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Secondary Intramedullary Nailing of the Tibia in an Animal Model of an External Fixator Pin Track Infection

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Thesis for Doctor of Medicine

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ABSTRACT

FACULTY OF MEDICINE HEALTH and BIOMEDICAL SCIENCES

DERA PORTON DOWN

Doctor of Medicine

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by Jonathan Charles Clasper

This thesis discusses the management of military tibial fractures and develops the hypothesis that secondary intramedullary nailing after initial external fixation may be the optimum method of stabilisation for high-energy military fractures. An *in vitro* long bone model was developed to determine the spread of contamination following a ballistic fracture. This demonstrated that the contamination was limited to the fracture site and, therefore, that external fixator pins could be safely inserted through uncontaminated areas.

Using a previously established model of a pin track infection, secondary intramedullary nailing was carried out in an *in vivo* ovine model. This confirmed previous clinical findings of widespread infection. Using this model a treatment group was studied when conventional methods of treating infection were utilised. Despite an increase in survival time, and an improved clinical course, 5 of 6 animals still had bacteriological evidence of infection, and all 6 animals had histological evidence of infection at post-mortem.

Although the technique of secondary intramedullary nailing has potential in the management of military tibial fractures, it cannot be recommended on the basis of this work. This model, however, could be used to study other techniques of infection control, and this is also discussed in this thesis.

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Preface

The lower limb is one of the most common sites of injury from missile wounds (Kirby and Blackburn 1981; Carrey 1996), and it has been estimated that as many as half of these injuries are associated with a fracture (Epps and Adams 1961). The tibia is frequently involved, and the prognosis of open tibial fractures is worse than for open fractures of other bones. This is true for both civilian (Swett 1928; Dellinger, Miller, Wertz *et al.* 1988), and military injuries (Hampton 1946; Jacob, Erpelding and Murphy 1992).

The optimal management of open tibial fractures remains a matter of some debate, especially the method of stabilisation. In the military environment this is a particular problem, as some methods of stabilisation are not possible for logistic reasons. Combined methods, such as early external fixation followed by a later conversion to an intramedullary nail may be very appropriate for the treatment of the military injury, and the role of this particular method of treatment needs to be investigated. In civilian practice the major complication of this technique is implant sepsis, which is directly related to previous pin track infection (Maurer, Merkow and Gustilo 1989). As military surgery is often carried out in less than ideal conditions, with limited resources, and military wounds are more extensive than civilian wounds (Jacob *et al.*1992), this is a major concern.

The aim of this thesis is to study contamination of the wound after a ballistic fracture, and to develop an animal model that allows study of early conversion to an intramedullary nail. The hypotheses are:

- that external fixation followed by early, planned conversion to an intramedullary nail is a safe and effective technique in the management of open tibial fractures caused by a missile injury.

- that the main complication, infection around the nail, can be prevented by treating pin track infection.

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Dedication

This work is dedicated to Gina and the girls, Jemma, Katie, Susie and Melissa

Abbreviations

With the exception of standard SI units, the only abbreviations used in this thesis are:

AO = Arbeitsgemeinschaft für Osteosynthesefragen
EDTA = Ethylenediaminetetra-acetic acid
HA = Hydroxyapatite.
ICRC = International Committee of the Red Cross
IM = Intramedullary
spp. = species

Publications and Presentations Associated with this Work

Publications:

Spread of infection, in an animal model, after secondary intramedullary nailing of an external fixator pin track infection
Clasper J C, Stapley S A, Bowley D M G, Kenward C E, Taylor V and Watkins P E
Journal of Orthopaedic Research, 1999, Vol 19, 155-159

The interaction of projectiles with bone and the management of ballistic fractures
Clasper J C, J of the RAMC, 2001, Vol 147, 52-61

Contamination of ballistic fractures; An *in vitro* model
Clasper J C, Hill P F and Watkins P E, Injury, 2002, Vol 33, 157-160

Presentations:

Widespread sepsis following secondary IM nailing of an external fixator pin track infection
European Society for Surgical Research, Berne, Switzerland, 23 Apr 99
and
Combined Services Orthopaedic Society, 14 May 99

Comminution and contamination after high-energy ballistic fractures of the tibia
Combined Services Orthopaedic Society, 14 May 99

An experimental study of secondary IM nailing in the presence of infection
Orthopaedic Research Society, Orlando, USA, 15 Mar 00

Posters:

Widespread sepsis following intramedullary nailing of an external fixator pin track infection
Clasper J C, Bowley D M G and Watkins P E.
British Orthopaedic Research Society, Liverpool, 15-16 Mar 99, and
European Society for Surgical Research, Berne, 23 Apr 1999

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Spread of infection after secondary intramedullary nailing of a pin track infection
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Clasper J C and Bowley D W G
JBJS, 2000, 82-B, Supp I, 55

1. Historical Review of the Management of Open Fractures

'War is the only proper school for surgeons' Hippocrates

'Throughout the ages, the progress of general surgery has been intimately related to that of military surgery' Trueta

1.1 Introduction

Hippocrates (460-377BC) was the first person to document the treatment of open fractures. He believed in the 'healing power of nature', and the basis for his treatment was antisepsis and the reduction and splintage of fractures. Turpentine and tar were used as dressings and the limb was splinted with wax, starch or clay-impregnated bandages (Gustilo 1982). The Hippocratic methods of decontaminating the wound, and immobilising the fracture site, are still the principles used today in the management of open fractures. Unfortunately these principles have often been forgotten and have to be relearned, usually in time of war.

Although Hippocrates was the first to record the treatment of open fractures, there is evidence that the management of these injuries pre-dates him by thousands of years. The Egyptians used the earliest known splints, approximately 5000 years ago (Elliot Smith 1908). It is likely that stone-age man also splinted fractures, as remains from the period show satisfactory healing in over half of the bones with evidence of previous fractures (Haeger 1988). The surgical treatment of open wounds was first recorded by the Egyptians; the *Edwin Smith papyrus,* dated to 1600BC, showed that they practised wound exploration to determine the depth and extent of a wound (Haeger 1988).

The physicians of the Roman Empire, however, were less concerned with the healing power of nature and attempted to produce, rather than prevent, wound infection. Galen (131-201), perhaps the greatest physician of this time, believed that pus was necessary for proper wound healing (Trueta 1943). Unfortunately this belief persisted for nearly 1400 years, and few advances were made in military surgery.

In mediaeval times a wound infection was still considered necessary, and various concoctions were developed to improve the suppuration. Guy De Chauliac (1300-1367) wrote on the practice of surgery in his *Chirurgia Magna,* and although he belonged to the

school of 'laudable pus', he described exploring wounds and removing foreign objects (Haeger 1988). De Chauliac also described what appears to be the first use of traction as a definitive means of treatment for fractures. Traction had been used previously in the management of fractures, but only as an aid to reduction, before the limb was splinted.

1.2 Early Management of Missile Wounds

In the Middle Ages, the major advance in warfare was the introduction of gunpowder, and the resulting wounds lead to changes in the management of open fractures. The wounds produced by early missiles were thought to contain poisons that had to be neutralised, and cauterisation of the wound became popular to counteract these. Ambroise Paré (1510-90) one of the greatest surgeons of the Renaissance period, was initially a proponent of this method of treatment. At the Battle of Turin, however, his supply of boiling oil ran out and instead he had to use 'a digestive of eggs, oil of roses, and turpentine'. The following day, Paré noted that the soldiers he treated this way were painfree, and had no evidence of sepsis. In contrast, the soldiers treated by boiling oil were feverish, with great pain and swelling of their wounds. Paré realised that there were no poisons as such, but that appropriate wound management was necessary to prevent infection (Guthrie 1958).

Paré is also credited with the first case report of an open tibial fracture. He described in detail his own treatment for an open fracture of the distal tibia (Peltier 1983). Paré was treated by reduction of the fracture without anaesthetic, and a dressing of 'egg white, flour and chimney soot, with fresh melted butter'. A wound infection developed but resolved, and both the wound and fracture healed. The prognosis for open fractures at that time was so poor that he was fortunate not only to avoid amputation, but also to survive the injury.

Desault (1744-95) was the first surgeon to define débridement, as a deep incision into the wound for exploration, and to allow drainage (Colton 1992). Despite the advances in the surgical treatment of these injuries, the morbidity and mortality from an open fracture during war was still high. Larrey (1766-1842), a student of Desault, and surgeon in chief to Napoleon's grand army performed 200 amputations in 24 hours at the Battle of Borodino (Guthrie 1958). The mortality rate from open fractures during the Franco-Prussian War (1870-71) was reported to be 41%, and for open fractures around the knee joint was 77% (Colton 1992). Even in the civilian environment a mortality rate of 64.7% from open fractures of the femur, and 38.3% from open fractures of the tibia was described (Bryant

1861). Bryant also reported a mortality rate of nearly 60% following below-knee amputation.

One of the major advances of the 19th century was the use of topical antiseptics. Lister in 1867 published the results of using carbolic acid packs in open fractures. He believed that wound infections were due to decomposition of tissue caused by floating particles in the air (Lister 1867). Lister advocated dressing the wound with a material capable of sterilising it. The use of antiseptics was universally adopted, although disasters still occurred as the principle of wound débridement was often forgotten. The philosophy at the time was to prevent infection of the wound by the use of antiseptics, while nature was allowed to heal the wound by cicatrisation (Carrel 1910). Fractures were also treated by splints, both for pain relief, and also to maintain a functional position while the fracture healed. Antonius Mathlisen (1805-78) is credited with the first use of the plaster bandage as a splint, and this was developed as a means of treating fractures on the battlefield (Van Assen and Meyerding 1948).

1.3 Advances of the 20th Century

During the First World War, research continued to find the antiseptic of choice. Dakin (1915), a chemist from America, investigated the properties of a number of chemicals and felt the best agent to use was sodium hypochlorite; this had a potent antiseptic action, but was non-irritant to the tissues. Carrel, a surgeon working in a military hospital in France, recommended the use of hypochlorite continuously for 3-5 days infused through rubber tubes that were placed in all areas of the wound (Dakin 1915). This method and its application were described in detail in the British Medical Journal (Anonymous 1915). It became known as the Carrel-Dakin method, and was used for the treatment of missile wounds during the First World War.

A further advance made during the war, was the introduction of the Thomas splint for the stabilisation of femoral and tibial fractures. This, together with improvements in wound care, is reported to have reduced the mortality rate of open femoral fractures from 80% to 20% (Watson 1934).

Considerable changes were made in the surgical management of the wounds. At the start of the war the Listerian philosophy of 'leaving the healing of wounds to nature' was universally accepted, and was endorsed by Watson Cheyne, then the President of The

Royal College of Surgeons of England. The role of surgery for the open wound was merely to 'see that the antiseptic has free access to every part of the wound' (Watson Cheyne 1916). It was not felt that every wound required surgery, especially if the wound track had been laid open by the missile. Some soldiers, wounded during trench warfare, had antiseptic paste applied as the only treatment for penetrating missile wounds (Watson Cheyne 1916).

During the first months of the war there was a high infection rate, and as a result a high mortality rate from open fractures; this was blamed on the surgeons rather than the surgical technique itself (Watson Cheyne 1916). Gradually the importance of adequate débridement was realised once more, although in some cases the surgery was too radical, aiming for an *en-bloc* excision of the wound and normal surrounding tissue (Max Page and Le Mesurier 1917; Scott 1953). By the end of the war, the technique of a careful but thorough débridement, removing foreign material, dead and contaminated tissue, and leaving healthy tissue was recommended (Fraser 1918). Amputation was still used extensively with an estimated 300 000 amputations carried out in Europe during the first 3 years of the war (Livingston 1985).

Careful débridement, splintage, and the Carrel-Dakin method of copiously irrigating the wound were the mainstay of treatment of open fractures between the wars (Foster 1933), and were still recommended in 1940 (Sherman 1940). Sherman also recommended the use of internal fixation with plate and screws for unstable or unsatisfactory reductions; stable reductions were splinted by plaster. Internal fixation was carried out after 10-12 days, through a separate incision. He described 630 open fractures of long bones, with 2 deaths, one from an embolus, and one from 'shock'. There were 5 amputations, only one of which was for infection, and no cases of septicaemia. Unfortunately Sherman did not report the healing rate of either the wounds, or the fractures, but reported that non-union was a frequent complication.

In Europe, Trueta (1897-1977) described a different method of treatment, which he used in the Spanish Civil War. Dissatisfied with the use of antisepsis and frequent wound inspections, he began to treat wounds by débridement, packing with dry sterile gauze, and encasing the limb in plaster (Trueta 1939). Trueta made no attempt to monitor the wound, which was allowed to heal by secondary intention beneath the plaster. He was influenced by Winnet-Orr who had originally described this for the treatment of acute osteomyelitis, but

then later recommended it for the treatment of open fractures (Winnet-Orr 1927). Winnet-Orr noted that open fractures were often treated as a simple wound initially, and the fracture was not managed until after the skin wound had healed. Splintage was often ineffective, and non-union and malunion often resulted. Interestingly, the first description of this 'closed treatment of open fractures' was actually in 1884 by Dennis, who proposed this as an alternative to the method advocated by Lister.

The results achieved by Trueta are impressive. He treated 1073 open fractures by total encasement in plaster, with 6 deaths of which 2 were due to gangrene. He reported that the 2 cases of gangrene were due to a failure of adequate débridement at the initial operation. Of 225 open tibial fractures, Trueta reported 198 (88%) good results, 25 (11%) bad results, and 2 deaths. His bad results included non-union, chronic osteomyelitis, delayed amputation and gross malunion. The incidence of shortening is not discussed (Trueta 1939).

In recent years a number of advances have been made in the management of open fractures. Despite these,adequate wound débridement remains an important principle, and although treatment in plaster is still appropriate under certain circumstances, advances have been made in the stabilisation of fractures. These methods, their complications and other more recent advances, will be discussed after a review of military injuries.

2. The Pathophysiology of Military Injuries

2.1 Introduction

Injuries to the limbs are the most common wounds seen in field hospitals (Jacob *et al.* 1992; Carrey 1996). As with civilian injuries, open tibial fractures in the military environment can be difficult to manage, and have a high complication rate. The aetiology, certain aspects of management and prognosis for military injuries are different from civilian tibial fractures, and these factors will be considered below.

