord contains the neural tracts connecting the base of the brainstem to the peripheries. The main descending tract is the lateral corticospinal tract which carries information to the contralateral side of the body (having decussated at the level of the medulla). Sensory fibres are transmitted (primarily) within the dorsal columns and the spinothalamic tract. The spinal cord normally finishes around the level of L1 (the conus) and beyond this the nerve roots travel distally before exiting through the spinal foramina. The multiple spinal roots within the dural sac or theca are known as the cauda equina. The spinal cord and cauda equina are surrounded by the fibrous dura, which contains the cerebrospinal fluid around the neural components.

Suggested factors affecting the extent and severity of penetrating spinal cord injury include [4]:

- Type of ballistic involved
- Degree of transection or contusion of the spinal cord
- Degree of concussive blast injury to the spinal cord

- Compression of cord by haematoma or displaced bony fragments
- Disruption of spinal cord vasculature
- Mechanical stability of the segment(s) involved [4]

15.3.1 Types of Spinal Injury

Spinal injuries can be classified by several different methods, either by mechanism (blunt vs. penetrating as described earlier), by specific clinic syndromes (anterior spinal cord, central cord, Brown-Sequard) or by assessing for particular clinical features (for example, to consider the severity of the injury—complete or incomplete injuries, or to consider if the injury would be considered stable or unstable). There are examples of specific syndromes being seen after penetrating spinal injury [20].

Regarding clinical severity, it is usual to classify the injury as either complete or incomplete, and early assessment of this is known to be a prognostic marker in penetrating spinal cord injuries. In a complete injury, there is no function below the level of the injury although the spinal reflexes may return with time. The injuries should be recorded in clear and concise manner, such as by using the ASIA classification from grade A to E, with A being a complete injury and E no injury [21]. In penetrating ballistic injury it is suggested that SCI can occur in three ways—either by direct injury along the path of the missile, by a pressure or shock wave phenomena or by a temporary cavitation effect [1]. A similar system in 2002 described the third group as being those injuries secondary to fractures or dislocations [9]. What is accepted is that the spinal cord does not need to be transected, or indeed even hit for a complete spinal injury to occur [8]. There has been suggestion that hitting the bony components of the spine up to 15 cm from the level of the spinal injury can cause microscopically detectable spinal injury (in the form of intramedullary haemorrhage—with more rarely extradural or subdural haemorrhage) [8, 22]. Injuries to the lumbar region are generally less severe, not only due to the fact that they occur at lower level, but also as the spinal cord has ended and the cauda equine seem able to better accommodate the injury.

15.3.2 Stability

In general, when considering spinal injuries, the stability of the spine is considered a key concern. Moving a patient with an unstable injury risks making their neurological injury worse and creating a potentially devastating outcome. Assessments of stability are based around both clinical and radiological features. The classifications used for assessing stability in fractures of the spinal cord have been developed for blunt, indirect force and the injuries these forces cause. Ballistic injuries are conversely a direct force and therefore the classification systems must be used with caution. Injuries which could be described as "three-column injuries" if caused by blunt force, may in fact be stable injuries after a penetrating gunshot injury [23]. Most gunshot injuries to the spine are stable as only those structures directly injured are damaged and stability is often preserved. For most civilian (and by inference low velocity) injuries instability is rare [1]. Instability is considered more common in military injuries, which may be due to a combined penetrating and blunt force in explosive injuries. Of note is that the chances of instability occurring is significantly higher by surgical decompression and this should be borne in-mind when embarking on spinal decompression (discussed further below) [1].

Battlefield fragment injuries to the cervical region are often fatal, and those who do survive very rarely have unstable injuries [19]. Current UK military guidelines do not recommend placement of a collar in penetrating cervical injury, due to the low occurrence of instability and collars are considered as possibly being detrimental due to masking other injuries, such as haematomas. The most common injuries requiring stabilisation are those with a transverse (side to side) injury involving the facets and pedicles [24]. If there is any listhesis or angulation then flexion/ extension radiographs should be considered [23]. If both pedicles are traversed in a coronal plane there is a high risk of instability and in most cases instability is caused due to surgical decompression.

15.3.3 Shock

After any penetrating injury, a primary concern is hypovolaemic shock. Spinal injury can also produce two separate distinct causes of "shock" which should also be considered (as well as the subsequent risk of septic shock from penetrating injury).

Neurogenic shock is caused by injury to the autonomic nervous system and the loss of sympathetic vascular tone. A significant proportion of the sympathetic nervous system needs to be injured and therefore it tends to occur in injuries that are at T6 level or higher. The injury results in bradycardia, hypotension and hypothermia. Peripheral vasodilation can also occur. Treatment is centred around judicious fluid resuscitation—urine output is considered a good marker of resuscitation; care needs to be taken as fluid-overload and pulmonary oedema are possible. Atropine can be used for treatment of the bradycardia. Hypoxia and tracheal washout can exacerbate bradycardia leading to arrest. Autonomic dysreflexia occurs in around 5% of patients with spinal cord injuries above T6. In this condition patients get an uncontrolled sympathetic reflex response to a usually mild stimulus (for example a full bladder, or bowel distension). Symptoms include flushing, headache, sweating, anxiety, hypertension with bradycardia. Treatment includes removal of the stimulus and elevation of the head. Hydralazine may on occasion also be needed.

Spinal shock is a flaccid paralysis, also thought of as a "concussion" of the spinal cord [25]. Spinal reflexes and tone are lost, which will then resolve, sometimes leading to hyperreflexia, hypertonicity and clonus. It is often considered that the more rapid the return the poorer the prognosis [2]. Once the sacral reflexes return (namely the bulbocavernous reflex and anal wink) it is considered that the spinal shock period is resolved, and therefore the true spinal injury can be assessed. It does not involve a hypotensive component.

15.3.4 Lead and Copper Poisoning

Lead poisoning presents with a variety of symptoms including hypertension, headache, mood change, abdominal pain and joint and muscle pain. There are some case reports of lead toxicity associated with rounds or fragments surrounded by CSF, but the evidence is limited. The primary treatment would be to remove the source, but current recommendations are not to primarily remove the fragment to prevent poisoning, as the incidence of toxicity are low. There is some in-vivo evidence of neural tissue necrosis from copper fragments but this has not been proven in humans [23].

15.4 Management Goals

The overall aim in management of penetrating spinal injury is to prevent further neurological deterioration and to avoid the complications associated with SCI.

15.5 Pre-hospital and Resuscitation

The pre-hospital management should be undertaken in-line with the current guidelines for the environment in which the injury takes place, ensuring that risk to the treating clinicians is reduced as much as possible. Treatment paradigms are designed to ensure that other, potentially fatal injuries that need treatment first are not missed. Shock should be considered hypovolaemic in the first instance and treated as such. Current UK military guidelines do not recommend the placement of cervical collars for penetrating neck injuries. This is supported in the civilian data, although other authors suggest they should be judiciously placed in some circumstances within the civilian environment [26, 27].

15.6 Assessment and Initial Treatment

When safe, a full and complete assessment of the patient should be carried out. This will be carried out again in the Battlefield Advanced Trauma Life Support (BATLS) manner aiming to identify all injuries, and expediently treating life threatening injuries. With penetrating wounds, there should be a low threshold for considering the possibility of spinal injury. A full neurological examination should be carried as soon as possible, and appropriately documented. This is important for both prognostication (it is quoted that 90% of presenting neurological deficits are permanent [1, 2]) and to allow for monitoring for deterioration (deterioration being considered a key indication for surgical intervention). Assessment should be carried out in line with the ASIA scoring sheet and includes sensory status, strength of muscle contraction, tone, reflexes and assessment of sphincters [28]. Ideally this full neurological should be completed within 24 h of injury. Further information can be found on the British Association of Spinal Care Injury Specialists website [29].

If a spinal injury is presumed then the case should be discussed urgently with a spinal surgeon, and transfer for assessment arranged as soon as possible dependant on the situation. Whilst awaiting transfer, good medical nursing care to prevent secondary injuries is essential. The aim is to maintain spinal cord perfusion and oxygenation, whilst monitoring for deterioration. The same care should be prescribed as for all patients with presumed spinal injuries. This includes:

- NG tube and PPI prescription to reduce the risk of stress ulceration
- Early establishment of feeding
- Urinary catheter and laxatives
- Nursing care to prevent skin ulcers
- DVT prophylaxis
- Chest physiotherapy to prevent chest infection
- Monitor for neurogenic shock—careful fluid management

15.7 Investigations

Initial investigation of penetrating spinal cord injury will be dependent on the environment and facility in which the patient is being cared for. In the first instance, only plain film or digital radiography may be available which will allow the presence and position of metallic objects to be assessed. CT is useful in giving accurate definition of bony injury, but artefact from metallic objects can be significant. Three-dimensional reconstructions can be useful to assess for trajectory of fragments. MR is the investigation of choice for assessing "soft" spinal injury normally, but again with penetrating ballistic injuries there can be significant problems with artefact, and there is the risk of fragment movement and heating during scanning. Myelography is now rarely used [30].

15.8 Definitive Care

Patients with spinal injury should be transferred as soon as possible to an appropriate spinal treatment unit for further assessment and consideration of on-going management.

15.9 Surgical Management

The timing and indication for surgery remains a point of controversy regarding ballistic penetrating spinal injury.

The aims of surgery are generally considered to be:

- to preserve or improve neurological function,
- reduce the risk of infection,
- stop CSF leak and
- treat instability [4].

The use of surgical intervention has varied from minimal procedures to more aggressive surgeries throughout the last 100 years. The literature is full of opinions on the question of when and what surgical intervention should be used in military penetrating spinal injuries [1]. The challenge of deciding on an optimal therapy persists and studies exist recommend for and against surgery. A recent review from the post-Vietnam era identified eight civilian and eleven military case series of penetrating spinal injury [1]. Methodological problems were noted by authors, as only four papers had sufficient data to look at the primary question of comparing decompressive surgery with conservative treatment, and there was often bias as no control data was used in several papers. The data from the civilian papers was noted as being of generally better quality and strongly concluded no benefit of surgery.

In the treatment of penetrating spinal injury the best prognostic predictor of future neurological grade was the initial neurological examination [1]. The final decision regarding surgery should be with the deployed spinal surgeon but, absolute indications for surgery would be progressive neurological decline with compression of neural elements on imaging and to repair a CSF-cutaneous or CSF-pleural fistula due to the increased risk of meningitis. Current recommendations for the treatment of penetrating spinal injury include [1]:

- that a laminectomy should only be considered if the patient has been stabilised from the point of view of other life threatening injuries.
- that a laminectomy should not be performed in those with a complete neurological injury, with the possible exception of a cervical lesion, with on-going compression, where the patient has arrived soon after injury at the surgical unit.
- that a laminectomy should be considered in incomplete injuries with on-going compression, with surgery taking place as soon as possible. There is a recommendation that instrumentation and fusion should occur at same time if the injury is considered unstable.

Removal of foreign bodies (FB) has previously been cited as a reason for surgical intervention. This was partially done to improve motor function, but also to reduce the risk of copper or lead toxicity and to reduce the presumed risk of infection. It is now noted that, whilst it removal can improve outcomes, it can also make the neurological status worse, and increase the risk of complications [31]. The risk of toxicity from fragments is considered very low and this is not now seen as indication for surgery. For FB in the Cauda Equina region there was previously recommendation that these should be removed, and recent case reports in the civilian literature still recommend this [32]. If this is to be undertaken then it is recommended that the patient be placed head up, so as to encourage the FB to move distally. Intraoperative fluoroscopy is of value to help localise the fragment, although these cases were noted to often be technically challenging.

Removal of FB to reduce infection, is considered unnecessary provided a thorough washout has occurred and antibiotics prescribed [1]. There is generally a feeling that there is no need to perform exploratory surgery as means to reduce gross infection (beyond local wound care) unless gross contamination of the wound. Military injuries from blast fragmentation do require a more aggressive debridement than civilian injuries [4]. If there has been a trans-colonic or trans-intestinal injury and there is an indication for decompression, it is recommended that decompression can occur despite the possible increased infection rate; however if fusion is required this should be delayed until after completion of the course of antibiotics [1].

If surgery is undertaken then care should be taken to ensure that handling the spinal cord is kept to a minimum. Easily removable fragments should be removed, and attempt made to close the dura to prevent CSF fistula. If spinal fixation is being undertaken, as alluded to above, unless there is gross contamination this should be completed early to reduce the need for further operations and to stabilise the spine allowing easier evacuation. Whilst the ideal would be to use spinal fixation equipment, there have been reports from Afghanistan of using other non-spinal orthopaedic equipment (off-licence) for fusions, when no other equipment was available to allow fusion, when no other materials were available [33]. These patients had very limited post-operative follow-up.

Existing studies pertaining to civilian penetrating spinal injuries should be interpreted with caution [5]. Supportive management should be the primary method of care. No major improvement benefit from surgery compared to conservative management is found, but complications are greater in the operated groups. There is some limited neurological benefit to surgical decompression with an incomplete lesion if the bullet lies within the canal or around the cauda equina.

15.10 Non-surgical Management

It is essential that the best possible nursing care is afforded to spinal injury patients to reduce the risk of secondary complications, as outlined in the initial treatment section above.

15.10.1 Antibiotics

There is no clear evidence on the type of antibiotics, or duration of course which should be given after a penetrating spinal injury [4]. Recommendations very between two and fourteen days, covering gram positive, gram negative and anaerobic organisms, but with generally a minimum of seven days if there is a retained foreign body or associated hollow visceral injury [1, 8]. Tetanus prophylaxis should also be given.

15.10.2 Steroids

There is no evidence that steroids improve outcomes, and may increase the risk of complications [2, 4, 5].

15.10.3 Bracing

Braces can be used to support the spine. However in the civilian population bracing is often over used in penetrating spinal cord injury and an increased number of complications are seen [34].

15.10.4 Vasopressors

A retrospective analysis of use of vasopressors to maintain MAP targets was published in 2016 [35]. The study only had a small sample of 14 patients, with only one seeing an improvement on their ASIA score despite supra-physiological MAP scores, whereas over 70% patients had side effects.

15.11 Outcomes

The best prognostic predictor of future neurological grade is the initial neurological examination [1, 4]. Improvement of fixed neurological deficit following penetrating spinal cord injury is rare. Military data and civilian studies suggest no significant benefit in neurological deficit with surgery compared to conservative management [1, 5].

15.12 Potential Surgical Complications

Both the civilian and military data agree that there are likely to be more complications in patients who are treated surgically, but this may well be due to bias that those patients treated surgically were those with a worse injury [1, 5]. Complications will occur with surgical management of these cases but these complications are manageable [1]. Those that have surgery were more likely to have a complication [36], which include perioperative deaths and deep wound infections. Instability with progressive kyphosis, and incomplete decompression are the main causes for reoperation [37].

15.13 Potential Non-surgical Complications

- Pain: various types have been described including from spasm, neurogenic, analogous, phantom limb

- Delayed deterioration: if his occurs then it is necessary to consider syringomyelia or arachnoid adhesions, as well as infection as possible causes. Further evaluation with cross-sectional imaging is necessary.
- Infection: a septic complication rate of approximately 10% is to be expected, which is not influenced by the presence of foreign bodies [9, 38]. There is evidence that steroids increase the rate of infections as well as non-infectious complications
- Symptoms of restricted movement: Skin breakdown, gastric ulceration, thromboembolic disease

Patients with spinal cord injury have complex requirements. Learning to manage the pain, together with other requirements including assessing their psychosocial, sexual, vocational, educational and recreational rehabilitation requires specialist MDT input.

Conclusion

Penetrating spinal cord injury remains a devastating injury. Whilst it no longer has the high mortality associated with it 100 years ago, the significant morbidity and associated on-going life-long care needs are considerable. Life expectancy is often not altered, so these are injuries which will have a significant effect on the patient and their family and carers for many years. The degree of injury immediately after the injury is the best prognostic marker of what the eventual outcome is likely to be, and surgery is normally reserved for a limited number of cases as it is unlikely to change the outcome. All surgeons and physicians should be aware of the controversies around the management of penetrating spinal cord injuries, as no matter what country they are based in, the incidence of terrorist attacks increases. The key aims of management are to prevent any further neurological deterioration, and prevent harm from other factors (complications). The requirement for good nursing care is paramount.

The incidence of spinal trauma (both blunt and penetrating) in modern military conflict has increased in the last 20 years. Previous guidelines looking at the evaluation and management of such trauma need to be re-evaluated given the increasing incidence of injury [39]. It remains critical that we continue to study and evaluate the injuries we treat so as to ensure we provide the best possible therapies. In spinal cord injury new therapies are being developed such as epidural stimulators and use of stem cells transplants [40, 41]. The next decades could see the development of these to improve the functional outcomes of our patients from these devastating injuries.

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Ophthalmic Injury

16

Richard J. Blanch

16.1 Introduction

Eye injury is very common. The Beaver Dam Eye Study reported a lifetime prevalence of 20% for all eye injuries in a civilian population, though the majority of these would be minor with only 1–2% likely to cause permanent visual loss [1]. Military personnel are more prone to sustaining severe eye injuries, with 5–15% of all military trauma involving the eye and greater than 50% of these having the potential to cause permanent visual loss [2]. In modern warfare, most casualties are civilian. In terrorist bombings in civilian settings the proportion of eye injuries has been reported as up to 20% though it varies depending on environment [3, 4]. The mechanism of injury is from missile fragments and secondary fragments of glass, cement and mortar that cause minimal damage to clothes or skin, but significant morbidity if they hit the eye. Unlike in peacetime where unilateral injuries are the rule, blast-related injuries are bilateral in 15–25% of cases [5, 6].

Though the eyes occupy 0.27% of the anterior body surface, military personal armour makes explosions more survivable but leaves the face and eyes relatively exposed. The development of weapons with higher explosive and fragmentation power led to a continuous increase in the proportion of eye injuries over the twentieth century. Uptake of ballistic eye protection probably contributed to the reduction of the proportion of eye injuries from 13% in Operation Desert Storm (1991) to 6% in Operations Iraqi Freedom and Enduring Freedom (2001–2005) [7, 8].

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16.2 Anatomy

The eye (or globe) is suspended in the bony orbit by connective tissue and muscle attachments. In addition to the globe, extra-ocular muscles and connective tissue, the orbit contains nerves, blood vessels, orbital fat and the lacrimal gland (Fig. 16.1). Anteriorly the orbit is covered by the eyelids, which contain part of the lacrimal drainage apparatus. The anterior segment of the eye (anterior to the lens) is covered by cornea and contains aqueous. The posterior segment (posterior to the lens) is covered anteriorly by translucent conjunctiva. Beneath the conjunctiva is vascular episclera and Tenon's capsule. Tenon's capsule covers the globe from the optic nerve to the limbus (junction of cornea and sclera) and is reflected back to envelop the extra-ocular muscles from their insertions onto sclera. The sclera is the tough collagenous outer coat of the globe. Inside the sclera is the choroid containing the choriocapillaris, which provides a rich blood supply, from which oxygen and nutrients diffuse to the outer retina (Fig. 16.2). Light enters the eye through the clear optical media (tear film, cornea, aqueous in the anterior segment, lens, vitreous) and is focussed on the retina. The tear film/cornea provide the main contribution to refractive power and the lens provides a smaller, but modifiable component. Vitreous

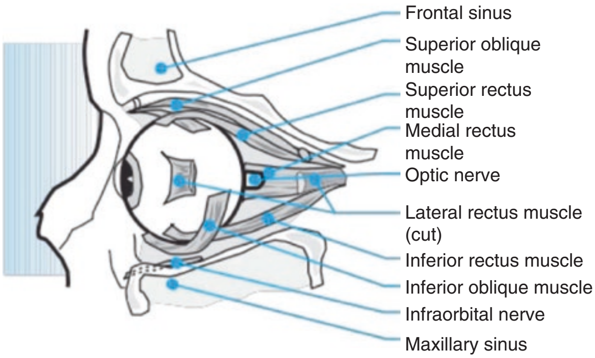

Fig. 16.1 Muscular attachments of the eye

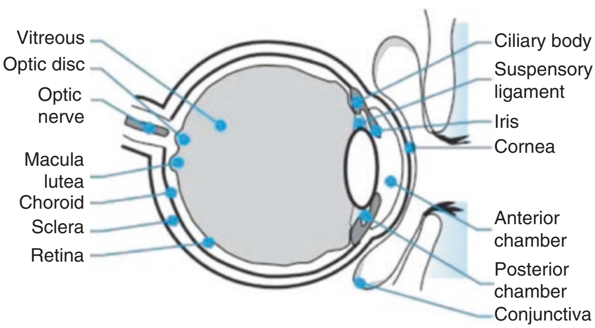

Fig. 16.2 Labelled components of the eye

gel fills the posterior segment of the eye and is composed of water, collagen and glycosaminoglycans (mostly hyaluronic acid) with very few cells. The vitreous body is strongly attached to the retina posteriorly.

16.3 Classification

It is important to understand a classification of eye injuries to enable clear communication with other professionals, but also because certain features carry prognostic significance. One commonly used classification is that described in the Birmingham Eye Trauma Terminology System [9] (Fig. 16.3, Table 16.1).

16.4 Ocular Trauma Scoring

Certain features on examination are useful markers for severity and also give a crude prediction of likely visual outcome (Table 16.2). From the ocular trauma score it can be seen that high energy injuries, which are ruptures and perforating injuries and those causing an optic neuropathy (signified by an afferent pupillary defect) carry a poor prognosis (Table 16.3). Intraoccular Foreign Body (IOFB) injuries are a specific subset that can achieve excellent visual results with appropriate

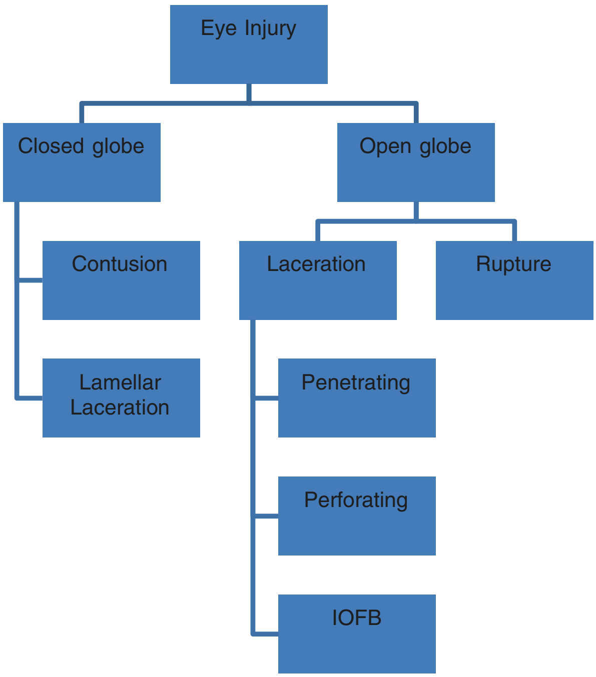

Fig. 16.3 The Birmingham eye trauma terminology system [9]

Table 16.1 The Birmingham eye trauma terminology system [9]

Closed globe injury	No full-thickness wound of eye wall
Open globe injury	Full thickness wound of eye wall
Contusion	No wound of the eye wall
Lamellar laceration	Partial-thickness wound of the eye wall
Laceration	Full-thickness wound of the eye wall caused by a sharp object
Rupture	Full-thickness wound of the eye wall caused by a blunt object
Penetrating injury	An entrance wound is present -zones: Corneal (I) Limbus to 5 mm (II) > 5 mm posterior to limbus (III)[a]
IOFB	One or more foreign objects remain within the eye
Perforating injury	Both an entrance and an exit wound are present

IOFB intraoccular foreign body
[a]A zone III injury overlies/involves the retina

Table 16.2 Calculating the ocular trauma score [10]

Variable	Score
Step 1—Assign a raw score on visual acuity	
Vision	
NLP	60
LP/HM	70
6/1200–<3/60	80
3/60–<6/12	90
>6/12	100
Step 2—Subtract specific modifiers	
Rupture	−23
Endophthalmitis	−17
Perforating injury	−14
Retinal detachment	−11
Afferent pupillary defect	−10

Table 16.3 Applying the ocular trauma score to predict visual outcome

Score	Predicted visual outcome
0–44	NPL
45–65	PL/HM
66–80	CF-5/60
81–91	6/60–6/13
92–100	≥6/12

treatment. Complications of intraocular infection and retinal detachment cause secondary damage and worsen the visual outcome.

16.5 History

History is a vital part of the ophthalmic assessment and should include features relevant to ophthalmic assessment and management. In particular it is important to establish the mechanism and circumstances of the injury. Was the injury blunt or sharp, high or low velocity and is there a possibility of a retained intraocular foreign body? Were corrosive chemicals involved and were they acid or alkali (alkaline are worse)? Was protective eyewear worn? Past history is also relevant—did the patient see normally before the injury or did the injured eye or fellow eye have a history for example of amblyopia? Visual impairment in the fellow eye may mean the injured eye is the patient's only good eye, adding pressure to the management and making consideration of occupational and social impact vital. Any previous treatment such as first aid or regular medication is also important. For example when antibiotic ointment has been instilled, visual acuity may be grossly reduced by the disruption to the tear film. Previous operations may predispose to particular injuries. Old extra-capsular cataract extraction wounds or corneal graft wounds are prone to rupture and in the case of a graft, consideration must be given to preventing rejection precipitated by the injury. As surgical management is often necessary, the patient's last oral intake should be noted.

16.6 Examination

Patients with eye injuries are usually anxious and in pain. Examination will be easier, visual acuity testing more accurate and the patient and physician will both be less distressed if appropriate topical and systemic analgesia and explanation are given before any examination (Fig. 16.4).

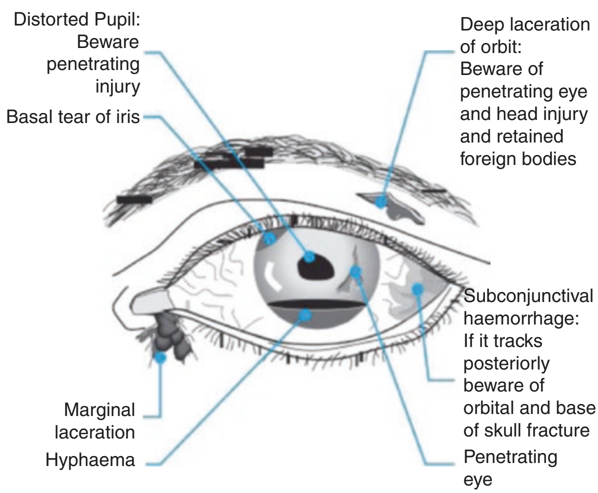

Fig. 16.4 A pictorial description of various eye injuries

16.6.1 Visual Acuity

Eye examination should be systematic. Visual acuity should always be recorded for conscious patients as the uniocular (with the other eye carefully occluded) best corrected visual acuity is measured by asking the casualty to read a standard reading chart (Snellen chart) at 6 m. The acuity is recorded as a fraction. The casualty's distance from the chart is the numerator and the smallest line achieved on the chart is the denominator (e.g., can see the 36m line at 6 m = 6/36). Measuring acuity with the subject looking through a pinhole can correct most refractive errors if the casualty's glasses are not available and should be tried when acuity is reduced below 6/6. If a pinhole occluder is not available a 1–1.5 mm hole should be fashioned in a sheet of paper.

If a Snellen chart is unavailable, acuity should be recorded as: Able to read normal text or only headlines (record distance read) > able to count fingers (e.g. CF at 30 cm) > able to perceive hand movements (HM) > perception of light (PL) > no perception of light (NPL). Good occlusion of the fellow is especially important when classing an eye as PL or NPL using a bright light source.

16.6.2 The Swinging Torch Test

This compares the relative sensitivity of both eyes to light. It is the most important objective test in ophthalmology and aims to compare the extent of pupillary constriction with the light shone in either eye, as an assessment of optic nerve function. Shine a bright light into the first pupil for 2 s and then the other pupil for a similar period, waiting 1–2 s on each eye before swinging rapidly across. This cycle is repeated several times. Both pupils should be the same size and constrict equally to light. If the pupils are less constricted when light is shone in the injured eye, there will be constriction of both pupils when the torch illuminates the normal eye and apparent dilatation when the injured eye is illuminated. If there is relative dilation, then that eye has damaged retinal or optic nerve function and a poor visual prognosis i.e., it has a Relative Afferent Pupillary Defect (RAPD). If one pupil is immobile, the test can still be performed by viewing only the reaction of the normal pupil when the light is shone into either eye, because pupil reactions are symmetric. The presence of a RAPD is specific for optic nerve and gross retinal pathology (e.g. extensive macula-off retinal detachment) and is not affected by media opacity (e.g. cataract, hyphaema, vitreous haemorrhage). Injury to the optic nerve is common in orbital and head trauma.

16.6.3 Fundoscopy

Fundoscopy is an important skill for examining the eye correctly (Fig. 16.5). The optic disc is the point of exit from the eye for retinal ganglion cell axons. Posterior to the disc (after the lamina cribosa), axons are myelinated in the optic nerve. In

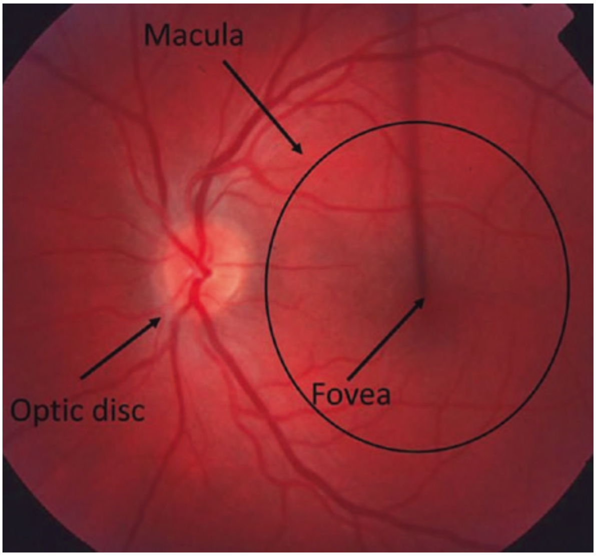

Fig. 16.5 A fundus photograph showing the features most prominent on fundoscopy of a normal human eye

Table 16.4 General measures for dealing with eye injuries

Systemic antibiotics and anti-tetanus.
Treat as a stretcher case.
Analgesics and antiemetics.
Topical antibiotics. Administer every 1–2 h with an initial loading dose (one drop every minute for 5 min). Do not use topical therapy if there is any likelihood of open globe injury.
Shield not pad. Padding the eye may extrude ocular contents or promote infection. It is better to leave the eye open and protect it with a shield.

their intra-ocular course they are usually unmyelinated. The fovea is the avascular central region of the macula responsible for detailed colour vision and contains only cone photoreceptors.

16.7 General Management of Ocular Injuries

Systemic prophylactic antibiotics (such as co-amoxiclav) and analgesia should be given to all patients with ocular injuries (Table 16.4). When small, intra-orbital foreign bodies are often best left undisturbed even in the long term. Large, protruding foreign bodies should be stabilised, protected with a shield where possible and the casualty transferred as a stretcher case to an ophthalmic unit. Further investigations that will be needed include CT scanning. Table 16.5 describes a list of useful ophthalmic preparations.

Table 16.5 Useful ophthalmic preparations

Preparation	Use
G Amethocaine, G Oxybuprocaine, G Lidocaine, G Proxymetacaine	Topical anaesthetic as required
G Fluorescein	Dye to highlight corneal and conjunctival epithelial defects
Oc Lacri-lube (Oc chloramphenicol commonly used instead in acute setting)	Lubricant as required
G Cyclopentolate (acts for 1 day), G Atropine (acts for 2 weeks)	Dilates the pupil and paralyses the ciliary muscle
G or Oc Chloramphenicol, Ofloxacin	Topical antibiotics
G Dexamethasone	Topical steroid preparation—use should be avoided by non-ophthalmologists
Ciprofloxacin (oral), Azithromycin (500 mg once daily orally)	Antibiotics that enter the eye when given systemically
Co-amoxyclav (i.v. and oral) ceftriaxone + metronidazole (*i.v.*)	Antibiotics for sinus fractures for prophylaxis and to treat infection
G Timolol (twice daily) Acetazolamide (max 500 mg iv stat/250 mg oral four times daily)	Treatment of raised intraocular pressure

Oc ointment, *G* drops
Topical preparations contain preservatives which are toxic if they enter the eye—avoid if there is a penetrating injury

16.8 Orbital and Zygomatic Injuries

Horizontal alignment of the eyes may be assessed using a straight edge or ruler. Each pupil and canthus (junction between upper and lower lids) should be an equal horizontal distance from the bridge of the nose and the same height vertically. An inferiorly displaced lateral canthus suggests a zygomatic fracture. Diplopia (double vision) and abnormal eye movement suggests injury to cranial nerves or muscle entrapment and infraorbital hypoaesthesia indicates involvement of the infra-orbital nerve in an orbital floor blow-out fracture. Palpating the orbital rim for steps and crepitus may detect a fracture of the orbital rim or fracture into a sinus causing surgical emphysema. Enophthalmos (eye moved deeper into the orbit) is most easily appreciated by viewing both eyes whilst standing above and behind the patient looking down and suggests an orbital blow-out fracture. Proptosis (eye moved forwards) with swelling suggests a retrobulbar haematoma. If there is no open globe injury, gently palpate over the upper lid to gauge orbital pressure.

The management of orbital fractures is not urgent in adults. The most appropriate imaging modality for orbital trauma is fine cut (1 mm) CT scanning of the orbits. Injuries may require reduction and fixation to treat diplopia and enophthalmos, usually performed within 2 weeks. The casualty should not to blow their nose or they may develop surgical emphysema and should have maxillofacial and ophthalmic follow up organised. Children have different patterns of injury, often much more subtle signs without bruising or haemorrhage and require referral within 24 h.

16.9 Orbital Compartment Syndrome

Orbital haemorrhage and infection pose a threat to vision from pressure effects. In orbital cellulitis, collections should be referred to an Ear Nose and Throat specialist to consider drainage and treated with broad spectrum i.v. antibiotics as dictated by local protocol. A tense orbit with reduced visual acuity, gross restriction of eye movements and RAPD indicates a severe orbital haemorrhage causing orbital compartment syndrome. Other features are severe pain and nausea, proptosis, raised intra-ocular pressure, chemosis (conjunctival swelling) and subconjunctival haemorrhage. This is a sight-threatening problem requiring immediate surgical decompression (see Sect. 16.15). Systemic drugs such as intravenous mannitol, azetolamide and steroids should only be considered as a temporizing measure and adjunct to definitive surgical decompression of the orbit.

16.10 Eyelid Injury

In lid injuries, the depth and site are key considerations (Fig. 16.5). Any lid injury, particularly those that are full thickness, should prompt a thorough search for globe injury and when the injury is penetrating, orbital and brain injury should be considered. Conjunctival swelling is common in lid injuries, and may hide an open globe injury. Injuries medial to the lacrimal puncti usually involve the lacrimal drainage apparatus and require specialist repair. Any possibility of a foreign body should always be excluded by imaging and exploration, particularly in patients with delayed presentation and recurrent or chronic infection. Asymmetry of the lid contours can be caused by ruptured canthal tendons, which attach the medial and lateral ends of the lids to the orbit and will also cause abnormal horizontal alignment, though this would most often be associated with avulsion or laceration of the eyelid. A flattened upper lid may mean the globe is perforated. If the eye is intact and an ocular surface foreign body is suspected, the upper lid should be everted (Fig. 16.6).

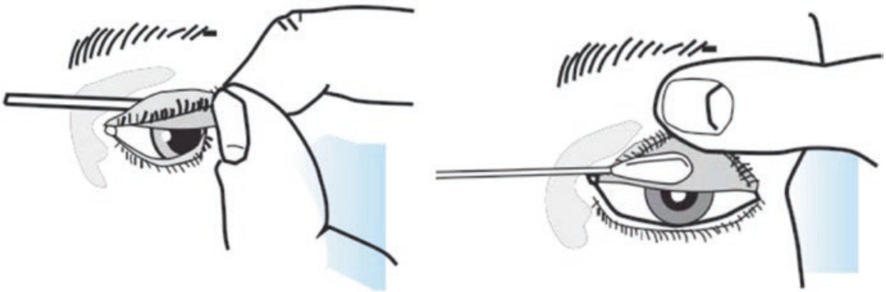

Fig. 16.6 Technique for everting the upper eyelid to inspect the globe

Before transfer, instil ocular lubricants or antibiotic ointment only if there no suspicion of open globe injury. The eye should be protected with a shield. Alternatively, a shield can be improvised from the base of a polystyrene cup or gallipot. If there is lid avulsion with gross exposure, copious ointment and paraffin-impregnated gauze or 'cling film' held in place by the shield can be used to prevent corneal desiccation. Approximately 5–10% of all burn casualties suffer damage to their eye lids. Principles of management are the same as for burns elsewhere. After eye irrigation to neutralise pH (if this is abnormal), lubricants should be used liberally. Corneal and conjunctival epithelial defects should be managed as for corneal burns. Initially, lid tissue swelling may protect the globe, but subsequent sloughing and contracture can lead to corneal exposure. Immediate care of the eye including prevention of corneal exposure and lubrication can improve visual outcome. Specialist ophthalmic intervention may include surgery to protect the corneal surface.

16.11 Open Globe Injuries

16.11.1 Assessment of Open Globe Injury

To examine the globe, the lids should be held open by pressure against the orbital margins and assessed for signs of an open globe injury (Table 16.6). A possibly penetrated globe should not be pressed upon (Figs. 16.7 and 16.8). An ophthalmic speculum or lid retractor can be used to aid examination and can be improvised (Fig. 16.9). This can be constructed with paperclips or wire using round tipped pliers. The paperclips are bent according to the drawings. Before usage the bent part of the retractor can be held in a flame for a few seconds to prevent contamination. After use, the retractors should be cleansed and kept in 70% alcohol or in acetone.

16.11.2 Imaging of Open Globe Injury

All open globe injuries should be assumed to have a retained intra-ocular or orbital foreign body until proven otherwise and be imaged with orbital CT

Table 16.6 Signs of open globe injury

Prolapse or expulsion of lens, iris, vitreous, choroid or retina or gross deformity suggesting loss of tissue
Soft or deformed eye
Total hyphaema
Abnormally deep anterior chamber (suggesting posterior rupture)
Dragging of pupil
Restriction of eye movement
Bloody chemosis (swelling of the conjunctiva) or extensive subconjunctival haemorrhage

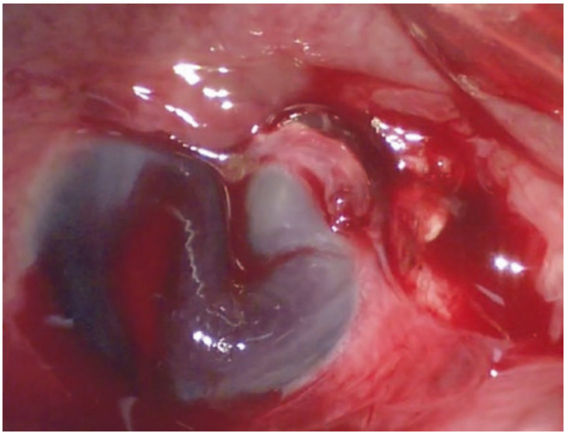

Fig. 16.7 Severe rupture with globe deformity and tissue loss. Final visual acuity was no perception of light (NPL)

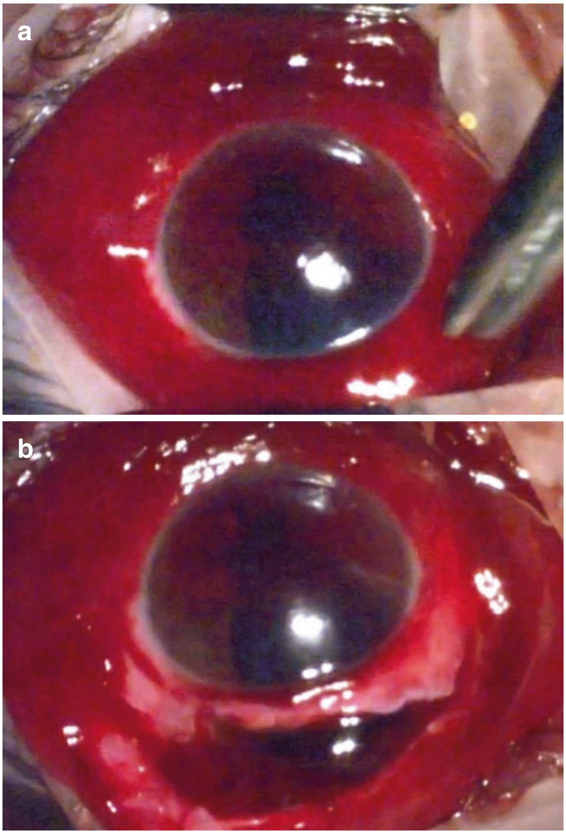

Fig. 16.8 (**a**) Rupture hidden by extensive subconjunctival haemorrhage. Note partially visible pupil is dragged inferiorly. (**b**) Inferior circumferential rupture revealed by conjunctival peritomy. Final visual acuity was 6/9 unaided

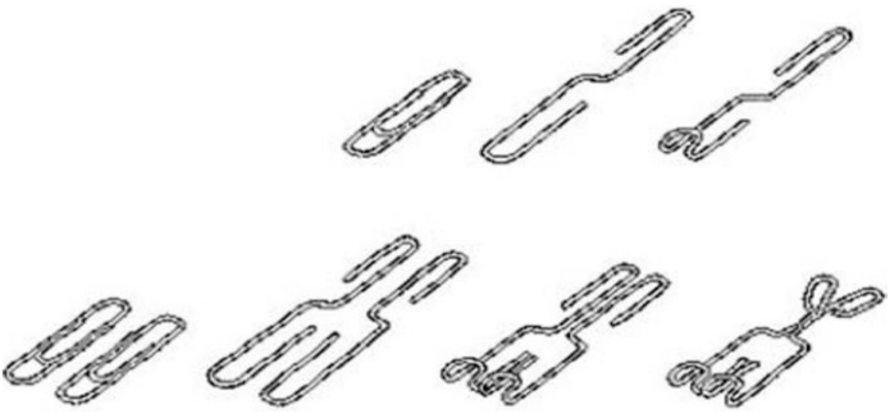

Fig. 16.9 Improvised eyelid retractor

scan with fine (1 mm) cuts. Ultrasound is a useful adjunct in experienced hands, but pre-operatively great care must be taken not to apply any pressure to an open globe. CT may sometimes be able to detect features of open globe injury.

16.11.3 Management of Open Globe Injury

Open globe injuries are emergencies. Repair should be conducted as soon as possible to restore normal intraocular pressure and function and minimise the risks of infection (endophthalmitis) and scarring (proliferative vitreoretinopathy). Repair after 24 h is associated with a higher risk of endophthalmitis. Before primary repair, application of topical medications may allow intraocular penetration of harmful preservatives and should be avoided. The main risk is extrusion of ocular contents either by pressure on the globe or when the casualty vomits. The patient should therefore be given analgesia and anti-emetics, nursed sitting up and the eye covered with a protective, non-contact shield (e.g. Cartella). Eye pads may apply pressure and should be avoided. Systemic antibiotics (such as oral ciprofloxacin 750 mg) reduce the risk of endophthalmitis and should be given early, along with a tetanus booster where appropriate.

The casualty requires urgent transfer to an ophthalmologist for surgical repair within 24 h. Intraocular air is also significant in cases where aeromedical evacuation is planned, depending on the initial altitude of the patient. Intraocular air depressurised to a normal cabin altitude pressure of 6–8000 ft. from sea level, will expand by approximately 20–25%. If there is sufficient gas in a closed eye, considered to be greater than 10% (0.6 ml or 10 mm diameter on CT) of the vitreous cavity volume, this can cause an acute rise in intraocular pressure. If the eye has an open wound and intraocular gas, its expansion may cause tissue extrusion. Where intraocular air has been diagnosed on CT scan aeromedical transfer with ground level cabin altitude pressure should be considered. Primary repair must be undertaken by an experienced ophthalmologist with the appropriate microsurgical skills. Inexpert repair is likely to do more harm than good.

Small corneal lacerations may self-seal and this can be assisted by placement of a bandage contact lens. Consideration should be given in such cases to the retained intraocular foreign body that caused the penetrating injury. Sympathetic ophthalmia is a blinding inflammatory condition that occurs days to years after one eye has been severely disrupted. It is rare if satisfactory primary repair or evisceration is carried out promptly and does not justify enucleation.

16.12 Anterior Segment Injuries

16.12.1 Red Reflex

The red reflex is a useful way to detect opacity in the clear optical media of the eye—any reduction in intensity indicates either something opaque between the examiner and the casualty's retina or a total retinal detachment. Media opacity may be located anywhere between the cornea (e.g. blood staining or scarring) and the vitreous (e.g. haemorrhage). The red reflex is best examined in a dark or dimly lit room, using a direct ophthalmoscope with a 0 power lens at a distance of 50 cm. The red reflex is a bright reflection from the casualty's retina, similar to the red eye on a photograph taken with a flash and should be compared between the two eyes.

16.12.2 Pupils

The pupillary shape, symmetry and reaction can be assessed directly and against the red reflex. The iris should be flat and the pupil central and round. Pupillary distortion suggests either direct iris injury or that the iris is plugging or prolapsing from a hole in the eye. Transillumination defects, when the red reflex is visible through the iris itself suggest the passage of an intra-ocular foreign body, though they may be iatrogenic (for example surgical iridotomy) or present in disease states.

16.12.3 Hyphaema

The presence of blood in the anterior chamber is termed a hyphaema (Fig. 16.6) and is usually associated with blunt trauma, though it is necessary to exclude a ruptured globe. Up to 25% of patients with hyphaema suffer a rebleed, which is usually more serious than the primary bleed, 33% being total and 50% leading to high intraocular pressure and corneal blood-staining. Raised intra-ocular pressure is difficult to detect without a tonometer, but may be suggested by pain and nausea. Hyphaema is managed by sedantary activity for 1–2 weeks, analgesics and antiemetics to prevent increased venous pressure from straining and vomiting (avoid aspirin and NSAIDs because of their antiplatelet effects) and pupillary dilatation with atropine (Table 16.6), which reduces the risk of rebleeding. The patient should be reviewed by an ophthalmologist within 24 h for an intraocular pressure check and intensive topical steroid treatment.

16.12.4 Lens

Lens opacities and edge effects are seen silhouetted against the red reflex. A visible lens edge without an iris defect indicates partial or total dislocation into the anterior chamber or vitreous. It may also be possible to see tracts in the lens made by the passage of a small foreign body or a traumatic cataract after a few days. If the lens capsule is ruptured, flocculent lens matter may be visualised in the anterior chamber or vitreous with +10 magnification on the direct ophthalmoscope and usually causes a severe inflammatory reaction and raises intraocular pressure.

16.12.5 Cornea and Conjunctiva

The cornea should be transparent and smooth, giving a bright and even reflection of the illuminating light. Abrasions, lacerations and foreign bodies are more easily seen after the instillation of fluorescein. Corneal injuries are very painful and topical anaesthetic aids examination. Corneal epithelial disturbance causes a foreign body or burning sensation, photophobia and watering. The eye is usually red and visual acuity may be reduced. A white corneal infiltrate usually indicates a corneal infection, in which case the anterior chamber may fill with pus (hypopyon).

16.12.6 Foreign Bodies

Removal of even superficial corneal foreign bodies is difficult without high, binocular magnification and good illumination. Corneal foreign bodies can be buried in the corneal stroma or protrude into the anterior chamber, when their removal creates an open globe. Small deep corneal foreign bodies are often well tolerated and can be left, as more severe damage and scarring may be caused by attempts to remove them. Loose foreign bodies can be irrigated from the eye, if not they may be removed under topical anaesthetic with a cotton bud or a needle, approaching the eye tangentially whilst steadying the casualty's head.

16.12.7 Epithelial Defects

Corneal abrasions are epithelial defects due to trauma; ulcers are epithelial defects caused by infection. If pain relief is required other than for examination, oral analgesics should be used, as regular topical anaesthetics slow epithelial healing. Medium-acting mydriatics (cyclopentolate or homatropine) are useful for symptomatic relief, by reducing photophobia. Topical antibiotics should be used to prevent infection (Table 16.6) and continued for 2–3 days after healing. Corneal abrasions usually heal within 24 h. If still unhealed after 48 h, copious ocular lubricants may help healing, but referral should be made to an ophthalmologist to exclude underlying infection such herpetic or bacterial. Topical steroids should never be used in the presence of an epithelial defect.

Corneal infection (infectious keratitis) is often associated with contact lens wear and misuse and requires transfer to an ophthalmologist within 12 h. If this is not feasible, treatment is with intensive, topical antibiotic drops for example, ofloxacin every 1 h (Table 16.6) and transfer as soon as possible.

Conjunctival laceration and foreign bodies can be diagnosed and managed in the same way as corneal injuries, lacerations usually healing rapidly with conservative management. Where lacerations occur though, it is important to consider the potential for an underlying scleral laceration or intra-ocular foreign body and ophthalmology referral is advisable. Very large lacerations may require closure with 8/0 or smaller corneal suture.

16.12.8 Ocular Surface Burns

In chemical and thermal injuries, irrigation should be performed immediately, before assessment. Acid burns may be caused by exploding vehicle batteries or chemical latrines and alkali burns are commonly seen in plasterers. Alkali is potentially more damaging to the eye than acid, because it can cross the cornea into an eye in 5 s, whereas acids coagulate tissue to form a barrier. Thermal burns are often also associated with caustic products left on the ocular surface and management should be as for chemical injuries.

The severity of ocular surface burns is graded by the Dua classification (Table 16.7), after assessment of the extent of conjunctival epithelial defect by fluorescein staining. Limbal ischaemia is seen as white areas of limbus lacking the normal fine superficial blood vessels and usually obviously different from the remaining limbus that is red and inflamed after the injury. Note that outcome is determined by the proportion of normal limbus and remaining conjunctiva from which re-epithelisation occurs. Corneal haze (obscuring iris details), raised intra-ocular pressure and cataract formation also indicate severe injury. A total epithelial defect can be easily missed, as no contrasting edge is visible, so it is important to be familiar with the normal appearance of fluorescein on the ocular surface.

Table 16.7 The Dua classification of ocular surface burns

Grade	Prognosis	Limbal ischaemia (blanched avascular areas)	Conjunctival epithelial defect
I	Very good	0 clock hours of limbal involvement	0%
II	Good	<3 clock hours of limbal involvement	<30%
III	Good	>3–6 clock hours of limbal involvement	>30–50%
IV	Good to guarded	>6–9 clock hours of limbal involvement	>50–75%
V	Guarded to poor	>9–<12 clock hours of limbal involvement	>75–<100%
VI	Very poor	Total limbus (12 clock hours) involved	Total conjunctiva (100%) involved

The limbus is the junction of clear cornea with white sclera [11]

A chemical injury to the eye is an emergency and when suspected one must irrigate the casualty's face and eyes immediately with sterile eyewash, saline or tap water if no other fluid is available. Topical anaesthetic and systemic analgesia makes this process less unpleasant for the patient. Retained particles may maintain an abnormal pH even after extensive irrigation and it is important to evert the eyelids (Fig. 16.6), remove any particles and direct irrigating fluid into the superior and inferior fornices. It is also important to consider chemical and thermal injury elsewhere, particularly to the airway. All patients should receive topical antibiotics, lubricants and dilating drops with oral analgesia. Any burns where an epithelial defect is present should be referred to an ophthalmologist in <24 h, who may use intensive topical steroids, topical and systemic sodium ascorbate and citrate, systemic matrix metalloproteinase inhibitors (e.g. doxycycline) and amniotic membrane grafting.

16.13 Fundus, Retina and Optic Nerve

Examination is difficult using direct ophthalmoscopy. It should be possible to visualise optic disc swelling (blurred disc margins, haemorrhages, obscurated blood vessels and venous dilatation) which may indicate raised intracranial pressure when bilateral or optic nerve compression when unilateral. An avulsed optic nerve may be seen as an absent optic disc (or portion of the disc when partial) associated with gross haemorrhage. Detachment of the central retina may also be visualised and looks like a waving net curtain. Only 12% of traumatic detachments occur immediately with most developing later associated with traumatic breaks and intra-ocular scarring. Visual acuity may be normal in retinal detachments if the macula is not involved and the media are clear and these detachments (macula on) require the most urgent surgery as macula detachment may be prevented.

16.13.1 Laser Injury

Laser light is collimated (stays as a narrow beam for very long distances) monochromatic (one wavelength) and coherent (in phase) meaning that all the power of the laser can be transferred to a very small area of retina (usually the fovea) over a very short time. Laser injuries have been reported in the UK and some commercially available laser "pointers" have the potential to damage the retina. Damage depends on the intensity of the burn. High energy injuries can cause corneal or lens opacity (cataract). Usually, the laser light will pass through the transparent media of the eye and cause a retinal burn. Effects can range from grey discolouration of the retina, a retinal hole, sub-retinal bleeding to an eye full of blood. No treatment will affect the outcome of the burn itself, but complications such as subretinal haemorrhage may require treatment.

16.13.2 Traumatic Optic Neuropathy

The optic nerve may be damaged by direct injury from bony fragments or projectiles, as a consequence of globe injury or (most commonly) indirectly in association with head injury. The only signs usually are reduced visual function and a RAPD. No treatments are proven to improve outcome but where a bony fragment or foreign body is seen to compress the optic nerve on imaging, consideration should be given to its urgent removal by a suitably experienced orbital/neurosurgeon. In general, disorders of the retina and optic nerve should be referred to an ophthalmologist for further assessment within 24 h.

16.14 Surgical Management of Lid Lacerations

The lids have an excellent blood supply, so wound excision should be avoided—even of tissue that may appear non-viable. Superficial lacerations not involving lid margins and with good levator palpebrae superioris function (lid opening), may be repaired with 6/0 Prolene. Full thickness injuries, especially those involving the medial lid (lacrimal drainage), require complex alignment and should be repaired by an ophthalmologist within 48 h of injury. Lower lid lacerations sometimes heal very well by secondary intent. Superficial lacerations or those for which specialist ophthalmic input is not available within 7 days may be repaired by the non-specialist. A corneal guard is used to prevent inadvertent placement of ocular sutures, whilst avoiding pressure on the globe in case there is an undetected perforation. 6.0 vicryl is used first to oppose the lid margins by placing partial thickness sutures through the tarsal plates to achieve good alignment, a suture posterior to the lashes (grey line) is tied on the lid margin and left long so it can be subsequently held away from the cornea. The skin is closed separately. Free flaps are rarely required in the acute management of lid lacerations.

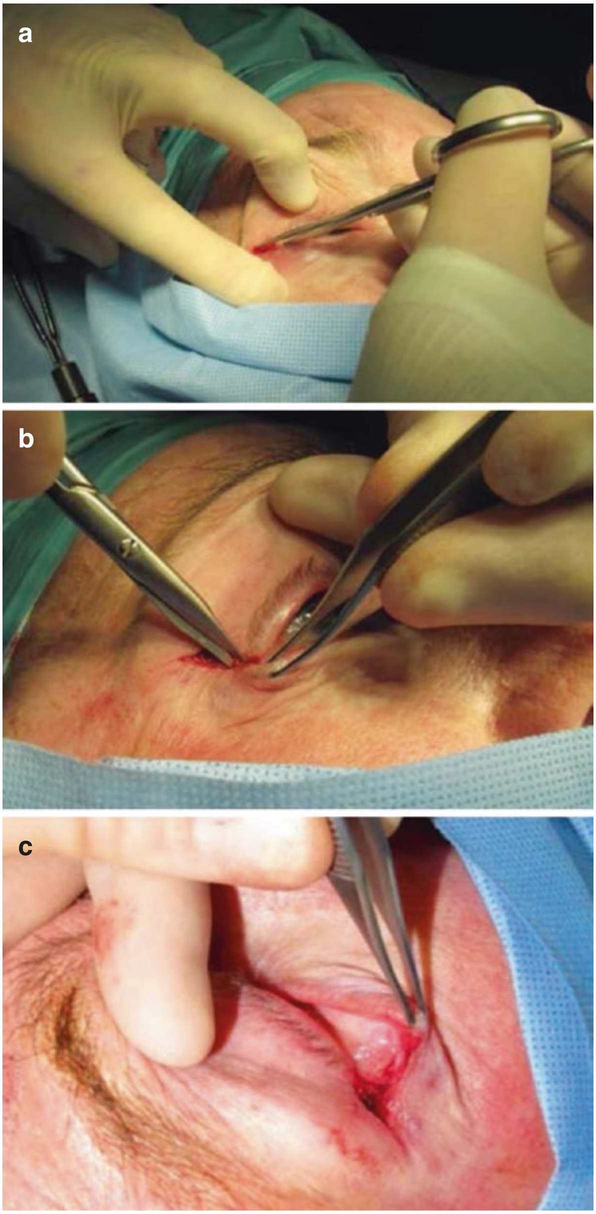

Fig. 16.10 Lateral canthotomy Crushing the lateral canthus (**a**); Division of lateral canthus down to periosteum (**b**); Inferior lateral canthal tendon released from orbital margin (**c**). Images courtesy of Mr. Aidan Murray, Consultant Oculoplastic Surgeon, Queen Elizabeth Hospital, Birmingham

Table 16.8 Steps taken in lateral canthotomy followed by inferior cantholysis for orbital compartment syndrome

Step	Procedure
1	Lidocaine 2% with adrenaline 1/200,000 to 1/80,000 local anaesthetic is infiltrated into the lateral lower and upper lid and then the needle advanced to the lateral orbital margin and anaesthetic infiltrated down to periosteum
2	The eye and lids are prepared using 5–10% povidone iodine in aqueous solution
3	Mosquito artery forceps are placed over the lateral canthus down to periosteum and then closed for 30 s to crush the tissues and aid later haemostasis
4	The artery forceps are released and the lateral canthus cut down to periosteum using Steven's scissors
5	The scissors are then turned inferiorly and used to divide the lateral canthal ligament (cantholysis) between the lower tarsal plate and the orbital rim. Success is judged by pulling the lower eyelid, which moves freely in a medial direction once it is no longer tethered to the orbital rim. There are many connections of the lateral canthal ligament to the orbital rim, which must all be divided—inadequate canthotomies are common. Some prolapse of orbital fat is normal and the eye should move forwards with associated pain relief
6	Pressure is applied against the orbital rim until bleeding settles
7	If necessary (orbit still tense), the upper canthal tendon may also be divided
8	The wound is filled with chloramphenicol ointment and covered with paraffin gauze dressing and an absorbable dressing

16.15 Lateral Canthotomy and Inferior Cantholysis

In cases of orbital compartment syndrome, when an ophthalmologist or maxillofacial surgeon is not immediately available, lateral canthotomy must be performed by the non-specialist to prevent retinal and optic nerve infarction (Fig. 16.10, Table 16.8).

16.16 Evisceration

In most cases after trauma, removal of the globe is only indicated in the case of a severely infected, painful or unrepairable eye with no perception of light. This is not an urgent procedure. However, where a large corneal or scleral wound with extrusion of intraocular contents cannot be repaired (or evisceration performed) by a specialist with appropriate experience within 2 weeks of injury, evisceration (removal of ocular contents) may be the best option for the non-specialist (Fig. 16.11). However, evisceration still requires training and any vascular uveal

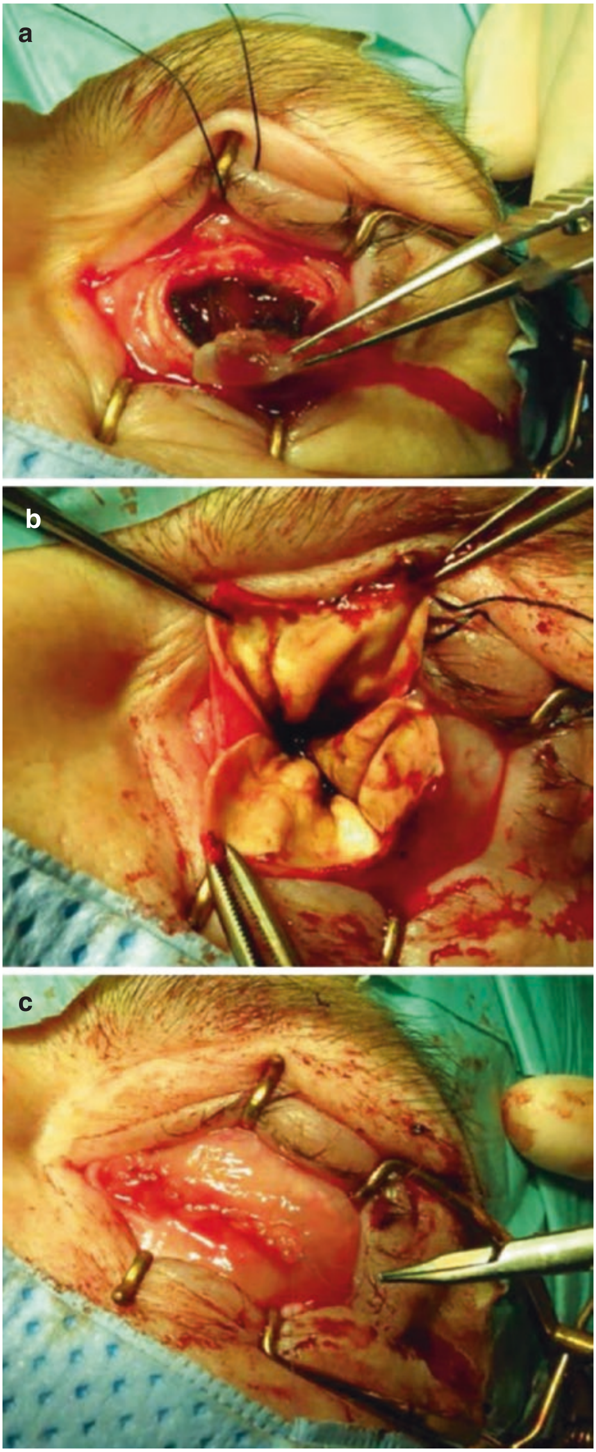

Fig. 16.11 Excision of corneal button (**a**); Divided scleral cup (**b**); Closed conjunctiva (**c**)

Table 16.9 Surgical steps in performing evisceration

Step	Procedure
1	General anaesthesia is necessary for evisceration
2	The eye is prepared using 5% povidone iodine in aqueous solution
3	A drape is used to cover the whole face except the eye and a Clarke's speculum used to open the lids
4	Using Wescott or Steven's scissors, the conjunctiva is dissected from the globe by performing a 360° peritomy at the limbus (where Tenon's and conjunctiva are fused) and the Tenon's capsule in the four quadrants between the recti muscles is blunt-dissected from sclera by advancing the scissors posteriorly along the sclera past the equator and spreading the blades.
5	An incision is made in the globe 1–2 mm behind the limbus and the corneal button is excised with a small rim of sclera
6	Ocular contents are then removed by inserting an evisceration spoon or freer periosteal elevator between the sclera and choroid and running around its inner surface before scooping out the contents. The optic nerve stump is then compressed using a fingertip until bleeding settles. Cautery is sometimes necessary. The scleral sac must be completely cleared of any uveal (pigmented) tissue and in eviscerations that have been delayed this may be stuck down and require dissection. The scleral sac is then thoroughly irrigated with antibiotics.
7	Infero-nasal and superotemporal anteroposterior cuts should then be used to divide the scleral cup in two back to the optic nerve
8	Placement of a primary implant is not usually recommended in trauma eviscerations due to the risk of infection and can be performed months later
9	Closure is with interrupted 8/0 vicryl and in three layers. The sclera is closed first, then Tenon's capsule is closed over sclera and conjunctiva closed over Tenon's
10	Orbital floor bupivacaine and cefuroxime are recommended for post-operative analgesia and infection prophylaxis and systemic antibiotic prophylaxis usually given

tissue left in the scleral cup will predispose the patient to blind inflammation in the other eye (sympathetic ophthalmia). Evisceration is generally preferable to enucleation (whole eyeball removed), which is a much more technically challenging procedure with a higher complication rate. Before removing an eye, the surgeon must consider the options available and the patient's preferences, which may include cultural and religious beliefs that mean the patient would rather keep the eye at all costs, precluding evisceration (Table 16.9).

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Ballistic Maxillofacial Trauma

17

Johno Breeze, Darryl Tong, and Andrew Gibbons

17.1 Introduction

Ballistic maxillofacial trauma encompasses all injuries sustained either directly from or secondary to firearms and explosive devices. Such injuries can occur in both the military and civilian environments, and generally the causes and patterns differ significantly. Maxillofacial ballistic trauma in the civilian environment is most commonly from low velocity weapons such as handguns and shotguns. In contrast energised fragments have been responsible for 79% of maxillofacial injuries sustained by UK soldiers during the recent Iraq and Afghanistan conflicts, with the remainder due to high velocity rifle bullets [1]. The incidence of facial wounds relative to other parts of the body varies widely, reflecting both the weapons used, the type of conflict and the availability of personal armour. Conflicts in the twentieth century generally had a lower incidence of maxillofacial injuries (14–21%)

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compared to those in the twenty-first century with incidences of craniomaxillofacial injury up to 42% [2–7]. However, care must be taken in comparisons between conflicts as the definition of what anatomical areas constitute ‘maxillofacial’ are rarely clearly defined and some figures from the twentieth century included disease and non-battle injury. Mortality from military maxillofacial injuries is generally low (2–3% of maxillofacial injuries result in death), and occurs primarily due to airway compromise [8].

17.2 Pathophysiology

Bullet wounds from high velocity rifles result in significant energy transfer and tissue cavitation. However it is a misconception that low velocity projectiles cause less maxillofacial injury. Projectiles passing through the face and jaws often strike hard tissues, namely the bony skeleton and teeth, resulting in high energy deposition and secondary missile formation from the hard tissue fragments. The most common cause of energised fragmentation injuries to the face and neck sustained both in the military and urban environments is from improvised explosive devices (IEDs). They are heterogenous group of homemade devices capable of explosively propelling any kind of debris. Most devices are buried and when detonated propel soil debris and other contaminants including the associated microbiological flora into any resultant wounds. In addition, human body parts can be incorporated in wounds in suicide bombings (see Chap. 7). IEDs produce injury in four ways, commonly termed primary, secondary, tertiary and quaternary [9]. Primary blast injuries are caused by the sudden increase in air pressure after an explosion and affect predominantly air-containing bones with greater effect such as the sinuses and orbits [10, 11]. Evidence of isolated blow out orbital fractures without surrounding rim fractures or penetration of the overlying skin has been described [11, 12]. Secondary blast injuries are caused by energised fragments such as bomb components or soil ejecta overlying buried explosive devices. A small proportion (4%) of battle injuries are thought to be from tertiary blast, which occurs when the casualty is thrown by the explosion and collides with nearby objects; such blunt injury produces patterns of injury reflective of that seen in civilian blunt injury. Quartenary blast injury is related to the thermal effects of the explosion and is responsible for facial burns.

The effectiveness of modern personal armour has changed the distribution of injuries sustained by both military and police forces (see Chap. 8). The face and neck have historically been left uncovered, favouring greater mobility, situational awareness and heat dissipation over protection. However there has been an increasing trend towards the wearing of ballistic eyewear and visors, and more recently mandible guards [13, 14]. The use of low impact ballistic spectacles when worn have in particular halved the incidence of ocular and peri-occular injury in combat operations from 10 to 5% (Fig. 17.1) [13]. As IEDs are generally placed at ground level or buried within soil, fragmentation and soil debris are directed upwards, placing anterior projections of the face, such as the mandible and nasal tip at increased risk (Figs. 17.2 and 17.3) [5].

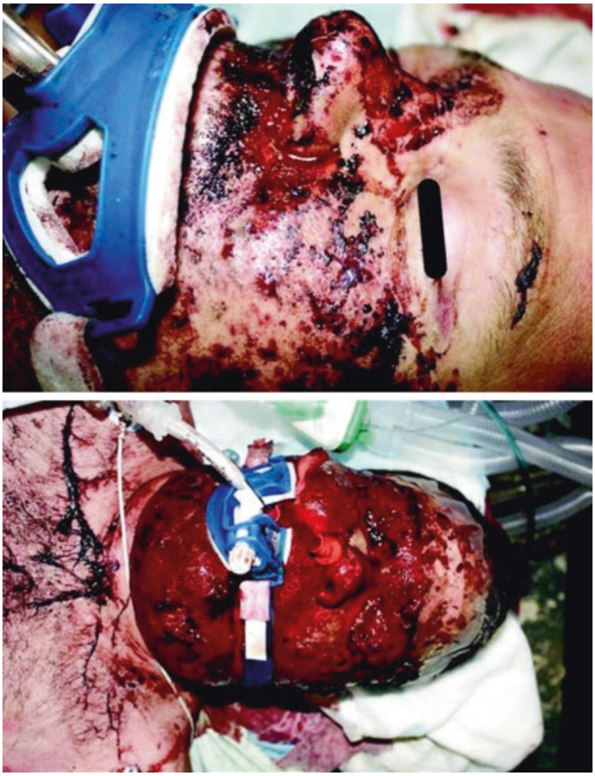


Fig. 17.1 Two soldiers injured within the same explosive event showing the demarcation between the injured facial region and the scalp which was protected by a helmet. The soldier in the *upper picture* was wearing ballistic spectacles that protected his eyes and peri-ocular region. Reproduced from reference [14] with permission of the publisher

Fig. 17.2 A soldier injured by an explosive device has damaged the tip of the nose and upper lip as this protrudes the furthest. Image courtesy of Group Captain Andrew Monaghan

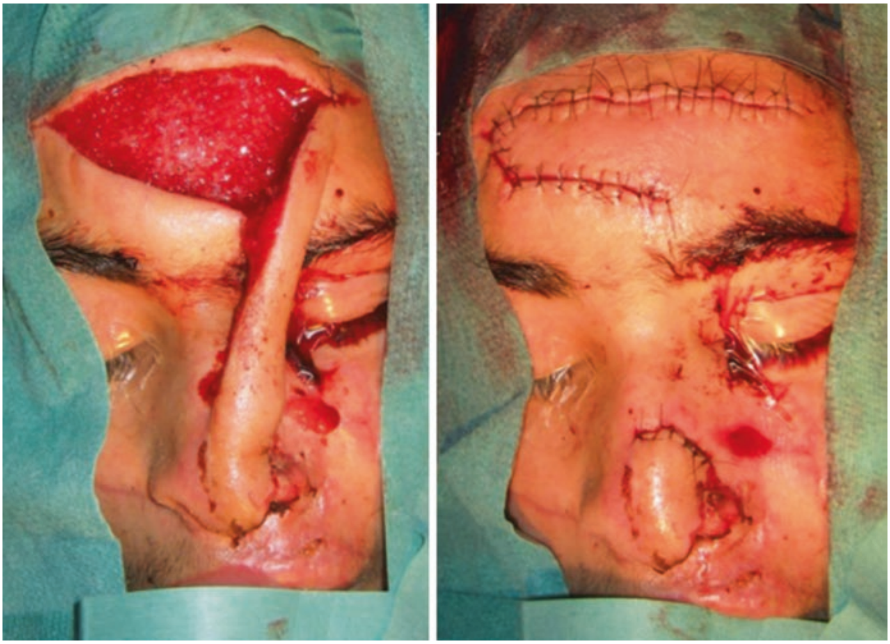


Fig. 17.3 Nasal tip injury repaired with a two stage forehead flap. Images courtesy of Colonel Douglas Bryant

17.3 Treatment Timelines

Differences in the mechanisms of injury and the environment within which they are sustained, necessitate different timelines in the treatment of military and civilian maxillofacial injuries. In both settings, damage control maxillofacial surgery should be commenced within an hour as temporary adjuncts to life threatening injuries (e.g. exsangunation and airway compromise) are likely to reach the limit of their effectiveness by then. However the severity of military maxillofacial wounds, as well as the need to often treat more life threatening injuries to other parts of the body first, means that definitive treatment of maxillofacial wounds are often delayed compared to the civilian setting. Well accepted treatment protocols developed for civilian ballistic trauma are rarely appropriate for managing military injury as these generally were based upon injuries due to low velocity bullets [15]. Newer military protocols based upon the experience of maxillofacial surgeons deployed to Iraq and Afghanistan have been developed (Table 17.1).

Table 17.1 Suggested pathways of care and sequences for treating military maxillofacial injuries

Timeline	Clinical concern	Suggested management
Immediate care (0–60 min)	Airway compromise	Cricothyroidotomy, intubation either directly or through defect
	Haemorrhage	Haemostatic dressing plus direct pressure
Damage control surgery (60 min–3 days)	Airway compromise	Surgical tracheostomy
	Haemorrhage	Packing, ligation, vessel repair, radiological guided embolism
	Soft tissue injury	Debridement, primary closure if tension free, packing with antiseptic dressings
	Bone injury	Stabilisation of grossly mobile bone fragments with intermaxillary or external fixation
Early care (3–28 days)	Bone injury	External fixation, reconstruction plates including those prebent on stereolithic models
	Soft tissue injury	Serial debridement if required, direct closure, local flaps, split skin grafts
Rehabilitation (1–3 months)	Avulsive bone defects	Bone grafts including vascularised, distraction osteogenesis
	Avulsive tissue defects	Vascularised flaps, prosthetics, revision surgery, composite tissue alloplastic transplantation
	Functional problems	Speech and language therapy, physiotherapy, psychological support, dieticians

17.4 Immediate Management

Immediate management of maxillofacial injury is based upon Advanced Trauma Life Support principles. Military personnel are taught a modification of these, in that control of catastrophic haemorrhage precedes the airway, recognising that in a combat environment exsanguination is more likely to be life threatening [16, 17]. Haemostatic agents are now available to first-responders but unfortunately most bleeding sources in facial injuries are often inaccessible [18]. No published evidence exists as to the efficacy and safety of haemostatic dressings applied to the face in the pre-hospital setting, and there is risk of damage to the eyes if the powdered types are used. Cervical spine fracture must always be suspected in soldiers exposed to blast injury who may have been thrown against objects by the blast wave. However in the military environment current evidence would suggests that cervical spine immobilisation is not indicated for maxillofacial wounds sustained by either high velocity gunshot or energised fragments unless the tactical situation allows [19, 20]. Cricothyroidotomy is the treatment of choice in the pre hospital setting

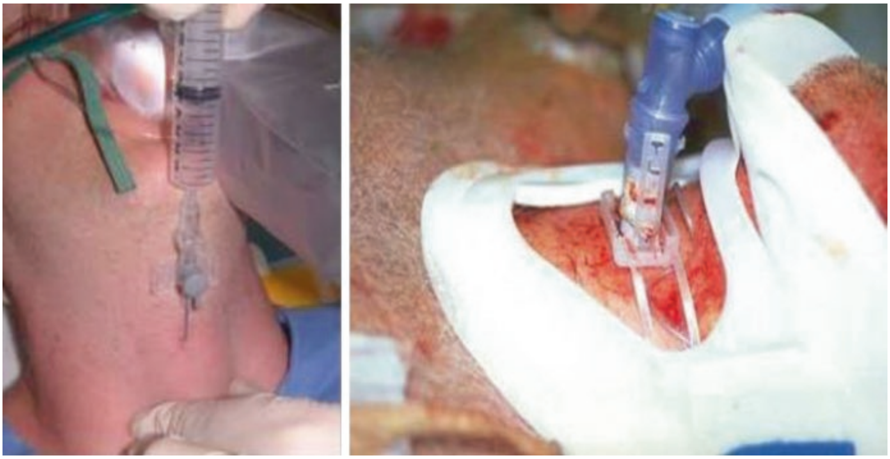


Fig. 17.4 Needle cricothyroidotomy (*left*) can only provide limited air entry. A surgical cricothyroidotomy enables a cuffed endotracheal tube to be utilised (*right*)

should intubation not be possible, with specialist kits available for first responders that provide a greater lumen diameter than using a wide bore needle cannula alone (Fig. 17.4).

