Interaction of penetrating missiles with tissues: some common misapprehensions and implications for wound management

It is apparent from review of published papers and books that misunderstanding and confusion exists in the minds of many authors describing the interaction of penetrating missiles with tissues. These misconceptions may influence the management of wounds by suggesting didactic approaches based upon a preconceived notion of the nature and severity of the wound for different types of projectiles. This review considers the biophysics of penetrating missile wounds, highlights some of the more common misconceptions and seeks to reconcile the conflicting and confusing management doctrines that are promulgated in the literature – differences that arise not only from two scenarios, peace and war, but also from misapprehensions of the wounding process. Wounds of war and of peacetime differ both in the nature of the wound and in the propensity for wound infection. Additionally, the limitations imposed by war dictate the type of management that may be practised and result in procedures that would be considered inappropriate by some in civilian clinical practice. Many of the procedures described in civilian peacetime settings, such as reliance on antibiotics alone for the control of infection in penetrating wounds, or minimal excision and debridement, can yield good results but would herald disaster if transposed to a war setting.

Keywords: Wound, penetrating, ballistics, debridement, wound infection

Perusal of nearly any textbook on trauma containing descriptions of the interaction of missiles with tissues reveals some common misconceptions about the relationship between the kinetic characteristics of the missile and the severity of the wound. Foremost amongst these is the role of impact velocity in determining the severity of a wound and the extent of indirect injury away from the track of the projectile resulting from ‘high velocity’ projectiles passing through soft tissue. These misconceptions may actually influence management of a wound in that there may be preconceived notions about wound severity in the light of presumed or actual knowledge of the type of wounding missile and generalizations regarding the characteristics of a wound.

Management doctrines must be influenced by the facilities available for surgery and postoperative care. The emphasis in most textbooks is upon management within a civilian clinical setting in peacetime. War imposes significant limitations on the type of surgery that may be practised (particularly in forward areas) and in the scale and nature of postoperative care that may be required during evacuation. Additionally, the type and severity of wound differs in many respects from those seen in the civilian setting, notably with respect to the greater potential for infection within the military wound.

The purpose of this paper is to review the biophysical aspects of the interaction between penetrating missiles and soft tissue and bone. Additionally, we identify general aspects of management of wounds that are specifically influenced by the conditions pertaining to war.

Interactions of penetrating missiles with tissues

Penetrating missiles, for practical purposes, can be classified into two major groups, fragments and bullets. Fragments are the most common wounding agents in war, accounting for between 44 and 92 per cent of all surgical cases during recent campaigns. Antipersonnel fragments from military munitions tend to be small and numerous to achieve a high probability of a hit, and to be fairly regular in shape to ensure adequate range and consistent performance. In civilian clinical practice, bullets are the predominant penetrating missiles although fragmentation injury occurs following terrorist bombings; these fragments usually originate from the environment within which the bomb explodes, tend to be irregularly shaped and have a wide range of masses and impact velocities. It is appropriate to differentiate initially between the behaviour of small, relatively uniform, projectiles such as antipersonnel fragments and the behaviour of bullets. The long, cylindrical shape of bullets influences the rate at which energy is transferred to a target and can result in a different pattern of injury along the wound track compared with that produced by fragments.

Most military antipersonnel fragments have poor penetrating power and limited effective range. They have low mass and ragged edges; consequently the drag on the projectile in air and particularly in soft tissue is high. The mechanical injury in casualties surviving to reach surgical facilities may be quite modest. However, many have multiple wounds, heavily

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contaminated with foreign bodies such as clothing, skin and soil. Antipersonnel fragments capable of penetrating skin have a range of impact velocities from about 100 m/s to beyond 1000 m/s but in spite of these very high velocities they generally result in wounds with the soft tissue injury principally confined to the immediate track of the missile. Bullets have greater range and penetrating power and are often classified as 'low velocity' or 'high velocity'. The classification arises from the nature of the weapon firing the projectile: low velocity projectiles are generally propelled from hand guns and high velocity bullets are fired from rifles. As with all generalizations, this may be true for most cases but there are notable exceptions. The major criticism of this type of classification is that it is often implied that low and high velocity projectiles equate to two specific wound classifications of the same name, thus implying that high velocity projectiles are always associated with severe injury. This is not the case and the impact velocity of a projectile can be a misleading indicator of its potential for injury and should not be used to classify wounds or threats from weapons.