2.2 Pathophysiology of Missile Wounds

2.2.1 Introduction

Missiles can cause injury by either direct or indirect mechanisms. With low-energy injuries such as from knives, the tissue damage is confined to the wound track, and is caused by cutting or crushing. Significant injury will only occur if a vital structure is damaged. However, with higher energy missiles such as bullets, energy may be dissipated to the surrounding tissues, to produce indirect damage outwith the wound track. Thus a vital structure may be damaged without actually being involved in the wound track. This is more likely to occur with high-energy wounds, especially, although not invariably, from high velocity rifle bullets.

The damage caused by a missile is related to the energy it transfers, as it passes through tissues. As a general rule, the greater the energy possessed by the missile, the greater the energy transfer, and therefore the more extensive the injury.

2.2.2 Energy transfer

A number of factors affect the energy transfer from the missile to the tissue:

2.2.2.1 Velocity of the missile

The kinetic energy possessed by a missile is determined by the formula:

$$\text{Kinetic Energy} = \tfrac{1}{2} \times \text{Mass} \times \text{Velocity}^2.$$

It can be seen that changes in velocity have a significant effect on available kinetic energy,

and the greater available energy accounts for the severe tissue damage seen after high velocity missile injuries. However, high velocity bullets do not invariably cause severe wounds, as the missile may pass through tissue without transferring significant energy. This occurs when the resistance of the tissues is low and the wound track is short, such that the bullet is not slowed, and therefore little energy is transferred. For this reason it is incorrect to divide wounds into high or low velocity. In addition, severe injury can occur from low velocity missiles, not only when a vital structure is directly injured, but also when the mass of the missile is large. This is particularly true for close-range shotgun injuries, which can cause severe tissue injury (Shepard 1980).

2.2.2.2 Shape of the missile

The smaller the area of the missile presented to the tissue, the lower the resistance to its passage, and therefore the lower the energy transfer to the tissue. Thus there is likely to be a lower energy transfer from a spherical object, such as a ball bearing, than a flattened irregular piece of shrapnel, despite the same available energy (Liu, Chen, Chen *et al.* 1988).

With a bullet the resistance afforded by the tissue is related to the orientation of the bullet. If the long axis of the bullet is aligned with the direction of travel, less energy is transferred than if the bullet yaws (or tumbles) and presents a greater surface area (Kirby and Blackman 1981). Bullets are inherently unstable in tissues, and the resistance of the tissue may be sufficient to cause a bullet to tumble. This will result in greater energy transfer and thus greater tissue damage. This is one reason why entry wounds are often small, and may be no larger than the diameter of the bullet, whereas exit wounds may be much larger, with torn skin, and a ragged star-like appearance (Janzon, Hull and Ryan 1997).

In addition, any deformation, or breaking up, of a missile will result in greater energy transfer and more extensive wounding. This is the main reason for soft nose, or hollow nose bullets, or dum-dum bullets when the round was deliberately notched to encourage breaking up, to increase the 'stopping power' of a round. Such modifications were made illegal by the Hague Declaration of 1899 (Coupland 1999). Despite the use of 'legal' bullets fragmentation can still occur, particularly if the bullet strikes bone, and this breakup, is accompanied by more severe wounding.

2.2.2.3 Resistance of the tissue

The energy transfer is also affected by the tissue involved in the wound track, and is related to the density and rigidity of the tissue. Muscle is more dense than lung tissue, and greater energy transfer occurs when a missile passes through muscle. More rigid tissue such as bone resists deformation, which also results in greater energy transfer. With high-energy wounds involving bone, this can result in extensive bony injury, with multifragmentary fractures.

2.2.3 Mechanism of injury

There are 3 possible mechanisms by which energy transfer may cause tissue damage.

2.2.3.1 Cutting and crushing

This is due to direct damage by the missile.

2.2.3.2 Overpressure

As the missile passes through the tissue, energy is lost due to the resistance of the tissue. This energy loss results in the development of an overpressure; compressive waves that radiate away from the missile, and can damage tissue. Debate centres on the ability of this wave to produce tissue injuries. Some authors feel that as much as one third of the tissue damage is due to the wave (Janzon and Seeman 1985), although other authors feel their role is insignificant (Ryan, Rich, Burris *et al.* 1997).

2.2.3.3 Cavitation

The formation of a temporary cavity, behind the missile, is the most significant factor in tissue injury from high-energy transfer wounds. As it passes through tissue, energy is transferred to anything in contact with the missile, and as a result of this energy, the tissue is accelerated away from the missile. This results in the formation of a temporary cavity as the inertia of the tissue results in continued displacement even after the missile has passed through the tissue. As well as the obvious injury caused by the compression and shear

forces applied to the tissues, the negative intra-cavity pressure (with respect to atmospheric pressure), can result in increased contamination of the wound track, by drawing material into the wound.

Extensive tissue damage can be caused by these effects, and in addition clothing, dirt and other debris may be drawn into the cavity by the subatmospheric pressure, producing a heavily contaminated wound.

2.3 The Extent of Bony Injury

Bone is a more rigid tissue than skin and muscle, and resists deformation. This rigidity produces a greater resistance and results in greater energy transfer, and commonly fracture of the bone as a sequel to ballistic injury. In addition to the soft tissue injury, instability of the limb may occur, requiring stabilisation of the fracture site.

Rose *et al.* in a retrospective review, analysed the extent of bony injury following gunshot injury, and divided the fractures into complete or incomplete, depending on whether some continuity of the bone was maintained (Rose, Fujisaki and Moore 1988). The authors further divided complete fractures into simple, when only 2 main fragments were present, and comminuted, when multiple fragments were present. Incomplete fractures were subdivided into drill hole type when a channel was created through the bone, and a divot or chip type, when part of the cortex was removed, but no channel existed (Rose *et al.* 1988).

Rose *et al.* reported that for high-energy weapons such as military or hunting rifles, all fractures were complete, and comminuted (multifragmentary). For low-energy weapons, such as handguns, 60% of the fractures were incomplete, and only 22% were multifragmentary (Rose *et al.* 1988).

Further confirmation that high-energy injuries were associated with greater bony damage came from an *in vitro* study from Ragsdale and Josselson (1988). They reported that increasing pre-impact velocity was associated with an increased cavitation effect and increased fragmentation. For a handgun with a pre-impact velocity of approximately 200 ms^{-1}, there were 2 fragments. However, for a military rifle with a pre-impact velocity of nearly 1000 ms^{-1}, there were 33 fragments (Ragsdale and Josselson 1988).

Experimental work using metaphyseal bone has reported that 3 distinct fracture zones were present with high-energy transfer wounds involving bone (Robbens and Küsswetter 1982). The primary zone consisted of the wound track, where a bone defect was present. The secondary zone extended approximately 3 cm from the track with multiple fragments, which retained their soft tissue attachments. A tertiary zone with minimally displaced fracture lines extended up to 9 cm from the wound track. The extent of bony involvement, in relation to the total length of the bone, can also be significant.

All these fractures were due to direct injury from the missile, but a fracture may also result despite the missile not actually striking the bone. These indirect fractures are thought to be due to the cavitation effect, with the acceleration of bone away from the track of the missile. This type of fracture is usually only seen with high-energy transfer wounds, and the fracture is usually simple rather than the multifragmentary pattern seen when the missile hits the bone (Liu *et al.* 1988).

Although the extent of bony injury has been graded, *in vitro*, little attempt has been made to classify fractures in order to develop treatment protocols. The management of fractures involving the adjacent joint differs greatly from a midshaft fracture of a long bone, both in the initial stabilisation, and also the definitive management.

2.4 Management of Casualties with Missile Wounds of the Limbs

2.4.1 General management

The management of open fractures resulting from wartime injuries should be exactly the same as that during peacetime. Life-saving measures take priority; maintaining an airway, and ensuring adequate ventilation and circulation. Unless there is life-threatening haemorrhage from an open wound, the fracture should not be dealt with until the secondary survey.

In general, however, during military conflict few survivors with significant limb injuries, who reach medical facilities, require aggressive resuscitation. It has been estimated that approximately 20% of personnel wounded during battle will die. Of the casualties killed during the Vietnam War, 90% died on the battlefield, before any medical attention was given. The majority of these died within 5 minutes of wounding (Bellamy, Champion, Mahoney *et al.* 1999).

The most common causes of death were:

- major haemorrhage (46%) - 80% of these were from major vessels in the chest or abdomen.
- brain injury (21%).
- respiratory injury (4.5%).
- combination of above (9%).
- mutilating blast injury (10%).

Ten per cent of deaths, in battle, were in casualties who survived to reach medical care, and again, the most common causes of death included brain injury and major haemorrhage (Bellamy *et al.* 1999).

The aim of the initial resuscitation, therefore, is to identify the small percentage of the patients with limb injuries who have life-threatening problems; these patients are often obvious, as they arrive in a moribund condition, with multiple injuries, to the trunk and head. The correct management for these limb injuries is an appropriate dressing and splintage of the fracture until the patient has been stabilised.

2.4.2 Management of the limb injury

For the majority of patients, with essentially isolated limb injuries, the priorities for the management of war wounds are also the same as in peacetime injuries. All these patients, with open contaminated open fractures require surgical treatment when facilities are available.

The wound should be explored and débrided. At débridement, non-viable skin needs to be excised and often, generous excision of muscle may be required. The principle of débridement is to remove all non-viable tissue, with the aim of leaving only pink, healthy-looking, contractile muscle. Fasciotomy, longitudinally dividing the deep fascia around a muscle group is commonly required, particularly with high-energy transfer wounds. Difficulties can often occur in the débridement of bone, particularly the fate of the many small fragments. Bone fragments without any soft tissue attachments are avascular and should be removed. Often, however, periosteal and other soft tissue attachments are

present and the viability of the fragment can be difficult to determine. Experience is probably the most important factor in deciding the viability of a bone fragment or muscle, although invasive and non-invasive methods of assessing blood flow, including the use of Doppler have been investigated (Hobbs and Watkins 2001).

In addition the wound should be thoroughly washed out, although inadequate quantities of lavage fluid may compromise wound management.

Delayed primary closure of military wounds is the rule, although certain injuries, such as wounds to the face can be closed primarily. High-energy transfer wounds, with comminution of the bone should never be closed primarily, and will often require plastic surgical techniques several days after the initial débridement.

2.4.3 Non-operative management of ballistic fractures

Whilst it is true that in certain circumstances low-energy missile wounds involving bone can be treated non-operatively, much of the data derives from American trauma centres (Knapp, Patzakis, Lee *et al.* 1996). There are significant differences between civilian wounds, and those seen during military conflicts; in particular the infection rate with military wounds is likely to be higher than with civilian wounds. This is particularly true for tibial fractures, which are associated with a higher infection rate than most other long bones (Seidenstein, Newman and Tanski 1968).

2.5 Comparison of Civilian and Military Open Tibial Fractures

2.5.1 The infection rate after open civilian and military fractures

The extent of the associated soft tissue injury is one of the major determinants of the infection risk after a civilian open fracture. Gustilo and Anderson (1976) have reported a grading of wounds, which remains a universally accepted classification of the wound associated with an open fracture.

Type I – An open fracture with a wound less than one centimetre long and clean.

Type II – An open fracture with a laceration more than one centimetre long

without extensive soft tissue damage, flaps, or avulsions.

Type III – Either an open segmental fracture, an open fracture with extensive soft tissue damage, or a traumatic amputation.

For Gustilo type I fractures an infection rate of 1% or less can be expected, and for type II fractures a rate of approximately 3% has been reported (Templeman, Gulli, Tsukayama *et al.* 1998). A modification to this grading was made by Gustilo *et al.* in 1984, when the type III fractures were subdivided:

Type IIIA - Adequate soft tissue cover of the bone despite extensive laceration.

Type IIIB - Extensive soft tissue loss, with periosteal stripping, and exposed bone. Usually associated with massive contamination.

Type IIIC – Open fracture with vascular injury that needs repair.

For type IIIA fractures an infection rate of 17% has been reported, and for type IIIB 26% (Templeman *et al.* 1998). Type IIIC fractures have a variable infection rate, depending on the soft tissue injury and delays in revascularisation.

Despite bacterial contamination of the fracture site at the time of injury, most subsequent wound infections are due to hospital-acquired pathogens (Roth, Fry and Polk 1986). *Staphylococcus aureus* and aerobic gram-negative bacilli are the most common pathogens (Templeman *et al.* 1998).

A number of authors have reported the infection rate after military fractures. Simchen and Sacks (1975) reported a wound infection rate of 18% for open fractures sustained during the 1973 Israeli war. Gram-negative bacteria caused most of the infections (66%); with pseudomonas as the most common infecting organism. As with civilian injuries, the infection rate after military fractures is also related to the location of the wound; in 1 report 27% of lower extremity wounds became infected, compared to only 9.5% of upper extremity wounds (Seidenstein *et al.* 1968).

It would appear, therefore, that the infection rate after military open fractures is at least as high as the most severe civilian open tibial fractures. There are a number of possible reasons.

2.5.2 Mechanism of injury

Both military and civilian open tibial fractures are commonly due to high-energy mechanisms, but the cause of the injuries does differ. Military injuries are usually due to penetrating trauma, whereas civilian injuries are usually caused by blunt trauma.

The majority of civilian injuries are due to road traffic accidents, from car or motorcycle crashes or in pedestrians struck by vehicles. These cause approximately 60 – 80% of open tibial fractures. Falls and work-related accidents account for 10 – 20% of civilian injuries, but the incidence is variable. Robinson *et al.* reported the microbiological flora contaminating open fractures, and work-related accidents were responsible for 52% of all injuries; traffic accidents accounted for only 28% of these fractures (Robinson, On, Hadas *et al.* 1989).

The aetiology of an open tibial fracture must be considered not only when treating these injuries, but also when reviewing the literature. In the series reported by Robinson *et al.* (1989), the majority of the injuries were Gustilo type II fractures that are associated with a much lower infection rate than the type III open fractures commonly seen after traffic accidents (Templeman *et al.* 1998). Some causes of open fractures, such as farm accidents, are associated with a very high infection rate (Templeman *et al.* 1998). As will be discussed, most military fractures can be compared to farm accidents, rather than industrial or traffic accidents.

Most civilian reports of open fractures are from the United States, and as a result gunshot wounds are also a frequent cause. Roth *et al.* (1986) reported firearms as the cause of 15% of open fractures in their series. These injuries however cannot be compared to the military gunshot wounds that are caused by high-energy weapons. Most of the civilian gunshot wounds from the United States are due to low-energy handguns, and these fractures have been reported to have a very low infection rate (Roth *et al.* 1986).