17.5 Damage Control Maxillofacial Surgery

Damage control surgery (DCS) is the concept by which surgical operations are shortened to the minimum in able to prioritise short-term physiological recovery over anatomical reconstruction in the seriously injured and compromised patient. Although originally developed to reduce the length of general surgical emergency laparotomies in physiologically unstable patients [21], the principles of the approach are highly applicable to ballistic maxillofacial wounds. The initial assessment of ballistic facial wounds is therefore rapid by necessity, with the clinical situation often requiring management of life threatening injuries to other body areas being prioritised. Seriously injured patients often bypass the emergency department and are taken straight to theatre for damage control surgery as part of the overall continuum of damage control resuscitation. However in most cases a rapid Computed Tomography (CT) scan will have been undertaken in between arrival and surgery, recognising the important diagnostic information that can be ascertained to determine intra-operative decisions (Fig. 17.5). It is often in the operating theatre that facial injuries are first assessed and therefore time must be taken to perform a meticulous examination in conjunction with review of the CT scans. Such an examination must ensure injuries such as scalp lacerations, nasal fractures, missing teeth and deep damage from small penetrating fragments are not missed.

The facial region itself is very rarely associated with significant mortality and yet vascular injury to the face is often accompanied by significant bleeding. Facial

Fig. 17.5 Computed Tomography scan of the face demonstrating retained 7.62 mm high velocity rifle bullet within the left ethmoid sinus

haemorrhage is frequently stopped by wound packing and compression at the site of injury alone. The face is rarely the site of torrential haemorrhage sufficient to be the sole contributor to hypovolaemic shock. Ligation of the ethmoidal arteries may be required to stop nasal haemorrhage but this is likely not be practicable in the emergency setting. Ligation of the external carotid artery may be required but this should only be performed under direct visualisation and after careful identification of the bleeding vessel. Blind clamping of bleeding areas should be avoided because critical structures, such as the facial nerve or parotid duct, are susceptible to injury. Cauterisation of nasal haemorrhage is often difficult in the acute setting and in addition is unlikely to respond to anterior nasal packing (such as with ribbon gauze or a nasal tampon). Posterior nasal packing is best achieved with a urinary (e.g. Foley) catheter size 10–14 French inserted into each nostril, which is gently inflated and then withdrawn until it lodges. The anterior nose should then be packed against this, which is best achieved with ribbon gauze (Fig. 17.6). A base of skull fracture should be ruled out by CT prior to insertion.

Early and aggressive debridement of military facial wounds is required to prevent infection and may involve the use of scrubbing brushes, pulsed lavage and copious irrigation. Surgical dermabrasion with a scalpel blade can be used to remove all debris that may cause subsequent wound tattooing, which is difficult to correct. Most facial wounds can be closed within 36 h after injury and delayed closure, as advocated for the rest of the body, is rarely necessary [22, 23]. Primary closure may be performed if the wound can be closed tension-free but if there are questions of

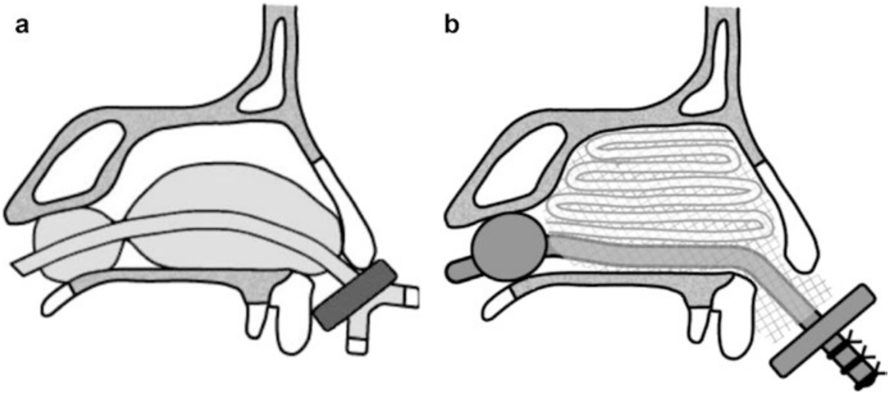


Fig. 17.6 A double lumen Foley catheter is the easiest method of obtaining both posterior and anterior packing (**a**). Improved control over the anterior nose can be achieved through packing with ribbon gauze (**b**)

Fig. 17.7 Despite their initial appearance many soft tissue injuries can be closed primarily as long as it is not under tension and does not distort the tissue architecture

soft tissue viability or if it is not possible to adequately debride the tissue, then delayed primary closure is advocated and the wound dressed with iodine soaked gauze (Fig. 17.7). If tissue vitality is questionable, the defect should be packed and only closed once the tissues are seen to be clean and healthy. Serial debridement for facial wounds is highly unusual and only indicated if an evolving pattern of tissue loss is observed due to the soft tissue injury or if delays in evacuation are likely to occur. If contused or ragged, trim 1–2 mm off the skin edge using ophthalmic scissors and a No. 15 blade so as to achieve non-contaminated, non-beveled edges. Clinical experience would suggest that removal of all embedded explosive fragments is futile and of no proven clinical benefit. If severed branches of the facial nerve or a damaged parotid duct are encountered they should be tagged with a non-absorbable suture for later anastomosis and the wound closed. A low threshold for

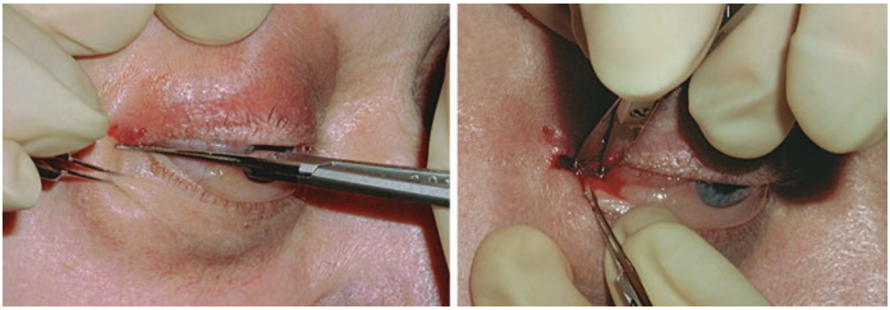


Fig. 17.8 Lateral canthotomy (*left*) should be followed by cantholyis of the tendon

planned tracheostomy should be adopted due to the risk of delayed airway swelling and the need for a definitive airway during evacuation for military casualties [22].

Damage control maxillofacial surgery should involve temporary reduction and fixation of mandible fractures when present, which can be highly effective in reducing both bleeding and pain [23]. The type of facial fractures sustained from ballistic trauma differ significantly from that seen from blunt impacts such as road traffic collisions. Military facial fractures are often comminuted and open to both the cutaneous and mucosal surfaces. The mandible is the most common site of fracture in explosive injuries, which is believed to be due to most improvised explosive devices detonating from below the level of the head [5]. In conflicts where bullets outweigh explosions then the maxilla is slightly more common than the mandible (47% all facial injuries) [24]. In explosions, the blast can cause blow out fractures of orbit and facial burns, both putting patient at greater risk of orbital compartment syndrome—should this be suspected then lateral canthotomy and cantholysis should be performed (Fig. 17.8). The presence of unique patterns of mandible fracture lines due to blast injury remains contested [25, 26] and the classification is of little value clinically.

In most situations a CT will be the default mode of imaging of any suspected ballistic facial fractures, although minimally displaced fractures can be missed with this modality alone (Fig. 17.9). Three-dimensional reconstructions of the CT scans may make visualisation of fracture displacement easier but care must be taken to look at the individual slices as processing may disguise fracture lines. Supplementation of CT with an orthopantomogram makes planning of fracture management easier. OPG radiographs cannot be used in patients who are supine (such as in cervical spine immobilisation) and will not be available in many austere environments. In such cases some additional information can be gained from taking lateral oblique, lateral skull or PA mandible radiographs (Figs. 17.10 and 17.11).

Upper and lower archbars (Erich type) are the “gold standard” for ensuring a correct occlusion during surgery and may enable closed reduction of many mandibular and, to a lesser degree, maxillary fractures as well as providing a stable platform for longer periods of elastic-band traction (Fig. 17.12). Archbars however are time consuming and require experience to perform correctly. There is also the

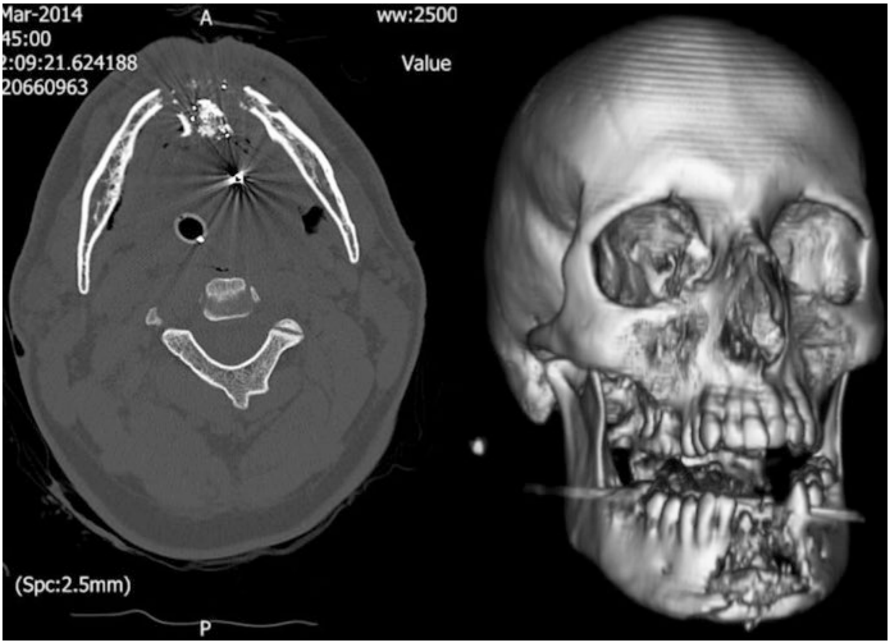
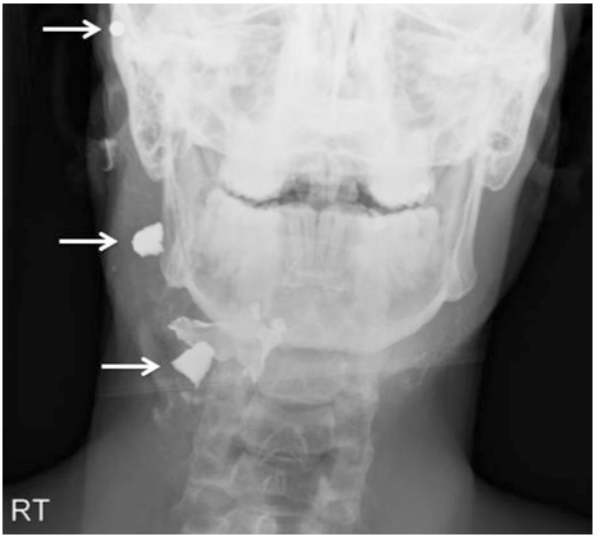


Fig. 17.9 A comminuted fracture of the anterior mandible visualised with computed tomography including three-dimensional reconstruction

Fig. 17.10 A PA mandible radiograph showing heterogenous metallic fragments imbedded into facial tissues produced by an improvised explosive device



considerable risk of a sharps injury when handling wires. Inter maxillary fixation (IMF) screws are often the easiest manner of ensuring reduction, although there is the risk of damaging tooth roots if performed incorrectly and loosening over time

Fig. 17.11 A lateral oblique radiograph demonstrating that archbars can be used in combination with an external fixation device

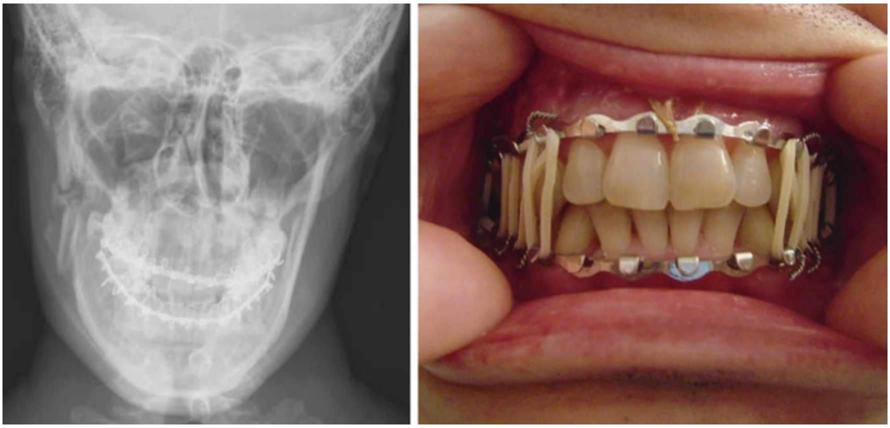


Fig. 17.12 Upper and lower Erich archbars placed for closed reduction with elastic intermaxillary fixation of a comminuted right angle of mandible fracture

(Fig. 17.13) [27, 28]. The use of tight elastics between IMF screws is encouraged instead of wires due to their ease in removal were vomiting to occur.

The use of an external fixator can provide anatomical reduction and fragment stability, and can be used with more conventional methods of closed reduction such as archbars (Figs. 17.11 and 17.14). For the mandible both the generic Hoffman device and newer mandible-specific external fixators are available. The mandible-specific devices are anatomically contoured, enabling the main bar to stand

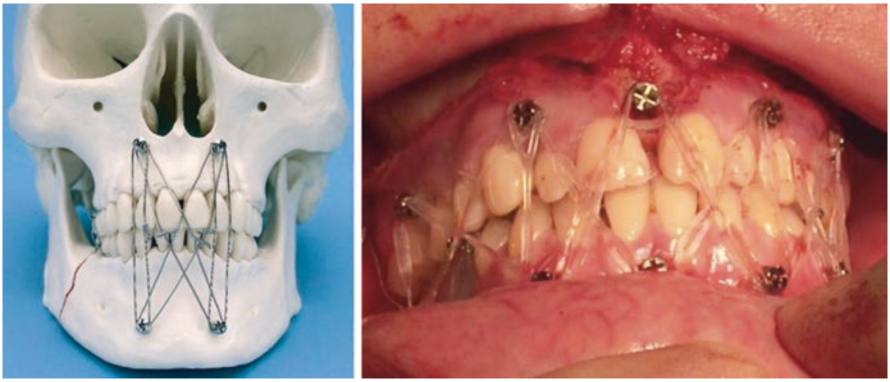


Fig. 17.13 Intermaxillary fixation (IMF) screws can be used with wire or elastics to reduce fractures or provide temporary stabilisation

Fig. 17.14 An external fixator being used to treat a comminuted mandible fracture

approximately 1 cm from the skin surface over the mandible so the whole system is less obtrusive. A fundamental principles of external fixators is that pins should not be inserted through infected bone or skin [29, 30]. As they exit from the skin the pins can be wrapped with antibacterial dressings such as iodine impregnated ribbon gauze. Unlike IMF, there is no compromise to the airway and no special precautions for the release of fixation are required during patient evacuation as they are attached to the mandible or midface alone. Any soft tissue or bony defects may continue to be debrided with the fixation device in situ. As the mouth can be opened during fracture healing, oral hygiene and patient nutrition are improved and trimus due to fibrosis and scarring is reduced.

If external fixation of the mid face is required, this is best performed with a Levant frame (maxilla or zygoma attached to supra orbital ridges), as this interferes less with the patient lying on their side for sleeping than other options such as a box frame. It may be necessary to combine techniques such as using standard miniplate fixation between smaller fragments to produce fewer, larger bony units, which can then be stabilised by an external fixator. Even if plate exposure does occur, generally infection can be stabilised with serial debridement and antibiotics, until bone stability is achieved by the external fixator with minimal resultant cosmetic defect [30].

17.6 Early Management

The extent of soft tissue facial wound necrosis should be known by approximately 36 h and it is relatively safe to close any wounds primarily at this stage should tension free closure be possible. Deep spaces should be debrided further and closed with absorbable sutures to prevent haematoma and pocket formation and subsequent infection. Surgical drains with suction bulbs should also be considered. If primary closure is not possible, local rotation or advancement flaps may be considered as they provide excellent colour and texture matches [31], although care must be made not to damage any vessels such as the facial vessels that might be needed for future anastomoses. These vessels may be already damaged and require ligation, but if they can be identified and preserved for future use then this should be done. Skin grafts are best avoided for the first 5–7 days as the risk of infection remains and they are more prone to wound contracture [32]. Once scar contracture develops it is almost impossible to rectify this fully at a later date.

Infection rates following war-related maxillofacial injuries have been poorly characterised with rates ranging from 7 to 19%. All bullet and fragmentation wounds are inherently contaminated [22], and contrary to popular belief the explosive process of firing a bullet does not in any way sterilise it; in fact these projectiles carry contaminants from clothing as well as skin flora into the wound. Explosively propelled devices are often buried underground or hidden within the landscape and therefore any soil or debris covering the device has the potential to be driven into the wound. Evidence of devices packed with human and animal excrement has been found and in those soldiers injured in suicide attacks there is the additional risk of human body part contamination. Patients returning from Iraq and Afghanistan were well documented to be colonised by Acinobacter baumannii [33]. Limited evidence exists to guide the choice of antimicrobial therapy for face and neck combat infections and therefore it is generally accepted that empiric broad spectrum antibiotics should be used to provide cover against staphylococci, Clostridium perfringens and Clostridium tetani [33]. These are generally given for 10–14 days, with cultures and sensitivities obtained as early as possible to direct antibiotic therapy [34] although some US authors have stated that far shorter courses are equally sufficient [35].

High energy transfer may result in temporary damage to the soft tissue microcirculation at a distance from the permanent wound tract, which must be considered when planning microvascular anastamosis. This is based upon an experimental study conducted by Tan et al. [36] who fired fragment simulating projectiles at the faces of dogs. They found thrombosis in the facial vessels up to 3 cm from macroscopic wound edge, which they attributed to the effect of the temporary cavity. These vessels began to repair between 7 and 10 days after which point all of the microvascular changes had resolved, with the recommendation that all anastamoses should therefore be performed at least 2 weeks after injury should this mechanism be suspected. Where there is any uncertainty regarding the patency of residual vessels to which potential micro vascular anastamoses are to be made, formal angiography is recommended. Finally anastomotic considerations are compounded by the fact that associated limb injuries are common and catastrophic, often resulting in amputation which has a major impact on the availability of donor sites.

In complex military ballistic facial trauma it has been the practice of both UK [30] and US [33] authors to secure the airway and reconstruct the mandible ideally within 3–5 days. Contemporary mandibular fracture management techniques are largely driven by miniplate osteosynthesis. However in the face of such significant comminution, periosteal damage, and the through-and-through nature of the injury, conventional direct miniplate fixation is often inappropriate [18, 27]. Open fractures should be debrided, irrigated and closed temporarily to prevent infection [18]. With the exception of fractures that compromise the airway or impair haemostasis [22] repair may be delayed for up to 2 weeks after injury, especially if a high energy transfer mechanism is suspected and when all infection has been cleared. Longer delays increase the chance of fibrosis and collapse of the soft tissue envelope, making it harder for them to assume their pre-morbid anatomy. Dental impressions can be taken for splint manufacture and custom archbars made using the mandible as the reference point. This will provide a guide of vertical height and the form of the dental arch, as it is easy to splay the angles resulting in excess facial width [18, 33]. Reducing fractures to their approximate anatomical position will aid soft tissue closure and immobilisation will promote healing. Fracture comminution often necessitates thicker profile ("reconstruction") plates in conjunction with bicortical locking screws to produce load bearing osteosynthesis. However limitations in their use still exist because they often require extensive stripping of the periosteum to provide direct bony contact. This must be avoided early after initial injury as the vitality of tissues is often unknown, especially in high-energy transfer wounds or in the presence of tissue avulsion and infection. The use of custom made plates pre-bent on three dimensionally printed models enables larger bony defects to be spanned and provides the surgeon with far greater confidence in correctly restoring mandibular width and providing adequate soft tissue coverage intra-operatively.

Adequate nutrition is known to be of the utmost importance in managing these extensively injured poly-trauma patients. Avulsive injuries to the face and neck may damage structures required in phonation, mastication and deglutition [33]. Even following reconstruction, direct damage to cranial nerves may make performing these functions a considerable burden, necessitating speech and language input in a manner analogous to that used for extensive oncological resections. Many of these patients will remain intubated and sedated for a while as successive operative treatments are undertaken, necessitating nasogastric feeding. Continuation of such feeding may also be required in awake patients with face and neck injuries, due to airway risk or intermaxillary fixation.

17.7 Long-Term Rehabilitation

The longer-term maxillofacial rehabilitation of those patients with gross bony injury revolves around provision of enough bone to enable placement of dental implants in a manner analogous to oncological reconstruction. Bone loss may be replaced by either free or vascularised bone grafts, with the latter generally taken from the iliac crest deep circumflex iliac artery flap, scapula flap or fibula flap (Fig. 17.15). The former two provide better bone height than the fibula but are inferior in terms of both bone length and vascular pedicle length. Great care must be made in the use of vascularised flaps due to the risk of non-macroscopic vascular damage from the temporary cavity placing the anastamosis at increased risk. In addition the use of block grafts means that it can be difficult to reproduce the vestibular anatomy, with subsequent difficulty in mastication and cleaning. This can be facilitated by insetting of a split skin graft taken from the thigh or less commonly from the arm due to the extensive leg injuries that some of these soldiers have sustained (Fig. 17.16). In later reconstruction distraction osteogenesis can provide additional bone [32] with the advantages of no donor site morbidity and slow growth enabling the overlying soft tissues to adapt to the new bone shape. Although autogenous reconstruction should be seen as the ideal, alloplastic methods utilising prostheses still have a role in those tissues that are currently challenging to aesthetically reconstruct, namely the ears, nose and orbit.

Psychological support should be given to all patients sustaining ballistic injuries to the face, particularly those resulting in scarring and avulsive tissue loss. Such pathways are usually automatically generated in military patients but clinicians should ensure that counselling occurs early in the recovery period. Many of these

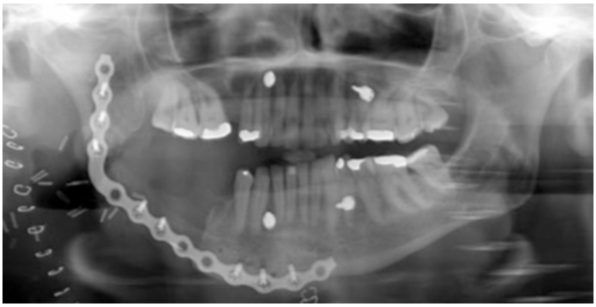


Fig. 17.15 A fibula osteocutaneous free flap has been anastomosed to a vessel in the neck to provide mandibular continuity with a pre-bent load bearing osteosynthesis plate

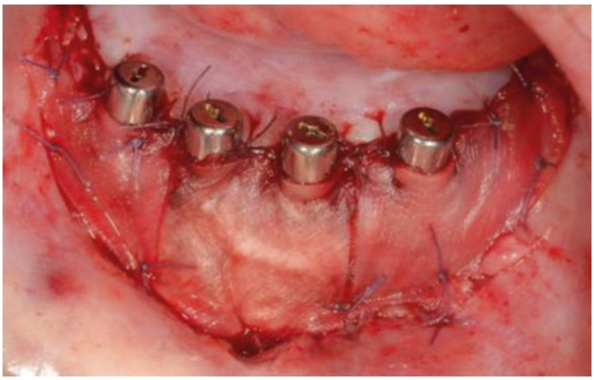


Fig. 17.16 Implants are excellent for providing teeth or as over denture abutments. Loss of labial sulcal depth can be improved by inserting a split skin graft

multiply injured military patients are managed on the ward for a number of months until they are fit enough to be discharged and during this time it is usual for their mood and attitude towards treatment to fluctuate. All soldiers injured are managed as part of a multidisciplinary approach in which psychological support is a keystone. Concerns include unrecognised combat stress, depression related to an injury and guilt related to leaving follow unit members or surviving can become evident. In addition facial appearance has been found to be an important variable in how patients are perceived by others and these patients with facial injuries must gain the additional coping skills to improve their self esteem and ability to continue with reconstructive surgery. Patients with self inflicted ballistic wounds following attempted suicide are at greatest risk, particularly those that are socially isolated, and liaison is required with the police services well before their predicted discharge.

Following discharge from the ward, all severely injured UK soldiers undergo a concentrated period of physical rehabilitation, which is currently undertaken at the Defence Rehabilitation Centre in Headley Court. Although the primary focus is on rehabilitation of injuries such as amputations, there is also an emphasis on trying to re establish some independence for the soldier. Complex maxillofacial penetrating trauma related to blast and ballistic injuries frequently results in aggressive, disfiguring scars. The combination of a high degree of wound contamination, wound avulsion, and loss of tissue vitality contributes to significant cicatrix formation and facial disfigurement [33]. Dirt and gravel impregnated into skin can produced unwanted tattooing effect, and there is usually hypertophic cicatrix formation. Avulsion of tissue presents great challenges with scar contracture. Common procedures performed during this phase include placement of occular, auricular or dental implants, including pre prosthetic procedures such as vestibuloplasty, ridge augmentation or orthognathic surgery to correct maxillary-mandibular arch discrepancies [33]. Methods for treating these scars includes dermabrasion 4–6 weeks after soft tissue closure or scar excision/revision. Injecting subcutaneous steroids to reduce hypertrophic scarring is also beneficial as long as long as low doses are used so as not to cause significant dermal atrophy or liponecrosis. Scar contracture and damage to the temperomandibular joint may limit facial movement and physical therapy in the form of mouth stretch devices such as the Therabite is advocated.

17.8 The Future

Developments in resuscitation and acute surgical care over the last decade of conflict have meant UK military trauma patients are surviving increasingly severe injuries. Unprecedented survival means a cohort of survivors with unprecedented injuries. This chapter has demonstrated that large soft and hard tissue avulsive defects are still challenging to manage despite huge advances in free flap surgery and custom bent osteosynthesis plates. Currently available synthetic materials do not remodel nor fully integrate with host tissues and can therefore become infected, often necessitate multiple revision surgeries and restore anatomical form that is often lacking in both aesthetics and function. One solution in the shorter term is vascularised composite allotransplantation (VCA), involving the transfer of a functional unit of multiple tissue types. Of the 29 face transplants that have been performed up to 2014, nearly a third have been performed because of ballistic injury [37]. Each of these cases has involved significant avulsion of soft tissue, and to a lesser degree the bony components, which has been unsuccessfully treated by multiple surgical procedures including vascularised free flaps. However, although 175 US soldiers with significant facial injuries are reported to be eligible for transplantation, to date only one transplant has been done on a soldier. The specifics of each face transplant vary with the anatomy and requirements of the individual patients, which will require careful multidisciplinary planning [38]. The surgery itself requires two experienced teams operating simultaneously on the donor and the recipient, with the key anastomoses usually being the facial artery and the Vth and VIIth cranial nerves. The sensory reinnervation of the face typically occurs faster and more reliably than motor nerves; however, early function in the facial nerve has been seen at 2 months post surgery [39]. The aesthetic and psychosocial benefits from VCA has already led to patients being able to reintegrate into society and resume employment.

Despite the considerable benefits of VCA it must be weighed against the necessity of lifelong immunosuppression and its potential sequalae. The US Department of Defense has recently developed a dedicated ‘facial regeneration programme’ in conjunction with multiple university hospitals that also includes research into new implantable polymers capable of administering adipogenic cells, angio-osteogenic factors and bone derivatives as well as drugs to prevent infection and promote wound healing. Although regenerative medicine is still in its infancy, it has the potential to culture in vitro tissues to replace bone, muscle and nerves as well as designing biological scaffolds to promote growth of tissues such as bone growth in vivo. This has particular relevance in those facial structures that are particularly difficult to reconstruct such as the nose, ear, orbit and lips but could also even be used to growth teeth.

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Penetrating Neck Injury

18

Johno Breeze and David Powers

18.1 Introduction

The neck is inherently vulnerable to penetrating injury as large vascular structures, and the airway, lie relatively superficial to the skin. It has little native protection from ballistic projectiles with the exception of the spinal cord, which is covered by vertebrae throughout its length. The structures at highest risk are the great vessels, namely the paired carotid arteries and internal jugular veins. These structures run in parallel with one another in conjunction with the vagus nerve, and any injury to one vessel should be assumed to have damaged the other until proven otherwise. The vessels increase in size and run deeper as they travel towards the mediastinum, making direct compression, as well as surgical access, more difficult. Surface markings for these vessels are the anterior border of the sternocleidomastoid (SCM) muscle, as it runs from the mastoid down to insert into the medial third of the clavicle. The trachea starts immediately under the larynx and is palpable for the first one or two rings in most individuals with the neck extended. The cricothyroid membrane is found by running a finger below the thyroid cartilage and is easily penetrated to gain access to the airway at a point below the vocal cords. Surgical tracheostomy is undertaken usually by cutting a window into the trachea at the level of the second or third tracheal rings. Pertinent anatomy includes the isthmus of the thyroid gland, and the laryngeal nerves that run bilaterally between trachea and oesophagus (Fig. 18.1).

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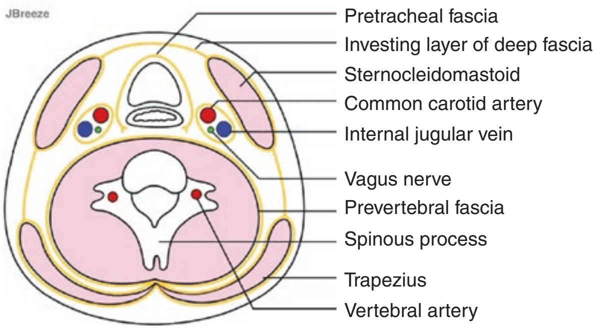

Fig. 18.1 A simplified demonstration of pertinent neck anatomy in the axial plane

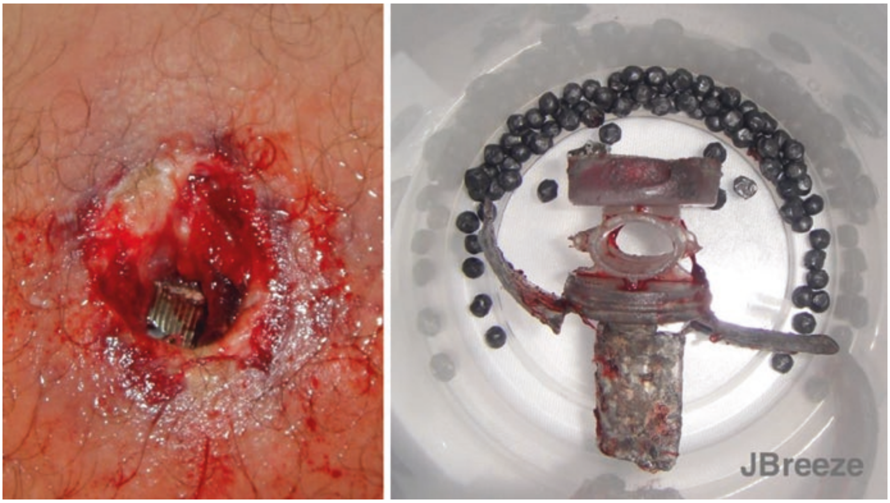

Fig. 18.2 Energised fragments can be irregular in shape and deposit energy rapidly into the target tissue (*left*). Multiple spherical fragments are produced by explosive ordnance such as from this cluster bomb (*right*)

Mortality from penetrating neck injury (PNI) is from large vessel haemorrhage, spinal cord trauma or from airway compromise due to direct laryngotracheal damage or haemorrhage into the airway [1]. The most commonly violated vessels are the carotids followed by the internal jugulars [2] reflecting their relative superficial course in the neck [3]. Despite recent diagnostic and surgical advances, the mortality of civilian firearm injuries to the neck is still greater than 10% [4]. Mortality rates from military wounds remain significantly higher, reflecting the nature of the wounding agents, as well as the time to available surgical care. Explosive events produce multiple energised fragments, each capable of damaging vital structures, with a resultant mortality quoted as greater than 40% (Fig. 18.2). During the recent conflicts in Iraq and Afghanistan, a high velocity projectile directly hitting the neck had a mortality of greater than 75%, reflecting the huge energy transfer produced by such weapons and that no practicable personal armour is currently capable of protecting soldiers [5].

18.2 Pre-Hospital Care

In addition to direct pressure applied with a bandage, the use of pre-hospital haemostatic agents is recommended, but should only be gently packed for fear of further damage to the underlying vasculature [6]. The probability of cervical spine instability from a firearm injury in a patient who is conscious and neurologically intact is low and immobilisation is on balance not recommended. Barkana *et al.* studied all Israeli soldiers who sustained penetrating neck injuries over a 4-year period. All patients were transported to a trauma centre will full cervical spine immobilisation. The incidence of cervical spine column injury was approximately 2%, with only 1% of patients having actual spinal cord injury. They found no survivable injury that would have benefited from spine immobilisation [7]. Arishita *et al.* evaluated over 4000 cases of PNI sustained in the Vietnam War and noted that less than 2% of patients with cervical spinal column involvement "might" have benefited from immobilisation. They concluded as well that cervical spine immobilisation in penetrating neck trauma is "neither prudent nor practical." [8]. Such a premise also applies to soldiers injured by explosively propelled fragments in a military environment unless the tactical situation allows [9]. Cervical spine fracture should be suspected in casualties exposed to an explosive event who may have been thrown against objects by the blast wave. Careful oral intubation is recommended to secure the airway, even should tracheal injury be suspected.

18.3 Damage Control Surgery for Penetrating Neck Injury

Damage Control Surgery (DCS) is the principle by which early identification of life-threatening injuries is made and the decision to avoid complicated, sometimes lengthy, definitive repairs in an unstable patient [10]. DCS involves the rapid control of the patient's airway, followed by packing or employment of catheters for haemorrhage control. Patients with 'hard signs' of PNI, particularly active bleeding, expanding haematoma, or airway compromise should be taken immediately to the operating room for exploration (Table 18.1). Intubation can be complicated by the associated expanding neck hematoma, laryngotracheal injury, and suspicion of an associated cervical spine injury. Early intubation is the key to control of a situation that can quickly deteriorate into multiple unsuccessful intubation attempts if deferred. The most experienced person available should be designated for control of the airway [4]. Active bleeding, if encountered, should be controlled with digital

Table 18.1 Clinical "hard signs" of penetrating neck injury warranting immediate surgical exploration

Vascular: ongoing bleeding from the neck region that is not amenable to pressure, an expanding haematoma and a bruit or thrill in the neck
Aerodigestive injury: crepitus or subcutaneous emphysema, dyspnea or stridor, air bubbling from wound, tenderness or pain over trachea, hoarse or abnormal voice, hematemesis or hemoptysis

pressure. This should be continued throughout the skin preparation and until proximal and distal control is obtained. Wounds should not be probed or locally explored as these manoeuvres can dislodge clot and lead to uncontrolled haemorrhage or embolism. A chest radiograph may demonstrate a potentially life-threatening issue that should be addressed prior to transport to the operating room such as a pneumothorax, haemothorax or tension pneumothorax [4].

18.4 Physical Examination

Some centres rely solely on serial physical examinations to guide their decisions for operative or non-operative management, whereas others will employ a cadre of diagnostic tests to definitively exclude injuries to the structures within the neck. Although recommended in a civilian environment, the role of serial physical examinations alone in the military setting is questionable due to the risk of occult injury [11], especially if injured by blast [12]. Asymptomatic patients injured by fragmentation were found to have vascular damage in 25% of cases even when no wound tract seem to involve vessel and no fragment in close proximity [12]. The presence of ‘soft’ and ‘hard’ physical signs, remain a useful adjunct when in situations where imaging is not available [2]. “Soft” signs include hematemesis, hemoptysis, hoarseness or change in voice, dysphagia, or odynophagia. In the stable patient, these signs mandate further evaluation and exclusion of vascular and aero-digestive injury. Prior to considering non-operative or selective management on a patient with penetrating neck trauma, one must consider the diagnostic modalities that are available and what degree of reliability can be placed on each of them. For penetrating neck injuries both the Glasgow Coma Scale (GCS) and a peripheral neurological exam should be performed to rule out direct spinal cord trauma or indirect damage due to vascular ischaemia.

Damage to the hypopharynx and oesophagus may be clinically silent initially if the airway is not compromised. Missed oesophageal injuries are the cause of the majority of delayed complications seen with penetrating neck injuries [13]. Early signs of oesophageal injury include subcutaneous air, crepitus, dysphagia, odynophagia, drooling, and hematemesis [14]. When an oesophageal leak progresses to mediastinitis, morbidity and mortality are significant. Early diagnosis may allow primary repair to be performed and generally results in superior outcomes [15].

18.5 Computerised Tomographic Angiography (CTA)

Patients presenting with haemodynamic instability or with “hard signs” of injury (Table 18.1) should undergo immediate operative exploration and repair and are not candidates for imaging triage. Otherwise Computerised Tomographic Angiography (CTA) remains the backbone of diagnosis with sensitivity and specificity quoted as 90% and 100% respectively for diagnosis of carotid and vertebral arterial injuries [16] (Figs. 18.3 and 18.4). It should be noted however that its specificity is less when used to assess airway or oesophageal damage [17]. In the military setting CTA

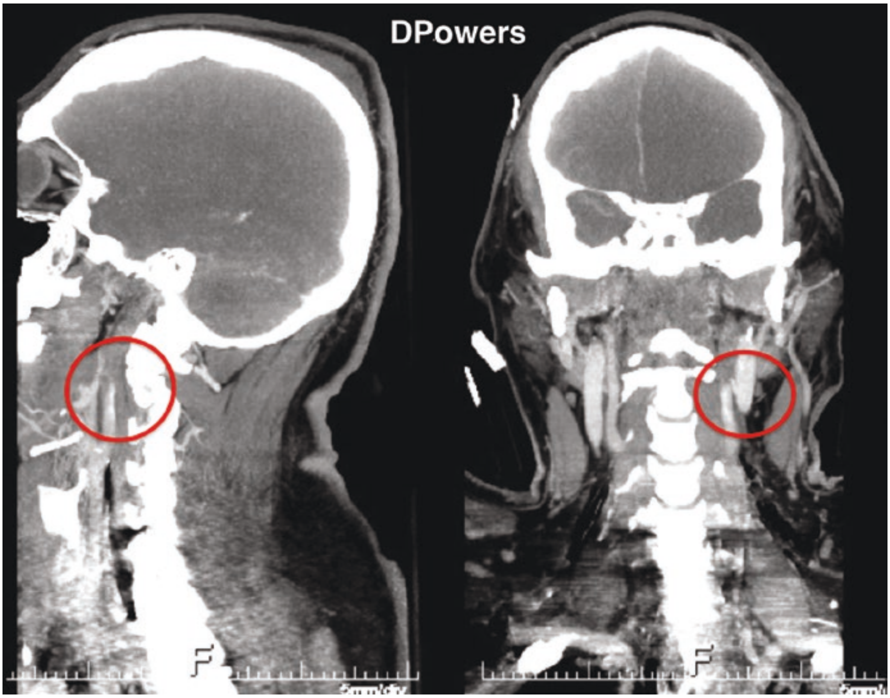

Fig. 18.3 A CT angiogram of the neck in a patient with a penetrating injury transecting the internal carotid artery

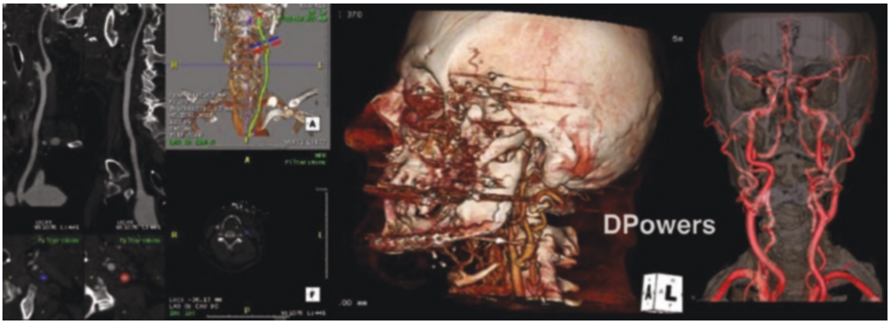

Fig. 18.4 CT angiograms with 3D reconstruction, which can serve as a valuable resource in the identification of potential vascular injury to the vessels of the head and neck

can be non-diagnostic in up to 20% cases due to metallic artefact [2]; these patients should ideally have digital subtraction angiography or duplex ultrasound but it is recognised that this unlikely to be available on current deployments [18]. CTA is performed using a helical CT scanner with approximately 100 ml of contrast injected and data acquired after a brief delay of 10–15 s.

18.6 Formal Percutaneous Angiography

Angiography remains the gold standard for evaluating and excluding arterial injury (Fig. 18.5). In addition, angiography can help in planning the operative approach in the patient with more than one zone involved. In evaluating the patient with PNI, an adequate angiogram should visualise the innominate artery, the common, internal, and external carotid arteries, the subclavian arteries, and both vertebral arteries as well. The facilities and expertise to perform formal angiography are limited in austere and military environments, leading to a lower threshold for surgical intervention should findings of vascular damage on CTA be equivocal.

Fig. 18.5 Formal percutaneous angiography of the carotid artery obtained in a field hospital for a patient with a penetrating neck injury. Note the limited field of view visualising only of the common carotid, internal carotid and external carotid arteries

18.7 Ultrasound and Magnetic Resonance Angiography

Colour doppler ultrasound has been proposed as a quick and efficient tool to evaluate stable patients penetrating neck trauma to exclude vascular injury. Although the equipment is readily available in most modern trauma centres, the technique is highly operator-dependent and cannot adequately assess the aerodigestive structures. Magnetic Resonance Angiography (MRA) is a sensitive imaging modality but is currently impractical due to its inconsistent availability, length of study time, and incompatible with various types of medical equipment. There is also minor concern regarding the presence of metallic fragments lodged in the cervical tissues being exposed to the high-powered magnet.

18.8 Investigations for Potential Airway Injury

Although injuries to the larynx and trachea are uncommon, they are associated with significant morbidity and mortality. The risk of death and complications associated with these injuries can be minimised by aggressive airway control and an expedient search for occult injuries, respectively. The endotracheal approach to intubation can be safely accomplished in selected patients with laryngo-tracheal injuries [19]. This approach allows for controlled placement of the endotracheal tube, as well as the evaluation of the hypopharynx, larynx, and proximal trachea through direct laryngoscopy. Once the airway is controlled, a careful evaluation of the laryngo-tracheal tree should be undertaken. Airway injuries are difficult to diagnose pre-operatively. Physical examination findings are sensitive for detecting airway injury but lack specificity. Clinical findings suggestive of hypopharyngeal penetration include dysphagia, odynophagia, hemoptysis, and subcutaneous emphysema. Diagnostic laryngoscopy identified injuries to the hypopharynx or larynx in over 90% of patients [20].

18.9 Investigations for Potential Oesophageal Injury

Physical examination does not appear reliable in excluding injuries to the oesophagus following gunshot wounds. Direct oesophagoscopy (preferably both flexible and rigid) provide the highest sensitivity for diagnosis of oesophageal injury but is technically difficult, especially in a patient with an immobilised cervical spine. A Gastrografin® contrast swallow imaging study is usually performed if suspicion of oesophageal injury exists [15]. Contrast studies require a stable, cooperative patient and are difficult to obtain in agitated or intubated patients. The sensitivity of contrast oesophagography in patients with oesophageal trauma varies from 48 to 100%

[21]. The contrast agent and technique employed for oesophageal evaluation both have a significant effect on the sensitivity and accuracy of this modality. Water-soluble agents are less viscous and dense and are, therefore, less likely to coat the mucosa adequately. Up to 55% of oesophageal perforations will be missed if a water-soluble agent is used alone. Patients unable to safely swallow should have the contrast agent instilled through a nasogastric tube under pressure. When used alone, oesophagoscopy and oesophagography have sensitivities of 60–80%. Combining the two, however, increases the sensitivity of detecting oesophageal injury following penetrating trauma to well over 90%. Demetriades and colleagues noted that physical examination combined with both endoscopy and oesophagography detected 100% of penetrating oesophageal injuries [22].

18.10 Trajectory Determination

A high index of suspicion, based on the bullet trajectory, is essential for early diagnosis of PNI, particularly aerodigestive injuries. Compared to missiles that do not cross the midline, transcervical GSW are twice as likely to injure vital structures in the neck [23]. This has led some authors to suggest that these wounds be considered as a separate category of neck trauma and even advocate mandatory exploration in this special population. However it is generally felt that a careful clinical examination combined with the appropriate diagnostic tests (particularly CTA) can safely select the appropriate treatment [23].

18.11 Management Decisions

The management of ballistic trauma to the neck will ultimately be determined by the experience of the clinicians and the imaging facilities available. In trauma centres where CTA is rapidly available, as well as the facilities to perform tests such as oesophagography, a "*watch and wait*" policy is prudent if no damage is seen. In more austere environments, or where such imaging facilities are not available, management principles are still best guided by dividing the neck into zones (Fig. 18.6, Table 18.2). Zone I is from suprasternal notch to cricoid cartilage. Zone II is from cricoid cartilage to angle of mandible. Zone III is from the angle of mandible to base of skull [24]. Due to the inherent difficulty in evaluating and obtaining vascular control in this area, selective management of injuries to Zone III has arisen out of necessity. Good evidence now exists that casualties with Zone II injuries in a civilian setting without hard signs and no pathology on CTA can be managed conservatively without surgical exploration [25]. Casualties with Zone I injuries should have CTA and should there be any equivocation I n the result then formal percutaneous angiography performed. Casualties with Zone III injuries without hard signs should have frequent intraoral examination to observe for oedema or expanding haematoma within the parapharyngeal or retropharyngeal spaces. Nerves exiting the skull base are in close proximity to the great vessels, thus neurological deficits in a casualty are suggestive of injury to the great vessels [26]. However designing a management algorithm based on these anatomical zones is problematic, as classifying an external wound to a particular zone does not guarantee the trajectory of the missile. In addition the numerous fragments that are produced by fragmenting munitions in a military environment can produce complex cervical injuries that often cross all three of the traditional neck zones [2].

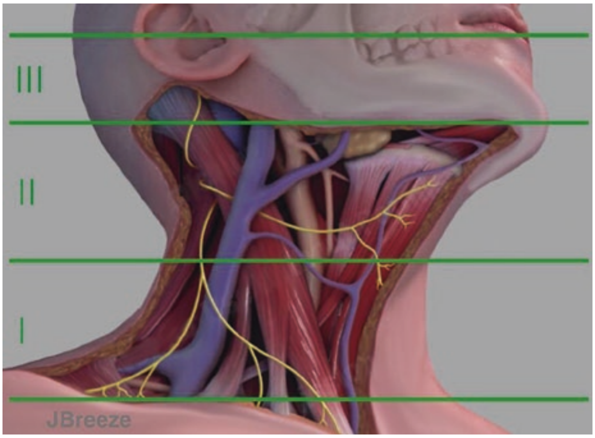

Fig. 18.6 The neck typically is divided into three zones of injury. Each zone has preferred diagnostic and therapeutic approaches. Zone I is from suprasternal notch to cricoid cartilage. Zone II is from cricoid cartilage to angle of mandible. Zone III is from the angle of mandible to base of skull

Table 18.2 Proposed management algorithms for penetrating neck injury in the deployed setting based upon neck zone of entry wound

Zone	Significance	Treatment if no 'hard signs' present	Treatment if 'hard signs' present
I	Mortality highest due to size of vessels and proximity to skin surface. Vessels difficult to access	Serial physical examination following CT angiogram. Formal arteriography as required	Median sternotomy or left anterior thoracotomy to control haemorrhage by appropriately trained surgeons
II	Management in a military hospital setting continues to be debated	Serial physical examinations with CT angiogram. In a military setting low threshold for surgical exploration if multiple penetrating wounds even in absence of hard signs	Incision parallel to sternocleidomastoid or horizontal neck dissection incision if access to mandible required
III	High mortality rate and access to vessels difficult due to skull base, styloid process, and mandible	Serial physical examination following CT angiogram. Formal arteriography as required	Temporary division of mandible or even craniotomy to control a high-carotid injury

Considerable care must be taken towards applying civilian management algorithms to military scenarios, as significant differences exist in the aetiology of injury and resources available. Civilian PNI is primarily from stab wounds and low velocity gunshot wounds, which is in direct contrast to military PNI of which 79% is due to explosive fragmentation and the remainder from gunshot wounds [12]. The action of explosive weaponry is to produce multiple small energised fragments, each with the chance of causing vascular perforation and therefore this mechanism greatly increases the probability of vascular perforation with resultant haemorrhage [11]. In the deployed military setting, the decision to surgically explore a neck wound that has breached platysma remains controversial and in many instances is dependent on the skill sets of the surgeons present [27]. A lower threshold for exploration is necessary in equivocal cases and if evacuation is potentially delayed. Even in asymptomatic patients, pathology was found in 78% of cases on neck exploration of soldiers injured by explosively propelled fragments. Consideration to removing larger fragments lying close to the great vessels or vertebral arteries should be made once the patient has been evacuated to the host nation but this should be an elective procedure with radiological assistance available [11].

18.12 Operative Surgical Approaches

The choice of surgical approach should be determined by the likely zone of injury and the type of structure requiring repair (Fig. 18.7).

18.12.1 Zone I

Injuries involving Zone I are the most technically challenging, generally have the highest mortality and therefore require the most pre-operative planning. Access is best achieved through a median sternotomy with supraclavicular extension or an anterior SCM incision. Vascular control of the vertebral arteries is among the most difficult to obtain, especially in the face of active haemorrhage. The majority of the vessel is contained within the bony foramina hindering adequate exposure. If one is required to obtain vascular control of a known vertebral artery injury, a supraclavicular incision will provide optimal exposure.

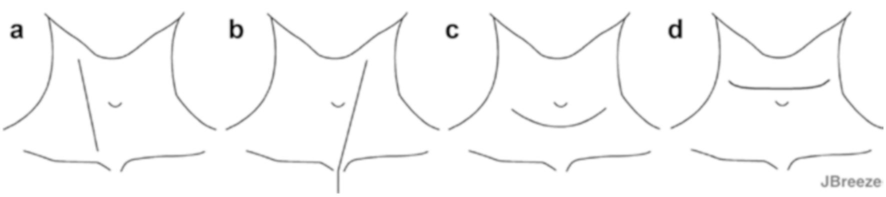

Fig. 18.7 Operative approaches to the neck include (**a**) anterior sternocleidomastoid incision, (**b**) sternocleidomastoid incision with sternotomy extension, (**c**) 'collar' incision, (**d**) 'visor' incision

18.12.2 Zone II

An anterior SCM incision allows for adequate exposure of unilateral neck injuries (Figs. 18.8 and 18.9). For transcervical or bilateral wounds, a transverse 'collar' incision can provide adequate exposure for the majority of Zone II injuries. Both the collar and the SCM incisions can be quickly extended into the chest should a sternotomy be required. Carotid injuries to Zone II can be adequately visualised through either incision. In the military setting it has been suggested that an extended collar incision is used, often termed a 'visor' approach, analogous to those used in an

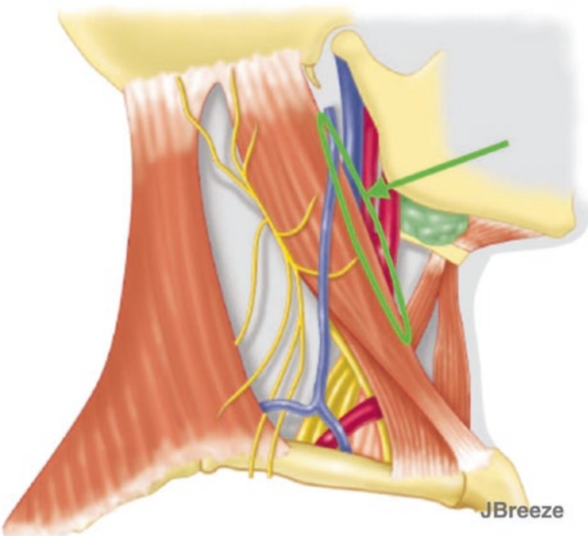

Fig. 18.8 Operative access to the carotid artery in Zone II of the neck is through an incision along the anterior border of the sternocleidomastoid muscle (*arrowed*)

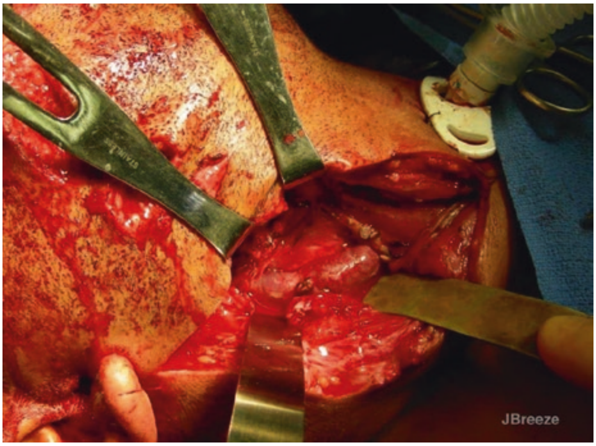

Fig. 18.9 Zone II exploration of the neck in a field hospital exposing the internal jugular vein and common carotid artery via the classic approach anterior to the sternocleidomastoid muscle

Fig. 18.10 A neck injury to Zone II with a contemporaneous anterior mandible fracture can be approached through a 'visor' neck incision enabling potential treatment of both injuries

oncological neck dissection (Fig. 18.7). Such an incision can be cosmetically superior and provide access to the lower border of the mandible for contemporaneous bony exploration and fixation [28] (Fig. 18.10).

18.12.3 Zone III

Due to the inherent difficulty in evaluating and obtaining vascular control in this area, selective management of injuries to Zone III has arisen out of necessity (Fig. 18.11). In addition to subluxation of the mandible, resection of the angle of the mandible or styloid process has also been described. If proximal control can be obtained, distal control of Zone Ill (and even some Zone II) injuries can be obtained without such morbid manoeuvres through the placement of a Fogarty catheter.

18.13 Surgical Treatment of Vascular Injury

Carotid artery injuries account for 10–20% of life-threatening injuries that occur in patients with penetrating neck trauma [26]. The primary objective during operative management is to restore antegrade flow to the carotid and preserve neurological function. Carotid injuries should be repaired unless the surgeons is faced with: (1) uncontrollable haemorrhage, (2) haemodynamic lability, (3) a comatose patient presenting with no evidence of antegrade flow, or (4) a devastating vessel

Fig. 18.11 A penetrating injury into Zone III of the neck due to an explosively propelled fragment. Following CT angiography to exclude underlying injury this wound was superficially debrided but not formally explored

injury technically impossible to temporarily bridge with a vascular shunt. In these circumstances, ligation can and should be employed. Some authors also advocate ligation if there is little to no “back bleeding” from the carotid artery, citing the likelihood of worsening an established ischaemic infarct or risk of embolising a distal clot is increased with attempts at restoring blood flow. Another controversy is whether to use a temporary vascular shunt, as even elective repairs near the carotid bifurcation can be difficult. If technically possible, a primary repair should be attempted on all common and internal carotid injuries [26]. Those involving the external carotid, however, should be ligated unless they are at or near the bifurcation [29]. Ligation of the external carotid and internal jugular are generally well tolerated unless performed bilaterally but ligation of the internal carotid has an approximately 50% incidence of stroke [3]. Surgical access is generally though a vertical incision parallel to the SCM. If the defect is greater than 2 cm in diameter, primary repair should not be attempted due to the excessive amount of tension on the repair and a vein patch should be used [26]. The jugular vessels should not be utilised for conduit in this setting considering the disruption to venous outflow associated with their harvest. In addition polytetrafluoroethylene (PTFE) grafts have been employed with increased frequency when primary repair is not possible.

Vertebral artery injuries may present initially with severe haemorrhage or in a delayed fashion, while diagnostic studies are in progress. If the diagnosis is made in a haemodynamically stable patient without active external haemorrhage, the vertebral artery should be embolised using interventional radiology. If the patient presents with active haemorrhage or experienced personnel are not available for angiography and embolisation, an attempt at operative surgical ligation is indicated through a supraclavicular or SCM incision. Use of a Fogarty catheter is great assistance as the balloon can be positioned distal to the point of injury and inflated.

A follow-up angiogram is usually obtained in the weeks after embolisation or surgical ligation to demonstrate haemostasis and exclude arteriovenous fistulae formation. In institutions without interventional or endovascular support, the Fogarty may be left in place for approximately 72 h. This allows adequate time for thrombosis of the artery, at which point the catheter can be deflated and removed. Pseudoaneurysm formation in civilian injury is a rare complication but is more common in military environment, and is believed to be related to the effect of multiple small energised fragments [2].

18.14 Treatment of Vascular Injury by Interventional Radiology

If a patient is medically stable, angiography can be performed to both establish a firm diagnosis and proceed with endovascular treatment when indicated. The location of the injury as well as the collateral cerebral circulation must be evaluated prior to an intervention. Transarterial embolisation is a fast and effective method for the treatment of an active haemorrhage, in particular when the injured vessel is relatively small and the collateral circulation allows for vessel's sacrifice. Endovascular stent placement may be more appropriate for injuries involving large- and medium-size vessels that must remain patent, such as the common carotid, internal carotid, or vertebral arteries in the absence of adequate collateral circulation. Currently facilities for performing interventional radiological techniques in the deployed military setting are totally dependent on the resources made available by the medical command structure, but it is likely that those clinicians capable of performing selective intravascular embolisation will deploy in more established medical facilities in the future (Fig. 18.12).

18.15 Surgical Treatment of Laryngo-Tracheal Injuries

Patients presenting with such injuries can be approached using either an anterior SCM or collar incision, although the later provides greater access. Lateral dissection should be minimised to protect the laterally based blood supply. Following debridement most laryngeal defects from penetrating trauma can be repaired primarily. Small defects noted on endoscopy can usually be managed non-operatively with airway protection, elevation of the head of the bed, and voice rest. If the cartilaginous framework has been disrupted beyond management with a primary repair, the airway should be stented with an endotracheal tube or silicone stent [4]. Tracheostomy should be avoided in the area of injury, but if necessary should be placed distal to the repair to protect the anastomosis. Laryngeal defects up to 3 cm diameter can be repaired primarily in a single-layer fashion after adequate mobilisation. The role of tracheostomy in these patients remains controversial [4]. Tracheostomy in this

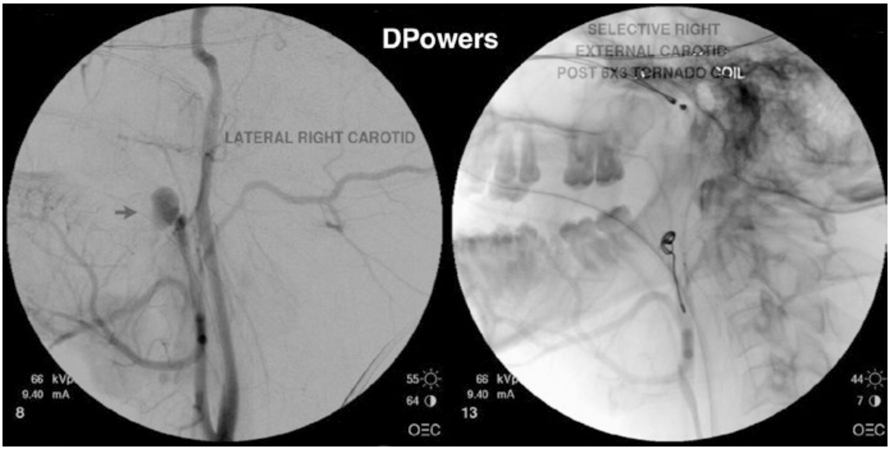

Fig. 18.12 A penetrating injury into Zone III of the neck due with injury to the external carotid artery presenting to a field hospital (*left*). The same wound after interventional treatment with a surgical coil (*right*)

setting has been associated with increased risk of infection, but many advocate its use in protecting the proximal repair.

18.16 Surgical Treatment of Oesophageal Injuries

The repair of an injury to the cervical oesophagus is best approached through an anterior SCM incision. Should there be an associated laryngotracheal injury, however, these combination injuries are best approached through a collar incision. Maximal exposure of the oesophagus is achieved through retraction of the trachea and thyroid medially and the carotid sheath laterally. An indwelling nasogastric tube can facilitate not only the localisation of the oesophagus, but also the identification of the oesophageal injury through the instillation of air or methylene blue. Nonviable edges should be sharply debrided prior to primary repair, which is then carried out in one of two methods. The two-layered repair is performed with an interrupted submucosal (resorbable suture) and a muscular layer (non-resorbable suture). Alternatively, a single layered interrupted repair can be performed with a non-resorbable suture. Whether a single or two-layered repair is chosen, good mucosal and muscular approximation is necessary to prevent delayed leakage [4]. The main complication from such injuries is the risks of tracheo-oesophageal fistula, although the majority of such fistulas will heal without surgical intervention. Their risk of occurrence can be minimised by using a tissue flap such as dividing the clavicular head of the SCM muscle and mobilising it to separate the trachea and oesophagus. All patients should remain nil by mouth until a barium swallow performed at 5–7 days postoperatively has excluded a leak.

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Management of Vascular Trauma

19

Claire Webster and Thomas C. König

19.1 Introduction

Recognising and managing bleeding in ballistic trauma is an early priority, and all clinicians must be familiar with the initial lifesaving procedures required to arrest major haemorrhage, and maintain patient physiology in order to enable definitive treatment. The <C>ABC paradigm of advanced trauma management denotes that recognition and management of catastrophic haemorrhage is the initial consideration to prevent rapid exsanguination and early fatality [1]. The introduction of major haemorrhage protocols has improved the outcomes in major haemorrhage in many trauma centres worldwide [2].

The burden of traumatic vascular injury worldwide is difficult to ascertain. As with trauma in general, data collection and record keeping is insufficient, particularly in the developing world [3]. In the United Kingdom, vascular injury in trauma centres is reported in 4.4% of cases, with 53% caused by penetrating injury, with mortality rates of around 10% [4]. The United States reports stable incidences of vascular trauma in the past 10 years, particularly secondary to ballistic mechanisms, due to the use of firearms in assault [5]. It is recognised that in the US, fatality from penetrating trauma and ballistics is in fact decreasing, however, incidence, particularly in ballistic trauma, is increasing [6]. This reduction in fatal wounding may be due to improvements in resuscitation and point of injury care, but increasing incidence means that continued efforts are required to understand the pathophysiology

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and appropriate treatment algorithms in order to maintain standards. Military centres on deployed operations in recent times have reported that vascular injury is present in between 4 and 9% of traumatic injuries [7, 8], however, it is implicated in over 75% of patients with haemodynamic compromise [9].

The majority of deaths from trauma in all areas of the world, particularly in major haemorrhage, occur in the pre-hospital setting [10]. Therefore, to reduce morbidity and mortality from major haemorrhage, it is important to consider the logistics of rapid prehospital intervention to control bleeding, arrange transfer to a hospital facility, and to recognise haemorrhage and/or ischemia secondary to vessel injury in hospital quickly, to permit early investigation and management.

19.2 Pathophysiology

The extent of damage to body tissues depends on the characteristics of the projectile, its mass and velocity, and cause injury by crush and stretch of tissues [11]. Both can cause injury to vessels in the form of transection, partial transection, and intimal damage causing thrombosis and partial stenosis or occlusion. External compression of vessels can be caused by expanding haematoma, or the presence of an embedded projectile. Stretch of body tissues from fragments can actually be relatively advantageous for vessels: both arteries and veins are relatively compliant and therefore may be preserved when other tissues fail, such as in cavitation. In many instances, fragments can travel along tissue planes, such as those around neurovascular bundles [12, 13].

Penetrating trauma to a vessel can result in vascular injury in a variety of forms: transection, partial transection, narrowing, occlusion, or external compression (Table 19.1). Consequent haemorrhage may be overt, external bleeding, contained (e.g. within a muscle compartment) or concealed (e.g. within the pleural cavity).

Key Point: Haemorrhage from vascular injury can be:
• Overt External Bleeding
– Contained
– Concealed

19.3 Clinical Features

A thorough history of the mechanism of injury should alert the clinician to the possibility of penetrating vascular injury. Bleeding at the scene at time of injury should be noted, and any information about initial bystander or professional intervention prior to your assessment should be recorded. Hard and soft signs of vascular injury should be noted, as well as the traditional ‘P’s of tissue ischaemia (Table 19.2).

Table 19.1 Types of vascular trauma, important considerations, and repair options

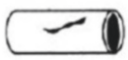
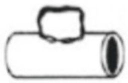
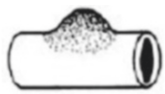
Injury	Description	Considerations	Repair options
 Laceration	Discreet perforation with no vessel wall loss	Ongoing haemorrhage Intimal flap	Direct axial suture—non-absorbable monofilament
 Transection	Complete division of a vessel wall	Distal ischaemia Ongoing haemorrhage	Shunt Primary Repair Bypass
 Vessel Wall Loss	Perforation with vessel wall loss	Ongoing haemorrhage Intimal flap	Shunt Patch repair Bypass Stent
 Arterial Spasm	Contraction of the muscular arterial wall due to injury	Distal Ischaemia	Explore Repair
 Contusion	Vessel abrasion but arterial continuity intact	Local thrombosis/occlusion Distal emboli	Conservative
 False Aneurysm	Arterial dilatation including only adventitial layer of vessel	Distinguish from true aneurysm	Conservative Repair
 Arteriovenous fistula	Direct communication between arterial and venous structure	Rupture, distal emboli, thrombosis	Conservative Repair (preferred if traumatic)
 External Compression	Narrowing of lumen due to structure outside vessel wall	Distal ischaemia Thrombosis formation	Removal of source, check for luminal patency
 True Aneurysm	Arterial dilation including all walls of the vessel	Distal emboli Rupture	Conservative Repair by graft/stent

Table 19.2 Hard and soft signs of vascular injury

Hard signs	Soft signs
Pulsatile bleeding	History of bleeding at the scene
Expanding haematoma	Peripheral nerve deficit
Absent distal pulses	Injury in close proximity to a major artery
Cold, pale limb	Diminished distal pulses
Palpable thrill	Multiple fractures and extensive tissue injury
Audible bruit	Small, non-expanding haematoma

Key point: The 6 'P's of ischaemia
Pain
Pallor
Pulselessness
Paralysis
Paraesthesia
Perishingly cold

19.4 Principles of Management

19.4.1 Resuscitation and Initial Management

Identification of vascular trauma rapidly in the initial assessment is important, and the following algorithm provides useful guidance (Fig. 19.1).

Once vascular injury has been recognised, initial control of haemorrhage must occur. In the event of catastrophic, life threatening haemorrhage, and in the event of single responder clinician resuscitation, this takes precedence over attending to the airway [1].

Methods to control haemorrhage may be employed in the early stages of patient treatment before transition to the operating theatre, with various techniques depending on the region: direct pressure, haemostatic agents, tourniquet use or (in the event of cardiac arrest due to hypovolaemia), thoracotomy with direct descending thoracic aortic pressure digitally, or by instrumental clamping. Proximal aortic control serves to control bleeding but also optimise myocardial and cerebral perfusion by maintaining afterload [14]. The initial resuscitation is a team approach, with the surgeon able to focus on haemorrhagic control, while the anaesthetist or emergency medicine clinicians manage the airway and volume replacement, preferably with blood and blood products if available.

Training for teams who deal with cases of major trauma must be considered prior to the event of it occurring, and repeated regularly [15]. Simulated trauma scenarios has repeatedly shown to be beneficial to improve communication, fluidity of treatment, investigation and transfer [16], and subsequently improved patient outcomes [17].

19.4.2 Investigations

Investigations requested in the initial phase of resuscitation in a patient with suspected or known vessel injury must be led by patient physiology, and not delay

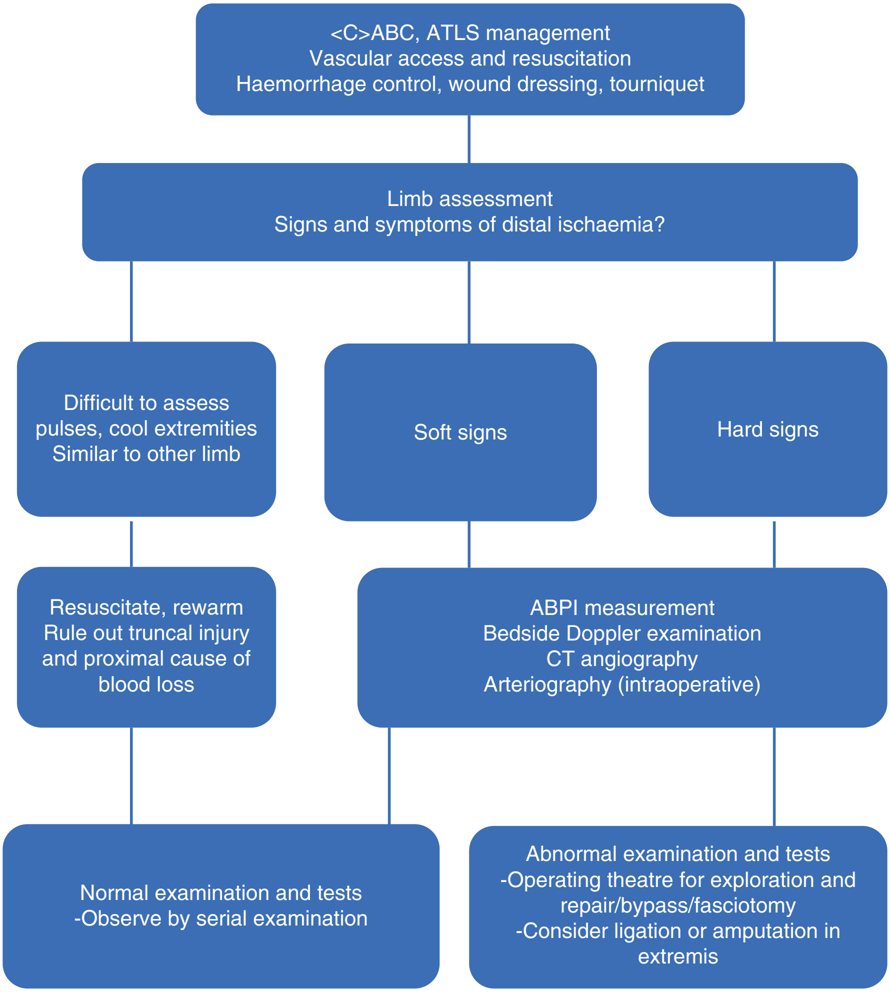


Fig. 19.1 The initial assessment of vascular injury

lifesaving treatment in patients in extremis. With this in mind, quick investigations in the emergency room can be helpful, without leading to a significant time delay.

19.4.2.1 Plain X-Ray Imaging

Plain chest X-rays are key, as part of the <C>ABC trauma paradigm, as part of breathing assessment, and must be ensured in the immediate phase of patient management, particularly in multiple injuries. Plain radiographs with suspected bony injury are useful as fracture patterns give useful clues as the likelihood of injury to adjacent vessels. Visualization of retained fragments or rounds allows estimation of wound track and at-risk vessels.

19.4.2.2 Vessel Imaging

Techniques to visualize arterial or venous systems include formal contrast angiography, computed tomographic (CT) angiography and duplex. Formal angiography with a view to intervention (embolisation, stent placement) is aided by involvement of an interventional radiologist working in a dedicated angiography suite. Diagnostic angiography does not necessarily require these assets, and may be undertaken in the operating theater using either C-Arm image intensification or a toweled plain X-Ray cassette beneath the patients' extremity. The upstream uninjured vessel is exposed, controlled, and a proximal clamp applied prior to cannulation and injection of contrast and image acquisition. One syringe is used for aspiration and flushing with heparinised solution and the other is used to inject full strength contrast. Failure to visualize the vessel axis must be correlated with the injury track and the patient's condition, recognizing that vessel visualization may be difficult in the shocked, cold patient. However, observed cut-offs in contrast filling should never be dismissed as "spasm"—especially if the casualty has been appropriately resuscitated.

Multi-detector CT angiography (CTA) now rivals contrast angiography in terms of injury detection (contrast "blush," pseudo-aneurysm, luminal filling defects), is non-invasive, can delineate non-vascular injury, and is particularly useful in truncal and neck trauma. CTA allows judicious selection of patients for appropriate endovascular techniques such as embolization in hard-to access vessels (such as the intra-cervical vertebral artery and in pelvic hemorrhage). One shortfall is the degradation of image from metallic artifact—making formal angiography a necessity in such cases. Color flow duplex is accurate in the delineation of pseudo-aneurysms and arteriovenous fistula in non-acute cases, but limited out-of-hours availability restricts overall utility in most trauma-receiving centers.

19.4.2.3 Ankle: Brachial Pressure Index (ABPI)

Many centres, especially in deployed military or humanitarian environments, may not have the luxury of CT or MRI scanning. Therefore, more crude estimates of vessel injury can be useful. The simplest adjunct to diagnosis of peripheral vascular trauma in the lower extremity is the Ankle: Brachial Pressure Index (ABPI). This is measured by obtaining the highest arterial occlusion pressure using a manual blood pressure cuff at the ankle and hand-held Doppler probe placed over the dorsalis pedis and the posterior tibial arteries. This pressure value is divided by the highest brachial systolic blood pressure. An abnormal ABPI is signified by any value <0.9. A pressure deficit of >10% or 20 mmHg compared to the contralateral uninjured limb is a "soft sign" of arterial injury and mandates confirmation with further investigations. In the absence of obvious signs of arterial injury, the arterial pressure index has been shown in civilian trauma to have a high sensitivity and specificity for arterial disruption, and can therefore be a useful diagnostic aid in the absence of a full complement of investigative options.

19.4.3 Tourniquet Use

Tourniquet use has undergone a worldwide revolution recently [18]. Previously, tourniquets were often left in place for up to 8 h and had a reputation for being the cause of limb loss in many injured soldiers. It took many decades to shake this reputation. Only during the past 15 years of conflict in Iraq and Afghanistan with experience with high volumes of multiply injured trauma patients have they been rehabilitated. The lifesaving use of the combat applicator tourniquet (CAT) [9, 19] (with relatively few complications versus survival benefit) [20] means that tourniquets now appear in the many civilian ambulances and emergency departments, and have been proven to improve outcomes in both military and civilian peripheral vascular trauma [21]. Tourniquets have variable tolerance among individuals. As low inflation/tightness as necessary to achieve haemostasis has been shown to increase compliance, as does the width of the tourniquet [22], but can also be dependent on additional factors such as physical fitness, age, hydration status and overall injury burden [23]. Increasing compliance with tourniquet use is important for prolonged use in trauma scenarios where evacuation to definitive care may be delayed, and the clinical consequences of prolonged use must be considered. Most studies suggest that tourniquet use up to 8 h is not associated with significant morbidity or mortality [24], however, use for longer than this has only been consistently documented in the two world wars, with high rates of limb loss and fatality. More knowledge is needed on safe tolerance of longer tourniquet times both to the patient comfort and physiology, and risk of subsequent morbidity and/or mortality.

