

Anti-Personnel Mine Injury; Mechanism and Medical Management

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Introduction

Injury from anti-personnel mines remains a serious threat to military and civilian populations, even after conflict has ceased (Groom 1984; Jeffreys 1996). It was estimated that in 1996, there were approximately 100 million anti-personnel mines laid worldwide and many of these were, and still are, situated in unmarked mine fields. This article discusses the mechanism, medical management and outcome from anti-personnel mine injury and also looks at recent advances in protection concepts.

Mine construction

Anti-personnel mines are small explosive devices of between 5 and 15 cm in diameter that can be laid either by hand in the ground just below the surface or scattered from dispensers. They are activated by either direct contact or a trip wire. They are designed to be easily transportable and laid in large numbers, and inflict debilitating injuries that end the victim's role as a combatant. There are numerous types of anti-personnel mines in existence and they vary in construction, explosive type and size (Figure 1). A typical mine contains about 40g of high explosive but explosive content may range from 20-200g.

The 1997 Convention on the Prohibition of the Use, Stockpiling, Production and Transfer of Anti-personnel Mines and their Destruction (known as the Ottawa Convention) defines an anti-personnel mine thus:

"...a mine designed to be exploded by the presence, proximity or contact of a person and that will incapacitate, injure or kill one or more persons. Mines designed to be detonated by the presence, proximity or contact of a vehicle as opposed to a person, that are equipped with anti-handling devices, are not considered anti-personnel mines as a result of being so equipped."

The anti-personnel mine is designed to maim rather than kill. It is thought that the injuries and traumatic amputations inflicted upon victims by anti-personnel mines, will have a greater psychological effect on fellow soldiers and the morale of a fighting force, than a sudden death. Casualties from anti-personnel mines represent a substantial logistical burden for treatment, casualty evacuation and rehabilitation (Korver 1994; Coupland 1996). It is for these reasons that anti-personnel mines have been extensively deployed in the past, and are still being used by some countries, despite initiatives such as the Ottawa Convention.

Mechanism of action

Although some mines are triggered by trip wire, the majority are activated by the mine being stepped upon by the unwary.

Upon detonation, an effectively instantaneous rise in pressure is produced, known as the shock wave. The shock wave has a sharp leading edge known as the shock front, which travels faster than the speed of sound in air. Associated with the shock front are the products of detonation and heated air. When the shock front is incident on the body, longitudinal stress waves are propagated through it. It is thought that these stress waves are an important factor in mine injury. The forces produced by the products and heated air (known as the dynamic overpressure) will have local effects on the footwear and foot, and may also induce forces leading to more distant injuries.

The anti-personnel mine is designed to release a large amount of explosive energy at a short range, which often leads to either an immediate traumatic amputation, or delayed surgical amputation due to the extent of soft tissue injury (Korver 1996). If injured, the soft tissues of the contralateral limb may be severely damaged, but there is not usually an associated traumatic amputation.

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Fig 1. Typical anti-personnel mines.

In simple terms, the damaging effects of the anti-personnel mines can be categorised as resulting from:

- i. stress waves entering the limb;
- ii. penetrating injuries from fragments, footwear and soil;
- iii. dynamic overpressure loads on tissues;
- iv. shear produced by the flow of products.

Stress wave interaction

Stress waves propagating through a limb travel at about the speed of sound in those tissues. These waves lose energy at the interfaces between tissues of differing acoustic impedance (related to density). This leads to cellular disruption, soft tissue destruction and bony microfractures (Hull 1996). The stress waves are propagated through bone, blood vessels and soft tissue planes and in certain types of injury, stress waves can be detected as far proximally as the upper thigh. It has also been shown that demyelination of nerves can occur up to 30 cm above the most proximal area of grossly identifiable soft tissue injury (Nechaev *et al* 1995). The stress wave will have been propagated from the mine to the tibial plateau within 200 μ s after detonation, and during this time frame, there may be minimal displacement of the limb.

Stress waves may also “concentrate” within structures by reflection. It has been shown that for stress waves entering the tibia laterally (from detonation of a bomb to the side of a victim), the shape and size of the bone result in peak stresses in the upper third - the most common site of amputation in these circumstances. The more localised longitudinal loadings from a mine lead to a higher incidence of distal fractures.