Bullets or other penetrating missiles cause the majority of military injuries. The relative proportion varies with the military situation; in a report of the conflict in Northern Ireland,

90% of the injuries were due to bullets (Barros D'Sa 1982). This is in contrast to the Gulf War, where Spalding *et al.* reported that 80% of the wounds seen at a British Field Hospital were due to fragments (Spalding, Stewart, Tulloch *et al.*1991). Military wounds are often caused by explosions, from mines or booby traps, and these are associated with the most severe injuries (Tong 1972). Half of the combined tibia and fibula fractures in one series of military injuries were due to explosions (Dempsey 1975), and a much higher infection rate could be expected from these grossly contaminated tibial fractures.

2.5.3 Time delay until treatment is initiated

A wound can be considered as contaminated for up to 6 – 8 hours after an open injury, as although bacteria will be dividing, local or systemic spread will not have occurred (Altemeier 1944). If adequate wound care has not been started by this time, and certainly by 12 hours, the wound can be considered infected. By this time the bacteria have become established, they will have spread to the lymphatics, and systemic signs and symptoms can occur. As a result of the bacterial spread, thorough local débridement will no longer be possible (Altemeier 1944).

Few authors report the time delay between injury and the start of treatment for civilian open fractures, but it is likely to be a few hours at most. The time delay is commonly reported for vascular injuries that require repair; Armstrong *et al.* reported a delay of 1-6 hours with a mean of 2.7 hours for popliteal vascular injuries admitted to a hospital in New Orleans (Armstrong, Sfeir, Rice *et al.* 1988). A delay of 60 minutes before arrival at hospital was reported for gunshot injuries to the groin in South Africa (Degiannis, Levy, Hatzitheofilou *et al.* 1996). In Northern Ireland, an even shorter delay has been reported, with over 50% of patients reaching hospital by 15 minutes after injury, and over 95% by 30 minutes (Barros D'Sa 1982).

This contrasts markedly with the delays reported during wartime. A mean delay of 9.8 hours (range 2 – 30 hours) was reported for vascular injuries from Croatia (Radonić, Barić, Petričević *et al.* 1994). In the Gulf War the mean delay at a British surgical Hospital was reported to be 10.2 hours for British soldiers, and 24.7 hours for prisoners of war (Spalding *et al.* 1991). A delay of several days before effective treatment is started, has been reported by surgeons working for the International Committee of the Red Cross (Gosselin, Yukka Siegberg, Coupland *et al.* 1993).

2.5.4 Associated injuries

Both military and civilian open fractures are associated with other injuries, and these can affect the risk of infection. Dempsey (1975) described a series of combat injuries to the lower extremity from the Vietnam War, and reported that 23% were associated with injuries to other body parts. Simchen and Sacks (1975) reported a 22% incidence of other injuries associated with open fractures, from the 1973 war in Israel. More severe injuries are associated with an increased rate of additional injuries; Tong (1972) reported that 33% of patients with severe extremity injuries from explosions required a laparotomy. Civilian open fractures are also associated with additional injuries, Behrens *et al.* reported that 36% of patients with severe open fractures had head, thorax or abdominal injuries (Behrens, Comfort, Searls *et al.* 1983).

Although both civilian and military patients commonly have additional injuries, the mechanism of these injuries is different. Military injuries are due to penetrating trauma, and abdominal injuries will be associated with bowel perforations. As a result there may be an increased risk of contamination of open fractures in military patients, when compared to civilian patients who have sustained blunt injuries. Blunt trauma is more likely to be associated with intra-abdominal haemorrhage. Gram-negative enteric bacteria are responsible for many wound infections after open fractures in both military and civilian patients (Simchen and Sachs 1975; Robinson *et al.* 1989), and associated bowel perforation is likely to increase the risk of subsequent wound infection.

In the military patient, open fractures, or any other injuries may not be treated ideally due to limited local resources. In a review of the medical statistics of battlefield casualties, Trouwborst *et al.* reported a hospital mortality of 6.4% from the Thai/Kampuchea border (Trouwborst, Weber and Dufour 1987). The authors felt this was high for a number of reasons, one of which was the shortage of blood. Casualties were not given blood during the initial resuscitation; this was only given after the haematocrit dropped below 0.20. Inadequate resuscitation may increase the risk of wound infection after open fractures, especially if it results in a reduced perfusion to the limb.

Civilian reports have recommended that open fractures are washed out with copious amounts of fluid to reduce the contamination, and 9 litres are commonly used (Sanders,

Jersinovich, Anglen *et al.* 1994). It is unlikely that this quantity of fluid would be available for every open fracture sustained in the military environment.

2.5.5 Bacterial contamination of military and civilian open fractures

Although most open fractures are contaminated at the time of injury, it is likely that military wounds are more heavily contaminated with bacteria than civilian wounds. Robinson *et al.* (1989) described the bacterial flora of 89 civilian fractures. Most were reported to be Gustilo type II open fractures and samples were obtained within 3 hours of injury. Of these 89 fractures, 74 (83%) were found to be contaminated. Gram-positive cocci were the most common bacteria isolated, but 34% of the positive isolates were gram-negative bacilli. Only one species of aerobic bacteria was isolated from most of the wounds, and no anaerobic bacteria were isolated. Robinson *et al.* also reported the results of wound cultures taken 24 hours later. Of the 89 wounds, 53 (60%) were sterile and the majority of the remainder isolated non-pathogenic bacteria. Only 4 of the samples taken at 24 hours isolated the same species of bacteria that had been isolated at the time of débridement, and all of these wounds became infected.

In their classic paper on the prevention of infection in open long bone fractures, Gustilo and Anderson (1976) reported that 70% of 158 open fractures were contaminated at the time of initial débridement. There were 143 bacterial isolates, and again only one species of bacteria was isolated from most wounds. Eighty-six of the bacterial isolates were gram-positive and 57 were gram-negative. Only 32 of the 158 (20%) wounds had a mixed growth of bacteria.

Contamination of nearly 100% of military wounds has been demonstrated by a number of authors. In the Korean War, Lindberg *et al.* reported that all medium and large wounds (wound > 1cm) were contaminated with clostridia, with a mean of 2 different strains per wound (Lindberg, Wetzler, Marshall *et al.* 1955). The authors report a seasonal variation in the aerobic bacteria contaminating the wounds. In summer 89% of wounds were contaminated, with faecal organisms the predominant bacteria. There was a mean of 1.7 species of aerobic bacteria isolated from the wounds, and all wounds were operated on within 5 hours of wounding. Most of the patients had already been given penicillin. In winter, 81% of the wounds were contaminated by aerobic bacteria, most commonly staphylococci and streptococci. There was a longer delay before surgery, with 8-9 hours between

wounding and débridement, and there was a mean of 2.8 species of aerobic bacteria isolated from each wound.

In a further report from Korea, Strawitz *et al.* reported the results of serial biopsies from 11 penetrating wounds (Strawitz, Lindberg, Howard *et al.* 1955). The authors noted that the extent of the wounds was usually worse than the skin wound suggested. They isolated clostridia from 9 of the 11 wounds at débridement, as well as isolating gram-positive cocci from all wounds, and gram-negative bacilli from 9 of 11 wounds (mean 5.5 species of bacteria isolated per open wound). Unlike the civilian wounds reported by Robinson *et al.* (1989), the wounds reported by Strawitz *et al.* remained contaminated after débridement. Wound biopsies 5-6 days after injury isolated 11 species of gram-negative bacteria and 10 of gram-positive cocci (mean 1.9 species of aerobic bacteria isolated per open wound).

These reports confirm that military wounds are more heavily contaminated than civilian wounds, with 3 – 4 different species of bacteria isolated from most military wounds, and up to 6 different species in some reports (Levaditi, Gérard-Moissonnier, Bréchot *et al.* 1939). This compares to only 1 species from most civilian wounds (Gustilo and Anderson 1976; Lawrence, Hoeprich, Huston *et al.* 1978; Robinson *et al.* 1989). The species of aerobic bacteria appear to be very similar, however anaerobic bacteria contaminate most military wounds but are rarely isolated from acute civilian wounds.

It has been reported that the level of initial contamination of a wound is related to the risk of subsequent wound infection (Robinson *et al.* 1989), and based on this, military wounds will have an increased risk of infection. In addition it has also been reported that the risk of wound infection is related to the level of contamination after débridement (Merrit 1988), and again it can be seen that military wounds are more likely to become infected. They remain colonized by pathogenic bacteria after débridement, and cultures taken several days after débridement isolate the same species of bacteria (Strawitz *et al.* 1955). This may be due to several factors including delay in treatment, heavier initial contamination, or possibly inadequate initial surgery.

Severe military wounds are associated with a greater degree of contamination, and also with an increased morbidity and mortality. Tong (1972) reported the results from 30 American soldiers wounded in Vietnam as a result of explosions. Most of the soldiers were evacuated to hospital within 2 hours. They sustained a total of 63 extremity wounds, and 18

amputations were required. At débridement there was a mean of 3.0 species of bacteria isolated from the wounds, and at 3 days after injury there was a mean of 2.0 species isolated. Twelve of the patients developed positive blood cultures, and in 8 of these patients the same organism was isolated from the wound and blood cultures. Three of the patients died with gram-negative septicaemia.

Gram-negative bacteria cause many wound infections, and often these are not present in the wound at the time of initial débridement. Most wound infections that develop after civilian open fracture are due to hospital-acquired infections (Roth *et al.* 1986). Gram-negative bacteria have been reported to be the most common cause of a wound infection in the military environment (Lindberg *et al.* 1955; Simchen and Sacks 1975; Seidenstein *et al.* 1968), but in most reports the bacteria were isolated from the wound at the time of initial débridement.

It has been reported that for open fractures, 'except in special cases of significant environmental exposure, the bacteria that initially are found in the wound are not the bacteria that cause the infection' (Templeman *et al.* 1998). In the civilian environment this would include injury in water exposure and farm accidents (Templeman *et al.* 1998). It can be seen, therefore, that military wounds can be considered as examples of significant environmental exposure, and should not be compared to civilian road traffic accidents. This must be considered when deciding the method of stabilisation for military open tibial fractures. As with peacetime injuries, the method of stabilisation of the fracture has been a subject of some debate. This will be considered in detail in the next chapter, together with a review of other advances in the management of open fractures.

3. Recent Developments in the Management of Open Tibial Fractures

3.1 Introduction

Many of the recent advances in the management of open fractures have also resulted from war. Advances have been made in 3 main areas:

- the use of antibiotics.
- the management of the wound after adequate débridement.
- the method of stabilisation of the fracture.

3.2 Antibiotics

Antibiotics were discovered by Alexander Fleming in 1929. While working with staphylococci, he noted that some colonies were destroyed by a contaminating mould. Fleming identified the mould as *Penicillium rubrum*, and described a yellow filtrate that seeped into the culture medium that he named penicillin (Fleming 1929). Unfortunately little further research was carried out until 1940 (Chain, Jennings, Florrey *et al.* 1940), and penicillin was not available commercially until 1942.

The first antibiotics that were widely available were the sulphonamides. These were the metabolites of the laboratory dye prontosil. Prontosil had little effect *in vitro* (Colebrook, Buttle and O'Meara 1936), but *in vivo* had a marked antibacterial effect due to its metabolism to a sulphonamide. One of the first reports of the local use of sulphonamides in open fractures was by Jensen *et al.* who used this both experimentally in guinea pigs, and clinically in 39 patients with open fractures (Jensen, Johnsrud and Nelson 1939). Only 2 of these fractures (5.1%) became infected compared with an infection rate of 27% in 94 open fractures treated without sulphonamides. All open wounds were treated by primary closure. The wounds were tightly sutured, as Jensen believed that tight closure was important to prevent the sulphonamides leaking out of the wound.

Campbell and Smith (1941) described the use of sulphonamides orally together with 5-20 grams in the wound. The use of the antibiotic reduced the infection rate in fresh open wounds from 33.3% to 18.1%. They also undertook primary closure of the wound, and noted that sulphonamides were probably not necessary in 'mild' open wounds as only 1 (2%) became infected in the non-treatment group. In addition to primary closure and

antibiotics, internal fixation was used in selected cases. The infection rate in moderate and severe wounds treated with sulphonamides was 35 % if internal fixation was used, and 21.2% if it was not used.

The use of antibiotics did not meet with universal approval especially when used as prophylaxis. At the time of the Korean War it was felt that the use of antibiotics in open fractures of the leg did not prevent infection, but may have masked or attenuated the infection (Altemeier, Culbertson, Sherman *et al.* 1955).

It was not until 1974 that a controlled trial on the use of antibiotics for open fractures was reported (Patzakis, Harvey and Ivler 1974). In a prospective study, Patzakis *et al.* allocated 310 patients with open fractures to 1 of 3 groups; to receive penicillin and streptomycin, a cephalosporin, or no antibiotic. In the group receiving no antibiotics, 13.9 % developed infections, in the group receiving penicillin and streptomycin 9.7%, and in the group receiving the cephalosporin the infection rate was 2.3%. All wounds were treated by débridement and primary closure, internal fixation was used in a minority of cases, with approximately the same number of cases in each group. No mention is made of the grading of the open fractures, which has an important bearing on the risk of subsequent infection (Gustilo and Anderson 1976). Of the organisms isolated from pre or postoperative wound swabs in the patients receiving penicillin and streptomycin, 62% were resistant to these antibiotics.

Patzakis *et al.* published a follow up report in which they specifically addressed the infection rate after an open tibial fracture (Patzakis, Wilkins and Moore 1983). The infection rate had been reduced from 14% to 4.5%, but by this time an aminoglycoside had been added to the antibiotic regimen. Unfortunately the reduction in the infection rate may not be attributed just to the change in antibiotics, as severe wounds were no longer closed primarily, and external fixators were used in selected patients.