Key Point: The use of tourniquets
Place as distal as possible whilst still controlling haemorrhage to preserve perfused limb length
Give analgesia in the awake patient to increase patient compliance
Record tourniquet time
Apply two tourniquets if necessary
Communicate to anaesthetist when removing tourniquet

19.4.4 Haemostatic Agents

It is important to consider a wide-reaching toolkit of options for control of major haemorrhage, depending on the anatomical area injured, the logistics of the operating environment (either on scene, in the emergency room, in the well-lit and well equipped operating theatre or the resource poor humanitarian situation) and the time in which you can afford, due to a mass casualty situation, or the requirement for rapid transfer and immediate surgical management. Tourniquets are effective in extremity injuries, but junctional wounds in the field are challenging, and haemostatic agents can be a helpful adjunct to direct pressure for severe junctional haemorrhage prior to theatre. Haemostatic agents such as Celox™, QuickClot™, and Haemcon™[25] impregnated dressings have been used over the years and gaining in popularity, and with no significant differences in the potential to arrest bleeding with proper use in animal studies [26, 27]. However, some have been known to cause undesirable exothermic reactions in contact with skin or eyes, and must be used with appropriate caution. Most haemostatic dressings are designed to be removed although some remain and are eventually absorbed. Chitosan based dressings achieve haemostasis by adhering to damaged tissues and creating a physical barrier to further bleeding. Acetylated glucosamine dressings work via a combination of platelet and clotting cascade activation, agglutination of red blood cells and local vasoconstriction [28]. Haemostatic dressings should not be placed within body cavities unless the surgeon is experienced with their use, and the presence of a haemostatic dressing should be noted to enable later removal if required.

19.4.5 Wound Management

Vascular injuries rarely present in isolation, and are often part of a larger wound, with surrounding soft tissue, bone, nerve and either local or distant organ injury. The very nature of a ballistic trauma results in wound contamination by skin commensals, and foreign debris, and if fragments do not pass through and out of the body then they embed and remain within the wound and zone of injury or may be distant to the entry site.

Plain radiography will detect foreign bodies for removal and guide debridement, as well as detecting underlying fracture, which may require reduction and fixation in combination with shunting or vessel repair to restore normal alignment.

Initial management of wounds includes reduction of fractures to restore bony alignment which, in turn, improves vascular integrity. Proximal and distal vascular control should be considered to avoid further uncontrolled bleeding during wound exploration. Vascular injury with coexisting fracture has historically yielded poor outcomes, with high secondary amputation rates [29], and therefore must be managed optimally. Shunting is a quick and reliable method to achieve temporary arterial continuity and extremity perfusion, to enable physiological ‘catch up’ with later definitive arterial repair [30]. There must be adequate tissue coverage of any exposed vessels, even in the short term, to ensure their protection, nutrition and hydration [31]. Initial tissue debridement aims to remove all non-viable tissue. Muscle tissue with suboptimal perfusion is dusky, non-contractile, and does not bleed.

The assessment of the viability of muscle tissue is deemed ‘the 4 Cs’ and can be subjective. In a recent study in 2016, only 50% of tissue samples assessed for viability by the surgeon had histological appearances in agreement with this impression [32]. Therefore, questionable tissue should be preserved at the first operation, as appearances and viability may become apparent on patient resuscitation and restoration of vascular continuity.

Key Point: The 4 Cs of viable muscle
Colour
Contractility
Consistency
Capacity to Bleed

Bony fragments that are loose should be removed, unless attached by a periosteal layer, as this layer may continue to perfuse the fragment [33], and may contribute to a later functioning intact limb or increase stump length in the event of an

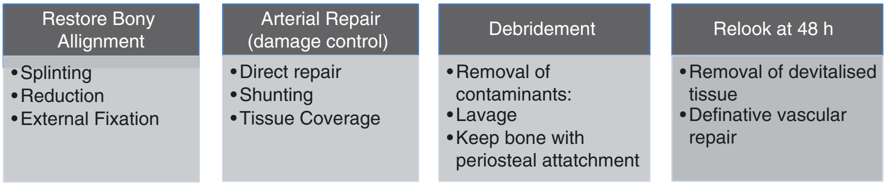


Fig. 19.2 The principles of damage control wound management with vascular injury

amputation, which improves later rehabilitation [34]. The principles of damage control wound management are summarised in Fig. 19.2.

19.5 Damage Control Vascular Surgery

19.5.1 General Operative Considerations

In the event of uncontrolled haemorrhage, control of bleeding, temporary or definitive, is vital. In the operating theatre, the surgeon, anaesthetist, nursing staff and theatre personnel should discuss the operative plan and equipment requirements. The management of the operating theatre in the stressful environment of major trauma must be handled carefully. It is important to make haste in the event of life threatening haemorrhage and a patient in extremis, however, taking just a few minutes to confirm the plan, and key steps and equipment required with the surgeon, anaesthetist and operating theatre staff could make all the difference between success and failure.

The patient must be prepped to ensure as much sterility as possible, and draped to cover all eventualities. This may include the torso in the event of a thoracotomy being required for proximal vascular control in neck and upper limb injuries, and the abdomen and groin for lower extremity injuries. Prepping a site for potential vein harvest should also be considered, if the patient is in a physiological condition amenable for such a definitive repair. The theatre should be warm, as a bleeding patient may be cool and coagulopathic.

19.5.2 Vascular Access and Proximal and Distal Control

Proximal and distal control can be achieved simply if a vessel is under direct vision, with digital pressure, clamping, or vascular sloops. However, this is more challenging when vessels cannot be identified readily, or an expanding haematoma requires exploration. In the event of uncontrolled bleeding in the zone of injury then proximal control needs to be gained as a priority. Proximal control is often more easily gained remote to the site of injury where tissue planes are undisturbed, and anatomy may be more favourable. Proximal control beyond anatomical barriers, for example,

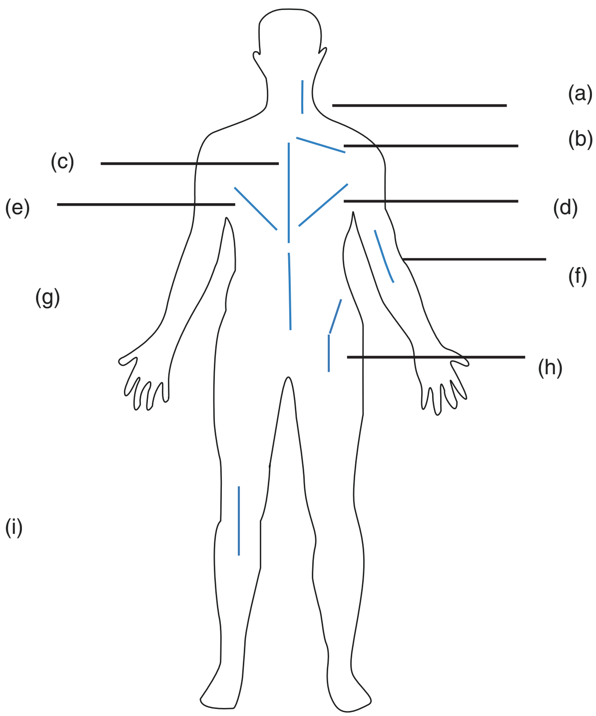


Fig. 19.3 Regions for proximal vascular control. (*a*) Longitudinal incision anterior to sternocleidomastoid for access to the carotid artery and jugular vein. (*b*) Superior and inferior incisions parallel to clavicle to access subclavian vessels, and proximal control in neck injury. (*c*) Median sternotomy for access to aortic arch and proximal control to neck vessels. (*d*) Left anterolateral incision for access to the heart. (*e*) Right anterolateral thoracotomy: extension with (*d*) to create a clamshell thoracotomy for access to heart and lungs. (*f*) Brachial incision for proximal control to distal limb vessels. (*g*) Laparotomy incision for control of abdominal aorta/iliac vessels. (*h*) Groin incision to access common, superficial and profunda femoral vessels, which can include a superior 'hockey stick' extension for initial proximal vascular control to the iliac vessels if required (*i*) popliteal incision to control popliteal artery and vein in distal limb haemorrhage (can be via medial or posterior approach)

above the inguinal ligament in lower extremity injury, should be considered. Distal control is also key, as prevents back-bleeding into the operative field, obscuring the operative view, and continuing volume loss. Incisions to consider in proximal and distal control are summarised below (Fig. 19.3).

After proximal vascular control has been attained, the zone of injury should be entered and explored. The incision over the wound may be generous and thought given to later skin coverage and the possible requirement for local or distant skin grafts and flaps. It is important to make a generous incision over the area of suspected vascular injury to allow adequate exploration, and with consideration to ease of incision extension if required. Initial control of bleeding by digital pressure allows temporary control, which can be delegated to the assistant, while the primary surgeon assesses the extent of vascular injury. Other techniques include clamping proximal and distal visible ends of vessel or the use of a Fogarty™ or urinary catheter balloon if the haemorrhage is within a cavity. Cessation of bleeding is important not only for the patient physiology, but for clearing the operative field to assess the injury.

19.5.3 Shunting

Arterial shunts permit quick reperfusion of limbs in peripheral, and occasionally central, arterial traumatic injury [35]. In instances where patients require damage control surgery and are physiologically unable to tolerate prolonged efforts at reconstruction, their use permits optimisation before definitive repair [30]. Where surgery occurs in a remote environment, shunts can be placed, secured and covered by wound closure or appropriate dressing to permit transfer for definitive treatment. Shunt placement also permits perfusion to occur while venous grafts are harvested and prepared. Proximal vascular control remains the initial manoeuvre after which the proximal and distal ends of the arterial injury are located and a shunt placed. It is important to ensure that there is good inflow and outflow/back bleeding before shunt placement [36]. A variety of commercial shunts exist, but other makeshift examples have been used in the event of specialised equipment not being available. These include appropriately cut intravenous giving set lines, endotracheal or nasogastric tubes [37, 38]. These need to be appropriately flushed with heparinised saline to prevent thrombus formation and subsequent occlusion (Fig. 19.4).

Durability of shunts depend on several factors both local and systemic. Local factors include laminar flow within the shunt, appropriate tension free placement,

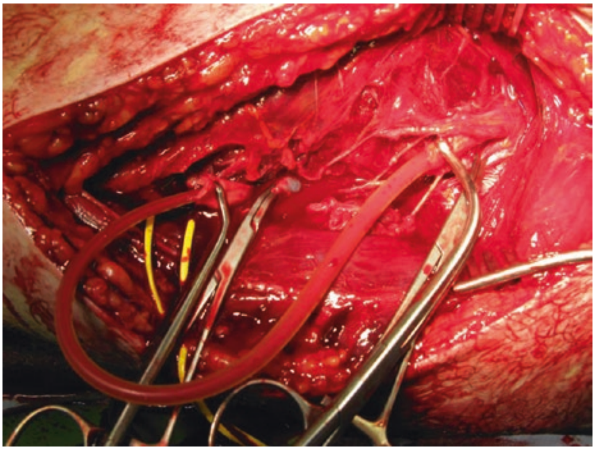


Fig. 19.4 An arterial shunt in situ in the superficial femoral artery. Reproduced with permission from Mr. David Nott, Consultant Trauma Surgeon

absence of clot and adequate flushing and heparinisation at the time of placement, and seal at proximal and distal ends. Systemic factors will include coagulation status of the patient, adequate intravascular volume, and peripheral perfusion [38]. Shunts placed more proximally have greater longevity. Limb fasciotomy should also be considered when shunts are placed [39]. Associated venous injuries can also be considered for shunt placement to promote outflow and improve arterial shunt longevity. Venous shunts are more prone to earlier occlusion compared with arterial shunts [40]. Recent outcomes following shunting in vessel trauma are positive, with rates of limb salvage at between 90 and 100% [41, 42]. There appears to be no relation between the time in situ and thrombosis formation between 0 and 24 h [41], however, times over 24 h have a higher rate of occlusion [42].

19.5.4 Ligation of Vessels

Patient physiology, and the operating environment, will guide how long the operating surgeon can afford to spend attempting to restore vascularity, and it may be that there is not the time, even for shunting to take place, if the patient is approaching their physiological limits. In this case, ligation of vessels may be appropriate, and it is absolutely essential for the trauma surgeon to know vessels one can safely ligate. In truth, the majority of vessels can be ligated as a lifesaving procedure if exsanguination is otherwise inevitable, with acceptance of the later consequences.

19.5.4.1 Arteries

There a few sequelae to ligating the internal iliac, axillary, subclavian, external carotid, or common carotid arteries. Ligating the external iliac, superficial femoral or common femorals can also be performed, with the understanding that the patient may be at risk of immediate limb loss, particularly in patients with existing arterial disease, and if the limb is retained in the short term, high risk of critical limb ischaemia later in life [43]. This is more likely in cases of large amounts of tissue destruction and therefore, absence of collateral circulation. Internal carotid artery ligation can lead to stroke in up to 20% of patients [44]. The coeliac axis arteries can be ligated, but superior or inferior mesenteric artery ligation can lead to gastrointestinal ischaemia. The suprapancreatic part of the superior mesenteric artery can be tied, thanks to collateral circulation from the coeliac axis [45].

19.5.4.2 Veins

Almost all veins, including the inferior vena cava, can be ligated if required. Oedema can occur as a consequence, in particular bowel oedema in the event of portal vein ligation [46].

19.5.5 Amputation Versus Limb Salvage

In the event of a patient in extremis, primary vessel ligation and early amputation in severe limb injury should be considered. This avoids the catastrophic consequences of reperfusion injury, and subsequent cardiac arrhythmia and organ failure, and can be considered a lifesaving procedure. Indeed, there are many instances of prolonged attempts at limb preservation leading to fatalities in cases with prolonged tissue hypoxia, extensive tissue damage and questionable viability, when early amputation may have been instrumental to survival. An initial attempt at limb salvage should be guided by close monitoring of tissue perfusion, patient physiology, and knowledge of the extent of remaining vasculature. It is not an easy decision to make, and consultation with another surgical colleague, anaesthetist, and the patient if possible may help with the decision making process [47]. Amputation sites should have consideration for later mobilisation and limb use [48], for example, long stump lengths where possible, and retention of joints if feasible for a below-hinge joint amputation, which provides greater mobility. Any surgeon responsible for performing amputations must be familiar with the mechanics of prosthetics in order to create stumps sympathetic to their application. Wounds should be left open for later review and delayed primary closure undertaken to ensure tissue coverage remains viable, clean and healthy.

19.5.6 Definitive Repair

Definitive repair of vessels, as opposed to ligation or shunting, is performed if the patient's physiology is amenable to a potentially lengthy restoration of vascular continuity. Primary closure with a fine monofilament suture can be achieved if there is no vessel wall loss. Sutures should be applied in a transverse fashion to avoid narrowing the lumen, which could lead to a risk of later ischaemic complications, or clot formation. Sutures should be applied 1 mm from the wound edge, and 1 mm apart in a continuous fashion. Patch repair may be required if there is vessel wall loss to avoid narrowing. Complete transection can be repaired with direct suture of vessel edges if healthy. The vessel should be dissected proximally and distally from surrounding tissues to ensure there is no tension within the repair, and ends should be spatulated to ensure laminar flow. In more extensive vessel loss, or in a contused, friable vessel likely to occlude due to widespread intimal disruption, bypass grafting is required. Vessel bypass procedures are best achieved using the patient's own vein, either reverse grafting (reverse the direction of the vein to avoid disruption to arterial flow from vein valves), or an *in situ* graft, in which the vein remains in the anatomical direction, but a valvulotome is used to remove any valves. Synthetic vascular prostheses are best avoided due to likely contamination of the wound with fragments, and stenting or shunting only used *in extremis*, and for temporary arterial repair. With any definitive repair, adequate exposure should be gained with a generous incision, and proximal and distal control must be achieved. Adequate heparinised saline (5–10 IU/ml saline[9]) flushing to prevent thrombus formation during the repair should be performed, as should proximal and distal trawl with a Fogarty™ catheter prior to final closure to remove any clot. Prior to the final suture being placed, removal of the distal clamp expels any air from the repair site. Once the repair of the vessel has been achieved, removal of the distal, lower pressure, clamp is preferable, followed by the proximal clamp.

19.5.7 Associated Venous and Neurological Injury

Associated large vein injuries should be considered for definitive repair or bypass grafting if injured. By improving venous return, arterial inflow is optimised. If repair proves difficult then consider ligation and manage limb swelling as it arises. Transected nerve edges if noted on initial debridement, or sought out if suspected clinically, may be repaired primarily but can be marked with a secure suture for later repair.

19.5.8 Antibiotics

Antibiotic use is likely to be beneficial in most patients with ballistic vascular injury, due to the strong likelihood of contamination of the wound site, and at least a single dose at operation in vascular repair or damage control is usually employed, although evidence for this is somewhat lacking [49]. Adequate tissue debridement and thorough lavage have been considered to be the 'best antibiotic' and can reduce the need for prolonged courses. The patient may of course have coexisting wounds that mandate antibiotic treatment.

19.5.9 Dressings and Drains

At initial operation, even in the majority of low energy transfer wounds, wounds are better left open to enable adequate tissue drainage and prevention of fluid accumulation which can be a nidus for later infection. As previously stated, any vascular structure must have adequate soft tissue coverage, and not be in direct contact with any dressing or drain material to prevent drying and erosion of the vessel. Topical negative pressure therapy has revolutionised the complex wound, and allows coverage and protection from contamination with a negative pressure seal, and drainage of fluid. Drains can be placed in primary closure of wounds, but these should be removed ideally within 48 h, as this foreign body can introduce bacteria and lead to wound infection, which has potentially dire consequences if a vascular structure is involved.

19.6 Decision Making in Vascular Injury

19.6.1 Damage Control or Definitive Repair?

Decision making in vascular depends on the number of affected casualties and capacity and skill of the team, and resources, as well as patient factors, and this is often as challenging as the operations themselves, and requires experience and practice. The algorithm for patient and wound considerations in decision making in arterial trauma is summarised in Fig. 19.5.

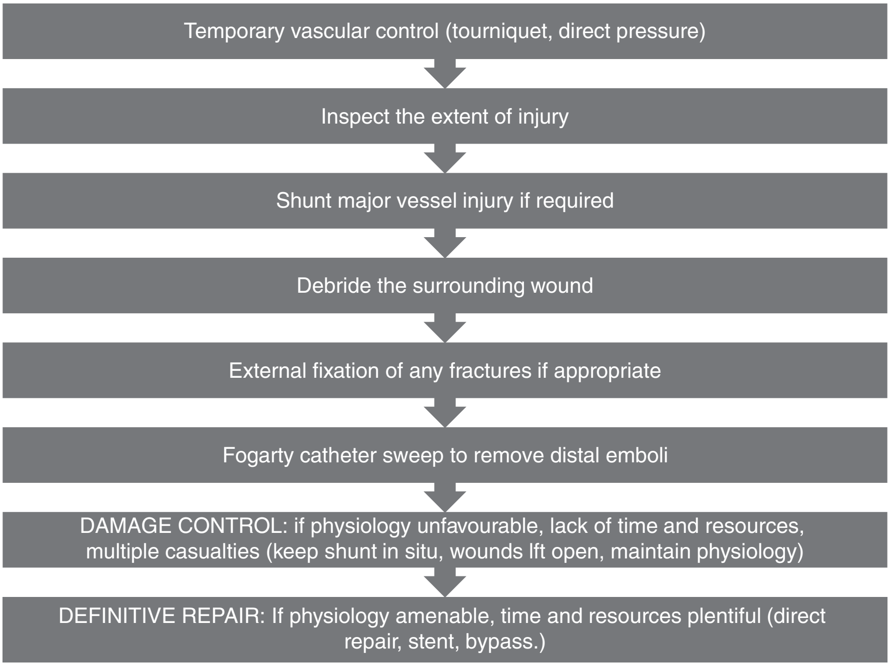


Fig. 19.5 Decision making process in vascular trauma

19.7 Regional Injury

There are specific pre-hospital and management considerations important to vascular control in various body regions.

19.7.1 Neck

Vascular injuries to the arteries and veins of the neck in ballistic trauma carry a mortality as high as 75% [50]. Such injuries are suspected when the typical ‘hard signs’ of vascular injury are encountered, in a history of blunt or penetrating trauma. Symptoms may include dyspnoea, hoarseness or stridor, drooling, haemoptysis, and pain when talking, swallowing or on tongue movement. Signs include distorted anatomical appearance, sucking wounds, haematoma (expanding or otherwise) and crepitus. A physical breach of the platysma heightens suspicions of vascular injury and is often quoted as a reason for surgical exploration [51]; this can lead to unnecessary surgical exploration although the gravity of a missed injury must be considered. The algorithm in Fig. 19.6 is helpful in defining an investigation and treatment pathway.

Due to the proximity of the airway and the risk of bleeding into a breached airway or an expanding haematoma causing later airway obstruction, early

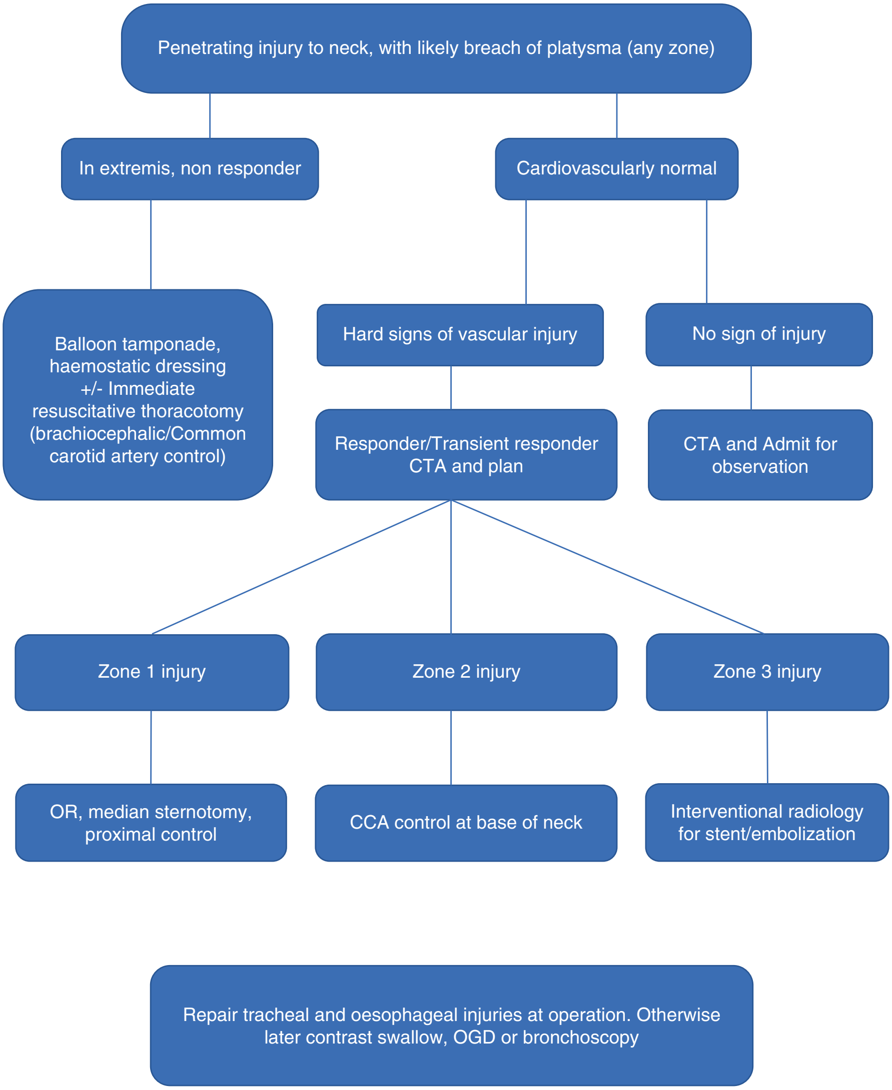


Fig. 19.6 Stepwise algorithm for the management of penetrating neck trauma

airway management using Rapid Sequence Induction (RSI) or a surgical airway should be considered [52], either as a response to airway compromise, or prophylactically, with the knowledge that later oedema and haematoma progression can occur. Airway control also permits advanced efforts at haemorrhage control. Haemorrhage control is treated using basic principles depending on the situation, with ligation, shunting, or definitive repair, with adjuncts such as topical haemostatic agents, pressure dressings and adequate wound closure, with

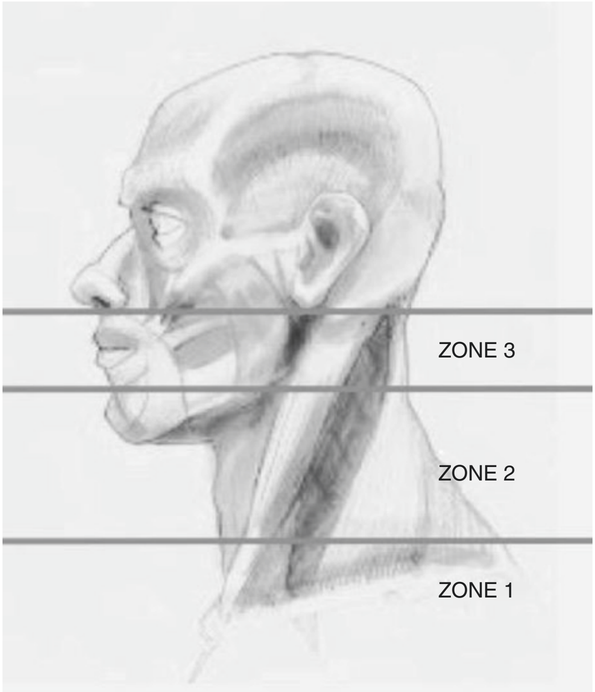


Fig. 19.7 Neck zones: Zone 3: base of skull to angle of mandible, Zone 2: angle of mandible to cricoid cartilage, Zone 1: cricoid cartilage to clavicle

closure of dead space to prevent fluid accumulation. Patients should be transferred from scene to hospital sitting up to reduce venous bleeding, and to aid breathing. For first aid measures in the pre-hospital setting, penetrating wounds can be packed with the balloons of Fogarty catheters or endotracheal tubes to provide local tamponade. The overlying wound can then be closed to increase the tamponade effect.

The anatomy of the neck is divided into three zones (Fig. 19.7) with anatomical landmarks dividing them. Each zone has specific considerations, should trauma be suspected. Injury at any location in the neck starts with the basic principles of airway control, assessment of breathing, and control of major haemorrhage.

19.7.1.1 Zone 1

Vascular injuries within zone 1 are challenging to access, and may require a median sternotomy for proximal control, incision anterior to sternocleidomastoid for distal control, and/or incision superior and/or inferior to the clavicle with removal of the clavicular head. Angiography with proximal control using interventional techniques is a preferred option in hospitals with the facilities, and as well as proximal control to enable subsequent operative intervention, can provide definitive treatment with covered stenting to arterial structures.

19.7.1.2 Zone 2

Injuries to zone 2 potentially have the most straightforward access points, although incisions for zone 1 and 3 injuries may be needed if proximal or distal control cannot be gained. An incision anterior to the border or sternocleidomastoid is used to access carotid and jugular vessels. A transverse ‘cervical collar’ incision can be used for proximal control, and extended to the contralateral side in the event of bilateral injuries, and subsequently be extended cranially to an incision anterior to the sternocleidomastoid for injuries to the carotid and jugular vessels.

19.7.1.3 Zone 3

Vascular injuries within zone 3 are also difficult to access, and mortality is high. Resection or dislocation of the mandible may be necessary for distal control. As with Zone 1 injuries, where possible, endovascular techniques are preferable.

It is important to be familiar with the anatomy of the structures within the neck, and injury to associated structures must be considered and addressed (Table 19.3).

19.7.1.4 Complications of Vascular Injury in the Neck

Complications of penetrating injury to the neck can also be life threatening, and it is important to acknowledge to avoid a later fatality after the challenge of surviving the initial insult. Rates of ischaemic stroke can be as high as 60% in arterial trauma within the neck [53]. Missed oesophageal injury can lead to later infective complications if not recognised and treated. Pseudoaneurysms in the neck have also been documented [54] in association with ballistic trauma. Arteriovenous fistulae are rare but manifest as high output cardiac failure, cardiac rhythm abnormalities and embolization [55]. Carotid-oesophageal fistula is also rare but recognised, and could have catastrophic haemorrhagic consequences [56].

Table 19.3 Zones of injury and injury to associated structures

Zone 1	Clavicle to cricoid cartilage	Subclavian vessels	Trachea
		Brachiocephalic veins	Oesophagus
		Common carotids	Lung apices
		Aortic arch	Cervical spine
		Jugular veins	Spinal cord
			Cervical nerve roots
Zone 2	Cricoid cartilage to angle of mandible	Carotid arteries	Pharynx
		Vertebral arteries	Larynx
		Jugular veins	Trachea
			Oesophagus
			Cervical spine
			Spinal cord
Zone 3	Angle of mandible to base of skull	Carotid arteries	Salivary and parotid glands
		Jugular veins	Oesophagus
			Trachea
			Spinal cord
			Spinal nerves

19.7.2 Chest

Penetrating injury to the major vessels within the thorax often proves fatal. Management of these patients is aimed at early airway control, large bore vascular access and timely on scene management and transfer to hospital; many patients with severe injuries do not survive the hospital transfer, particularly with prolonged transfer times, or delays in pre-hospital intervention [57]. In situations of impending circulatory collapse or cardiac arrest then resuscitative thoracotomy and immediate vascular control and vessel repair should occur. High energy penetrating myocardial wounds are often fatal but low energy wounds from shrapnel can be repaired and the pericardium opened and drained to prevent or to treat tamponade [58].

Catastrophic haemorrhage from pleural injuries that result in both blood losses into the pleural space and bleeding into bronchioles with subsequent VQ mismatch due to inadequate ventilation should be treated as a matter of urgency. These manifest as a 'white out' on initial chest radiograph or the drainage of a large volume of blood on performing thoracostomy as a precursor to intercostal drain placement [59]. Patients who drain over 1 l initially and whose physiological state is poor should undergo early thoracotomy and repair. Damage control manoeuvres for pleural injury and bleeding include lung twist and hilar clamping to gain vascular control followed by partial or total lobectomy or pneumonectomy. Hilar vessel injury results in catastrophic haemorrhage and repair is difficult [60].

Injuries to the aortic root and branch vessels are associated with significant bleeding. Proximal control is vital. Side clamps permit repair of vessel wall injuries while maintaining a degree of distal flow. Clamshell thoracotomy is quick but median sternotomy may be better at allowing access to the arch vessels [61]. The clamshell can be converted to a median sternotomy in extreme circumstances.

Penetrating injuries to the descending thoracic aorta are often fatal and patients often die before presentation. In the field, proximal vascular control can be attained by digital pressure or vessel clamping, and attempts to re-start the heart to should be carried out by intravascular filling and internal cardiac massage [62]. The effects of later re-perfusion may prove catastrophic and cardiac bypass and extracorporeal membrane oxygenation (ECMO) should be considered [63].

19.7.3 Abdomen

Penetrating vascular injuries to the abdomen are considered non-compressible and so if bleeding is left unchecked the mortality is high [64]. Concomitant solid organ and hollow organ injuries should always be considered and time to surgical repair is vital. There are few effective prehospital interventions and scene times should be short [65]. In traumatic cardiac arrest and when a physician led response is available, resuscitative thoracotomy and proximal aortic control in the thorax should be considered in an effort to restart the heart and provide after load to optimise myocardial and cerebral blood flow while restoring the circulating volume and expediting transfer to an appropriately forewarned medical facility.

A number of adjuncts are being developed and used with some degree of success, namely the abdominal aortic tourniquet [66], abdominal injectable foam [67] and resuscitative endovascular balloon occlusion of the aorta (REBOA) proximal to the vessel injury [68].

19.7.3.1 Technical Techniques at Open Surgery for Abdominal Trauma

At laparotomy, proximal vascular control remains the initial manoeuvre. Supra coeliac aortic control should be sought as a priority to both gain control and can be used to provide cardiac filling by increasing afterload. The visceral vessels are easily to hand and can be repaired or ligated. The aorta and its branches and the inferior vena cava and its tributaries reside within the retroperitoneum and can be conveniently divided into zones (midline supra mesocolic, midline inframesocolic, lateral perinephric and pelvic). In penetrating trauma, only the lateral perinephric region can be considered for selective conservative management. All the other injury patterns should be explored with initial proximal vascular control either at the supra coeliac aorta or infra renal aorta or at the bifurcation respectively. It is important to also consider that there may be a degree of back bleeding, therefore distal vessel control should be sought as well. Medial visceral rotation (Kocherisation, Cattel-Braasch manoeuvre and the Mattox manoeuvre) are the manoeuvres to permit access to the retroperitoneal large vessels. Injuries to the coeliac artery, superior mesenteric artery and inferior mesenteric artery are in essence side holes in the aorta. A number of techniques exist to repair them, but ligation remains an option but runs the risk of gut ischaemia and infarction. Expanding haematomas in the perinephric regions should be explored. Hilar injuries are again to be considered a hole in the aorta. Coming at the aorta and hilum from lateral to medial, while dissecting the kidney from within gerotas' fascia is the best option to prevent excessive hilar blood loss during dissection. Nephrectomy after hilar clamp and subsequent proximal renal artery suture ligation is the simplest option.

Inferior vena caval injuries can be repaired primarily. As the vessel is thin walled clamping is to be avoided for fear of tearing the vessel. Direct pressure with right angled retractors or 'swab on a stick' provides a bloodless field in which to operate. Injuries to the back wall are troublesome as the vessel cannot be mobilised to permit posterior access. In these instances, the anterior wall may be opened or injury extended to permit repair. A surgical knot can be left on the inside and the anterior wall repaired with a continuous suture. Topical haemostatic agents (Veriset™) are available and can be placed over the repair or used as a primary haemostatic patch. In extremis, the infrarenal IVC can be ligated and lower body and limb swelling treated expectantly. Lower limb fasciotomy should be considered.

Retro hepatic IVC injuries are fraught with danger and if possible should be left alone and packed, as once the liver is mobilised bleeding can quickly become uncontrollable and the patient will quickly exsanguinate.

19.7.4 Resuscitative Endovascular Balloon Occlusion of the Aorta (REBOA)

The use of balloon occlusion devices to gain proximal vascular control is not new. There are early reports of its use during the Korean war [69] and the inflation of an occlusive balloon is a familiar tool to control arterial bleeding during endovascular procedures.

Pelvic fracture secondary to blunt trauma or blast injury can result in significant arterial and venous bleeding. REBOA is now being considered to gain proximal vascular control and therefore reduce arterial bleeding, promote clot formation and to support the circulation during the resuscitative phase of care [68, 70]. It also has a use in gaining proximal vascular control for junctional bleeding in the contralateral limb vessels.

Cannulation of the common femoral artery (often assisted by ultrasound guidance) is followed by a Seldinger™ technique to pass a wire into the aorta, followed by sheath and then balloon over wire (Fig. 19.8).

The aorta has been described in terms of zones that guide placement of the inflated balloon (Zone 1 the descending thoracic aorta, Zone 2 the visceral segment and Zone 3 the infra renal aorta to the bifurcation). There are now reports of its successful use in the pre hospital arena [71]. After balloon inflation, the time to definitive haemorrhagic and vascular arterial control is vital. 'Below balloon' vascular imaging (CT angiography) is difficult due to the presence of the occlusive balloon. The patient is then either taken to the operating theatre for surgical control of the vessel and balloon deflation and removal of sheath or taken to the interventional radiology suite for endovascular control of bleeding. Clot formation along the wire, proximal to the balloon and within the sheath should be considered and presence of clot should be actively sought and excluded either by imaging or operative intervention. Robust clinical outcome data for this intervention are needed.

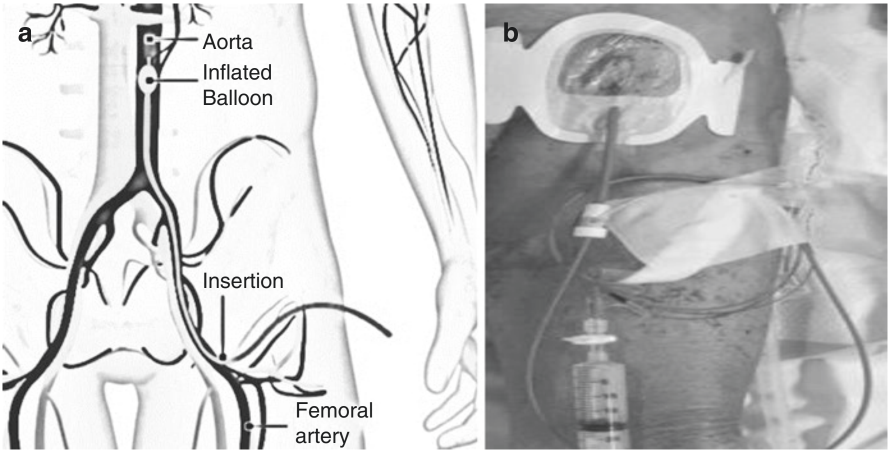


Fig. 19.8 The REBOA catheter (**a**) and the device in situ (**b**)

19.7.5 Pelvis and Groin

Haemorrhage within the pelvic region and groin is technically challenging, as it may not be amenable to initial tourniquet placement or direct pressure. Pelvic binders are helpful in the pre-hospital setting to maintain pelvic volume and enable tamponade within the retroperitoneum, and research into the efficacy of abdominal tourniquets continues [72]. A laparotomy may be required for proximal control via aortic clamping, or an oblique incision from the anterior superior iliac spine to the pubic tubercle to access the iliac vessels. Pelvic and groin arterial trauma is repaired using the usual techniques of direct suture, shunting, graft placement, or ligation in extremis, with named venous injury repaired directly or ligated, and generalised venous injury either treated conservatively with active physiological monitoring, or with haemodynamic compromise, laparotomy and pelvic packing. Interventional radiology procedures are very useful adjuncts in both assessment with angiography, and subsequent embolization in isolated arterial injury. However, in ballistic trauma, injury to other structures must be considered, and a laparotomy may be required.

19.7.6 Management of Extremity Trauma

Vascular injury to the extremity is managed with consideration to the entire wound, and temporary or definitive vascular repair decisions must be taken, skeletal fixation performed if applicable, wound debridement, and coverage to any vascular repair must be managed. The following algorithms may be helpful in the sequence of diagnosis and management in extremity trauma (Figs. 19.9 and 19.10).

19.8 Endovascular Management

Endovascular management of vascular trauma is possible in well-equipped centres, with interventional suites and interventional radiology specialists around the clock to be able to respond rapidly to a patient rapidly losing blood volume. The past 20 years have seen huge advances in endovascular techniques for managing vascular trauma. As a relatively recent initiative, there is somewhat less evidence in the literature than for traditional open repairs. However, despite this, there are initial studies stating a clear survival benefit in those receiving endovascular treatment in the subclavian, carotid and thoracic aortic regions [73], and experience is being gained in peripheral arterial trauma with good results [74]. Certainly, endovascular techniques offer a solution in areas difficult to access surgically, such as zone 1 and 3 cervical injuries, descending thoracic vessels, and pelvic bleeding. Even in those areas within the comfort of the vascular surgeon, an endovascular approach offers a

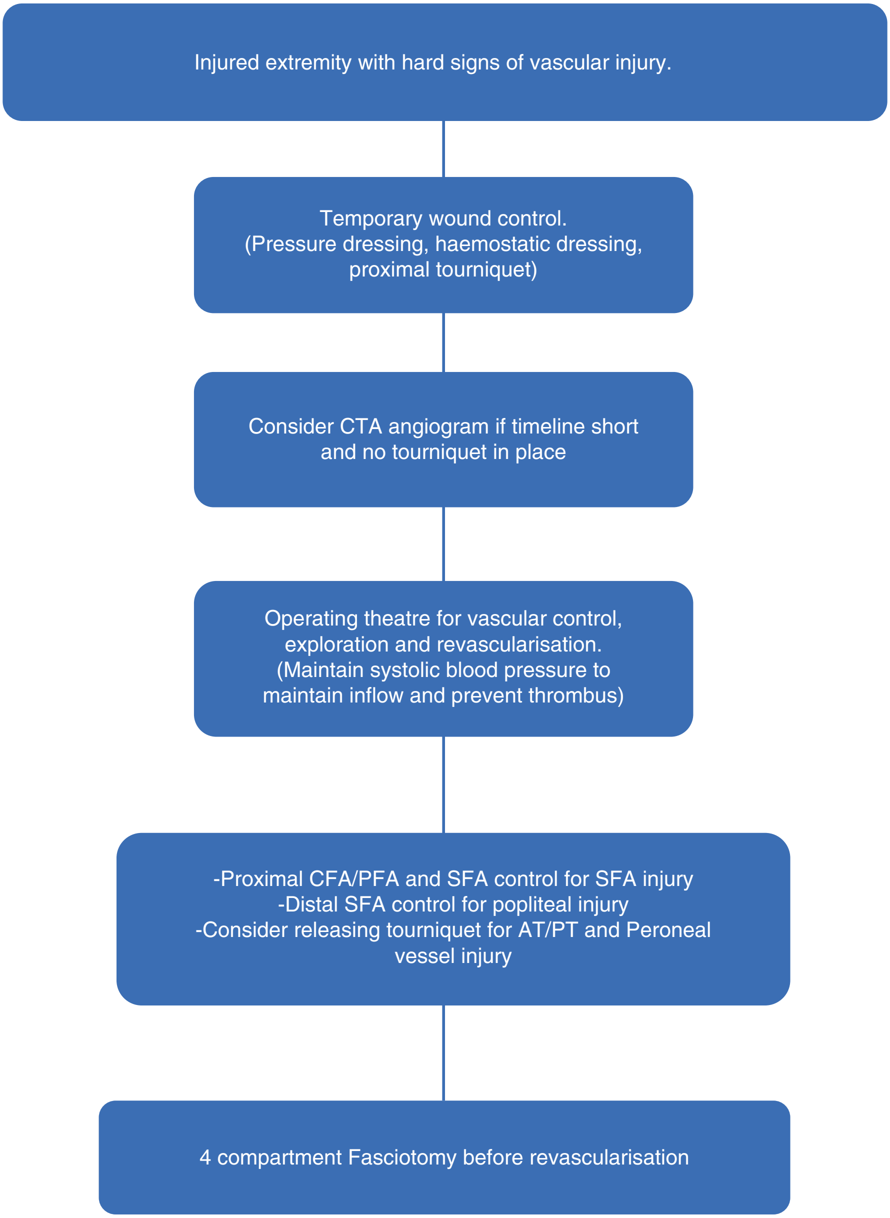


Fig. 19.9 Stepwise algorithm for the management of extremity trauma: diagnosis and initial management

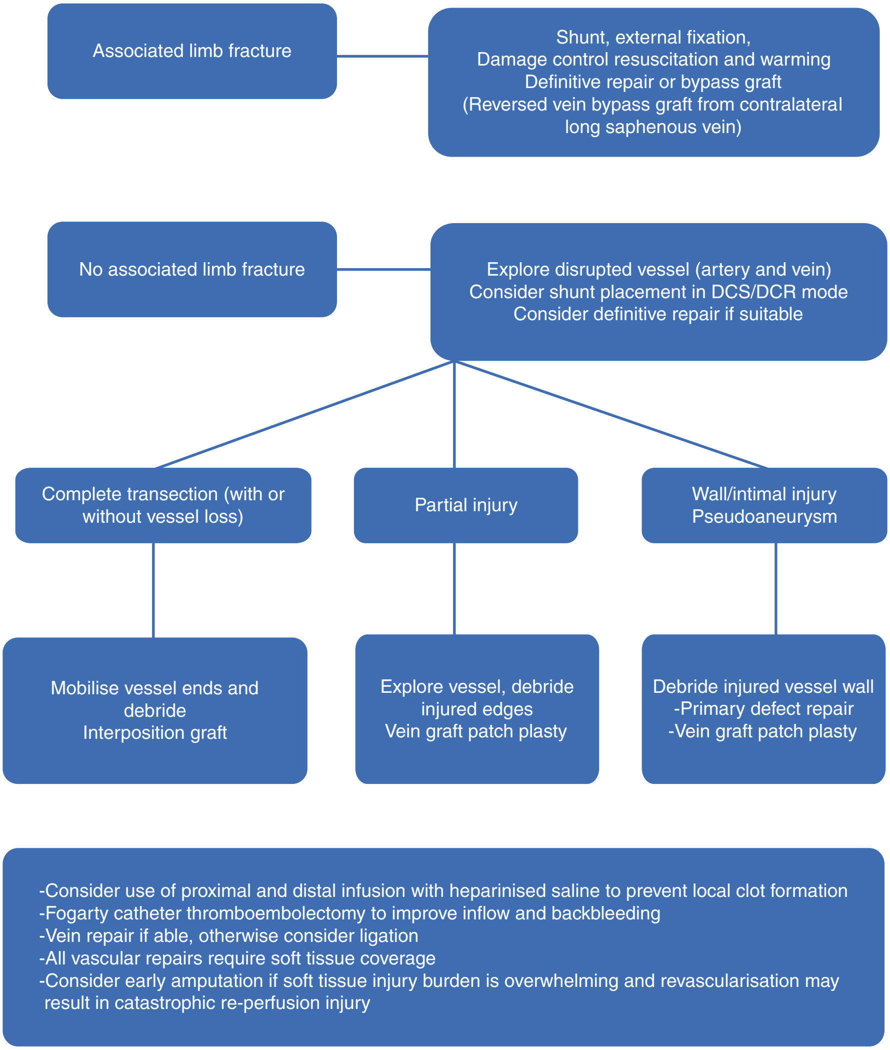


Fig. 19.10 Stepwise algorithm for the management of extremity trauma: definitive treatment pathways

reduction in overall injury burden imparted by large incisions. This can include higher levels of post-operative pain and reduction in mobility post operatively with subsequent ramifications of immobility; increased risk of venous thrombosis, respiratory tract infections, and slower rehabilitation [75]. Introduction of endovascular techniques into the trauma team paradigm is key to advancement of the management of vascular trauma. Despite this, austere settings may not be able to provide the supporting infrastructure, therefore open surgical skills will always be essential to the trauma surgeon.

19.9 Complications of Vascular Injury

19.9.1 Early Complications

19.9.1.1 Compartment Syndrome and Requirement for Fasciotomy

Compartment syndrome can occur in any body space or cavity, even after seemingly insignificant wounds. Compartment syndrome is a vicious cycle in tissue expands due to haematoma and oedema (secondary to capillary leak). This leads to increased compartmental pressure to the lack of compliance of the investing fascia. In turn, this reduces capillary perfusion (even though arterial pulsation may still be felt). This generates a further ischaemic insult to the capillary endothelium, enhancing the leakage. Compartment syndrome must also be a consideration on revascularisation of a limb, as the subsequent reperfusion can cause resulting tissue oedema, and this phenomenon must be considered proactively to prevent preventable muscle death.

Fasciotomy should ideally be performed as soon as possible, and prior to vascular repair, as this is associated with higher levels of viable tissue and limb preservation [76].

Symptoms of compartment syndrome are as follows:

Key Point: Symptoms and signs of compartment syndrome
Pain out of proportion to the clinical findings
Pain on passive stretch of muscles
Pain on palpation of affected muscles
Pain relatively unresponsive to analgesia

Consideration of fasciotomy closure should be considered after 48 h, and this is either by primary closure of the wound edges, or, if the wound edges do not oppose easily, split thickness skin grafting. In anticipation of a later primary closure, a running suture can be applied at the time of factiotomy, and then pulled tight, even on the ward, although a final relook to consider tissue viability is often required in theatre, and the wound closed in this environment.

19.9.2 Lower Limb Fasciotomy

There are four compartments in the calf that require fascial incisions to enable full decompression: the anterior, lateral, superficial and deep posterior compartments. Two longitudinal incisions are made 2 cm medial and 2 cm, lateral to the tibial plateau. It is an error to make incisions too short; they must be made the entire length of the fascia to decompress the entire compartment (Figs. 19.11 and 19.12).

There are three compartments in the thigh: the anterior, posterior and adductor. Two incisions are made, one from the greater trochanter to the lateral femoral condyle, to divide the fascia lata, with dissection posteriorly to enter the posterior compartment. The standard incision for access of the femoral vessels is used and extended to access the adductor compartment.

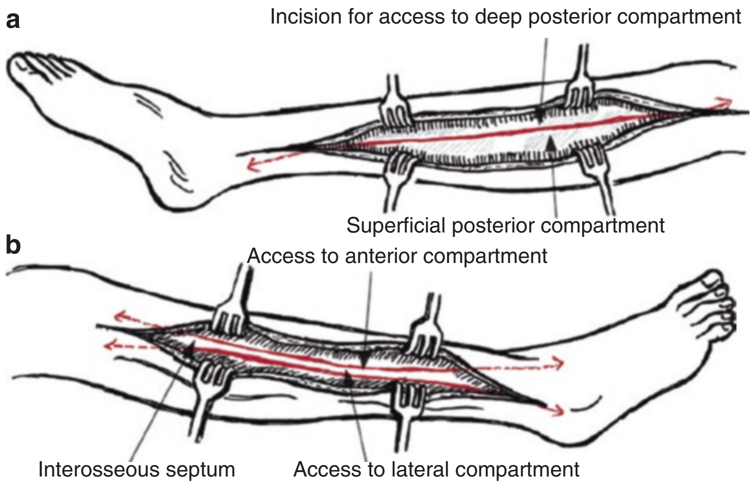


Fig. 19.11 Access to superficial and deep posterior compartments (**a**) and anterior and lateral compartments (**b**) of the leg in calf fasciotomy. Reproduced with kind permission from N Papas, ICRC [12]

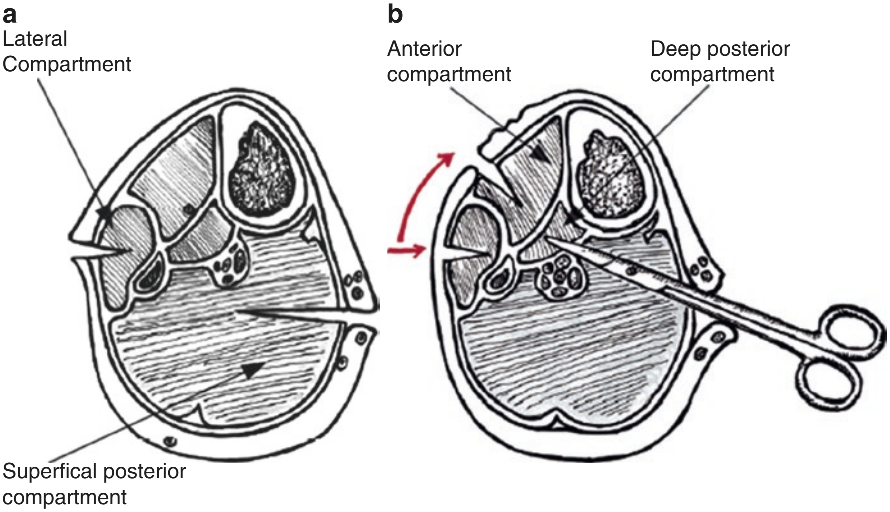


Fig. 19.12 Cross sectional views of calf fasciotomy (**a**) lateral and superficial posterior compartments (**b**) anterior and deep posterior compartments. Reproduced with kind permission from N Papas, ICRC [12]

19.9.3 Fasciotomy of the Foot

The nine compartments of the foot are listed below (Table 19.4):

These compartments are decompressed using three dorsal incisions in the interosseous compartments (Fig. 19.13).

Table 19.4 The nine compartments of the foot

Compartments of the foot			
Compartments	Muscles	Vessels	Nerves
Medial	Flexor hallucis brevis Abductor hallucis		
Lateral	Abductor digiti quinti Flexor digiti minimi		
Superficial	Flexor digitorum brevis Lumbricals Flexor digitorum longus tendons		Medial plantar nerve (?)
Interosseus (x 4)	Interossei		
Adductor	Adductor		
Calcaneal	Quadratus plantae	Posterior tibial artery	Posterior tibial nerve
		Posterior tibial vein	
		Lateral plantar artery	Lateral plantar nerve
		Lateral plantar vein	
			Medial plantar nerve (?)

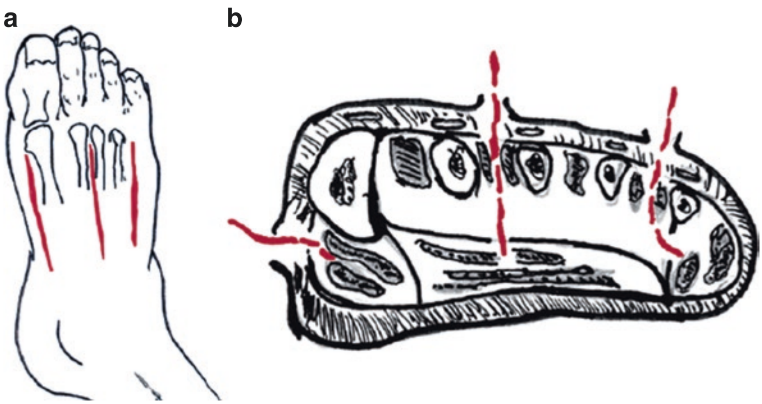


Fig. 19.13 Foot fasciotomy incisions (**a**) and cross sectional view (**b**). Reproduced with kind permission from N Papas, ICRC [12]

19.9.4 Upper Limb

Upper limb fasciotomy is performed as shown below, with important consideration to both dorsal and volar decompression. The compartment containing the brachio-radialis, often called the ‘mobile wad’ compartment is also considered a separate compartment, and is decompressed using the same incision as the flexor compartment. The dorsal compartment is decompressed with a midline incision from the elbow to wrist, to include incisions between second and third, and fourth and fifth metacarpal bones. The volar aspect is decompressed using a ‘s’ shaped incision, from the lateral to medial elbow crease, extending down to medial anterior forearm, terminating in the skin crease of the thenar eminence (Fig. 19.14).

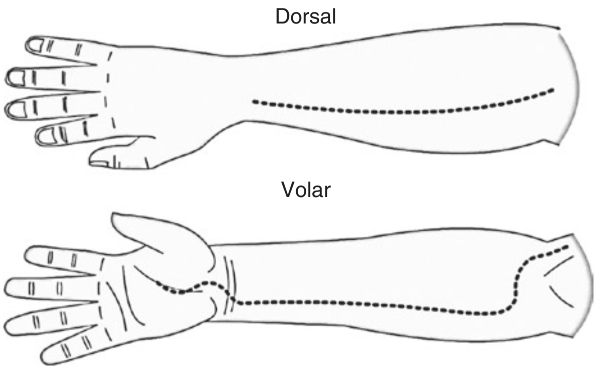


Fig. 19.14 Dorsal and volar compartment fasciotomy of the arm. Reproduced with kind permission from N Papas, ICRC [12]

19.9.5 Dressings After Fasciotomy

It is important that dressing for fasciotomy is non-restrictive to allow muscle expansion without redevelopment of pressure, and non-adherent to allow easy removal. Vaseline impregnated mesh is an excellent dressing, as it moistens the area, is easily removed, and the mesh means that it is non-restrictive. Absorbent gauze should then be placed, to absorb fluid, followed by a crepe bandage. Topical negative pressure can also be used on fasciotomy wounds if available.

19.9.6 Reperfusion Injury

As stated previously, consideration of the sequelae of revascularisation, particularly after a prolonged period of tissue ischaemia has consequences locally, and systemically. The consideration of the development of compartment syndrome and early fasciotomies has been discussed. However, the systemic consequences of reperfusion must, again, be anticipated and expected. Ischaemia causes a build-up of carbon dioxide, potassium and products of protein break-down, as well as oxygen free-radicals and white blood cell infiltration. When released into the systemic circulation these can cause disastrous consequences, with widespread vasodilation, capillary permeability, and the potential for cardiac arrhythmias and death [77]. The removal of clamps after restoration of vascular continuity must be performed in conjunction with your anaesthetic colleague. Under no circumstances should a clamp be removed without their prior knowledge, as close monitoring will subsequently occur, noting changes in electrolytes and physiology, and a clamp may need to be reapplied, or removed in stages to enable gradual metabolism of by-products of ischemia.

19.9.7 Late Complications of Vascular Injury

Those sustaining vascular injury secondary to a ballistic event, even in an uncomplicated repair, must be monitored for later complications. Infection of any graft placement may manifest as raising inflammatory markers, signs of systemic infection, sepsis or hemorrhage at the anastomotic site. These can be treated with antibiotics, which may be required long term, or may necessitate removal/replacement of the graft. Failure of vascular repair may necessitate a re-do procedure, or requirement for later amputation depending on the patient's physiology, or the viability of the affected limb. Later claudication can manifest in ligation of extremity arteries and is managed as per chronic limb ischaemia, and late amputations can prove necessary. Traumatic arteriovenous fistulae secondary to a traumatic mechanism are usually repaired surgically, as are traumatic pseudoaneurysms [78].

19.10 Long Term Management of Vascular Injury

As with all patients undergoing repair of a vessel they should be followed up in a suitable trauma or vascular clinic. Later symptoms of limb ischaemia such as claudication may manifest themselves [43]. A number of patients will collateralise and so optimise their own distal flow. Smoking cessation is important and they may benefit from antiplatelet therapy.

19.11 Basic Vascular Toolkit

A basic surgical set can be supplemented with a few key pieces to make vascular injury a less daunting task, particularly to those for whom vascular surgery is not their primary specialty. Vascular sloops, bulldog clamps of various sizes, non-toothed forceps, Satinsky clamps are all useful adjuncts. Vascular sutures are fine, non-absorbable monofilaments. Fogarty and urinary catheters are useful, and heparin, and contract media can be useful if mobile X-ray facilities are available. Improvisation of some instruments may be necessary. Non crushing intestinal clamps can be used as a non-traumatic option for vessels. It is important for the surgeon to be involved in the selection of equipment, if travelling to a remote area, where replenishment and instrument acquisition in the community is not possible. Sterilisation facilities must be available if replenishment of instruments cannot be achieved.

19.12 Summary

It is key to recognise and vascular injury as soon after point of wounding as possible, moving medical care into the pre-hospital environment as much as logistically possible in civilian and military environments. It is important that the general trauma clinician is appropriately trained in damage control techniques, and there is a facility to transfer or take advice from specialists in vascular trauma. With adequate initial management, definitive care, ongoing medical management and rehabilitation if required, vascular injury is a potentially preventable cause of death in ballistic trauma.

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Ballistic Genitourinary Trauma

20

Angus Campbell and Davendra Sharma

Key Points

1. Scrotal and testicular trauma forms a diverse group of injuries usually affecting the young population. Evaluation should include history and careful examination.
2. Ultrasonography is the diagnostic investigation of choice in blunt trauma.
3. Penetrating scrotal injury, presence of a large or expanding haematocele or suspicion of testicular rupture should always prompt immediate surgical exploration, debridement and repair.
4. Orchidectomy should only be considered if reconstruction cannot be achieved.
5. Holistic management approach considering the potential for infection, fertility preservation, hypogonadism and psychological effects.

20.1 Introduction

Injury to the GU tract occurs in 10% of cases of trauma [1]. Penetrating injury accounts for about 16% of all GU trauma [2, 3]. GU tract injury is relatively rare due to the protected position of the organs: the kidneys in the retroperitoneum, the bladder deep within the pelvis, and the testes mobile in the perineum.

Severe genital blast injury came to the forefront in the conflict in Afghanistan due to the preferential use of ground-level improvised explosive devices (IED).

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The result was the devastating 'signature injury' of that conflict, consisting of lower limb amputation, pelvic fracture and genital injury [4]. These life-changing injuries have huge psychosocial consequences [5]. These injuries are unlikely to be replicated in civilian terrorist attacks due to the infrequent use of ground level IEDs, which have a relatively low 'strike rate'. However, the lessons learnt from the recent military conflicts are significant and of value when preparing for a civilian incident.

20.1.1 Setting the Scene

There are five general factors to consider:

1. The scale of the event—mass casualty scenario
2. The number of organs affected—polytrauma
3. The capabilities of the receiving institution
4. The genitourinary organ affected
5. Patterns and mechanisms of injury

Genitourinary injuries are rarely life threatening. The exception is the traumatised and actively bleeding kidney, which needs urgent attention. Most GU injuries are of a lower priority and do not need immediate attention. However, prompt recognition and management is crucial to avoiding longer-term morbidity, aiding functional recovery and optimising quality of life. In a mass casualty event or with severe polytrauma, the actively bleeding kidney will be the GU injury of high priority.

The capability of the receiving institution is critical to achieving the best possible outcomes. Major trauma is managed in networks in many countries but choice may be limited depending on the location of the incident. Central to this is the well-prepared trauma team and ready access to cross-sectional imaging (CT) and interventional radiology.

20.1.2 Patterns and Mechanism of Injury

The kidney has been the GU organ most commonly affected by trauma. However with the use of effective torso protection, particularly in the military, the proportion of external genital injury has increased. Bladder and urethral injury are most commonly associated with pelvic fractures. Ureteric injuries are rare.

In the blast setting, the injuries may be due to penetrating, blunt or a combination of mechanisms. Blunt trauma replicates typical civilian injuries but may be of a higher grade. Penetrating trauma due to fragmentation is likely to be of higher severity than low energy civilian injuries such as knife and handgun assaults. Cross sectional imaging is particularly effective at picking up fragmentation injury.

Bladder injury is likely to result in haematuria (95% of cases). A higher index of suspicion is required for ureteric injury in the presence of fragment injuries to the abdomen.

20.1.3 Individual Organ Injury

There are three principles when considering individual organ injury [6]:

1. Haemorrhage control.
2. Managing contamination—necrotic tissue and urinary extravasation.
3. Organ preservation.

20.2 Renal Injury

The majority of renal injuries are managed non-operatively. The tamponading effect of the retroperitoneum, the ability of the kidneys to heal, and excellent cross sectional imaging by CT have allowed successful conservative management. This includes penetrating trauma with the concept of "selective conservatism" introduced in the 1960s, later validated by several series [7–12] (Fig. 20.1).

20.2.1 Diagnosis and Staging

The diagnosis of renal injury is now made with contrast CT scanning, ideally with a delayed phase (10 min) to identify urinary extravasation [13–16]. The patient is likely to have haematuria, flank bruising and pain. Marking the entry and/or exit wounds with improvised radio-opaque markers (e.g. taping a paperclip over the

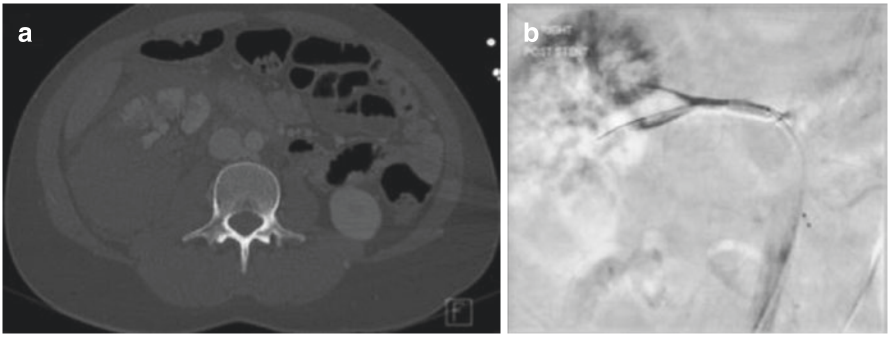


Fig. 20.1 (**a**) Axial CT showing retroperitoneal tamponade. (**b**) Fluroscopy during right segmental renal artery embolization (Images: Mr. D Sharma)

wound) is described and will assist the radiologist in defining the wound track [17]. The value of the one-shot intraoperative IVU remains questionable given the poor images that often result. Trauma surgeons have moved towards palpation of the contralateral kidney as a more reliable assessment of its normality [18].

In routine practice Grade 1–4 injuries are managed non-operatively [9, 19–21]. Grade five injuries usually require intervention although this may be initially non-operative with angioembolisation or arterial stenting (Table 20.1) (Fig. 20.2).

Table 20.1 Kidney organ injury scoring system

Grade[a]	Type of injury	Injury description
I	Contusion	Microscopic or gross hematuria, urological studies normal
II	Laceration	<1 cm parenchymal depth of renal cortex without urinary extravasation
III	Laceration	>1 cm depth of renal cortex, without collecting system rupture or urinary extravasation
IV	Laceration	Parenchymal laceration extending through the renal cortex, medulla, and collecting system
V	Laceration	Completely shattered kidney

Source: Moore et al. [22]

[a]Advance one grade for bilateral injuries up to grade III

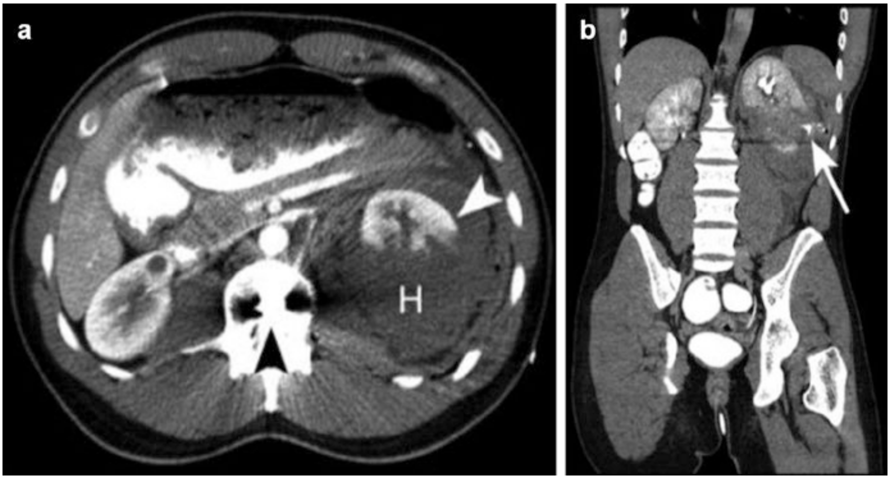


Fig. 20.2 Penetrating trauma right Grade IV renal laceration with collecting system injury [14]. (**a**) Axial postcontrast CT during the nephrographic phase in a patient presenting after gunshot wound to the left flank. The image shows a deep laceration through the inferior aspect of the left kidney (*arrowhead*), large perinephric hematoma (H), and a bullet fragment lodged in the vertebral body. (b) Coronal CT during the excretory phase demonstrates extravasation of contrast (*arrow*) from a tear in the collecting system

20.2.2 Management

20.2.2.1 Persistent Haemorrhage

Active bleeding requiring intervention is now managed with angioembolization (AE) [16, 23]. Primary embolization failure requiring re-intervention is common; up to 88% in some series and as low as 12% (Fig. 20.3). Re-intervention with AE had success rates between 97 and 50% [23, 24]. In the mass casualty, polytrauma setting, this may not be appropriate with a rapid damage control nephrectomy being a life-saving manoeuvre.

Absolute indications for exploration of the kidney are: [26–28]

1. Hemodynamic instability due to renal injury
2. Expanding perinephric hematoma (seen at laparotomy)
3. Incomplete radiological assessment of a renal injury.

20.2.2.2 Collecting System Injury

Urinary extravasation from the kidney **does not** require intervention in most instances [29–31]. Persistent urinary leakage may require a ureteric stent or percutaneous drain. A disrupted pelvi-ureteric junction will require a planned surgical repair.

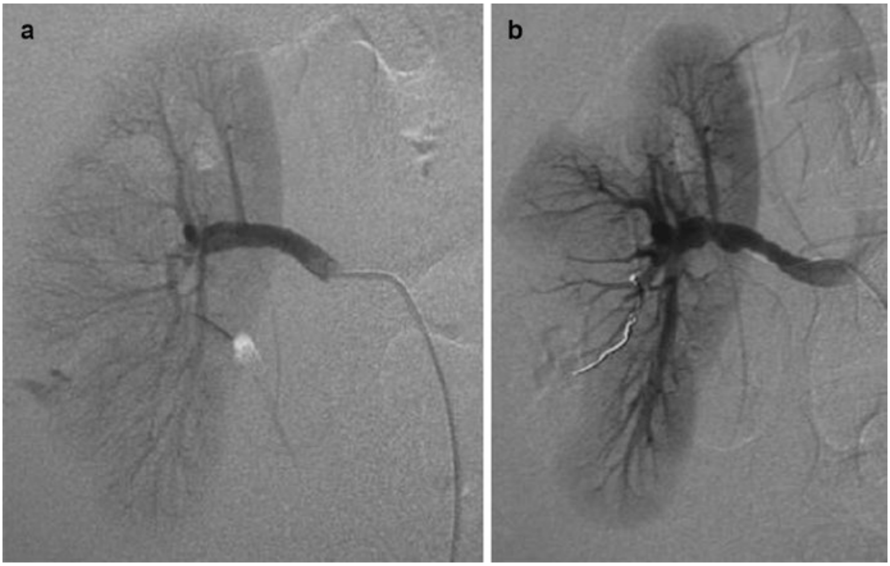


Fig. 20.3 Angioembolisation of renal laceration: [25]. (**a**) Arteriography demonstrating active bleeding. (**b**) Coil embolization used to control bleeding. Note presence of coil and large, triangular area of infarct

20.2.2.3 Renal Pedicle Injury

The management of renal pedicle injuries is contentious. The narrow interval for renal warm ischaemic time of less than 60 min limits opportunities and significantly affects outcomes. In a stable patient in the mass casualty setting, injuries such as arterial intimal flaps or contained venous injury are best managed conservatively. For penetrating Grade IV renal vascular injuries, organ loss is highly likely. Pooled data for all grade IV and V injuries suggest a 15–20% early nephrectomy rate with long-term functional outcomes being difficult to establish [32, 33]. Endovascular intervention, particularly angioplasty with stent re-vascularisation, is a minimally invasive option increasing in popularity but evidence is limited to a few case reports [34] (Figs. 20.4 and 20.5). Pedicle avulsion or major segmental arterial injury warrants operative intervention, usually nephrectomy.

20.2.3 Penetrating Trauma

The traditional view that penetrating injury needs to be managed operatively has changed with high quality cross sectional imaging and increased experience with non-operative management [9, 10, 12]. The entry and exit wounds are critical to the assessment. Injury tracts passing posterior to the anterior axillary line may allow conservative management in an imaged and stable patient [26, 35] (Table 20.2).

Fig. 20.4 Selective angiography of the left renal artery showing occlusion 1.5 cm from the origin (*black arrow*) [30]

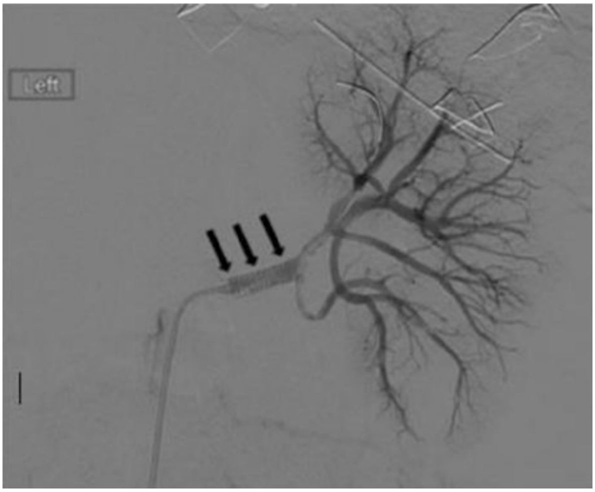


Fig. 20.5 Selective angiography of the left renal artery after intervention showing stent (*black arrows*) and reconstitution of the left renal perfusion [30]

Table 20.2 In hospital conservative management of renal trauma—a pragmatic approach

	Repeat investigations	Early mobilisation	DVT prophylaxsis	Antibiotics
Grade 1–2	FBC × 1	Yes	Yes	No
Grade 3	FBC × 2	No	Yes	No
Grade 4	FBC, clinical exam daily	No	No	?
Grade 5	FBC, clinical exam twice daily, repeat CT 48 h	No	No	Yes
Penetrating injury	FBC, clinical exam twice daily, repeat CT 48 h	No	No	Yes

Table derived from recommendations by Hayne et al. 2017 [36]

20.2.4 Operative Management of Renal Trauma

There are four scenarios

- *The unstable patient with renal haemorrhage*
  Rapid or "scoop" nephrectomy is required. Midline abdominal laparotomy approach is standard. Swiftly incise the peritoneal surface lateral to the injured kidney, reflect the colon and enter Gerota's fascia. The plane behind the kidney is developed with the surgeon's hand and the kidney is reflected anteriorly and medially to allow the renal pedicle to be controlled with digital pressure and vascular clamps.
- *Renal preservation—Proximal vascular control*
  This much discussed but rarely used manoeuvre is recommended if renal preservation is to be attempted i.e. the rare situation where there are bilateral renal injuries or an injured solitary kidney.

The renal pedicle is accessed anteriorly by performing medial visceral rotation and exposing the retroperitoneum. A vertical incision is made in the peritoneum over the aorta and extended superiorly to the ligament of Treitz. A large retroperitoneal hematoma may obscure these landmarks but the inferior mesenteric vein is usually visible, in which case the incision is made medial to that vein. The anterior surface of the aorta is identified and dissection proceeds superiorly to identify the left renal vein. The vessels ipsilateral to the injured kidney can then be dissected out posteriorly. Gerota's fascia can then be opened lateral to the kidney.

- *Renorraphy*
  Renorrhaphy is a time consuming option and generally not recommended in the polytrauma patient. Bleeding vessels in the renal parenchyma can be ligated with suture ligatures. Injuries in the collecting system should be repaired with continuous fine absorbable suture. Omental or peritoneal flaps can be mobilized to cover extensive defects or to separate the injury from an associated visceral injury. Partial nephrectomy can be used in cases where the pole of the kidney is injured.
- *Renal vascular injury*
  Renal vascular injuries are challenging due to warm ischemic time constraints. Direct vessel repair can successfully be performed. Arterial reconstruction with prosthetic grafting is possible in higher-grade injury but outcomes are generally poor. Interventional radiological stenting as an early functional salvage maneuver is increasingly popular and significantly less morbid [15, 23, 37, 38].

20.2.5 Complications

Complications of renal trauma include re-bleeding, infection with abscess formation, persistent urinary leak, collecting system obstruction and partial or total organ loss. In higher grade and penetrating injury, repeat cross sectional imaging is recommended after 24–48 h [26].

Key Points
• 3-phase CT is the imaging modality of choice to assess the injured kidney
• The majority of renal injuries are managed non-operatively.
• Active bleeding can be managed with angioembolization.
• Absolute indications for renal exploration are hemodynamic instability, expanding perinephric hematoma, and incomplete radiological assessment of a renal injury.

20.3 Ureteral Injuries

Ureteral injuries from non-iatrogenic trauma are rare, comprising about 1% of all genito-urinary injuries and about 2–4% of all gunshot wounds to the abdomen [39]. Direct injury is not essential as the cavitation and fragmentation effect of high velocity fragments may cause significant injury, including disruption and devascularisation.

Table 20.3 Ureteric organ injury scoring system

Grade	Type of injury	Injury description
I	Haematoma	Contusion or hematoma without devascularization
II	Laceration	<50% transection
III	Laceration	>50% transection
IV	Laceration	Complete transection with 2 cm devascularization.
V	Laceration	Complete transection with >2 cm devascularization

Source: Moore et al. [43]. Advance one grade for multiple injuries

20.3.1 Clinical Findings

There are no reliable clinical signs or investigations to diagnose ureteric injury in the acute setting. The injury is generally unrecognized at presentation. The late signs of flank pain, fever, and fistula formation from urinary leakage prompt later investigation. Delay in diagnosis occurs in up to 57% of cases and leads to urinoma, infection, urinary sepsis, and prolonged hospital stays [39–42]. A high index of suspicion is necessary in all patients with penetrating abdominal injury i.e. a gunshot or fragment wound in proximity to the ureter warrants careful dissection of the ureter, avoiding it's devascularization (Table 20.3).