Flow of explosive products

The products are incident on the contact footwear and limb shortly after the shock front and produce substantial distortion and erosion of these structures some 1 to 2 ms post-detonation. The detonation products cause destruction of already traumatised soft tissues, depending on distance from the explosive source. In contrast to the shock front, the detonation products induce high degrees of displacement and the limb is exposed to significant bending stresses and torsion. It is thought that torsion induced by the detonation products, occurring about a stress wave-induced bony fracture, may be the mechanism leading to traumatic amputation (Hull 1992; Hull 1994).

Figure 2 illustrates the distortion produced by the interaction of the products. Figure 2a shows a flash radiograph taken just before the detonation of a mine below the heel. Within the boot is a simple, frangible Lower Limb Model of tibial injury developed by DERA Porton comprising the hind limb of a red deer. The tibia (A), os calcis (B) and mine (C) are marked. Figure 2b shows the response of the model at 1.6 ms (left) and 2.0 ms (right) after detonation. The stress wave will have passed through the model within microseconds and is not visible. However, the gross distortion of the boot and foot is evident. The radiographs show boot components (D); tissues being eroded (E) and boot nails from the sole are visible. The upper part of the boot has not moved significantly. There is a fracture in the tibia (F) and the distal shaft is rotating. These high speed radiographic techniques are currently being used at DERA Porton to unravel the sequence of events in traumatic amputation.

Depending on mine type and injury pattern, the detonation products may also produce soft tissue disruption far proximal to the level of traumatic amputation.

Penetrating missiles

Although most mines do not contain primary fragments that are specifically designed to produce penetrating injuries, environmental debris and to a lesser extent the minimal metallic components of the mine produce penetrating wounds to the contact limb, contralateral limb and perineum. The magnitude and dispersion of this material is dependent upon the soil type, presence of stones and the depth of burial of the mine. Pieces of the footwear may also be driven into tissues.

The products of detonation and associated debris may also induce eye injuries. The incidence of ocular injury in the Afghanistan War, was reported as 4.5% of all anti-personnel mine induced injuries (Dalinchuk 1994). The majority of these injuries were penetrating in nature (64.8%).

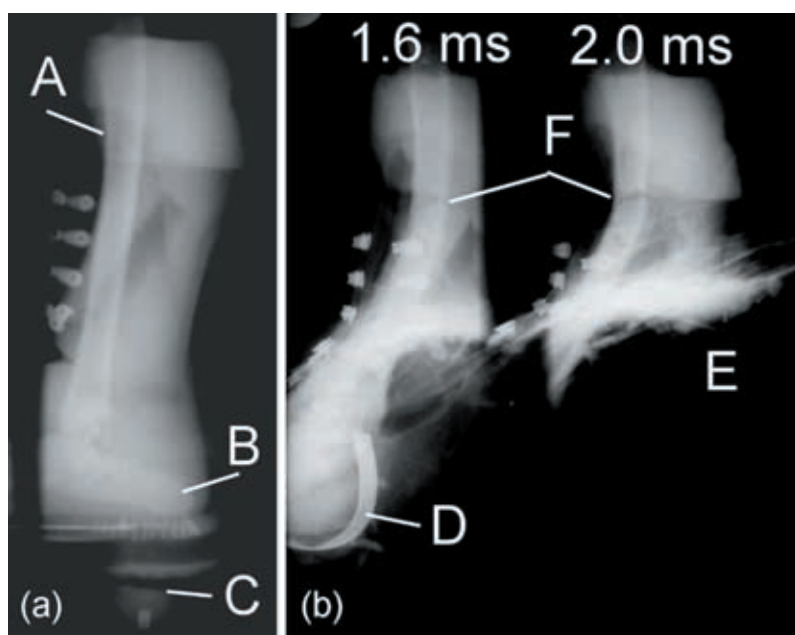


Fig 2. Flash radiographs of the detonation of a mine beneath a model of the human lower limb (red deer bone) - (a) a limb model before detonation; (b) radiographs taken 1.6 milliseconds (left) and 2 milliseconds (right) after detonation.



Fig 3. Traumatic below-knee amputation.

Overall effect

In combination, the components of the mine explosion produce a familiar, devastating, repeatable pattern of injury. There is complete destruction of tissue in close proximity to the explosive source which is often accompanied by a traumatic amputation at a variable anatomical level. Proximal to the level of amputation there is often stripping of soft tissue from the underlying bone and there is separation of fascial planes, often associated with a high degree of contamination, with soil debris, clothing and microorganisms.