All projectiles perform work on the body, lacerating, contusing and displacing tissues. The capacity of a projectile to perform work is defined by its available kinetic energy (\( \text{Joules} = m \cdot v^2 \)), where \( m \) is in kilograms and \( v \) is in metres per second). The available kinetic energy defines only its capacity to perform work on tissue; the proportion of this energy that is ultimately transferred at each centimetre along the track is determined by the degree of retardation of the projectile by the tissues. This in turn is governed by many factors, principally the mechanical properties of the tissue, the velocity and the presented area of the projectile as it penetrates the tissues. The available kinetic energy is 1500–3000 J for military rifle bullets. Most bullets from hand guns have available energies of about 300–500 J. Antipersonnel fragments have low available energies and, in those casualties surviving to reach surgery, available energies would have ranged from about 10 to 150 J.

An appropriate classification of the work performed within a wound is the ‘energy-transfer’. It is important to differentiate at this stage between mechanical distortion (work) that arises from the energy-transfer and the pathophysiological consequences of this distortion. Some elastic tissues may have significant work performed on them but modest tissue injury results (see below). Further, it is important to realize that projectiles may produce indirect injury to tissues not directly in their path. A general classification of the extent of soft and bony tissue involvement is based upon the incidence of indirect injury.

In low energy-transfer wounds, soft tissue injury is confined to the track of the projectile. The wounds arise simply from the cutting action of the projectile as it penetrates the tissues. Most antipersonnel fragments and many hand gun bullets produce wounds of this classification.

In high energy-transfer wounds, injury usually occurs radial to the track of the projectile in addition to the mechanical disruption (laceration and crushing) directly produced. The indirect injury peripheral to the track is produced principally by the formation of a temporary cavity (with non-fragmenting projectiles), a consequence of increasing levels of energy transferred.

### Temporary cavitation

If the available energy is substantially increased by using a projectile of a greater mass and velocity, not only is the penetration distance increased but, as a result, the greater retardation forces leading to a greater transfer of energy, a temporary cavity is formed behind the projectile (Figure 1). The cavity results from the acceleration of material radial to the path of the projectile and reaches its maximum volume within 2–3 ms. The cavity pulsates and eventually collapses in elastic media such as gelatin or soft tissue. A common misconception is that the formation of a temporary cavity is an ‘all or none’ phenomenon. The maximum size of the temporary cavity is related to the energy-transfer and even low energy-transfer projectiles will produce cavities, although these are quite small and may be of little biological significance: a pebble entering water at very low velocity will produce a temporary cavity whose collapse produces the characteristic ‘plop’.

In a material such as gelatin or soft tissue, the size of the temporary cavity at a particular location along the wound track is determined by the energy deposited at that site. Fragments have little change in presented area as they tumble during the penetration process. The maximum energy-transfer, and hence the maximum cavity size, is close to the entry point where the velocity and thus the retarding forces are at a maximum. The formation of the temporary cavity is an important, but not the sole, feature involved in the production of high energy-transfer wounds; break-up or fragmentation of projectiles and bone may also occur, resulting in direct mechanical injury.

### Yaw and changes in presented area

Most bullets are long and thin and are spun along their long axis to provide stability, and thus accuracy. The spin stabilization is overcome upon entering dense material such as soft tissue. Bullets become unstable and will tumble (yaw) during their passage through the material (Figure 2). If the wound track is long enough, they may turn through 180°. The major consequence of this yawing is that it increases the presented area of the projectile to result in significantly higher retarding forces, rather like the increased retardation experienced in dragging a flat palm of the hand through water. High retardation forces reduce further the velocity of the projectile, resulting in greater energy-transfer to the tissue. These forces are highest when the bullet is at 90° to its trajectory.

The energy-transfer from military bullets may be substantial and may result in large temporary cavities. Because the bullet reaches 90° some distance into the track, the maximum size of the temporary cavity with most non-fragmenting bullets is deep within the track and not necessarily close to the entry point. If the wound track is long enough, all bullets will yaw. The feature that may differentiate the performance of bullets is the penetration distance before the yaw cycle commences. Small calibre bullets (5.56 mm) generally start their yaw cycle earlier than large calibre bullets (7.62 mm). This difference may be readily demonstrated in a clear, homogenous material such as gelatin.
The formation of a temporary cavity has two consequences as gelatin but may not be quite so obvious or significant in long wound tracks within soft tissue. The energy-transfer into gelatin for each centimetre of penetration for a military rifle bullet is shown in Figure 3. The site of 90° yaw is identified by the maximum degree of energy-transfer; this will also be the site of maximum temporary cavity diameter (Figure 4).