All of the early reports showed a benefit from the use of antibiotics, but in these reports the wounds were closed primarily. It has been shown that delayed primary closure is associated with a lower infection rate than primary closure (Fraser 1918; Daland 1934), and it is likely that appropriate wound management is more important than the use of antibiotics (Ger 1970). This is particularly true with the military wound that may be highly contaminated, and there may be a considerable time delay before appropriate management can be

started. In a report on the American invasion of Panama, there was a wound infection rate of 22% in patients operated on in Panama (Jacob *et al.* 1992). This compared with an infection rate of 66% when wound débridement was delayed until the patient was evacuated to the United States. The higher infection rate was despite the use of early broad-spectrum antibiotics, and delayed primary closure of the wounds. Jacob *et al.* also noted that open tibial fractures had a higher infection rate than other open fractures of long bones. This finding had been reported previously in both the civilian (Dellinger *et al.* 1988), and the military environment (Hampton 1946). The higher infection rate was felt to be related to the relative vascularity of the lower leg, and the fact that the wounds were all contaminated (Ger 1970).

3.3 Management of the Wound

3.3.1 Introduction

The Carrel-Dakin method of continuous irrigation, and allowing wounds to heal by secondary intention with contraction of the wound edges, was widely practised at the end of the First World War. Sherman was still recommending this method of treatment in 1940. There were concerns however, that frequent dressing changes may introduce infection (Swett 1928), and this lead to the Winnet-Orr method of 'rest and drainage'. The wound was dressed, and then left to granulate. The limb was stabilised by total encasement in plaster, and the original dressing was not disturbed unless the patient developed septicaemia. In addition, some surgeons were prepared to close the wound primarily.

3.3.2 Primary closure

Larrey, one of the earliest surgeons to describe and practice early wound débridement, also recommended early closure of the wound (Ritter 1937), and this was widely practised in the 19th Century. Usually the wound would be closed at the time of initial surgery, but some surgeons would insert sutures at the initial débridement, leaving them untied. The sutures would then be tied after 48-72 hours if there was no evidence of infection (Ritter 1937).

Early wound closure in open fractures was thought to reduce the infection rate, and improve healing of the fracture (Cannaday 1929). With the introduction of antiseptics, closure of the wound to exclude air was thought to be less important (Lister 1867), and therefore primary closure at the time of initial surgery was less widely practised. A distinction was made

between wounds caused by the bone fragments, and those caused by an external cause (Estes 1929). Many surgeons recommended the primary closure of small puncture wounds made by the bone fragments; they reserved the Carrel-Dakin method for the larger, more contaminated wound. The Carrel-Dakin method was also used if the wound became infected after primary closure (Swett 1928).

A review of different methods of wound management was reported by Daland in 1934; he described the outcome of 169 open fractures, 60 of which involved the tibia. Daland reported an infection rate of 33% for open tibial fractures when the wound was débrided and closed, and 18% when the wounds were débrided and left open. This was an unexpected finding, the wounds left open were the most contaminated, the ones débrided and closed were thought unlikely to become infected. Although this was not a controlled trial the results do suggest that open fracture wounds should not be closed primarily. This was also the conclusion of Epps and Adams (1961), who reviewed 85 open fractures, 49 of which involved the tibia. They reported an infection rate of 8.3% after delayed closure, and an infection rate of 34.1% after primary closure.

In his paper, Daland also reported that wounds treated by the Carrel-Dakin method had a higher infection rate than wounds treated by other methods, with 31% of wounds treated by the Carrel-Dakin method becoming infected compared to 22% of the wounds treated by all the other methods. This may be due to the extent of the wound; as noted previously, some surgeons reserved the Carrel-Dakin method for the more contaminated wounds. However Daland's paper is often quoted as evidence against the Carrel-Dakin method.

3.3.3 Delayed primary closure

Delayed primary closure was originally a military practice developed due to of the risk of wound complications during casualty evacuation. Wounds were débrided at a forward surgical centre, and then delayed primary closure was carried out at a base hospital when the casualty could be observed more closely. Delayed suture of wounds at an interval of 2-4 days was recommended for the treatment of gun shot wounds during the First World War (Fraser 1918). Fraser defined delayed primary closure as closure of the wound before 'granulations' had formed; suture after this granulation tissue had formed was defined as secondary suture. One of the advantages of the technique was the ability to determine the microbiology of the wound prior to suturing. Fraser stressed the high complication rate of

suturing wounds that were contaminated by haemolytic Streptococci; but he was prepared to close wounds contaminated by other organisms. At the end of the war this technique seems to have been neglected.

In the Second World War, the technique of delayed primary closure of wounds from missile injuries was again described (Cleveland and Grove 1945). The wounds were associated with fractures of the long bones, skull, and pelvis in servicemen. Cleveland and Grove emphasised the role of careful débridement, lightly packing the wound with a vaseline gauze dressing, and then encasing the limb in plaster. They described delayed primary closure by direct suture or skin grafting at an average of 14 days following wounding. In 2393 patients they described complete success in 66.5%, and partial failure, with a small sinus or stitch abscess or partial loss of skin graft, in 26.8%. Overall 93.3% of wounds had healed by the time the patient was discharged; complete failure with dehiscence or osteomyelitis occurred in only 6.7%. Unfortunately Cleveland did not give the healing rates for specific fractures. The interval of 14 days was not planned, but was a result of the evacuation time to a base hospital.

Casualty evacuation was also the reason for the 3-week delay that occurred between primary and secondary surgery in 84 open tibial fractures treated by Witschi and Omer (1970) during the Vietnam War. They also reported good results with this technique, together with early weight-bearing in a cast. Early weight-bearing was used extensively by the military for both open and closed fractures of the tibia, and one report describes a 100% healing rate for the fractures (Brown and Urban 1969).

3.3.4 Plastic surgical techniques

Basic plastic surgical procedures have been used for many years in the treatment of open fractures. They were initially used as a method to allow primary closure of the main wound; relaxing incisions were often made parallel to the wound to allow closure of the soft tissues over the fracture (Cannaday 1929). If the wound could not be closed it was allowed to granulate, and split skin or pinch grafts applied (Ritter 1937). Cross leg skin flaps were also used (Foster 1933).

Stark described the use of a more advanced technique of a pedicle muscle flap in 1946. This was described in wounded servicemen, and was used as a treatment for osteomyelitis

rather than in the acute management of soft tissue loss. Ger raised the possibility that a muscle flap may actually improve the healing of tibial fractures in 1968 when he discussed the management of pre-tibial skin loss. He primarily used the soleus muscle, and covered this with a split skin graft. Local muscle flaps began to be widely used, especially in the acute management of skin loss (Weiland, Moore and Hotchkiss 1983), and modifications were made to the original technique described by Ger.

The benefit of local muscle in fracture healing was confirmed experimentally by Holden (1972). He reported a delay in healing in rabbits when the surrounding muscles were rendered ischaemic. Further experimental evidence was provided by Richards and Schemitsch (1989) who demonstrated an increased blood flow in a devascularised segment of canine tibia covered by a muscle flap, compared with cover by skin alone.

One of the problems with a local muscle flap was the possibility that the muscle itself had been damaged if it was within the zone of initial injury. This concern was removed when the first free flaps were described (Daniel and Taylor 1973), with the technique of distant tissue transfer using microvascular anastomosis. The main techniques used today in the management of the severe open tibia fracture remain the free flap, and the local muscle flap (Weiland *et al.*1983).

3.3.5 Timing of soft tissue procedures

The optimal time for wound closure by tissue transfer has recently been debated as reports have shown an improved outcome in severe open tibial fractures treated by the early use of muscle flaps. Cierny *et al.* compared the outcome in severe open tibial fractures treated within 7 days, with those treated between 8-30 days after injury (Cierny, Byrd and Jones 1983). Of the fractures treated by early soft tissue cover, 'wound healing disturbances' occurred in 20.8% and the fracture healed after a mean of 4.0 months. This compares to an 83.3% rate of 'disturbance', and a mean healing time of 6.4 months in the group treated by late soft tissue cover. However, the possibility must be considered that the delay in soft tissue cover may have been due to a more severe or contaminated injury, or a more ill patient. This may be the reason for the poor results.

A more recent report (Fischer, Gustilo and Varecka 1991) has agreed with that of Cierny. Fischer *et al.* reported that deep infection occurred in 18.2% of the 11 fractures with early

muscle flap (less than 10 days), compared to 69.2% of 13 treated by a later flap. Nineteen wounds were allowed to granulate and then covered with a split skin graft, 53% of these subsequently developed a deep infection.

In addition to the lower infection rate, the survival of the muscle flap has been shown to be higher when the procedure is carried out early. Godina (1986) has reported a flap failure rate of only 0.75% when the procedure was carried out less than 72 hours after the injury.

Major advances have been made in the management of the soft tissue injury associated with an open fracture. Ideally all open fractures should be closed by suture or tissue transfer within days of the injury. In the military environment, this means that the casualty must be evacuated out of the combat zone to a stable base hospital where the necessary surgical facilities are available. This has implications on the method of stabilisation of open fractures.

3.4 Stabilisation of Open Fractures

It was noted previously that prehistoric man splinted fractures. The oldest known splints were used in ancient Egypt, approximately 5000 years ago (Elliot Smith 1908). These consisted of a number of wooden struts that appear to have been wrapped around the limb with a linen bandage. Elliot Smith described 2 splints that were used to splint an open fracture of the femur, and of the radius and ulna. In both cases the patients died soon after injury. Elliot Smith, a Professor of Anatomy to the Egyptian government, maintained that the ancient Egyptians often achieved excellent results in the treatment of fractures.

Stabilisation of fractures provides pain relief, and helps to prevent further bone and soft tissue injury. Stabilisation, with the fracture reduced, allows functional use of the limb and improves healing (Winnet-Orr 1927). It has been suggested that complete immobilisation of the bone ends is essential for the treatment of open fractures. This is said to reduce the risk of infection (Rittman and Webb 1991), and therefore plaster is not a suitable method of stabilisation (Chapman 1982). Gustilo and Anderson (1976), however, in an important paper on the prevention of infection in open fractures held the opposite view. In the prospective part of their study, only 8 of 326 open fractures (2.4%) became infected. Only 2 open fractures, both in association with a vascular injury, had primary internal fixation carried out; both became infected. The authors concluded that, to avoid infection in open fractures, adequate débridement and copious washout of the wound should be carried out.

This should be followed by early closure of the wound, by suture, split skin graft, or appropriate flaps. Gustilo and Anderson recommended that primary internal fixation by plates or intramedullary nails should not be used, but that stabilisation by skeletal traction, or transfixion pins incorporated in a plaster is used. They recommended external fixation when stability is required to facilitate care of an open wound.

By 1990 Gustilo had changed his opinion on the role of operative methods of stabilisation (Gustilo, Merkow and Templeman 1990). In a review article, the authors advocated operative fixation in open fractures, to reduce the fracture and provide bony stability. Gustilo *et al.* felt that with the recent technical advances, wound healing could be improved, and therefore the infection rate lowered by operative stabilisation. At that time they considered intramedullary nailing was a good option for type I and II tibial fractures. By contrast, the authors favoured external fixation for type III fractures. They noted that with type III open fractures, there was an infection rate of 7-14%, and a non-union rate of 20-30% (Gustilo *et al.* 1990).

Thus most methods of fracture stabilisation have been considered in the management of open fractures, and may be suitable for the treatment of military fractures. The following methods will be considered in more detail:

- conservative methods: plaster splints and traction.
- internal fixation, usually with plates and/or screws.
- external fixation.
- intramedullary nail.

3.5 Conservative Methods of Stabilisation

3.5.1 Civilian injuries

Until the middle of the 19th Century, the majority of fractures were managed conservatively, using external splints or occasionally traction. The main advantages of plaster, or other external splints are that they are non-invasive, cheap, and relatively easy to apply. One of the main disadvantages of splints is the difficulty of access to the wound, for dressings or further soft tissue procedures. With the advances that have been made in the management of the soft tissues, this can be a major problem.

In addition, there is a high rate of malunion following plaster treatment of open fractures. One of the problems with plaster or other splints is failure to adequately maintain length, and shortening at the fracture site can occur. This is particularly important after tibial fractures, where shortening can be a major functional problem. It can be prevented by incorporating skeletal pins in the plaster, or the use of traction, but this can affect the healing of the fracture.

Ellis (1958) reviewed the effects of traction as a treatment option for tibial fractures. He noted that fractures treated by traction were slower to unite than those treated in casts. If distraction of the fracture site occurred, then not only were these fractures slower to unite, but the non-union rate was also higher. Ellis also discussed the factors that influenced the rate of healing of tibial fractures. The 3 main factors that delayed healing were complete displacement, severe open fracture and severe comminution. These were all related to the energy of the initial injury, and he noted a delay in healing with increasing severity of injury. Ellis noted that, 'minor degrees of compound wounding' had no demonstrable effect on the time to union. Infection occurred in 5 out of 105 open fractures, but fracture healing did not appear to be delayed, when compared to non-infected fractures of comparable severity or treatment.

Darder and Gomar reported a review of tibial fractures treated by non-operative methods of stabilisation in 1975. They reviewed 202 fractures, 39% of which were open. Treatment consisted of plaster, with 1 or 2 transfixion pins, and an additional os calcis pin for unstable fractures. The average time to union was 19 weeks, and they defined delayed union as occurring when a fracture had not united by 20 weeks. In the absence of comminution, displacement, or an open fracture they reported a delayed union rate of 9.1%. The effect of these factors when present can be seen below (table 3.1).

Table 3.1 - Factors related to delay in healing of tibial fractures – from Darder and Gomar (1975)

Factor	Delayed Union Rate
Simple, undisplaced, closed fracture	9.1%
Comminution at fracture site	14.3%
Displacement at fracture site	32.6%
Displaced, open fracture	75.0%

The authors reported a delayed union rate of 33% in open fractures without comminution or displacement, but only 3 of the 79 open fractures could be assigned to this group.

3.5.2 Conservative treatment of military injuries

Although non-union is reported to be common after plaster treatment of open tibial fractures (D'Aubigne, Maurer, Zucman *et al.* 1974), this may be related to the soft tissue injury rather than the method of treatment (Holden 1972). The high non-union rate is often quoted as evidence against the use of plaster, but it must be realised that most of the evidence is from the management of civilian tibial fractures. Coupland (1994) emphasised the difference between penetrating war wounds, and the high-energy wounds seen in civilian practice, usually from road traffic accidents. Most penetrating war wounds are low-energy injuries, and are not associated with the extensive soft tissue injury, or periosteal stripping seen in civilian wounds, even though there may be gross contamination. As such it is possible that the non-union rate in military wounds will be less than with civilian wounds, even if the infection rate is higher.