Classification of landmine injuries

Before considering the specific treatment of anti-personnel mine injuries, it is necessary to review possible injury patterns, and also post-injury outcome. A retrospective analysis from the International Committee of the Red Cross, of 757 victims of anti-personnel mines, has identified 3 patterns of injuries amongst survivors (Coupland 1991). Pattern 1 injuries occur when a buried mine is stepped upon and produce severe lower limb injuries including traumatic amputations (Figure 3); accompanying perineal and genital injuries are common.

With pattern 2 injuries, the device explodes near to the victim. This may be due to a buried mine activated by another individual, or due to a pull-action mine which is placed above ground level and activated by triggering a trip wire connected to the device. Lower limb injuries occur, but are less severe than in pattern 1, with traumatic amputations less common. Injuries to the head, chest and abdomen are common.

Pattern 3 injuries occur when the device explodes whilst the victim is handling it, and this induces severe facial and upper limb injuries.

In addition, other device specific injuries can occur. For instance after triggering, the M16 anti-personnel mine is designed to be propelled up to 1m into the air before detonating (Adams 1988). This produces a pattern of severe injuries to the face, thorax and upper limbs. The majority of victims of these devices die.

Medical management of Land Mine Injuries

As with all trauma casualties, the basic principles of trauma life support should be followed. The **Airway** must be cleared and secured, with control of the cervical spine. **Breathing** must be confirmed with examination of the chest to determine adequate respiration. **Circulation** must be maintained by stopping external bleeding and administering intravenous fluids.

At all times the prevention of further injury must be considered, both to the casualty and to all personnel within the vicinity. Further explosive devices may be present, which may have been deliberately placed to cause further injury. Danger from damaged buildings and other local hazards must also be considered.

Although only a minority of the victims will have immediately life-threatening injuries, resuscitation should still be based on trauma life support guidelines. Airway compromise is always a potential problem, and must be considered with pattern 3 injuries or in unconscious patients. To control haemorrhage, local compression and pressure dressings will be adequate for most injuries, but the use of tourniquets should also be considered if control of haemorrhage is less than satisfactory. In one review, tourniquets were routinely applied to all patients with traumatic amputations, with satisfactory outcome (Traverso 1981).

All patients will require wound débridement, and many patients will require laparotomy. As a general rule, all penetrating wounds near the abdomen, including the back, chest and buttocks, must be considered as penetrating abdominal wounds with a low threshold for performing a laparotomy. Thoracotomy and craniotomy are not usually necessary, unless as part of the wound débridement, as most victims with severe chest or head injuries die before reaching medical care.

Principles in the Management of Limb Injuries

All patients with severe injuries to the limbs require surgical débridement, and many will require amputation. The principle of débridement is no different from other military surgery, with the aim of excising all non-viable and foreign material. At this stage the definitive care of the limb is of lesser concern; non-viable tissue must not be left in

an attempt to salvage a limb. The explosive force of the mine induces separation of the fascial planes, often far proximal to the site of injury, and these must be explored for contamination and tissue viability. The options for treatment of contaminated tissues are a combination of excision, lavage, dressings, systemic antibiotics and delayed primary closure (Covey 2000).

Following the explosion of the mine, the limb may already be amputated. If not, then amputation must be considered as part of the débridement, taking into account that severe soft tissue loss, bone loss, arterial or neurological injury are all relative indications for early amputation. If more than one problem is present, particularly with limited resources or a significant delay in treatment, the limb should be amputated.

Relative indications to attempt limb salvage include upper limb injuries, bilateral limb injuries, and injuries in children. If the necessary facilities are not available, for example plastic surgery, or the level of experience is low, then the limb should be amputated. A deformed, un-united limb, persistently discharging or with an insensate foot, is far worse than an early, healed below-knee amputation stump.

Most amputations will be carried out below the knee, although of the 484 battlefield casualties in the Vietnam War who subsequently underwent lower limb amputation, 30 individuals (6%), had bilateral above knee amputations (Dougherty 1999). Through-knee amputations should be avoided, particularly in less developed countries, although they may be indicated for potential bilateral above-knee amputees, where mobility will be a serious problem. An initial through-knee amputation may be required in the seriously ill patient, particularly at risk of infection or the effects of a prolonged anaesthetic. In this instance, a guillotine-type amputation can be very quickly performed, and the presence of the articular cartilage on the distal femur acts as a barrier to infection. A definitive above-knee amputation can be performed a few days later when the patient has stabilised. Wherever possible, however, guillotine amputations should be avoided.