20.3.2 Immediate Management

Most patients with ureteral injury require laparotomy for the associated injuries. Obvious ureteric injury or disruption requires repair. Contusions from nearby injury may disrupt local vascularity and result in strictures [44, 45].

During laparotomy, the ureter must be identified and inspected. The appropriate management of an injury depends on the site and severity of injury, delay in diagnosis, the patient's condition, and the surgeon's experience.

Ureteric injuries in an unstable patient in which the time cannot be taken for repair over a double-J stent may be managed by cutaneous ureterostomy or exteriorization of a stent passed into the proximal transected ureter [26, 46]. Concomitant renal, ureteric, and associated intra-abdominal injuries may warrant nephrectomy. In a life-threatening situation, the ureter can be ligated and a delayed percutaneous nephrostomy performed.

20.3.3 Ureteral Reconstruction

Urologic consultation should be sought. There are a variety of techniques for reconstruction but all follow the guiding principles of adequate debridement, a spatulated, tension-free repair with absorbable sutures and adequate drainage (Fig. 20.6).

Injuries in the lower third usually are managed by reimplantation into the bladder, either directly or by mobilizing the bladder with a psoas hitch or Boari flap.

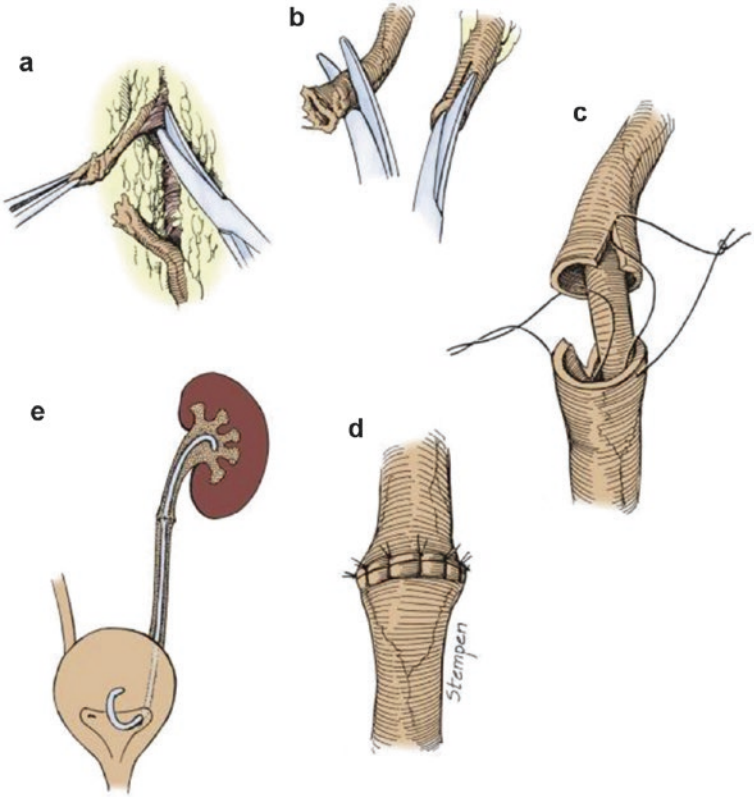


Fig. 20.6 Technique of ureteroureterostomy after traumatic disruption. (**a**) Injury site definition by ureteral mobilization. (**b**) Debridement of margins and spatulation. (**c**) Stent placement. (**d**) Approximation with 5-0 absorbable suture. (**e**) Final result

Injuries in the middle and upper thirds usually are managed with a primary uretero-ureterostomy over a double-J stent.

Long segmental defects may require transureteroureterostomy, autotransplantation, or interposition with an ileal graft (Table 20.4).

Table 20.4 Selection of ureteric repair based on level of injury

Level of ureteric injury	Types of repair
Lower third	Direct re-implantation
	Re-implantation + Psoas Hitch
	Re-implantation + Boari flap
Middle third	Primary ureteroureterostomy + JJ stent
Upper third	Primary ureteroureterostomy + JJ stent
Long segmental defects	Transureteroureterostomy
	Autotransplantation
	Interposition ileal graft

Key Points
• Ureteric injuries are often unrecognized.
• Operative management is often required.
• The reconstructive technique depends on the site and severity of injury.

20.4 Bladder Trauma

90% of bladder injuries are associated with pelvic fractures [23]. The triad of lower abdominal or suprapubic pain, inability to void and visible haematuria suggests a bladder injury particularly in the setting of a pelvic fracture [18].

20.4.1 Laboratory Diagnosis

Gross haematuria is seen in 95% of cases of penetrating bladder injury (Table 20.5) [26].

20.4.2 Classification of Bladder Injuries

Bladder injuries can be extraperitoneal (60%), intraperitoneal (30%), or a combination of both (10%) (Table 20.6) [47, 48].

20.4.3 Penetrating Trauma

Penetrating injury to the bladder accounts for 4–25% of bladder injuries [49, 50]. Extraperitoneal penetration is more common than intraperitoneal penetration. A projectile passing through a full bladder may cavitate, increasing intravesical pressures and can cause rupture in addition to the entry/exit wounds [51]. The injury is suggested by wounds to the lower abdomen, pelvis, or perineum. These high-risk injuries would require open surgical management.

Table 20.5 Clinical signs and symptoms associated with bladder injury

Clinical signs of bladder injury
Haematuria
Inability to void
Abdominal tenderness
Abdominal distension (urinary ascites)
Suprapubic bruising
Entrance/exit wounds in lower abdomen, perineum or buttocks (penetrating injury)

Adapted from Lumen et al., EAU Trauma Guidelines, 2016 [26]

Table 20.6 Bladder organ injury scoring system

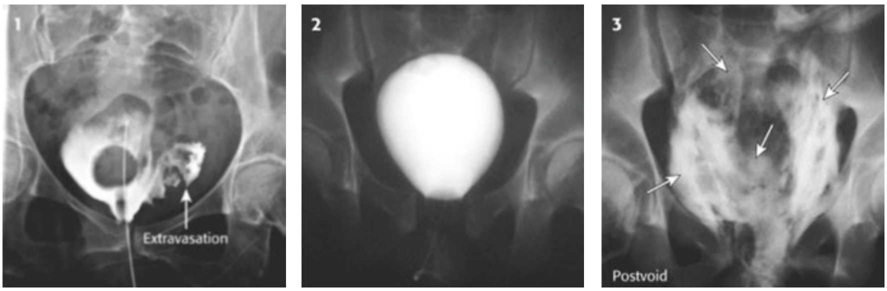
Grade	Type of injury	Description of injury
I	Haematoma	Contusion, intramural hematoma
	Laceration	Partial thickness
II	Laceration	Extraperitoneal bladder wall laceration <2 cm
III	Laceration	Extraperitoneal >2 cm or intraperitoneal <2 cm
		Bladder wall lacerations
IV	Laceration	Intraperitoneal bladder wall laceration >2 cm

Source: Moore et al. [43]. Advance one grade for multiple injuries

20.4.4 Imaging

The diagnostic approach to suspected lower genitourinary (GU) tract trauma is to investigate in a retrograde fashion. Start from the urethra (retrograde urethrography) to the bladder (conventional or computed tomographic [CT] cystography) to the kidneys and ureters (CT urography with delayed/excretory images). In the civilian trauma setting a CT is often performed first and the clinicians select these investigations on a case-by-case basis.

Cystography is accurate and performed by distending the bladder via a Foley catheter with 400 ml of contrast material under X-ray screening. Early leakage mandates termination of the investigation. The bladder then is emptied and a post-drainage film obtained to avoid missing subtle posterior injuries (Figs. 20.7 and 20.8).



Extraperitoneal bladder perforation. Contrast material is seen adjacent to the bladder neck. The bladder itself is displaced rightward by an adjacent hematoma.

Posterior injury. On this AP film, the bladder appears normal, and no extravasation of contrast material is noted. However, postvoid films are required to rule out posterior injury.

The postvoid film demonstrates substantial posterior extravasation of contrast material. This injury would have been missed if only the AP study were performed.

Fig. 20.7 A cystogram performed using plain films [52]. Delayed or excretory images, if performed at the time of the traumogram, may prompt a CT cystogram to accurately image suspected lower tract injury [53, 54]

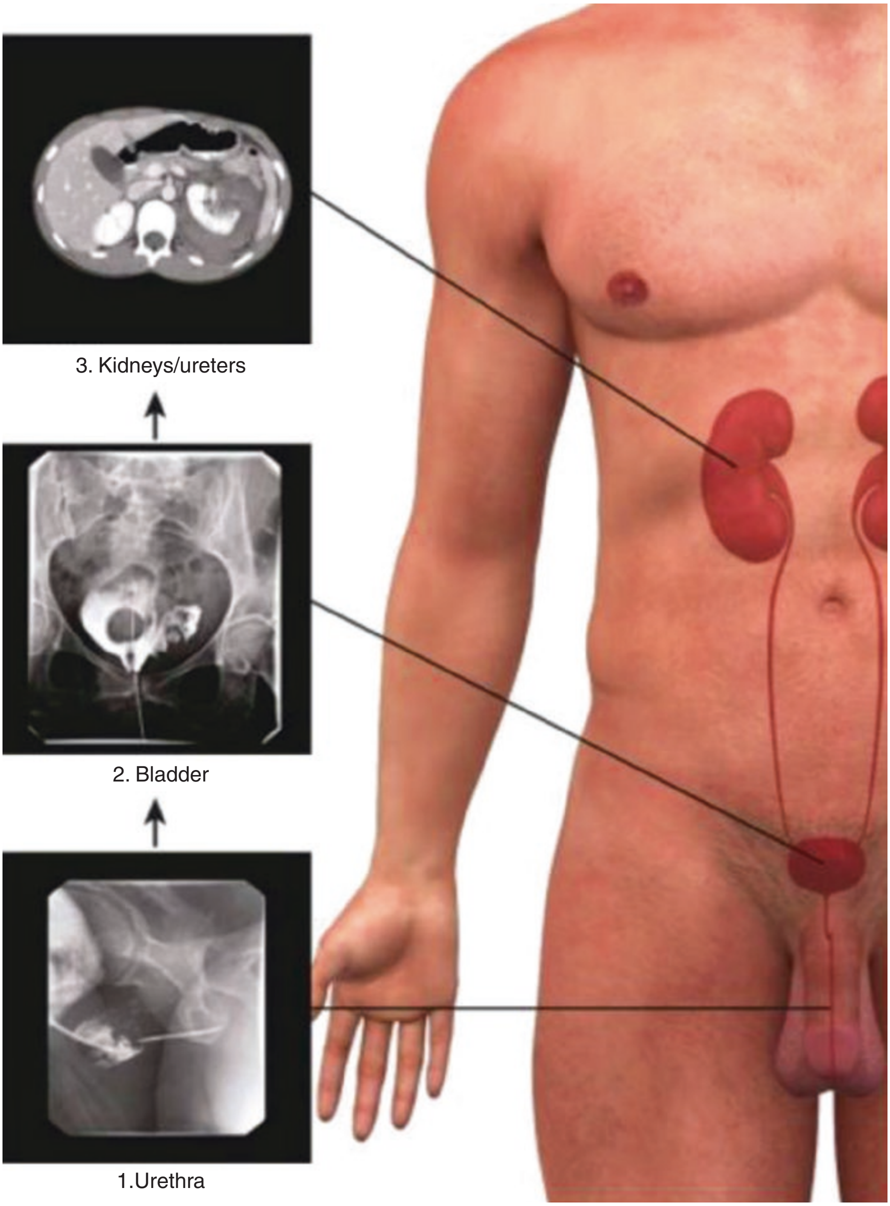


Fig. 20.8 Sequential imaging for suspected genitourinary trauma [52]

20.4.5 Management

Uncomplicated extraperitoneal bladder injuries are managed conservatively by free drainage of the bladder with a urethral catheter for 10–14 days, antibiotics and clinical observation [47, 48].

Complicated extraperitoneal bladder injuries, such as bone fragment intrusion, and the presence of rectal or vaginal lacerations, require surgical intervention [48]. Persistent urinary extravasation; failure of catheter to drain; patients undergoing surgery for a pelvic fracture or other viscus organ repair are also indications for surgical repair of the bladder [47, 48].

Intraperitoneal bladder ruptures are usually caused by a "blowout" injury, whereby there is a sudden rise in intravesical pressure [55, 56]. Usually this leads to rupture at the dome of the bladder, its weakest and most mobile point [56]. While this pattern of injury occurs after ground IED injury, as seen in Afghanistan, it is otherwise usually a feature of blunt injury and unlikely to occur frequently after blast injury in the civilian context. Interruption of the intraperitoneal surface of the bladder results in urinary extravasation and it is unlikely to heal without surgical intervention and can lead to further complications such as peritonitis, systemic sepsis and death [47, 56]. Formal surgical repair of intraperitoneal injuries of the bladder is required with a two-layer closure if possible [55, 56].

20.4.6 Operative Approach

Once intra-abdominal injury has been excluded at laparotomy, the space of Retzius is opened and the anterior bladder dissected away from the pubis. This area may already be open due to the pelvic fracture or prior dissection. The anatomy is often distorted by the injuries and haematoma formation. The bladder is opened vertically via an anterior cystostomy to allow examination of the entire interior surface. The ureteric orifices must be examined for injury (Figs. 20.9 and 20.10).

Lacerations are closed with absorbable sutures in one or two layers. A drain is recommended but not always necessary. Injuries extending into the trigone require careful reconstruction of the bladder neck or risk incontinence or contracture.

Penetrating bladder neck injuries in both sexes are extremely rare but are associated with potentially life threatening concomitant injuries. Delayed repair and suprapubic catheter insertion is the preferred option as the injury is not life-threatening. Patients are often explored to reduce contamination of displaced pelvic fractures or prevent fistulas when there is associated rectal injury [26, 58, 59] (Fig. 20.11).

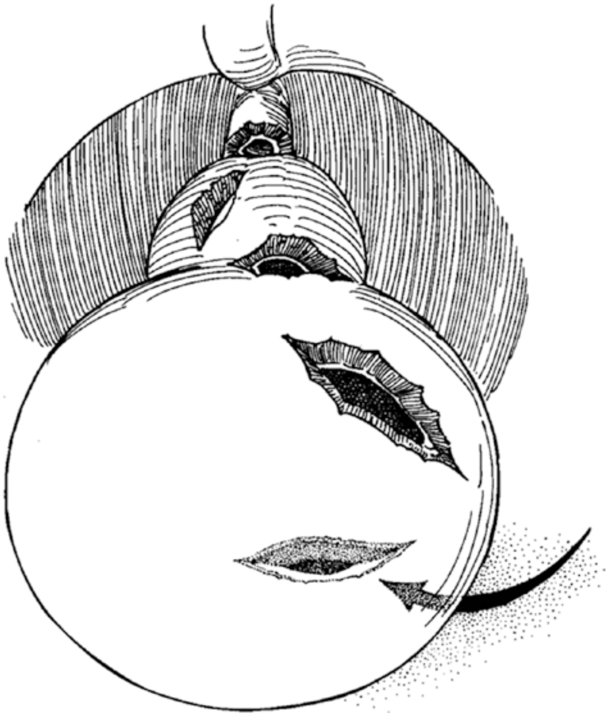


Fig. 20.9 Main potential sites of lower urinary tract injury: Urethra, prostate, bladder neck and bladder (intraperitoneal and extraperitoneal) [57]

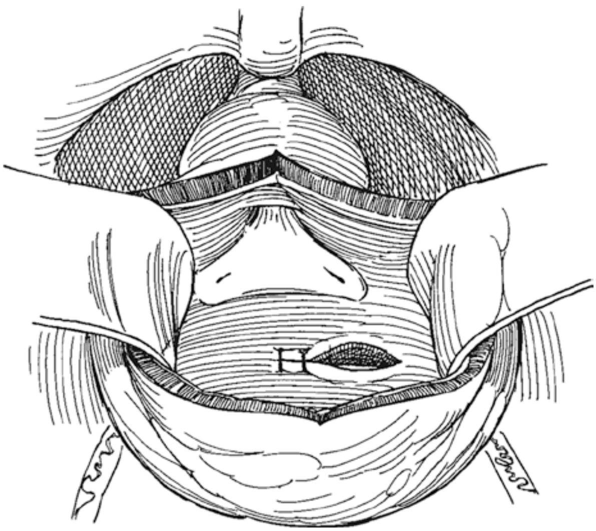


Fig. 20.10 Exposure for repair of extraperitoneal bladder rupture. The bladder is opened surgically and repaired from the inside [57]

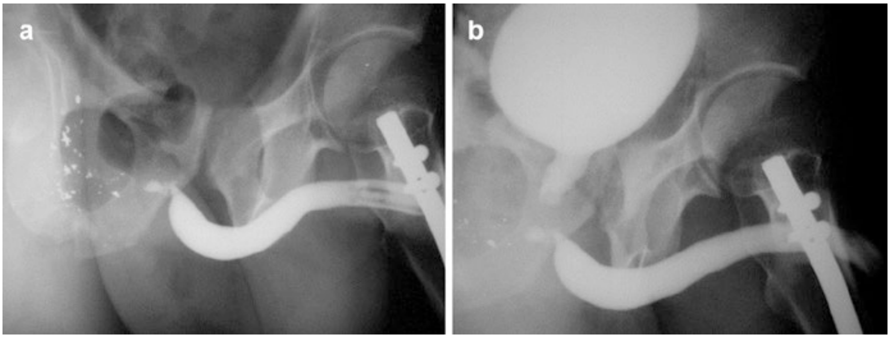


Fig 20.11 Penetrating bladder neck injury in a man. (**a**) Retrograde urethrogram showing contrast occluded at the level of the prostate/bladder neck and bullet fragments in the soft tissues after GSW. (**b**) Simultaneous antegrade and retrograde urethrogram of same patient, revealing approximately 2 cm stricture [58]

20.4.7 Follow-Up

A follow up retrograde cystogram should be performed at 2–3 weeks to assess for complete healing of the bladder injury after conservatively managed and surgically managed extraperitoneal injuries [60, 61]. The bladder heals well in almost all cases. Patients can develop bothersome urinary symptoms, which will require urology review.

Key Points
• Intraperitoneal ruptures require surgical repair.
• Complicated extraperitoneal bladder injuries should not be managed non-operatively.
• Follow up cystogram is mandatory after bladder repair.

20.5 External Genital Injury in Men

20.5.1 Introduction

Traumatic injury of the scrotum and its contents is relatively uncommon. The structures are relatively protected by the dependent and mobile nature of their anatomy. However, severe testicular trauma resulting in organ loss can affect fertility, hormonal status, and affect social confidence and psychology, particularly in young men [5]. Prompt assessment, operative intervention, and establishing processes to deal with the consequences of injury are essential to restoring quality of life.

Blunt scrotal trauma accounts for 75–85% or injuries and can cause scrotal skin ecchymosis, testicular haematoma, haematocele, testicular rupture or testicular dislocation [2, 62, 63].

Table 20.7 AAST testicular injury scale [43]

Testis injury scale	
Grade[a]	Description of injury
I	Contusion/Haematoma
II	Subclinical laceration of tunica albuginea
III	Laceration of tunica albuginea with <50% parenchymal loss
IV	Major laceration of tunica albuginea with >50% parenchymal loss
V	Total testicular destruction or avulsion

[a]Advance one grade for bilateral lesions up to grade V. From Moore et al. [70]

External genital injuries form up to 40–60% of all penetrating genitourinary trauma [2, 64]. While bilateral testicular injury is very rare in blunt trauma, it may be present in up to 30% of all penetrating scrotal injuries [55, 63–65]. The most common causes of penetrating scrotal injuries in civilian series are gunshot wounds (55–95%), stab wounds (5–42%) and animal bites [64, 66].

External genital injuries have increased in the modern battlefield due to blast injuries from fragmentation devices and the lack of protective armour of the genital area [44]. These devastating injuries are associated with lower limb injury, pelvic fracture and a high mortality [4]. Outcomes have improved with the development of protective equipment, advanced combat casualty care survival, acute sperm retrieval and hormone replacement [67–69].

The American Association for the Surgery of Trauma produced a five-grade scale system for scrotal and testicular injuries (Table 20.7).

20.5.2 General Evaluation

The history should include the mechanism of injury, symptoms and previous scrotal pathology or surgery. The injured scrotum is difficult to examine. Marked tenderness and swelling make it challenging to assess the integrity of the testis. The degree of scrotal ecchymosis, swelling and haematoma may not correlate with the severity of testicular injury, while lack of these signs does not always rule out testicular rupture [48]. An empty, ecchymotic hemiscrotum should raise suspicion of testicular dislocation.

20.5.3 Imaging

Ultrasonography is the most useful adjunct to clinical examination [56]. Testicular rupture may appear as a discontinuity of the tunica albuginea with an associated contour abnormality due to protrusion of the testicular parenchyma [56]. This is unreliable and operator dependent. However, heterogeneous echogenicity within the testis is considered a pathognomonic sign of rupture [71–73] (Fig. 20.12).

Contusions, hematoceles, testicular dislocations, intratesticular haematomas can also be detected [75]. Computed tomography may be useful in suspected testicular

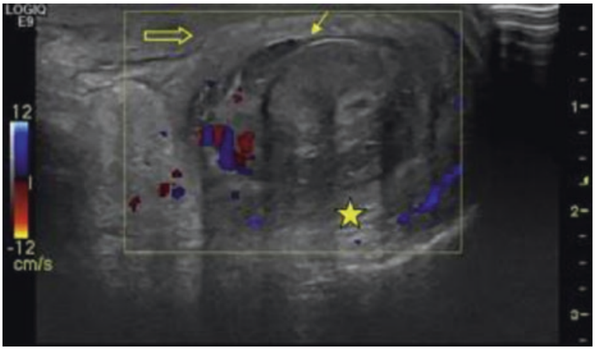


Fig. 20.12 Transverse image of the ruptured testis with color Doppler imaging. The central tissue is devascularized. A rim of vascular tissue represents a portion of viable testis, although it is abnormally heterogeneous and discontinuous from the rest of the organ. The testicular capsule is discontinuous (*arrow*). Echogenic, heterogeneous material surrounding the testis represents hematoma (*star*). The overlying scrotal skin is thickened and edematous (*open arrow*) [74]

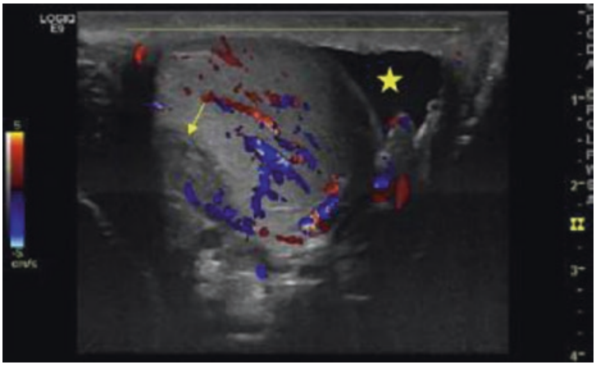


Fig. 20.13 Sagittal image of testis after a low-grade groin injury. Intratesticular hematoma. A hypoechoic, ovoid region with decreased to absent blood flow in the testis represents intratesticular hematoma (*arrow*). The overall contour of the testis is preserved and the capsule is intact. Anechoic fluid around the testis represents a hydrocele (*star*) [74]

dislocation to reveal the position of the displaced testicle. Ultrasonography may not always identify the testis; however, if found, colour-flow Doppler can assist in evaluating its viability (Fig. 20.13).

20.5.4 Management

20.5.4.1 Acute Management

Penetrating Scrotal Injury

Penetrating injuries to the scrotum generally require surgical exploration with debridement of non-viable tissue. Primary approximation and closure is easily performed in most cases. Prophylactic antibiotics and tetanus prophylaxis are recommended [26].

When complete disruption of the spermatic cord is present, vascular realignment without vaso-vasostomy can be considered when technically feasible [76–78]. Microsurgical reconstruction of the vas deferens should only be performed in the haemodynamically stable patient or as a secondary surgical procedure.

Testicular salvage in civilian gun-shot injuries may be as low as 10%, however contemporary series show that up to 75% of testes can be anatomically reconstructed [64, 79]. Functional outcomes are poorly reported, however. If there is extensive testicular injury where reconstruction cannot be achieved or the patient is haemodynamically unstable, orchidectomy is indicated [78]. If both testes are severely damaged or not salvageable, acute sperm retrieval should be considered for future assisted reproduction [67, 80].

20.5.4.2 Scrotal Skin Injuries and Scrotal Reconstruction

Lacerations of the scrotal skin can be closed primarily when there is no suspicion of injury to the scrotal organs. Wound contamination requires extensive washout and debridement of contaminated and non-viable scrotal tissue. Meticulous haemostasis is important to avoid haematoma development. A Penrose drain can be used to limit haematoma formation [81].

The dependent nature of the scrotum allows for extensive mobilisation and primary closure of most defects. However, scrotal reconstruction may be required in the presence of scrotal avulsion or when surgical debridement results in significant scrotal skin loss. Testes and spermatic cords can be buried in a lateral thigh pouch or in a subcutaneous abdominal pouch. This is rarely necessary as meticulous wound care with subsequent skin grafting is now the preferred option [81]. The spermatic cords and testes should be sewn together before grafting to prevent a bifid neoscrotum.

20.5.4.3 Haematocele

Haematocele is an extratesticular injury where bleeding is confined within the tunica vaginalis [56]. Small haematoceles may be managed conservatively with elevation, ice packs, non-steroidal anti-inflammatory drugs, bed rest and close monitoring [82]. Delayed surgical intervention may be necessary in cases of suspected infection or undue pain [78]. Scrotal exploration is indicated when a haematocele is greater than 5 cm or expanding or causes extrinsic compression on surrounding blood vessels and reduce flow on Doppler ultrasonography [56, 75, 83]. Furthermore, ultrasonography may not be able to demonstrate a tunica rupture in the presence of a large haematocele. These cases should be managed operatively with scrotal exploration, evaluation of the blood clot and meticulous haemostasis, even in the absence of testicular rupture.

20.5.4.4 Intratesticular Haematoma

Small haematomas confined in the tunica albuginea, with no evidence of rupture, can be managed non-operatively with serial ultrasound examinations until their resolution which exclude incidental malignancy [73, 83]. Large intratesticular haematomas are best managed by drainage to reduce the risk of pressure necrosis, atrophy and orchidectomy [56, 84].

20.5.4.5 Testicular Rupture

The incidence of testicular rupture may be up to 50% in blunt scrotal injuries [84]. Blunt scrotal trauma was treated conservatively with surgical interventions preserved only when complications arose [85]. However, there is no role for conservative management of testicular rupture in contemporary practice [86]. Early surgical intervention may result in testicular preservation in over 90% of cases while intervention after 3 days result in orchidectomy rates of 45–50% [84]. Early repair preserves hormonal function and may preserve fertility [87]. Surgical management involves exploration and evacuation of haematoma, excision of any necrotic testicular tubules and closure of the tunica albuginea, often with continuous absorbable suture material [78]. Extensive destruction of tunica albuginea or excessive testicular swelling may not allow for approximation and closure of the tunica albuginea. In these cases, the parietal lamina of tunica vaginalis can be mobilised or used as a vascularised flap and sutured to cover the defect (Figs. 20.14 and 20.15).

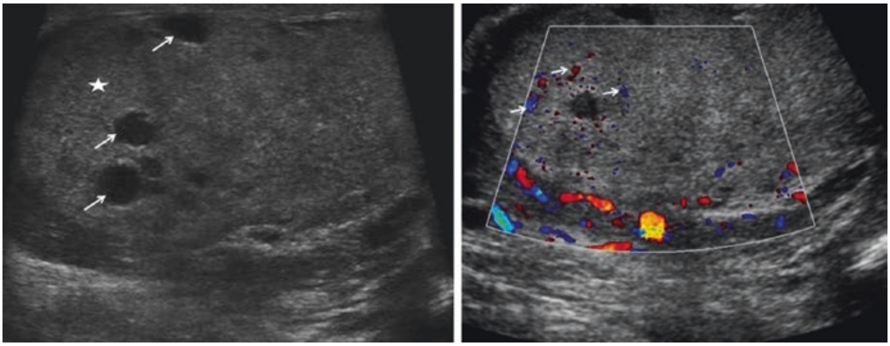


Fig. 20.14 Longitudinal ultrasound image of the right testis. Enlarged upper pole (*star*) and several areas of low reflectivity at the site of trauma (*arrows*) [88]. Doppler image showing ischaemaia [88]

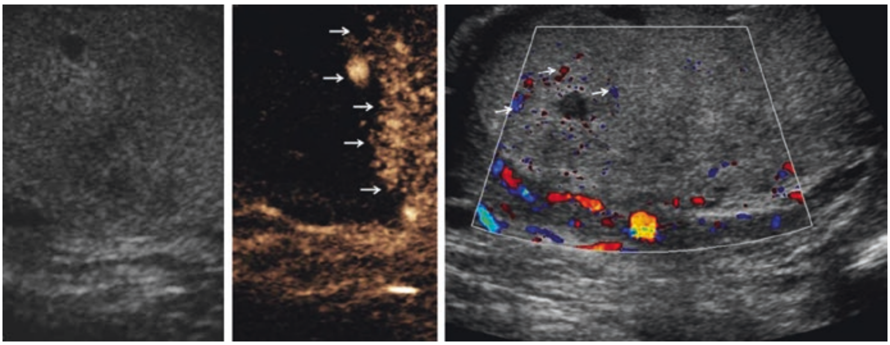


Fig. 20.15 Longitudinal ultrasound image of the right testis. The right testis with microbubble contrast imaging, 24 s after administration of SonoVue™ (Bracco SpA, Milan, Italy), demonstrating a clear demarcation between vascularised and non-vascularised tissue (*arrows*)

20.5.4.6 Testicular Dislocation and Testicular Torsion

Traumatic dislocation of the testicle can occur in severe blast injury. The superficial inguinal area is the most common site of testicular dislocation with the perineal, retrovesical or acetabular regions being less common [56]. It is a rare finding and commonly missed. Bilateral testicular dislocation has also been reported in high impact collisions [89, 90]. Manual repositioning should be attempted but if unsuccessful exploration and orchidopexy is required [91].

Trauma-induced testicular torsion has also been widely reported in the literature, possibly as a result of forceful contraction of the cremaster muscles [92–94]. Principles of urgent scrotal exploration and orchidopexy apply as with spontaneous cases.

20.5.5 Combat-Related Scrotal Injuries

The majority of urological injuries in Western troops in Iraq and Afghanistan involved the pelvic organs and external genitalia. The shift away from torso injuries is due to the use of body armour and the prevalence of ground-level fragmentation devices [44, 69]. Pelviperineal injuries, primarily due to improvised explosive devices, accounted for 5.4% of UK military trauma patients with a mortality of 47%, reflecting the severity of associated injuries [4] (Table 20.8).

Combined perineal and pelvic fracture injuries have a significantly higher mortality compared to perineal injuries alone (41 vs 18%) [4]. During the Iraq war, 34% of lower genitourinary trauma cases in a single US military field hospital were scrotal injuries with a high salvage rate of 86%. The leading cause for death in the cohort was associated major blood vessel injury [95]. As a result, modern modified body armours include a detachable flap to protect the genital and medial groin regions [96].

In the setting of traumatic testicular loss in the polytrauma patient, the focus of treatment is damage control by haemostasis, resuscitation and management of concurrent life-threatening injuries. Multiple reoperations may be required to control infection in combat wounds. This may implicate atypical infections, such as fungal organisms, making management even more challenging [68].

Uncompromising initial debridement, immediate faecal diversion, urinary diversion and early enteral feeding is recommended in severe pelviperineal trauma [4]. Patterns of survivable injury in warfare have changed in recent years as wounding mechanisms have altered, ballistic protection has improved and the military chain of trauma care and expertise has evolved [6, 97].

Table 20.8 AAST scrotal injury scale [22]

Scrotum injury scale	
Grade	Description of injury
I	Contusion
II	Laceration <25% of scrotal diameter
III	Laceration >25% of scrotal diameter
IV	Avulsion <50%
V	Avulsion >50%

From Moore et al. [73]

Servicemen that have suffered extensive genital injury, highly rate the importance of sexual function as a part of their lives prior to injury. The majority describe their genital injury as more important than losing their legs [5]. Early and close involvement of clinical psychologists is important. Patients seem to come to terms with their injuries far better if they have fertility preserved or a sperm sample saved. Early aggressive intervention to ensure samples are taken is required. The UK Defence Medical Services developed a unique process for acute sperm retrieval to meet the needs of these severely injured servicemen, with follow-up to ensure that fertility is preserved through hormonal and surgical interventions [5]. Live births have been achieved despite complete testicular loss [98].

20.5.6 Future Fertility

Experimental data in rats suggest that unilateral testicular trauma can significantly reduce fertility to 27% with the contralateral testis showing decreased volume, smaller seminiferous tubular diameters and various degree of aspermatogenesis due to immunological etiology [99]. A study on pre-pubertal rats showed that even Grade 1 unilateral blunt testicular injury can significantly affect germ cell maturation in both ipsilateral and contralateral testis and alter the sex hormone profile [100].

Trauma cases have poor rates of follow-up therefore analysis of any long-term outcomes is limited. It is estimated only 22–40% of trauma cases are followed up due to a variety of reasons (resolution of symptoms, socioeconomic factors, incarceration status or hospitalisation for confounding mental illness) [47, 64, 66].

Small case series and case reports suggest that testicular salvage with early testicular repair protects fertility [87, 101]. Testicular atrophy after testicular injury is common and semen analysis may show objective signs of subfertility, oligospermia, asthenospermia and low sperm motility are unlikely to be affected [87, 101]. Sperm density may be reduced but is reported to remain within normal range following orchidectomy [101].

Cryopreservation of sperm and testicular tissue has been used for patients with threatened future reproductive function similar to testicular cancer management. Perioperative consent is imperative and can cause difficult issues especially if the patient does not survive trauma surgery. Consent can be obtained post-operatively and a referral can be made for assisted conception. This intraoperative procedure should be considered in patients with injury to a solitary testis or patients with bilateral testicular trauma [67, 102, 103]. Acute sperm retrieval can be performed and involves dissection and excision of a healthy, proximal segment of vas. Also, sperm can be aspirated from the vas deferens and epididymis at the time of surgery [67, 80]. Samples are given to embryologists for analysis and preparation of the sperm for storage. HIV and HepB status have practical implications for sperm storage facilities.

If the patient has one normal testis, then sperm retrieval (or even normal fertility at recovery) is possible in the more elective and informed setting. In the UK, initial semen analysis is performed by the General Practitioner or accredited laboratory. Abnormal results are then managed by local Andrology units in specialist fertility multi-disciplinary teamss. Non-obstructive azoospermia patients with failed attempts at sperm retrieval with PESA, MESA, TESA or conventional TESE, will be offered mTESE.[1] Repeat attempts of mTESE will be available [103, 104].

20.5.7 Endocrine

There is conflicting evidence on the effect of testicular trauma on gonadal endocrine function. Kukadia et al. followed eight patients who had normal serum hormonal profiles following operative management [87]. In a seven patient case series, Lin et al. found that baseline FSH, luteinizing hormone (LH) and post-stimulation LH were significantly increased in patients that underwent orchidectomy compared to patients that had testicular repair. Serum testosterone, however, was normal regardless of surgical intervention [101].

Hormone replacement therapy should be considered in patients with bilateral testicular trauma [102, 103]. Furthermore, symptomatic swinging temperatures in the patient with significant gonadal loss may be a sign of traumatic andropause and should not be mistaken for sepsis [68]. Secondary hypogonadism should also be considered especially in patients with chronic pain or those on opiate drugs [105].

20.5.8 Psychology

Genital trauma may have cause significant psychological challenges to the patient. Overwhelming emotions and adjusting to injuries may be a long process requiring expert psychology input [106]. Following orchidectomy, patients may experience feelings of loss and uneasiness or shame. Testicular prosthesis has been shown to improve the extent of psychological trauma in cancer patients [107].

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[1] Percutaneous epididymal sperm aspiration (PESA), Microsurgical epididymal sperm aspiration (MESA) Testicular sperm aspiration (TESA), also described as testicular fine needle aspiration (TEFNA), Testicular sperm extraction (TESE) and Microdissection testicular exploration and sperm extraction (mTESE).

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Ballistic Wound Management and Infection Prevention

21

Jowan G. Penn-Barwell, C. Anton Fries, and R.F. Rickard

Key Points

1. No ballistic wound (with the possible exception of head and neck wounds) should be closed primarily.
2. Ballistic casualties need urgent systemic antibiotics.
3. Ballistic wounds should be irrigated with saline.
4. Wounds with retention of the round, fragmentation or bone strike should be regarded as higher energy transfer: consideration should be given to fasciotomy and more aggressive wound exploration.
5. Low energy transfer wounds should be considered for less aggressive surgical management if the wider healthcare context permits easy return to theatre.
6. Tissue excision should be performed after extension of the wound beyond the zone of injury.

21.1 Introduction

The primary surgical manoeuvres in the treatment of ballistic injuries are to save life and limb, in accordance with the principles of damage control resuscitation. In subsequent procedures the focus of surgical treatment shifts to preventing morbidity,

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and to the optimisation of reconstruction. Surgical treatment of wounds should take place as soon as possible after wounding once life-threatening injuries and haemorrhage control have been addressed.

Gunshot wounds (GSWs) are typically less contaminated than injuries caused by projectiles energised by explosive munitions. However they are occasionally associated with considerable tissue destruction, which may be deep within the wound, as described in Chap. 5. Infection following open fractures caused by GSWs and explosive weapons occurs in approximately 25% of cases [1, 2] and is associated with revision surgery and subsequent amputation [3]. Prevention of infection is achieved by creating a clean vascularized wound bed by excising all non-viable or contaminated tissue, and by reducing the number of viable microorganisms present by copious irrigation. The residual burden of contamination is thereby reduced to a level where the patient's immune system is able to suppress the development of infection.

In this chapter the term 'debridement' is not used in order avoid confusion. This term entered the English-speaking surgical lexicon after the Inter-Allied Surgical Conference of 1917, and in the 100 years since then it has been used interchangeably to mean either, or both, the act of *incision* and decompression (or un-bridling the tissue) and/or the *excision* of necrotic or grossly contaminated tissue. For simplicity, this chapter will use the terms *excision*, *incision* and *decompression*.

All ballistic wounds, both GSWs and those from explosive weapons, evolve over time. They should never be closed at the first surgical episode and may require recurrent surgical episodes for further assessment, tissue excision and eventually closure or coverage. Time between surgical episodes is usually 2 days, though they can be safely delayed for 5 days in a patient not showing any signs of sepsis. The only exception to the rule of delayed closure are head and neck wounds which are typically more forgiving due to their vascularity.

The majority of GSWs affect the limbs in both the military [4] and civilian setting [5]. This chapter will focus on the prevention of infection in limb wounds, and will predominantly consider those injuries caused by firearms.

21.2 The Ballistic Wound and Infection

The Jackson model of burns [6] describes a wound in three zones, as shown in Fig. 21.1 below. Devitalised, dead tissue is described as the *zone of necrosis* while only slightly traumatised tissue is referred to as the *zone of hyperaemia*. In between these extremes lies the *zone of stasis,* which can most usefully thought of as being *vulnerable but viable* tissue.

This conceptual model provides a useful theoretical construct for understanding ballistic wounds and the rationale behind their treatment. Key to this is preserving the vulnerable but viable tissue by preventing further damage and necrosis.

In practice, application of this principle is a dynamic process. The clinician must make a judgement on the status of the wound, the patient's comorbidities and resuscitative status, together with the constraints of the environment and the chronicity of presentation.

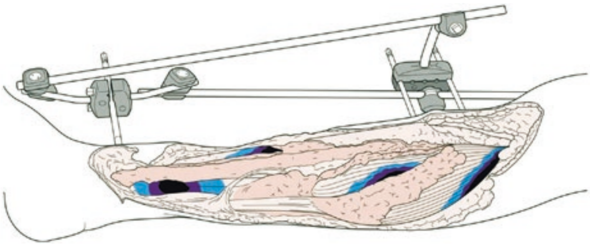

Fig. 21.1 Diagram of complex open fracture wounds showing zones of necrosis (*black area*); surrounded by vulnerable but potentially viable zones of stasis (*violet area*); surrounded by the zones of hyperaemia (*blue area*)

In the absence of other constraints, the excision of tissues that may have large functional impact should be subject to a more expectant approach. Examples of where this may be appropriate would be injuries to major nerves, those involving structures of the head and neck, and in cases of urogenital injury.

21.3 Wound Incision and Compartment Decompression

The passage of bullets and fragments through muscular compartments imparts energy into those tissues. Muscle tissue can survive the stretching effect of the temporary cavity but will be left inflamed, leading to swelling and the generation of exudate. Whether or not this occurs with significant haemorrhage, there is great potential for compartment syndrome to develop.

In the presence of features associated with high-energy transfer, prophylactic full fasciotomies should be considered. This approach is particularly important in an austere or mass-casualty setting, where the ability to monitor a patient or rapidly return to theatre, is limited. Obviously, clinical symptoms of compartment syndrome mandate formal fasciotomies following ballistic trauma as it would with any other injury mechanism.

Wounds should be extended longitudinally along the limb. The incision should be sited to permit formal fasciotomies and avoid perforating vessels that may be required for future reconstruction. Longitudinal incisions across flexor creases should be avoided in favour of oblique or curved incisions. Even in cases where formal, full fasciotomies are not judged necessary, local decompression of fascia to well outside the zone of injury is a safe strategy which will permit post-operative swelling as well as aiding drainage.

The benefits of wound incision should not be negated by tightly packing the wound or application of restrictive, circumferential bandages.

21.4 Wound Excision

The aim of wound excision is to convert a necrotic and contaminated wound to a clean and healthy one.

Necrotic tissue is a potential site for microbial organisms to colonise as it provides a source of nutrients and is isolated from the patient’s immune system. The accepted treatment strategy is to remove this potential site of colonisation by surgically excising all necrotic tissue.

Skin is an elastic tissue that tolerates the stretch of temporary cavitation well. In the words of Sir H Ogilive "one lesson that must be relearned in every war is that skin is very viable and very irreplaceable and as little of it as possible should be removed." [7].

The common pitfall for those not familiar with excising ballistic wounds is to start from within the wound, enlarging it until all the contaminated tissue has been removed: this approach risks both inadequate tissue excision and inadvertent damage to neurovascular structures.

A preferable approach is to ensure that the wound is extended to outside of the zone of injury. If neurovascular structures are suspected to cross the zone of injury, then they should be identified in uninjured tissue and traced along their path. This approach also permits easier identification of the wound zones described above facilitating decision-making regarding non-viable tissue.

21.4.1 High-Energy Versus Low Energy Gunshot Wounds

In order to identify and excise all necrotic tissue in a GSW, exposure or *laying open* the entire wound tract wound be necessary. This could potentially require the transection of otherwise un-injured muscle compartments and result in greater functional damage than the original injury. Despite this concern, this aggressive surgical strategy has previously been advocated in military GSWs [8]. It is now recognised that in a low-energy wound, there may only be a small amount of necrotic tissue of a quantity manageable by the patient's immune system. Surgeons with experience of GSWs from the pre-antibiotic era in the First World War regarded the laying open of a through and through wound as a 'cardinal sin', since they healed up well without invasive surgery and the further insult this involved [9].

After the major conflicts of Korea and Vietnam, military surgeons used animal models to confirm their clinical experience that 'simple' through and through wounds of the limbs can be managed with wound lavage, local fascial decompression and delayed closure or secondary healing [10, 11].

Civilian surgeons working in an environment where they can be confident of the low energy nature of the injury, for example due to the use of handguns, and with adequate resource to enable early access to the operating theatre if required, have even advocated non-operative treatment of these wounds. The safety of this approach is supported by randomised controlled trials which demonstrate no greater rate of infection in GSWs from handguns treated operatively versus non-operatively [12, 13]. However, when the weapon and circumstances are unknown, it is important to treat the wound and not the weapon.

Coupland suggested that all GSWs with a skin wound greater than the diameter of 2-fingers involved significant energy transfer suggestive of cavitation and therefore the wound tract should be fully explored and laid open [14, 15]. This strategy was based on the hospital experience of the International Committee of the Red Cross (ICRC) when dealing with injuries that were often presenting after a delay of several days without antibiotic treatment. In a similar setting, and with delayed presentation, a more aggressive approach may be mandated. A more aggressive approach is also appropriate if there uncertainty about if repeat surgical treatments may be possible.

However, rather than relying on absolute 'rules' a more nuanced approach to GSWs is possible: In the recent experience of management of GSWs from high-energy military weapons in Afghanistan, it has been possible to stratify wounds according to the amount of energy transferred from the projectiles into the tissues. As described in Chap. 5, greater energy transfer occurs with bone strike, bullet fragmentation or bullet retention. These factors can all be determined at time of initial assessment by radiological and clinical examination [4]. High-energy transfer wounds require thorough and careful assessment of the whole wound tract for potential deep pockets of necrotic tissue.

If a GSW lacks the features of high-energy transfer surgeons can consider minimal debridement of visible wounds, local release of fascia and fluid lavage. This can possibly be augmented by flossing the tract with saline soaked ribbon gauze introduced by the passage of a Rampley's clamp along the wound tract. This conservative treatment of low energy transfer wounds can only be safely carried out in specific circumstances. The initial surgical exploration should be done within 24 h from point of wounding, in a patient who has had early administration of systemic antibiotics and when circumstances easily permit return to theatre should signs of local or systemic infection develop. If these conditions are not met, a more aggressive surgical exploration is likely to be a safer strategy.

Cases of delayed reconstruction may be expected in a mass casualty terrorist firearms attack, either due to local facilities being overwhelmed or prolonged transfer timelines to supporting hospitals. This is especially pertinent in the case of limb injuries requiring reconstruction as they are likely not life-threatening and may therefore be triaged into lower categories. In these situations the presence of bacterial biofilms covering wound surfaces is a key concept in the management of infection [16]. Authors have coined the term "tumour like excision" in orthoplastic practice, and suggested practical techniques including staining the wound cavity with blue ink and excising all the stained tissue, or stapling a gauze pad into the wound and excising the tissue with the gauze in continuity [17].

21.5 Wound Irrigation

At the start of the First World War, GSWs were irrigated with a variety of antiseptic solutions. Sir Alexander Fleming was working as a Lieutenant in a British Field Hospital in Belgium and recognised the hundreds of ballistic wounds being treated with various irrigation solutions were a grim natural experiment. He took numerous samples of wound tissue from injured soldiers and demonstrated that there was increased bacterial loads in wounds that had been treated with antiseptics.

He ascribed this counter intuitive observation to the toxicity of chemical antiseptics to the host tissue: "it also makes it necessary in the estimation of the value of an antiseptic, to study its effect on the tissue more than its effect on the bacteria" [18].

In terms of the Jackson wound model, this effect is the chemical damage of antiseptics on the vulnerable but viable traumatised tissue, tipping the balance towards necrosis. This effect has been demonstrated in animal models of traumatic wounds [19]. Since Fleming's work in the First World War, there have been no clinical or pre-clinical studies that have demonstrated superior efficacy of anti-septic chemicals over saline [20]. The recent FLOW study in 2015 confirmed the superiority of wound irrigation with low-pressure saline [21].

In summary minimising infection in gunshot wounds is achieved by physically removing contaminants and wound exudate. This is best done by irrigating the wound with large amounts of normal saline delivered at low pressure.

21.6 Antibiotics

Ballistic wounds are always contaminated; in fragmentation injuries this contamination can be massive. The administration of systemic antibiotics is a priority; early administration of systemic antibiotics, even in the pre-hospital context, can allow surgical treatment of wounds to be more safely delayed [22], an important consideration in a mass casualty situation or in an austere environment.

The application of local antibiotics after wound incision and excision enables a higher concentration of antibiotic to be achieved in the wound whilst avoiding systemic toxicity. Presently there is no ideal vehicle for the administration of local antibiotics [23], but the use of antibiotic impregnated Polymethylmethacrylate (PMMA) beads to create a high local concentration of antibiotics is well accepted [2, 24].

The choice of antibiotics will be guided by local policy and the circumstances of wounding. For example, wounds sustained in an aquatic environment may require gram negative cover and those potentially contaminated by faeces (as with some suicide bombings) or sewage may need anaerobic cover [25].

It is important not to regard ballistic injuries as exotic or inherently different from other injuries; even in wounds sustained on the battlefield, *S. aureus* is the most common causative agent of wound infection [2].

21.7 Dressings

Once wounds have been rendered clean and healthy dressings need to be applied. The primary aim of the dressings is to prevent secondary contamination, and allow exudate to safely drain from the wound.

For the same reason that antiseptic solutions should not be used to irrigate wounds, antiseptic-soaked wound packs should never be applied to traumatised tissue [26]. Loosely packed gauze, either dry or soaked in saline or impregnated with petroleum jelly, and secured with wool and crepe bandages is a safe, and low-cost dressing. However in large wounds these dressings can rapidly become saturated

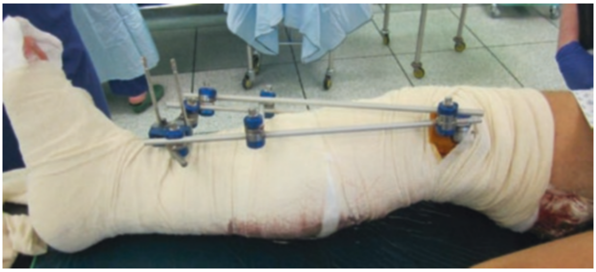

Fig. 21.2 Excessive exudate saturating the dressing covering a open tibia fracture caused by a high-energy transfer GSW. The ankle is immobilised with a gypsum plaster splint to prevent movement of tissues in the lower leg, necessary despite the tibia being stabilised with an external fixator

with exudate, causing an unpleasant odour for the patient and a site for bacterial colonisation [27], as shown in Fig. 21.2.

The use of nanocrystalline silver dressings has not been shown to be more effective than plain gauze dressings in a randomised, controlled trial performed on patients with ballistic wounds [27].

Topical Negative Pressure (TNP) dressings, also referred to by their proprietary names (e.g. Vacuum Assisted Closure (VAC®)), provide an alternative dressing for ballistic wounds once they have been adequately treated surgically. These dressings satisfy the aims of ballistic wound dressings by effectively sealing the wound from outside contamination while simultaneously removing exudate as it is discharged. They have the added advantage of being able to keep patients clean and comfortable in cases of very large wounds, e.g. bilateral lower limb amputation [28]. It is important to state that TNP dressings do not negate the need for adequate surgical treatment of wounds as soon as possible after wounding. In the absence of clinical signs of sepsis, TNP dressings can safely be left over an adequately debrided wound for up to a week [29].

All limbs traumatised by a ballistic wound should be splinted, even in the absence of a fracture. In those limbs with an underlying fracture, splints should be used to rest the tissues, which are susceptible to infection if used excessively (Fig. 21.2).

Conclusion

Prevention of infection is the priority for managing a ballistic casualty as soon as life and limb threatening injuries are addressed. Administration of systemic antibiotics and the surgical treatment of ballistic wounds should take place as soon as possible after injury. It is possible to judge the likely amount of energy transfer into the wound by use of clinical and radiographic evaluation. Surgical treatment should be tailored according to energy transfer: wounds sustained through higher energy transfer require more aggressive tissue excision. Low pressure saline irrigation should follow adequate wound incision and excision. Ballistic wounds should never be closed at the first surgical episode with the possible exception of head and neck injuries. Topical Negative Pressure dressings are an ideal choice for covering wounds in between surgical episodes.

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Human Factors in Ballistic Trauma

22

Simon J. Mercer

22.1 Introduction

Human Factors are described as '*enhancing clinical performance through an understanding of the effects of teamwork, tasks, equipment, workspace, culture and organisation on human behaviour and abilities and application of that knowledge in clinical settings*' [1] and also as '*the cognitive, social, and personal resource skills that complement technical skills, and contribute to safe and efficient task performance*' [2]. Healthcare has taken the lead from the aviation industry where it was estimated that approximately 70% of errors investigated were attributable to failed communication, poor decision- making and ineffective leadership [3].

Human Factors are now common in a healthcare setting, having been initially highlighted by two high profile reports [4, 5] and subsequently several high profile cases which have highlighted severe failures [6, 7]. Although initially adoption of the principles has been slow, there has been a recent drive with the signing of a national concordat by many of the lead organisations in the UK including the General Medical Council [8]. Non-technical skills frameworks have been developed for anaesthesia [9], surgery [10] and perioperative practitioners [11]. The anaesthetist's non-technical skills framework (ANTS) is broken down into four separate behaviour categories: task management, team working, situational awareness and decision-making with each category having its own elements (Table 22.1). Although a framework for trauma has not yet been developed there is considerable overlap that can be transferred to the trauma team. Human factors were thought to have played an important role in the management of casualties in the recent conflict in Afghanistan [12, 13] with rehearsal in pre-deployment training [14] and refinement on operations. They have recently been described in civilian complex trauma management [15].

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Table 22.1 The anaesthetists non-technical skills framework [9]

Category	Element
Task management	Planning and preparing management
	Prioritizing
	Providing and maintaining standards
	Identifying and utilizing resources
Team working	Coordinating activities with team members working
	Exchanging information
	Using authority and assertiveness
	Assessing capabilities
	Supporting others
Situational awareness	Gathering information awareness
	Recognizing and understanding
	Anticipating
Decision making	Identifying options
	Balancing risks and selecting options
	Re-evaluating

Damage control resuscitation is now recognised as the standard of care for the severely injured patient [16, 17]. The National Institute for Health and Care Excellence (NICE) have recently suggested that healthcare professionals who deliver care to patients with trauma to have up-to-date training in the interventions they are required to give [18]. It is important that individuals are given the opportunity to practice using simulation in their work place to test the systems in place [19], and rehearse protocols and guidelines and ensure equipment competencies. The establishment of major trauma centres around the UK has allowed for the concentration of trauma experience in key hospitals and the development of the trauma team. There is evidence that more effective clinicians use first-rate non-technical skills as part of their working routine [20].

22.2 Preparing to Receive a Patient

Multi-professional team-working is defined as '*a dynamic process involving two or more health professionals with complementary backgrounds and skills, sharing common health goals and exercising concerted physical and mental effort in assessing, planning, or evaluating patient care. This is accomplished through interdependent collaboration, open communication and shared decision-making. This in turn generates value-added patient, organizational and staff outcomes.*' [21]. The activation of the trauma team is dependent on a pre-determined criteria based on anatomy, physiology and mechanism of injury (Table 22.2). Patients with ballistic injuries would automatically activate the trauma team. The personnel involved in the trauma team are listed in Table 22.3 and are a resource rich unit of individuals with specific skills and competencies required to stabilise a casualty and then make rapid decisions about further management. Salas describes a team as being '*a*

Table 22.2 Trauma team activation criteria (taken from Kings College Hospital London, Major Trauma Service: Information for Members of the Trauma Team)

1. Traumatic event and one of the following:
• Oxygen saturation <90%
• Systolic arterial pressure 90 mm Hg
• Respiratory rate <9 or >29 bpm
• GCS <14
2. Penetrating injury to
• Head
• Neck
• Chest
• Abdomen
• Pelvis
• All gunshot wounds
3. Fractures
• Open or depressed skull fractures
• Pelvic fracture
• Two or more proximal long bone fractures
• Flail chest
4. Traumatic amputation
5. Blast or crush injury
6. Major burns
• 10% total body surface area but lower threshold in child or elderly
• Combination of burns and trauma
7. Road traffic crash
• High speed crash (0.30 mph) or pedestrian vs. vehicle at 0.20 mph
• Separation of rider and bike
• Intrusion into passenger compartment
• Ejection from vehicle
• Death in the same passenger compartment
• Bull's eyed windscreen
• 20 min extrication time
8. Falls
• Height of >3 m
• Paediatrics—consider the age and height of the child in relation to the height fallen
9. HEMS transfer
10. Drowning/submersion

This will apply to patients arriving at the hospital or who have a prehospital alert

distinguishable set of two or more people who interact dynamically, interdependently, and adaptively towards a common and valued goal, who have each been assigned specific roles or functions to perform, and who have a limited life-span membership' [22] and this definition fits nicely to the trauma team who are summoned from various areas of the hospital to assess and stabilise a patient and then return to their other duties.

Table 22.3 Typical UK National Health Service Trauma Team in a Major Trauma Centre

• Trauma team leader (Emergency Medicine Consultant)
• Primary survey doctor (Emergency Medicine Registrar)
• Anaesthetist 1 (Registrar/Consultant)
• Anaesthetic nurse or practitioner
• Scribe (trauma nurse coordinator)
• ED nurse 1 (circulator)
• ED nurse 2 (rapid infuser)
• ED nurse 3 (rapid infuser)
• Runner (Health Care Assistant)
• Orthopaedic surgeon (Registrar/Consultant)
• General surgeon (Registrar/Consultant)
• Radiographer

The trauma team leader (TTL) is usually a consultant in emergency medicine and is responsible for leading the trauma team. The definition of a leader is '*a person whose ideas and actions influence the thought and the behaviour of others*' [2]. In this role they must influence, inspire and direct the actions of the team in order to attain a desired objective, namely to rapidly assess and stabilise a patient and make a decision regarding their next location of treatment. This also requires management as situations are analysed, goals set, activities co-ordinated and the team directed. The TTL at times will have a job similar to that of the conductor of an orchestra [23] with multiple teams all working on a severely injured patient and numerous others supporting the resuscitation this has also been described as '*driving the ship*' but essentially means that their role is 'hands off' maintaining a complete overview of what could potentially be a rapidly changing situation.

Once assembled, the TTL will deliver a brief to the team. This will confirm information from the pre-hospital team, the mechanism of injury any physiological signs available and the time of arrival. At this point the TTL will also confirm their mental model, this is essentially what they expect to happen or what the likely clinical sequence will be, based on their own previous experience. One example of this might be in the case of a traumatic cardiac arrest where the administration of adrenaline and commencing chest compressions are no longer recommended [24] and it is important to recognize the need for oxygenation, correction of hypovolaemia and management of cardiac tamponade and tension pneumothorax [25]. This also might require an emergency thoracotomy of which the trauma team must be prepared for. This brief not only prepares the team but encourages good followership. The team is introduced by name and role and competencies confirmed. Contingency planning is also discussed, for example dealing with a difficult airway and discussing which member of the team will perform a surgical airway. Once the team has assembled then they must remain in the trauma bay until the trauma team leader dismisses them.

In essence it is the job of the TTL to maintain the situation awareness of the team defined as '*the perception of elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future*' [26], and this accurately describes how the TTL should be thinking throughout the assessment in the trauma bay. Depending on the severity of the injuries a ‘code red call’ might be triggered. Code Red activation criteria include a systolic arterial pressure <90 mm Hg (at any time), patients who are non-responders to fluid boluses and suspected or confirmed haemorrhage [15]. The protocol enables blood products to be available prior to the patient arriving and additional consultants to be summoned. This can be activated by the pre-hospital clinician [27]. Major trauma centres will have a massive transfusion protocol [28]. Blood delivered in the form of a ‘shock pack’ must be supplied in a box with a timer on it so that products that are not required can be returned under the direction of the TTL to be used for another patient.

Additional jobs in the preparation period include checking equipment, preparing drugs and communicating with other agencies in the hospital such as radiology (for CT), laboratory and communication with the operating theatre. It is particularly important during this time that the operating theatre to be used is identified, additional staffs are summoned and specialist equipment prepared.

22.3 Patient Arrival

The European Trauma Course teaches team-working and leadership and uses a 5-s check performed by the team leader on the arrival of the casualty, prior to the team starting work [29, 30]. This confirms that the patient is alive, has a patent airway and does not have visible catastrophic haemorrhage. This process allows the team leader and team members an overview of the patient, which is vital to maintaining situational awareness and forming a mental model. Once this check is performed, the pre-hospital clinician will be invited to deliver their handover. This is performed in silence with all team members listening and one example, the AT-MIST handover is described in Table 22.4.

22.4 Patient Assessment

Once the handover has been delivered the primary survey is immediately commenced. This is conducted in a <c> ABC [31] fashion but using a horizontal approach [32] so that in reality many aspects of the primary survey are all performed at the same time and has been likened to a ‘Formula One pit-stop’ [15]. This can only be achieved if coordinated by the TTL who is waiting for information to be

Table 22.4 AT-MIST handover

A	Age
T	Time of injury
M	Mechanism of injury
I	Injuries sustained
S	Signs and symptoms
T	Treatment given

Table 22.5 Initial management tasks performed by the trauma team in ballistic trauma management

• Primary survey <c> ABC
• Checking of tourniquets and pelvic binder positioning if applied
• Administration oxygen (15 L via non-rebreather mask)
• Cervical spine mobilisation
• Additional IV access inserted and then blood samples taken for
– Full blood count
– Thromboelastometry (e.g. RoTEM®)
– Venous blood gas
– Group and save
• Focused assessment with sonography for trauma scan (FAST)
• Chest and pelvis X-rays
• Commencement of haemostatic resuscitation if appropriate via a rapid infuser (Belmont)
• Rapid sequence induction may be required.
• Consideration of drugs
– Antibiotics
– Tranexamic acid (15 mg/kg)
– Tetanus
– Analgesia as required
– Consider calcium chloride

communicated to them from the team. Table 22.5 details some of the initial tasks that must be performed in the first few minutes in the emergency department. This is the gathering information stage of the TTL's situational awareness [2]. The other stages are interpreting the information and then anticipating and planning for the future. Patients seriously injured by ballistics may rapidly change their physiology and so situational awareness is very important.

By having a dedicated TTL who is completely 'hands-off' and maintaining situational awareness, members of the trauma team are now permitted to focus on their immediate tasks. If there were not a team member 'driving the ship' then there is the potential to lose situational awareness, and potentially develop fixation errors (i.e. focusing on a single problem to the detriment of the casualty as a whole) [33]. In stressful situations individuals can very quickly fill their 'bandwidth' (the available mental capacity) and become overloaded and this too can lead to errors. Should a rapid sequence induction be required, this would ideally occur in silence similar to a 'cock pit moment' such as the 'take off' or landing of a plane [34], with all team members focused.

Following the end of the primary survey, a decision will need to be made on the next stage of the patient pathway. In order to facilitate decision making and communication a 'Trauma WHO' has been suggested [35]. The World Health Organisation (WHO) introduced a surgical safety checklist with three components; a pre-surgical check, a time out prior to starting surgery and a 'sign out' and this has already been reported to have reduced hospital mortality [36]. In time critical situations such as complex trauma this checklist was thought to not be appropriate and could even hinder the timeliness of interventions [35]. The four components of the ‘Trauma WHO’ are

- The Command Huddle
- Snap Brief
- Regular Sit-Reps (Situation Updates)
- Sign out (handover)

22.4.1 Command Huddle

At the end of the primary survey the Command Huddle should occur. This will allow an initial treatment plan to be determined (or the futility of continuing with treatment discussed). Options for onward management will include an immediate transfer to the operating theatre for damage control surgery, transfer to radiology for a CT scan or interventional radiology (this may or may not be in the emergency department), to critical care or to the trauma ward. Key people involved in the decision making process will be

- Trauma Team Leader—Who provides overall leadership and situational awareness, including an understanding of the resources available
- Lead Surgeons (There will be a trauma (general) surgery and orthopaedic surgeon) who will provide expert assessment of the injuries found, surgical options available, and priorities for surgical treatment
- Lead Anaesthetist—Who provides expert assessment of physiological stability, response to transfusion, and priorities for airway management

The key decisions that must be considered by the Command Huddle are

- Is treatment futile? This is a hard decision to make but a catastrophic injury may necessitate stopping treatment.
- Can the patient be treated at the current hospital or do they require a transfer for specialist services and if a transfer is required then what are the relative risks of this?
- What is the most appropriate next stage of treatment? Is it to transfer to CT Scan or transfer directly to the operating theatre or is interventional radiology more appropriate?
- Will the patient tolerate a delay in surgery to have a CT scan?
- If transfer to the operating theatre is recommended, then which body cavity is to be opened first?
- Does the patient require a Rapid Sequence Induction of Anaesthesia? If so, should this be performed in the emergency department or in the operating

theatre? How great is the risk of airway obstruction or respiratory failure before reaching the operating theatre?
- If the patient requires a transfer (either intra or inter-hospital) then can they tolerate this without anaesthesia?

22.4.2 Snap Brief

Once positioned on the operating table and prior to the start of surgery a snap brief is conducted. The key points of information that must be communicated include [35]:

- The main injuries found on clinical examination and reported radiology
- The current physiological status and degree of stability of the patient
- The transfusion status including the volume of blood and blood products administered, estimated on going requirements and the coagulation status (using near point testing e.g. RoTEM©
- The surgical plans and expected timescale of the operation.

The surgical plan may consist of several options and these should be written out on a white board in theatre with the trigger points to move to the plan.

22.4.3 Sit Reps

Once surgery is underway a series of SIT REPS (situation reports) [35] should take place. These provide the opportunity to bring the whole team '*back on the page*' and to maintain situational awareness and should be conducted when there is a new piece of information or every 30 min. Recently the mnemonic for the sit-rep has been changed to STACK [*Personnel communication Lt Col Harry Pugh*] (Table 22.6).

22.4.4 Sign Out

At the end of the surgery there is a formal 'sign out' with a handover to the critical care team who will then assume responsibility for the patient. This might also be an appropriate time for a debrief (although this could potentially be delayed for 24 h if necessary).

Table 22.6 Sit-rep mnemonic

S	Systolic blood pressure
T	Temperature
A	Acidosis
C	Coagulation
K	Kit (including blood products used)

22.5 Summary

Human Factors are now a common place in healthcare and their importance in complex trauma has been described in both military [13] and civilian practice [15]. The trauma team, once activated is a resource rich unit that facilitates a rapid assessment of a casualty and robust decision making concerning their treatment. The 'Trauma WHO' [35] provides a structure to allow communication with the team in complex trauma.

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23 Management of Paediatric Trauma in an Austere Environment

William Tremlett, Johno Breeze, and G. Suren Arul

23.1 Introduction

The Uppsala Conflict Data Programme held by Uppsala University reported 149 state and non-state conflicts worldwide in 2015, with over 118,000 deaths [1]. By inference, humanitarian, training, and peacekeeping missions are necessary to provide medical support to those injured in these conflicts. The presence of such military medical facilities will inevitably create pressure to provide emergency medical treatment for children and other civilians. This is exacerbated by the destabilising effects of conflict on local healthcare systems, which may arise from destruction of facilities, lack of supplies, or lack of trained staff. Such systems may also have limited resources to begin with, and the additional workload and resource requirement may prove unmanageable. It is difficult to deny the devastated parents, presenting with a grotesquely injured child, the possibility of treatment. Regardless of the intended mission, medical teams working in conflict areas therefore need to be prepared to manage paediatric trauma safely, and effectively.

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23.2 Epidemiology of Military Injuries

Military field hospitals are all tasked under the Geneva Convention to provide emergency care for their own troops, enemy combatants and if needed, the civilian population injured in the conflict. A significant proportion of those civilian casualties will be children. Studies which have looked primarily at civilian treatment facilities show that children appear to make up about 20–60% of all casualties [2–5] whereas in the setting of a military field hospital they make up a much smaller percentage of overall attendances [3–12]. However, it is clear that as a percentage of the civilian population treated in these military facilities, childhood casualties represent approximately one-third of attendances [6–9]. An overall paediatric admission rate of 6–8% should be expected, with the commonest cause of injury being blast, generally due to the inadvertent triggering of an improvised explosive device (IED) or a unexploded ordnance (UXO) from legacy munitions [10, 11].

Treatment of children requires a significant amount of resources of both the operating room, and in-patient beds [7, 8]. McGuigan *et al.* demonstrated that despite children only representing 3% of total patients, they required between 7 and 11% of the total ICU and hospital bed day [6]. In Israel, children injured in terrorist incidents (predominantly blast or gunshot wounds) required more surgery, more intensive care admissions, and longer stays in hospital than those injured in non-terrorist trauma incidents [13]. Blast injured children required more operative procedures than adults in Afghanistan and Iraq, although this was not the case in children under the age of 3 years in spite of the higher mortality in this group [14, 15]. This is likely due to a combination of more severe injuries and multiple anatomical regions affected by the blast in a small child, but also lack of specialised personnel and equipment in combat hospitals treating these very young patients [11]. In addition, injured children can have a disproportionate effect on the morale of medical personnel in the treating unit. There are ethical and logistical dilemmas that arise from either withdrawal of treatment, or transfer to a local facility with fewer capabilities which can complicate management of patients with chronic diseases. Finally, follow up care may not be possible in some countries with a limited medical infrastructure.

23.3 Patterns of Military Injuries

Anywhere between 10 and 60% of civilian admissions to a Role 3 or Combat support hospital will be children depending on the situation and the eligibility matrix. Of these the median age will be approximately 8 years with a median weight of 20 kg; although in one study, 75–80% of paediatric admissions in Iraq and Afghanistan were male [10, 11]. The most common causes of combat paediatric trauma encountered specifically during war fighting operations (accounting for up to 60% by admission) are blast injury followed by gun shot wounds [9, 11, 14–16] (Table 23.1).

Table 23.1 Mechanism of injury leading to admission in a military environment. Derived from references [9, 11, 14–16]

Mechanism	In = 82
Blast/fragmentation	43 (52%)
Gun shot wound (GSW)	9 (11%)
Non-battle trauma	25 (31%)
Medical	3 (3.5%)
Elective	2 (2.5%)

Table 23.2 Pattern of injury of children admitted with traumatic injuries secondary to battlefield related trauma (reproduced from [11] with permission)

Anatomical area sustaining injury	Number (percentage)	By region
Head	24 (12%)	Head and neck 32%
Face	21 (11%)	
Eyes	14 (7%)	
Neck	3 (2%)	
Chest	14 (7%)	Torso 25%
Abdomen	24 (12%)	
Perineum	7 (4%)	
Back	5 (2%)	
Arms	31 (16%)	Extremities 44%
Legs	54 (28%)	

Battle related injuries were caused by blast in 43% and Gunshot Wound in 11% in Afghanistan whereas in Iraq GSW accounted for over 56% [9, 11]. The commonest cause of blast injury in Afghanistan was the Improvised Explosive Device (IED) and the legacy of 30 years of conflict means that there is a significant amount of UXO left in the ground. These injuries reflect the indiscriminate nature of these weapons and the fact that the inquisitive nature of children puts them at particular risk by discovering weapons and unknowingly using them as play things. Similar population studies have confirmed significant morbidity and mortality in Cambodia, Africa and Chechnya [17, 18].

A detailed review of all traumatic admissions to the Role 3 hospital, Camp Bastion in Afghanistan found that 44% of admissions had some form of extremity trauma (Table 23.2) but injuries were seen to all body systems. These patients were resource intensive with 40% requiring intensive care, 33% requiring blood transfusion and 74% visiting the operating theatre for a surgical procedure. They are much higher proportions than would be seen for admissions to a UK civilian Accident and Emergency department and reflect the severity of the injuries—using the new severity scoring system (NISS) 30% of admissions in the critical group had NISS > 25. At the time of this study severe head or eye injuries would be transferred to a nearby facility with neurosurgical and ophthalmology capability. The procedures these children needed reflected the anatomical distribution of injuries. Burns patients required the greatest number of trips to the operating room and all the procedures were performed by general surgery, orthopaedics and plastic surgery (Table 23.3). The authors of this study stated that none of the procedures needed the specific skills of a paediatric surgeon or anaesthetist [11].

Table 23.3 Major operative interventions required in 82 paediatric admissions to Camp Bastion over a 3 month period (derived from [11] with permission)

Procedure	Number of cases
Debridement soft tissue wounds only	29
Laparotomy	10
Skin grafts & flaps	7
Orthopaedic fixation	4
Vascular repair	4
Primary closure of wound	4
Enucleation	2
Elective	2
Tracheal repair	1

23.4 Differences Between Children and Adults in Terms of Blast

If the effects of blast alone are considered then we see clear differences between adults and children. This has been looked at for both civilian terror events [19–23] and war fighting associated injuries [11, 16]. Children are particularly susceptible to blast injury for three main reasons:

- They are smaller so more of their body is exposed to the direct effects of the primary and secondary blast
- Their lower weight means they will be thrown more violently to suffer more from tertiary injury
- Their smaller size also means that their face/torso is more likely to be exposed to burns for quaternary injury.

Detailed studies of the pattern of injury caused specifically by blast that children have a higher proportion of significant head injury but a lower incidence of extremity trauma than adults exposed to similar blasts [16, 24]. Reasons for this include:

1. Children being shorter, and are therefore more likely to have their head and face near the blast (especially IEDs & mines).
2. Children with significant extremity trauma (such as amputations) may be less likely to survive the pre-hospital phase.
3. Other local facilities, commanders, and approaches to the matrix for eligibility and medical rules of engagement for the conflict, may skew admission rates to individual units.

In spite of these differences, the types of procedures done on small children to treat blast injury were not significantly different from adults: mainly soft tissue debridements, vascular access procedures and decompressive procedures such as fasciotomy and craniectomy. Amputations were also common. This implies that for the majority of older children, the operative resources and personnel will be similar to adults [14, 16]. However, infants and toddlers will likely require specialised equipment and training that may not be possible at every remote treatment facility [15].

23.5 Pre-Deployment Training for Potential Paediatric Admissions

Most studies of role 3 or combat support hospitals within a war zone suggest that about 5–10% of admissions will be children [9] and could be much higher [5] so consideration must be made prior to deployment to prepare medical staff to deal with this. Although a significant portion of these injuries will be due to blunt trauma or burns, which are not unlike the injuries seen at Western trauma centres, no amount of civilian experience will expose clinicians to the injuries associated with battlefield trauma such as blast injuries, fragmentation and high velocity gun shot wounds. As discussed in the section on pattern of injury, the diversity of surgical procedures requires generalists with trauma experience and not the specialist skills of a paediatric surgeon or anaesthetist. Various courses can help prepare clinicians to deal with children such as the Advanced Paediatric Life Support course (APLS). Specific trauma surgery and anaesthetic courses (i.e. The UK's Military Operational Surgical Training or MOST course) can help by offering guidance on, for example, massive transfusion protocols, and also by raising awareness of the issue so that clinicians can prepare themselves mentally for the distressing sight of a severely injured child with penetrating wounds [25]. Readily available on line access to paediatric sub-specialists and clinical practice guidelines for traumatic injury would be useful for the generalist in a combat environment. Having a paediatric medical specialist assigned to a combat hospital as a consultant for all injured children is ideal but not essential [26].

23.6 Epidemiology of Civilian Ballistic Injuries

In civilian practice, the majority of paediatric gunshot injuries tend to be low velocity hand gun injuries. However in those less common instances where military style automatic weapons are used mortality is high, as demonstrated at Sandy Hook where all 20 children sustaining bullet wounds subsequently died [27]. In 2009 in the United States, there were over 7000 admissions for firearms related injuries in children aged 0–19 years, with an in-hospital mortality of 6.1% [28]. Overall, in the period 1999–2006, there were almost 24,000 firearm related deaths amongst children aged 18 years and under in the United States [27]. The patterns of civilian gunshot injury are generally different to those arising from military action. Patients were most likely to be black males, and aged 15–19 years of age. The most common injuries were open wounds (52.0%), fractures (50.4%), and torso injuries (34.2%). However, 20.8% of children less than 5 years of age suffered a traumatic brain injury, as compared to 8.3% of 15–19 year olds [28]. Reported in-hospital mortality rates range from 21% in a series from Alaska [29], to 2.5% in South Africa [30]; however the inclusion of mortuary statistics in the latter paper gives an overall mortality rate for firearm injured children of 17.6% (34/193). The in-hospital gunshot wound mortality from Camp Bastion 12.5% [31] is comparable to these figures.