We have seen that high energy-transfer wounds are characterized by soft and bony tissue injury away from the path of the projectile. It is tempting to presume that the temporary cavity is responsible for this injury. For non-fragmenting bullets in a homogeneous elastic medium, this is the case (although stress waves associated with the penetration process may also be implicated). It must not be assumed, however, that all soft tissue involved in the formation of a temporary cavity is injured by it. This is a common misconception which has recently been the subject of criticism. These are not theoretical arguments for they have significant implications for the degree of excision of soft tissue that is contused but may be viable. This is a very contentious undertaking, for it is rarely necessary in the civilian environment and its necessity is therefore doubted by civilian surgeons. It is of note that, while military surgeons and civilian surgeons who have had war experience recognize the need for this approach, they would add that the excision of viable but contaminated tissue requires experience and value judgement. The procedure is likely to be of value where infection in large numbers of casualties is produced by inappropriate excision: such a time is war.

Indirect injury by projectiles may extend to other types of tissue; for example the spinal cord may be involved in wound tracks close to the vertebral column. The exact mechanism of this form of injury has not been fully elucidated. It has been suggested that compressive stress waves (colloquially and inaccurately called shock waves), generated in blood vessels and soft tissues by the passage of the bullet, may be involved. Some authors suggest, for example, that abdominal injury may result from high-energy-transfer penetrating wounds to the thigh. Although stress waves may be implicated in 'spinal shock' and indirect long bone fracture, indirect injuries produced by stress waves originating from penetrating missiles extend of soft tissue injury occurring radial to the track as the result of the formation of a temporary cavity. In dense, homogeneous tissues, particularly if enclosed within a connective capsule or casing (liver, spleen and brain are examples), the effects of cavitation may be quite devastating; the physiological consequences of injury to these sites are rather obvious — high-energy-transfer injury in these circumstances carries a very high mortality rate.

The position as far as skeletal muscle is concerned is less clear and more contentious. The rapid strain produced by the cavity produces contusion injury and, close to the track, radial laceration may be seen occasionally. The viability of contused muscle is difficult to ascertain; the judgement of the surgeon based on experience and indications such as colour, consistency, contractility and capillary bleeding has long been relied upon but is now being called into question by some authors. They suggest that excision of skeletal muscle in peripheral wounds has been too radical and that in practice very little tissue needs to be removed. There are others who maintain that most of the soft tissue involved in the temporary cavity must be excised.

An important purpose of wound excision is the removal of the source of infection. The widespread contamination, particularly in the military environment, may lead to excision of soft tissue that is contused but may be viable. This is a very contentious undertaking, for it is rarely necessary in the civilian environment and its necessity is therefore doubted by civilian surgeons. It is of note that, while military surgeons and civilian surgeons who have had war experience recognize the need for this approach, they would add that the excision of viable but contaminated tissue requires experience and value judgement. The procedure is likely to be of value where infection in large numbers of casualties is produced by inappropriate excision: such a time is war.

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Figure 2. The axis of a bullet during flight does not lie along its trajectory. The angle ($\theta$) between the trajectory and the axis is the angle of yaw. The spin stabilization of the bullet induces a circular motion of the nose around the trajectory. The yaw angle before interaction with the dense medium (shaded) is exaggerated in this diagram and is usually less than $1-2^\circ$ in practice when the bullet has stabilized. Instability due to venting of propellant gases close to the muzzle may induce high initial yaw ($3-5^\circ$) at close ranges. The spin stabilization of the bullet is overcome upon entering soft tissue; the yaw angle progressively increases (tumbling) and the bullet departs from the initial trajectory. The retarding forces upon the bullet are at a maximum when the yaw angle is 90°. The maximum energy-transfer and temporary cavity diameter are located at this point.

Figure 3. The energy transfer resulting from the interaction of a high available-energy military rifle bullet with 20 per cent gelatin. The energy transfer (J/cm) is plotted against penetration distance into the gelatin (cm). The bullet has tumbled (yawed) shortly after penetration; the site of 90° yaw is coincident with the site of maximum energy transfer.

Figure 4. The temporary cavity produced by impact of a high available-energy military rifle bullet with 20 per cent gelatin. This picture was taken about 2 ms after the bullet entered the block from the left. The maximum diameter of the cavity corresponds to the site of maximum energy transfer (compare with Figure 3). It must not be assumed that all, or even a significant proportion, of the soft tissue affected by the temporary cavity is injured by it.
have little clinical significance in the management of penetrating wounds in humans. They can occasionally be demonstrated as petechial haemorrhages in animal models.