If a below-knee amputation is performed, an adequate stump must be preserved (10 cm below the tibial tubercle), particularly in less developed countries with a limited prosthetic service. Soft tissue coverage of the tibial stump should be ensured, and this can be carried out using a medial gastrocnemius flap (Coupland 1989). Gastrocnemius originates from the distal femur, from where the blood supply is derived, and this is often preserved after landmine injury and creates excellent stump coverage.

The wounds should be left open for delayed primary closure after 2-5 days. Often further débridement is necessary prior to definitive

closure, and re-amputation for infection, at a higher level, is common (Chaloner 1996). Dougherty (1999) reports that 12 percent of amputations carried out on military casualties of anti-personnel mines during the Vietnam War were due to secondary infection. When definitively closed, the skin must be sutured without tension, and split skin grafting of an amputation stump should be avoided if possible.

The contralateral limb

The incidence of injuries to the contralateral limb is high, and the necessity for meticulous wound care, débridement and attention to asepsis cannot be overstressed. There is often little that can be done to influence the outcome of the affected limb, but attention to the contralateral limb may prevent amputation.

Primary Closure and Limb Salvage

Some reports of primary closure after injuries caused by anti-personnel mines have indicated a favourable outcome (Atesalp 1999), but for the vast majority of injuries, primary closure is inappropriate. Contamination of the wound with soil debris, clothing and micro-organisms is common, and casualty evacuation and surgical treatment are often delayed due to geographical situation. For these reasons, delayed primary closure remains the treatment of choice for the majority of mine induced wounds.

Limb salvage for anti-personnel mine injuries has been reported (Selmanpakoglu 1998), but this was carried out for localised foot defects (mainly heel with a viable forefoot). Free muscle flaps were required in all patients, with bone grafting and internal fixation. A high complication rate was reported and few patients are suitable for this type of surgery. In developing countries, or in the mass casualty situation, this is an inappropriate form of surgery.

Short term outcome of landmine injuries

In general, the mortality rate after anti-personnel mine injury is low. In one review of 40 patients admitted to hospital in Northern Thailand with mine injuries, no deaths were reported. (Traverso 1981). In another study there were only 6 reported deaths in 757 anti-personnel mine casualties (0.8%) (Coupland 1991). Both of these studies were retrospective reviews of hospital admissions, and therefore fatalities at the scene were not included. However, an article by Chaloner in 1996, which reported only 1 death in 60 patients (1.7%) injured by anti-personnel mines in Angola, was based on figures obtained from accident records, and thus included victims killed at the scene.

Despite the low mortality rate, the morbidity after landmine injury is very high. Of the 40 anti-personnel mine casualties reported by Traverso *et al* (1981), 90% sustained traumatic amputations, most of which were below the knee. Two patients (5%) sustained bilateral traumatic amputations, and all 40 patients required definitive surgical amputations. In another report of 201 patients who had sustained pattern 1 injuries (see above), 186 lower limb and 5 upper limb traumatic amputations were sustained (Coupland 1991). In addition, most of the patients sustained injuries to the contralateral limb, which were usually salvageable, and 13% of the patients sustained genital injuries.

Of the pattern 2 injuries, only 5% of the patients required amputation, but with pattern 3 injuries 80% of the victims sustained traumatic upper limb amputations, and many of the survivors required a definitive surgical amputation for non-salvageable injuries.

In summary most victims who stand on an anti-personnel mine will survive, but may sustain or require amputation of the leg. All patients will require limb surgery, the aim of which is adequate débridement, to reduce the risk of local infection and the provision of a satisfactory below or above-knee stump following delayed primary closure. As stated above, particular attention should be paid to the contralateral limb.

Long term outcome

A 28 year follow up of surviving American Servicemen, who suffered bilateral above knee amputations as a result of ordnance injuries received during the Vietnam War, was carried out using the SF-36 physical functioning score. This scoring system concentrates upon physical functioning, pain, general health, vitality, social functioning and mental health. The report concluded that the patients in the study led a relatively normal life despite the use of orthotics, when

compared to a gender and age matched control group (Dougherty 1999).

Protection approaches

Protection against mine injury is targeted at the individual user; a de-miner will require maximum protection, which may be at the expense of comfort and ease of movement. However, an infantryman in a conflict area with low risk of mine injury, will require a lower degree of protection, but with maximum capability to move and be versatile.