Conservative management of open tibial fractures was practised with good results in the Vietnam War. Witschi and Omer (1970) reported the outcome of 84 tibial fractures caused by missiles, 23 of these were classified as high velocity injuries. The wounds were treated by skin grafting as appropriate, and a well fitting plaster was applied with early weight-bearing encouraged. All fractures healed, the high velocity fractures taking a mean of 22 weeks, and the low velocity injuries taking a mean of 18 weeks. Despite weight-bearing,

83% healed with less than 1cm of shortening. Eleven of the high velocity fractures had associated neurovascular injuries but this did not affect the fracture healing. Witschi reported 7 (8.3%) cases of chronic osteomyelitis in healed fractures.

Plaster does have advantages, and in the management of the open tibial fracture is a safe method of treatment. Its disadvantages are related to stability and access to the wound. In the management of comminuted fractures, or fractures with bone loss, plaster will be unable to prevent shortening. If access to the wound is required, or if stability is required after vascular repair or soft tissue transfer, plaster should probably not be used as the definitive method of treatment of an open fracture of the tibia.

3.5.3 Other external splints

The Thomas splint was specifically designed for the evacuation of patients with ballistic fractures of the femur during the First World War. With the increased use of intramedullary nailing of civilian femoral fractures, its use has diminished. It is a useful method of stabilising fractures in the military environment, either alone or in combination with plaster, and can be used in the definitive management of military fractures. The disadvantages of the Thomas splint are related to the prolonged immobilisation necessary, and the difficulty with access to wounds.

Other splints are available, including malleable wire and inflatable devices, but their main role is the short-term stabilisation of fractures treated in civilian hospitals.

3.5.4 Traction

Prior to the advances in both internal and external fixation, traction was used widely to control fractures that were difficult to manage in plaster, particularly unstable or open fractures. It still has a place in the management of fractures when limited resources are available, but is less than ideal when rapid, prolonged, or repeated evacuation is necessary. To obtain good results experience in the use of traction, and regular adjustments may be required; this may be difficult to achieve in the military environment. It does, however, have potential in both the initial and the definitive treatment of military fractures.

3.6 Internal Fixation

3.6.1 Introduction

The first attempts to plate fractures were made by Hansmann of Hamburg in 1886 (Colton 1992). His plate and screws resembled modern external fixators rather than the plate and screws used today. Hansmann's plate was bent to 90 degrees at one end, with the end protruding through the skin for ease of removal. His screws were also percutaneous (Colton 1992). This design was improved upon by Lambotte, Lane, and Sherman, to produce implants that are similar in appearance to those used today (Colton 1992).

The early attempts at internal fixation were to treat non-unions, or to prevent malunion in unstable fractures. Robert Danis (1880-1962) was the first surgeon to recommend stable internal fixation of acute fractures to allow early rehabilitation. His aims were to allow immediate and active movement of the surrounding muscles and joints, restore the bone to its pre-injury form, and to achieve primary bone healing without the production of callus (Colton 1992). His ideas were taken on, and further developed by Müller, and the AO group was formed (AO = Arbeitsgemeinschaft für Osteosynthesefragen).

3.6.2 Internal fixation of open fractures

3.6.2.1 Introduction

Sherman (1940) was one of the first surgeons to recommend internal fixation in the management of open fractures. He was a believer in the Carrel-Dakin method of treatment, and used this in combination with plating for unstable open fractures. Internal fixation was carried out around 10 days following the injury; the main indication was failure to maintain satisfactory reduction after manipulation and traction (Sherman 1940). In his report, Sherman made no comment on the infection rate after this procedure.

Campbell and Smith (1941) reviewed the effect of internal fixation on 92 'moderate and severe compound' fractures. In a group of 40 fractures treated by internal fixation, 14 (35%) became infected, and 11 (27.5%) developed a non-union. They compared this to a group of 52 fractures where internal fixation was not used, 11 (21%) became infected, and only 3 (5.8%) developed a non-union. Campbell and Smith admit to using internal fixation in the more severe fractures with the worst prognosis. Their figures do however provide an

indication of the infection rate following the internal fixation of open fractures. The fractures were treated before the introduction of penicillin, but sulphonamides were used.

3.6.2.2 Wound healing following internal fixation

Veliskakis (1959) discussed the problem of wound healing following internal fixation for open tibial fractures. He described 95 closed fractures of the tibia treated by internal fixation, usually with a plate; 2 (2.1%) developed deep infections. Two further patients developed superficial wound problems. He compared this with 80 open fractures treated by internal fixation and primary wound closure. The results are shown below (table 3.2).

Table 3.2 - Wound complications following internal fixation of tibial fractures – from Veliskakis (1959)

		Infection		Skin Loss	
Type of Fracture	**Number**	**Superficial**	**Deep**	**Mild/Moderate**	**Severe**
Closed	95	2.1%	2.1%	1.1%	-
Open – Grade 1	12	-	-	8.3%	-
Open – Grade 2	63	6.3%	7.9%	9.5%	-
Open – Grade 3	5	20%	60%	-	60%

Veliskakis defined grade 1 as a wound less than 1 inch with no skin loss, and minimal muscle damage. Grade 2 open fractures had a wound greater than 1 inch, skin contusion, and muscle that required débridement. Primary wound closure of these wounds was possible. Grade 3 wounds were caused by severe crush injuries, with extensive damage to skin and muscles.

3.6.2.3 Movement at the fracture site

Several radiographs are shown in the paper by Veliskakis (1959), and the plates demonstrated appear thin and narrow. It unlikely there was any compression at the fracture site; as a result there may not have been rigid fixation, and micromotion may have occurred. This may be a factor in the high infection rates, as it has been shown that

unstable fixation of an experimental open fracture is associated with a higher infection rate than that associated with the use of stable fixation devices (Friedrich and Klaue 1977; Worlock, Slack, Harvey *et al.* 1994).

In their paper Warlock *et al.* achieved rigid fixation by the use of compression plating, with unstable fixation the result of a loose fitting IM rod. Therefore, it could be argued that the increased infection rate may be related to the method of fixation rather than any instability. However in their paper Friedrich and Klaue demonstrated that, in the rabbit tibia, stable fixation by either plate or an IM device resulted in fracture healing, but that with unstable fixation using either technique failure of fracture healing occurred with clinical evidence of osteomyelitis.

The results following open reduction and rigid internal fixation, (using the AO technique), of open tibial fractures were described by Olerud and Karlström in 1972. The AO group had been set up to study internal fixation of fractures. For internal fixation of tibial fractures, AO recommended a thick compression plate, at least 3 bicortical screws on either side of the fracture and compression of the fracture site (Schatzker 1991). Despite the rigid fixation that was possible using this technique, Olerud and Karlström described 'severe healing disturbance' in 34% of 38 open transverse fractures of the tibia, and 'practically none' of the fractures with comminution and muscle damage healed without complications.

3.6.2.4 Timing of internal fixation

Smith (1974), in a review of tibial fractures, discussed the effect of the timing of fixation. He divided the fractures into 2 groups based on the interval between injury and operative fixation. The immediate group were fixed on the day of injury, and the delayed group were fixed 1-3 weeks after the injury. The initial treatment of the wounds is not discussed by the author. The results are summarised (table 3.3).

Table 3.3 - Complications with tibial fractures and the effect of timing of fixation – from Smith (1974)

		Complication		
Time of fixation – Open or closed fracture	**No.**	**Delayed Union**	**Wound Infection**	**Osteo-myelitis**
Immediate – Open fracture	219	48%	20%	12%
Immediate – Closed fracture	180	30%	6.6%	5.5%
Delayed (23 open, 55 closed)	78	16.6%	6.4%	3.8%

It appears that a delay in fixation of tibial fractures is associated with a reduction in the complication rate. Many surgeons recommend a delay in fixation of closed fractures to allow the soft tissue injury to resolve. The position with open fractures is more difficult, as early surgical débridement of the wound is required. In addition, early stabilisation of the fracture is considered necessary to facilitate the management of the wound, and so reduce the infection rate (Rittman and Webb 1991).

External fixation has been considered as an alternative form of stabilisation for open fractures (Gustilo and Anderson 1976). Bach and Hansen reported a prospective trial of plate versus external fixator for severe open tibial fractures in 1989. Of 26 fractures treated by plate fixation 9 (35%) developed wound infections, and 5 (19%) developed chronic osteomyelitis. Of the 30 fractures treated by external fixation 4 (13%) developed wound infections, and only 1 (3%) developed chronic osteomyelitis. At final follow-up all the tibial fractures had healed, but the conclusion of the authors, and that generally held today, is that plate fixation has little role in the stabilisation of severe open tibial fractures (Templeman *et al.* 1998).

3.6.3 Internal fixation of military fractures

Internal fixation of open fractures, due to war injuries, was dismissed by the British during both the First (Max Page and Le Mesurier 1917), and the Second World Wars (Furlong and Clark 1948). The American military did, however, use delayed internal fixation with some success (Hampton 1946).

In the Second World War, the Americans used internal fixation in the treatment of open fractures from missile injuries. Hampton (1946) reviewed the results of internal fixation in the Mediterranean theatre of operations. He reviewed 332 fractures treated by 50 American military surgeons. Overall, 61.5% of the patients ultimately had healing of both fracture and wound without further surgery required. A further 15.7% had a good result, but required implant removal or sequestrectomy. Plate fixation produced worse results than wires or screws alone, but plates were often used where there was a bone defect. It is apparent from the figures that fractures of the tibia have a worse prognosis, especially when plates are used. Only 60% of open tibial fractures treated by plating had a good result, compared with around 75% for fractures of the femur, humerus, radius or ulna. Hampton concluded that the results of internal fixation were satisfactory with the exception of those in tibial fractures that had been plated, and those associated with massive soft tissue loss.

During this period, British surgeons rarely carried out internal fixation with plates, for an open tibial fracture (Osmond-Clarke and Crawford Adams 1953). The opinion of surgeons in the war surgery supplement of the British Journal of Surgery was that 'internal fixation of open fractures of the tibia should never be done' (Furlong and Clark 1948).

Internal fixation of fractures is technically demanding both in surgical skill and equipment. Very good post-operative management is required, and plastic surgical procedures are often necessary. Internal fixation of fractures therefore, could not be used close to the front line.

The advantages of internal fixation with plates and/or screws are the accurate reduction, and rigid fixation that can be achieved. This could have a place as a secondary method of treatment, possibly in combination with initial plaster. Delayed internal fixation has been shown to have a lower complication rate than acute plating (Smith 1974). Despite this, the complication rate of both infection and delayed healing is still high, and with the other advances that have been made, internal fixation probably has little place in the management of the military fracture. This is particularly so if the infection rate following military fractures is higher than civilian injuries.

3.7 External Fixation

3.7.1 Early fixators

The first external fixator was designed by Malgaigne in 1843 and consisted of a claw-like device designed for patella fractures (Colton 1992). Two points engaged the proximal fragment, and 2 points engaged the distal fragment; a ratchet was then tightened to draw the fragments together. Over the next few years a number of other designs were introduced using the same basic principle of a sharp point pushed through skin to engage one cortex of the bone. However, it was not until 1893 that the modern technique of inserting pins through both cortices of the bone was described (Keetley 1893).

Keetley inserted a single pin into both proximal and distal fragments; these pins had been bent to 90 degrees, and were then wired together. This device had very little stability, and considerable motion could occur at the fracture site, however, Keetley felt that additional external splints could be used if necessary (Keetley 1893).

Parkhill was the first author to report an external fixator that is similar to modern designs (1898). Two steel pins were used in both proximal and distal fragments, with a metal plate fastened to the threaded end of each pin by 2 nuts. All 4 plates were then clamped together. A variety of different sized components were available for individual bones, and the steel pins were heavily coated in silver to try to prevent infection. Parkhill's main reasons for adopting an external frame were to avoid the prolonged use of metal components in the body, and to avoid the requirement for a second operation to remove the implant (Parkhill 1898).

3.7.2 External fixation in the 1st half of the 20th century

From the early 1900's, the use of external fixators fell out of favour until the 1930's. The reasons are not clear, but one possible reason was the rise in popularity of open reduction and plating. During most of the 19th century there were no good implants or instrumentation for internal fixation. With the development of more rigid fixation systems, together with the use of antisepsis, open surgery for fractures became more popular. It is likely that the poor stability of external fixators also played a part in their unpopularity.

In 1931 Conn described a fixator with a number of modern developments. He used stainless steel pins to avoid corrosion, with specially machined threads to increase their pull-out strength, and these were attached to a slotted plate. Conn used a plate with a central universal joint to allow the fracture to be reduced after the fixator was attached.

Anderson (1934), a surgeon from Seattle, developed a device using 2 thin transfixion wires proximally and distally in the tibia. These were connected to a traction device that could also be used to adjust angulation and rotation of the fracture. When the desired reduction had been achieved the leg was encased in plaster incorporating the pins. The traction device could then be removed, and the reduction maintained by the pins and plaster. Anderson subsequently modified the technique in femoral shaft fractures using an external bar connected to 2 half pins inserted into the proximal femur. Plaster was still required, but patients could be mobilised and discharged from hospital much earlier (Anderson 1936).

Otto Stader, a veterinarian, also described a reduction splint for treating long bone fractures, in dogs (Stader 1937). He had developed the device as an alternative to plaster as dogs often chewed at, or fouled their splints. The fixator consisted of 2 pins above and 2 pins below the fracture site, the 2 sets of pins were each connected to a pin clamp. The principal advantages of the Stader device was a bar connecting the 2 pin clamps which maintained the reduction, and so no external splints or plaster were required.

Both the Stader apparatus (Shaar, Kreuz and Jones 1944) and the Anderson device (Bradford and Wilson 1943) were modified for use in man. The Anderson device had been issued to military hospitals and Bradford and Wilson reported the early results of its use in 61 patients. The indications for external fixation were thought to be casualty evacuation or multiple injuries. No long-term follow up is available, but Bradford and Wilson reported no pin track infections or delayed unions. Despite this early promise, the American Army prohibited widespread use of the method (Cleveland 1956). This was due to the later reports of a high rate of complications; pin track infection and osteomyelitis, and problems with the healing of fractures. However, no details of the actual complication rates are given in the report.