23.7 Paediatric Trauma Bay

As with all trauma resuscitations, good organisation can help make things significantly less stressful. The paediatric experience of any one trauma team attending to an injured child will be variable. However, at the start of a tour if the paediatric experience of clinicians and nursing staff is known, then the best adhoc team can be assembled if children are admitted. A specific paediatric trauma bay, or if this is not possible a trolley, should be stocked with relevant equipment such as airway and venous access devices of appropriate sizes. One of the most useful adjuncts is the Broselow tape, which can be laid on the resuscitation trolley prior to the arrival and gives estimates of age, weight, drug doses and essential anaesthetic equipment such as endotracheal tubes etc. A moveable wipe board can be helpful to allow the calculation of drug doses & fluid boluses. A warming device should be available and placed early on the child because of the increased risks of hypothermia. Weight estimation should be done immediately. In some parts of the world many children and their parents do not know their date of birth let alone their age, so many of the formulas that we have cannot be applied. The standard Western formula (2× (age+4)) or the Broselow tape, have been based on calculations from Western populations so tend to overestimate the weight—in the Afghan population this was thought to be by about 20%. The calculation for children aged 1–5 years was reduced by 2 kg, and the weight for older children reduced by 4 kg [26].

23.8 Assessment of the Injured Child

It is beyond the scope of this chapter to give a detailed insight into the assessment of the severely injured child. However, certain principles should be born in mind:

1. *Response to hypovaemia*: children respond to hypovolaemia by intense vasoconstriction and tachycardia and thus sustain their blood pressure until the bradycardia associated with peri-arrest. For this reason blood pressure is not a good guide to adequacy of resuscitation. Heart rate, capillary refill, mentation, invasive arterial blood pressure, blood gases and urine output are more reliable indicators [26, 32].
2. *Psychological trauma*: beware of children that are excessively quiet with staring eyes and an intense pallor, the striking lack of crying and response to pain is more likely to be secondary to severe shock.

3. *Presence of family members*: children are usually scared and disorientated by being brought to hospital. Thus having a relative in the resuscitation room with them can enormously help the assessment and cooperation of the child. Performing resuscitation on a very sick child (including cardiopulmonary resuscitation) with a relative present is the norm in Western paediatric emergency rooms, but it takes confidence and can be disconcerting initially for the non-specialist. One strategy, if resources allow, is to allocate a nurse and interpreter to stay near to the child and maintain eye contact and conversation with both the child and the relative. They can explain processes and offer comfort. If the relative is unable to cope then the nurse can escort the relative away so that there is no disruption to the resuscitation.
4. *Gastric decompression*: crying children tend to swallow large amounts of air which can quickly impair ventilation. Unless contraindicated by a severe craniofacial injury, gastric decompression should be done early in the assessment.
5. *Analgesia*: any injured child will be in pain, which will make both the assessment and any attempts at gaining cooperation more difficult. Judicious use of intravenous analgesia titrated in small aliquots can be of great benefit to both the child and the resuscitation team, and decrease the likelihood of severe post traumatic stress disorder.
6. *Vascular access*: peripheral venous access should initially be attempted but can be very difficult in an alert, uncooperative child, or a child in shock. If this is not successful, an intraosseous line should be placed without delay. Intraosseus access has transformed our ability to resuscitate shutdown children. The proximal tibia followed by the humerus are the best sites; the sternal intra-osseous site should not be attempted in children under the age of 12 years. Once the needle is in place, the extremity needs to be monitored closely for evidence of compartment syndrome (which can occur if the needle is dislodged into the soft tissue). More definitive peripheral or central access will need to be obtained within 12–24 h to avoid this complication as well as osteomyelitis.
7. *Teamwork*: good communication, leadership and coordination are key to any resuscitation but are particularly important when associated with a sick child and the presence of a distressed relative. Discussion of these issues and practicing scenarios before hand are the best way to optimise performance.

23.9 Role of Imaging in Assessing Paediatric Trauma Patient

While the role of FAST scans have not been validated in children with blunt trauma they are a major part of the assessment of adult patients and thus should be used if available. Remember, however, that in the context of blunt trauma alone finding free fluid within the abdomen does not necessitate a laparotomy. Similarly, lack of free fluid does not eliminate the possibility of a solid organ injury in a child after blunt injury. The splenic and hepatic capsules in children are more robust, therefore a significant injury may be present even without much haemoperitoneum. In penetrating abdominal trauma associated with gun shot wound or fragmentation, a positive FAST scan and a haemodynamically unstable patient is an indication to go straight to the operating room. Diagnostic peritoneal lavage has no place in paediatric practice. If available the gold standard for imaging in children is the CT scan with intravenous contrast. The latest 64-slice CT scanners provide excellent anatomical imaging and enormously benefit the surgeon trying to plan an operation. Likewise detailed knowledge of the position and path of a projectile can prevent unnecessary opening of body cavities. As the lifetime risk of radiation in children is greater than in adults, one should not perform unnecessary scans. However, it is clear that in the severely injured child the morbidity and mortality associated with their injuries outweighs the risks of radiation, and accurate knowledge of the internal anatomy is of paramount importance in optimising treatment. Establishing appropriate protocols to do a non-contrast CT of the head followed by a contrast CT of the remainder of the body can save time. It is important to realise that the scanning room is not an ideal environment for a sick patient, so these children must be transferred by an experienced anaesthetist and team with appropriate emergency drugs and equipment.

23.10 Cervical Spine Injury

Blunt injury to the paediatric cervical spine is exceedingly uncommon, with figures quoted in the region of 0.5% for children aged 0–9 years at major urban trauma centres [33]. The incidence increases with age, to 2.6% of adolescents [33]. Similarly to adults, children can have their cervical spine cleared based on clinical criteria alone, even if they are preverbal [34]. However, due to the higher incidence of ligamentous injuries and lack of soft tissue around the spine, a normal cervical spine CT scan does not eliminate the possibility of injury in a young child where there is clinical suspicion.

23.11 Vascular Access

In the seriously sick child central venous access will eventually be necessary to give resuscitation fluids and monitor central venous pressures as a guide to intravascular filling. The great veins of the neck are the site of choice but the femoral vein can be used if necessary. An ultrasound guided approach to the internal jugular vein is the best choice and ultrasound should always be used if available, because of the variability in anatomy that occurs with age. A shocked, shutdown child will have virtually empty great veins, increasing significantly the risk of being unable to access the vein and the associated complications of pneumothorax, haemothorax, pericardial tamponade and arterial puncture. Portable ultrasound machines with a high frequency (5–10 MHz) hockey stick probe are now widely available in emergency departments and operating theatres. This procedure should be done only under controlled settings in the sedated and anaesthetised child. Central venous lines can be very helpful in the immediate post-operative period as blood sampling or peripheral venous access can be difficult for non-specialists. However, ease of access is no excuse for leaving in a central line in for any longer than absolutely essential. They should all be removed after a week in the deployed setting, as this is a generally less clean environment than a hospital ward; all central venous lines should be accessed with an aseptic no touch technique.

23.12 Damage Control Resuscitation and Surgery

The initial management of the severely injured adult has now been well established with Damage Control Resuscitation (DCR) following the <C>ABC principles, followed by damage control surgery to control bleeding, limit contamination and reduce the bacterial load by debridement of dead dirty tissue and irrigation. The patient is then admitted to intensive care for correction of the deadly triad of acidosis, hypothermia and coagulopathy, before returning for definitive repair. Though there is a wealth of information on the benefits of damage control surgery in adults there is little equivalent literature in children. It was reported that children with critical injuries at Camp Bastion responded well when managed by the same principles of damage control surgery as practiced for adults [11]. The mortality in this study was 3%. Hence the same principle of management should be applied to children who physiologically are very similar to young fit adults. They respond well to control of bleeding, aggressive fluid replacement and rewarming. As children have a good blood supply and are inherently good at healing, debridement should be as conservative as possible to preserve tissue which may be of importance to future growth and development.

Avoidance of hypothermia is essential in all DCR, but is of particular importance to consider early in children whose larger relative body surface area makes them especially prone to it. Adjuncts such as fluid warmers, thermal mattresses, raising the temperature of the operating theatre and avoiding excessive exposure of the body especially during surgery can all help. For the patient who arrives hypothermic, forced air warmers and peritoneal or bladder lavage with warm saline may be useful [35]. The principle of DCR in adults is to replace intravascular volume with packed red cells and fresh frozen plasma in a one to one ratio. Definitive studies on this are lacking in children, although many centres have adopted the following approach (Fig. 23.1). Fluid is given in boluses of 10–20 mL/kg, and in the bleeding patient, or the patient in clinical shock due to a penetrating injury, blood should be given as early as possible. Setting up a system that allows this to be done easily while still incorporating a blood warmer is essential, and such a system was successfully used in Afghanistan [32, 36]. To help guide the clinician a worksheet (Fig. 23.1) has also been developed for use in the massive transfusion situation. Rotational thromboelastography (ROTEM®, Pentapharm Gmbh) can help guide the need for blood products and anti-fibrinolytics in trauma associated coagulopathy. A fluid warmer is also essential for all fluids and transfused products.

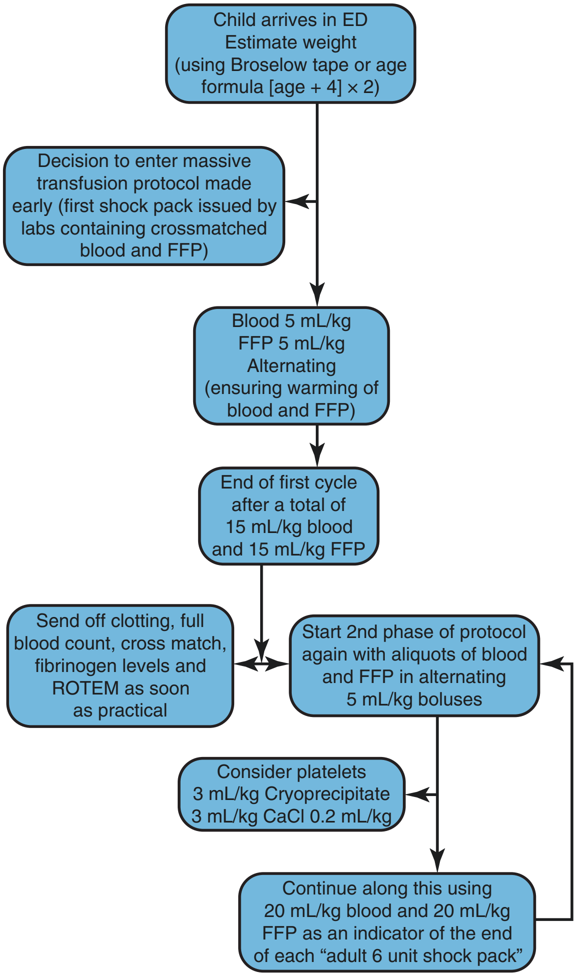

Fig. 23.1 Pediatric massive hemorrhage resuscitation protocol. Reproduced from: Bree S, Wood K, Nordmann GR, McNicholas J. The paediatric transfusion challenge on deployed operations. J R Army Med Corps. 2011;156(4 Suppl 1):s361–4. *ED* Emergency Department; *FFP* fresh frozen plasma; *RoTem* rotational thromboelastometry (Tem innovations GmBH, Munich, Germany)

Fibrinolysis is a risk for the most severely injured patients and the CRASH 2 trial showed a benefit of using tranexamic acid early in the management of major trauma in adults. There is no equivalent study in children but at the UK Role 3 Hospital, Camp Bastion between 2006 and 2013, tranexamic acid was given at a dose of 15 mg/kg *early* in the resuscitation [32, 36]. Calcium Chloride is also given at regular intervals in the massive transfusion protocol as dictated by the ionised calcium result and guided by a massive transfusion worksheet.

23.13 General Surgery

Children should be managed in the same way as adults for all ballistic trauma. For penetrating abdominal injury the quickest access to the peritoneal cavity is a midline incision rather than the transverse incision that is usually used for elective paediatric surgery. However in small babies it is still possible that a side to side incision provides the best access to the entire abdomen. Care should be taken because the abdominal wall is much thinner and the liver protrudes below the costal margin so is at risk of laceration on entering. In all other aspects, however, the child's abdomen is relatively easy to operate on as the abdominal wall is usually thin with little fat, the organs are relatively easy to reach and the pelvis is relatively shallow. Blunt chest injury rarely causes rib fractures but does often lead to significant pulmonary contusion. These can be managed conservatively with good pain relief and assisted ventilation. Due to the mobility of the paediatric mediastinum, pneumothorax can progress rapidly to tension physiology. Therefore, all children with suspected trauma to the chest should have a chest radiograph. If chest drains are required for significant pneumo- or haemothorax then these are inserted in the usual way. However, remember that different sizes will need to be available, and that a finger sweep once into the cavity is near impossible. If a thoracotomy is needed for penetrating trauma then a clam shell incision should be used. An antero-lateral left sided thoracotomy will usually need early conversion to a clam shell simply to allow the operator to get their hands into the pleural cavity.

23.14 Orthopaedic Surgery

In current conflicts extremity trauma is the commonest injury experienced by children, although traumatic amputations were relatively rare during the Afghanistan conflict [10, 11, 16]. One potential explanation is that proximity of the torso and head area means that blasts causing amputations are more likely to be fatal. Children's bones and soft tissues are different to adults; their skeletons and soft tissues are smaller, more elastic, quicker healing and the bones are growing due to the active growth plates. Management should still be along damage control principles but if there is no need for great urgency then obvious fractured limbs require AP and lateral x-ray views. Any limb with significant fragmentation injuries should also have a single AP view to determine if there are any retained fragments. All patients with significant trauma should have a 'CT traumagram' from head to pelvis. If there is evidence of vascular compromise then a CT angiogram of the limbs can be done at the same time.

Ballistic limb injuries in children need to be treated along the same principles as adults i.e. thorough debridement & washout of wounds followed by stabilisation of fractures. All devitalised and grossly contaminated tissue must be excised, but areas of questionable viability can be kept for a second look at 48 h with delayed primary suture of day 5 if the wounds are clean and healthy. As a rule, children heal very well so err on the side of preserving tissues when there is doubt about their viability. Stabilisation of fractures can be achieved in a number of ways, but Plaster of Paris is the most practical form in a war zone in many parts of the world. Longitudinal traction using a Thomas splint for long bone fractures is another possibility, but the ability of the ward or ITU to apply traction should be checked first. Formal exploration of limb injuries with possible vascular or nerve injuries and distal ischaemia or neurological deficit may be required. Discussion should be had between the surgeons, medical director and family prior to embarking on a long and complex reconstruction as early amputation may give earlier return to activity and better long term function. Fortunately whatever limb injuries the child has they usually heal well; children with at least 2 years of growth left (generally aged 14 for boys and aged 12 for girls) will substantially remodel any fractures and have minimal disability.

23.15 Maxillofacial and Cervical Trauma

The management of facial fractures is highly dependent upon the patients age, with children over approximately 12 years old generally being treated such as adults. Controversy exists over the need for removing titanium miniplates used in young patients and no evidence exists that this is required once growth is complete. The use of resorbable plates is useful in selected cases, particularly for paediatric mandible fractures. Technically their placement can be challenging due to their relatively large size as paediatric sized adsorbable plates are not readily available.

The diagnosis and treatment algorithms for paediatric cervical trauma are similar to that of an adult. As such they are highly dependent upon the diagnostic facilities available and the experience of the clinicians involved. No consensus exists as to the requirement for the need for surgical exploration of penetrating injury. Zone 2 (cricoid cartilage to lower border mandible) injuries can potentially be explored without the need for the adjunctive procedures required for Zones 1 and 3. Laryngeal trauma is uncommon in paediatric patients because of the elevated position of the larynx underneath the mandible, and the cartilaginous structure of the paediatric larynx (which is commonly ossified in adults). Presenting symptoms of laryngeal trauma include hoarseness, stridor, crepitation and subcutaneous emphysema. Acute management consists only of appropriately securing the airway. Definitive management can then be performed by the appropriate specialists.

23.16 Penetrating Head Injury in Children

Penetrating head injuries can range from the relatively minor to catastrophic. Mathew *et al.* reported a series of 16 children in Afghanistan, all with ballistic penetrating head injuries [37]. All were treated with intravenous antibiotics, excision of devitalised tissue, and irrigation; none required brain resection. Minor cases of penetrating injury simply required scalp and extradural space exploration only. Moderate cases, with wider haemorrhagic tracts seen on CT were managed with removal of a bone flap, clot extraction, and irrigation. Of these cases, 2/7 had the bone flap replaced immediately, whilst 4/5 subsequently returned for delayed cranioplasty. One case was lost to follow up. This series demonstrates that such injuries can be effectively managed in austere environments, provided that a commitment is made to facilitating follow-up surgery.

23.17 Maintenance Fluids

As soon as is practical the child should be weighed so that accurate calculations of drug doses and intravenous fluids can be made rather than an estimate based on age or the Broselow chart. Maintenance fluids can be calculated from the following simple formula:

$$4\,\text{mL}/\text{kg}/\text{h for the first } 10\,\text{kg} + 2\,\text{mL}/\text{kg}/\text{h for second } 10\,\text{kg}$$
$$+1\,\text{mL}/\text{kg}/\text{h for anything over } 20\,\text{kg}$$

This will give a good estimate of the maintenance fluid requirement over 24 h. Hartmann's is a reasonable choice of fluid as there is no risk of giving excessive amounts of hypotonic fluid. In all children and in particular those who are small or malnourished, there is a high chance of developing hypoglycemia. In neonates (less than 28 days of age) 10% dextrose with 0.45 or 0.9% saline (half normal or normal saline) is the fluid of choice. It is usual not to add potassium for the first 24 h but after that it should be added at 20 mmol/L. Urea and electrolytes should be tested daily in any child on intravenous fluids but can be done with a finger prick if venous blood is difficult to get.

23.18 Nutrition

Nutrition is essential for all trauma patients but is particularly important in children because of their high basal metabolic rate. Parenteral nutrition is not available in the deployed setting but enteral nutrition via nasogastric (NG) or nasojejunal (NJ) tube should be started as soon as the ileus starts to resolve. Children develop a profound ileus after almost any form of severe stress or sepsis even if it does not directly affect the abdomen; the signs of an ileus are thick bilious dark green aspirates from the NG tube. Attempts at feeding during an ileus tend to make the child distended and vomit, all of which is upsetting for both the child and the parent. If the child is thirsty with a dry mouth clear fluids can be allowed while the NG tube is left on free drainage. Once the ileus starts to resolve feeds can be started as a continuous infusion and should be continued until the child is feeding well by mouth. If the child is just starting to get an appetite then one strategy is to give tube feeds overnight and allow normal diet during the day to encourage eating. In children over the age of 1 year, adult tube feeding formulas may be used if they are all that is available. They will have protein concentrations generally 1–2 times what is needed for children. If needed, additional non-protein calories can be given in the form of vegetable oil (6.6 kcal/mL) or dextrose (3.4 kcal/mg). Infants in general should only be given breast milk or infant formula rather than cow's milk due to immaturity of the gut [38].

23.19 Specialist Advice in a Conflict Zone

In developed health care systems most severely injured children will eventually be transferred to a specialist children's hospital for continued care. This is simply not an option for most adult generalists who have to deal with children from the local population injured in a war zone. It is recommended that any clinician deploying in austere settings should develop a relationship with a tertiary level teaching hospital via a reliable telephone link or preferably videoconferencing [31]. In the British medical unit in Camp Bastion, Afghanistan, such a direct link to the intensive care unit of a tertiary children's hospital also enabled the provision of paediatric sub-specialist advice through a single point of contact [31]. Where longer-term medical input is anticipated, links to local or non-governmental healthcare facilities will help guide realistic expectations as to the resources which are available, and thus medical management.

23.20 Withdrawal of Treatment

Terrible injuries are seen in war and there is nothing more distressing than the sight of injured children with their distraught parents. Decisions about treatment in such scenarios will also need to consider competing pressures for critical care resources, and the ability of deployed or local medical services to provide potentially long-term care and rehabilitation [31]. In all cases it is kinder for the clinician to be honest with the family at an early stage about the potential for survival and the likely level of disability. When there is no likelihood of survival, or if after initial treatment it is felt that future intervention is likely to be futile, then a palliative treatment pathway should be instituted as early as possible. The Basic Symptom Control in Paediatric Palliative Care has guidance on best practice in these difficult situations [39].

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Ballistic Trauma in Pregnancy

24

Tracy-Louise Appleyard

24.1 Introduction

It has been reported that trauma will complicate approximately 1 in 12 pregnancies [1]. Within the UK the latest triennial report on maternal deaths 2012–2014 reported that 41/241 women died as a result of 'coincidental' deaths (deaths from unrelated causes which happen to occur in pregnancy or the puerperium) [2]. Of those 9 were the result of homicide and 32 by 'other causes' which include trauma. No suicides were caused by gunshot in this triennium. Morbidity data is not routinely collected nationally. In a large retrospective study 9% of the admissions involved penetrating trauma to the abdomen and 77% were gun related (22/321) [3]. Worldwide there is a paucity of good quality data evaluating ballistic trauma in pregnancy with mainly case reports and retrospective studies looking at penetrating trauma. A systematic review reported estimates of incidence/prevalence of penetrating trauma of 3.27/100,000 live births which are the same as those reported outside of pregnancy (using data from 2009 Centers for Disease Control and Prevention) [4]. The maternal mortality rate from penetrating trauma is less than in the non-pregnant population possibly due to the protective effect of the gravid uterus to the internal organs [5]. Trauma is pregnancy is mostly associated with intermittent partner violence (IPV) and road traffic accidents [4].

All forms of trauma in pregnancy can result in injury or death to the pregnant woman and the fetus. There is increased incidence of preterm labour, miscarriage, preterm premature rupture of membranes, uterine rupture, caesarean delivery, placental abruption and stillbirth [4]. In major trauma in pregnancy, abruption occurs in 70% of cases with fetal loss in 35% of cases whilst uterine rupture is less common (less than 1%) but with a 10% maternal mortality rate. Fetal death occurs in up to 40% of major and 2% of minor injuries [6].

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24.2 Changes in Pregnancy

Pregnant women undergo unique physiological and anatomical changes and knowledge of these can aid the team in management of the pregnant trauma patient. The possibility of pregnancy should be considered in all female trauma patients of reproductive age. A co-ordinated multi-professional approach to the care of pregnant women will improve the standard of care they receive and the latest MBRRACE-UK report highlighted that doctors should be appropriately trained in and engaged with the care of pregnant women [2].

24.2.1 Physiology

Significant physiological changes occur in pregnancy even within the first trimester and awareness of these can help in the management of pregnant women with trauma, Table 24.1.

Changes within the cardiovascular system are the most marked and occur even within the first few weeks of pregnancy. Cardiac output increases by 20% within the first trimester probably to compensate for the peripheral vasodilation which causes a 25–30% fall in systematic vascular resistance. By 20–28 weeks cardiac output has increased by up to 40% through an increase in stroke volume and to a lesser degree by increases in heart rate. Blood pressure falls within the 1st and 2nd trimesters and rises to non-pregnant levels in the 3rd trimester.

Plasma volume increases throughout pregnancy to approximately 150% of normal by 34 weeks' gestation (from 5 to 6–7.5L). This increase is greater than that of the red blood cell mass resulting in a dilutional anaemia (normal Hb > 105 g/dl). The platelet count falls progressively but usually remains within the normal range and women are not thought to thrombocytopenic unless the level is $<100 \times 10^9$ cells/l. Further changes within the coagulation cascade induce a pregnancy-induced hypercoagulability which is protective, preventing bleeding in labour and the post partum period. Pregnant and postnatal women are at increased risk of venothromboembolism.

The gravid uterus compresses the vena cava and aorta in the supine position and at term the inferior vena cava is occluded in 90% of supine pregnant women. This decreases venous return and cardiac stroke volume (up to 70%). During assessment and resuscitation of a pregnant woman, aortocaval compression should be kept to a minimum. This can be achieved by manual uterine displacement to the left when supine or by tilting the firm surface she is on, e.g. the operating table, 15–30 degrees to the left; Fig. 24.1. Once the baby is delivered then the vena cava flow returns and both venous return and cardiac output return to normal.

The physiological changes mean that a woman can tolerate haemorrhage of up to 1500 ml with almost no noticeable changes in her vital signs. Uterine artery vasoconstriction occurs to maintain the mother at the expense of the fetus and there is no autoregulation of uterine blood flow. Assessment of the pregnant woman should include assessment of the fetus as the fetus can show signs of poor uteroplacental blood flow before the mother shows changes in her vital signs (5th vital sign).

Table 24.1 Physiological changes in pregnancy

Cardiovascular		
• Cardiac output	Increases by 20–30% (by 10 weeks) and 40% at term	
• Heart rate	Increases by 10–15 bpm (16%)	
• Blood pressure	Decreases by 10–15 mmHg systolic and diastolic in 1st and 2nd trimesters	
• Peripheral vascular resistance	Decreases	
• Plasma volume	Increases by 50%	Dilutional anaemia
• Aortocaval compression	In supine position the gravid uterus compresses the inferior vena cava, reducing venous return to the heart	
Respiratory		
• Diaphragm	Splinting and elevation by 4 cm	Susceptible to hypoxia sooner—Smaller reserve to withstand apnoea. More difficult to ventilate.
• Minute ventilation	Increases by 40–50%	
• Tidal volume	Increases by 30–40%	
• Oxygen requirement	Increases by 20%	
• Functional residual capacity	Reduces by 20%	
• pH changes	Fully compensated respiratory alkalosis pH 7.40–7.46	
Gastrointestinal		
• Gastric emptying	Delayed	Vomiting and passive regurgitation more common
• Oesophageal sphincter	Relaxes	
Other		
• Coagulation cascade	Reduced platelet count Increase in fibrinogen (up to 50%) Resulting in a hypercoagulative state	Protective to prevent bleeding in labour and postpartum
• Musculoskeletal	Increased ligament laxity	

There is a 20% increase in the oxygen requirement (fetus and mother) through an increase in the metabolic rate and increased consumption of oxygen. There is a 40–50% increase in minute ventilation mostly due to an increase in tidal volume with no real change in the respiratory rate and a consequent maternal hyperventilation. A mild compensated respiratory alkalosis is normal in pregnancy (7.40–7.46) compared to the non-pregnant state (7.34–7.44). The gravid uterus causes upward displacement of the abdominal organs, diaphragmatic elevation, subsequent decreased lung compliance and a resultant reduced functional residual capacity by up to 20%. This means that pregnant women become hypoxic quicker (smaller reserve to withstand apnoea). There is significant need to protect the airway and provide adequate ventilation, which is also hindered by oropharyngeal oedema, weight gain and larger breasts. Women can also experience a subjective feeling of breathlessness without hypoxia.

Fig. 24.1 Manual uterine displacement to the *left*

24.2.2 Gastrointestinal Changes

Nausea and vomiting are very common complaints in normal pregnancy (50–90%). Delayed stomach emptying and oesophageal sphincter relaxation are increased in pregnancy increasing the chance of pulmonary aspiration of stomach contents. Use of H_2 antagonists e.g. Ranitidine can reduce the risk. At the start of the 2nd trimester the gravid uterus begins to rise out of the pelvis pushing the bowel upwards. The peritoneum is less sensitive and the omentum is less able to contain local inflammation.

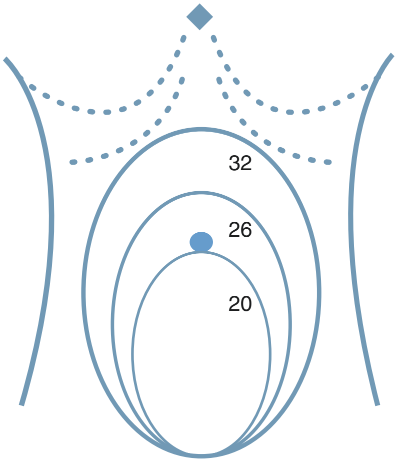
All the physiological changes result in:

- The woman being able to sustain significant blood loss before showing changes in her vital signs
- The fetus potentially showing signs of maternal compromise before the mother
- The woman not being able to tolerate apnoea for even short periods becoming hypoxic quickly
- Aortocaval compression in the supine position from the gravid uterus requiring manual displacement to the left or lateral tilting
- Apparently minor maternal trauma causing major morbidity or mortality in the fetus

24.2.3 Anatomy

Anatomical changes also take place, the most important in the abdomen and chest. The gravid uterus slowly rises out of the pelvis from 12 weeks gestation displacing the abdominal organs upwards. By 20 weeks gestation the fundus is at the level of the umbilicus and to just at the level of the lowest ribs at 32 weeks; Fig. 24.2. As the pregnancy advances the uterus changes from a thick walled structure protecting the small fetus with a relatively large amount of amniotic fluid to a thinner walled structure with a large fetus and proportionately less amniotic fluid. Thus the fetus presents a larger target for traumatic injury. The gravid uterus affords some protection to

Fig. 24.2 Fundal height and gestation



retroperitoneal structures and in late pregnancy the liver and spleen, but also makes the assessment of likely injury more challenging. The peritoneum is less sensitive and the omentum is less able to contain local inflammation. The diaphragm is elevated and splinted. Smooth muscle relaxation occurs causing oesophageal sphincter relaxation with a higher risk of gastric aspiration. There is dilatation of the renal pelvis and ureters. The symphysis pubis and sacroiliac joints widen. There is generalised oedema which can involve the oropharynx. Women tend to gain weight and have larger, heavier breasts.

These changes result in:

- Pattern of injury more difficult to predict
- Risk of gastric aspiration increased
- Risk of difficult intubation
- Ventilation more difficult
- Assessment of injury more difficult
- Resuscitation in the supine position more challenging
- Placement of thoracostomy tubes should be 1–2 intercostal spaces above the usual site of insertion

Ballistic trauma associated with blast cause varying degrees of injury with the primary blast injury and then secondary blast (fragment) injuries. The main concern is of placental abruption with massive haemorrhage and fetal death. Placental abruption is the commonest cause of fetal death [4]. Placental abruption is generally associated with abdominal pain, uterine tenderness, uterine rigidity (woody) and vaginal bleeding but none of these can be present and massive haemorrhage can be concealed within the uterus. Another risk is preterm labour or miscarriage following trauma even if the injury was assessed as minor.

These changes can result in it being more difficult to recognise the deteriorating patient as identified in MBRRACE 2016 [2]. Indeed MOET (Managing Obstetric Emergencies and Trauma, Advanced Life Support Group), the Maternity Foundation (Practical Obstetric Multi-Professional Training) and the RCOG have all put together teaching packages to help with this [6, 7]. Presentation may be atypical or insidious. Signs and symptoms can be attributed to normal pregnancy changes and those not trained in pregnancy specific changes may misinterpret findings.

Modified Early Obstetric Warning Score (MEOWS) charts are very helpful in identifying the 'abnormal.' Regular monitoring of observations will aid in the recognition of changes in condition and can improve detection of life threatening illnesses; Fig. 24.3. All women who enter an acute hospital setting should have their observations recorded on a MEOWS chart [8, 9]. Changes in the scores allow prompt escalation to a specialist and reduce likelihood of delay in recognising deterioration.

24.3 Initial Assessment of the Pregnant Woman with Ballistic Trauma

Initial management follows the usual systematic approach employed by ATLS but with reference to MOET and PROMPT both of which guide management in pregnant women [6, 7, 10]. A multidisciplinary trauma team approach including an obstetrician, obstetric anaesthetist, midwife and neonatal team improves outcome [6]. The obstetrician can assess gestation, optimise uteroplacental perfusion and assess fetal wellbeing.

24.3.1 Primary Survey

If the woman is able to communicate, then directed questions concerning pregnancy, the gestation and presence of fetal movements should be asked. Women are not always aware that they are pregnant and women should be assumed to be pregnant until proven otherwise. A urinary pregnancy test should be taken if possible. Pregnancy causes profound physiological changes even in the 1st trimester and management decisions will be affected. Immediate life threatening problems must be managed as soon as they are identified systematica lly in the primary survey in the standard approach of A, B, C. Resuscitation of the mother is the priority and in doing so will optimise the outcome for the fetus. The team should ensure they avoid the lethal triad of hypothermia, acidosis and coagulopathy.

A quick assessment of gestational age should be made to ensure manual uterine displacement of the uterus to the left or left lateral tilt 15–30 degrees if being nursed in the supine position and over 20 weeks gestation (uterine fundus at the umbilicus), Fig. 24.1.

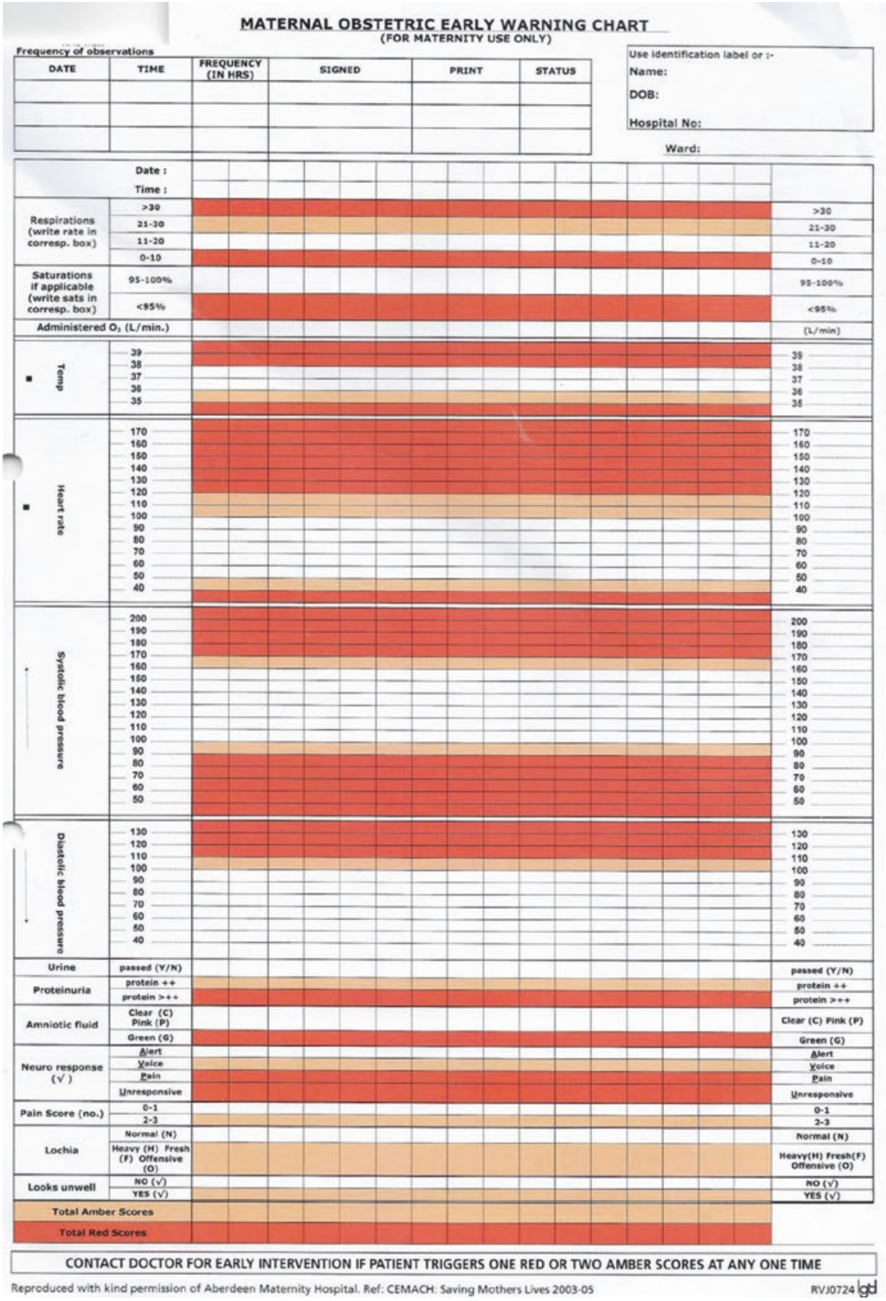


Fig. 24.3 An example of a Modified Early Warning Score (MEOWS) chart (reproduced with the kind permission of the PROMPT Foundation)

24.3.1.1 Airway

Pregnant women have a greater risk to their airway and difficult intubation compared to non-pregnant women. If airway problems are anticipated given the injury sustained then early intubation should be considered. To avoid gastric aspiration a woman with reduced consciousness should have a naso-gastric tube inserted insert two large-bore intravenous cannulae whilst taking baseline full blood count, coagulation, group and save and renal function.

24.3.1.2 Breathing

High flow oxygen via a rebreathe mask should be given to maintain maternal oxygen saturation above 95%. If a thoracostomy tube is needed then it should be inserted 1–2 intercostal spaces above the usual site of placement [6].

24.3.1.3 Circulation

Two large-bore intravenous cannulae should be inserted to allow rapid infusion of warmed crystalloid fluid or blood products. Bloods can be taken for full blood count, clotting, cross-match, renal function and a Kleihuaer test (fetal-maternal haemorrhage). Fluid resuscitation should be initiated early in pregnant women to maintain normal plasma volume but the team should be mindful of dilutional coagulopathy. Hypotensive resuscitation is not recommended in pregnant women [4, 6]. Early activation of the 'massive haemorrhage protocol' should be considered. If fully cross-matched blood is not available after 2–3.5 l of intravenous fluids have been given or if bleeding is ongoing then O-negative or type specific blood should be given without delay [11]. Clearly, this approach to the use of crystalloid fluid is a distinct feature of trauma management in obstetric patients. Vasopressors should not be used routinely in pregnant women with hypotension, rather, they should have judicial fluid resuscitation. Vasopressors have adverse effects on uteroplacental perfusion. Usual transfusion protocols should be followed with a ratio of 4 units of FFP to 6 units of red blood cells being recommended [7], and replacement of other products e.g. cryoprecipitate to keep fibrinogen greater than 2 g/l and platelets should be given when the platelet count is less than 75×10^9/l [12]. If the woman is Rhesus negative then Anti-D should be given within 72 h unless the injury is remote from the placental site [13].

Haemorrhage control should also follow the same principles as in non-pregnant patients. Compressible haemorrhage should be controlled but haemorrhage from injury to the uterus is not compressible whilst the fetus is in-utero. Specific techniques are discussed later.

Observations should be documented onto a MEOWS chart to allow easy recognition of parameters outside 'normal' for pregnancy. It should be remembered that the usual signs of hypovolaemic shock are not always easily seen in the pregnant woman.

If the woman collapses or develops cardiac arrest then the usual Advanced Life Support guidance should be followed [14]. (See Maternal Collapse).

24.3.2 Secondary Survey

Again, this should follow the standard approach but should include assessment of fetal wellbeing and abdominal pain. Maternal haemorrhage results in maternal hypovolaemia and hypoxia but can show as signs of fetal hypoxia before signs are seen in the mother. Early siting of a nasogastric tube should be considered to reduce risk of aspiration of stomach contents. Catheterisation of the bladder is helpful for monitoring but also to aid investigation of injuries sustained e.g. blood stained urine could indicate uterine trauma. Abdominal examination may reveal palpation of fetal parts ex-utero indicating uterine rupture. Continuous CTG monitoring should be considered. Assessment of fluid loss per vagina could reveal bleeding or ruptured membranes.

The woman can have all the usual diagnostic investigations to assess her injuries and these should not be delayed because of concern about radiation risk for the fetus. The majority of imaging techniques required for the management of a pregnant trauma patient deliver acceptably small doses of radiation to the fetus [6]. Cases should be discussed with a radiologist but never denied on the basis of risk to the fetus if the mother is seriously injured.

24.3.2.1 X-ray

Standard chest x-ray with shielding of the gravid uterus should be performed with the same threshold as in non-pregnant trauma.

24.3.2.2 FAST Scan

Good results have been noted in pregnancy for Focussed Assessment by Sonography in Trauma (FAST), it being a bed-side, non-invasive, repeatable test. The limitations to its use however include difficult evaluation of the Pouch of Douglas, unless in the early part of pregnancy, and it may not identify small intraperitoneal bleeds, injuries to the bowel, pancreas and diaphragm or placental abruption (misses up to 75%) for which clinical suspicion is a much better test than ultrasound [13]. Advantages of its use are for fetal heart visualisation and placental location [6].

24.3.2.3 CT

CT imaging is a highly sensitive and specific examination, superior to FAST, in detecting retroperitoneal injuries with a high negative predictive rate. It should only be performed in stable patients when there is as yet no clear indication for laparotomy [6, 10]. Although concern is often raised over the effect on the fetus of the dose of ionising radiation the majority of imaging techniques required for seriously ill patients deliver acceptably small doses of radiation to the fetus (chest, abdomen and pelvis CT scan mean 0.06–25 mGy). Imaging of pregnant woman should always be discussed with the radiology team but should rarely be denied on the basis of risk to the fetus in a seriously ill pregnant woman [6, 15].

24.3.2.4 Diagnostic Peritoneal Lavage

Although rarely used in modern trauma management, diagnostic peritoneal lavage should be done as an open supraumbilical procedure [6].

24.4 Structured Trauma Laparotomy

When a woman has sustained ballistic trauma to her abdomen the site of entry is important in deciding whether a trauma laparotomy is needed. If the entry wound is in the upper abdomen with penetration of the peritoneum there should be a low threshold to perform a laparotomy particularly if liver or spleen injuries are suspected. If the entry wound is below the level of the uterine fundus, the woman stable and the fetus dead or less than 23 weeks gestation selective non-operative management with close observations and a vaginal birth may be considered [5]. The uterus offers some protection to other structures. At laparotomy, the uterus should be carefully inspected without twisting or excessive traction and the surgeon should exclude it as a source of concealed haemorrhage. A trauma laparotomy is not an absolute indication for a caesarean section. The risk of precipitating labour after exploratory laparotomy is negligible, if proper care is taken [6]. A routine caesarean section can add a further 1000 ml of blood loss and as such significantly increase the blood loss and operative time.

24.4.1 Intraoperative Cell Salvage

This is now used routinely in obstetric practice where women are at risk of massive haemorrhage or where women refuse blood/blood products [13]. Previous concerns about amniotic fluid contamination returning into the maternal circulation causing AFE appear to be unfounded. Its use could be considered in trauma cases, although not where there is injury to the bowel or other contamination.

24.5 Caesarean Delivery

Indications for urgent caesarean delivery should include suspected uterine injury or rupture and should be only performed with an uninjured uterus to allow access to extra-uterine injuries e.g. low rectal injury or need for retroperitoneal exposure, where pelvic fixation is required to control haemorrhage, maternal cardiac arrest, suspected amniotic fluid embolus and fetal distress but remembering that maternal wellbeing is the priority. In cases of fetal death it can be more appropriate to induce labour and achieve a vaginal birth later.

24.6 Specific Haemorrhage Control

24.6.1 Antepartum Haemorrhage (APH)

When the injury is thought to be associated with massive antenatal haemorrhage (direct trauma to the uterus, uterine rupture or placental abruption) then expediting delivery is the most effective way of managing the haemorrhage control [13]. In the trauma situation this is most likely to be through a caesarean section unless the woman is in labour with the cervix fully dilated. A caesarean section in association with massive antepartum haemorrhage will be technically challenging regardless of cause. Senior obstetric assistance should be sought as well as from the neonatal team, even when there is thought to be no fetal heart activity. The baby when delivered can be examined by the neonatal team who can then decide if resuscitation is futile. Assessment of the fetal wellbeing in these situations is very difficult antenatally and so it is better than the team are present at the start of the caesarean and not called urgently later [13]. Neonatal anaemia is associated with APH. Uterine rupture, once the baby is delivered, should be repaired in a 2 or 3 layer continuous closure using an absorbable suture (Vicryl 0 or 1). Preparations should be made for a hysterectomy if bleeding persists. An APH is a major risk factor for a postpartum haemorrhage (PPH). “APH weakens and PPH kills.” Regardless of the gestation, resuscitation and management of the mother take precedence.

24.6.2 Postpartum Haemorrhage (PPH)

Once the baby is delivered PPH can occur. At caesarean section it is advised that oxytocin 5 iu be given iv as the anterior shoulder of the baby is being delivered. This reduces the risk of PPH [12]. Ongoing bleeding can be managed through uterine massage—“rub up a contraction, expel clot and aim for a uterus like a cricket ball” [7]. Addition of further medications is possible with Syntometrine (oxytocin 5 IU and ergometrine 500 mcg) and/or oxytocin alone 5 IU iv. Both are equally efficacious with blood loss >1000 ml and Syntometrine better at loss <1000 ml. Oxytocin is the drug of choice if maternal blood pressure is not known or she is hypertensive but caution should be used when there is maternal hypotension as it can reduce the blood pressure further. Once a contracted uterus has been achieved then an oxytocin infusion (40 IU in 500 ml normal saline and ran at 125 ml/h for 4 h) could be commenced [7, 12]. Further medical management could include carboprost 250 mcg deep im into the leg every 15 min for a maximum of eight doses. Misoprostol can be considered in low resource settings where more effective drugs (oxytocin) not available. Tranexamic acid can be used and reduces PPH [12], but further studies are needed to evaluate its use thoroughly and the WOMAN (World Maternal Antifibrinolytic) trial is due to report soon [16].

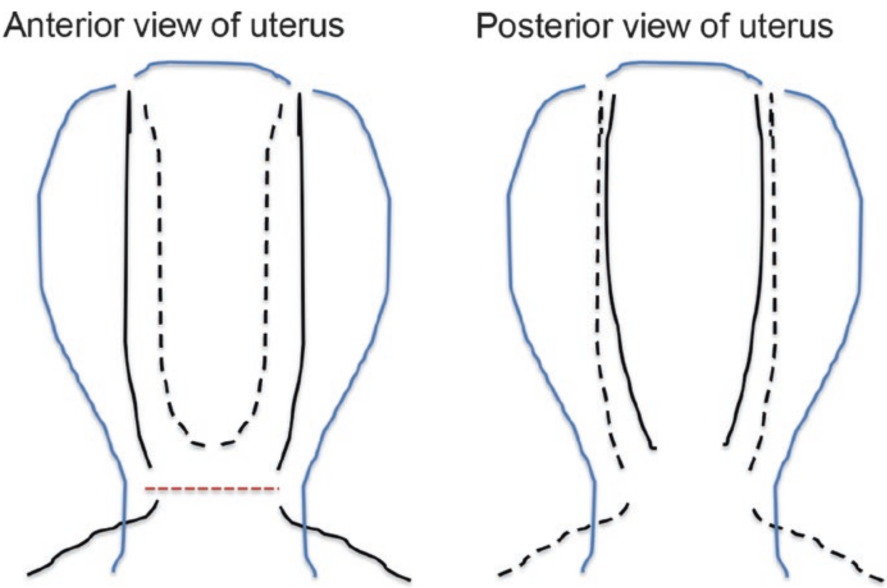


Fig. 24.4 An example of a 'Modified B Lynch suture'

As with all trauma, one needs to decide whether the haemorrhage is compressible. Bimanual compression is an excellent way of stemming the bleeding along with direct pressure to the injury while the anaesthetist resuscitates the woman. Surgical repair of injuries to the vagina, perineum or cervix with an absorbable suture should be performed. In very severe cases aortic compression until the femoral pulse is absent could be employed. Uterine balloon tamponade is recommended as the first line surgical management for treating PPH secondary to uterine atony [12]. The balloon catheter is inserted into the uterine cavity and up to 500 ml of warm saline is used to inflate it. An oxytocin infusion can be started. It can be left for 24 h. B Lynch brace suture and other compression suture methods are known and are most likely to be effective if the bimanual compression technique has achieved reduction in blood loss; Fig. 24.4. Uterine vessel and internal iliac artery ligation can be attempted but both are challenging with the gravid uterus in situ and generally needs vascular surgeon assistance. Hysterectomy may be necessary to control on-going bleeding or to remove a very damaged uterus following trauma. This should be performed earlier rather than later [12]. Ideally and when feasible, a second experienced clinician should be involved in the decision for hysterectomy [12].

24.6.3 Interventional Radiology

This is difficult to arrange in an emergency setting but can be useful if the mother is stable, the baby has been delivered and there is continuous bleeding.

24.7 Specific Obstetric Problems

24.7.1 Amniotic Fluid Embolism (AFE)

This may occur following uterine trauma. It is a serious condition which can occur with an intact uterus. Although not well understood it is thought to be a syndrome of peripartum collapse with coagulopathy which is similar to anaphylaxis in response to fetal material in the maternal circulation. Different patterns of presentation have been seen: maternal loss of consciousness or seizure then delivery (35%), fetal distress and then maternal collapse (23%), maternal hypotension, breathlessness, fetal bradycardia then delivery (14%), maternal collapse after CS (14%), and loss of conciousness or seizure immediately following birth of baby [2, 6–8]. In each case this was then followed by coagulopathy (disseminated intravascular coagulation (DIC)) and significant maternal haemorrhage. Treatment is resuscitative initially with correction of the coagulopathy and management of massive maternal haemorrhage (involvement of haematology team).

24.7.2 Air Embolism

Can occur with rupture of the uterus, during administration of intravenous fluids, blood products under pressure or following manipulation of the placenta at caesarean. It is typically associated with chest pain and collapse. Classically diagnosed through the auscultation of a typical waterwheel murmur over the precordium. Initial management involves preventing further air embolism (stop the pressurised fluids, tilt the patient head-up to increase venous pressure, flood the surgical field with saline) and supportive treatment [6, 7].

24.7.3 DIC

DIC can occur after massive haemorrhage, AFE or massive abruption. This results in a consumptive coagulopathy (low platelets, fibrinogen, bleeding). Point of care coagulation testing can be helpful. Tranexamic acid should be considered [6, 7].

24.7.4 Musculoskeletal Trauma

A major pelvic disruption usually presents as a cardiovascular problem and should be managed in the same way as in the non-pregnant patient to try to manage the uncontrolled bleeding. Pelvic fracture may cause fetal head fracture and injury particularly if the fetal head is engaged. An AP x-ray of the pelvis is very helpful. Resuscitate and immobilise the pelvis if fracture is suspected to 'turn off the tap.' Massive retroperitoneal haemorrhage from pelvic fracture is more likely as the pelvic vessels are very engorged and major pelvic disruption tears the pelvic venous plexus. Delivery of the fetus by caesarean section is often required to 'save' the fetus but, even if the fetus is dead, it is needed to allow access to control the haemorrhage [6, 10]. Pelvic fractures pre se are not an indication for caesarean delivery as most women can safely attempt vaginal birth following a pelvic fracture, even those that occur in the third trimester. Long bone fractures should be treated as normal but it is occasionally necessary to empty the uterus to allow access for proximal vascular control.

24.7.5 Maternal Collapse

It is important that resuscitation starts as soon as possible with manual uterine displacement to the left. Classically it has been taught that at 4 min from the start of resuscitation of a mother with cardiac arrest then a perimortem caesarean should be performed with the aim of delivering the fetus (emptying the uterus), if more than 20 weeks gestation, at 5 min [14]. Increasingly, evidence is emerging that collapse to birth times of less than 3 min are associated with better maternal outcomes [7]. Therefore once resuscitation has commenced if not immediately successful the uterus should be emptied. Delivering the baby will immediately reduce any aortocaval compression, increase venous return, reduce oxygen requirement and increase the likelihood of successful resuscitation. The procedure should be 'announced' to the team. It should occur where she is being resuscitated and she should not be moved. The equipment required to start the procedure is a disposable surgical knife only. This should be taped to the outside of the 'perimortem caesarean section pack.' Entry into the abdomen should be based on operator preference. The 'classical' midline incision uses the natural diastasis of the recti abdomini that occurs later in pregnancy and is relatively bloodless. Obstetricians however are more familiar with the lower transverse abdominal incision and can deliver a baby in less than 1 min. The incision on the uterus should then be a midline incision (classical caesarean section) to avoid the need to reflect the bladder. A small vertical incision is made and once the uterine cavity is entered then scissors could be inserted to further open the uterus to avoid harm to the fetus. Once the baby is delivered the uterus and abdomen can be packed and definitive closure occur later if resuscitation is successful. The midline incision is helpful when there is trauma to the abdomen (trauma laparotomy) and it can allow the heart to be reached through the diaphragm for open cardiac massage. Cardiopulmonary resuscitation should continue throughout the delivery process. A neonatal team will need to be present if the fetus is at least 23 weeks gestation. The caesarean, although performed to aid resuscitation of the mother, has been shown to improve survival of the fetus [2, 8]. In the 2006–2008 report, when done at less than 28 weeks, there were no neonatal survivors but at more than 36 weeks there was a 47% survival and all of these were delivered soon after cardiac arrest [8].

The decision to stop should be a team approach including an obstetrician, if available. It should be noted that no doctor has been found liable for performing a peri-mortem caesarean section.

24.7.6 Maternal Collapse Outside Hospital

It is important that resuscitation starts as soon as possible with manual displacement of the uterus to the left. The aim should be to rapidly transfer the woman to hospital for a perimortem caesarean section although there are instances where this can be performed by a trained team in the community. Emergency department staff and surgical members of the trauma team should be taught how to perform this procedure in the absence of an obstetric team.

24.8 Neonates

Involvement of the neonatal team when the woman is at least 23 weeks gestation is paramount. Preterm babies born at less than 28 weeks gestation should be placed in a polythene bag (up to their neck) without drying immediately after birth. They should be nursed under a radiant heater and the bag remain in place until care is taken over by the neonatal team [7, 17]. If the pregnancy is less than 35 weeks gestation and there is a chance that she will not deliver for more than 24 h then antenatal corticosteroids can be given to the mother to aid maturity of the fetal lungs [18]. These are given at time 0 h, 24 h and the maximum benefit is thought to be seen from 48 h. These could be considered by the obstetric team. The RCOG recommend that magnesium sulphate should be given to women at risk of preterm birth (at less than 30 weeks gestation) as a neuro-protective function for the fetus and to improve long term outcomes [19]. Ideally this is given at least 2 h before delivery. This could be considered by the obstetric/neonatal team along with antenatal corticosteroids.

24.9 Summary

Box 24.1 reiterates key issues in the resuscitation of pregnant women after trauma. Although ballistic trauma is rarely seen in pregnant women an understanding of the physiological and anatomical changes that occur can aid management. There is a paucity of data surrounds the subject. Crucially, a team approach including obstetricians, neonatologists, midwives and obstetric anaesthetists should be used. Resuscitation of the woman is the priority. It must be understood that pregnant women tend to compensate well and that signs of shock is a late and ominous sign with assessment of the fetus sometimes highlighting concerns in the mother.

Box 24.1
Five important points when resuscitating pregnant women:

1. Resuscitation of the mother is the priority and resuscitating the mother will resuscitate the fetus
2. Compression of the vena cava by the gravid uterus must be avoided and manual uterine displacement of the uterus or 15–30 degree tilt must be maintained throughout resuscitation
3. Signs of shock are a very late sign during pregnancy and indicate a significant blood loss (>25%)
4. All trauma should be considered significant
5. If maternal cardiac arrest then consideration should be made to deliver the baby by caesarean section (resuscitative hysterotomy) and started as soon as initial attempts deemed unsuccessful with no delay (within 4 min)

The management of trauma in pregnancy where the outcome is poor can be very traumatic to staff involved. The welfare of all members of the team should be considered and a debriefing session should be offered where all can contribute if they wish.

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Managing Ballistic Injury in the NGO Environment. A Personal View

25

David Nott

25.1 Introduction

In conflicts where surgical humanitarian intervention is required, it is always in suboptimal conditions. Although the surgical team may be based at a freestanding hospital within or close to the fighting, much of the equipment left either does not work or requires significant ongoing maintenance. Many of the senior local surgeons and their families may leave during protracted hostilities as they see a total collapse of their country's infrastructure. As the senior surgeons depart, the country is left more than often with enthusiastic but junior surgeons who will take the brunt of dealing with trauma. They may have started specialisation in their training but very quickly need to adapt to cope with the full spectrum of trauma surgery. This is the nub of the problem. Most surgeons at this level are inexperienced and yet they have to deal with very difficult trauma from gunshot wounds and fragmentation injuries. Along with the surgical challenge of how to deal with these injuries, come the constraints of a significant reduction of surgical supplies including blood and surgical materials. There are also the issues of austere post-operative management, lack of intensive care facilities including ventilators and lack of biochemical and haematological laboratory investigations. Discharge from hospital may also be difficult, in that homes may be bombed and patients may have to be discharged to tented accommodation where there is no heating or sanitation. The field hospital must discharge early or it will not have the beds available to function.

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As well as acute injuries, many of the patients suffer from chronic open wounds, especially those with limb injuries with open fractures. A working knowledge of how to get skin and muscle cover is an essential part of the humanitarian surgeon's armamentarium; in fact, working as a surgeon for an NGO in a conflict area requires a significant knowledge of both immediate trauma care and reconstructive trauma care. This knowledge can be acquired in the field but is not readily available in other settings.

Good patient management involves appropriate surgery in a hostile environment with limited supplies. Appropriate surgery means surgery suitable for the injury, taking into account all the factors present: lack of expertise, lack of equipment, lack of medical supplies and blood and lack of post-operative management. For example, consider a significant thigh injury involving soft tissue, bone, arteries and veins that would require fracture stabilisation, vascular reconstruction and soft tissue management as the standard procedure. Depending on the surgeon's experience and prevalent conditions, including numbers of casualties, surgical manpower and surgical equipment, it may be more appropriate to perform a quick above-knee amputation.

The NGO environment that the surgeon may find himself working in has changed over the years. The ICRC no longer have freestanding hospitals such as those in Lokichokio and Peshawar and most surgeons work in a team, usually based in ministry of health hospitals in the failing state. Freestanding NGO hospitals relying on tented accommodation are usually established after earthquakes and tsunamis. Safety of the surgical team in conflict zones is paramount and in these circumstances walled and roofed accommodation is essential. Indeed, more recently, the safety of patients and staff necessitates underground hospitals. Prehospital care has also significantly changed over the years: no longer do we see patients who have taken days to come to the hospital and have self-triaged *en route*; more and more often we deal with patients who have just been injured and are driven at high speed to the hospital, usually within the golden hour of injury. This makes decision-making even more difficult as some of these patients have lost significant amounts of blood and thus require intensive resuscitation which may exhaust the blood bank and also take a significant period of operating time.

There has been much written about how many civilians to combatants are injured during war. It is often repeated that there are nine civilians killed to one combatant [1]. The truth of the matter is that it is probably very difficult to get accurate numbers, but certainly in recent conflicts there have been large number of civilians including women and children who have been caught up in the crossfire between two warring factions. However, this doesn't really matter to the humanitarian surgeon who will have in front of him a human being that has been injured who may be a combatant, friend, foe or civilian.

The Geneva conventions and international humanitarian law should apply to the safety of healthcare workers, doctors, hospitals, ambulances, civilians and all injured combatants. There have been significant violations of this over the past 20 years or so, including the recent televised streaming of direct attacks on hospitals in Syria, which the world has witnessed at first hand. The humanitarian surgeon working in these areas needs to be aware of the politics of the situation. Although, in reality the surgeon and team are apolitical and neutral, they may not be seen as such, and the adage ‘the doctor of your enemy is not your enemy’ is something that must be worked into the psyche of all those involved in war in the future. It must not become the norm that supply, denial or destruction of healthcare is a weapon of war. Nonetheless, while these principles go unobserved by belligerents, NGOs must regard the safety of their own workers as paramount, and this has led some organizations to withdraw from certain conflict areas.

There is a significant difference between the NGO environment and the military environment. Military medical teams are there because of the political will of the country which is at war or they have been invited in to the country through a government-to-government request for military humanitarian aid from the stricken country. NGO teams enter the country after the organisation gathers information relating to the humanitarian need. This may be from the state itself or may be unofficial, due to a lack of medical support from local health facilities in time of conflict or catastrophe. Some NGO’s work under this principle, while others such as the ICRC always require invitation from the sitting government.

A field hospital deployed by a Western state will differ markedly from the most basic hospital facilities seen in the context of failed states where protection and support is denied to humanitarian actors; other NGO facilities will lie on a continuum between these extremes. Within the military establishment, there are high standards of predeployment training in field and hospital care, including specific surgical preparation. Medical staff are of consultant status and nurses are trained to the highest levels. Patients can be afforded a good standard of critical care under the care of dedicated intensivists. Patients who will require extended treatment and recovery can be evacuated to other levels of care, even if this involves repatriation to the deploying nation while intubated and ventilated. There are clear lines of command and responsibility and robust supply lines.

In an NGO hospital, usually the surgeon is in charge. There are no levels of care and all injuries are dealt with in the same hospital, with very little prospect of transfer to specialty hospitals. There may be the specialists still within the vicinity who may give advice and instruction, but usually remaining surgeons tend to be fairly junior. (Having said that, it is always worth involving as many colleagues as possible in difficult cases as this helps to cement medical friendships in times of stress.)

One of the most important aspects of team working is that there must be morning rounds with the whole of the staff sitting round a table to discuss the cases so that everybody can feel that they are involved in the care and management of all the patients in the hospital. At that time the operating list may be formalised and day-to-day duties given out. There may be an on-call system if there is more than one surgeon, such that others can get rest.

The biggest difficulty is that the NGO surgeon must be able to deal with all the injuries that come into the hospital. Ballistic injury knows no regional boundaries and the surgeon must be able to deal with head injuries, maxillofacial injuries, thoracic injuries involving heart, lung and great vessels, injuries to the abdomen including the major organs vessels, leg and arm injuries which comprise soft tissue injuries, orthopaedic injuries and vascular injuries. Not only that, but a significant proportion of the work may be related to obtaining skeletal coverage following significant fragmentation wounds which will require a good understanding of plastic surgery to enable the rotation of myocutaneous flaps.

25.2 Mass Casualty Incidents

The principle of achieving the 'best for the most' is the essence of the triage plan. The author has been involved in several mass casualty incidents over the years where he has been either the sole surgeon or working with a small team. In all incidents the number of casualties overwhelmed the hospital. The ICRC teaches that there should be one triage officer and that all his decisions must be complied with. There must be one entrance to the emergency department and rapid decisions should be made at the door to sort out those patients requiring entrance in hospital and those who are the walking wounded. More importantly, relatives and onlookers are kept out of the emergency department: they only make matters worse by increasing the noise levels and distracting the team from their important decisions.

In stand-alone NGO hospitals where everybody knows who everybody is and triage can be practiced at least once every 6 weeks then this approach does work. However this rarely occurs. In reality, the situation the NGO surgeon usually finds himself/herself in is a small team which becomes part of the larger local hospital population. A bomb, suicide bomber, aerial bombardment with the release of rockets or heavy artillery fire are usually the causes of multiple casualties (Fig. 25.1).

Fig. 25.1 The aftermath of a suicide bomb attack. Multiple casualties are attended by personnel with little medical training. Triage at the scene will not occur

Gunfire from small arms does not usually produce mass casualties. Therefore, when the call goes out that multiple casualties are coming, one can expect very difficult injuries to deal with. Many patients will arrive completely filthy, their clothes ripped off, covered in dust and blood and sometimes it is even difficult to know whether you are examining the front or back of the head because hair mats into the skin of the face.

No matter how professional one would like to remain, the whole situation is complete pandemonium. It is a very difficult situation to be in. Patients will be brought in, either carried or on stretchers, but usually accompanied by 2–3 people each. Imagine a large room which was very orderly with a few trolleys a few moments ago, now suddenly is filled with around 40 seriously injured, dying and scared people. On top of that, you are in a different country probably unable to speak the language fluently, unaware of where the injuries occurred, unsure of a lot of the people that are suddenly standing around. Suddenly, you find that you are on your own and that the team disappears to help others. It is inevitable that this will happen. Some of your colleagues who were in quieter moments rational and professional suddenly become severely stressed which leads them to become extremely angry. Language barriers can make the situation much worse (Fig. 25.2).

Although you may yourself be feeling the same, it is imperative that as the surgeon you stand back. Try to maintain calmness and adopt a very professional attitude. People will be coming up to you and shouting in your face. Try not to appear stressed. Do not get caught up helping one person because you will lose the bigger

Fig. 25.2 The reception area of a hospital receiving multiple casualties. The orderly running of the unit has ceased. Patients have been placed wherever space is available. Staff and members of the public mix together. Noise exacerbates the chaos

picture. Your role eventually will be to sift and sort out who needs to go to theatre first. In my experience, the stress levels are so high that even the most able clinicians forget to do the primary survey. So, your first triage move is to make sure nobody is bleeding to death and that tourniquets have been adequately positioned. The second move is to assess the airway. This is more difficult than one may imagine because a lot of these patients will be brought in with bad burns to their face, neck and chest and they may also be covered in blood and dust and hair. It is important to clean around the mouth with a clean towel and to assess the airway. This is the most important message to get across to everybody in the situation. Patients in obvious respiratory distress need a bilateral chest drain inserted prior to any fluid resuscitation. Many of the staff's first reaction will be to try to put in venflons and to give resuscitation fluid. This will only waste time because the chances are the patient will be shut down and it will be impossible to get a peripheral line in. It is more important to be able to feel a pulse and assess the consciousness level, airway and breathing. It is impossible to stop the staff from trying to give peripheral fluids unless you can find more urgent tasks for them, and make these clear. All this may take as much as 30 min, given the number of patients. Next, patients will need to be fully assessed by taking off their clothes and doing a proper examination of the front and back assessing for any penetrating injuries.

You will notice that I have not mentioned a triage officer. That is the gold standard but in reality there is usually no one available to perform this role as a dedicated duty. The senior surgeon and anaesthetist will need to make decisions together. They will need to know how much blood is available. A call at this stage must go out to the civilian population to request for blood.

The fact that the hospital is full does not matter. Patients can be managed post-operatively on the floor anywhere within the Hospital. What matters is making the right decision about who to take to theatre first. This has actually been made easier because damage control surgery (DCS) limits the time necessary in the operating theatre. But, it is easy to forget damage control principles and spend longer in the operating theatre than is required. As a general rule, in the mass casualty situation, I would not take a head injury to the operating theatre; that is usually a significant secondary stage procedure. Remember, in most NGO situations you do not have access to CT and even if you do have x-ray the quality may be very poor. Reliance on clinical examination is paramount to making the right decisions.

25.3 Damage Control

In austere settings, the concept of damage control mainly relates to damage control surgery rather than damage control resuscitation because it is very difficult to replace blood with blood in the NGO environment, and there are certainly no blood products such as packed cells, fresh frozen plasma and platelets. However, the concept of prioritizing the physiology of the patient over addressing the anatomy is an important one to adhere to when dealing with acute ballistic injuries. DCS may also be adopted to abbreviate an operation so that other urgent casualties can be operated on more quickly.

An assessment needs to be made of whether patient will require damage control surgery. This mostly depends upon assessment of the blood loss. To assess this in the austere environment, reliance is made on the pulse and blood pressure. A patient who is shocked, that is a pulse above a hundred beats per minute and blood pressure below 100 mmHg, should be considered for damage control. This is because resuscitation must require a combination in this instance of crystalloid and blood. There may be a significant lack of blood available and therefore do not assume that if the patient is responding to resuscitation then damage control surgery is not necessary. This can lead one into a false sense of security because performing surgery to correct the anatomy may take a long time and the patients are likely to become hypothermic and coagulopathic over time. There may not then be enough blood available to maintain coagulation factors and the patient will subsequently continue to bleed.

If possible, the blood must be whole fresh blood and warmed. Studies have shown that 30% of all trauma patients who have lost a significant amount of blood are hypothermic and 30% are coagulopathic [2, 3]. In this environment it is easier to assume that all are hypothermic and coagulopathic. In this regard, try to use fresh whole blood; even one unit will provide functional red cells, and will be equivalent to two units of FFP and at least 10 units of platelets as the platelets work very well in fresh whole blood [4]. If a blood warmer is not available then simply fill up a bucket with hot water from a kettle. It has been shown that if your hands can just cope with the heat for around 30 s, then this temperature will be around 43 °C. Place bags of saline and blood in the bucket for as long as you can prior to using them. It has been shown doubt if the haemoglobin can be kept up above 6 g/L and the cardiac output maintained then the majority of cases oxidative respiration will continue if careful surgery has been performed and all bleeding curtailed and all organs oxygenated by arterial shunting if necessary [5]. The specifics of the damage control surgery will be dealt with below.

25.4 Surgical Management

25.4.1 Head

Most NGO hospitals do not have a CT scanner, therefore it is not possible to estimate the size of intra-cranial focal traumatic lesions. It is instead left to clinical examination alone, comprising principally of assessment of the level of consciousness and limb weakness, and a head examination for signs of external injury to determine if an operation is indicated. The decision also takes into account the haemodynamic status and stability of the patient, neck and torso injuries that may mandate either treatment limiting decisions or immediate surgery that takes priority over neurosurgery to control life-threatening bleeding. The majority of head injury seen in ballistic trauma is penetrating and the aim of neurosurgery in this instance is to prevent infection and treat critically raised intracranial pressure.

For those inexperienced in dealing with surgery to the head, it is important that you do not lose your landmarks and therefore the whole head should be shaved.

Fig. 25.3 Fragmentation injury to the head. The hair obscures the extent of the injury and must be removed

Fig. 25.4 After shaving, the injuries can be fully evaluated and the necrotic tissue is excised

Whilst the clinical diagnosis of penetrating head injury may be obvious, hair and blood may combine to make the detection of small holes of the scalp extremely difficult (Figs. 25.3 and 25.4). Care must be taken to avoid the danger areas of the frontal region containing the frontal sinus and anterior superior sagittal sinus, the midline with the underlying superior sagittal sinus widening from anterior to posteriorly and also where the confluence of the sagittal and transverse sinuses meet, which is at the back of the scalp.

In the NGO environment, there are really two reasons to operate. Those that are fully conscious, that is the GCS of 14–15, but with a significant injury can be managed by a limited wound excision. This involves removing foreign material and copious washout with a thorough excision of the wound but not going any deeper into the brain tissue, which could exacerbate further bleeding and swelling. Once the scalp edges are cleaned then it is advisable to simply close the scalp over the injury and make it watertight. Antibiotics must be given. Those that have a GCS between 11 and 13 and are localizing to pain should have a decompression procedure. If the wound is in the area which is deemed safe, then a limited wound excision is performed using carefully placed burr holes, equidistant from the entry wound. The extradural space beneath the skull between the burr holes can be developed with a dissector to allow the passage of a Gigli saw-guide and then a Gigli saw to join up the four burr holes. If an extradural hematoma is found then the cause can be ligated or diathermied. If the hematoma is spontaneously emerging from the underlying, revealed dural entry, then this is allowed to extrude fully. It is better neither to enlarge the dural tear nor to begin exploring the tract, as bleeding will no doubt worsen and perhaps become uncontrollable. The goal of this procedure is to simply let the blood out to depressurize the brain. The dura is not closed and the bone is replaced unsecured and the scalp carefully sutured and made watertight. These patients can be woken up immediately.

For patients with GCS of nine who are flexing to painful stimuli then non-operative treatment is the preferred option. However, if there is obvious signs of a dilated pupil on the injured side then the similar operative craniectomy should be considered as a large extradural may be the cause. But if both pupils are relatively equal then a nonoperative approach should be taken as it is assumed that there is an intracerebral injury. These patients should be given non-operative support on the ward with an optimistic approach to nursing care, since recovery can occur in some cases.

25.4.2 Neck Injuries

Injuries to the neck involving the external carotid artery and internal jugular vein are treated with ligation; the common carotid artery is repaired using vein patch techniques. Injuries to zone three of the carotid artery are treated by ligation. One would have to accept the risk that 50% would develop a stroke. Remember that the injuries may be very dirty and do not hesitate in excising tissue combined with copious washout. An injury to the trachea is best treated by performing a tracheostomy rather than to attempt a closure unless the defect is very small. Injuries to the oesophagus can be closed primarily using 2/0 Vicryl if the injury is less than 24 h old. It is best to drain older injuries, making sure a nasogastric tube has been passed and to try to cover the defect with a sternomastoid flap (Fig. 25.5). The blood supply of this muscle is a bit tenuous and, if it is going to be interposed between the trachea and the oesophagus, make sure that limited dissection is used as the blood supply to the middle third is from the external carotid artery. Therefore, mobilise it by disconnecting the inferior insertions.

Many ballistic injuries cause significant tissue loss in the neck and face and the knowledge of how to raise the latissimus dorsi flap, deltopectoral flap and pectorals major flap are extremely useful plastic surgical techniques in your armamentarium.

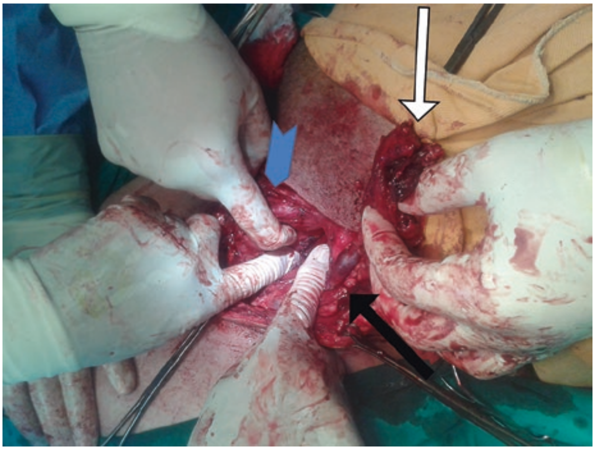

Fig. 25.5 Injury to the cervical oesophagus. The head is top right and there is a transverse neck incision. The inferior part of Sternocleidomastoid has been disconnected and reflected upwards (*white arrow*). The internal jugular vein is revealed (*black arrow*) and it has been retracted (along with the other contents of the carotid sheath) posteriorly. The strap muscles (*blue arrow head*) have been retracted medially. This reveal an injury to the oesophagus (seen between the three finger tips) behind the trachea. This was repaired using the sternocleidomastoid as a flap

25.4.3 Thoracic Injuries

During triage it is often very difficult to hear anything, never mind to listen to breath sounds using a stethoscope. Once you are sure that the airway is clear then very quickly assess the trachea and feel for crepitus around the neck and chest. Look at the patient for signs of respiratory distress and, if you think there is a problem, have no hesitation in placing chest drains into both chest cavities. Patients need to be on a trolley for this, so that an underwater seal can be used, and there may not be enough trolleys available in a mass casualty situation. However, there may be a flutter valve type chest drain that will allow the patient to remain on the floor (Fig. 25.6). 90% of all chest injuries can be managed with a chest drain. Those injuries that require further intervention are due to significant haemothorax or signs of a cardiac tamponade. Follow, the ATLS guidelines of 1500 mL immediately or 200 mL per hour every hour for 4 h. The treatment in this environment it is usually a single side thoracotomy. This is fairly contentious, as it is taught in trauma that all thoracic chest injuries should be opened using a clamshell thoracotomy. However, in my experience if you feel that it is just one side then put the patient in a posterolateral position and perform a one-sided thoracotomy. If on the right-hand side, this will allow you to look into the pericardium to look for blood within the pericardium during the procedure. Remember, that most of the injuries in ballistic trauma that survive to reach medical care will either be due to chest wall injuries or lung injuries. The latter will require a non-anatomical resection of the lung using a soft bowel clamp and oversew of the lung

Fig. 25.6 Flutter valve chest drains obviate the need to nurse patients on trolleys (above an underwater seal) and can facilitate transfers

with either vicryl or prolene; for through-and-through injuries to the lung due to a bullet then perform a tractotomy using bowel clamps followed by and oversewing of the lung defect.