The strain or instability within the soft tissue surrounding the cavity may actually produce sufficient force to cause indirect fracture of a long bone: a bullet resulting in high energy-transfer need not strike bone to fracture it. Stress waves may also be implicated in indirect long bone fracture.

The sizes of missile entry and exit holes are governed by the size and shape of the penetrating missile and the degree of energy-transfer at the site. The formation of a large temporary cavity at either site invariably results in gross soft tissue injury and the skin may exhibit stellate lacerations. Although a large tissue defect is quite obviously the result of large energy-transfers or missile fragmentation, the corollary that small entry and exit wounds imply low energy-transfer is not true; high energy-transfer may have occurred internally. This is particularly true of long wound tracks such as abdominal wounds where significant yaw and energy-transfer may occur within the abdominal cavity and result in serious injury to viscera, although the projectile may retain little energy in the distal parts of the track and produce a small exit wound or may remain lodged in the tissues.

Wound contamination

The dispersal of wound contaminants by the temporary cavity is underestimated. The contamination is a notable problem in military wounds where there is high available energy and has major implications for the control of wound infection. Fragments and any other projectiles with sharp, irregular surfaces transfer notable quantities of skin and clothing material into wounds. With low velocity projectiles, the clothing tends to be a ragged piece. At increasing impact velocity, clothing is shredded and, if a temporary cavity is formed by the projectile, fibres and large pieces of material may be dispersed radial to the missile track and may result in contamination of tissues and fascial planes where there is no evidence of physical injury.

Most bullets are pointed and transfer little material from the entry site but if a temporary cavity involves the exit wound, substantial quantities of material may be sucked into the wound from the exit hole, creating widespread contamination and potential for infection at multiple sites. Wound debridement and excision therefore have a role additional to the removal of non-viable tissue, namely, the removal of visible contaminants. This may involve the excision of viable but heavily contaminated soft tissue.

Bullet fragmentation

A possible consequence of the changes in presented area as a bullet yaws within soft tissue is break-up or deformation; the pathophysiological sequelae may be devastating. Military bullets comprise lead and steel components clad within a metal jacket. If jacketed bullets do disrupt, it is usually by extruding lead from their base as a result of distortion of the jacket induced by high forces during yaw. This is particularly pronounced at very short range (less than 50 m) when not only is the available energy high, but also bullets are relatively unstable and may strike with a yaw of 3–5°. As a consequence of this small but significant yaw in air, the yaw cycle may be induced immediately upon entering soft tissue resulting in excessively high forces on the jacket with the risk of distortion or break-up.

The tendency to break-up is governed not only by the construction of the bullet, principally the thickness of the jacket and the efficiency of the base in preventing extrusion. Some bullets for police use and for hunting are designed to fragment but the Hague Declaration of 1899 ruled that such bullets should not be used in armed conflicts.

The disruption of a bullet into small pieces produces irregular fragments which result in high retarding forces and the transfer of larger quantities of energy. The resulting large temporary cavity will be associated with multiple, diverging wound tracks. One clinical result is multiple laceration of the tissues surrounding the original wound track, and although one may argue about the role of the temporary cavity in rendering tissues non-viable, there can be no argument about rapidly moving pieces of metal disrupting and lacerating tissue.

Another interaction that may involve disruption is contact with hard, high density bone. Retardation forces are high and energy-transfer is increased. Fragmented bone provides a large number of secondary fragments which may combine with bullet fragmentation to produce widespread soft tissue disruption in the vicinity of the bone. The impact of any high available-energy projectile upon compact bone will invariably result in bullet fragmentation and more serious wounds, not only due to the fracture itself but also due to injury to blood vessels, nerves and other soft tissue.

The effect of tissue density upon the transfer of energy is also significant in the lung. The lung has a specific gravity of 0.2–0.3 and produces modest retardation to high available-energy projectiles. Little energy-transfer occurs, and temporary cavities are small. Lung is a very elastic tissue and can accommodate temporary cavities with minimal parenchymal injury. The consequence is that nearly all wounds to the lung can be classed as low energy-transfer and thus even high velocity rifle bullet wounds to lung alone carry a low mortality rate, the principal threat being haemopneumothorax.

Although the temporary cavities produced in materials such as gelatin are spectacular with long 'wound' tracks, many wound tracks within human bodies, particularly those involving the limbs, are quite short. Short wound tracks involving soft tissue alone may retard stable bullets very little by failing to induce significant yaw within their short length (Figures 2 and 3). A good example is the self-inflicted wound to the foot. At point blank range the bullet from a rifle has relatively high yaw but even so does not change orientation significantly within the 2–3 cm track and results in a low energy-transfer wound.