3.7.3 Fracture healing with external fixation

Many of the problems associated with external fixation arose from a lack of understanding of bone healing. This is discussed in detail in Section 10.4, however, if a fracture is compressed and rigid immobilisation is achieved, direct bone healing without the production of external callus can occur. This usually occurs when a fracture is plated, and a compression screw is used. Direct bone healing is unlikely to occur when an external fixator is used unless there is anatomical reduction, compression and no comminution is present at the fracture site. In addition, the external fixator must be sufficiently rigid to prevent any micromotion. Primary bone healing is a slow process taking many months, and if the implant is removed too early, refracture may occur. This may require a fixation device to be left in place for 12-18 months. There would probably be a high complication rate, if an external fixator was applied for this length of time.

With most external fixators, movement at the fracture site prevents direct bone healing, and results in the production of external bridging callus. In addition, in fractures treated by external fixation, movement at the fracture site stresses the pin/bone interface, and may result in bone lysis and loosening of the pin (Pettine, Chao and Kelly 1993). This can lead to loss of fracture reduction with subsequent shortening or malunion. Pin problems are more likely if there is thermal necrosis of the bone during pin insertion, or with soft tissue problems around the pin (Green 1981). Pin track complications and difficulties with fracture healing have been the main reason for the lack of popularity external fixators, but these complications are usually due to the prolonged use of the devices.

3.7.4 Modern external fixators

Primary bone healing using a rigid external fixator was reported by Lawyer and Lubbers in 1980, when they published a review of 34 complex tibial fractures treated by the Hoffman apparatus. Hoffman had developed his fixator design in 1938, using a pin clamp attached to unilateral half pins, and with the pin clamps connected by steel bars (Hoffman 1942). His original design was modified by Vidal using transfixion pins, where both ends of the pin protrude through the skin, with 4 connecting bars to produce a more rigid bilateral frame (Lawyer and Lubbers 1980).

Many of the fractures reviewed by Lawyer and Lubbers had healed without callus, and the

time to union was related to the accuracy of the fracture reduction, and therefore the possibility of compression across the fracture site. Compression would be possible due to the rigidity of the bilateral frame. Malunion was not a major problem, all fractures healed at anatomic length. Pin track infections did occur. Three of the 10 (30%) severe open fractures had pins that required débridement to treat infection. Closed or less severe open fractures had an infection rate of (4.5%). However, despite the improved healing with transfixion pins, they have been associated with a much higher pin track infection rate (Clifford, Lyons and Webb 1987), and this has resulted in the technique being abandoned by most surgeons.

By the 1980's external fixation was considered the treatment of choice for open tibial fractures, especially Gustilo type III fractures. Although the complication rate associated with external fixation of these fractures was high, ultimately most would heal. At that time it was thought that no other fracture device was suitable for these fractures, and that the final result was better than an amputation. The patients usually required several operations; Lawyer and Lubbers (1980) documented an average of 5 operations per patient.

At the state trauma centre in Maryland, Edwards *et al.* described the results of staged reconstruction in Gustilo type III tibial fractures (Edwards, Simmons, Browner *et al.* 1988). Immediate débridement, repeated if necessary, was carried out with stabilisation by external fixation, and early soft tissue reconstruction and bone grafting. The surgery was performed under the direct supervision of attending orthopaedic surgeons with an interest in musculoskeletal trauma, and treatment was carried out as part of a prospective protocol. Union occurred in 159 out of 171 fractures (93%) at an average of 9 months following injury, but 28% of these had been bone grafted. Malalignment of more than 10 degrees occurred in 9%, and pin track infection also occurred in about 9% of patients.

At that time, this was considered the correct management of these injuries. There was no doubt that adequate wound débridement was vital, and early soft tissue reconstruction seemed to improve the outcome. These fractures had to be stabilised, and open reduction and internal fixation had fallen out of favour because of the complication rate. External fixation did have high complication rates, but the ultimate result was usually good. Intramedullary nailing was considered to have a role in closed, or Gustilo type I or II fractures, but was thought by Edwards *et al.* (1988) and others to have an unacceptably high infection rate if used for type III open fractures. However this opinion changed during the 1990's.

3.7.5 External fixation of military injuries

3.7.5.1 Introduction

The use of an external fixator for managing war wounds has been debated, with opinions both for and against its use. Bradford and Wilson reported the use of the Anderson device in 1943, when it was first issued to American military hospitals. They felt its use was indicated in patients with multiple injuries, infected fractures, or to prevent complications during evacuation. However Cleveland (1956) in a post war summary reported:

> *'External fixation soon proved itself to be a method totally unsuited to the management of military casualties.....its use in both simple and compound fractures was inevitably associated with a high percentage of both infection and delayed union....The use of this method was therefore forbidden and the apparatus was removed from the hospitals'*

However, as noted previously, plaster is not the ideal method of treatment for fractures with bone loss, vascular injury or extensive soft tissue loss. Given that internal fixation, or IM nailing (see below) are not suitable procedures to be carried out in a forward surgical facility, then external fixation has to be considered as an option in the initial management of these complex injuries.

Zinman and Reis (1984), described the use of an external fixator in the treatment of casualties during the Lebanon War. The indications were severe bone or soft tissue injury, fractures associated with burns or those requiring vascular repair. Of the 45 fractures, 15 involved the tibia. Two of the tibial fractures developed a non-union, unhealed after 1 year, and 1 further patient suffered a refracture that healed with conservative treatment. There were no cases of chronic infection, but pin track infection occurred in 6.2% of all pins. This required pin removal and débridement to treat the infection.

Coupland (1989), based on his experience with the International Committee of the Red Cross (ICRC), felt that the main role of the external fixator was in the treatment of large soft tissue wounds associated with fractures. He once more emphasised that its role was secondary, and that adequate wound débridement was the main priority. Coupland

believed that application of the external fixator should be delayed for about 5 days following the initial surgery, in case further wound débridement was necessary. He felt that the fixator hampered wound débridement, and was concerned about the possibility of infection if pins were inserted immediately after the patient had been 'brought in from the field'.

External fixation has been accepted by the British armed forces but they have not as yet fully established the indications. Few external fixators were used during the Falklands War. Spalding *et al.* (1991) reporting on 63 patients with penetrating missile injuries, described the use of the 'Centrafix Military Pattern' fixator during the Gulf War. Twenty-three patients had fractures, and external fixators were applied to 8 of these 23; 4 other patients were treated by primary amputation, and 11 were treated by plaster. External fixation was used when there was comminution at the fracture site or bone loss; all of these unstable fractures were associated with severe soft tissue injury. Unlike Coupland, Spalding *et al.* found that immediate external fixation helped rather than hindered wound management. Spalding *et al.* also found that the external fixator was of benefit when patients were evacuated further down the medical chain. This is a benefit that must be considered in patients with fractures who will be transferred out of a medical facility early. Patient transfer was considered by Coupland (1989), but he noted that patients treated by the ICRC were not normally evacuated. There is no follow-up for the patients described by Spalding *et al.,* as they were evacuated at an early stage, and many were prisoners of war.

3.7.5.2 Complications of external fixation for military injuries

A detailed follow up on the use of the external fixator during the war in Croatia, was provided by Dubravko *et al.*; in this series 4 different types of fixator were used (Dubravko, Zarko, Tomislav *et al.* 1994). During an 18 month period 116 external fixators were applied to 109 patients with open fractures from missile injuries, 46 of these fixators were used to treat tibial fractures. Of the 116 fixators, complications occurred in 79 (68.1%); pin track infection occurred in 35.3% of all patients, and pin track osteomyelitis in 7.8% of patients. It should be noted that in one of the authors' radiographs, some of the fixator pins appear to cross the fracture site in the region of the wound. This is likely to increase the risk of infection at the fracture.

Information on fracture healing is only available for 37 patients. Twelve of these patients required bone grafting for extensive bone loss, but it is unclear from the report when this

was undertaken. Of the remaining 25 patients, fracture healing took a mean of 193 days; this is longer than the mean time to healing in the 'high velocity' fractures treated conservatively by Witschi and Omer (22 weeks - 1970). Of the 116 fractures treated by Dubravko *et al.*, 8 (6.9%) required reoperation for loss of reduction of the fracture site.

Has *et al.* discussed the treatment of limb injuries in a further retrospective review of war injuries from Croatia (Has, Jovanovic, Wertheimer *et al.* 1995). Of 1320 open fractures treated, external fixation was used in 215 (16.3%); 7 different types of fixators were used. Of the 215 fractures treated by external fixation, 20 (9.3%) developed osteomyelitis, and 21 (9.8%) developed a non-union. Nine of these 21 subsequently developed osteomyelitis (4.2% of original 215). No information is given about the other 1105 fractures treated by methods other than external fixation, and yet the authors conclude that external fixation is the method of choice for these open fractures. This was also the opinion of a report from Sarajevo, where most open fractures from missile wounds were treated by external fixation, using a locally produced 'Sarafix' fixator (Lavy 1995). No follow up is available for these patients.

Labeeu *et al.* reported the use of 149 'FESSA' external fixators in the management of fractures of the lower limb during the Rwandese War (Labeeu, Pasuch, Toussaint *et al.* 1996). Again no follow up is reported, but infections were said to be 'quite numerous especially in pin track infections'. These infections were blamed on the patients' 'African way of life'. The authors felt that in theory all war fractures should be treated by external fixation, and yet they do not appear to have treated many fractures by any other means.

It can be seen, therefore, that external fixation has been accepted as the treatment of choice by many surgeons in the management of open fractures from missiles. This is despite the fact that few reports have any follow-up studies, and those that do report a pin track infection rate of up to 35.3%, and osteomyelitis in 7.8% of patients (Dubravko *et al.* 1994). Fracture healing is often delayed, with a non-union rate of 9.8% (Has *et al.* 1995). Given that military open tibial fractures have a higher infection rate than civilian injuries, then pin track infection may also be more common with military injuries. Malunion rates have not been reported, but 6.9% of fractures in one series required reoperation for loss of reduction (Dubravko *et al.* 1994).

Coupland, in a review article (1994), advised caution when considering external fixation as the treatment of choice for fractures in the military environment. He emphasised the importance of good initial wound débridement, relegating the means of stabilisation as a secondary consideration in most situations. He emphasised that the International Red Cross hospitals usually had no specialist surgeons, or onward evacuation, but Coupland did feel that casualty evacuation was one indication for external fixation. He felt that other indications included multiple injuries, fractures with associated vascular injuries, and significant bone or soft tissue destruction. External fixation should be avoided in children, fractures of the humerus, and especially when there was lack of surgical follow up.

Hammer *et al.* described the use of a new 'simplified' fixator during war conditions (Hammer, Röoser, Lidman *et al.* 1996). This was used on 96 patients in Somalia, 'but no long term follow up was possible'. The authors state that no fixator was removed due to pin related complications, but admit that the incidence of pin track infection was not known. The authors further state that the rigidity of this frame is sufficient for soft tissue recovery, and yet there is no published information on the degree of rigidity required for 'soft tissue recovery'. In addition it has been demonstrated that the rigidity of a frame is not solely dependent on the design, but is also related to the way it is applied (Goodship, Watkins, Rigby *et al.* 1993). Coupland's experience, together with historical reports, would suggest that plaster provides sufficient rigidity to allow 'soft tissue recovery' to take place.

3.8 Intramedullary Nailing

3.8.1 Introduction

Intramedullary (IM) fixation, often considered a development of the 20th Century, was practised in one form by the Aztecs 500 years ago (Haegar 1988).

> *'First the broken bone should be splinted, extended, and fitted together...and if this not effective, an incision should be made, the bone-ends exposed and a branch of fir-wood inserted in the marrow cavity...'*

Lambotte had been using 'the axial method of osteosynthesis' since 1907. In addition, Rush and Rush (1967), and Lambrundi (1940) had also described their technique of IM pins, but

all of these surgeons used relatively small implants (Soeur 1946). Gerhardt Küntscher developed the current system of IM fixation in the 1930's. He was the first surgeon to design a canal-filling implant, for which Küntscher chose the term 'nail' using the analogy of the carpenters' nail becoming fully impinged in bone by elastic forces (Küntscher 1958). The implant was shaped like a clover-leaf in cross section, to take advantage of the elastic forces produced by deformation, and also to allow the nail to support considerable axial loads. Küntscher developed a closed technique of insertion of the nail using fluoroscopic guidance, and was prepared to nail open fractures (Le Vay 1950).

His method was criticised in Britain, where it was felt that the technique evolved because of a shortage of hospital beds or skilled nurses (Le Vay 1950). Concerns were raised about the risk of sepsis from moving the lights and the screening equipment, and amputation of fingers and gangrene of the nose were expected as a result of the radiation (Le Vay 1950). Closed IM nailing was said to carry 'an unbelievable number of complications' and a section of The Journal of Bone and Joint Surgery was devoted to the problems and complications (Watson-Jones 1950). This pessimistic view of IM nailing was in contrast to a number of reports in the same journal in the previous years. Soeur (1946) had described his first 2 years experience with the technique in 55 fractures. He reviewed the literature on the possible effects of the nail on the bone marrow, and the possibility of infection and fat embolus, and concluded it was a safe and effective technique. At that time he did not recommend IM nails for open femoral or tibial fractures (Soeur 1946).

3.8.2 The effect of IM nails on the cortical blood supply

This was one of the concerns of many authors, amongst them Trueta and Cavadias (1955), who reviewed the effect of an IM device in rabbits. They demonstrated the importance of the nutrient artery, and showed that if this was occluded, the inner two thirds of the cortex became necrotic. Küntscher admitted that the technique destroyed both the bone marrow and the medullary part of the nutrient artery, but based on his experience, and animal experiments, felt that there was no effect on the healing of the fracture (Küntscher 1958). Rhinelander (1973) confirmed this finding, and demonstrated that a number of adaptive measures occurred to maintain the viability of the bone. In areas of cortical bone not in direct contact with the nail, medullary vessels rapidly regenerated. Where the nail was in direct contact with bone, osteoclastic removal of necrotic cortex occurred, with replacement by vascular medullary tissue. Rhinelander also demonstrated that the nutrient artery

adapted to the nail. Normally the nutrient artery does not branch until the centre of the medullary canal. After insertion of a nail filling the medullary canal, the artery formed intracortical branches which revascularised the inner cortex of the bone.

3.8.3 Increased popularity of IM nailing

The first report of a series of patients from Britain treated by an IM nail was by Alms in 1962. He described 50 patients with tibial shaft fractures, and emphasised the convenience of the procedure, with an earlier return to work and the avoidance of a long leg plaster. Alms modified a femoral clover-leaf type nail, and reported neither non-unions nor sepsis. Eight of the 50 fractures were open, and Alms felt that the wounds should be observed until there was evidence of healing without sepsis prior to nailing. He did however state early nailing might be justified if there was sufficient skin loss to require a cross leg flap.