Be aware of the signs of cardiac tamponade, that is an injury to the anterior chest wall with hypotension. Usually, Beck's triad of distended neck veins, muffled heart sounds and low blood pressure do not occur as the patient often has lost a significant amount of blood from other injuries and it is almost impossible to listen for muffled heart sounds. The treatment of a cardiac tamponade is a left anterolateral thoracotomy and immediate incision of the pericardium above the phrenic nerve in a longitudinal direction, cutting the pericardium widely. The gush of blood confirms the diagnosis and then it may be possible to repair the injury to the heart or if there is not enough space then the sternum can be divided with a big pair of Mayo scissors and a retractor placed to give more access.

In the NGO environment the only reasons for doing a clamshell thoracotomy is for a trans-mediastinal gunshot wound or for a high injury in the thorax involving the arch of the aorta and subclavian vessels. The chances of salvage in this situation are very small and techniques to repair these vessels are outside the confines of this environment and therefore life-saving single vessel ligation is probably the only option.

25.4.4 Resuscitative Thoracotomy in the NGO Environment

Patients are often brought to the emergency department within the first hour of the injury, whether this be a high energy gunshot wound or a single fragmentation wound to a major artery. Often, these patients are bleeding significantly to the extent that external cardiac massage is being used to support or maintain the cardiac output. To get to that stage, these patients have bled about 3 L of blood. A decision must be made whether to carry on the resuscitation or stop. In this situation, resuscitation requires a resuscitative thoracotomy which means immediate access for fluid replacement via an internal jugular or subclavian vein while at the same time performing an anterolateral thoracotomy, clamping the distal thoracic aorta, opening the pericardium and performing internal cardiac massage until the heart becomes full and begins to beat again. Following that the cause of the haemorrhage will need to be attended to.

Remember, that one unit of blood is around 500 mL. To replenish 3 L requires six units of blood. The amount of blood used for the resuscitation process will probably require another six units of blood. The blood required to complete the process of performing damage control on the blood vessel and stopping all the bleeding around the area will probably be another six units of blood. Post operatively, the may require another six units of blood. So in total the patient will require around 24 units of blood. This is probably an underestimate. In the patients that I have dealt with in this situation, all required at least 20 units of blood and the mortality was in the order 80%.

In my opinion, in the NGO environment one should not consider performing a resuscitative thoracotomy followed by further surgery unless one has a significant amount of blood in the blood bank and a significant backup support on the ward including a fully equipped intensive care unit that has facilities for ventilation.

25.4.5 Abdominal Injuries

The bullet does not respect anatomical regions and may traverse through the thorax into the abdomen. There is often the dilemma about which region to open first, the chest or the abdomen. In my opinion, the thorax should have a chest tube inserted followed by a laparotomy extended into the chest as necessary. Always check the diaphragm for a defect on both sides when the injury is primarily in the abdomen, as this may allow herniation of the small bowel if missed. Diaphragmatic injuries are repaired with a running Prolene suture. Injuries to the spleen necessitate splenectomy; there is no room for preservation. Injuries to the liver are best dealt with packing; there is no benefit from careful suture ligation because more blood will be lost. Following packing, and if the situation is under control, then one good option is to bring patient back 2–3 days later day. If oozing still occurs then use the greater omentum as a pack and sew the omentum into the liver using big sutures (Fig. 25.7).

Renal injuries are often seen and are more than likely due to a penetrating injury following a bullet or a fragment. I try to preserve the kidney as much as I possibly can. Obviously, if there is a significant kidney hilar injury then there is little to do apart from nephrectomy. If the kidney can be preserved then that must always be the best option. A partial nephrectomy and pledgetted sutures using the fascia from the posterior abdominal wall is effective (Fig. 25.8).

In the damage control scenario, the bowel injury is removed and the bowel ends are ligated and the abdomen packed and the skin sutured. The patient is then brought

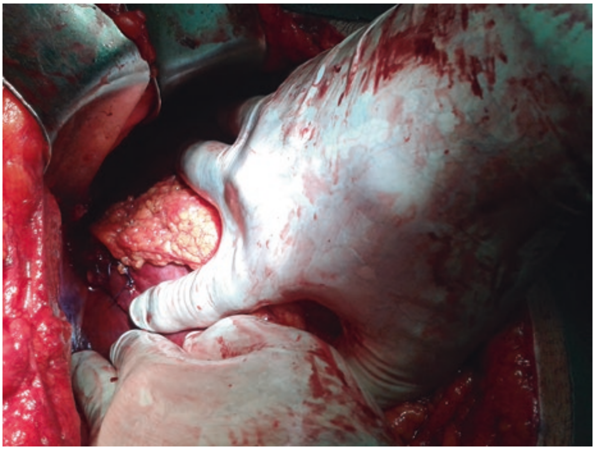

Fig. 25.7 At second look laparotomy the greater omentum has been sutured into a defect in the liver

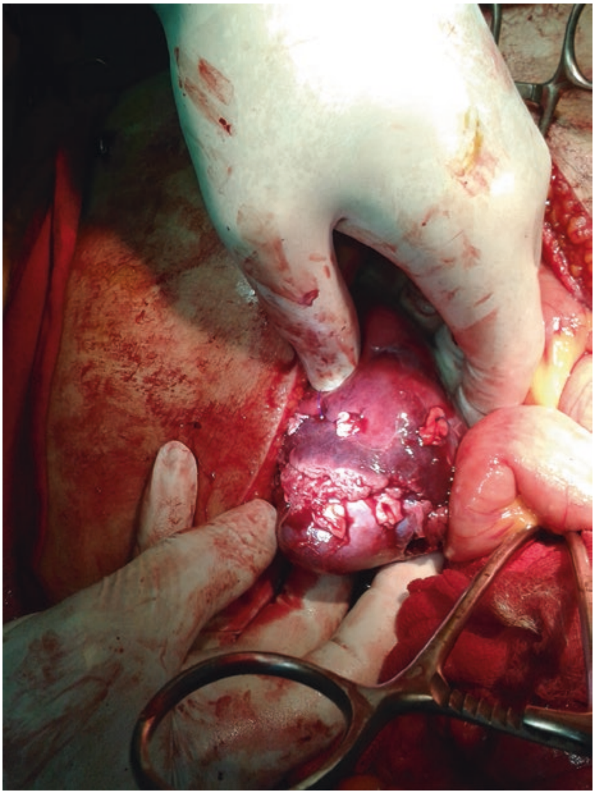

Fig. 25.8 The kidney has been repaired using pledgetted sutures. The pledgets are made from the fascia of the posterior abdominal wall, which is easily accessible once the kidney has been mobilised

back 24 h later for bowel anastomoses. In Africa, I have seen Ascaris lumbracoides several times swimming around the abdomen in a pool of blood (Fig. 25.9). In endemic areas, always think of worms and parasites and use two or three layer

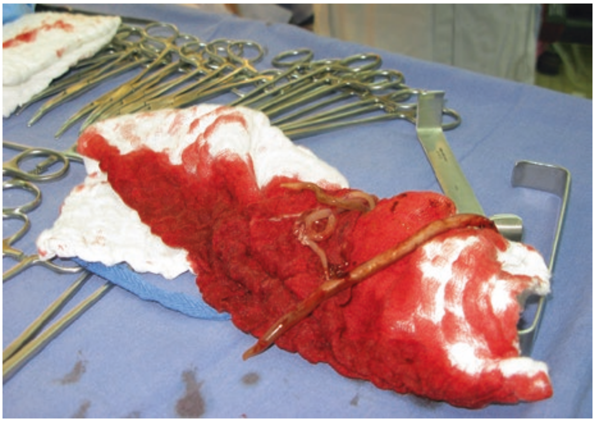

Fig. 25.9 Ascaris lumbricoides worm

closure to stop these worms from getting through your anastomoses. As regards the colon, a lot of patients do not wish to have a colostomy. Stress to the patient that this is very temporary and try to reverse the colostomy as soon as you can.

Massive arterial and venous injuries are often seen in ballistic trauma. Venous injuries tend to be seen more often than arterial injury as those patients typically succumb to massive haemorrhage before they are operated upon. Not only that, repair of massive arterial injuries requires a large amount of blood and the likelihood of having enough blood in the blood bank to sustain both the haemoglobin and blood pressure is unlikely. As in all damage control scenarios with massive bleeding it is important to get control of the blood vessel as quickly as possible. Major aortic abdominal injuries usually require a left anterolateral thoracotomy and clamping of the distal thoracic aorta before opening the abdomen. The chances of doing this successfully in this environment are extremely slim.

Prior to the understanding of the benefits of damage control resuscitation, injuries to the abdomen requiring damage control surgery would have the problem of massive third space oedema, not only of the bowel but also tissue of the abdominal wall and retroperitoneum. This would make closure of the abdomen difficult and the tamponade developing if the abdomen was closed would increase the risk of renal failure and poor outcome. Hence a lot of patients receiving resuscitation with saline would have a laparostomy with a Bogotá bag or vacuum dressing followed by either slow closure of the laparostomy or mesh repair. In the austere environment, although a Bogotá bag could be an option, it carries a very high morbidity and mortality because of the risk of infection and usually it is impossible to discharge the patient. To this end I have used the technique of component separation, described for repair of incisional hernias, to enable closure of the abdomen in these circumstances. Usually after 36 h the abdomen can be closed either using one side component separation which gives an extra 7 cm of abdominal wall laxity or 14 cm if both sides are used. There has not been one case where it has not been possible to close the abdomen in these circumstances (Fig. 25.10).

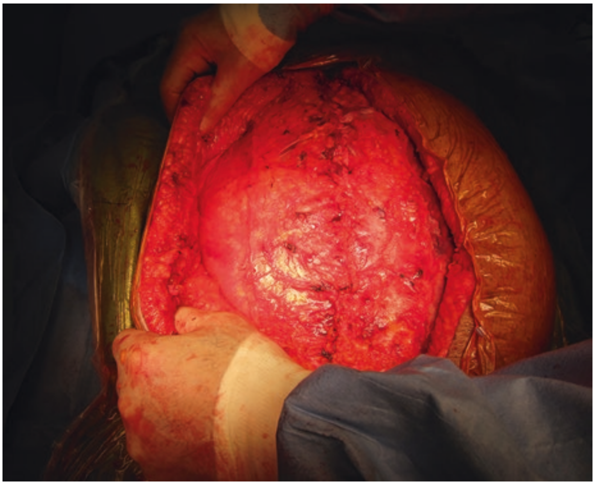

Fig. 25.10 Component separation technique. A flap of skin and subcutaneous fat is raised, extending lateral to the linea semilunaris and as far caudad and cephalad as necessary, usually along the full length of the recti so that the whole abdominal wall can be mobilised. The aponeurosis of external oblique is divided just lateral to its insertion into the linea semilunaris

25.4.6 Limb Injuries

Limb injuries are the commonest injuries that are dealt with. These often require the surgeon to be adept with an understanding of plastic surgery, orthopedics and vascular surgery. Many of the injuries that occur in ballistic trauma will require the combined use of all these specialties. Again, the principles of damage control are used depending on the physiology of the patient on admission. Shunting of vessels using sterile conduits of nasogastric tube and IV tubing are necessary to maintain oxygenation of the distal part of the limb. The fractures can then be reduced and held in place either by plaster of paris or external fixation. Procedures using reverse vein graft and vein patching are necessary techniques to master.

The management of soft tissue injuries from fragmentation injuries and blast injuries is difficult. It will take a lot of resources and time to excise dead and ischemic tissue. A decision often has to be made if the injury to the lower leg and knee area is so great that a primary amputation higher up in removing all the damaged tissue might in the end be the best option rather than sequential excision of necrotic and threatened tissue. In all amputations, it is mandatory to leave the wound open rather than close it, using fluffy gauze for a period of 3–4 days and then bring the patient back to theatre for wound closure if there are no signs of infection.

Soft tissue injuries involving fractures are best treated in the leg using external fixators followed by excision of non-viable tissue and covering bone as quickly as possible. This again requires a significant knowledge of how to rotate fasciocutaneous flaps such as random flaps, cross leg, lateral peroneal and sural flap and rotation of muscle flaps such as medial gastrocnemius, soleus and vastus lateralis and sartorius for thigh and groin injuries. Remember it is not just bony defects that need to be covered but also vascular anastomoses (Fig. 25.11). Occasionally, a massive groin injury which has taken out the common femoral artery and vein and also

Fig. 25.11 Cross-leg flap. A ballistic injury to the right tibia with vascular involvement has been treated with external fixation, vascular repair and a cross-leg flap. The left leg has also had an external fixator applied in order to maintain its position until the flap has secured a local blood supply and can be divided

caused significant amount of soft tissue damage may necessitate cover using a combined sartorial and gracilis flap or, if much larger, a rectus abdominis flap.

25.4.7 Burns

There will be times when patients are admitted with severe burns, either due to the incendiary element of the explosion or following a fire due to the aftermath of the explosion. When patients arrive the initial action is to give pain relief and sedation followed by washing the patient with soap and water. This action allows you to distinguish between areas of normal skin and erythema and the rest, which will be the burn wounds. The burn wounds will be partial thickness or full thickness. The partial thickness wounds will be divided into superficial partial thickness or deep partial thickness depending on the colour and sensitivity. Assess the burn wound using the total percentage body area. There are many charts but in the initial situation it is much easier to use the rule of nines or use the size of the patient's palm. If the burn is around 20% of total body surface area then intravenous fluids must be started immediately. A catheter must be placed to monitor urine output which will be 0.5 mL/kg/h in adults and 1 mL/kg/h in children. If the patient also has full thickness burns it may be necessary to perform an escharotomy immediately (Fig. 25.12).

The wounds will then need to be addressed using local protocols to provide an inner component which applies antibacterial agent to the wound (for example sulphadiazine) and jelonet and an outer component which absorbs exudate and protects the wound such as thick gauze swabs. Subsequent management, is guided by answer to the simple questions. Is excision of the wound going to be needed? If so, when? The question is simple but the answers difficult. In my opinion, it is worth sitting tight and not performing urgent excision of the burn. In all significant burns, the thermo-coagulated tissue dries out leaving an eschar. In superficial partial thickness burns this eschar usually separates after a week leaving good quality skin beneath it. In deep partial thickness the eschar separates at around 2–3 weeks leaving poor quality skin which heals at around 6 weeks. In the deepest burns, the eschar remain stuck and may then become infected at around day eight. These wounds produce granulation tissue and heal by scarring with contracture.

Fig. 25.12 Escharotomy. Full thickness burns to the torso were constricting the chest and preventing normal ventilation. Division of the eschar in two planes relieves the problem

So, in the NGO environment it is best to cover the wounds first and inspect the wounds every 2–3 days. You will be able to make judgements on the depth of the wound in the operating theatre. That will allow you to make decisions about tangential excision using a Humby knife with early split skin graft or continual dressing. When doing tangential excision of small areas small areas of burnt skin I remove until capillary bleeding is seen.

Do not underestimate the amount of manpower and time needed to deal with one patient with significant burns. These can be managed well but the patient needs to be brought back every 2–3 days and have dressing changes and careful monitoring and management. It is a huge undertaking and the burden on the hospital and equipment is not something that should be taken lightly.

25.5 Training

Surgery in the NGO environment is a very enjoyable experience. It deals with not only severe trauma cases but also the general surgical management of civilian populations in failing states requiring significant outside help. The surgeon will of necessity have to deal with most of the surgical operations required in this environment from trauma involving every region to general surgery, paediatrics, obstetrics and gynaecology, plastics and orthopedics. Most Western surgeons now are specialists and super specialists, used to working with high-technology equipment. To go from specialist to generalist and then to generalist in an austere environment requires significant understanding of what you can and cannot do. The ICRC provide a war surgery course in Geneva. In London, we provide the Surgical Training for the Austere Environment (STAE) course, which aims to equip surgeons with the knowledge of how to deal with these injuries. It is a 5-day course which will provide you with the confidence of being able to make the correct judgement calls when dealing with many of these problems. There is a scholarship program that runs throughout the world which will provide the financial support for surgeons to come on this course and prospective scholars are advised to apply to the davidnottfoundation.com.

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26 Forensic Aspects of Ballistic Injury

Jeanine Vellema and Hendrik Scholtz

Clinical forensic medicine is best defined as the application of forensic medical knowledge and techniques to the solution of law in the investigation of trauma involving living victims [1–5]. In the setting of emergency departments, these techniques include the correct forensic evaluation, documentation, and photography of traumatic injuries, as well as the recognition and proper handling of evidentiary material for future use in legal proceedings [1–8].

While the tasks of documenting, gathering, and preserving evidence traditionally have been considered to be the responsibility of the forensic pathologist or the police, the roles of the trauma physician and forensic investigators actually have several areas of complementary interest. These arise from the dual purposes of providing immediate care for the individual victim or patient and the longer-term reduction and prevention of injury and violence in the community as a whole [6, 9].

Appropriate documentation and handling of evidence by trauma personnel assist the forensic pathologist in evaluating cases of initially non-fatal traumatic deaths and assist the police and legal authorities responsible for investigating both civil and criminal cases in deceased and surviving injured patients [6].

In addition, emergency physicians could play an important role in informing police about patients presenting to them with non-fatal forensic-related problems such as gunshot wounds. In these instances, consent to report must be obtained from the patient so as not to breach physician–patient confidentiality. Patients should be advised that it is in their interest, as well as the interest of the wider community, to report offenses, but it remains the patients' decision whether such offenses are reported [9, 10].

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In September 2003, the General Medical Council (GMC) in the UK published "Reporting Gun Shot Wounds. Guidance for Doctors in Accident and Emergency Departments." The guidelines were developed with the Association of Chief Police Officers and supported by the College of Emergency Medicine. In essence, the guidance is that the police should be informed whenever a person has arrived at a hospital with a gunshot wound, but initially identifying details such as the patient's name and address usually should not be disclosed. The treatment and care of the patient remains the doctor's first concern. If the patient's treatment and condition allow them to speak to the police, then they should be asked if they are willing to do so. If they refuse or cannot consent, then information still may be disclosed if it is believed this is in the public interest or is required by law. The patient should be informed of the disclosure and an appropriate record made in their notes. Copies of the guidelines can be obtained from the GMC.

Thus, while the main priority of trauma physicians always will be to provide timely and optimal care for the individual living patient, they also could serve society in general by applying some forensic principles in their approach to patients who are victims of violence [5–8].

26.1 The Forensic Evaluation

In a firearm-related injury, the direction that a bullet travels through a body may have little relevance in a patient's clinical management, but it usually has profound medico-legal implications. The appearance of a gunshot wound may not only indicate the bullet's direction and trajectory, but also the type of ammunition and weapon used and the range of gunfire. Additionally, it may assist with the manner of gunshot injury or death with respect to it being accidental, homicidal, or suicidal in nature [2, 11].

Proper forensic evaluation of patients in the clinical environment is often neglected in the hurried setting of a resuscitation [6–12]. Such an evaluation should be documented comprehensively and should include a history and physical examination with accurate descriptions of wound characteristics supplemented by diagrams or line drawings [3–8, 13]. Use of a proforma, which includes a simple diagram, has been shown to improve the quality of documentation [14–17].

Ideally, photographs should be taken whenever possible. However, consent must be obtained first from patients for photography, unless they are unconscious. The consent form must become a permanent part of the patient's medical records. In unconscious patients, "implied consent" is the legal construct used to secure consent when the photographs may aid in the subsequent conviction of those individuals who perpetrated a crime. If implied consent was used, the physician later must obtain consent from either the patient or next of kin [3].

In addition to the above documentation, recognizing, collecting, and preserving physical evidence while maintaining a "chain of custody" is another important responsibility of trauma personnel; this will be dealt with comprehensively later in this chapter [1–8, 12–16].

26.2 Documentation of Gunshot Wounds

Emergency physicians are ideally positioned to describe and document gunshot-wound appearances before such wounds are altered by surgical intervention or the healing process [3, 17].

The interpretation of gunshot wounds with respect to "entrance and exit," direction of fire, or type of firearm or ammunition used need not be commented on. Clinicians should confine themselves to recording accurately the location, size, and shape of all wounds, as well as any unusual marks or coloration associated with these wounds. Surgical procedures such as drain sites must also be recorded to prevent subsequent interpretive difficulties for the forensic pathologist, should the patient die [17–21].

Differentiation between entrance and exit wounds can be difficult, and information from patients or witnesses may be false or inaccurate. In a study of 271 gunshot-wound fatalities, it was found that trauma specialists had misclassified 37% of single exiting gunshot wounds with respect to entrance or exit wounds and 73.6% of multiple gunshot wounds had been misinterpreted with respect to total number of wounds, as well as erroneous identification of entrance or exit wounds [17].

If descriptive documentation is accurate, acknowledged experts in forensic wound ballistics can use these descriptions to make the necessary forensic interpretations pertaining to direction and range of gunfire, as well as type of weapon and ammunition used [17–22].

An emergency physician may be called upon by the courts to give evidence regarding injuries sustained by a gunshot victim and, in nonfatal gunshot victims, may be the only person who can testify as a witness of fact to the original appearances of the gunshot wounds.

An expert witness is someone who, because of training and depth of experience, may be asked to give an opinion based on the observation of others, as opposed to merely testifying as to the facts of the case [12].

Thus, a trauma surgeon may be called as a "factual" witness regarding the wound(s) appearances, but may also be called as an expert witness regarding the severity or lethality of a wound. The expert forensic ballistics witnesses may be asked to interpret the documented factual findings in a gunshot-wound victim and define the wound descriptions as entrance or exit, as well as give an expert opinion as to range and direction of fire, type of firearm, and ammunition used [12].

The quality of both factual and expert testimony will depend on the accuracy of the original clinical documentation, which in turn may influence the outcome of the court case [1–8, 15–22].

26.3 Forensic Concepts

Accurate descriptions of gunshot wounds require a basic understanding of firearms, ammunition, and wound ballistics, as well as the relevant forensic terminology [2, 3]. Ballistics is defined as the science of motion of projectiles and can be divided into interior ballistics, the study of the projectile in the gun; external ballistics, the study of the projectile moving through the air; and terminal ballistics, the study of the effects the projectile causes when hitting a target, as well as the counter effects produced on the projectile.

Wound ballistics is considered a subdivision of terminal ballistics, which concerns itself with the motions and effects of a projectile in tissue [23–25].

Chapters 4 and 5 dealt with firearms and ammunition. Only a brief summary of some pertinent forensic issues pertaining to the above will be given here.

26.3.1 Forensic Aspects of Firearms and Ammunition

When a firearm is discharged, the primer is crushed and ignited by the firing pin producing an intense flame, which ignites the propellant gunpowder in the cartridge case. The rapidly burning gunpowder results in the formation of relatively large volumes of very hot gas within the cartridge case, and the pressure of these gases on the base of the projectile result in the projectile being forced out of the cartridge and propelled through the barrel of the firearm.

As a consequence of these events, the ejected projectile is accompanied by a jet of flame, hot compressed carbon monoxide-rich gases, soot, propellant particles, primer residue, metallic particles stripped from the projectile, and vaporized metal from the projectile and cartridge case [23–32].

In revolvers, similar substances may emerge from the cylinder-barrel gap, the amount of which will depend on the manufacture, quality, and age of the weapon [23]. These residues are most commonly referred to as gunshot residue (GSR), but the terms cartridge-discharge residue (CDR) or firearm-discharge residue (FDR) also are used [32].

Additional components that may be expelled and deposited on a bullet when a firearm is discharged are the elements fouling the barrel of a firearm. These could include rust particles, lubricating oil, dirt, and even biological material resulting from blowback of blood and tissue into the barrel of the weapon, as sometimes happens in hard-contact entrance wounds [23, 24, 27–31].

This has forensic relevance in that:

1. In addition to the ejected bullet, the residual materials resulting from the discharge of a firearm may impart specific characteristics to the appearances of gunshot entrance wounds depending on the range and angle of discharge of a firearm, the type of firearm, and type of ammunition used; [23–31]
2. The description, detection, and identification of expelled residual materials may provide valuable investigative information, allowing for scientific range estimates, identification of the ammunition or firearm(s) used, and thus identification of the assailant(s) [23, 24, 32].

It is of major clinico-forensic importance for trauma personnel to recognize that in addition to the bullet and its cartridge case, all of the above barrel emissions constitute potential evidentiary material that may be deposited in and on the clothing, hair, body, and wounds of a gunshot-wound victim, or even an assailant. By being aware of the presence and value of gunshot-related evidence, such evidence may be identified, collected, and preserved rather than inadvertently being destroyed [1–8, 13–16].

26.3.2 Forensic Aspects of Wound Ballistics

Penetrating projectiles can be classified broadly into two major groups, namely fragments and bullets. Fragments from military munitions are the most common wounding agents in war, although fragmentation injuries also may occur following civilian terrorist bombings. Bullets are the predominant penetrating missiles in civilian clinical practice [33].

Weapons originally designed for military use are also used frequently in civilian settings, leading to blurring of the distinction between military wounds arising from high-velocity rifles and fragments and civilian wounds arising from handguns with lower muzzle velocities [34].

There are three mechanisms whereby a projectile can cause tissue injury:

1. In a low-energy transfer wound, the projectile crushes and lacerates tissue along the track of the projectile, causing a *permanent cavity*. In addition, bullet and bone fragments can act as secondary missiles, increasing the volume of tissue crushed [15, 23–42].
2. In a high-energy transfer wound, the projectile may impel the walls of the wound track radially outwards, causing a *temporary cavity* lasting 5–10 ms before its collapse, in addition to the permanent mechanical disruption directly produced in (1) (Fig. 26.1) [23–31, 33, 34, 38–42].

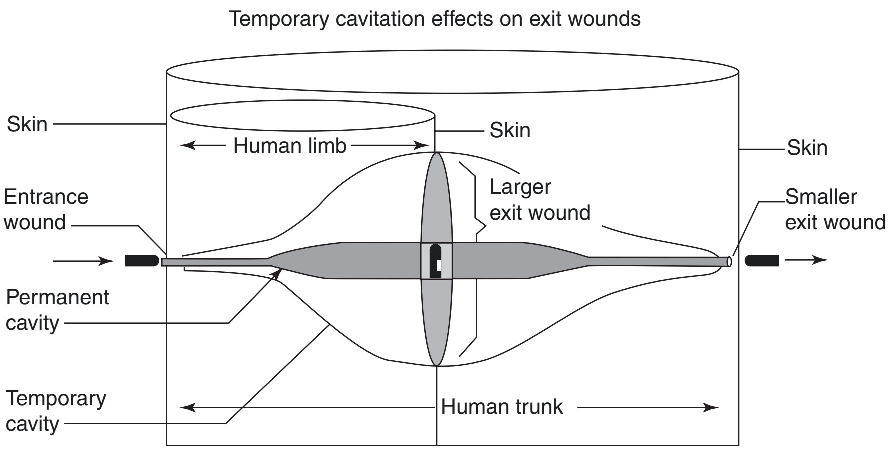

Fig. 26.1 Schematic profile of the variable sizes of exit wounds caused by the same projectile, as influenced by the diameter of the temporary cavity at the point of exit. The *narrow column* represents the diameter of a limb and the *wider column*, the diameter of a trunk

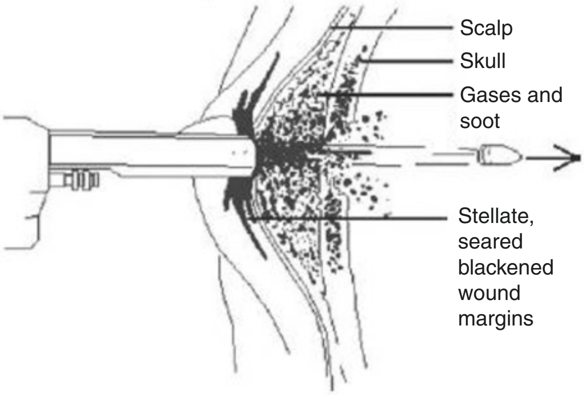

Fig. 26.2 Contact gunshot wound of the head showing compressed gases expanding between the scalp and the outer table of the skull, with soot deposition in the subcutaneous tissues and on the bone

3. In wounds where the firearm's muzzle is in contact with the skin at the time of firing, tissues are forced aside by the gases expelled from the barrel of the firearm, causing a localized *blast injury* (Fig. 26.2) [15, 38].

Several misconceptions exist about the wounding effects of high-velocity projectiles, particularly when their kinetic energy (as determined by muzzle or impact velocity alone) is presumed to be the sole determinant in size of temporary cavity formation [33, 34, 38–43].

The severity and size of a gunshot wound is related directly to the total amount of *kinetic energy transfer* to the tissues, not merely the total amount of kinetic energy possessed by the projectile. Kinetic energy transfer is proportional to the degree of retardation of the projectile in the tissue, which in turn is determined by four main factors [23, 33, 34, 38–43]:

1. The amount of kinetic energy (KE) possessed by the bullet at the time of the impact, which is dependent on the velocity and mass of the bullet ($KE = 1/2\ mv^2$) [23–25, 33].
2. The angle of yaw of a bullet at the time of impact, which in turn is dependent on the physical characteristics of the bullet (its length, diameter, and density), the rate of twist imparted by the barrel, and the density of the air. The greater the angle of yaw when a bullet strikes a body, the greater the retardation of the bullet and consequently the greater the amount of kinetic energy transfer. This explains why unstable projectiles in flight cause larger entrance wounds on impact with the body. Once the bullet enters the denser medium of tissue, its yaw angle increases progressively until the bullet becomes completely unstable, tumbles and rotates by 180°, and ends up traveling base forward. Tumbling of the bullet in tissue increases the presented cross-sectional area of the bullet, resulting in more direct tissue destruction and increased retarding (drag) forces, with consequently greater kinetic energy transfer and larger temporary cavity formation.

The sudden increase of the drag force also puts strain on the bullet, which may lead to the break up of the bullet and more tissue destruction [23].

3. The caliber, construction, and configuration of a bullet also influence the amount of kinetic energy transfer to tissue [23]:
   - Blunt-nose bullets and expanding bullets designed to mushroom in tissues are retarded more than streamlined bullets, resulting in more kinetic energy transfer to the tissue.
   - The caliber and shape (bluntness of the nose) of a bullet determine the initial presented cross-sectional area of the bullet and thus the drag of the bullet, but are of less importance when bullet deformity occurs.
   - Deformation of a bullet depends on both the construction of the bullet and the bullet velocity.
   - Construction of a bullet refers to the jacket, the length, thickness, and hardness of the jacket material, the hardness of the lead in the bullet core, and the presence or absence of special features, such as a hollow point.
   - Soft- and hollow-point rifle bullets expand and may shed lead fragments from the core, irrespective of whether they strike bone, resulting in a lead snowstorm image as visualized on X-ray. This fragmenting phenomenon appears to be related to velocity and does not happen with handgun bullets unless they strike bone. The lead fragments in turn act as secondary missiles increasing the size of the wound cavity.
   - A full metal-jacketed rifle bullet also may break up in the body without striking bone because of its velocity and tendency to yaw radically. As stated earlier, the significant yaw results in a sudden increase in the drag force, straining the structure of the bullet and resulting in break up of the bullet.
4. The fourth factor influencing kinetic energy transfer is the density, strength, and elasticity of the tissue penetrated by the bullet and the length of the wound track. The denser the tissue, the greater the angle of yaw and consequently the greater the degree of retardation and kinetic energy transfer [23].

Thus, while the *capacity* of a projectile to cause tissue damage is defined traditionally by its available kinetic energy, the muzzle velocity of a firearm and the impact velocity of a projectile can be misleading indicators of their potential for injury when the *kinetic energy transfer variables* are ignored [3, 33, 43].

Temporary cavitation is merely a transient displacement or stretching of tissue where the size of the cavity is determined by the characteristics of the tissue and the amount of energy transferred. The damage and external wound appearances caused by a temporary cavity can vary greatly depending on its size and anatomic location (see Fig. 26.1). Tissues containing a large amount of elastic fibers, such as lung, muscle, or bowel, can withstand some mechanical displacement without significant damage, but denser tissues with few elastic fibers, such as liver and spleen, and encased tissues, such as the brain, may be lacerated severely.

While considered rare, temporary cavitation may cause vascular disruption and bone fractures distant to the permanent wound track [33, 39, 40].

26.4 Forensic Terminology and Gunshot Wound Appearances

Gunshot wounds may be either *penetrating* or *perforating*. The term *penetrating* wound is used when a bullet enters the body or a structure, but does not exit. The term *perforating* wound is used when a bullet passes completely through the body or a structure [23].

26.4.1 Entrance Wounds

Range of fire is the distance from the muzzle to the victim and can be divided into four broad categories: contact, near-contact or close-range, intermediate-range, and distant-range. Each category has specific identifying features that are imparted both by the bullet and the various emissions accompanying the bullet from the muzzle of a firearm [3, 23, 24].

The presence of clothing or hair acting as intermediary barriers may obscure the typical wound characteristics of contact, close-range, and intermediate-range wounds. It is of great forensic importance that the integrity of such intermediary barriers be maintained and such items preserved as evidentiary material.

Other intermediary targets such as doors or windows also may influence the appearances of entrance wounds as discussed under the heading, "Atypical Entrance Wounds." [23, 24]

It must be noted that the size of an entrance wound is a poor indicator of the caliber of the wounding bullet because of variations in anatomic anchoring and elasticity of skin [23].

26.5 Contact Wounds

In contact wounds, the muzzle of the firearm is held in contact with the victim's body or clothing at the time of discharge. Contact wounds may be subdivided further into hard-contact, loose-contact, and incomplete- or angled-contact wounds. In the latter, the complete circumference of the muzzle is not in contact with the body [3, 23, 24].

In hard-contact wounds, the muzzle is pressed firmly against the body. All the muzzle emissions accompanying the bullet—the flame, the hot gases, the soot, the propellant particles, the primer residue, and metal particles—are forced into the wound (see Fig. 26.2). The wound appearance can vary from a small perforation with searing and blackening of the wound edges caused by the hot gases and flame, to a large, gaping stellate wound, with soot visible within and around the wound, and searing of the wound edges from hot gases and flame [23, 24].

The large wounds occur over areas where only a thin layer of skin overlies bone, such as the head. On discharge of the firearm, the compressed gases injected between

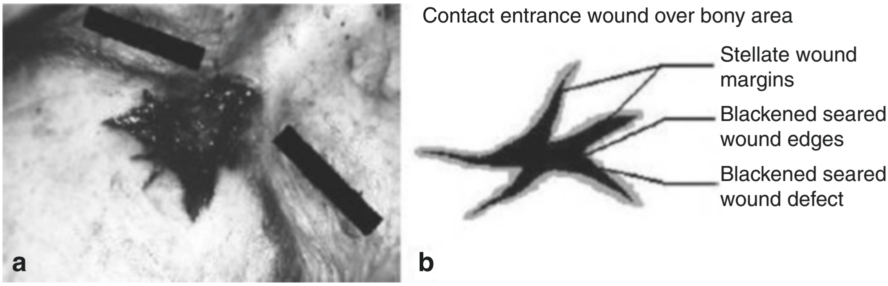

Fig. 26.3 (**a**, **b**) Contact gunshot wound of the forehead showing a large, stellate, lacerated wound with soot blackening visible within the wound and on the wound margins

the skin and the skull expand to such an extent that the skin stretches and tears. These tears radiate from the center, resulting in a large stellate or cruciform entrance wound with blackened, seared wound tissues and margins [3, 23] (Fig. 26.3a, b). The inner wound tissues may appear cherry pink due to the carbon monoxide in the gases [23].

Stellate lacerated wound appearances are not only found in hard-contact entrance wounds, but also may be found in tangential, ricochet, or tumbling bullet entrance wounds, as well as some exit wounds. However, in these wounds, soot and propellant will not be present within and around the wound, and the wound margins will not be seared [3, 23, 24].

In some hard-contact wounds, the gases expanding in the subcutaneous tissues may slam the stretched skin against the muzzle of the firearm with enough force to leave behind a muzzle-imprint abrasion or contusion on the skin (Fig. 26.4). Patterns like these may be helpful in determining the type of firearm used and should be described, documented, and ideally photographed before wound alteration by debridement, surgery, or healing [3, 23, 24].

In both loose-contact and incomplete- or angled-contact wounds, soot and other gunshot residues are present within and around the wound. Soot, which is carbon, is produced by the combustion of propellant and imparts a black color to the areas where it is deposited. In addition, flame and hot gas emissions result in searing of the skin around the wound. Scattered grains of propellant may accompany the jet of gas and be deposited in the seared and blackened zones of skin. The angle between the muzzle and the skin will determine the soot and searing pattern [3, 23].

In a perpendicular loose- or incomplete-contact wound, the distance between the muzzle and the skin is too small for propellant particles to disperse and mark the skin; the resultant wound appearance is that of a round central defect surrounded by a zone of soot overlying seared skin [23, 24]. In an angled loose- or incomplete-contact wound, the zone of searing and soot deposition around the wound is elongated in shape. A fan-shaped pattern of powder tattooing resulting from propellant grains skimming over the seared skin may be observed at the distal end of the entrance wound. This pattern can indicate the direction in which the gun was angled [23].

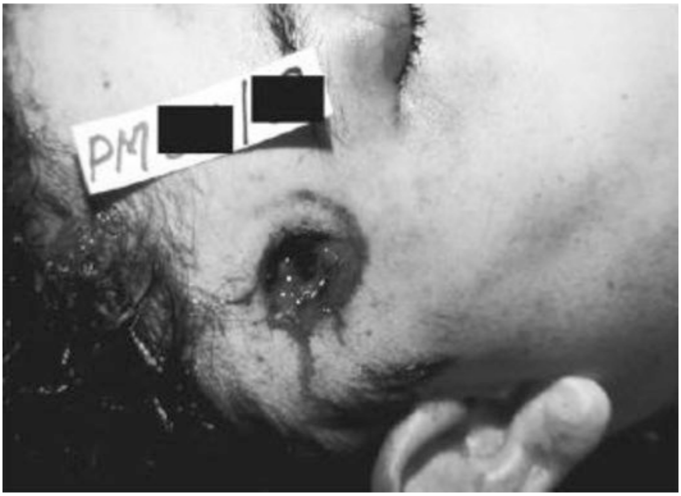

Fig. 26.4 Hard-contact gunshot wound of the temple, with a partial muzzle-imprint abrasion around the soot-blackened wound

Fig. 26.5 Slightly angled near-contact wound with the wider zone of soot-blackened skin on the same side as the muzzle of the weapon, i.e., pointing towards the weapon

26.6 Close-Range or Near-Contact Wounds

There is considerable overlap between the appearance of close-range and loose-contact wounds, making it difficult to differentiate the two. Both have an entrance defect with a surrounding zone of seared, soot-blackened skin. Close-range can be defined as the maximum range at which soot is deposited on the wound or the clothing, usually with a muzzle-to-target distance of up to 30 cm in handguns.

Because some of the soot can be washed away, its presence and configuration should be described accurately and documented, and photographed if possible, prior to cleansing or surgical debridement (Fig. 26.5). Cleaning a wound with a spray of hot water or pouring hydrogen peroxide on wounds caked with clotted blood should wash away or dissolve the blood but preserve the soot pattern. Propellant particles may be deposited in the seared zone surrounding the wound defect, but tattooing from the dispersal of propellant generally is not seen [23].

26.7 Intermediate Range Wounds

The hallmark of intermediate-range wounds is the phenomenon of so-called powder tattooing. This tattooing consists of numerous reddish-brown punctate abrasions surrounding the entrance wound, caused by unburned and partially burned propellant particles impacting against the skin (Fig. 26.6). Tattooing may be observed in wound-to-muzzle distances between 1 cm and 1 m, but generally is found at distances of less than 60 cm in handguns. The lesions of tattooing are actual small abrasions and thus cannot be washed off [3, 23, 24, 28, 29].

With respect to searing, soot deposition, and powder tattooing, the following must be noted [23]:

- The zone size, concentration, and pattern of both soot deposition and powder tattooing depend on the muzzle-to-target distance and angle, the type of propellant powder and ammunition, the barrel length, and the caliber and type of weapon.
- Accurate documentation and photography of patterns of skin searing, soot deposition, and powder tattooing accompanied by simple line drawings will allow for comparative test-firing studies to give more accurate range-of-fire estimates.
- Test firing is conducted at forensic ballistic laboratories where the offending weapon is fired at a target from different ranges using similar ammunition to that

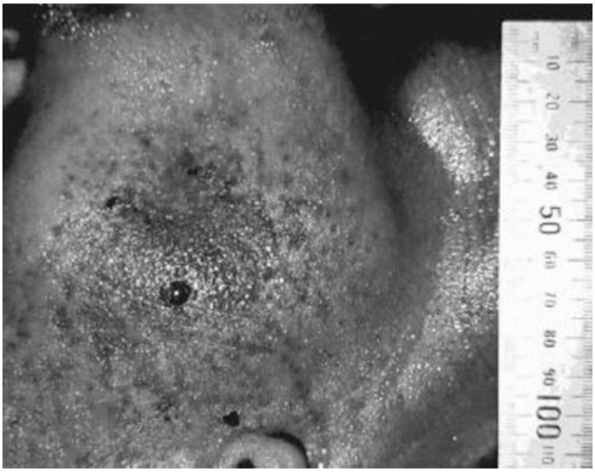

Fig. 26.6 Powder tattooing around an intermediate-range gunshot entrance wound

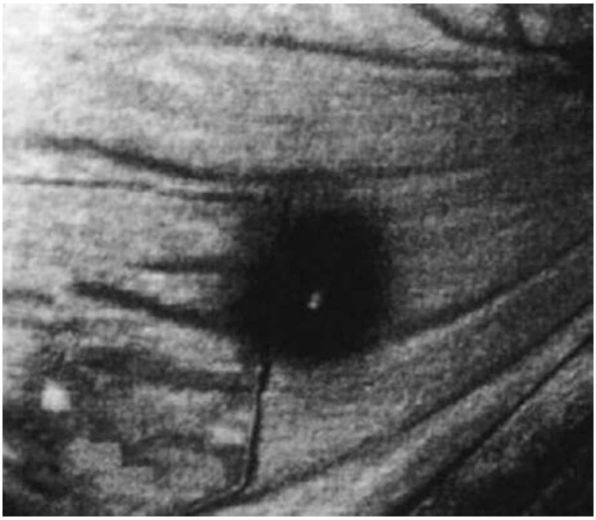

Fig. 26.7 Soot deposition on clothing in a close-range firearm discharge

which caused the wound. The target appearances then are compared with those of the wound and the range determined.

- Intermediary barriers such as hair or clothing may obscure or prevent skin searing, soot deposition, or powder tattooing from occurring (Fig. 26.7). At close and intermediate ranges, ball powder may perforate 1–2 layers of cloth to produce powder tattooing, but flake powder usually does not even perforate one layer of cloth. Clothing also may result in redistribution of soot and powder patterns among the layers of clothing or on the skin in a hard-contact wound, altering the wound appearance to that of a loose-contact wound. It also may absorb completely the soot of a close-range wound, altering its appearance to mimic that of a distant-range wound.
- The correct handling of the clothing of gunshot-wound victims as evidentiary material will allow for further forensic investigations pertaining to range, direction, and firearm or ammunition identification to be conducted on such items.
- Microscopic examination and elemental analyses could be performed on excised gunshot wounds to assist with range, as well as entrance versus exit wound determinations [23, 30, 37].

26.8 Distant-Range Wounds

In distant-range entrance wounds, the only marks left on the body are produced by the mechanical action of the bullet perforating the skin. There is no searing, soot deposition, or tattooing associated with the skin defect [23].

Regardless of range, most entrance wounds have a zone of abraded epidermis surrounding the entrance hole, which is called an "abrasion ring" or "abrasion collar." This abrasion ring traditionally is considered to be caused by friction between

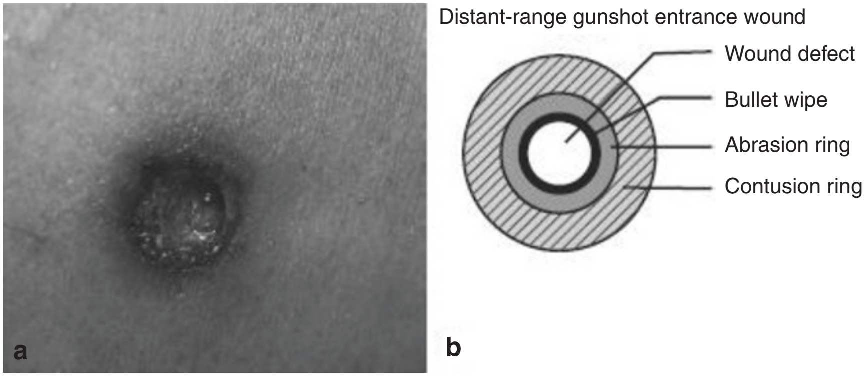

Fig. 26.8 (**a**, **b**) Slightly angled distant-range gunshot entrance wound with punched-out neat wound margins. A slightly eccentric abrasion ring and narrow contusion ring are present around the wound defect

the bullet and the epithelium, which occurs as the bullet indents and perforates the skin [23, 24, 27–31]. In a recent study utilizing high-speed photography and the "skin–skull–brain model," it was postulated that the abrasion ring is due to the massive temporary overstretching of the skin adjacent to the bullet perforation [35]. The abrasion ring is due neither to the bullet's rotational movement nor to thermal effects of the bullet on the skin (Fig. 26.8). The width of an abrasion ring varies with the caliber of the firearm, the angle of bullet entry, and the anatomic location. The abrasion ring may be concentric or eccentric, depending on the angle between the bullet and the skin (see Fig. 26.8a).

Distant-range entrance wounds of the palms, soles, and elbows do not have abrasion rings and appear stellate or slit-like due to the thickness and rigidity of the skin in those regions. Some high-velocity distant entrance wounds may have no abrasion ring and may show small "micro-tears" radiating outwards from the edges of the perforation, which may be visualized with a dissecting microscope [23].

Most distant-range entrance wounds are oval to circular with a punched-out, clean appearance to the margins, totally unlike those of exit wounds [23]. A contusion ring may also be present around the wound defect due to damaged blood vessels in the dermis [35]. However, distant entrance wounds over bony surfaces may have stellate or irregular appearances [23, 24].

Distant-range wounds may have a gray coloration to the abrasion ring, which is called bullet wipe. This occurs when powder residue, soot, gun oil, or dirt deposited on the bullet surface as it moves down the barrel is rubbed off the bullet by the skin as the bullet penetrates the body. Bullet wipe is commonly observed in clothing overlying entrance wounds and is also referred to as a grease ring [23, 24, 27, 28, 35] (see Fig. 26.8b).

It is not possible to determine an exact range of fire in distant-range entrance wounds. Here, only the ring of bullet wipe may be of value in linking a wound to a weapon because metallic elements from the primer, cartridge case, and bullet may be present in the bullet wipe [23]. However, it must be re-emphasized that soot and propellant from close- and intermediate-range wounds may be deposited on the clothing overlying the wound, resulting in a skin wound that *appears* to be of distant-range [3, 23, 24, 26–31].

26.8.1 Exit Wounds

Most exit wounds have similar characteristics irrespective of whether they result from contact, intermediate, or distant ranges of firing. An exit wound typically is larger and more irregular than an entrance wound. This is mainly due to two factors [23, 24]:

1. Increasing projectile instability as it travels through the tissue, resulting in accentuated yaw, eventual tumbling, and the bullet exiting base first if the wound track is long enough;
2. Projectile deformation in its passage through the tissues as seen in the mushrooming of a bullet.

Both factors result in a larger area of projectile presented at the exit site, with a resultant larger, more irregular exit wound. Exit wounds result from the stretching force of the bullet overcoming the resistance of the skin. The skin is perforated from the inside out, causing eversion of the wound margins and protrusion of tissue tags through the wound defect [23, 24] (Fig. 26.9).

Exit wounds can be difficult to interpret because they vary in size and shape and are not necessarily consistently larger than their preceding entrance wounds. Factors other than projectile deformation and projectile instability affecting the size and appearance of an exit wound include [23, 24]:

1. Velocity and temporary cavitation effects of a bullet at the point of exit (see Fig. 26.1);
2. Fragmentation of the bullet;

Fig. 26.9 Irregular exit wound with eversion of the wound margins

3. Secondary missile formation, such as bone or jacket fragments accompanying the bullet through the exit wound;
4. Bone under the skin in the area of exit;
5. Objects pressing against the skin in the area of exit.

26.8.2 Atypical Entrance Wounds

Atypical gunshot entrance wounds occur when bullets become unstable and nonaxial in their flight before striking the body. Unstable nonaxial flight may be caused by intermediary objects, ricochet, inappropriate weapon–ammunition combinations, poor weapon construction, or use of silencers, muzzle brakes, and flash suppressors. Of significance in these instances is that distant-range gunshot entrance wounds may be confused with contact, close-, or intermediate-range entrance wounds, and even exit wounds, particularly when intermediary objects or ricochet bullets are encountered [23, 44].

If a bullet passes through an intermediary object, before penetrating a body, fragments of glass and even bullet fragments may strike the skin, producing stippling around the entrance wound, mimicking an intermediate-range gunshot entrance wound [23, 44–46]. Di Maio [23] defines the term “stippling” as multiple punctate abrasions of the skin due to the impact of small fragments of foreign material. If the material is propellant, it is called powder tattooing, but if the stippling is produced by material other than propellant, it is called pseudo-powder tattooing.

Pseudo-powder tattoo marks generally are larger, more irregular, and more sparse than true powder tattoo marks, and fragments of foreign material from the intermediary object, such as glass, may be found embedded in the marks [23] (Fig. 26.10).

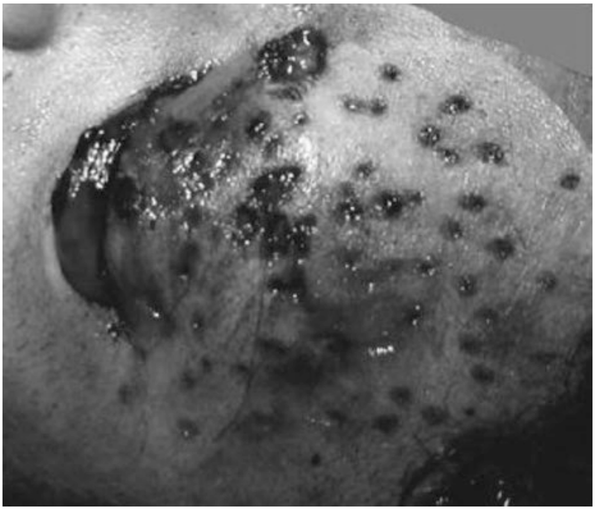

Fig. 26.10 Larger, more irregular stippling or pseudo-powder tattooing due to fragments of glass

Pseudo-soot blackening effects may occur in ricochet off material such as black asphalt, with deposition of fine black asphalt powder on a victim. Likewise, the lead core of a bullet may disintegrate following ricochet or intermediary object perforation, with powdered or vaporized lead deposition on a victim simulating soot blackening [23, 45–47].

The entrance wound of an unstable or deformed bullet may have a large stellate configuration. In the absence of any stippling or pseudo-soot, it may mimic a contact entrance wound or mimic an exit wound [23]. Bullets recovered from a body following ricochet or intermediate object impaction may be markedly altered in appearance, or even fragmented. If the recovered bullet is handled correctly, forensic scientific examination of such a bullet could reveal the type of material the bullet impacted prior to penetrating the body. This may facilitate the subsequent scene reconstruction and legal proceedings [13, 23, 24].

Contact gunshot wounds from firearms fired with silencers, muzzle brakes, or flash suppressors may leave unusual patterns of seared, blackened zones around their entrance wounds (Fig. 26.11). These result from the diversion of muzzle gases by such devices. A silencer may even filter out all the soot and powder emerging from the barrel [23].

A graze wound resulting from tangential contact with a passing bullet may reveal the direction of fire. Careful hand-lens examination of such a wound may reveal skin tags on the lateral wound margins of the graze-wound trough pointing towards the weapon. The lacerations along the wound-trough margins point in the direction the bullet moved [23, 48]. Piling up of tissue may occur at the exit end [23].

A pseudo-gunshot wound may be defined as an external wound with features resembling those of a gunshot wound, which on further examination is shown to be non-gunshot in origin, such as a stab wound caused by a pointed instrument like a screwdriver (Fig. 26.12) [24, 49].

Fig. 26.11 "Petal" pattern of soot and searing around a contact entrance wound. A flash suppressor was attached to the muzzle of the military rifle used to inflict this wound

Fig. 26.12 Oval pseudo-gunshot entrance wound with an "abrasion ring" around the wound defect. This penetrating wound was inflicted with a screwdriver

26.8.3 Atypical Exit Wounds

Exit wounds may have abraded margins resembling the abrasion collars of distant entrance wounds. This occurs when the skin is reinforced or supported by a firm object at the instant the bullet exits. The exiting bullet everts the skin, impacting and abrading it against the firm object, such as a floor, a wall, or even tight garments like belts or brassieres. These wounds are called shored exit wounds [3, 23, 24]. Occasionally, the pattern of the material may be imprinted on the edges of the wound [23]. Elemental analysis of excised shored exit wounds by scanning electron microscope–energy dispersive X-ray spectrometry (SEM-EDX) may reveal the nature of the shoring material [23, 50].

26.8.4 Shotgun Wounds

Shotgun wounds are also classified on the basis of range of fire into contact, close-range, intermediate-range, and distant-range wounds.

The components of a shotgun discharge giving rise to differing wound appearances include the propellant, flame, soot, carbon-monoxide–rich gases, pellets, wads, detonator constituents, and cartridge-case fragments [23, 24, 27]. The terms used to describe the effects of these shotgun components are the same as for rifled weapons [24].

The characteristics of shotgun entrance wounds vary with the caliber (gauge) of the weapon, degree of choke, size and number of pellets, as well as the range of fire. Searing, soot deposition, and powder tattooing may be present in close-range and intermediate-range shotgun wounds. The precise range of discharge for a given shotgun can be accurately assessed only by test firing that shotgun with the same brand of ammunition and then comparing the findings with the description of the shotgun wound [23, 24, 27].

The wound description should include [23, 24, 31]:

1. The presence of a wad in the wound and the measurements of the wound defect, as well as the searing, blackening, and powder tattooing patterns around the wound (Close-range: <30 cm).
2. The presence of a wad in the wound and measurements of the wound defect, noting the presence or absence of crenated or scalloped wound edges and surrounding powder tattooing (Intermediate-range: 30–120 cm).
3. Measurement of the diameter of the spread of "satellite" pellet wounds around the measured central defect and the presence or absence of an adjacent wad impact abrasion (Distant-range: >120 cm) (Fig. 26.13).
4. The absence of a central wound defect with measurement of the diameter of the spread of pellet wounds (Distant-range: >600–1000 cm).
5. The presence of a wad or pellets in the clothing.

The range estimates given in brackets above are only a rough guide.

Perforating wounds of the trunk from shotgun pellets are uncommon, but when they do occur, the exit wounds vary from large, irregular, gaping wounds caused by a mass of pellets exiting, to single, slit-like exit wounds produced by single pellets [23, 27].

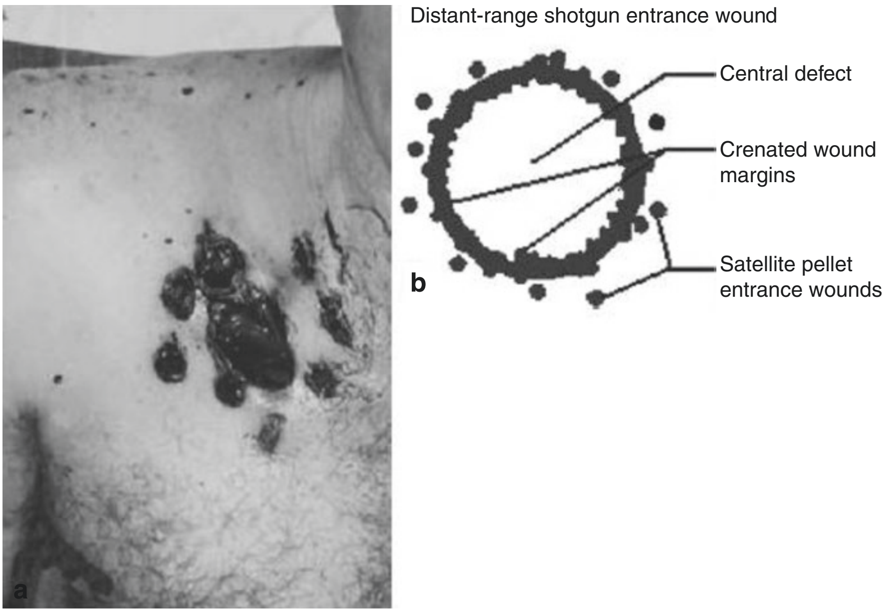

Fig. 26.13 (**a**, **b**) Distant-range shotgun entrance wound with surrounding satellite pellet entrance wounds. Range is estimated at 1.5–2 m

When found, shotgun pellets and wads should be removed and handled as evidence, as examination of the wad could indicate the gauge of the shotgun and make of the ammunition, whereas the pellets will give the pellet size and shot category [23].

26.9 Forensic Evidence

The value of forensic evidence in gunshot cases in determining ranges of fire, entrance versus exit wounds, types of ammunition and firearms, manners of injury, and even identification of the assailant cannot be over-emphasized. Therefore the collection, handling, and documentation of evidence during the initial evaluation of a gunshot victim should be standard practice in the emergency setting [1, 3–8]. Hospitals should have written protocols that incorporate proper procedures for the collection and retaining of forensic evidence [6, 7, 51]. A clear understanding of what constitutes evidence is necessary for the successful implementation of such protocols [4, 52].

The term *evidence* is used to describe the nature by which information is presented to the courts; it may be either *informational*, by way of documents and orally, or *physical*, by way of objects such as bullets [4, 52]. All physical evidence must be collected carefully, packaged, sealed, and labeled, and it should include the patient's name and hospital number, as well as date and time of specimen collection, specimen type, site of collection, and collector's name and signature [4, 7, 13, 51, 53].

26.9.1 Informational Evidence

In the context of gunshot victims, informational evidence should include a history, examination, and accurate documentation of the gunshot injuries on admission, supplemented with line diagrams, X-rays, and, where possible, photographs. Objective descriptive terminology stating location, size, and shape of wounds, and any unusual marks or coloration should be used to describe the wounds, rather than making potentially inaccurate ballistic interpretations [1–8, 11–22]. All iatrogenic interventions must also be recorded to prevent subsequent interpretive difficulties by the forensic pathologist.

X-ray studies indicating the location and the number of bullets in the body must be included. The path and fragmenting nature of a bullet may be revealed, but opinions regarding the type of ammunition used are best left to ballistics experts [8, 11–24]. When bone is traversed in the path of a bullet, an X-ray may provide valuable information as to the direction of fire, as the bullet displaces the bone fragments in the direction it travels [23, 24].

26.9.2 Physical Evidence

Physical evidence is real, tangible, or latent matter that can be visualized, measured, or analyzed [4]. Any belongings, body fluids or tissues, or foreign objects found in or on the patient constitute potential evidence. If physical evidence is very small or microscopic, it is referred to as “trace evidence.”

In gunshot victims, physical evidence would include:

1. Trace evidence such as:
   - gunshot residue (GSR) or blood-spatter on the victim’s hands, hair, and clothing [23, 32, 54–59]
   - hairs, debris, or fibers on the victim’s body or clothing [4, 7, 53, 60]
   - blood or tissue under the victim’s fingernails [3, 23, 54]
2. Blood, urine, or tissue samples
3. Clothing with or without bullet holes
4. Bullets and cartridge cases in the victim’s body or clothing [4–7, 13, 51, 53].

26.10 Trace Evidence

The individual collection of trace evidence by “tape lift” or “swabbing” ideally should be performed by trained forensic personnel and falls outside the scope of the trauma surgeon [4, 32]. However, by merely collecting and preserving the clothing of a gunshot victim in totality, trace evidence collection and analyses of GSR, fibers, hairs, debris, or blood on the clothing can be performed at forensic laboratories [4, 7, 23, 32, 53–60].

If a physical altercation occurred prior to the shooting incident, fingernail scrapings could be used for comparative DNA analyses. Special crime kits for the collection of such samples are available in most centers, but ideally staff with appropriate forensic training should collect these samples [1–8, 16].

Once the patient is stable, GSR testing on the hands of victims could be performed by forensic investigators, as particles may be detectable for up to 12 h following the shooting incident, using SEM-EDX techniques. A GSR test may determine whether a person has fired a firearm by testing for primer-residue constituents containing barium nitrate, antimony sulfide, and lead peroxide [23, 32–55].

If GSR or DNA testing is to be performed on the patient’s hands, the hands should not be cleaned with soap or alcohol. Paper bags should be placed over the hands and secured with elastic bands. Plastic bags should not be used as condensation or moisture in the plastic bags may wash away primer residue or cause fungal degradation of biological evidence [3, 4, 7, 13, 23, 53].

26.11 Laboratory Samples

Admission blood samples for alcohol or drug analyses taken prior to dilution by volume expanders or transfusions will yield the most accurate results. Urine specimens also may be used, but they are less valuable for quantification of results [7].

The victim's blood could be used for comparative DNA analysis with blood spatter found at a scene, on a suspect, or on a firearm, as well as with tissue particles found on a spent bullet recovered at a scene [23, 54].

Surgical debridement of a gunshot wound will permanently alter the wound appearance. If not properly documented, photographed, or retained for microscopic evaluation, this may result in misinterpretation by subsequent examiners [1–8, 51]. Excised wound margins could allow for microscopic and SEM-EDX evaluation in cases where it is important to [23, 30, 37, 51, 55–58]:

- confirm the range of an entrance wound
- establish whether one is dealing with the pseudo-effects of soot blackening or powder tattooing
- establish which of two gunshot wounds is the entrance wound
- ascertain the type of weapon or ammunition used

For SEM-EDX GSR trace analysis, the excised skin specimen should be placed outer surface upwards on a layer of dry gauze, on top of a piece of cotton wool dampened (not soaked) with formalin, then placed inside a specimen bottle. The skin sample must be secured in this position by placing another piece of dry gauze over it before closing and sealing the bottle. Suspension of the specimen in liquid formalin should be avoided to prevent particles from being washed off prior to analysis (B. A. Kloppers, personal communication).

26.12 Clothing

The clothing of victims often contains valuable clues, including trace evidence and macroscopic bullet holes [13]. Examination of clothing may reveal information as to range and direction of fire, type of ammunition and firearm used, and allow for confirmatory trace evidence analysis. Therefore, all clothing of gunshot victims should be preserved and retained [3–8, 13, 23, 24, 32, 54–61].

Emergency personnel should not cut through the convenient starting point of the bullet holes for purposes of removing clothing because disruption of the bullet defect site may destroy evidence. Clothing should be searched for pieces of spent bullets such as bullet jackets [13, 53]. It also should be noted whether any garments on the victim were "inside out," as clothing fibers bend in the direction of the path of the bullet, and the true orientation of the fabric may be important to forensic investigators in confirming the circumstances surrounding the incident [13, 23].

Propellant residue and soot will deposit on clothing in contact, close-, and intermediate-range discharges, as they would on skin (see Fig. 26.7). Contact wounds in synthetic material may even cause "burn holes." Bullet-wipe residue also may be observed as a gray to black rim around an entrance hole in clothing. Trace evidence on retained clothing, including fibers, debris, blood spatter, and GSR, may be detected and analyzed to corroborate or complement macroscopic findings with respect to circumstances, range, and direction of fire and type of firearm or ammunition used [3, 23, 32, 54–60].

Bloody garments should be air dried before being packaged in correctly labeled paper bags to prevent degradation of evidence by fungal or bacterial elements [4, 7, 13, 23, 53].

26.13 Bullets and Cartridge Cases

When bullets or projectile fragments are found or surgically removed from the patient, their integrity must be maintained as much as possible for subsequent ballistic investigations [23, 24, 53]. A bullet's unique markings are called *class characteristics*, which result from its contact with the rifling in the gun's barrel when the firearm is discharged. They may indicate the make and model of a firearm using comparative analytical techniques [23, 24]. Standard metal instruments such as forceps can scratch the jacket or lead of the bullet, producing marks that could hamper or prevent analysis of bullet striations, and thus firearm identification [23, 62]. Russel et al. [62] suggested using a "bullet extractor" to accomplish the dual purpose of safe handling (as in the case of bullets with pointed ends, jagged projections, and sharp edges, for example the Black Talon Bullet) and evidence preservation. The bullet extractor is a standard curved Kelly forceps fitted with 2-cm lengths of standard-gauge rubber urinary catheter as protective tips [62].

The retrieved projectile should be examined for macroscopic trace evidence such as fibers and glass. If none is found, the projectile may be rinsed gently to remove excess blood or body fluids [62]. If the surgeon chooses to mark the bullet with his initials, such marks should be put on the base of the bullet so as not obliterate the rifling marks on the side of the bullet [23].

Deformed sharp-edged bullets or bullet fragments should be placed in hard plastic containers rather than traditional bullet envelopes to prevent accidental puncture through the envelopes and subsequent loss or injury [62, 63]. The bullet container or envelope should be annotated with the date, time, anatomical location of the bullet, the name and hospital number of the gunshot victim, and the collector's name. Tamper-proof seals should be used whenever possible [23, 53, 62].

Cartridge cases that may be found in the victim's clothing also have unique microscopic marks on their bottoms or sides, imparted by contact with the firing pin, the breechlock, the magazine of semiautomatic weapons, and extractor and ejector mechanisms. These may be used to identify the type, make, and model of the firearm used. Therefore they should be handled and preserved in the same careful way as described above for bullets [23].

26.13.1 The Deceased Gunshot Victim

When a gunshot victim dies in the hospital, the clinical documents forwarded to the forensic pathologist must indicate clearly whether any bullets or projectiles were retrieved from the body of the patient. The location of the bullet before retrieval must be noted. The documents must also include a summary history and examination of the victim at the time of admission, accurate admission wound descriptions, and subsequent iatrogenic procedures performed. If the death is delayed for a period of time, a summary of the patient's management, clinical progress, and any complications must also be recorded. If X-rays were taken, the exact location of any remaining projectiles must be documented clearly [1–8, 13, 61].

If a gunshot wound victim dies soon after arrival at the hospital, it is recommended that the deceased's hands be encased in paper bags. If the clothing is still on the body, it should not be removed before placing the body in a body bag for transfer to the mortuary [4]. To facilitate the comparison of clothing defects with wounds on the victim's body, all removed clothing still in the custody of the hospital should accompany the body to the mortuary [53]. All intravenous lines, catheters, tubes, sutures, and drains should be left in situ to minimize possible confusion of gunshot wounds with surgical wounds [4].

26.13.2 The Chain of Custody

The chain of custody is the pathway that physical evidence follows from the time it is collected until it has served its purpose in the legal investigation of an incident. A record of the chain of custody will reflect the number of times a piece of evidence has changed hands or location prior to its final destination [4]. Minimizing the times that evidentiary items change hands will assist in protecting the integrity and credibility of such evidence [53]. Failure to protect the chain of custody may cause evidence to be inadmissible in court, even though it is physically present, as defense attorneys often attempt to cast doubt on the integrity of the evidence by attacking the chain of custody [4, 53].

All potential evidentiary items should be placed in appropriate containers that can be sealed with tape and labeled appropriately [4, 53]. A standard chain-of-custody form attached to the container could be used to document all transfers of the evidence, with the dates, details, and signatures of all the individuals who handled the evidence recorded on it. A copy of this chain-of-custody form should be kept in the patient's hospital record. If the chain is properly recorded, hospital personnel may not be required to testify in subsequent court proceedings, especially when testimony is needed simply to establish the chain of custody [4, 51, 53].

Written protocols incorporating the proper handling of forensic evidence, together with standard chain-of-custody forms should be implemented at all hospitals [6, 7, 51]. A hospital "property custodian" should be appointed to safeguard all evidentiary items until their collection by law-enforcement officials [4, 7].

26.13.3 Explosions and Evidence

With the dramatic increase in the incidence of domestic bombings and mass-casualty incidents worldwide, all hospitals must have mass-casualty plans in place in order to optimize medical care for victims [64, 65]. In addition, emergency departments must recognize that criminal prosecution or civil litigation against parties responsible for injurious explosions may follow such events. While it may be very difficult in mass-casualty situations, the forensic aspects of documentation and evidence collection must remain in place [34, 65].

A variety of explosive devices exist, including many which are homemade. Emergency health-care workers must protect themselves and their patients from further injury by ensuring that contaminated clothing and potential flammable material is removed from the patient, keeping in mind that all material removed is potential forensic evidence and should be treated as such [64]. Clothing and hair of victims may contain macroscopic and trace evidence that may reflect the type of explosive used, confirm the chemical composition of incendiary devices, indicate the presence or absence of fire or smoke, and may provide clues as to the location of a patient in relation to the blast [27–29, 64].

The patterns of injuries and shrapnel retained in patients may also provide valuable information as to all of the above. Careful descriptions and documentation of all injuries, total-body X-ray investigations, and retrieval of foreign materials during surgery that may include bomb fragments, must be performed [27, 28, 34]. Small metal objects forming part of the bomb mechanism may be invaluable in allowing experts to recognize the handiwork of a particular bomb maker or terrorist group [27–29].

Conclusion

When clinicians are remiss in the adequate forensic evaluation of gunshot patients, it could have far-reaching medico-legal implications in the increasingly litigious construct of society and could result in obstruction of the ends of justice with respect to the forensic and legal needs of individual patients, as well as society in general [1–8, 16, 20, 52].

Three separate retrospective analyses have shown that clinical records in gunshot cases routinely lack adequate wound descriptions [14, 18–22]. In addition, the correct handling of potentially short-lived evidentiary material and the preservation of a chain of custody is frequently neglected in clinical settings [5–8].

If a gunshot victim is killed outright and examined by a competent forensic pathologist, precise descriptions of the wounds will be obtained and forensic evidence will be handled correctly. However, if the patient initially survives and remains in hospital for a period of time, then wound healing or sepsis and surgical interventions can cause considerable difficulty in interpretation for the forensic pathologist if the documentation of gunshot wounds and iatrogenic procedures and the collection of forensic evidence have been neglected [13, 15, 17–20].

In summary, the comprehensive forensic evaluation of a gunshot victim should include the following:

1. Recording of the patient's and clinician's names, date and time of admission, full history and examination, and date and time of death (when applicable)
2. Recording of anatomical location, size, shape, and characteristics of the gunshot wound(s), including associated marks or coloration

3. Recording of surgical resuscitative procedures, as these may obscure or alter gunshot wound appearances, or result in "additional wounds"
4. Augmentation of narrative descriptions with X-rays, diagrams, and photographs where possible
5. Use of a proforma, including a simple line drawing, to improve the quality of documentation
6. Refraining from "forensic interpretations" of gunshot wound appearances with respect to entrance, exit, direction, or range of fire
7. Recording of the patient's clinical management, progress, or complications, as well as special investigations and further surgical interventions
8. Recording and correct handling of all evidence collected and proper maintenance of the chain of custody.

Lastly, a succinct observation by William S. Smock [3] that reflects the merits of clinical forensic training and the consequent appreciation of the value of forensic evidence in the emergency department, bears iteration:

> What was once considered confounding clutter that gets in the way of patient care (such as clothing and surface dirt) takes on a whole new significance when recognized for what it really is - evidence [3].

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Critical Care for Ballistic Trauma

27

Andrew McDonald Johnston

27.1 Introduction

There is no clear guide to the number and demographic characteristics of patients who may require critical care after ballistic trauma. This is dependent on the location and target of the attack, for example terrorist incidents against an unprotected civilian population producing different injury patterns from those against military personnel who have protective equipment such as body armour. Gunshot wounds, explosive trauma, fragment injuries and burns may all be present in any individual patient, or a single injury type may predominate in multiple patients. Depending on location and what other medical facilities are available locally, patients may include children, adults including pregnant women, and elderly patients. Epidemiological studies give some guidance, but each incident is different [1].

27.2 Assessment on Admission to the Critical Care Unit

On arrival in the critical care unit from the operating theatre or emergency department the patient's condition should be assessed systematically, with confirmation of endotracheal tube position and adequate ventilation and oxygenation. In the face of impaired oxygenation consideration should be given to endotracheal tube displacement or malposition, and to tension or simple pneumothorax. A secondary survey should be carried out to identify any injuries that may have been missed in the initial assessment of the patient. Patients with bullet wounds to the thorax may have significant pulmonary contusions, see Fig. 27.1, including those with bullet

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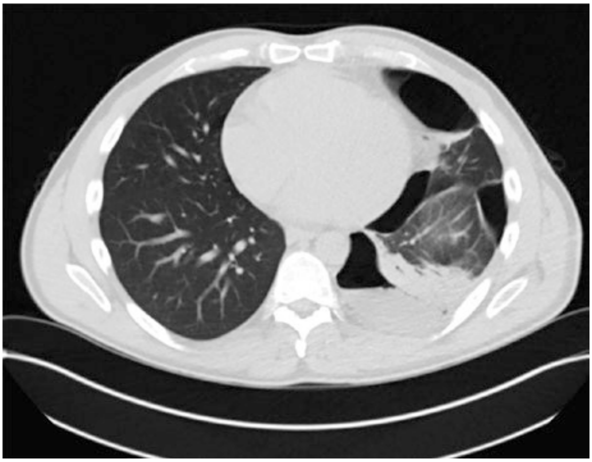

Fig. 27.1 Computed tomographic scanning of a patient's chest showing hydropneumothorax and residual lung contusion after a gunshot wound to the left chest and lung. Image reproduced with patient consent

tracks that have not disrupted the pleura, and patients with injuries from explosions may have blast lung [2, 3]. Low tidal volume ventilation is beneficial in trauma patients [4, 5] and is indicated in all patients with the possible exception of those with neurotrauma.

27.3 Ongoing Resuscitation

Postoperative cardiovascular instability most often will be due to haemorrhagic shock and further resuscitation may be required with blood, fresh frozen plasma or other clotting products. Crystalloid may also be given once haemorrhage has stopped. Attention should be given to restoring normothermia, as this will reduce coagulopathy. Some patients will require returning to the operating room for surgical control of haemorrhage. Hypotension may also be due to cardiac injury or to injury to the spinal cord with associated spinal shock. Resuscitation may be guided by clinical parameters such as blood pressure and urine output. In hospitals with access to invasive cardiac monitoring there may be a place for its use in selected patients. Focussed transthoracic echocardiography shows promise as a useful modality to examine cardiac contractility and assess intravascular volume status based on respiratory variation in the inferior vena caval diameter with respiration [6, 7].

27.4 Ventilation

Many patients admitted to the critical care unit with ballistic trauma have lung injury, either directly from bullet or explosive injuries to the lungs, or from blast injury, see Fig. 27.2, which may occur in combination with other injuries. Trauma patients as a group are at risk of ongoing lung injury and the acute respiratory

Fig. 27.2 Computed tomographic scan of thorax showing primary blast lung injury with perihilar, interstitial and alveolar haemorrhage and oedema. Image reproduced with patient consent

distress syndrome (ARDS). Lung protective ventilation with tidal volumes of 6 ml/kg ideal body weight and plateau pressures of less than 30 cmH_2O are recommended for all such patients to reduce the risk of progression to ARDS. Some patients will require a period of permissive hypercapnia to allow lung protective ventilation. Data on a large group of military trauma patients suggest that high frequency oscillatory ventilation may be of help in a small proportion of patients [8] although it should be cautioned that in larger studies of civilian patients with other conditions this therapy was not effective [9, 10]. Small numbers of military trauma patients have been evacuated to higher levels of care on extracorporeal membrane oxygenator circuits or extracorporeal carbon dioxide removal therapy with good outcomes [11].