In order to develop effective protection against anti-personnel mines, it is essential that the mechanisms of the injury are known. In particular, the time after detonation that the explosion-induced fracture occurs is very important. The timing of this fracture will indicate the mechanism. Concepts to protect personnel against fracture will be dependent upon the principal failure mechanism - stress waves or bending/ torsion. At DERA Porton Down, the simple Lower Limb Model (LLM) has been developed to replicate the bony pattern of anti-personnel mine-induced tibial fractures (Figure 4). A complicating factor is that steps taken to reduce the erosion of the foot by the products, may actually increase the transfer of energy to the tibia. Plainly, protection concepts need to address the system as a whole and the timing of the various events are critical. In general, there are four approaches to offering protection: stand-off, modulation of the stress wave, diversion, and prevention of erosion.

Stand-off

Blast overpressures decay very rapidly with distance - in simple terms the peak overpressure decays as a function of $R^{1/3}$ where R is the radius from the detonation source. Thus increasing the stand-off can reduce the energy exposure at a given distance from the explosive very effectively, but an increased stand-off may sacrifice functional stability of the protective footwear. Another approach using separation is to offset the detonation from the foot. Med-Eng Systems Inc of Canada have developed a boot that uses this principle - the Spider Boot (Figure 5). It comprises four feet in a



Fig 4. The Lower Limb Model (LLM) used to investigate the failure mechanisms in bone. The bones within the model are from red deer.



Fig 5. One approach to lower limb protection - the Spider Boot.

tetrapod formation. This has the effect of providing a protective stand-off, and because only the feet of the spider boot can initiate detonation, and these are placed away from the axis of the limb, energy transfer is not directly upwards through the heel and tibia.

Modulation of the stress wave

Previous work at DERA Porton Down on thoracic blast has shown that a stress wave may be 'decoupled' (Cooper 1991) by allowing it to cross a physical barrier constructed of two materials of differing acoustic impedances. It is thought that stress waves produced by anti-personnel mines may also be decoupled, allowing them to lose energy into a decoupling protection, in the same way that they do when incident on the body. However, it must be borne in mind that lowering the anatomical level at which energy expenditure takes place by the use of decoupling materials, may not be of overall benefit. In the absence of protection, an injury may be induced at 30 cm from the mine e.g. mid-tibia. In the presence of a decoupling protection, this anatomical level of injury may be lowered, to 10 cm for instance, which may have the effect of inducing a talar fracture instead of a tibial fracture. This change may have implications for fracture management, fracture healing and functional outcome.

Diversion

Some commercial manufacturers have used wedges within the sole of the boot to divert (presumably) the shock wave and products. Intuitively this would appear to be an approach with merit but the efficacy of wedges at diverting the blast forces and reducing the overall coupling of energy to the lower limb needs clarification. Wedges plainly have implications for the depth of the sole and the trade-off of wedge angle and energy attenuation must be known.

Prevention of erosion

Within the defence and industrial communities, the prevention of intrusion by detonation products into the limb is considered to be the most important factor in preventing serious injury from anti-personnel mines. It is thought that this can be achieved by combining a protective boot and gaiter with a protective sole plate that prevents breach of the boot by products of detonation. This plate could also form part of a decoupling mechanism to attenuate the stress wave.

Conclusion

Anti-personnel mines and the injuries they produce will challenge both de-mining personnel and medical staff for the foreseeable future, in spite of the benefits of the Ottawa Convention. Civilians remain the principal victims of anti-personnel mines.

The clinical experience obtained by both governmental and non-governmental medical organizations has allowed the development of well-recognised treatment strategies.

There has been less co-ordination in the commercial sector in the development of protective measures for de-miners. It is a fundamental fact that to counter the very intense forces resulting from the detonation of a mine in contact with the limb, it is essential that the mechanism of the injury is known. Guesswork or intuition will not succeed. Sound engineering principles must be applied to unravel the interaction of the blast with the limb. However, two issues must be borne in mind: (i) steps taken to attenuate some routes of energy transfer may actually exacerbate forces elsewhere in the limb, (ii) the outcome must be focussed at clinical benefit - not protection at all costs. Although total protection may be a worthy target, it is unlikely to be achieved in practice. If some injury is inevitable, it is essential that medical staff focus the efforts of the scientists to ensure the best overall outcome for the patient. It is not simply a matter of engineering.

Acknowledgements

Figure 3 is reproduced with the permission of Lt Col P Parker RAMC.

Figure 5 was provided by Med-Eng Inc, Canada.

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