Hamza *et al.* reported a further series of 50 fractures from Britain, including 22 open fractures, in 1971 (Hamza, Dunkerley and Murray 1971). They reported that 47 (94%) of the patients had good or excellent results, with normal function. The average time to radiographic union was 4 months. Three of the patients had shortening of over 2.5cm, 2 of these were in open fractures (9.1%). Three wound infections occurred, all in open fractures (13.6%), but all wounds eventually healed, with no evidence of osteomyelitis.

The indications for IM nailing were expanding in the 1970's, especially with development of interlocking devices proximally and distally to help to control length and rotational stability. This again had been Küntscher's idea with modifications by Kempf *et al.* and others (Kempf, Grosse and Beck 1985), and was first introduced in 1972. Intramedullary nailing was also being used as a secondary salvage procedure especially for non-unions in fractures treated conservatively.

Olerud and Karlström (1972) reported the use of secondary IM nailing following plating of tibial fractures. They described 15 fractures, eight of which were open. Fourteen of the 15 fractures healed without complications. In one patient with previous wound infection, a persistent discharge occurred but the fracture healed. They reported good or excellent results in 13 of the 15 (86.7%).

A much larger series of fractures was reported by D'Aubigne *et al.* (1974) who described

849 tibial fractures treated by different methods. The complication rates for the methods of treatment are tabulated below (table 3.4). The authors defined delayed union as a fracture that required an additional surgical procedure, before the fracture healed. It should be noted that for some of the complications D'Aubigne included patients from a previous report. The infection rate following internal fixation is not described in the report.

Table 3.4 - Complication rates of different methods of treatment – from D'Aubigne *et al.* (1974)

	Closed Fractures			Open Fractures		
Method of Treatment	**Number**	**Delayed Union**	**Infection**	**Number**	**Delayed Union**	**Infection**
IM nail	384	1%	0.8%	256	4.7%	6.6%
Plaster	119	4%	1.6%	31	16%	8.3%
Internal Fixation	46	8%		13	61.6%	

These figures demonstrate a low complication rate following IM nailing of both open and closed fractures. As discussed previously plaster is an ideal method of treating closed fractures, but is associated with a high complication rate in treating open fractures. This is confirmed by D'Aubigne's data.

Bone and Johnson (1986) reviewed the results of 112 fractures treated by IM nailing. Seventy-six nailings were carried out for recent fractures, the remaining 36 as secondary procedures. Twenty-six of the 76 fractures were open, and 90% of the recent fractures were caused by a high-energy mechanism. Acute fractures were nailed at an average of 3 days following injury. The average time to union was 17.8 weeks, with 2 (2.6%) delayed unions. Both of these fractures united after further surgery, bone grafting in 1, and exchange nailing in the other. Infection occurred in 4 patients, in 2 (4%) patients with closed fractures, and in 2 (7.7%) open fractures; all 4 fractures united.

3.8.4 Reamed versus unreamed IM nailing

There is little difference in the 7.7% infection rate in open fractures described by Bone and Johnson (1986), and the 6.6% infection rate described by D'Aubigne *et al.* (1974). There is

however, a major difference in the technique used by the authors, Bone used a reamed technique, D'Aubigne avoided reaming, as he felt it increased the risk of infection without providing any mechanical advantage. Reaming was originally recommended by Küntscher who described it as the 'final but most important step in intramedullary nailing'. He recommended reaming to widen the canal over its entire length, both to increase the contact area and to allow a larger, stronger nail to be used (Küntscher 1958). Reaming is also recommended by the AO group, although they have introduced a solid unreamed tibial nail (Müller, Allgöwer, Schneider *et al.* 1991). Prior to the introduction of the Küntscher nail, all IM devices were unreamed, and were hammered across the fracture site.

With the increased use of IM nails in the management of open fractures, concerns have been expressed about the infection rate following reaming. The effect of reaming on the vascularity of the tibia has been questioned (Schemitsch, Kowalski, Swiontkowski *et al.* 1994), and experimental studies have reported a higher risk of distant infection following reaming (Curtis, Brown, Dick *et al.* 1995). Unreamed nails are smaller than those used following reaming, and a higher rate of locking screw breakage has been reported (Schandelmaier, Krettek, Rudolf *et al.* 1995). In addition a higher rate of delayed union has been reported following the use of unreamed nails (Court-Brown, Will, Christie *et al.* 1996).

Despite these reports a recent prospective study by Keating *et al.* demonstrated no difference in the clinical and radiological outcome of open tibial fractures following either reamed or unreamed IM nail (Keating, O'Brien, Blachut *et al.* 1997).

3.8.5 Intramedullary nail or external fixation in the management of open tibial fractures

In the late 1980's external fixation was considered the treatment of choice for severe open fractures of the tibia (Edwards *et al.* 1988). However, good results had been reported with IM nailing of open fractures (Bone and Johnson 1986).

Schandelmaier *et al.* (1995) reported a retrospective, non-randomised comparison of unreamed nailing and external fixation in the management of tibial fractures, where the treatment method was determined by surgeon preference. Sixty-six fractures were treated by external fixation (39 open fractures), and 48 were treated by unreamed nailing (34 open). The fractures treated by external fixation required significantly more re-operations, 1.84 per patient (compared with 0.81 in the nail group), most of these operations were bone grafts.

Bone grafting was carried out if there was no radiographic progression to union by 16 weeks. There was no significant difference in the healing between the groups, although each group had its individual complications. Pin track infection occurred in 25.8% of the external fixators, and 18.8% of IM nails had interlocking screws break.

The functional outcome based on return to work, shortening, and malalignment was significantly better in the IM nail group, and based on this, and the lower reoperation rate, the authors concluded that the unreamed IM nail was the better treatment option.

Many surgeons now feel that IM nailing rather than external fixation is the method of choice to stabilise the fracture (Schandelmaier *et al.* 1995; Templeman *et al.* 1998). An IM nail allows better access to the wound and the improvement in plastic surgical techniques may be more important than the method of stabilisation. For this reason IM nailing may be the better option for open tibial fractures.

The ability to redisplace the fracture site with an external fixator, compared with a nail, allows repeat débridement of the bone ends if necessary. External fixation may therefore be the better treatment option in the heavily contaminated wound. Curtis *et al.* (1995) have shown in a goat model with a contaminated wound that there were significantly fewer and less severe infections in fractures stabilised by external fixator, when compared with both reamed and unreamed nails. In this model however the fracture site was contaminated after the fracture was stabilised, and so does not truly represent fixation of an open fracture that would already be contaminated. Hill *et al.*, using a sheep model, have recently demonstrated extensive osteomyelitis when a fracture site was nailed 6 hours after heavy contamination of the wound (Hill, Parker, Clasper *et al.* 1998).

3.8.6 Intramedullary fixation of military fractures

Intramedullary fixation with a nail is currently considered to be the method of choice for the stabilisation of open tibial fractures in the civilian environment (Tornetta, Bergman, Watnik *et al.* 1994; Templeman *et al.* 1998).

Its main disadvantage is that the operation is technically very demanding. It requires even more equipment than plating, including image intensification. For IM nailing to be performed in a military environment, it would require a relatively static surgical facility, and would be

unsuitable for use near a front line. Intramedullary nailing of femoral fractures caused by war wounds has been reported by Dudley (1973), based on his experiences in Vietnam, although there is no follow-up of the patients. His method of open nailing, without the ability to statically lock the nail, is likely to result in a high complication rate if used for open tibial fractures.

In a further report from Vietnam, Rich *et al.* reviewed the results of open fractures that required a vascular repair (Rich, Metz, Hutton *et al.* 1971), and discussed the method of stabilisation of the fracture. They reported that when IM nailing was used, 50% of the nails required removal for complications directly related to the implant. The most common complication was infection, and the authors concluded that, in the military environment, external splints with the use of transfixion pins was a safer option for the stabilisation of fractures associated with vascular injuries.

The advantages of IM nailing are the high rates of healing for both wound and fracture. No additional splints are necessary, and this allows full access to the wound for inspection, dressings or plastic surgical procedures. As with internal fixation, IM nailing should probably be considered as a secondary method of treatment. This could be carried out after evacuation of the casualty, possibly after plaster immobilisation, which would be a good method of initial stabilisation.

3.8.7 Summary of methods of stabilisation

It is apparent that plaster and external fixation are the methods of choice for the initial stabilisation of military fractures. For many fractures, plaster is the ideal method, but for complex injuries external fixation is required. These indications include:

- unstable fractures, due to severe comminution or bone loss where plaster can not maintain adequate stability.
- severe soft tissue injury, where microvascular anastomosis may be required, such as free tissue transfer.
- fractures with associated vascular injury, where vascular repair is required
- multiple injuries.
- patients requiring evacuation, especially with femoral fractures.

3.9 Secondary Treatment of Fractures

3.9.1 Introduction

For many fractures a change in the method of stabilisation may be necessary. This may occur for two main reasons, either a complication in the initial method of stabilisation, or a planned conversion as part of a treatment protocol. Examples of the former include infection of a plate or intramedullary nail which require its removal, or secondary internal fixation for delays in healing or malunion with plaster or external fixation (McGraw and Lim 1988; Törnqvist 1990). More recently, however, conversion from one method of fixation to another has been part of a planned protocol (Blachut, Meek and O'Brien 1990). This is usually carried out to avoid prolonged orthopaedic surgery in unstable trauma patients who may not be able to tolerate the procedure (Clasper, Turen and Vanko 1998). Secondary internal fixation can then be carried out at a later date when the patient has stabilised. A similar treatment protocol could be considered for military fractures.

3.9.2 Initial treatment in plaster

For fractures treated by plaster, if a satisfactory position is confirmed on subsequent radiographs, plaster can be used as the definitive treatment. If any delay in healing occurs, early bone grafting with or without appropriate internal fixation should probably be carried out. If the position in plaster is unacceptable, then early internal fixation, with either plates or an intramedullary nail can be considered. In general, if excessive delays are avoided, secondary internal fixation can be carried out safely, although, as discussed above, infection after secondary plating may occur.

3.9.3 Initial treatment by external fixation

For the more complex injuries an external fixator may have been applied. However the long term outcome of external fixation in the treatment of military fractures is not known, and complications do occur with the civilian use of external fixators. Many of the problems associated with external fixation are due to its prolonged use, and it is possible that initial external fixation should be used followed by conversion to a different method of stabilisation at a later date, when better facilities are available.

In the civilian environment this technique has been used successfully in the management of both femoral and tibial fractures, particularly with critically ill patients. The main problem with initial external fixation followed by early IM nailing, has been an increased risk of nail infection (Blachut *et al.* 1990). However, this has been shown to be due to previous pin track infection and protocols have been recommended, and techniques established. This will be considered in more detail below.

3.9.4 Fractures with joint involvement

If the fracture involves a joint surface, and the fragments are displaced, plaster, external fixation and IM nailing are not suitable methods of definitive treatment. If reconstruction is possible and suitable facilities are available, early fixation with screws and/or plates should be carried out. If reconstruction of the joint is not possible, the position should be accepted and early mobilisation started. Fusion of the joint is an alternative for some joints, particularly the ankle and wrist but should be avoided at the hip and knee, and particularly the elbow if possible.

3.10 Stabilisation of Specific Bones

In general, fractures of the upper limb are best treated by plaster and other external splints, avoiding external fixation unless there are specific indications. With the humerus, shortening, one of the problems of treatment with plaster or other splints is not a functional problem, whereas external fixation of the humerus has been associated with a high risk of pin track infection (Burny 1984). Successful treatment of gun shot wounds of the humerus has been reported, but the majority of these were low-energy injuries (Wisniewski and Radziejowski 1996). Forearm fractures are difficult to treat by external fixation, and better results are obtained by initial splintage followed by early internal fixation when the patient reaches a base hospital.

Fractures around the wrist, however, are eminently suitable for external fixation and this is commonly performed in the civilian environment as well (Abbaszadegan and Jonsson 1990). Pins are inserted into the distal radius and (usually) the index finger metacarpal.

External fixation is commonly indicated for lower limb injuries. Fractures of the femur should initially be stabilised by a Thomas splint or external fixation. Secondary conversion to an IM

nail can be considered at a base hospital. Open fractures of the tibia will be one of the more common injuries seen during armed conflict, and initial stabilisation by plaster or external fixation can be recommended.

Most severe open fractures treated with external fixators will eventually heal, but many, if not the majority, will develop complications. The long-term complications of the use of external fixators have not been addressed in war wounds, but it has been recommended that external fixation be discontinued as soon as another form of stabilisation can be used (Jacob *et al.* 1992). External fixation has become less popular for peacetime open fractures, and often IM nailing is considered the better treatment option (Tornetta *et al.* 1994; Templeman *et al.* 1998). Unfortunately primary IM nailing is not a practical proposition in the field, in wartime conditions, but secondary IM nailing is certainly an option if evacuation is possible.

One method of treatment, which has been considered for peacetime fractures of the tibia, but has never been investigated for war injuries, is external fixation at the time of initial débridement followed by early conversion to an IM nail. This conversion might be possible at the time of wound closure, if the casualty has been evacuated to a hospital with the necessary facilities. This has all of the initial advantages of external fixation, providing immediate stability, and facilitating evacuation. Early conversion to an IM nail would avoid the disadvantages of delayed union or pin track infections, which are associated with the prolonged use of external fixators. This technique would also allow the definitive management of the injury to be safely delayed until all treatment options are available.

This technique will be discussed in detail in the next chapter.

4. Conversion of External fixation to Intramedullary Nail

4.1 Introduction

4.1.1 Initial reports

Rohan and Miller (1969) were the first authors to report secondary IM nailing following pin fixation of a tibial shaft fracture. One of their patients was initially treated by traction, which was then converted to transfixion pin fixation incorporated into a plaster. The patient subsequently developed a pin track infection, the pins were removed and plaster reapplied. Despite several more months in a plaster, followed by secondary IM nailing, the implant became infected, and ultimately the patient required an amputation.

The first report of converting from an external fixator to an IM nail was by Karlström and Olerud in 1975. In a report of 28 patients treated by external fixation, they describe 1 patient who had conversion to a nail carried out 3 months after the original injury, for a delayed union. This became infected, and 2 revision procedures and bone grafting were carried out before the fracture finally healed and the infection was 'cleared'.