27.5 Thromboprophylaxis

Thromboprophylaxis should be started at some point after surgery as patients are at risk of thromboembolism. The literature does not address when to start thromboprophylaxis in this patient group. The authors typically start low-molecular-weight-heparin within 12 h of surgery, with the exact timing depending on the amount of postoperative bleeding and surgical judgment of the risk-benefit ratio of heparin use. There is no high quality evidence for the use of inferior vena cava filters to prevent thromboembolism and several issues with serious harm are associated with current devices including failure to retrieve leading to a requirement for long-term anticoagulation and risks of venous damage during retrieval [12].

27.6 Renal Replacement Therapy

A small proportion of patients with ballistic trauma may require renal replacement therapy on the critical care unit. Certain types of incident such as multiple crush injuries from building collapse and explosion or severe burns may rapidly increase the number of patients that need renal replacement therapy. There is probably no benefit in early dialysis in patients who do not meet conventional dialysis triggers, [13] though patients with rhabdomyolysis following crush injury may be an exception to this.

27.7 Transfusion

In critical care patients who are not actively bleeding, transfusion to a haemoglobin of greater than 70–80 g/l appears to be harmful and is associated with an increased morbidity from systemic infection. Therefore after the initial resuscitation stage, in stable patients we set conservative transfusion triggers in this range.

27.8 Neurotrauma

Patients with traumatic brain injuries following ballistic trauma can have very good outcomes and with good rehabilitation may return to work, even with poor levels of consciousness at the time of injury [14]. In this subgroup of patients a balance must be struck between strict lung protective ventilation and neuroprotective strategies which aim to maintain a normal partial pressure of carbon dioxide.

27.9 Feeding

Trauma patients are in a catabolic state and should be fed, although evidence that this improves the catabolic state is lacking. There are few contraindications to enteral feeding by mouth or nasogastric tube. There is little evidence that nasojejunal feeding is any better than nasogastric in critically ill patients [15]. There is evidence early parenteral feeding is harmful and it should be avoided if enteral feeding can be established within 8 days [16]. Enteral feeding should be instituted early and patients fed to a caloric goal of approximately 25 kcal/kg/day. Care should be taken in malnourished patients to avoid precipitating the refeeding syndrome where rapid correction of starvation results in severe metabolic abnormalities and in some cases death.

27.10 Analgesia

The use of morphine early in resuscitation is strongly associated with a reduction in subsequent post-traumatic stress disorder in military patients [17]. It is not yet clear whether other analgesics such as fentanyl and ketamine are equally effective in reducing subsequent psychiatric problems. Early aggressive pain management with combinations of neuraxial blocks, regional techniques and multiple medications including opiates, non-steroidal anti-inflammatory drugs and acetaminophen was associated with a reduction in the pain suffered by patients in a military hospital [18].

27.11 Microbiology

Patients with complex traumatic injuries are at risk of wound infection, as well as the more familiar line and lung infections associated with prolonged stays on the critical care unit. Subgroups of patients, particularly those with abdominal trauma are at a higher risk of sepsis. If patients are transferred into your hospital from another hospital they will be at risk of carriage of any resistant organisms that are found in the referring facility. Any central venous lines and peripheral cannulas inserted in the referring institution should be changed with full sterile technique in the receiving hospital. In particular patients transferred from terrorist incidents overseas are at an increased risk of carriage or infection with antibiotic resistant organisms. These include multi-drug resistant Acinetobacter baumannii which can be a major risk for the individual patient and for spread to other patients within the receiving institution [19]. Patients injured in explosions from military trauma and in some civilian setting are also at risk of invasive fungal disease, which can require prolonged treatment with systemic antifungal agents [20, 21]. Expert microbiological input is invaluable in managing ballistic trauma patients and antibiotic stewardship is very important in ensuring that overuse of antibiotics is avoided, for example discriminating between wound or site colonisation, which does not require antibiotic treatment, and wound infection, which does.

27.12 Evacuation to Definitive Care

Evacuation to a higher tier of medical care may involve lengthy journeys by land or air, with all of the considerations of civilian aeromedical evacuation [22] and additional ones of physical security of crew, patients, medical attendants and aircraft. Ballistic trauma can generate very large numbers of casualties necessitating moving large numbers of critically ill patients at one time [23]. If the patient is to be evacuated by air within a short period of time early postoperative extubation may not be contemplated, as reintubation in flight may be more difficult than in a hospital due to noise, vibration and other factors. Other considerations include restrictions on cabin altitude for patients with profound lung injury or intracranial air [24]. The receiving hospital must be prepared to accept multiple severely injured patients with all of the implications for subsequent use of surgical and operating theatre time, critical care occupancy and the associated impact on radiology, transfusion, laboratories, physical therapy and other hospital departments.

Ongoing surgical treatment of patients may take a long time and require numerous returns to the operating room for wound debridement and reconstructive surgery

[25]. Rehabilitation often takes months, and may be complicated by traumatic brain injury and post-traumatic stress disorder. With modern treatment preventing early death from haemorrhage, prehospital and resuscitative treatment in transit and in the emergency department followed by definitive surgical treatment and rehabilitation, casualties of very severe injuries can survive and often return to work [14].

27.13 Staff Support and Patient Follow-Up

Providing medical and nursing care for patients injured in war or terrorist incidents is upsetting and difficult. Some staff may find that pastoral support is helpful. Patients who are injured in terrorist incidents may have seen severe injuries and deaths of those injured close to them including relatives. These patients may be at a high risk of post-traumatic stress disorder. Studies of military patients with ballistic injuries show that delirium is common [26] and some patients find that addressing delirium in clinic follow up after discharge is helpful and provides reassurance.

27.14 Organisational Factors

The critical care unit will be best able to deal with an influx of a large number of patients following a terrorist incident if the unit staff, including clerical and administrative, have exercised for major incidents and understand what is required. Additional critical care beds can be procured by utilising other areas of the hospital such as anaesthetic rooms, which have mechanical ventilators. Consideration should be given to feeding and accommodation for staff in the case of major incidents that disrupt the transport infrastructure or communication networks. Staff training should include regular revision of the role of individual staff members and the critical care unit as a whole in the event of a major incident.

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28 Transfer and Evacuation

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28.1 Introduction

The aim of evacuation is to get the casualty from the point of wounding to definitive care. To do this safely requires comprehensive and robust plans in place by the local healthcare provider to ensure appropriate teams are tasked with the right resources to get the patient to the right treatment location. Depending on the clinical and logistical circumstances, this may require a number of staged transfers between medical treatment facilities. Intervention maybe necessary at these intermediate facilities in order to stabilise the patient for the onward move.

In the UK, the introduction of Major Trauma Centres (MTC) and Trauma units in a network arrangement have facilitated the improved care of patients. They have also resulted in a reduced need for secondary transfer between hospitals [1]. This reduction in secondary moves is due in part to the implementation of protocols which allow the Ambulance Service to bypass local hospitals in order to get the patient to the MTC. If the patient is too unstable for a prolonged transfer, then they will go to the local Trauma Unit where they will be stabilised first.

The factors to be considered when developing a patient transfer service include: Patient population at risk; geographical area; personnel; equipment; vehicles; clinical guidelines; administration and governance. Pre-hospital care transfer teams, as well as in some areas secondary care transfer teams are now common in the UK. These are usually provided by a mix of NHS and charity funded organisations. They also utilise a mix of air and land based assets.

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28.2 The Military Experience

The military have gained a comprehensive knowledge of trauma management over a 15 year period in Iraq and Afghanistan. Part of this has been the development of safe and effective transfer teams in the pre-hospital environment as well as for secondary transfers following initial stabilisation. Some of this experience has been successfully transferred into the civilian environment. This has included clinical elements such as the introduction of pre-hospital blood products and in training by developments in medical simulation. Such experience may be particularly useful in preparation for and response to mass casualty trauma incidents such as those seen in the Paris terrorist attack (2015) and London bombings (2007).

For the most seriously injured patients in the combat environment, damage control surgery and resuscitation is usually performed prior to transfer to higher levels of care [2]. In a major civilian event, it may be that local Trauma Units or even ad hoc surgical teams on scene have to undertake this function. This would ensure the entire trauma network is utilised more effectively and patients who require further management at the MTC reach it in a more stable state. Clearly the role of each element of the trauma network will be incident related and will require direction from the command teams at the time.

In the military, casualty evacuation is typically divided into three phases: forward, tactical and strategic. Forward medical evacuation is movement of the casualty from the point of injury to a medical facility within the operational area. Tactical evacuation moves the patient from the initial medical facility to another with higher levels of care still within the operational area. Strategic evacuation moves the patient to the highest level of care outside the operational area.

The forward area involves the location of the original incident therefore evacuation may need to be carried out whilst under fire. This means that assets should be readily available and well prepared to operate under such circumstances. Initial evacuation may even be on foot if the local medical aid post is close by. If not, then depending on the distances involved, the terrain and availability of assets, evacuation may be by land or air.

The tactical area involves the wider operational area but remains under control of the local commanders. Evacuation to levels of intermediate care often involves air assets either rotary or fixed-wing. These transfers are usually under less time pressure than those from the forward area which means crews may not be held on the highest state of readiness. It may even involve re-tasking of aircraft in order to undertake the transfer.

Strategic evacuation often means transferring the patient back to their country of origin, but this is not always the case. They may be moved to another nations facility but the key is that the patient is moved to a safe location outside the operational area with the highest level of care.

Casualties are prioritised into three main categories using the ‘P’ system to classify in order to influence those responsible for arranging initial treatment and transport as well as a guide to the receiving medical facility. Exact time frames may depend somewhat on the situation but utilising clinical priorities as part of the initial medical planning should ensure appropriate resources are in place in order to provide timely treatment:

- Priority 1 (P1)—highest priority and these patients usually need resuscitation and urgent surgery or other interventions—evacuation should be undertaken as soon as possible.
- Priority 2 (P2)—may require surgery or other treatment but can be delayed for a few hours without immediate threat to life
- Priority 3 (P3)—may still require early treatment but can be delayed if necessary without anticipating clinical consequences

The choice of assets to move the patient will be guided by clinical need, availability, terrain and the combat situation. The latter two factors often mean that an air frame is the optimal choice if the transfer is over a significant distance. Mountainous terrain and lack of adequate road infrastructure in particular will also favour aeromedical evacuation.

Rotary wing aircraft have several advantages including flexibility over landing sites and flight path. The disadvantages include potential vulnerability to attack, load restrictions and patient access issues. Fixed wing aircraft have the advantage of height and speed but their use maybe restricted by availability of adequate landing sites.

The choice of escorting medical personnel will be dictated in part by availability, the dependency of the patient and the length of the transfer. For the critically injured this transfer will often be undertaken by specialist teams. In the pre-hospital environment this may consist of a Doctor, Nurse and Paramedic. This was seen to good effect in Afghanistan with the use of the Medical Emergency Response Teams (MERT). The aim for future conflicts will be to replicate this capability with appropriate operational modifications. For transfer to higher levels of care following initial stabilisation, the UK military capability of choice is the Royal Air Force (RAF) Critical Care Air Support Team (CCAST) (Fig. 28.1). This team will be discussed later in this chapter.

28.3 Major Incidents

In the UK, evacuation of civilians following for example a domestic terror incident is likely to follow the local major incident planning protocols. These will involve the MTCs and the associated network of trauma units outlined above. A major incident in the UK is that which requires special arrangements to be implemented by one or more of the emergency services. The casualty numbers that define this will vary between areas. It is usually necessary to call in extra personnel and equipment in order for it to be dealt with effectively.

The initial scene may well be chaotic with uncertainty about further hazards until command and control is established by the emergency services. Once a triage process has commenced evacuation of the priority casualties from the scene will begin. Depending on the location this may be by a combination of air

Fig. 28.1 CCAST. Reproduced from Ryan's ballistic trauma 3rd Edition, drawn by the Artist Tony Green

ambulance and the local road ambulance service. In the case of large numbers of casualties, the MTC would be the primary receiving unit for the most severely injured with the surrounding trauma units taking the less injured. The exception to this is where damage control surgery and resuscitation is required to stabilise, in which case the local Trauma Unit may be better placed to do this depending on geographical location.

Domestic terror events whilst uncommon do not just have the potential to cause significant numbers of casualties with the resultant impact on local health care services. There is also the risk of further incidents and if there is chemical, biological or radiation elements involved, then responding emergency personnel as well as the wider public could be at risk. There may also be a danger to local infrastructure which may influence how the emergency services are able to respond. The need to react in a structured and well planned manner is vital to ensure that all such potential incidents are dealt with effectively.

For the purposes of transfer and evacuation of casualties this includes ensuring teams are prepared for such attacks with appropriate training, adequate equipment and specialised drugs. For hazardous and particularly for toxic environments, the ability to deploy expert medical response teams is essential. In the UK this includes an integrated approach between all emergency services and for the NHS in England and Wales, the use of Hazardous Area Response Teams (HART). The personnel on such teams include Paramedics who have undergone training in use of specialised personal protective equipment, working at height, and working on water. In addition, they are specifically able to deal with chemical, biological and radiation incidents whether those are deliberate or accidental.

28.4 Transfer by Land

For trauma patients in the UK, transfer by land is far more common but also not without challenges. Depending on the position of the casualties evacuating them quickly by land could be difficult. This could be due to the rural, even mountainous location of the incident but equally could be just as limited by the traffic congestion of major cities. In mass casualty events, the use of novel transfer vehicles such as coaches or trains may be necessary for even the severely injured in order to get them away from the scene if there are ongoing hazards. This is not without risk of course and needs to be carefully weighed up. In the modern military, transferring patients by land is often reserved for moves over shorter distances due to limitations of terrain, potential for ground attack and location of medical facilities. When air transfer is not feasible due to the combat situation, environment or availability of assets then if appropriate and available a dedicated medical vehicle should be used. The British military use the Battlefield Ambulance (BFA) as the primary ground transfer vehicle (usually a Land Rover Defender), one limitation of this vehicle is it is not armoured. Therefore, if the transfer is prolonged and there is a significant ongoing risk of attack an armoured vehicle will be more robust. This may be a dedicated medical vehicle or an armoured personnel carrier adapted to the role.

28.5 Transfer by Air

The primary strengths of air power are height, speed and reach. It is these same characteristics that mean an aircraft can be a very effective platform on which to transfer patients. This can be particularly relevant in the combat environment where ground transfers may be limited due to the reasons outlined above. The choice of aircraft will be determined by several factors including other taskings if there is no dedicated medical air frame. Negotiations maybe necessary in order to secure an aircraft for medical transfers but where the patient is a P1 there is usually little that would take precedence.

The military will consider whether there is a need for air transfers as part of medical planning for any operation. Where the risk of significant casualties is high then they may incorporate an air based response team such as MERT as part of the deployment. There will also be a plan for escalation to higher levels of care as part of the same medical plan. This may involve deployed or host nation medical facilities.

The nature of rotary wing aircraft means that their value lies in the forward area. Whilst generally slower (100–150 mph) they have much more flexibility and manoeuvrability around landing sites compared to fixed wing. The crew need to be prepared to respond quickly and this is the benefit of having a dedicated medical air frame. If not, then the aircraft will need to be adapted quickly to undertake the medical role for each mission. In the forward environment there may be the requirement to put force protection personnel on the aircraft to protect it, the crew and the patient. They cannot be pressurised and therefore are altitude limited, usually 10,000–14,000 ft compared to over 30,000 ft for fixed wing. This may also put the aircraft at risk if there is a ground threat of surface to air missiles. Limitations in the medical role include the number of patients that can be transferred at the same time and the stability of the platform.

In the civilian environment rotary wing aircraft are used extensively in the air ambulance role. They offer the ability to transfer patients rapidly over longer distances to the regional trauma centres. In the larger urban areas such as London, the benefit comes from being able to bypass congestion on the roads. London Air Ambulance carries a doctor trained in pre-hospital care as well as dedicated paramedics. They began carrying blood in 2012 and since then many air ambulances in the UK have also introduced this as well as lyophilised plasma and tranexamic acid [3].

In the case of urban mass casualty incidents, the air ambulance would be of limited use in moving patients due to capacity. However, the London Air Ambulance was used to good effect in the 7/7 bombings, as it was employed to move medical personnel forward in order to improve initial triage and treatment. This was thought to have helped reduce the critical mortality at one receiving hospital to 15% [4].

Fixed wing aircraft are especially useful for covering long distances at speed but they are limited by the need for some form of stable runway. Some military aircraft such as the Lockheed C130 Hercules can land on small areas of unprepared ground but even they need the area to be free of obstructions and relatively flat. Fixed wing aircraft such as the Boeing C17 Globemaster III, allow strategic moves over intercontinental distances and provide a relatively stable environment in which to provide treatment to multiple critically ill patients if required. The utility of these aircraft is such that during military operations in Iraq and Afghanistan, the RAF CCAST were often able to transfer patients back to the Role 4 hospital in Birmingham within 24 h of injury.

28.6 Critical Care Transfers

When the patient is critically injured they will require specialist clinical care during the transfer, which depending on the context may be over many hours. In the forward combat environment, the critically injured casualty is likely to need resuscitation and stabilisation. This is usually started by team medics and combat medical technicians who will subsequently hand over to pre-hospital care teams such as MERT, for the transfer back to a medical treatment facility (MTF). When a doctor deploys with the MERT it is designated MERT((E)nhanced). Both Anaesthetists and Emergency Medicine Physicians have fulfilled this role in the past.

During the transfer various medical interventions such as endotracheal intubation or thoracostomy may be delivered. In effect it is possible to commence damage control resuscitation prior to arrival at the MTF, including the administration of blood products. It is therefore essential that the team are confident in providing this care in the austere military aviation environment. This has been achieved in the past by enhanced pre-deployment training, standard operating procedures and the MERT course [5].

Critically injured patents transferred by air who have undergone initial stabilisation at an MTF but require onward movement to a higher level of care are also escorted by specialist teams. These are formed from within the Critical Care cadre of medical and nursing staff. In the UK military sphere, these are drawn from the Royal Air Force and formed into Critical Care Air Support Teams (CCASTs). Such transfers may be in the tactical environment, moving patients within the theatre of operations for clinical reasons such as neurosurgical intervention. Strategic transfers were undertaken to move the patient outside the theatre of operations and for the UK this usually meant transfer back to the Role 4 facility in Birmingham. This transfer could take between 10 and 14 h depending on air frame and route.

These teams have a core structure of:

- Two intensive care trained nurses called a Flight Nursing Officer (FNO) or a Flight Nurse (FN) one of whom is also the Team Leader.
- A flight Medic who assists with patient interventions, transfer of the patient, and administrative duties.
- A medical devices technician who maintains the equipment and also provides assistance with transfer of the patient.
- A Consultant Anaesthetist.

This core team of five personnel has the capability to transfer one critically ill patient. The missions can be long and complex and therefore one of the Nurses undertakes the team leader role. This allows the Consultant and other Nurse to concentrate on clinical care whilst the team leader manages the mission. This will include liaison with aircrew, ground crew and the MTF.

The team may be augmented with a third nurse (FNO or FN) which increases the capability if there are more patients. The team will also often have a FNO, FN, Medic and/or an anaesthetist under training as it is essential for personnel to gain experience of the CCAST environment before being tasked to undertake unsupervised missions. This team, in addition to their core training for their specialty, also undergo specific training relevant to their mission, whether that be the specific clinical challenges of transferring a patient long distances at altitude (with the consequent effects on the patient's physiology) or the practical considerations of travel on military aircraft (evacuation, safe use of aircraft systems, safe loading of patients and equipment and Dangerous Air Cargo regulations).

Following the beach terrorist attack in Tunisia in 2015, the RAF CCAST were deployed on a Boeing C17 Globemaster in order to repatriate the critically injured to the UK. They were able to do this quickly due to the flexibility and responsiveness of the capability. The short 'notice to move' time and the ability to work on a variety of air platforms contributes to this as well as the thorough training the teams undertake.

The employment of such military teams as part of a wider civilian response can be a sensible use of resources when appropriate. In the case of this particular incident, this not only allowed the evacuation of patients back into the UK healthcare system to be nearer their families but also relieved pressure on the local medical facilities in Tunisia.

28.6.1 Equipment

Equipment for use during critical care transfers should be robust, durable and lightweight. The requirement to transfer a military casualty from the point of injury increases the demands on the equipment. This includes the potential need to operate in extremes of temperature as well as withstanding ingress of dust and water. It must also be able to function consistently in a range of ambient temperatures, humidity and pressure.

Once disconnected from mains electricity it is essential to ensure the equipment can continue to function on battery power. It may be possible to access power on the aircraft but this has the potential to interact with the avionics. Therefore, it must be either cleared for use in advance or the aircrew are made aware and a risk assessment made. The RAF CCAST run all equipment on batteries independent of the aircraft. In addition to the reduced risk to the aircraft systems, this provides flexibility should it be necessary to change air frames or there are delays in the transfer. Medical equipment has the potential to create electromagnetic interference (EMI) as well as being susceptible to it. EMI may also originate from the aircraft systems. Electromagnetic compatibility is an issue that needs to be considered as it has implications for both aircraft and patient safety. This phenomenon is not limited to just the equipment itself; power cables can also radiate emissions and act as aerials [6]. All equipment must go through a period of airworthiness testing to ensure that any interference is identified and steps taken to remove this (for example, with shielding).

28.6.2 Monitoring

There are well recognised minimum standards for monitoring that should be applied during any transfer of critical care patients whether that is within the hospital environment or between facilities [7]:

- Continuous cardiac rhythm (ECG) monitoring
- Non-invasive blood pressure
- Oxygen saturation (SaO2)
- End tidal carbon dioxide (in ventilated patients)
- Temperature

In the aeromedical transfer environment there are additional challenges in accurately monitoring the patient that require specific consideration as well as extra vigilance from trained personnel. Aircraft noise and vibration mean that clinical assessment of the patient by techniques such as auscultation and percussion can be impossible. The use of audible alarms can also be limited for the same reason therefore it is usually more effective to use medical equipment with clear visible alarms (e.g. amber and red flashing warning lights). ECG, non-invasive blood pressure and pulse oximetry are prone to artifact from functioning in the aviation environment. This can lead to inappropriate activation of alarms and increase 'alarm fatigue' for personnel [8].

Given the duration of transfers for strategic aeromedical evacuation as outlined earlier, there is the requirement for additional monitoring. Invasive blood pressure monitoring using a transduced indwelling arterial cannula is strongly advised; it negates some of the difficulties encountered by artifact on non-invasive monitoring and allows for arterial blood gas analysis. Notwithstanding EtCO2 monitoring and pulse oximetry, blood gas analysis remains the gold standard [6]. It also has the added benefit of providing supplementary clinical data such as basic biochemistry. Hand held analysers are available on the market and should be seen as essential on transfers more than a few hours long.

Central venous cannulation is required for administration of inotropes and can be transduced to provide clinical data in the form of central venous pressure. If not already provided from blood gas analysis, blood glucose analysis is simple to carry out using either a visual colour coded strip, or more accurately with a small, hand-held digital analyser.

Intracranial pressure (ICP) can be measured when an extra-ventricular drain is in place by connection to an appropriate transducer and thus displayed as part of invasive pressure monitoring. It is also feasible to measure ICP by an intra-parenchymal micro-sensor although this requires the use of a dedicated air worthy monitor.

Ideally, monitors should be able to measure and display ECG, pulse oximetry, non-invasive blood pressure, up to three invasive pressures, capnography, and temperature [7]. The monitor currently used by RAF CCAST is the corpuls [3] (GS Elektromedizinische Geräte G. Stemple, Kaufering, Germany) which has an integrated defibrillator and pacer. It can be split into three components (screen, patient box and defibrillator) which communicate with each other via wireless technology (Fig. 28.2). This provides greater flexibility and allows for easier monitoring during transfer, particularly when moving the stretcher.

Fig. 28.2 Corpuls [3] monitor, patient box and defibrillator/pacer. Combined together with the associated cables and consumables in side pouches (*left*). Broken down into the three component parts (*right*)

28.6.3 Batteries

RAF CCAST advocates and operates self-sufficiency in terms of electrical power. This self-sufficiency, along with the requirement that equipment be lightweight, means that the type of batteries utilised is significant; the battery will largely determine the size and weight of any device, and its duration of function. When calculating the electrical (and therefore battery) power it should be anticipated that there will be delays, such as to aircraft departures, arrivals, and even emergency diversions for clinical or aviation reasons. Secondary, or rechargeable, batteries are more commonly used especially in larger pieces of equipment with higher energy requirements such as patient monitors and ventilators. Smaller items of equipment may be designed to operate on primary, or disposable batteries and can operate for many hours. They are, however, usually less mission critical, have relatively low energy requirements and can usually be relied on to last many hours more than the transfer requires.

Rechargeable battery technology has improved significantly in the last couple of decades, largely due to the popularity of personal electronic devices such as laptops and mobile phones. Improvements have in turn enhanced the capability of medical transfer equipment. The main battery options commonly available are lead-acid, nickel cadmium (NiCd), nickel metal hydride (NiMH), and lithium-ion (Li-ion), each with their own particular advantages and disadvantages. A principle consideration is that of weight and size, both for ease of movement on the ground with the patient and in reducing the “footprint” onboard the aircraft.

The batteries with the highest energy density are Li-ion, commonly used in laptops. These would seem ideal as they provide a lot of stored energy for a relatively small and lightweight battery. Unfortunately, they pose a theoretical fire risk if abused and are treated as dangerous air cargo by many airlines [9]. Lead acid batteries have the lowest energy density, but are a tried and tested technology and have been in use for over a century. As this lower energy density suggests, they will be larger and heavier than other batteries and are thus not always the ideal choice for energy demanding medical equipment, and a possible handicap in transferring a patient. Of the remaining options, NiMH has a higher energy density than NiCd. The NiCd can suffer from memory effect, where its capacity is effectively “lost” over time. The newer generation NiMH batteries seem to have overcome the memory effect issue and are now taking much of market share traditionally held by NiCds.

Batteries work most efficiently within specific temperature ranges. The storage, use and charging of them in extremes of temperature are likely to decrease battery life and increase recharge times [10]. The extent of this will vary between battery types; ideally battery options would be varied dependant on environmental conditions. This is impractical, so attention must be paid to buy the most flexible option at the procurement stage. When not being used, most batteries will drop from their fully charged state. This self-discharge is obviously more significant the longer a battery is “sat on the shelf” and may be more pronounced in NiMH; for this reason, batteries should be either regularly checked or stored on a trickle-charger. Ultimately, each manufacturer will give the most appropriate advice for its own particular brand and this should be followed as strictly as practicable; some manufacturers advising a re-conditioning processes to prolong the life of the battery. This re-conditioning can often be carried out whilst the battery is in the equipment connected to a power supply.

28.6.4 Oxygen and Ventilators

Supplemental oxygen should be carried with the assumption that the patient's oxygen requirements will increase at altitude. Indeed, it should also be assumed that the patient may deteriorate and thus require supplemental oxygen in excess of that required by altitude and consequent pressure changes alone. The safest approach is to assume that a ventilated patient will require ventilation at an inspired oxygen concentration (FiO2) of 100%, and as with determining battery power consumption, delays should be anticipated. Sufficient oxygen must be carried; a diversion due to insufficient oxygen almost certainly indicates poor planning, carries a heavy financial burden and is rarely in the patient's interests.

Oxygen cylinders are treated as dangerous air cargo and must be handled and stored in accordance with the carriers instructions. The explosive nature of oxygen cylinders was seen in 2008 when a civilian Boeing 747 suffered a rapid depressurisation event secondary to failure of an oxygen cylinder in the cargo hold [11].

Integral to calculating oxygen consumption, users must know the quantity of oxygen consumed by the particular ventilator being used. This will vary depending on the technology utilised and whether gas or turbine driven; certain models of the latter are gas inefficient. At an FiO2 of 100%, the volume of gas used beyond the delivered minute volume, i.e. wasted, can range anywhere from 1 to 11 L/min [12].

In terms of monitoring, transport ventilators should, as a minimum, have [7]:

- Disconnection and high pressure alarms
- Ability to deliver positive end expiratory pressure (PEEP)
- Variable FiO2
- Variable respiratory rate, inspiratory:expiratory (I:E) ratio and tidal volume

There are also a range of desirable characteristics, particularly for use in the military aviation environment during strategic aeromedical evacuation. They should be lightweight, simple to operate and ideally function without the mandatory need for compressed gas. In addition, the ability to efficiently ventilate both healthy and injured lungs as well as allowing spontaneous breaths (pressure support and continuous positive airway pressure (CPAP)) provides the necessary flexibility on long transfers [13]. Audible alarms remain essential but as with the alarms on the monitors the environment limits their usefulness. Therefore, constant vigilance by a dedicated member of staff is essential, particularly with regard to disconnection alarms during movement of the stretcher.

Some ventilators may require manual compensation for pressure changes due to altitude, or delivered tidal volumes will be significantly different to the set value [6]. Accompanying personnel must be aware of these issues. Equipment that will automatically compensate for altitude and meets both desirable and minimum specification is preferable and is widely available on the market.

28.6.5 Patient Preparation

Preparing the patient for aeromedical transfer follows many of the same general principles required for a road transfer and these are covered in suitable detail by the Intensive Care Society Guidelines [7]. It may be necessary depending on the context of the incident, to ensure the patient does not pose a risk to the transfer team from chemical or biological agents for example. In the case of large scale attacks this should be addressed by the initial response teams. If identified, then appropriate personal protective equipment should be worn and the patient decontaminated. However, less common agents may not be identified early therefore signs of illness in emergency service personnel should be taken seriously.

Where possible, the patient should be placed on a suitable transport ventilator in advance of the planned move in order to ensure they are stable on it. This should be followed up with an arterial blood gas prior to the move in order to confirm suitability of the settings. The patient should then be transferred onto a transport stretcher or gurney. A useful addition to this is the use of a transfer vacuum mattress, a sealed mattress that is similar to a beanbag in texture and composition. This can be moulded around the patient as air is pumped out of it, leaving a supportive rigid structure. This contours underneath and around the sides of the patient but leaves their front exposed. It has numerous benefits: it provides additional support in the case of spinal injury; it can help splint fractures, particularly of limbs; and it can effectively tie in loose lines. Care must be taken, however, to ensure that pressure areas are closely monitored; lines and cables must not press against exposed skin and in the case of longer transfers, the patient's position should regularly be changed.

The monitoring that has been used at the bedside should be changed for the monitors that will be used for the transfer. This opportunity should be used to ensure elements of the monitoring such as adhesive ECG electrodes, blood pressure cuff and pulse oximetry are adequately positioned and robust. Particular attention should be paid to the airway, invasive lines and nasogastric tubes. Any loose lines or cables should be secured. As a final step, the patient is secured to the stretcher using a harness. The RAF uses a specially designed 5-point harness for all aeromedical transfers. This is ideal for the strategic transfer of the critically-ill patient since it secures them for all stages of the evacuation: movement from Field Hospital to ambulance; ambulance to aircraft; and from aircraft to ambulance on arrival in the UK. Similar to the vacuum mattress it can also facilitate the securing of intravenous lines and cables. Consideration must be given to hearing protection for the patients during aeromedical transfer therefore foam plugs should be placed prior to the move.

The patient should also have their physiology optimised in readiness for flight where feasible. This should include correction of hypovolaemia as it is poorly tolerated once the patient is exposed to acceleration and deceleration forces of take-off and landing [7]. If the patient is loaded head first then blood will pool in the lower extremities on take-off. If they are loaded feet first, then there maybe elevation of the intra-cranial pressure. The critically injured patient may not be able to adapt to these rapid changes therefore they should be anticipated and treated accordingly.

For strategic aeromedical evacuation back to the UK, the patient should have no active bleeding and a haemoglobin level adequate for the journey. Blood products can be carried by the CCAST where deemed necessary and this may also include lyophilised plasma.

Other physiological factors to consider include correction of metabolic acidosis, seizure control and optimisation of intracranial pressure. Whilst such measures should be undertaken prior, the context of the evacuation may mean this is not possible. RAF CCAST has the capability to provide treatment *en route* beyond that of a simple transfer facility. It can initiate and continue advanced medical management throughout the evacuation chain until the patient reaches a definitive MTF. Where necessary they will request diversion to an appropriate facility if the patient deteriorates in-flight and needs more complex intervention.

28.6.6 Administration

Whilst undertaking the preparation of the patient for transfer it is essential that attention is also paid to the administrative elements. This includes copies of medical notes, blood results and radiological investigations. The latter can often be stored in electronic form such as a CD and then uploaded to the imaging system of the destination medical facility. A passport is still required for evacuation back to the UK where immigration procedures will still be in force. In the event of aircraft diversion to anywhere apart from the UK, difficulties with the host nation would undoubtedly ensue if a patient's passport was not available. Any belongings must, however, be rigorously checked for any items of dangerous air cargo; in the transportation of military casualties a search for live ammunition is pertinent.

As with any patient transfer, arrangements for onward movements must be made including contact with the receiving hospital and advice on expected timelines. Transport from the airhead of arrival should be confirmed so the transfer team are confident that the plans are robust; delays stretch oxygen and battery resources and potentially impinge on patient safety, at a time when the accompanying medical team are already likely to be fatigued. As an example, RAF CCAST have well organised reception arrangements in the UK. This is coordinated by the aeromedical team at the Role 4 hospital in Birmingham and the Aeromedical Evacuation Control Centre (AECC) at RAF Brize Norton.

28.6.7 In-Flight Care

All aspects of care, drugs administered, and regular clinical observations should be recorded in-flight. As previously alluded to, many treatments can be initiated either before or during transfer. In the shorter, tactical, aeromedical transfer there will probably be little time to undertake significant elements of nursing care. Time is usually available in the longer strategic transfers. Pressure areas should be observed and the patient's position changed during transit; even if the patient does not have formal clearance from spinal injuries, at cruising altitude, most aircraft afford a suitably stable platform in which the patient can be safely log-rolled. Eye and mouth care are routine within a static intensive care facility and this should be viewed no differently during strategic aeromedical evacuation. It may be difficult to access water in some aircraft, particularly military cargo airframes, however cleansing wipes offer a good alternative for maintenance of patient hygiene. Hand hygiene is still paramount; universal precautions should be utilised where possible and an alcohol based skin cleanser used to augment hand-washing. The minimum standard achievable in helicopters, where water is absent, is likely to be the wearing of disposable gloves.

28.7 Operational Aspects of Aeromedical Evacuation

In the UK, a Strategic CCAST is maintained at a permanent 6 h' Notice to Move (NTM) readiness state. This means that the Team must be capable of being in the air within 6 h of notification of a mission. In reality there is usually more than 6 h notice but if there is an aircraft available and the patient will be ready to move then the team should be prepared for that. Tactical CCASTs may be on even shorter NTM restrictions as the operational tempo dictates. If the patient and the CCAST are co-located (as is frequently the case in established operations), the patient and equipment can be prepared and ready to board the aircraft in as little as 60–90 min from the notification of a mission.

Planning of CCAST missions will usually start long before the patient is ready to be transferred. If a patient is brought into the Emergency Department (ED) with obvious critical injuries, a Tactical CCAST may be notified that a transfer is likely to be required while the patient is still in the ED or the Operating Theatre. This transfer may be for specialist intervention (neurosurgery, cardiac surgery, specialist imaging) or evacuation. This gives the team the maximum time to prepare for the mission. Similarly, it takes time to task an aircraft for any mission and these administrative tasks can be started before the patient is ready for transfer. If a patient is obviously going to need a period of Intensive Care after their initial resuscitation in a field hospital then it is important to immediately start planning for their onward evacuation as intensive care beds are usually in very short supply in operational theatres and these patients use up large amounts of resources, both in equipment and in clinical time (each patient requires one-to-one nursing whilst on the intensive care unit). Both of these resources are often limited in the operational environment making rapid evacuation essential to maintain operational capability.

If a patient who initially requires intensive care improves rapidly in the deployed setting their level of dependency will be reduced and they may be transferred by general aeromedical evacuation teams rather than a CCAST. The level of medical support is determined by the clinical scenario prevailing at the time. If the patient has a medical (non-surgical) problem (such as angina or an uncomplicated pneumothorax) then it may be appropriate for a physician trained in aviation medicine to accompany the patient in addition to the FNO/FN and an FNA. Surgical patients are sometimes transferred with an anaesthetic escort as their in-flight problems are most likely to be related to pain management and the physiological effects (usually respiratory) of altitude. Advanced pain management techniques such as continuous peripheral nerve blockade have been utilised with good effect during aeromedical evacuation [14].

Civilian aeromedical evacuation teams also provide a critical care repatriation service and responsible for transfer of British citizens from overseas medical facilities. They are usually commercial organisations based out of regional airports and use dedicated aircraft such as Bombardier Challenger and Learjet. The larger companies may have extensive medical and logistics links in other countries to facilitate patient moves. They often work in liaison with travel insurance companies when tourists are involved and international corporations who have globally based employees. Costs can be in excess of £100,000 for a long haul critical care transfer.

28.8 Aviation Physiology

This section is not intended to provide comprehensive coverage of aviation physiology. It will give a brief overview of the effects of changes in the composition of ambient air and the pressure and volume changes associated with an ascent to altitude.

For the purposes of this chapter, the atmosphere can be considered to have a constant relative composition of gases, namely:

- Nitrogen 78%
- Oxygen 20.9%
- Argon ~1%
- Carbon Dioxide 0.04%
- Neon, helium, methane, krypton, and hydrogen, all of which comprise less than 0.01%
- Water vapour

Water vapour is the only component whose percentage varies significantly over the altitude range concerned, being between 1% and 4% at the surface but averaging 0.4% over the whole atmosphere. Pressure varies inversely with altitude, decreasing to approximately 50% at 18,000 ft and to a quarter at about 33,700 ft. Table 28.1 gives the pressures in kilopascals and millimeters of Mercury (mmHg for various altitudes above sea level. For the remainder of this chapter, feet will be used to

Table 28.1 Pressure changes with altitude

Altitude (ft)	Altitude (m)	Pressure (kPa)	Pressure (mmHg)
0	0	101.3	760
1000	305	97.7	733
2500	762	92.5	694
5000	1524	84.3	632
10,000	3048	69.7	523
20,000	6096	46.6	349
30,000	9144	30.1	226
36,090	11,000	22.6	170

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measure altitude as this is the unit generally used in aviation. Similarly, kPa will be used as the standard unit for pressure. The US uses mmHg to measure physiological pressures and these will be included for completeness where appropriate.

28.8.1 Hypoxia

An inspired oxygen concentration (FiO2) of 21% roughly corresponds to an arterial oxygen tension (PaO2) of 13.3 kPa (100 mmHg) due to a variety of physiological reasons that mean that not all the inspired oxygen reaches the alveolar capillaries. One reason for this is that inspired oxygen is humidified, either by evaporation from the respiratory epithelium or by humidification systems within the ventilator circuit in the intubated patient. This water vapour has a constant pressure of 6.3 kPa (47 mmHg) irrespective of altitude and should be removed from the total pressure prior to performing the partial pressure calculation. Thus inspired air has a partial pressure of $(101.3 - 6.3) \times 0.21 = 20$ kPa at sea level but has a partial pressure at 36,000 ft of $(22.6 - 6.3) \times 0.21 = 3.4$ kPa and not 4.8 kPa as might be expected from dry air.

The relative increase in significance of this water vapour further impairs the body's ability to cope with increasing altitude and mandates supplementary oxygen for all but low level flights. Furthermore, any physiological derangement of the patient's respiratory function becomes far more significant at altitude. A patient who requires 60% oxygen at sea level in order to maintain a normal PaO2 will require 90% oxygen at 10,000 ft. It is therefore not difficult to see how the patient may deteriorate quickly in flight if the changes in respiratory physiology are not anticipated and managed appropriately.

28.8.2 Effects of Gas Expansion

Another major consideration caused by altitude is the change in the volume and pressure of gases trapped within the patient, for example, in a pneumothorax, a pneumocranium, or in a paralytic ileus. Boyle's Law states that for a fixed amount of gas at a constant temperature, the volume is inversely proportional to the pressure. Care must therefore be taken to ensure that all trapped air is ventilated before flight, by means of a nasogastric tube for the stomach or a chest drain for the thorax. Patients with eye injuries and those with bowel anastomosis are also at risk of adverse effect from pressure changes. The aircraft cabin maybe typically pressurised to 8000 ft and therefore expansion of contained gas by around 10% is to be expected [15].

If there are concerns that the resultant pressure changes will cause clinical deterioration, then a lower cabin altitude restriction can be applied. This is achieved by taking a feed from the compressors in the aircraft engines but it has the implication of reducing fuel economy. A sea level cabin altitude will also reduce the maximum operational ceiling for the aircraft as only a certain difference in pressure between the cabin and the outside air can safely be maintained. This reduced ceiling (to maybe 25,000 ft) reduces the possible speed achievable in flight and increases drag, further reducing fuel economy. Flight planning is affected as lower airspace is under different restrictions and some mountain ranges cannot be crossed at this altitude, requiring alternative routing. All these considerations may mean that a flight that could have been completed without refuelling may now require at least one stop for fuel thereby further increasing the length of the flight. Therefore, the request for altitude restrictions should be carefully considered.

Air is also contained within the sinuses of the face (predominantly the maxillary and frontal sinuses), the middle ear, teeth, and abscess cavities. Obstructed sinuses and eustachian tubes (due to a simple cold or similar upper respiratory tract condition) will not be able to equalise pressures via the usual routes on descent and cause excruciating facial and ear pain. On ascent the increased pressure relative to the outside environment is usually sufficient to overcome any obstruction (this is the cause of your ears "popping" in aircraft). People for routine aeromedical evacuation who cannot clear their ears should not be flown unless absolutely necessary. Vasoconstrictor nasal sprays such as xylometazoline can improve symptoms but their effect is slow and these should not be relied upon except in extreme cases. Dental pain may also occur in flight for due to expansion of air trapped between a deep cavity filling and the tooth substance on ascent.

As has been discussed above, these considerations primarily apply to fixed wing aircraft. Rotary wing aircraft cannot be effectively pressurised and so the likely altitude of flight must be considered when calculating oxygen requirements and considering pressure effects.

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Soft Tissue Reconstruction

29

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Key Points

1. A multidisciplinary patient centred approach to complex soft tissue reconstruction is essential to achieve the optimal functional outcome.
2. Initial resuscitative and excisional surgery should be performed with the principles of functional reconstruction in mind.
3. Expeditious coverage of vital structures with vascularised tissue has reconstructive benefits, but complex procedures can be counterproductive in a patient who is not physiologically or psychologically prepared.

29.1 Introduction

The pattern of injury associated with a marauding terrorist firearms attack (MTFA) is limitless in scope and may encompass a combination of high-energy projectile injury, as well as blast and fragmentation components. This chapter discusses the reconstruction of soft tissue wounds with particular focus on those associated with actual or pending functional deficit, such as those involving vital neurovascular or musculoskeletal structures.

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29.2 Physiological Preparation

It is axiomatic, and beyond the scope of this chapter, to state that the physiological optimisation of the patient prior to embarking on major reconstructive procedures is an absolute requirement. The absence of infection and optimisation of nutritional status including trace elements is highly desirable; the latter may be a concern in the multiply injured patient who has been subject to a lengthy hospital stay or indeed be a premorbid condition. There is evidence to suggest that a mild anaemia is protective of free tissue transfer anastomotic patency, hence over transfusion is not advocated, however haemoglobin below 9 g/dL or haematocrit below 25% has been associated with increased flap failure rates [1]. Smoking status is a significant predictor of wound complications but not anastomotic failure in free flap surgery, however smoking has particular implications for certain local flap reconstructions such as forehead flaps and digital replantation or transfer [2, 3]. Peripheral vascular disease may be a concern with respect to raising free fibular osseous flaps. It must be borne in mind that in an MTFA the potential patient demographic will encompass the representative population and the entire spectrum of pre-morbid disease states must be considered.

29.3 Multidisciplinary Care

The management of major trauma is necessarily a team effort. Trauma care practitioners, from the point of wounding until discharge from rehabilitation services, have been early adopters of multidisciplinary working. Team working, leadership, communication and the interplay of different disciplines are some of the most rewarding aspects of working in this field. With respect to reconstructive surgery the roles of the dietician, physiotherapist, occupational therapist, psychologist and the patient's own support network are critical, as well as the microbiologist and other medical and surgical specialists who may be involved in managing a specific wound area. The patient's nutritional status must be optimal. Injured limbs must be protected in appropriate splints, whilst the suppleness of joints must be maximised. Wounds must be dressed appropriately and microbiological control achieved.

The rehabilitation potential of the patient must be established by close attention not only to any medical comorbidities but also to the patient's expectations of outcomes and ability to participate in rehabilitation programmes. The patient's work, hobbies and support networks all have an interplay in this, as well as their willingness or reluctance to engage in further surgery; potentially having already undergone multiple procedures. The patient must be appropriately supported in making informed decisions about, for example; limb salvage versus amputation, or tendon transfers versus fusions or use of splints. A delay in reconstruction is to the patient's overall benefit while such issues are fully explored.

29.4 Excisional Surgery and Wound Preparation

The meticulous excision of all devitalised tissue and wound contaminants is a prerequisite for reconstructive surgery and is described in greater detail in Chap. 22. Performing initial surgery with the requirements of eventual reconstruction in mind is of manifest benefit, and has lead to guidelines mandating the involvement of plastic surgeons in the first line of surgical care in both military and civilian trauma settings [4]. Key manoeuvres in this setting include the placement of fasciotomy incisions so as to preserve local perforating vessels and hence local flap options, achieving soft tissue coverage of structures to prevent desiccation, and "expectant" debridement of vital structures. The latter point has two facets; the first being that in areas where small amounts of tissue may have huge functional import, such as the major nerves, head and neck or urogenital tract, giving small amounts of tissue the "benefit of the doubt" may be appropriate. Secondly some authors have applied the principles of Jackson's model of burn injuries, to traumatic wounds, and suggested that the intermediate "zone of stasis" which may be expected to recover following appropriate resuscitation may also recover in the trauma setting [5]. This is particularly true in the richly vascularized tissues of the head and neck, where circumspect debridement is likely to maximise functional and cosmetic outcomes, without exposing the patient to a dangerously high burden of necrotic tissue.

29.5 Timing of Reconstructive Surgery

There are physiological, psychological and logistical constraints in the timing of reconstructive surgery that may compete in their primacy in individual cases. The landmark paper by Godina on microsurgical free tissue transfer identified a "subacute" phase between 72 h and 3 months where flap failure was higher [6]. This early work has been critiqued in the light of technical improvements over the last 30 years, however most reconstructive surgeons would recognise this phase being associated with increased tissue oedema, friability of vessels and hyperaemic bleeding. More recent reviews have shown the safety of operating in this period when surgeons are mindful of the technical challenges that may be encountered [7]. In general early coverage of vital structures with vascularised tissue, by means of local flap or microvascular free tissue transfer, offers an improvement in functional outcome. By this mechanism a vascularized bed, or gliding plane, is established before healing by contraction scarring and fibrosis has occurred. In the case of extremity reconstruction this may aid in maintaining suppleness of joints and thus facilitate delayed procedures such as tendon or nerve transfers. In the management of open fractures it has been demonstrated that early wound closure is associated with reduced deep infection rates. Reconstruction in other areas, for example the urogenital system, may benefit from delay; as such tissues may become more robust over time.

From the physical and psychological rehabilitation perspective adequate time for discussion with relevant members of the multidisciplinary team (MDT) must be allowed prior to surgery taking place. This team may include the prosthetist, therapists and psychologist, and may also include other patients who have undergone a similar reconstructive journey.

29.6 The Use of Local Flaps or Free Tissue Transfer

The use of local flaps in trauma reconstruction is becoming less favoured as the popularity of perforator free flaps increases, due to minimal donor morbidity and increasing reliability, and an appreciation of the risks of transposing local tissues which are necessarily proximate to the zone of injury [8]. Additionally, patients previously thought to be at most risk with respect to undergoing free tissue transfer are of course more prone to wound complications when local flaps are used. Several series have confirmed the safety of performing free flap surgery in elderly and comorbid patients [9, 10]. Despite these caveats there still exists a role for the use of local flaps in trauma reconstruction, in particular in the head and neck, where the use of supraclavicular, "blushing" tissue provides superior cosmesis compared to transplanted tissues.

29.7 Photography

High quality medical photography is an integral part of the medical record of trauma patients, having clinical, educational and medico-legal roles. A record of the patient journey can be highly therapeutic, and can aid communication from both physician to patient and patient to physician with respect to further treatment planning. Thankfully MTFA are rare in their incidence and the specialty of trauma reconstruction is developing, accordingly the use of clinical photography for training, education, research and dissemination of information is vital and the appropriate consent should be sought from patients. Finally, the reality of these incidents is that a criminal investigation of the event may well require medical photographs as part of the information collection process.

29.8 Open Fractures & Limb Salvage

The combined management of open fractures of the tibia by orthopaedic and plastic surgeons using "orthoplastic" principles has lead to the development of integrated pathways for the treatment of these injuries, improved rates of limb salvage and reduced rates of deep infection [11]. This topic is also covered in Chaps. 21 and 30, suffice it to note that principles of early debridement by experienced teams, appropriate antibiotic therapy and timely definitive fracture fixation combined with soft tissue coverage are undisputed mainstays of treatment. The value of topical negative pressure dressings as a temporising measure is being evaluated by an on-going multicentre study. Debate as to the optimal soft tissue coverage, between the use of fasciocutaneous or muscle flaps has generated much research interest. Recent reviews have highlighted broadly similar outcomes and most in the field would tailor their approach based on the requirements of specific wounds [12, 13]. For example a fasciocutaneous flap is easier to monitor, likely to have a flatter contour and to be easier to re-elevate for any revision procedures. Meanwhile muscle flaps are typically faster to elevate, can fill more complex 3-dimensional tissue defects, and have been shown in preclinical studies to deliver higher blood flow to the fracture site in the acute phase.

With respect to the lower limb the decision to attempt salvage or perform amputation can be a difficult one and is discussed in detail in Chap. 31. Enthusiasm to attempt limb salvage, which may involve multiple lengthy procedures, is tempered by high profile cases of amputees performing at a highly athletic level. The LEAP study has shown that, for lower limbs, functional outcomes at 2 years were broadly similar between limb salvage and early amputation groups, longer term data in a military population has also failed to show a difference in outcome between these groups [14].

29.9 Nerve Injuries

Clinical examination of trauma patients for signs of nerve injury is challenging in the acute setting; distracting injuries, patient sedation (or intubation) and the non-conducive trauma room environment combine to make initial assessment difficult. Standard imaging modalities are not sensitive to detect nerve transection in the context of a cavitation injury. A high index of suspicion combined with a meticulous secondary survey is therefore mandated, and a low threshold for surgical exploration is required.

The zone of injury in a ballistic wound may be extensive and may progress over time. Trauma surgeons have drawn a distinction between nerve injuries due to penetrating ballistic injuries due to GSW versus those caused by blast with fragmentation. The latter cause a larger zone of neuronal injury with concomitant reduction of functional outcome, and increased rates of neuropathic pain [15]. The criterion standard treatment of a transected nerve is direct tension-free repair at the earliest opportunity using microsurgical techniques. This approach is fraught with difficulty in the case of ballistic injury as judging the nerve ends that are healthy enough to be suitable for direct repair is difficult, and segmental injury is the more common finding. If nerve ends cannot be coapted using an 8–0 suture following simple mobilisation procedures then an interposition strategy must be employed. At the time of writing a hierarchy of nerve substitutes exists, with autologous nerve being preferred to vein graft, artificial conduit and nerve allograft, current thinking supports the use of conduits for shorter defects (<3 cm) but recommend considering the use of allograft for longer defects [16]. The use of autologous graft has drawbacks with respect to loss of function of the donor nerve and potential neuroma formation at the site of harvest. In addition, the length of nerve available may be limited and in major polytrauma blast injured patients other donor sites may be severely constrained. The requirement for immunosuppression during allograft engraftment is a potential concern, (*vide infra* "vascularized composite allotransplantation"), however the natural history of nerve regeneration results in an autologous nerve once neuro-regeneration has occurred, and immunosuppression can be ceased [17]. This is an active area of research and various conduits and neuroregenerative agents are being evaluated.

If a peripheral nerve is not found to be transected then judging the zone of injury and degree of damage is extremely difficult. These injuries should be managed expectantly in the first instance. The use of acute nerve transfers as "baby-sitter" procedures or tendon transfers as "internal splints", or definitive treatments, in the acute setting is highly specialised practice therefore specialist opinion should be sought in these cases. The duration of time that is suitable for expectant management is also a subjection of contention. A period of 6 months is suggested, as this balances the potential for spontaneous recovery with the inevitable loss of functioning neuro-muscular end-plates which can be re-innervated. Earlier intervention may have potential for a better result, whilst delay up to 2 years would be advocated to realise the full potential of recovery with conservative management. A very difficult balanced decision must be reached by the physician and patient in consultation with the multidisciplinary team.

Nerve repairs or grafts must be covered by healthy vascularised tissue to prevent desiccation and treatment failure. This may be achieved by mobilising local tissues or by free tissue transfer. Neuropathic pain has been a feature of trauma patients treated by split thickness skin grafts placed directly over injured or exposed nerves.

29.10 Muscle and Tendon Injuries

Loss of functional units due to segmental loss of muscle or tendon, compartmentectomy or the loss of multiple compartments following debridement of ballistic injury may be managed by acute functional reconstruction or expectantly by achieving expedient wound closure and delayed functional reconstruction. Early grafting of segmental tendon loss following GSW to the forearm, for example, and coverage with a fasciocutaneous free flap will offer the best chance of good functional recovery as scarring from delayed healing is minimised. This approach may be appropriate in isolated injuries, or where minimally morbid donor options will suffice, such as the use of palmaris or plantaris tendon grafts.

More complex injury patterns requiring more morbid reconstructions may be better managed expectantly; with the patient exploring the limits of their rehab potential with their therapist before making a decision on surgery following discussion with the MDT. Nerve and/or tendon transfers are complex procedures associated with lengthy rehabilitation periods. In the motivated patient, however, and for the right indication they can be highly rewarding. The first principles of tendon transfer are that the joints which are subject to the forces of the transferred tendon must remain supple, as passive range of movement cannot be improved by the transfer. This requires active management by the therapy team and the appropriate use of splints. There must be adequate vascularised soft tissue coverage and a gliding plane for the transferred tendon to travel in - this may require the importing of vascularized tissue by means of free tissue transfer or pedicled flap. Groin flaps have great utility in the upper limb and have particular pertinence in the multiply injured patient, where other donor sites are lacking. Split skin grafting is not suitable. The transferred tendon should be expendable and it should have adequate power; a transferred tendon can be expected to have a power one grade less in the transferred compared to the native position, according to the Medical Research Council (MRC) grading system. The transferred tendon can only move through a single pulley vector, and preferably none, and can only be expected to perform a single function in its transferred position. Finally, the tendon selected for transfer should have an action that is synergistic with the new function, for example using a wrist flexor to power finger extension, as this requires less cortical plasticity in rehabilitation.

Nerve transfers are subject to similar principles; they have advantages over tendon transfers in that often dissection and bleeding are reduced, along with the duration of splinting and postoperative stiffness. There are however fewer options available and outcomes are less predictable.

Finally, if no local transfer options are available then importing a functional muscle may be appropriate. Typical choices include functioning gracilis or pectoralis minor transfer. Each of these muscles has minimal donor morbidity and may be suitable for transfer to reconstruct an excised compartment in the upper or lower limb, for example to achieve dorsiflexion in the event of all wrist extensors being lost. Rectus femoris is advocated as a muscle transfer where power of the transferred muscle is critical, for example in dorsiflexion at the ankle. However as a major knee extensor the risk / benefit of transfer must be carefully explored by the patient along with the MDT.

29.11 Toe to Hand Transfer

The hand that has lost prehensile function due to multiple finger amputations or thumb amputation may be reconstructed by a variety of toe transfers [18]. The patient must balance the donor morbidity with the anticipated return of function based on their current functional deficits. Thumb amputation is particularly debilitating, accounting for 40% of hand function, and this may be reconstructed most effectively with a trimmed great toe transfer. A less cosmetic option is to perform a second toe transfer, however in this case the donor morbidity is less. In the case of multiple finger amputations following blast injury resulting in a so-called “metacarpal hand” it is desirable to create at least “tripod” grip by transferring two toes; this may be in the form of bilateral second toes or by transferring the second and third toes from 1 foot and then splitting them. The latter operation has the advantage that the second foot remains as a pristine donor site should further transfers be desirable.

29.12 Abdominal Closure

Full thickness loss of the abdominal domain, combined with intra-abdominal trauma following ballistic injury to the abdominal contents, frequently leads to difficulty in achieving abdominal closure. Multiple injuries, or those requiring complex bowel resections, anastomoses and or stomas are particularly high risk. Achieving abdominal closure is critical to the physiological recovery of these patients. The components separation technique described by Ramirez in 1990 can be applied in the subacute setting to achieve closure [19]. In the case of traumatic injury surgeons must be mindful of the vascularity of the components to be separated and moved, the placement of stomas and traumatic wounds from the original injury must be noted and any effect on the vascularity of the rectus muscle in particular must be accounted for [20].

Functional abdominal wall continuity can be achieved using mesh, biologic materials such as acellular dermal matrices (the latter being preferred in potentially contaminated wounds) or vascularised tissue such as a tensor fascia lata free flap. To achieve closure of the external abdominal wall local or free flaps may be required.

29.13 Vascularised Composite Allotransplantation

Reconstructive transplantation of composite tissues from cadaveric donors is the most sophisticated form of reconstructive surgery. While there is no "donor morbidity" in the traditional sense, ethical issues regarding donation are a concern not only to the donor family, but also to the potential impact on the donation of lifesaving solid organs. There is a requirement to take lifelong immunosuppression with associated morbidity and mortality [21]. At the time of writing over 200 VCA transplants have been performed, most commonly to the hand and face, but also abdominal wall, uterus and penis. VCA transplants have been successfully performed for blast and GSW victims.

VCA is currently considered an experimental treatment in all the centres in which it is performed. Each case is subject to individual Institutional Review Board approval however, given some very encouraging outcomes, recent authors have suggested that for indications such as bilateral hand amputation, VCA may be soon classified as the "standard of care" [22]. Numerous studies have shown improvements in quality of life for VCA patients, in particular with transplanted hand function being found to be superior to functional outcomes with the use of prostheses [23, 24]. However, individual patients and the clinical teams who care for them, must balance these benefits with the risks of immunosuppression treatment.

Conclusions

Reconstructive surgery in the setting of ballistic injury requires the involvement of a multidisciplinary team at the centre of which is the patient. Unlike many other aspects of caring for such patients, urgency of intervention is less critical than understanding the individual functional aspirations and potential of each patient. Sir Harold Gillies' principle borne from the founding of plastic surgery treating ballistic injuries from World War I was to "never do today what can honourably be put off until tomorrow." As all reconstructive surgery involves "robbing from Peter to pay Paul" patients must be adequately counselled as to the potential complications relating to the donor site for any reconstructive surgical procedure and the burden of rehabilitation that may come with it. That being said, the functional, cosmetic and psychological improvements that can be achieved by reconstructive surgery as part of a rehabilitation programme can be highly rewarding for victims of ballistic injury.

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30 Skeletal Reconstruction

Daniel J. Stinner and David J. Tennent

30.1 Introduction

In 2015, the National Consortium for the Study of Terrorism and Responses to Terrorism found that over 35,000 people were injured and 28,000 killed in over 11,000 blast or firearm related terrorist attacks worldwide [1]. Much of our current understanding on how to treat these injuries has come from the lessons learned during military conflicts and terrorist attacks.

As seen in several epidemiologic studies worldwide, the extremities are most commonly injured. While 45–65% of these injuries are soft tissue injuries that may be treated as an outpatient, they frequently have devastating orthopaedic related injuries that can require urgent surgical management due to the degree of soft tissue damage or bone loss [2–5].

30.2 Injury Characteristics and Challenges

When evaluating a penetrating ballistic wound on the battlefield or in the hospital setting, the amount of energy transferred at the time of injury must be considered in order to avoid underestimating the corresponding zone of injury. The degree of energy imparted on the superficial and deep soft tissues is often a surrogate of the weapon or type of offending agent as described in greater detail in Chaps. 2, 3, 4 and 5.

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The degree of injury can often be underestimated due to small visible entrance wounds despite a devastating underlying soft tissue or bony injury. As such, clinical assessment must be focused on determining the degree of contamination, concomitant abdominal injury or bowel perforation, possible vascular injury, type of weapon, whether high velocity or low velocity, and proximity to the blast origin as these will dictate operative and reconstructive measures.

In those injuries requiring operative intervention, definitive bony reconstruction cannot begin until there is a healthy tissue bed. This may require temporary skeletal stabilization but will certainly require thorough excision of all heavily contaminated and non-viable tissue. Furthermore, in those penetrating injuries where the zone of injury is not immediately apparent, repeated assessment in the operating theatre with further tissue excision if required as described in Chap. 21.

Special attention should also be paid to penetrating abdominal and pelvic injuries where the projectile crosses the abdominal viscera as these injuries are at high risk of requiring repeated surgical treatment or systemic antibiotics due to bowel content contamination of a fracture site or joint as shown in Fig. 30.1. Retrospective studies have shown up to a four times higher infection rate when a bowel injury has occurred from a gunshot wound and concomitant fracture [6, 7].

Peri-articular injuries often have severe cartilage loss and/or bony defects that can complicate the final reconstructive options due to the need for additional bony or

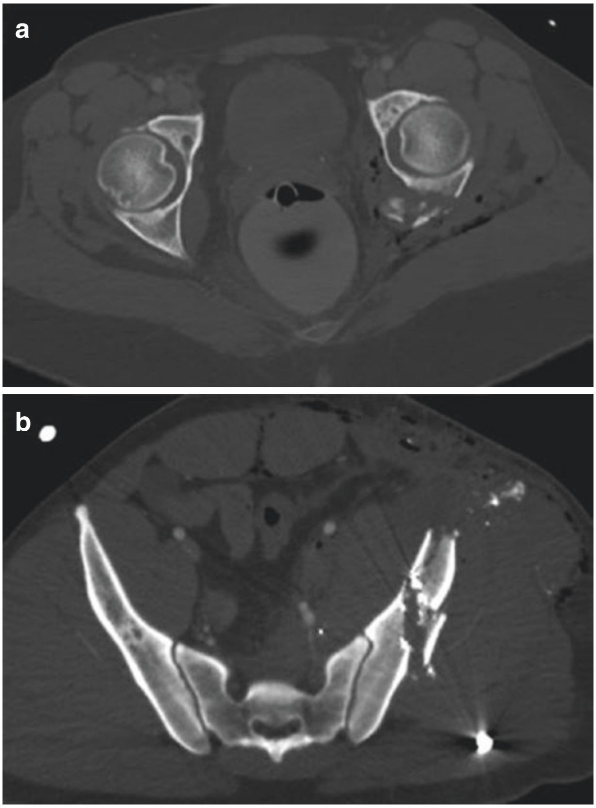

Fig. 30.1 A posterior column fracture (**a**) and a fracture of the ilium (**b**) are shown. Both did not require operative fixation, but did undergo exploratory laparotomy due to associated bowel injuries

implant augmentation. Intraarticular fragments should be excised either arthroscopically or through an arthrotomy, if required, in order to diminish the likelihood of plumbism and the mechanical effects to the cartilaginous surfaces (Fig. 30.2) [8, 9].

A high rate of vascular injuries have been seen in battlefield blunt and penetrating extremity trauma as described in Chap. 21. These injuries often play a vital role in determining the role of damage control orthopaedic principles and final reconstructive options. If immediate definitive vascular repair is not feasible, temporary shunting with a Javid or Argyle shunt can be placed to restore distal blood flow. These repairs often require the addition of a temporary external fixator placed during the initial operative intervention in order to protect the vascular repair. This can subsequently be converted to definitive fixation when the vascular repair has been deemed successful. Alternatively, if definitive fixation can occur expeditiously, i.e. tibial intramedullary nailing, and the bone and soft tissue injury is amenable, it can occur immediately prior to the vascular reconstruction.

Ballistic and blast injuries are often associated with critical bone loss. This is defined as the smallest defect in a specific bone which does not heal spontaneously,

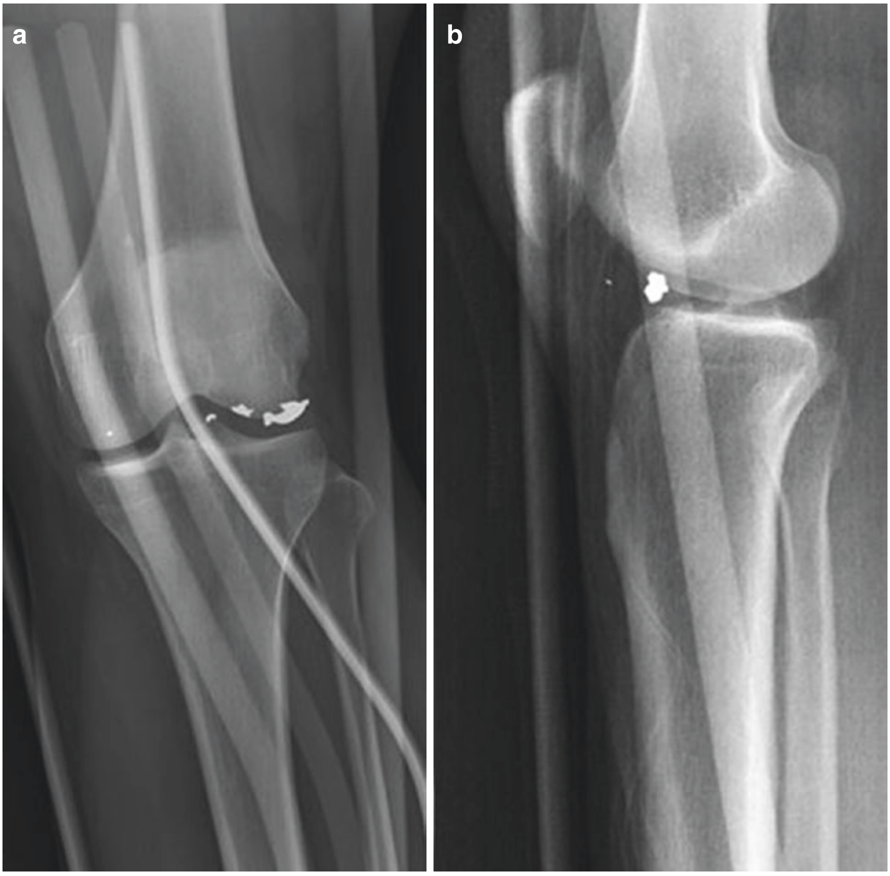

Fig. 30.2 AP (**a**) and Lateral (**b**) X-rays are shown demonstrating intra-articular fragments following a low-velocity gunshot wound

Fig. 30.3 Following debridement after a high-velocity ballistic injury, this patient was left with a 6 cm segmental defect of the tibia

which is often 2–3 times the diameter of the involved bone (Fig. 30.3) [10–13]. These defects will frequently require various temporary stabilization techniques, bony and soft tissue augmentation, and/or concomitant nerve and vascular reconstruction. As such, these devastating injuries require a multidisciplinary approach, are associated with a prolonged treatment course, and are often wrought with complications. Ultimately, the patient must understand that the acute treatment course and subsequent recovery process is not linear and that there are often late, unanticipated complications. It is important that this is discussed early to assist with managing the patient's expectations so that they can begin to recognize that their recovery may have a long, protracted course.

30.3 Immediate Assessment and Care

30.3.1 Pre-Hospital

Immediate prehospital care should consist of patient stabilization and transportation to an appropriately equipped medical treatment facility. Initial focus should be on saving life and normally following ballistic trauma this is focused on controlling haemorrhage as is discussed in detail in Chap. 8.

The role of splinting in the prehospital setting cannot be understated as it can prevent additional tissue damage and bleeding while assisting with pain control. There should be a low threshold for pelvic stabilization with an appropriate binder (e.g. Sam Sling®) if the patient has been close to an explosion or it there is clinical suspicion of a pelvic fracture. Rapidly applied, non-circumferential temporary splints (e.g. SAM splint) and non-invasive extremity traction (e.g. Kendrick Traction Device®, Buck's Traction splint®) should be considered in unstable fracture patterns. The immediate use systemic antibiotics in open fractures is mandatory [14].

30.3.2 Imaging

Upon arrival to the hospital, appropriate trauma and life-support guidelines should be initiated to appropriately evaluate and treat the patient to include pelvic imaging. Ideally, if there is suspicion of a pelvic injury CT imaging should be performed. If initial imaging occurs when a pelvic binder is *in situ* and is negative, it should be repeated when the patient is stable when the patient is stable following pelvic binder removal.

In the setting of extremity ballistic and blast injuries, the entire extremity, to include the joints above and below the level of injury, should be fully imaged in orthogonal planes using plain radiography. Penetrating wounds should be marked with a radio-opaque marker.

In cases of an intra-articular injury, CT imaging should be performed of the involved extremity in order to determine the extent of articular comminution and to guide further surgical reconstructive interventions. The treating surgeon should consider that in the setting of damage control orthopaedics, delaying CT of an intra-articular fracture until after reduction and temporary stablisation might yield greater information for planning the definitive fixation procedure. Furthermore, CT angiography or a formal angiogram may be indicated in cases of suspected vascular injury.

30.3.3 Antibiotics

Multiple studies have elaborated on the role of early systemic antibiotic administration, wound debridement and early soft tissue coverage in decreasing the risk of infection in high-energy orthopaedic trauma. Low velocity ballistic wounds not requiring operative stabilization may be treated by a short course of oral antibiotics and local wound care without an increase in infection risks [15–17].

In those injuries where severe comminution or osseous defects occur, typically from high velocity ballistic injuries, early systemic and local antibiotics should be considered. Antibiotic impregnated absorbable carriers (e.g. calcium sulfate, antibiotic powders, etc.) should be considered in wounds that can be definitively closed to further deter infectious complications [18, 19]. Furthermore, in cases where a large defect remains and future reconstructive procedures will be attempted non-absorbable antibiotic carriers such as Poly-Methylmethacrylate (PMMA) should be considered to allow the local bacterial control while providing dead-space management and further soft-tissue healing.

Topical negative pressure wound dressings with or without silver augmentation should be considered in all cases in at risk wounds or to assist with temporization in patients not ready for definitive management [20–22]. Locally administered antibiotics via antibiotic beads, absorbable chitosan sponges, or directly applied antibiotic powders should also be considered to further augment negative pressure wound therapy as these have all be shown to effectively decrease local bacteria in contaminated wounds [18–20, 23].

While a first generation cephalosporin is commonly recommended for ballistic injuries, special consideration should be given in the management of fractures with a concomitant bowel injury as the literature suggests that the use of broad-spectrum antibiotics administered for 48–72 h are optimal for minimizing the risk of infection [15].

30.4 Initial Surgical Management

It is important to note that not all ballistic injuries require operative stabilization or bony reconstruction. The literature has demonstrated that low velocity ballistic injuries can be safely managed with local debridement and irrigation, tetanus prophylxais when required, and antibiotics followed by splinting or casting as long as an adequate reduction can be obtained and maintained (Fig. 30.4) [24]. However,

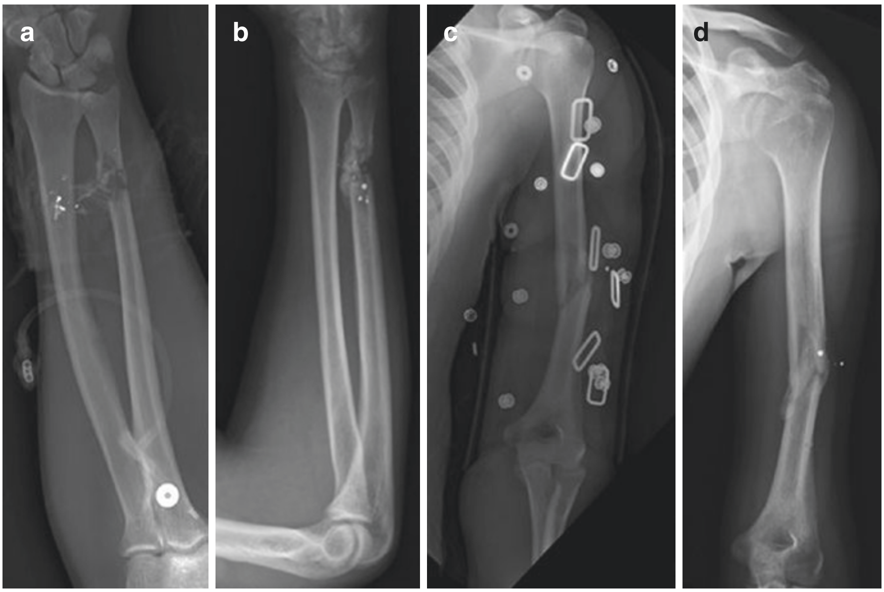

Fig. 30.4 A low velocity ballistic injury to the ulna (**a**) and humerus (**c**) went on to union (**b** and **d**) without the need for surgical intervention

for those fractures caused by low velocity ballistic injuries that are unstable or whose reductions cannot be maintained, they can often safely be managed with acute definitive operative fixation and stabilization if patient factors allow.

In a patient *in extremis*, the principles of damage control orthopaedics should be followed and temporary stabilization via external fixation performed with consideration of future operative plans. Studies have shown that definitive intramedullary nailing and open reduction and internal fixation can occur in the setting of severe open lower extremity fractures without an increase in infection rates provided concurrent wounds are closed or covered with viable soft-tissue [25]. As such, if soft tissues allow, all attempts should be made to definitively stabilize the fractures. In those cases where soft tissues are tenuous, repeated debridement and irrigation is indicated, or soft tissue coverage is required, an external fixator is often applied that can be later converted to definitive fixation.

Dead space management can be obtained using non-absorbable antibiotic carriers such as PMMA beads [18]. Soft tissue approximation should proceed as soft tissues allow using monofilament sutures. Negative pressure wound dressings, progressive soft tissue closure techniques (e.g. Jacob's ladder) and negative pressure wound therapy can assist with non-closable or at-risk wounds.

The surgeon should maintain a low threshold to perform fasciotomies in high energy ballistic or blast injuries as compartment syndrome is a well-documented complication [26]. Furthermore, in the setting of a vascular insult or prolonged tourniquet times, fasciotomies should be considered due to the concern for a reperfusion induced compartment syndrome. When performed, fasciotomies should be progressively closed or grafted with a split-thickness-skin graft. Dermal substitutes and acellular dermal matrices can further assist in cases of exposed tendinous or bone structures prior to skin grafting when further soft tissue coverage cannot reasonably occur [27, 28].

30.5 Definitive Fixation

When discussing management of the high-velocity ballistic injury to an extremity, it is important to consider the tenets of the limb salvage process. Internal fixation should only occur at the time of or after the soft tissue wounds have been closed or covered. Implants should never be used if wound closure is not possible.