Aspects of treatment

'Treat the wound not the weapon' is an apt aphorism that emphasizes that there should be few presumptions when faced with a missile entry and exit wound; knowledge of the wound weapon occasionally offers insight into wound pathology but should not be seen as the determinant of wound severity. High velocity rifle bullets may produce low energy-transfer wounds, although with many wound tracks in the human body, interaction with bone or long wound tracks can occur and result in high energy-transfers. Although low velocity hand gun bullets often produce low energy-transfer wounds, their projectiles may be designed to deposit all their available energy with a short wound track at the expense of penetration, resulting in the production of relatively superficial high energy-transfer wounds.

Because of factors unique to either battle or peacetime, it is difficult to formulate a management approach that will meet both civilian and military needs. The Defence Medical Services in the UK have developed protocols for penetrating wound management in war and these have been equally influenced by battlefield experience and research. The approach is based on the recommendations of the Inter-Allied Conference held in 1917. By this stage of the First World War, allied surgeons generally agreed that the approach to be adopted for all ballistic wounds should consist of debridement, wound excision and delayed primary closure at 4–5 days after primary surgery.

Critics of this approach regard it as didactic and insulting as it deprives the surgeon of his or her own valued judgement. This may be true but, for general war, departure from this surgical approach has repeatedly resulted in disaster. The reasons for these disasters are not entirely clear: experienced civilian surgeons seem consistently to underestimate the pathophysiological consequences of ballistic injury, particularly in the military environment. Odling-Smee relates this point in
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chilling detail\textsuperscript{13}. A further factor is the success of minimal surgery and primary closure of ballistic wounds in the ideal clinical setting of a late 20th century general hospital. Such wounds are usually single, caused by hand gun bullets, and result in minimal contamination. This approach cannot be transferred to the battlefield.

We do not believe that current controversies in the role of wound excision need unduly worry surgeons faced with the management of penetrating missile wounds. The need to excise obviously non-viable soft tissue and muscle is generally agreed. Whether excision should extend to include obviously viable but heavily contaminated tissue is more contentious. Nevertheless, experienced surgeons should have little difficulty if they approach these wounds individually and follow accepted general surgical practice. In the military field-surgical setting, the extent of excision may well be influenced by such factors as delay, early postoperative evacuation, poor conditions and relative inexperience initially with the management of military wounds. It is under these conditions that a tendency towards radical excision is often appropriate. The corollary equally holds. In an ideal clinical setting it may be quite appropriate to lean towards less radical excision; here the patient may be kept under careful review by the operating surgeon and further intervention may be undertaken if appropriate. This approach was adopted successfully by Broome and his colleagues after the Hungerford shooting incident\textsuperscript{19}.

In war the surgeon is faced with unique considerations; these may include delays of 12 h or more from time of wounding to first surgery, wounds heavily contaminated with filthy field clothing and skin fragments, multiple wounds caused by fragments, large numbers of casualties, poor working conditions and staff inexperience. The war wound is, therefore, more than just a physical injury to soft tissue. For management to be effective a great deal of tactical information is required by the surgeon, matters that are rarely of concern in the civil setting.

Wound ballistic science has developed to a stage where a clear understanding exists of the mechanisms involved in the wounding process. It would seem reasonable, therefore, to expect universal agreement on management; such is not the case and the reasons are complex. Increasing urban violence has presented civilian surgeons with large numbers of patients with ballistic wounds. Effective treatment regimens have been developed in large, sophisticated urban hospitals. These regimens have been influenced by the availability of multidisciplinary teams, sophisticated investigative techniques including computerized axial and nuclear magnetic resonance scans, new generation broad spectrum antibiotics (which may be administered within minutes of wounding) and ready access to intensive care units.

This ideal set of circumstances has resulted in the successful use of techniques that would be quite inappropriate on the battlefield: minimal or no surgical intervention for some uncomplicated soft tissue wounds, primary closure of wounds and increasing reliance on antibiotics as the mainstay of treatment\textsuperscript{17–19}. It is timely to remind our civilian colleagues that this approach transferred to the battlefield will result in catastrophe for many of the wounded. There are compelling writings of Ogilvie\textsuperscript{14} and Odling-Smee\textsuperscript{13} as evidence for this view and we entertain the hope that sufficient evidence, both historical and scientific, now exists to prevent repetition of the mistakes of the past.

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Paper accepted 4 January 1990

Br. J. Surg., Vol. 77, No. 6, June 1990