Definitive fixation can only occur if the patient and the limb have been appropriately prepared:

1. Resuscitation of the patient: physiological stabilization is required, if this cannot be achieved due to the extent of the injury, amputation should be considered.
2. Resuscitation of the wound: Thorough irrigation and debridement, stabilization of the bone, and liberal use of fasciotomies when indicated.
3. Secondary management: Reassessment of the wound with continued debridement of nonviable tissue. There is a continued emphasis on the prevention of infection to include the management of soft tissue defects and dead space

management. Through each subsequent operative intervention, the patient should be one step closer to definitive reconstruction.

4. Definitive management: This period is marked by stabilization of the patient's general health status as well as limb injury evolution. This definitive phase involves reconstruction of bone and soft tissues using a variety of techniques.

It is important to note that the patient with an isolated extremity injury from a low velocity projectile with no associated vascular injury may progress rapidly to definitive management if the patient, bone and soft tissues are amenable.

There are three principle methods of skeletal stabilization in the treatment of ballistic injuries requiring operative stabilization.

1. Plates
2. Intramedullary Interlocking Nails
3. External Fixation

30.5.1 Plates

Plates can be applied to perform various functions such as compression, protection (neutralization), buttress, tension band, or bridging. Depending on the technique used, the plates can function to provide either absolute or relative fracture stability. Due to advances in modern nailing, open reduction and internal fixation with traditional plating systems is commonly reserved for upper extremity fractures and periarticular fractures of the lower extremity.

Plates are commonly used for the management of upper extremity fractures (Fig. 30.5) due to the need to obtain anatomic reductions, i.e. radius and ulna fractures. They also have the advantage of providing optimal fixation for very short proximal or distal bone fractures, i.e. periarticular injuries, where intramedullary implants may not be able to provide adequate fixation.

Through traditional plate osteosynthesis, a significant surgical exposure is often required to anatomically reduced and stabilize the bone. Variations to these approaches such as minimally invasive approaches can be used to minimize the soft tissue injury incurred using traditional approaches. Furthermore, due to the degree of soft injury and zone of injury sustained from high-energy ballistic trauma, unconventional surgical exposures may be required to allow for appropriate debridement and irrigation and successful fracture fixation. Standard surgical exposures can be used for low-velocity ballistic fractures, when a surgical debridement and irrigation of the projectile path or cavity is not necessary. In high-velocity injuries, where a surgical debridement and irrigation is recommended, the wounds are extended to allow thorough debridement of all nonviable tissue. Since these wounds are often not along traditional surgical soft tissue planes, they may necessitate alternative surgical approaches as to not cause further soft tissue damage.

While many ballistic injuries are amenable to compression plating and absolute stability, which allows primary bone healing, injuries with extensive comminution or bone loss may require bridge plating (Fig. 30.5). The application of a bridge plate

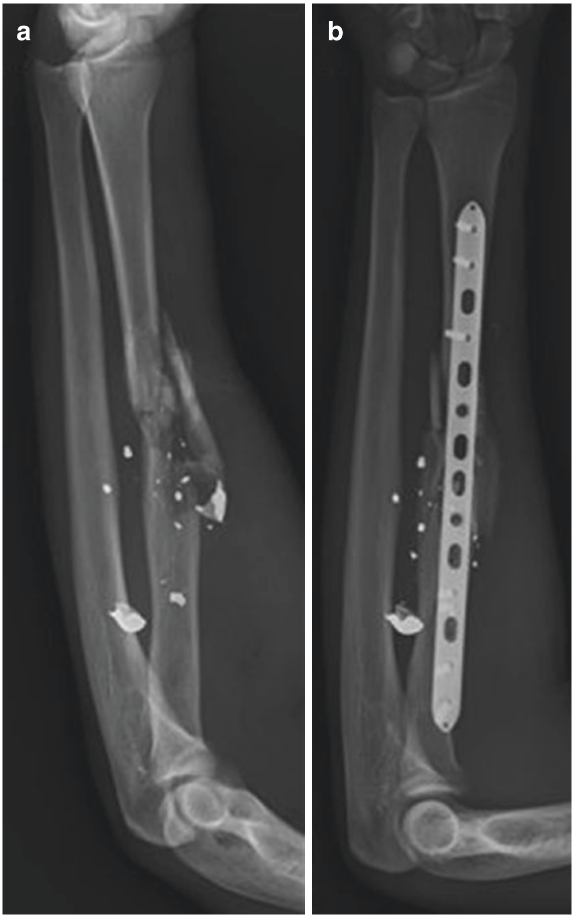

Fig. 30.5 A low velocity ballistic injury to the radius resulting in shortening and loss of radial bow (**a**) was treated with bridge plating to restore length and alignment (**b**)

spans the comminution or area of bone loss creating a relative stability construct, which will heal through secondary bone healing and subsequent callus formation.

30.5.2 Intramedullary Nails

Modern intramedullary nails (reamed with interlocking bolts) have the significant advantage of offering satisfactory biomechanical stability to allow early weight bearing. In addition to the ability to often allow early, if not immediate, weight-bearing following fixation with an intramedullary nail, these intramedullary implants are also ideal for the management of tibia fractures where delayed union is more common.

Intramedullary nails offer several additional benefits. It is a familiar technique to most orthopaedic surgeons and minimizes soft tissue dissection, which can be beneficial in an extremity that already has a significant amount of soft tissue injury due to the ballistic injury. One concern for the use of an intramedullary nail in the setting

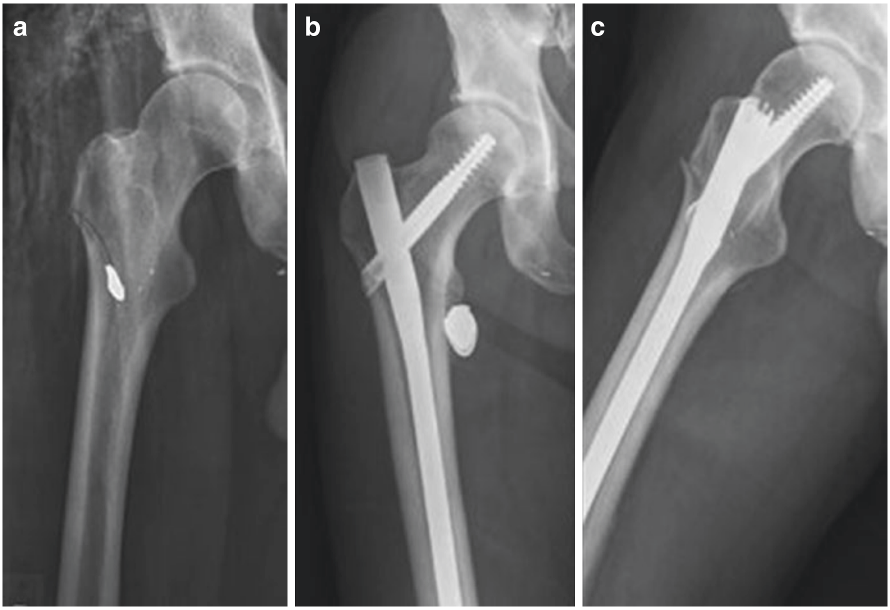

Fig. 30.6 After a low-velocity ballistic injury causing a *right* intertrochanteric hip fracture (**a**), the hip was stabilized with a cephalomedullary nail (**b** and **c**)

of ballistic or open fractures is the risk of infections and difficulty treating it should one occur with an intramedullary implant. However, the literature suggests that they can be safely used in these injuries, although as the severity of injury increases, so does the risk of infection [29–32].

For low-velocity injuries requiring operative stabilization amenable to an intramedullary nail, the fracture can be treated similar to a closed injury without the need for a surgical debridement and irrigation of the soft tissue wound (Fig. 30.6) [29]. For high-velocity injuries, a surgical debridement and irrigation should be performed of the wound, which is often followed with temporary external fixation depending on the extent of the soft tissue injury. Definitive fixation can occur once the soft tissues are amenable.

30.5.3 External Fixation

External fixation is versatile and can provide rapid and safe stabilization of severe open fractures, whether from high-velocity or low-velocity ballistic injuries [33]. They can be used to restore limb length and alignment and can provide adequate bony stability while allowing access to the wound for vascular or plastic surgery if needed.

The goal of temporary external fixation is restoration of length and general alignment without concern for achieving anatomic reduction (Fig. 30.7). It avoids unnecessary trauma to the tissues and can be performed rapidly. When placing a

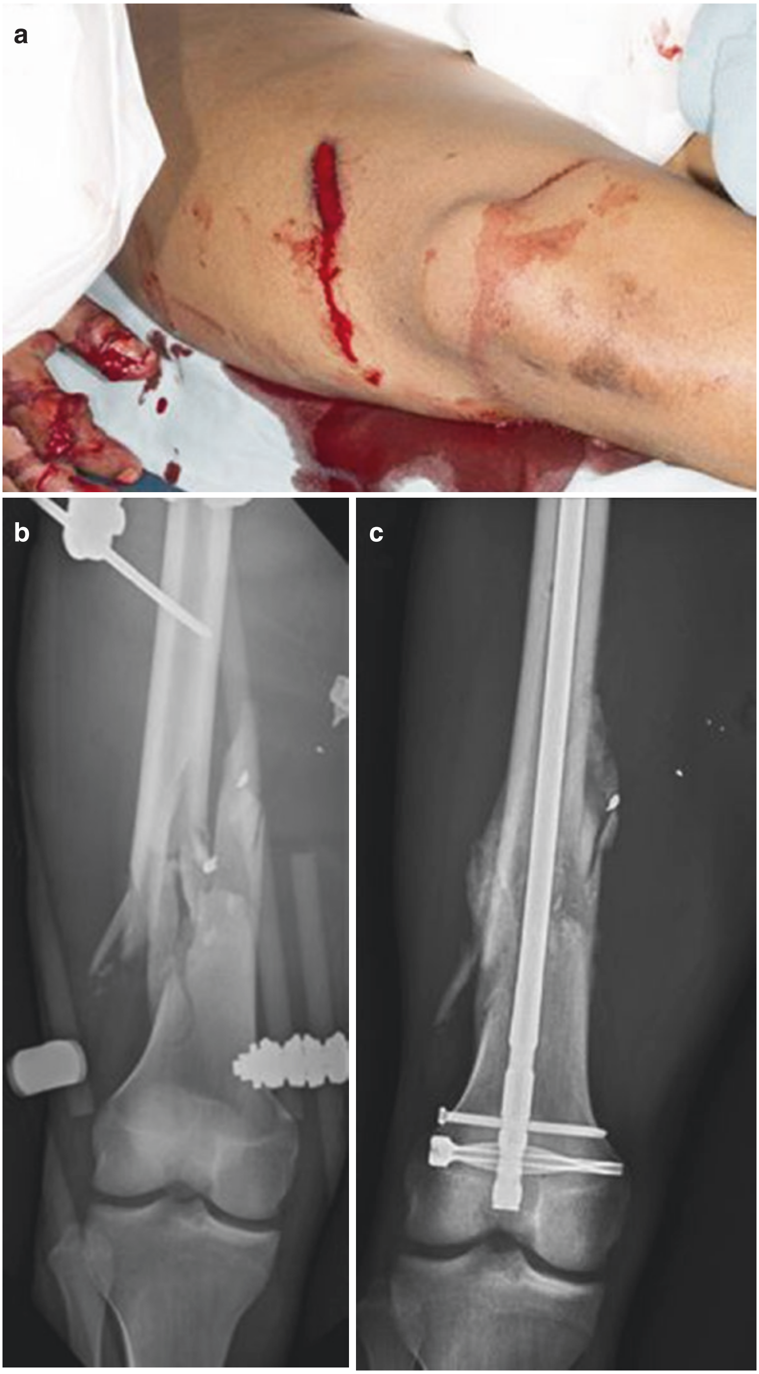

Fig. 30.7 This patient sustained multiple ballistic injuries to his chest and abdomen in addition to his *right* thigh (**a**) and presented to the hospital hemodynamically unstable. As a result, he underwent temporary external fixation of his *right* femur fracture (**b**) and was converted to definitive intramedullary nail 1 week later (**c**, shown healed)

temporary external fixator, it is important to try and keep Schanz/half pins out of the zone of injury, and when possible, distant to any planed definitive fixation. However, pin-plate overlap has not been demonstrated in the literature to increase the risk of infection [34]. Due to decreased stability with uni-planer frames, ringed fixation is commonly used for definitive management in an external fixator. Good results have been achieved using this method in the management of severe open tibia fractures in both the military and civilian setting. When temporary external fixation is used, it is ideal to convert to the definitive method of fixation within 2 weeks if using plates or an intramedullary nail in order to decrease complication and infection rates [35, 36].

An additional benefit to the use of ringed external fixation is the ability to manage both the bone and soft tissue injuries. For injuries that have both segmental bone and soft tissue loss, an acute shortening (Fig. 30.8) or a shortening and angulation can be performed [37–39]. In other cases, the limb can be deformed at the fracture site to achieve wound closure. If there is segmental bone and soft tissue loss, to include a neurovascular injury, the limb can be shortened to allow end to end repair of the neurovascular structures. Once epithelial healing begins, length can be restored through distraction osteogenesis via a distant corticotomy. When performing these procedures, care is taken to ensure adequate

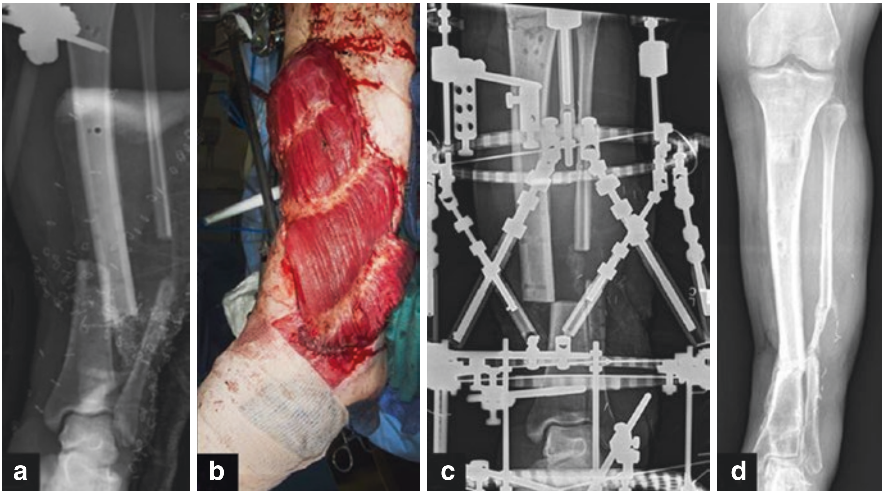

Fig. 30.8 An AP radiograph of a severe open lower extremity fracture with significant bone loss that underwent acute shortening (**a**), which was performed in conjunction with a free flap (**b**) due to the combined bone and soft tissue loss. Distraction osteogenesis was then performed with a ringed external fixator (**c**) to achieve restoration of limb length and alignment (**d**)

limb perfusion is maintained throughout the process with the use of a Doppler. Any change in the quantity (number of audible vessels) or quality (diphasic, triphasic) of the signal requires modification followed by reassessment of the signal.

30.6 Special Considerations: Bone Loss

Bone loss can occur acutely following ballistic injuries, particularly in the setting of a high-velocity injury. It can also occur as a result of the complications following the initial management of these injuries. For example, if a patient develops an infected nonunion, infected or nonviable bone may need to be debrided resulting in subsequent bone loss (Fig. 30.9). There are critical size bony defects that require additional treatment strategies because they will not heal independently—commonly referred to as segmental defects. They are frequently managed by the following two methods: (1) Masquelet Technique/Induced Membranes and (2) Distraction Osteogenesis.

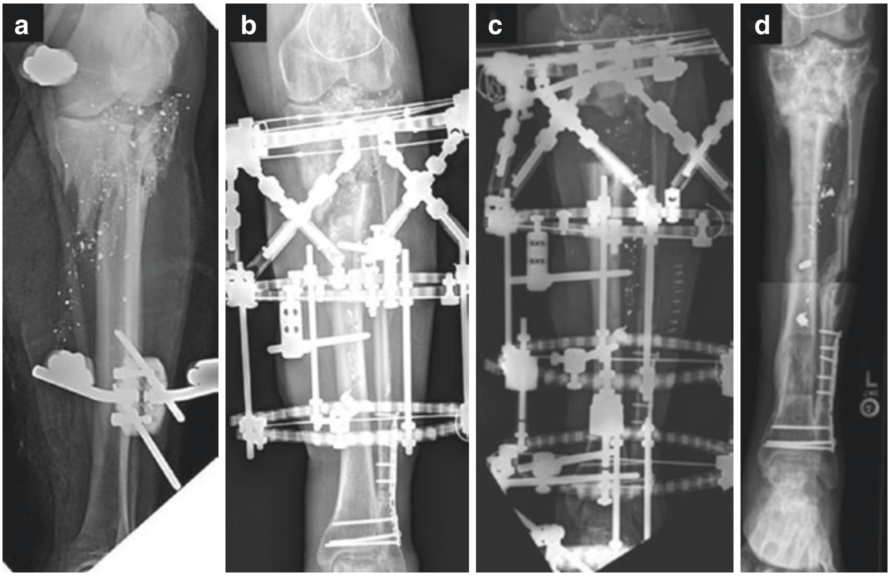

Fig. 30.9 After a high-velocity ballistic injury causing a devastating intra-articular proximal tibia fracture (**a**), the patient went on to develop an infected nonunion (**b**). His frame was modified to perform distraction osteogenesis after 5 cm of necrotic bone was excised from his proximal tibia (**c**) and eventually went on to union (**d**)

30.6.1 Masquelet Technique/Induced Membranes

In patients with a segmental defect and a stable fracture following fixation, the defect is filled with PMMA, typically loaded with an antibiotic to help minimize the risk of infection. Four to 12 weeks later, the membrane is incised and the PMMA is removed [40]. The timing for performing the bone grafting is important. Historically, it was done between 10 and 12 weeks after initial placement of the PMMA spacer; however, recent evidence suggest that the growth factors within the induced membrane that forms around the PMMA spacer are at their optimal levels at 4 weeks [41].

Care is taken not to disrupt the membrane that has formed around the PMMA other than enough to remove the PMMA. The bone ends are prepared to ensure that they remain viable with healthy bone bleeding and autograft is placed within the defect and the wound is closed. The choice of the autograft is up to the treating surgeon as there are many options to consider, including: the iliac crest (posterior or anterior), the femoral canal via use of the Reamer-Irrigator-Aspirator (RIA), or the proximal tibia. Quantity of bone required, location of the defect, and surgeon experience are all factors that can influence the choice. Alternatively, allograft bone graft and bone graft substitutes can be used, but autograft is considered the gold standard. As a result, they are commonly used as bone graft extenders rather than in isolation.

30.6.2 Distraction Osteogenesis

Distraction Osteogenesis refers to the tension-stress model where slow steady stress, or in this case distraction, causes the bone and soft tissues to become metabolically active, which results in a controlled bone growth. In order to perform distraction osteogenesis an implant must be used that can also 'grow'. These commonly include ringed or mono-lateral rail external fixators. In the setting of a segmental defect, the fixator is applied to stabilize the limb. A distant corticotomy is performed, usually in the metadiaphyseal region of the bone due to the regenerative characteristics of this region (Fig. 30.10). After a short latency period, the segment where the corticotomy was performed is lengthened at a rate of 1 mm per day and the segment where the defect is located is shortened at the same rate. As a result, the defect is closed as new bone and soft tissue are regenerated at the distant site. This continues until the defect is closed and limb length has been restored [42, 43].

If an acute shortening was performed initially, where bony contact is achieved without a segmental defect, then the distant site is distracted until limb length is restored. If there was shortening and/or angulation performed, the deformity can be corrected gradually through the use of a ringed external fixator once soft tissue healing occurs followed by lengthening if required.

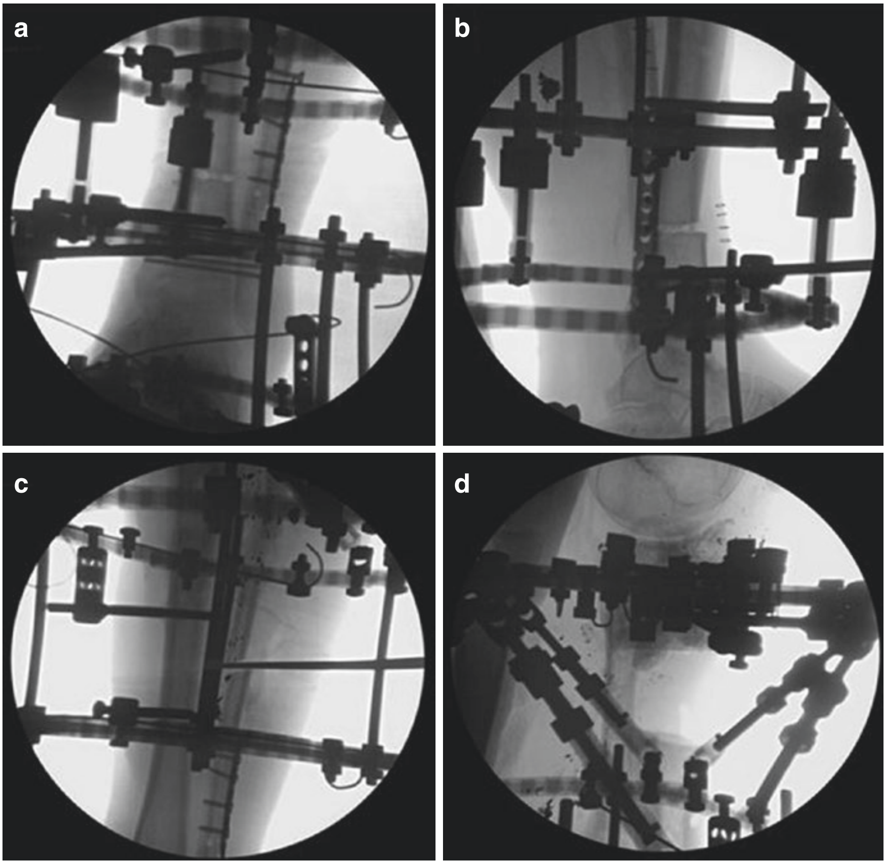

Fig. 30.10 A corticotomy was performed in the metadiaphyseal region of the distal tibia (**a** and **b**). A corticotomy must also be performed of the fibula to allow distraction, but this is done at a distant site (**c**). This will allow the *middle* segment of the tibia to be transported into the large defect (**d**) while bone regenerates distally

Conclusion

There is a wide spectrum of bone and soft tissue damage that can occur as a result of ballistic injuries. It is important to treat each one individually as the treatment may vary depending on multiple factors, the most important being the patient's physiologic status. For the definitive management of all fractures, there are a variety of techniques that are possible. The choice of one technique over the other depends on the individual surgeon's clinical experience and technical expertise.

Conflict of Interest The views/opinions expressed in this presentation do not reflect the views/opinions of the United States Government, the Department of Defense, or the U.S. Army.

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Amputation

31

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Key Points

1. Amputation is a rehabilitative procedure that can afford an excellent outcome if performed well.
2. Decisions regarding amputation or limb reconstruction are complex and should be based on the best functional outcome for the patient, not scoring systems nor simply what is technical feasible.
3. Surgeons need to consider the general condition of the patient, and the overall healthcare resources when deciding on amputation or reconstruction or the zone of amputation.
4. In general residual limb length should be maximised and muscle groups secured but this may not be possible when amputating through the zone of injury in the acute phase.
5. Osseointegration offers a potential method of limb fitting for patients with short and irregular residual limbs.

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31.1 Introduction

Amputation is an integral part of the surgery for ballistic injuries, for many years it was *the* surgery for ballistic limb injuries [1]. However, as the ability to stabilise fractures, treat wound sepsis and reconstruct soft tissues has evolved, amputation has ceased to be the default treatment for ballistic limb injuries.

Amputation may be regarded as an admission of failure by some surgeons, but for those with devastating limb injuries following ballistic trauma, a well performed amputation is the first step in rehabilitation and eventual return of both function and independence.

This chapter will explore the enduring role of amputation in the treatment of ballistic limb injuries; discuss the many factors influencing decision making in this area and final offer points specific to amputation in the context of ballistic trauma.

31.2 Amputation Versus Reconstruction-Decision Making

As surgical techniques for skeletal fixation and soft tissue reconstruction have evolved, surgeons are faced with a dilemma: whether to amputate or to reconstruct a severely traumatised limb.

The somewhat heroic term of 'limb salvage' is often used, but in this chapter we use the term reconstruction to refer to the surgical technique of fracture fixation wound closure and coverage.

31.2.1 Wider Considerations

It is important to recognise the wider context, beyond the traumatised limb in which these decisions are made. Firstly the patient as a whole: is their overall burden of injury almost overwhelming so they would not tolerate prolonged reconstructive surgery? Technical perfection is of no value if the surgical insult tips a patient into multiple organ failure.

More importantly is the wider context of the healthcare setting: Are there large numbers of casualties that will prevent the healthcare system from dedicating significant resources to complex and lengthy surgery for an individual? In the context of healthcare provision to refugees and internally displaced patients, the mobile nature of these groups means that there may be doubt as to whether a patient can be followed-up. This can preclude the staged surgery and treatment for complications almost inevitable with complex limb reconstruction.

In these cases, the surgeon should consider that amputation will normally be far quicker and associated with less re-operations and complications compared to reconstruction [2]. In the most resources constrained environments, amputation proximal to the zone of injury will potentially offer the least complications.

31.2.2 Scoring Systems

The decision on whether to amputate or reconstruct a traumatised limb is one that few surgeons make regularly. There have been at least six scoring systems proposed to guide the surgeon in this decision and purport the advantage of making this difficult decision with life-long implications less subjective [3–8]. Unfortunately these systems have been shown to be poor predictors of limb viability in both the civilian [9] and military practice [10].

These scoring systems also have a fundamental disadvantage: they focus on whether a limb *could* technically be reconstructed as opposed to *should* a limb be salvaged in terms of enabling a superior outcome to be achieved for the patient. The experience of both the US and UK military casualties have failed to demonstrate superior outcomes from limb reconstruction compared to amputation following severe tibia fracture [11, 12]. After severe hindfoot injury there is a demonstrably superior outcome for military patients with amputation, either primarily or delayed compared to 'successful' amputation. It is however, challenging to predict at time of ballistic injury which patients would eventually function better with an amputation and a reasonable strategy may be to consider reconstruction as the 'default', accepting that some patients may opt for amputation later, without prejudicing their eventual outcome [13].

Ideally, decisions regarding salvage or amputation of a severely injured limb should be made jointly by an orthopaedic and plastic surgeon with appropriate experience of limb salvage surgery and with careful counselling of the patient about their likely outcome with the two treatment options [14]. Limbs should be X-rayed and photographed and the vascular and neurological status of limbs carefully recorded. It is important to note that decisions of limb viability should not be based on sensory deficit as this is often due to transient and recoverable neuropraxia [9].

A useful method for approaching a severely traumatised limb is not to regard the decision to primarily to amputate or reconstruct, but rather manage it as a traumatic wound and simply excise the non-viable or grossly contaminated tissue. A ballistic wound will likely require a repeated assessment in theatre with further excision in approximately 48 h. After this process-it may well be that the extremity has essentially been amputated and the attention can therefore shift to surgical formation of the most viable residual limb.

In cases of bilateral lower limb injury, considerable effort should be made to reconstruct at least one limb as this will have a significant long term implications for rehabilitation and eventual function compared to bilateral lower limb loss [15]. In these circumstances, acute limb shortening to reduce bony and soft tissue defects can be considered.

31.3 Amputation Level Decision Making

The strategy for determining the amputation level is based on balancing the mechanical advantage of the longest achievable residual limb against the need to create a stable and durable weight-bearing surface. As a rule, there is considerable functional advantage in maintaining the knee or elbow joint wherever possible, even if the segment distal to this is very short.

The traditional approach has been to perform an amputation proximal to the zone of injury which allows a viable weigh-bearing surface to be constructed from healthy, and uninjured tissue. This approach has the benefit of typically requiring fewer procedures to achieve a primarily-closed wound, but at the potential cost of a shorter residual limb than might otherwise be possible. This strategy may be appropriate in a resource constrained, or mass-casualty environment.

The alternative strategy that was increasingly adopted in the recent conflict, focuses on achieving the maximum residual limb length by serial tissue excision from within the zone of injury, with dubiously viable tissue left *in-situ*. This process is repeated until the wound has stopped evolving, and between surgical episodes, the open-residual limb is dressed with gauze based Topical Negative Pressure (TNP) dressings, often using drains laid along tissue planes incorporated into the dressing [16].

This approach requires acceptance of an irregular residual limb that may require a range of techniques to achieve coverage/closure. This strategy will achieve the maximal residual limb length, however it does require significant surgical resources, multiple operative episodes and considerable prosthetic expertise to fit a socket to an often sub-optimal and irregular residual limb.

31.4 Surgical Strategy

As a general rule, the goal should be to preserve maximal length of the residual limb, particularly in the upper limb and the thigh [15]. The length is dictated more by the injuries to the soft tissue injury rather than the bone. If necessary, more proximal fractures should be fixed and tissue transfer used to maintain limb length [17, 18]. Another option to achieve the optimum residual limb length is distraction osteogenesis using an circular frame [19].

The main exception to the preference for limb length remains a trans-tibial amputation where residual limbs can be *too* long. Most surgeons have adopted the ratio of an inch of tibial length measured from the medial joint line for every foot of height (2.5 cm per 30 cm of height) [20]. This ratio typically results in a bone length of around 15 cm which provides an optimal length for the prosthetists to achieve an ideal fit between the socket and the residual limb and have sufficient space for the shank and the foot and ankle unit.

Neurovascular structures need to be addressed carefully. Vessels should be dissected out individually and ligated using a No. 1 vicryl suture passed through the vessel. Mass ligation risk capturing nerves and resulting in chronic pain. Nerves should be cut under gentle tension and ideally the nerve ending should be allowed to retract and become 'buried' in muscle tissue ensuring it is away from weight-bearing areas. In transecting the sciatic nerve in a trans-femoral amputation, the vessels accompanying the sciatic nerve will bleed profusely if not addressed.

It is important to realise that in trans-osseous amputation, load-bearing does not occur predominantly via end-bearing via the transected diaphysis, rather the load is transmitted through the whole of the residual limb within the socket. This is why sockets for trans-tibial prosthesis are cast with the knee slightly flexed to allow for transmission of load to the prosthesis from the front of the knee-a situation that the body is well adapted to.

31.4.1 Myodesis and Myoplasty

When muscle is transected, it retracts and atrophies; aside from the loss of the direct effect of the muscle, there are other adverse effects. The loss of the action of the muscular pump effect on the venous system leads to venous engorgement in the residual limb, and as the muscle slowly atrophies there is change in muscle bulk over many months results in persistent limb fitting issues [21].

In order to avoid this, ideally muscle tissue should either be re-attached to bone i.e. *myodesis* or attaching antagonistic muscles to each other i.e. *myoplasty*, under appropriate tension.

The surgical approach to myodesis and myoplasty in amputation varies according to the specific situation:

- The formation of a stump from the residual limb tissue from within or very near the zone of injury in the acute setting.
- Amputation proximal to the zone of injury in the acute setting.
- Elective amputation in a patient dissatisfied with a limb after reconstruction.

A different surgical strategy is required for these different scenarios.

31.4.2 Acute Amputation from Within the Zone of Injury

In the this scenario, tissue will be vulnerable and inflamed as shown in Fig. 31.1. Tight closure of residual limb ‘stumps’ in order to achieve a firm, stable weight-bearing surface may result in areas of localised compartment syndrome, prevent drainage of tissue exudate, resulting in wound breakdown and infection. Tight myodesis and myoplasty should be avoided and instead tissues ‘tacked’ into place.

The experience from operating on blast patients sustaining traumatic amputation was that formal myodesis using heavy braided sutures through bone led to complications including deep infection and should be avoided. Numerous visits to theatre may have to be undertaken before a surgeon is content that the soft tissue envelope may be closed. When the decision to close has been made, deep drains should be placed into any dependent areas and TNP dressings laid over the closed wound edges to aid healing and removal of exudate. Complications should be expected with return to theatre not uncommon.

Fig. 31.1 Acute trans-tibial amputation from within the zone of injury. The transected end of the tibia has been covered by a posterior muscle flap, but split-skin graft has been used to cover other areas of the wound [22]

31.4.3 Acute Amputation Proximal to the Zone of Injury

Trauma Surgeons must avail themselves with a working knowledge of the pathophysiology of blast and will thereby understand that the tissue proximal to the obvious zone of injury may still be damaged [23]. However, the surgeon should aim to perform a more traditional amputation with formation of a stable, firm soft-tissue envelope over the weight-bearing surface with myoplasty and or myodesis. However, if a trans-tibial amputation is being performed acutely for a hind-foot injury, then the posterior flap may well be close to the zone of injury.

31.4.4 Delayed Amputation

The expectation should be that this would be similar to elective amputation for e.g. vascular disease. However, the presence of previous soft tissue reconstruction and atypical anatomy may require careful surgical planning and anticipation of precarious soft-tissue vascularity.

It has also been observed that patients injured by explosive weapons who sustained a significant burden of injury can demonstrate a marked inflammatory response when undergoing later significant surgery. This should be anticipated in delayed amputation, even months or years after their initial injury and critical care be available if required.

31.5 Specific Anatomic Considerations

Amputation surgery performed following ballistic trauma typically cannot be performed in accordance with a proscriptive technique as the injury patterns are heterogeneous. However, surgeons should be cognisant of certain considerations for amputation at specific sites.

31.5.1 Upper Limb

Due to the reliance on the upper limbs for independent living, every effort should be made to maintain all possible length and tissue. Almost any hand-tissue is functionally superior to none and similarly almost any elbow function can provide a patient with an ability to grip an object in the elbow whilst it is manipulated with the contralateral hand. Therefore every consideration should be given to the full range of reconstructive options including free tissue transfer and even use of amputated lower limbs as a source of donor graft material.

If the elbow joint is within the zone of injury but preserved, then heterotopic ossification is likely and in a physiologicaly stable patient, steps should be taken to mitigate against its formation.

31.5.2 Hip Disarticulation

This is a highly challenging procedure in any context, but particularly following ballistic trauma. Typically amputation at this level occurs after an explosive injury and is a result of repeated surgical episodes of tissue excisions in an attempt to control infection in a setting of extensive tissue damage and contamination. There is typically loss of the contra-lateral limb [24] and there may well be pelvic and abdominal injuries as shown in Fig. 31.2 below.

The injury may be so extensive that free-tissue transfer is required for wound coverage. In the context of bilateral lower limb loss, the most likely donor site is the latissimus dorsi, resulting in weakened shoulder adduction, an essential manoeuvre for a bilateral lower limb amputee. In the acute phase after an explosive injury, micro-vascular anastomosis necessary for free-tissue transfer can have increased failure. It may be more appropriate to gain temporary, but sub-optimal coverage with either split-skin graft or dermal regenerative templates e.g. Integra™ (Integra Life Science, NJ, USA) [16]. With planned free-tissue transfer at a later date when the patients is physiologically more able to tolerate this.

Fig. 31.2 A CT scout image showing *left hip* disarticulation, *right* trans-femoral amputation and a pelvic external fixator

31.5.3 Trans-Femoral Amputation

The challenge for amputation at this level is to balance the muscles, mainly *Adductor Magnus* whose distal fibres attach to the adductor tubercle on the medial condyle. Since it is so much more powerfull than adductor brevis and longus, its loss leaves the more powerful hip abductors unopposed, if feasible, fibres of *Adductor magnus* should be attached to the femur, though this use of intra-osseous sutures should be avoided in the acute phase [25].

31.5.4 Knee Disarticulation

Amputation at this level has been questioned following the findings of the Lower-Extremity Amputation Project (LEAP) that trans-femoral amputees had a higher patient reported outcomes than those with knee disarticulations (KD). This was based on follow-up of only 16 patients at 2 years and 15 at 7 years [26, 27]. A meta-analysis of outcomes following amputations for injury found that when comparing 48 patients with knee disarticulations to 187 trans-femoral amputees, found the mean SF-36 Physical component score was 45 in the KD patients superior to the mean of 38 in trans-femoral patients ($p < 0.0001$) [15].

Where possible the patella tendon should be sutured to the anterior cruciate tendon. If there is difficult fashioning a sturdy soft tissue envelope over the distal femur, then the epicondyles and posterior condyles can be trimmed, but ideally the weight bearing articular surface is maintained. This is less bone resection than a formal Gritti-Stokes where the distal femur is transected at the level of the trans-epicondylar line or the adducctor tubercle [28]. If any of the distal femur is resected, this should be done at time of closure as intact articular cartilage is a potent barrier to bacterial colonisation of metaphyseal bone and its removal in an open wound would potentially allow this to occur.

Unlike trans-osseous amputations, the knee-disarticulation creates a true load-bearing end to the limb. There is concern that since the prosthetic knee joint will be distal to the contra-lateral knee (in a unilateral amputee) there will be an unsatisfactory cosmetic result, particularly when sitting. However this offset by a greater walking distance and SF-36 score in patients with KD compared to trans-femoral amputation [15].

31.5.5 Trans-Tibial Amputation

This is normally the most common level for amputation following injury comprising 68% of the amputations recorded in the LEAP study. As described above, the optimum length for a transtibial amputation is around 15 cm although this should be slightly longer in tall individuals. The fibula is typically cut approximately 1-cm shorter than the tibia.

A variety of techniques have been described for the soft-tissue flaps for trans-tibial amputations: the posterior flap [20, 29], sagittal flaps [30, 31] and oblique or 'skew' flaps [32]. Most surgeons use the posterior flap which covers the end of the tibia with a flap of gastro-soleus [33]. However, as previously noted, when fashioning a residual limb following ballistic trauma, traditional flaps might not be possible and instead 'flaps of opportunity' used [18].

A unique feature of ballistic trauma, especially injuries resulting from the casualty standing on an explosive device, is disruption of the intra-ossesous membrane between the fibula and tibia. This can result in painful instability of the abnormally mobile fibula.

Based on his surgical experience of caring for casualties from both World Wars, the Hungarian surgeon Janos von Ertl proposed an 'Osteoplastic' technique for creating a bony bridge or *synostosis* between the fibula and tibia [34]. Proponents of the Ertl procedure postulate that it stabilises the fibula, provides a greater bony surface area that permits direct end-weight bearing and that sealing the tibia intramedullary canal prevents bone spurs and restores venous return [21, 35, 36]. However, contemporary studies have failed to demonstrate improved outcomes following an Ertl trans-tibial amputation over a traditional technique [37, 38]. The Ertl procedure was not used when performing trans-tibial amputation in British military casualties from the wars in Iraq and Afghanistan [39].

31.6 Long-Term Surgical Care of Residual Limbs

As described above, amputation is a rehabilitative procedure. In order to aid the patient to realise their maximum rehabilitative potential, it is likely that revision surgery will be required at some stage. It is worth noting that 30% of amputee patients in the LEAP trial requiring re-hospitalisation, and in a military series, the re-admission rate was nearly 50% [39].

31.6.1 Residual Limb Revision

The strategy of maximising limb length by amputation through the zone of injury leads to irregular residual limbs which undergo considerable change in size and shape other the first 12–18 months [40]. This is due to two main factors: muscle atrophy and oedema. This change in shape and volume can result in increases in bony prominence, increased propensity to soft-tissue shear and generalised difficulties in socket fitting. Revision surgery should be aimed at resecting bony prominences or improving their cover; improving soft-tissue stability, typically by myodesis and may require complex orthoplastic surgical reconstruction to achieve these goals.

Another indication for revision surgery is to treat painful neuromas. Accurately diagnosing the source of pain in a residual limb can be challenging due to general disruption of the usual neurological architecture in the residual. Ideally as part of the work up for surgery, a diagnostic USS guided local anaesthetic injection into around the neuroma should be performed. If this improves the pain, then the neuroma excised, the nerve re-cut proximally and the end re-burried in muscle tissue away from bony prominences.

31.6.2 Heterotopic Ossification

As described above, in order to provide the maximal residual limb length to amputees, amputations have been performed within the zone of injury. This strategy of ‘stump salvage’ with multiple surgical episodes and extensive use of TNP dressings potentially increases risk of heterotopic ossification (HO) [41].

Short, irregular residual limbs with florid HO can be extremely challenging for the prosthetist to achieve a satisfactory interface between the residual limb and prosthetic socket, especially when HO is ‘spikey’. Conversely in some patients with more ‘mushroomed’ shaped HO, this can actual aid limb fitting, permitting these patient to fulfil the functional outcomes that are potentially achievable.

Florid ‘spikey’ HO may require surgical resection to ameliorate pain and improve socket fit-this should be performed when HO has matured and is radiographically stable and/or ‘cold’ on a bone scan.

31.6.3 Osseous Integration

Despite extensive and skilled rehabilitative efforts, some patients remain unable to ambulate on prosthetic limbs. This is because of limb fitting difficulties caused by either florid HO, a very short residual limb or poor soft-tissue envelope or commonly, a combination of all of these factors. The ideal solution may be a direct connection between the prosthesis and the skeleton. This can be achieved with osseointegration (OI) of an implant which crosses the skin and provides an external coupling for the prosthesis.

Osseointegration was used for the first time in an amputation patient in 1990 in Sweden at the Sahlgrenska University Hospital, Goteborg, Sweden [42] and further refined by other groups in Germany, the Netherlands and Australia [43].

Amputees injured in explosions typically have massive wound contamination, predominantly soil and debris; this material is driven up tissue planes by the force of the blast and probably never fully removed from wounds. In addition, as previously described, the soft-tissue envelope covering the end of bones is not consistently robust tissue. In this potentially contaminated environment the insertion of an implant was previously considered high risk of development of deep infection. However, initial results of OI in UK servicemen with high bilateral transfemoral amputation has significantly improved mobility with no deep infections.

Conclusions

Amputation following ballistic injury is a rehabilitative procedure that if performed well, can allow a patient to rapidly rehabilitate to independence and high levels of function after a ballistic injury. Decisions regarding amputation or reconstruction can be challenging, even for surgical teams experienced in dealing with these injuries. Decisions should be based on achieving the best outcome for the patient, not what is surgically or technically possible and should not rely on scoring systems. If possible, every effort should be made to maintain limb length.

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Conflict Rehabilitation

32

Alex Scott and John Etherington

The Key Principles of Successful Rehabilitation of Patients with Ballistic Trauma

1. Early Assessment.
2. A multi-disciplinary team approach.
3. Active case management.
4. Evidence based to rehabilitation.
5. Rapid access to further specialist opinion and investigation.

32.1 Introduction

The rehabilitation of patients who have suffered multiple injuries is a critical element of the patient pathway. There is a duty to those injured either through military service, criminal act or terrorist attack. Providing the best possible care for these patients involves maximising their physical, psychological and social outcome. The aim is to take a casualty from point of wounding through surgical and medical management to rehabilitation and eventually return them to highest possible levels of function and integration back into military duty or society. Recent conflicts have challenged combat casualty care, military rehabilitation services and society as a whole [1–3].

Rehabilitation in this group of patients is complicated by a number of factors. There are frequently multiple injuries which include the musculo-skeletal, and neurological systems therefore it is not possible to compartmentalize treatment to one therapeutic approach. Psychological factors will be a major influence on long-term success of rehabilitation. Exposure to psychological trauma prior to injury, the death of colleagues, friends and family, the near death experience itself, disfigurement and

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perceived disability will complicate rehabilitation outcomes. Patients with similar injuries from similar circumstances may have widely different outcomes because of the individual's emotional response to the traumatic event. Similarly, mild traumatic brain injury can have devastating consequences—as it can impact on cognition and adaptability to life-changing events.

32.2 Early Assessment

Assessment of a patient needs to occur as soon after the point of wounding as possible to identify rehabilitation needs and to initiate earliest stages of physical rehabilitation This will include the intensive care unit. Psycho-social factors can be identified and peer support can be initiated.

32.3 Use of a Multi-Disciplinary Team

The medical consultant-led MDT is vital in these type of cases. The complexity and multi-system nature of these injuries means that they cannot be allocated to single therapy teams. A multi-disciplinary team might include:

- Medical staff
- Physiotherapists
- Occupational therapists
- Social work/welfare workers
- Exercise therapists
- Prosthetists
- Podiatrist/orthotists
- Mental health and psychology support

There must be regular multi-disciplinary team meetings with goal setting and treatment planning for each patient.

32.4 Active Case Management

Active case management means that a patient's care pathway is planned from injury, throughout their acute management until they are discharged from rehabilitation. Relying on multiple external agencies to coordinate their activities is unrealistic and frequently leads to failure of the pathway. The rehabilitation MDT is the key to facilitating the ongoing medical and social management of the patient. There is a need to coordinate medical care (including ongoing surgical review), investigations, equipment (e.g. wheelchairs) and social and welfare support. This may include planning for resettlement into supported living environments. If one tennet of this approach fails e.g. timely provision of equipement, then the whole effort is compromised.

32.5 Exercise-Based Rehabilitation

Exercise-based rehabilitation relies on the physical training of the injured body to enhance function, improve well-being and generate confidence. This relies on an understanding of tissue healing processes, exercise physiology and the ability to modify exercise programs to suit patients with multiple concomitant injuries. While trained physiotherapists should oversea this therapy, in the UK military, they are assisted by physical training instructors who have undergone additional training. This exercised based rehabilitation is typically delivered to groups of patients with similar levels and types of injuries.

32.6 Rapid Access to Further Specialist Opinion

Rapid movement along the treatment pathway from reconstructive to rehabilitation phases is desirable. However, this may mean that there is need for several follow-up surgical procedures including orthopedic, plastic and reconstructive surgery occurring during the rehabilitive phase of treatment. This may draw upon the skills of the original surgical teams or alternative specialist units with experience in, for example, neuro-urology and peripheral nerve injury. Psychiatric services and psychological support are essential.

32.7 Rehabilitation Process

The rehabilitation process will vary between services and what is outlined below are based on the principles used in the UK Armed Forces and is coordinated through the Defence Medical Rehabilitation Programme. This has at its core the main specialist rehabilitation unit at the Defence Medical Rehabilitation Centre. Supporting this are Regional Rehabilitation Units, which are supported by Primary Care Rehabilitation Facilities—physiotherapy-led departments. Not all trauma rehabilitation requires secondary care services and as patients spend more time at home and work they will rely on primary care support.

Rehabilitation is an interactive process with patients attending for 3–4-week periods of treatment, a period of recovery or consolidation at home or work, followed by readmission to provide further rehabilitation and a more intense level of therapeutic exercise or intervention.

The process comprises the following elements:

- Patient tracking
- Patient assessment
- Goal-setting
- Treatment planning
- Exercise-based rehabilitation
- Case management
- Discharge—readmission cycle

- Discharge planning
- Vocational rehabilitation
- Reintegration into society
- Follow-up

32.7.1 Patient Tracking

Effective rehabilitation depends on the ability to deliver the appropriate care package to the appropriate patient at the appropriate time. Identification of casualties who require rehabilitation may be challenging. The most seriously injured will pass through a hospital to undergo definitive reconstructive surgery and may require intensive care. The patient will be identified from the onset of trauma and a rehabilitation programme set in motion. Less seriously injured patients may have only transient periods in a secondary care facility and and be discharged to local physiotherapy services. The risk of this process is that apparently minor injuries with significant functional sequelae are passed to inexperienced services. These cases may be at greater risk of severe psychological disturbance than the more severely injured. There is a tendency to underestimate the severity of some injuries and the psychological consequences of even minor trauma may be significant.

To avoid the loss of patients from rehabilitation services the UK Armed Forces have developed a patient tracking system. The patient's journey through the pathway can be monitored and the appropriate medical service notified of the patient's whereabouts and needs. The experience of civilian trauma centres—particularly in moments of extreme demand—suggests that similar tracking systems need to be in place to ensure patients are correctly referred for rehabilitation.

32.7.2 Patient Assessment

The medical team play a critical part in the initial stages of the rehabilitation process when the patient may not be medically stable. Rehabilitation must commence on ITU but for the patient to be able to make significant progress he or she must be medically stable, free from serious infection and not undergoing frequent medical procedures which interfere with the continuity of rehabilitation. Wound or skin contamination with organisms such as MRSA does not exclude treatment but will alter how the patient is managed. Pain needs to be controlled and an understanding of pain management including neuropathic pain is vital.

32.7.2.1 Key Elements in the History

- Nature of wounding, single or multiple entry wounds
- Level of energy transfer
- History of impairment
  - Did impairment arise at the time of wounding or later in the course of the condition?

- History of loss of consciousness
- Pain quality and level
- Time on intensive care
- Nature of surgical and medical interventions
- Patient perception of injuries
- Social history
- Home support
- Past medical history
- Current medication
- History of psychological disturbance in particular nightmares, flashbacks, and intrusive thoughts. Changes of mood
- Cognitive deficits; word finding difficulties, memory, concentration, and executive skills
- Sensory deficits including tactile, visual, and auditory

32.7.2.2 Examination Skills

It is essential that the examiner has skills in both musculo-skeletal and neurological examination to diagnose deficits, record impairments, and monitor change.

32.7.2.3 Multi-Disciplinary Assessment

A multi-disciplinary assessment is vital. Assessments by medical, physiotherapy, occupational therapy, social work, exercise therapy, and nursing staff inform the rehabilitation plan. After a multi-disciplinary assessment good communication in an MDT meeting will produce a problem list from which goals are set and a treatment plan derived.

Goal Setting is an important element of the rehabilitation program. Goals need to be set over the long (6 months), medium (2–3 months) and short term 3–4 weeks. The SMART (Specific, Measurable, Achievable, Realistic, and Time bound) model is frequently used. Critically, they need to be set in discussion with the patient, although frequently patients—particularly service personnel—need to be given guidance so as to avoid setting unattainable goals in unrealistic time frames. Alternatively, their goals may be very general and therefore difficult to extrapolate a treatment plan from—'I want to return to running'. Once long-term goals are set the shorter goals can be developed. Goals must be set in accordance with the patient's wishes and personal aims.

For example:

Long term goal	In 6 months I will return to part-time sedentary work
Medium term goal	In 3 months I will be walking on my prosthetic for 1 km using one stick
Short term goal	At the end of this 1 month admission I will be wearing my new prosthesis for 3 h/day.

It may be necessary to determine goals over even shorter periods, such as week, in order to demonstrate to the patient measurable improvement in their function when they are sceptical of their progress. Alternatively, patients may need short-term goals in order to rein-in their over-enthusiastic activity detrimental to their outcome. Patients may need encouragement and support to improve their performance but many cases require limitation to be placed on their activity—particularly in high achieving military or sporting personnel.

Goal setting should focus on occupational outcomes when dealing with people capable of returning to functional employment. A lack of focus on this aspect of rehabilitation will limit overall vocational outcome. Returning patients to work de-medicalises them and reaffirms their usefulness to society and family.

32.7.3 Treatment Planning

Treatment goals are set after discussion between the therapy staff, doctors, and the patient. Patient involvement is critical to success and may require involvement of the family and their employer. Ideas, concerns, and wishes may need to be explored and an explanation of the treatment and the prognosis improves a patient's concordance. A joint treatment plan is produced which includes the timelines for treatment, and indicates the external agencies to be involved, including employers and social services. Decisions should be recorded on a shared MDT document and actions identified for individual therapists and doctors to perform.

Once rehabilitation has commenced regular MDT planning meetings are essential and progression recorded and discussed with the patient. Regular review of the patient is essential and planning for discharge should take place as soon as the patient is admitted.

At discharge, there is readmission planning and a selection of goals to be carried out whilst the patient is at home, which allows for continued progression and improved progression on return.

32.7.4 Delivery of Exercise-Based Rehabilitation

In UK military, rehabilitation is undertaken over short periods—up to 4 weeks at a time and much of the structure of rehabilitation focuses on exercise which is frequently delivered in a group setting.

32.7.4.1 Group Therapy

Exercise therapy is usually delivered in groups with each group being composed of patients having similar injuries and level of function. All groups complete a varied daily program of 5 h of exercised-based activity that includes: Class Therapy, Hydrotherapy, Postural Re-education, Walking/Running and Gait Re-education, Recreational Therapy with individually tailored treatment programs. Many of the outcomes rely on the training benefits of exercise and therefore dependent on the intensity, frequency and duration of exercise.

Peer support is important in overcoming the psychological consequences of this trauma and group therapy is a major contributor to this. Being surrounded by injured patients from similar backgrounds and experiences aids concordance with treatment and improves recovery. External social interactions are vital at an early stage in the rehabilitation to improve long-term social integration.

32.7.4.2 Physiotherapy

Physiotherapy is a key component of the rehabilitation service provided for patients with severe physical injury. Treatments typically take place on a one-to-one basis. Core skills include manual therapies such as mobilization, manipulation, soft and deep tissue massage, and scar tissue mobilization. Physiotherapists will provide orthotics, correct gait abnormalities and muscle imbalances, provide stretches, exercise therapy, and advice on progression. They supervise the exercise therapy and may use acupuncture and a number of electrotherapy modalities particularly for pain relief.

32.7.4.3 Social Work

Specialist medical Social Workers play a key role in the rehabilitation process and should have expertise in health-related issues that individuals or families may experience following trauma or illness. They offer the following services:

- Assessment and Counseling
  - Guiding the patient and their family along the process of adjustment, providing support and assisting the individual and their relatives to plan for change.
- Care and Discharge Planning
  - Providing information about resources such as, resettlement and retraining opportunities, housing, welfare benefits and access to legal advice.
- Advocacy
  - Representing the patient view at clinical meetings and with outside agencies such as Housing Departments or welfare agencies.
- Resettlement
  - The Social Worker, in conjunction with the Occupational Therapist, will advise patients on opportunities for vocational assessment and retraining.

32.7.4.4 Occupational Therapy

Occupational Therapy enables patients to be as independent as possible in activities of daily living, their chosen occupations or leisure.

They provide the following services:

- Education and practical advice about the nature of the injury and how to deal with its effects on their lives. Advice on work, personal care, and leisure activities.
- Activities of Daily Living
  - Assessment and treatment of limitations of personal care. This may involve home visits to advise on equipment or adaptations that are required to improve safety and aid independence.
- Provision of Equipment
  - Specialized equipment to solve the problems of temporary or permanent disability e.g., wheelchairs, bathing aids, pressure garments, and cushions.
- Community Living Skills
  - Assessment and training in community living skills such as traveling on public transport, shopping, and accessing local community facilities. Driving assessments and advice on equipment and adaptations to enable individuals to return to driving.

- Emotional Support
  - Practical support and coping strategies to help patients adjust to their limitations and explore their concerns.
- Cognitive Rehabilitation
  - Assessment and treatment of the functional impact of cognitive problems such as memory, concentration, and processing in brain injury.
- Work Skills
  - Assessment of skills and advice on strategies and adaptations that can be implemented to improve return to work. Through a graded program of work hardening, individuals can be gradually introduced back to their trade. If they are unable to work, recommendations can be made regarding future employment, training, or rehabilitation.

32.7.4.5 The Nursing Team

A named nurse is responsible for a nursing care plan for the patient and for supporting the patient through his rehabilitation. The nursing team requires nurses knowledgeable in orthopedics, neurological rehabilitation, amputee care, spinal injury, sexual dysfunction, mental health and continence care. Of particular importance is tissue viability expertise for multiple wounds, split skin grafts, reconstruction flaps and burns. Nursing staff assist patients with activities of daily living in order to promote and encourage independence.

Nutritional support is critical in enhancing the recovery of patients who have been in a highly catabolic state for many weeks and who need nutritional support during a period of intense physical activity. PEG feeding may be required in more dependent patients.

32.7.5 Case Management

At all times, the rehabilitation program should focus on reintegration of the patient into society at work or home. There requires coordination of external agencies involved in this, including Social Services, the Health Service, the employer, and housing agencies. On-going specialist medical investigations and treatments may be required, for example urodynamics to inform bladder management in the spinal cord injured patients or bone infection management. The consultant which leads the MDT is responsible for the case management of these cases and must ensure the rehabilitation process is a smooth as possible.

32.7.6 Discharge: Readmission Process

The scheme below demonstrates a program for serial admissions to a complex trauma rehabilitation team. Patients are admitted for approximately 4 weeks at a time. Within 10 days the goals for that period are stated, agreed, and written in the MDT summary. At discharge Readmission goals are set for the patient to achieve while they are away and for the first 10 days of their admission. At the end of the

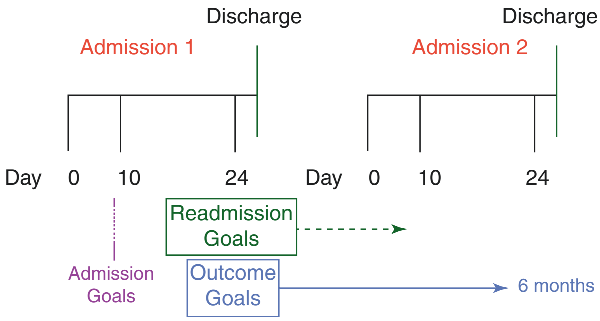

Fig. 32.1 The discharge: readmission process

first admission long term Outcome goals are set to determine what is expected to be the clinical outcome after 6 months. In this way a series of admissions are conducted with greater periods of time away on sick leave, or later, back at work (Fig. 32.1). This system allows for a greater throughput of cases.

32.7.7 Discharge Planning

The MDT must work closely with the patient, their family, and outside agencies to co-ordinate a package of care that meets the needs of the patient. This often involves liaising with Health Authorities, Social Services, and other external organizations to negotiate the appropriate level of support for the individual. A main focus of rehabilitation is on returning to work and to facilitate this vocational Occupational Therapists can liaise between the MDT, the patient and their employer to ensure that the maximum number of patients return to gainful employment. Where appropriate the patient will be sent to their workplace for a period of work assessment; if this is not possible patients will be supported with further neurological and/or vocational rehabilitation.

Reintegration into society may be difficult and will depend on a number of factors including, the physical, mental, and cognitive status of the patient, the family support the individual receives, and the support from society itself.

32.8 Measuring Outcome

Outcomes can be measured in a number ways:

- Success of the team in accurately predicting goals, using goal attainment scaling
- Repeated measurements of standardized physical tests e.g., 6 min walk test, multi-stage fitness tests
- Patient Reported Outcome Measures e.g. SF 36, Reintegration to Normal Living Index (RNLI)

- Validated questionnaire-based therapist completed outcome measures e.g. SIGAM, AMP Q, Mayo-Portland Adaptability Inventory 4 (superior to FIM FAM in this patient population [4])
- Return to work data

32.9 Specialist Rehabilitation Issues: Amputee Rehabilitation

32.9.1 Considerations

Rehabilitation of the patient who has sustained an amputation as a result of a ballistic injury requires special consideration. The majority of cases of amputation in the developed world affects the older population, over the age of 50 with diabetic or vascular causes of limb loss. The population affected by trauma is younger and has higher levels of physical function and expectation of recovery [5]. The increase in disabled sport, particularly in response to the Paralympic movement, has demonstrated the high level of functional outcome attainable from these patients and has set the bar higher for clinical success. However, as described in Chap. 31, following ballistic injury residual limbs may be irregular and have more scarring [6] providing a greater challenge to the prosthetist compared to a more typical elective dysvascular amputee.

The improvements in the technical provision of prosthetic components have revolutionized the prognosis for patients with amputations. In particular socket-suspension system developments have significantly improved comfort and practical function.

32.10 Principles of Prosthetic Fitting

There are seven elements to a prosthetic prescription depending on the level of amputation [7].

32.10.1 The Structure

In developed medical societies the usual structure is the endoskelatal form of prosthesis, which consists of metal or composite materials (e.g. carbon fibre) strut attached to the end fittings which may be covered by a cosmesis. The structure holds the socket in the correct linear and angular orientation.

32.10.2 Socket

Transmits the forces between the residual limb and the prosthesis;

- Vertically for weight-bearing in the stance phase and some suspension in the swing phase

- Horizontally and rotational about the long axis. To stabilize the socket and energize the prosthesis.

The socket shape is usually a modification of the residual limb shape as it has to take into account the contained skeleton, the consistency of the soft tissues, the limb volume and pressure sensitive areas. It is possible with the development of osseointegration as discussed in Chap. 31 that traditional sockets may become unnecessary in some cases.

32.10.3 Suspension

This may come from the socket shape and material or additional belts. More commonly in this patient population the use of silicon suspensory sleeves with ratchet or vacuum suspension systems the gold standard. These systems give the patient more freedom of movement, greater comfort, are well-tolerated and are robust. Their selection is usually based on personal preference and tolerance [8]. They allow good suspension particularly for high performance amputees where residual limb shape or scarring is less than optimal. They may increase sweating, but this frequently adapts, can be corrected by better fitting or can be treated with aluminum based deodorants or botulinum injection.

32.10.4 The Ankle and Foot

Are usually considered as one unit and have to transfer forces between the prosthesis and the ground but also have to modify this transfer in the gait cycle. This may be provided by a mechanical uni-axial joint providing movement in one plane only or a flexible bush allowing multi-axial movement, an assembly of spring components producing multi-axial movements or compression wedges at the heel. High performance limbs for running may use a spring system like the carbon fibre Flex-run® or Cheetah® systems.

32.10.5 Knee Joint

These joints may be uniaxial or polycentric and whereas there are many knees, including the simplest locked systems only released for sitting—the patient population in this situation usually require high performance prosthetics.

The most significant innovations of recent years for the trans-femoral amputee have been the introduction of microprocessor controlled knees such as the C Leg® or the Genium® These systems have revolutionized knee control, particularly where stability is critical in such as the bilateral trans-femoral amputee.

These systems use a knee-angle sensor to measure the angular position and angular velocity of the flexing joint. There are moment sensors, using multiple strain gauges, to determine exactly where the force is being applied to the knee from the foot and the magnitude of that force. Measurements are taken 50–100 times a second. A microprocessor receives signals from each sensor and determines the type of motion and phase of gait of the amputee. The microprocessor directs a hydraulic cylinder to control the knee motion accordingly.

These systems can provide a close approximation to an amputee's natural gait and increase their walking speeds. Variations in walking speed are detectable by the sensors and communicated to the microprocessor, which can alter the swing through stance phases of the prosthesis. The knee system will allow the amputee to walk down stairs with a step-over-step approach, rather than the one step at a time approach used with mechanical knees and it can deliver additional stability in other contexts—including recovery from stumbles.

The microprocessor, however, are expensive, are limited by battery time, susceptible to water damage and require a lot of patient training. The price may be outside the range of most developing nations and may not be funded by health commissioners, even in developed countries. Nevertheless, they can dramatically help the bilateral trans-femoral amputee, significantly increasing their physical activity during daily life and an improved quality of life [9].

32.10.6 Hip Joint

In the event of hip disarticulation or trans-pelvic amputations a hip joint is required. Fortunately, this is a relatively rare phenomenon [6] as the functional limitation on such patients may be severe. The hip joint will need to be mounted onto the anterior inferior surface of the socket, in order to allow the patient to sit. It may be uni-axial, polycentric or may incorporate one of the microprocessor joints described for use in the knee. Given the severity of the injury, initial mobilization is relatively straightforward as the shallow nature of the hip disarticulation socket means that the patient, for all practical purposes, 'sits' on the socket when walking.

32.10.7 Miscellaneous Units

Axial units will allow rotation about the long axis of the prosthesis against resistance—provide greater freedom of action and reduce the torque applied between the socket and residual limb. This is of particular use in high functional end patients for example in those who wish to play golf where a rotational motion would aid the swing.

The successful provision of a prosthetic limb to an amputee relies on close interdisciplinary working with all members of the team. The prosthetists, prosthetic technicians, and physiotherapists must work closely to provide equipment which fits and which the patient knows how to use. The particular prosthetic skill is in the provision of a comfortable well aligned socket.

Residual limb volume rapidly changes in the earliest stages of rehabilitation and may continue to decrease for up to 2 years after amputation. Early use of compression socks such as the Juzo® will aid this and reduce healing time. The rapid loss of volume will lead to a need to use additional socks to ensure a comfortable fit with the prosthesis. When the volume has changed significantly a socket change should be done as rapidly as possible so that time is not lost from rehabilitation and the patient does not become frustrated or disillusioned. This can be expensive and time consuming as sockets may need to be changed every 6 weeks.

32.11 Neurological Rehabilitation

Ballistic injury can affect any aspect of the peripheral and central nervous system. The most devastating are the consequences of traumatic brain injury as described in Chap. 14. The neurological rehabilitation team at the Defence Medical Rehabilitation Centre provides comprehensive assessment, rehabilitation, and management of neurological illness and injury for a range of conditions including brain injury, stroke, and neuro-degeneration. The majority of cases are acquired brain injury as a result of road traffic accidents and assault—the same principles apply for treatment whether there has been a closed or open injury to the brain.

The aim is to provide an intensive program of rehabilitation including vocational assessment, which is delivered by a specialized and experienced multi-disciplinary team. The structured program of therapy addresses the physical, cognitive, communication, psychosocial, vocational and daily life issues. Involving families and carers in the patient's recovery is essential.

The principles of management are identical to other areas of rehabilitation but the length of treatment required is longer and the pace of treatment slower. It is good practice to assign a key worker to each patient to co-ordinate their treatment and to liaise with the patient and their family, about any areas of concern.

Cognitive deficits frequently overshadow physical deficits as the cause of difficulties in social adaptation, independent living, family life, and vocational activity. Without appropriate intervention, cognitive deficits can lead to frustration, anxiety, depression, and social withdrawal. Cognitive rehabilitation is provided by specialist occupational therapists. It focuses on regaining those cognitive skills, which are lost or altered as a result of neurological trauma or illness. The process includes gaining skills through direct retraining, learning to use compensatory strategies and education about cognitive skills.

32.11.1 Mild Traumatic Brain Injury

Recently there has been increased awareness of mild traumatic brain injury. This has fallen out of the observation that a number of soldiers, particularly from US deployments, have displayed cognitive deficit after exposure to blast, in the absence of evidence of other ballistic trauma, and a causative relationship inferred. This has generated a significant degree of medical controversy [10, 11], not least because of confusion over terminology. A severe brain injury may leave a patient with major cognitive impairment and other impairments—but the outcome is highly unpredictable. For example, there is a poor correlation between Glasgow Coma Scale at time of injury and prognosis. It is possible that a severe acute injury leaves a patient with only mild functional impairment; conversely a minor injury can produce socially devastating consequences.

32.11.2 Lessons Learnt in Rehabilitation from Recent Conflicts

32.11.2.1 Injury Severity at Presentation Is Not Associated with Long Term Vocational Outcome

Injury severity scores such as the ISS and GCS should not be considerd predictive of long-term prognosis, quality of life or employability therefore frontline military clinicains should be encouraged to actively intervene and treat patients with severe traumatic brain injury in the knowledge that recovery is possible. Ninety-three percent of those patients with brain injury and an ISS of 75 were capable of returning to work 4 months after the completion of rehabilitation [12].

32.11.3 Attempt Limb Salvage

As described in Chap. 31 the decision regarding limb amputation or salvage is challenging. It is reasonable to try and preserve an injured limb if possible and allow further surgical interventions and rehabilitation to try and maximise function and minimise pain. Painful limbs of limited function can be removed at a later date if necessary. Most patients are glad to have the opportunity to make an informed decision for themselves later. The literature is inconclusive about whether limb salvage or amputation is more effective in terms of hospital stay, pain and functional outcome [13]. But data from our group has shown that patients with unilateral amputations can walk further in 6 min than a limb-salvage group and those patients with limb salvage were less capable of running independently than amputees. The unilateral amputation group demonstrated a significant functional advantage over the limb-salvage group. Those electing for below knee amputation later, still achieved superior functional gains compared to limb salvage cases and experienced no functional or mental health disadvantage compared to those who had an immediate amputation [14].

32.11.4 The Ideal Stump

The technology now available for fitting limbs in this patient population allows a wide degree of flexibility in stump length, quality and scarring. Healed split skin grafts will usually tolerate the silicon sleeves and suspension systems well.

In the trans-tibial amputation an optimal range would be 12–16 cm when measured from the medial joint line and in trans-femoral 14–21 measured from the crotch, or 23–30 cm measured from the tip of the greater trochanter. Ideally, the optimal stump length should be proportional to the overall stature of the patient. An 'ideal' length of 16 cm in someone with short legs may not leave enough ground clearance to fit in the total length of the modular components in the prosthesis. This may be particularly critical in the high performance amputee where the prosthetic componentry may need to be longer. In a trans-tibial amputee an approximate guide is for 8 cm of stump length per metre height. Anything shorter than 7 cm in a trans-tibial is very difficult to fit. In the trans-femoral patient a gap of 15 cm above the medial tibial plateau is described as ideal for fitting a knee joint system in place whilst retaining a sufficient lever arm. Often of greater difficulty is the management of a bulbous residual limb. A residual limb with a distal circumference greater than that measured at the level of the patella tendon can be difficult to fit. In the case of complex trauma choice of the residual limb length may not be open to the clinician—the prosthetist will have to deal with what they are given.

Post-operative oedema can be reduced with stump shrinkers and early mobilisation with PAM- aids (Pneumatic aid to mobilization). But excess muscle bulk is the main source of the problem. This more commonly occurs in a posterior flap rather than a skew flap technique which produces a more conical shape which allows better prosthetic fitting. However, these are deliberate decisions that should not be made in the first surgical episode and over-long or badly scarred stumps can be revised at a later date.

32.11.5 Through-Knee (Disarticulation) Can Be a Very Effective Amputation

There is considerable bias against the use of knee disarticulation as a surgical option in trauma. This is based on poor experience of the procedure in civilian practice and reflects real concerns but ones which are not always applicable to military practice [15, 16]. The main advantage of the through knee amputation is an end weight-bearing stump. Once the prosthesis has been fitted then the patient can make rapid progress to high-level weight-bearing activity and a level of function, including running, in excess of that expected from a trans-femoral amputation. Disadvantages are mainly cosmetic, as the knee system will sit at a level below that of the contralateral knee. On sitting the knee joint on the prosthetic limb will protrude further forward than the non-affected side. Lowering the centre of rotation of the joint may produce a minor biomechanical disadvantage but this is more than compensated by the stability and control gained from the long lever arm, deep socket and polycentric knee joint combined with hydraulic swing phase controls.

32.11.6 Concomitant Injuries May Be the Factor Limiting Recovery Rather than the Amputation

The functional performance of the lower limb prostheses in many of our amputees is so good and the socket/stump interface so effective in many that the main limitation to mobilisation is frequently the concomitant injury. Fractures have a rate of healing considerably slower than prosthetic fitting and multiple fractures in a contralateral limb, particularly the foot can have a considerable slowing effect on the rehabilitation process. This frequently leads non-amputees with protracted rehabilitation due to delayed fracture union to request an early amputation. This requires careful counselling.

32.11.7 Aggressive Treatment of Neuropathic and Phantom Pain Is Critical: Non-Pharmacological Methods of Pain Control Are Important

Anecdotal evidence would suggest the importance of early, aggressive treatment with analgesics to prevent the development of neuropathic pain. This includes the use of opiates, and drugs such as gabapentin, amitriptylline and pregabalin. There should be no hesitation in using maximum doses of all this medication to obtain complete control of pain. Audit of our practice shows that, once in the rehabilitation setting, the requirement for analgesic rapidly diminishes and very few of our patients require long standing medication for phantom pain control. Education, reassurance, peer support, and physical distraction all play a part in this. Wearing the socket and physical activity often dramatically improve the pain. Other modalities such as mirror therapy and acupuncture can be very effective in certain cases although carry over can be limited.

32.11.8 Early Assessment of Peripheral Nerve Injury with Surgical Repair Will Reduce Pain and Limit Disability

It is important to avoid a nihilistic approach to peripheral nerve injury. Early expert assessment is important following primary repair and follow-up vital. Persisting pain following brachial plexus or peripheral nerve injury warrants consideration of surgical exploration and repair or grafting if needed. Monitoring progress of nerve re-growth allows interventions to be carried out rapidly if the graft or repair is failing. There may be a later requirement for tendon transfer to return function, which further demands the need for expert follow-up [17].

32.11.9 The Psychological Component to Rehabilitation Has an Influence on Outcome

It is evident that the psychological status of the patient has a major influence on physical outcome. Self efficacy is associated with good outcomes in spinal rehabilitation and probably this complexity of injury also. Depression, persistent adjustment reactions, and PTSD are all detrimental to recovery. What is remarkable is the low level of psychological morbidity detectable in these patients [18]. Peer support is an important factor in this, as is the patient having a clear sense of the long term pathway for recovery. Many patients have mild psychological morbidity in the early stages of their rehabilitation but the long-term outcomes are unknown.

32.11.10 Concomitant Traumatic Brain Injury Is a Major Prognostic Determinant of Polytrauma Outcome

In assessing outcome from polytrauma and amputation there is a tendency to dwell on the surgical and physiological factors which determine outcome. Additional injury—particularly brain injury may not be apparent at review but could have a major effect on physical outcome including donning and doffing the prosthesis, ability to understand rehabilitation instruction, balance, and return to work.

32.12 Outcomes

The recent conflicts in Iraq and Afghanistan have helped develop and test the systems described above. Enhanced survivability on operations as a result of improved combat casualty care has, by increasing the number of "unexpected survivors," resulted in considerable rehabilitation challenges. The multidisciplinary clinical teams of the Defence Medical Rehabilitation Centre at Headley Court in Surrey have worked to enhance the outcomes of severely injured UK battle casualties.

Retrospective reviews of polytrauma patients at discharge showed that, 95% (n = 62) of the complex trauma patients were independent in all activities of daily living with an aid or adaptation. Over 90% (59) of amputees, around half with multiple limb loss, walked independently over all terrains, and 75% (6) of triple amputees did not require a wheelchair for daily activities [18]. Amputees show an average walking speed and energy expenditure comparable to a normal, age matched, healthy population. Only for bilateral transfemoral amputees was the walking speed significantly slower (1.12 ms vs. 1.29 m/s, p = 0.025) and cadence reduced. Oxygen costs of walking for unilateral trans-tibial amputees were the same as controls and only 60% greater for bilateral transfemorals compared to controls.

From a mental health perspective combat amputees had PHQ-9 (patient health) scores compatible with moderate to severe depression in 3.1% of cases, compared with 1.6% of the general population. GAD-7 (anxiety and depression test) scores indicating severe anxiety and depression were present in 1.5%, compared with 1.3% of the general population [18].

Of 91 patients with moderate to severe brain injury 79 (87%) were living independently, and 92% (84) were in some form of employment 4 months after discharge [19]. Most of those with the worst possible ISS and GCS injury scores at presentation were able to return to work [12].

These outcomes are encouraging and indicate high quality trauma care, including specialist rehabilitation. This has significant implications for the lifelong physical, mental and vocational outcomes of these patients and will have major economic benefits for the individual person and the nation. To determine the long-term outcomes of these cases and, in particular the long-term cardiovascular risk of trauma UK Defence Rehabilitation will determine the 20 year outcomes of this cohort with the Armed Services Trauma Rehabilitation Outcome (ADVANCE) Study. This study will investigate the 20 year outcomes of battlefield casualties from the Iraq and Afghanistan campaigns. The medical, physical, and psychosocial outcomes of this cohort will be compared with service personnel who did not sustain injuries during operations.

Conclusion

Patients injured through military service, criminal act or terrorist attack undoubtably deserve the highest quality of care available. Despite perfect resuscitation and reconstruction, without high-quality rehabilitation, patients will not achieve their full potential in terms of maximal physical, social, functional and psychological recovery.

This requires a skilled, consultant-led, multidisciplinary team with rapid access to modern rehabilitation technologies. It requires systems in place to identify and track the patient through the care pathway and needs a focus on a high expectation of functional and work-related outcome.

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