In a review of their experience with IM nailing, Bone and Johnson (1986) described 5 patients who had initially been treated by external fixation. One of these patients developed infection around the nail; the fracture healed, but a chronic sinus developed. No additional information is given about the other 4 patients.

McGraw and Lim (1988) were the first authors to specifically report a series of patient who had conversion from external fixation to an IM nail. They described 16 patients who had nailing carried out after complications following external fixation. The patients were treated with an external fixator for a mean of 8.5 weeks, this was then removed, and IM nailing carried out at a mean of 3 weeks later. Only 5 of the 16 fractures healed without major complications, or further surgery being required. Non-union occurred in 8 patients, and persisted in 5, all of whom had deep infections. The authors concluded that alternative forms of treatment should be considered. Of note, however, is the fact that 7 of the 16 patients had a history of complications before the IM nailing was carried out, and this was related to subsequent problems. Five patients who had previous wound infections developed deep infections after IM nailing.

Initial attempts at conversion from external fixation to an IM nail were therefore associated with a high complication rate, particularly infective problems. In an attempt to reduce the infection rate, some authors developed a protocol for secondary IM nailing. Hansis and Höntzsch (1988) reported a series of 39 patients where IM nailing was carried out as a salvage procedure following external fixation, for both open and closed tibial fractures. They describe their protocol, which included 8-10 days in plaster while the pin sites healed, peri-operative prophylactic antibiotics, and the use of intraluminal drains. Of their 39 patients, 2 (7.7%) developed early postoperative deep infections, both with a history of previous pin track sepsis. One other patient developed a late infection.

4.1.2 Role of previous pin track infection

Maurer *et al.* (1989) reported 24 patients with a duration of external fixation of 52 days, followed by an interval of 65 days prior to IM nailing. Six (25%) of their patients developed an infection around the nail. The authors looked for predictors of infection, and found that duration of external fixation, wound coverage, or other injuries were not related to subsequent infection around the nail, but that pin track infection was. Of 7 patients with previous infection at one or more pin sites, infection developed around the nail in 5 (83.3%). Of the 17 patients with no history of pin sepsis, subsequent infection developed in only 1 (5.9%) patient.

Several other authors have reported pin track infection as a risk factor for subsequent sepsis, and the relationship between osteomyelitis around the nail, and previous pin track infection can be seen in table 4.1. Not all patients with pin track infections developed osteomyelitis after IM nailing, but a very high percentage of patients with osteomyelitis had a previous pin track infection (66.7 – 100%).

Table 4.1 - Relationship of infected nail to previous pin track infection

Author	Number of Patients	Duration of External Fixation	Interval Before IM Nail	Number of Infected IM nails	Number with Previous Pin Track Infection
Hansis & Höntzsch	39	-	8-10 days	3 (7.7%)	2 (66.7%)
Maurer *et al.*	24	52 days	65 days	6 (25%)	5 (83.3%)
Törnqvist	6	72 days	218 days	4 (66.7%)	4 (100%)

Törnqvist (1990) agreed with previous authors about the risk of pin track sepsis. He reported 12 non-unions, where the initial treatment had been by methods other than external fixation. All of the fractures healed after secondary IM nailing, without any complications. Törnqvist compared this to 6 cases of non-union where the initial treatment was by external fixator. All 6 had a history of pin track infection, and 4 of these 6 developed intramedullary sepsis, with the same bacteria as previously isolated from the pin sites. This is despite a mean delay of 218 days (range 112-449 days) between the removal of the fixator and secondary IM nailing.

Only one report dismisses pin track infection as a risk factor for subsequent infection (Marshall, Saleh and Douglas 1991). In a retrospective review of 25 fracture non-unions or limbs undergoing lengthening, Marshall *et al.* reported only 1 deep infection, despite all patients having pin track sepsis prior to nailing. This deep infection occurred in a patient with evidence of previous osteomyelitis. Of the 25 cases, only 9 involved the tibia.

Most authors however, accept that previous pin track infection is a risk factor for subsequent infection, and many would regard it as a contraindication to secondary IM nailing. Johnson *et al.* reported 13 patients, 3 with segmental fractures, all of which healed following secondary IM nailing for tibial fractures (Johnson, Simpson and Helfet 1990). Six of the fractures were closed and the authors specifically excluded any patient with a Gustilo type III fracture, or any patients with previous pin track sepsis or osteomyelitis. In their series, external fixation was used for a mean of 12 weeks (range 3-25 weeks), with a mean interval of 13 days (range 5-30 days) between fixator removal and IM nailing. The authors concluded that the procedure was a relatively safe option, after excluding potentially high-risk patients. In Johnson's patients, as in the previous reports, secondary IM nailing was being used as a salvage procedure when the previous method of treatment had failed.

4.1.3 Planned conversion to IM nail

Blachut *et al.* (1990) were the first authors to describe secondary nailing as part of a planned treatment, rather than as a salvage procedure after failed external fixation. They reviewed 39 patients, all with open fractures with a mean duration of external fixation of 17 days (range 6-52 days). Conversion to IM nailing was carried out after a mean of 9 further days in plaster (range 0-24 days). Two of the patients developed pin track sepsis, but neither had problems at subsequent nailing. Two patients did develop deep infections following IM nailing, but neither had pin track problems prior to nailing. One of these patients had simultaneous external fixator removal and IM nailing, without a period in plaster. The authors concluded that this sequential treatment protocol, with a short period of external fixation yielded excellent results.

Siebenrock *et al.* considered that changing to an IM nail after treatment of an open tibial fracture was a more effective means of treatment, than continuing with external fixation, or plating a fracture (Siebenrock, Schillig and Jakob 1993). The results are summarised below (table 4.2).

Table 4.2 - Complications of different methods of secondary treatment of tibial fractures following initial external fixation – from Siebenrock *et al.* (1993)

Method of Secondary Treatment	Number	Osteomyelitis	Non-union	Malunion
External Fixation	73	8.2%	8.2%	32.8%
IM Nail	24	4.1%	4.1%	24%
Plate	38	10.2%	7.8%	29%

There was however, a difference in the timing of the procedures. Secondary IM nailing was carried out at a mean of 6.4 weeks after injury, compared to a mean of 13.1 weeks for delayed plating. In both groups about 50% of the patients had fixator removal and the secondary procedure carried out at the same operative session. Siebenrock *et al.* also noted that secondary IM nailing could be carried out following external fixator removal, without a period in plaster. It was suggested that this should be done soon after injury, 1-3

weeks after the external fixator was initially applied.

Antich-Adrover *et al.* published a more recent comparison of different secondary treatments following initial external fixation of open tibial fractures (Antich-Adrover, Martí-Garin, Murias-Alvarez *et al.* 1997). They removed the external fixator at 4-5 weeks post injury, and compared definitive treatment in plaster (27 patients), with secondary IM nailing (17 patients).

Secondary IM nailing was delayed by a mean of 10 days to allow the pin sites to heal. Time to union was shorter in the group treated by IM nailing (26 weeks vs 35 weeks), the incidence of malunion was lower, and the rate of non-union was less (5.8% vs 29.6%). One patient treated by IM nail developed a deep infection that required nail removal, bone grafting, and reapplication of the external fixator.

In recent years there has been a change in the role of secondary IM nailing of tibial fractures, from salvage of a non-union, (which can be associated with a high complication rate), to planned early conversion to IM nail. The early conversion is often planned when an IM nail is felt to be the initial treatment of choice, but this cannot be carried out for medical reasons. This may be in the polytrauma patient, fractures with severe soft tissue injury, or in the patient considered medically unfit to undergo IM nailing at that time. These indications are similar to the role of early conversion to IM nail for femoral fractures (Clasper *et al.* 1998).

Höntzsch *et al.* reported a prospective study of 61 femoral, and 106 tibial fractures, where conversion to IM nail was carried out within 3 weeks of injury (Höntzsch, Weller, Engels *et al.* 1993). A one-stage conversion, with removal of the fixator, and IM nailing during the same operative session, was carried out in 55 of the 106 tibial fractures. A two-stage conversion with removal of the fixator and IM nailing at a separate time, was carried out in the remaining 51. In two stage procedures the IM nail was carried out when the wounds had healed, usually at 5-8 days following fixator removal. The infection rate for the tibial fractures, after IM nailing, was only 1.9%.

It can be seen therefore, that the main complication of secondary IM nailing is due to pin track infection. Despite this, secondary IM nailing has been carried out successfully, despite previous pin sepsis (Blachut *et al.* 1990). If the pin track infection can be prevented, or

managed appropriately, it would appear that initial external fixation followed by a planned early conversion to an IM nail is a safe and effective procedure in selected patients. In a military environment where initial IM nailing is not possible, but evacuation to a facility capable of IM nailing is likely, this technique has much to offer. It is possible however, that pin track infection may be more common in the military injury, and therefore, it is necessary to study the effect of secondary IM nailing when there is a history of pin track sepsis.

4.2 Pin Track Infection

4.2.1 Introduction

The incidence of external fixator pin track infection is reported to vary between 0 – 100% (Green 1983), but overall is thought to occur in approximately one third of patients, and involve 10% of all pins (Edwards 1986). The incidence increases with duration of external fixation (Green 1981), but even with a short duration of 17 days, an incidence of 5.1% has been reported (Blachut *et al.* 1990).

Harkess *et al.* have classified the severity of pin track infection by its clinical appearance (Harkess, Ramsey and Harkess 1996):

Grade 1 - Serous drainage.

Grade 2 - Superficial cellulitis.

Grade 3 - Deep infection.

Grade 4 – Osteomyelitis.

Green (1983) described a simpler classification, dividing pin track infections into major and minor. A major infection is defined as sufficient redness, pain or discharge to require hospital admission for parenteral antibiotics and/or pin removal. Any other pin reaction, including serous discharge, is defined as a minor infection.

Pin track infections have been associated with loosening of the pin (Mahan, Seligson, Henry *et al.* 1991), but it is not known whether infection or loosening occurs first. It has been demonstrated that pins may loosen in the absence of sepsis (Pettine *et al.* 1993), but again,

it is not known if loosening is necessary for a pin track infection to develop.

Pin loosening can be assessed clinically, or quantified by measuring the maximum extraction torque of the pin. Burny has devised a clinical grading of loosening (Burny 1984):

Stage 1 - Perfect anchorage; no perceptible motion between pin and bone.

Stage 2 - Slight motion noticeable between pin and bone.

Stage 3 - Considerable motion between pin and bone (clinical loosening).

Stage 4 - Possibility of manual extraction (or spontaneous pull out) of pin.

In a further report, Burny *et al.* reported the mean torque of external fixator pins in the clinical setting, and documented a reduction of torque with time (Burny, Domb, Donkerwolcke *et al.* 1984). In well-fixed pins, the mean torque measured after 45 days was 65% of the torque at insertion. The authors also documented a mean torque of 57% for stage 2 loosening, 26% for stage 3 loosening, and 12% for stage 4 loosening. The duration of external fixator for the stage 2-4 loosening is not reported by the authors.

In an animal model, pin loosening was reported to be more common with an unstable fracture (Pettine *et al.* 1993), but a 40% reduction in torque was noted in pins inserted into an intact tibia. This reduction in torque may be related to creeping substitution of the bone. Aro *et al.* demonstrated that 43% of the cortical bone had been replaced by 12 weeks after pin insertion (Aro, Markel and Chao 1993). Aro *et al.* also demonstrated that unicortical loosening of the pin was evident within 1 month; they felt this represented local bone failure caused by high stresses.

4.2.2 Models of pin track infection

Animal models of pin track infection have been developed (Respet, Kleinman and Meinhard 1987; Warme, Brooks, Carpenter *et al.* 1998), but these models have a number of shortcomings.

Respet *et al.* (1987) were the first authors to develop an animal model to study pin track

infection. In a canine model they reported that the medullary canal of 2 out of 4 (50%) pin tracks (2 animals) were contaminated by 2 weeks, and that 6 out of 9 (67%) were contaminated by 4 weeks (5 animals). The authors did not contaminate the pins, and the infecting organism in 7 of the 8 (88%) contaminated pin tracks was also cultured from the skin. Respet *et al.* used 0.062 inch wires rather than 4 or 5mm half-pins, and there was no fracture of the bone. The pins were inserted with a hand drill to avoid thermal necrosis of the bone.

Respet *et al.* also reported the results of delayed culture of the bone following pin removal. Bacteria could still be isolated from the medulla 2 weeks after the pin had been removed, but by 3 weeks following pin removal, all medullary cultures were negative. It should be noted that Respet's results relate to a canine model; dogs behave differently from humans, and often lick pin sites. This could explain both the early contamination, and the prolonged contamination of the medulla following pin removal.

A caprine model has recently been described (Warme *et al.* 1998), where the pins were deliberately contaminated with *Staphylococcus aureus*, and then inserted into an intact tibia. However the 5mm pins were contaminated during insertion, and this does not truly represent the clinical situation. Clinically, infection is most likely to occur after the pin has been inserted, and then spread to the medullary canal. In their model, the authors were unable to comment on the bone as a barrier against infection, or to determine if infection is present within the medullary canal.

This may be particularly important in any study on secondary nailing in the presence of a pin track infection. If infection is confined to the superficial wound, then it is possible that IM nailing could be carried out safely, especially if débridement is carried out and specific antibiotics are administered. However, if infection has spread to the medulla of the bone then IM nailing is likely to disseminate infection, particularly if reaming of the canal is carried out.

A further animal model has, however, demonstrated that bacteria spread rapidly to the medulla of the bone, and that contamination may be present despite a normal clinical appearance (Clasper, Parker, Simpson *et al.* 1999). A number of aspects of external fixator pin track infection have been studied by this author, using an ovine model (Clasper 2000).

In this model three 4mm pins were inserted into the intact tibia of a sheep. Following satisfactory placement of the pins, they were contaminated with *Staphylococcus aureus*, and the animals allowed to recover and weight-bear as tolerated. A pin track infection developed around all contaminated pins, with spread of infection to the medulla in all cases. Given the clinically relevant method of contamination, and as infection developed at all sites, this is an ideal animal model to study secondary IM nailing in the presence of a pin track infection. In order to use this model to study secondary IM nailing in the military environment, it is necessary to confirm the clinical finding that implant infection develops after IM nailing in the presence of a pin track infection. This is one of the aims of this work.

4.2.3 Aetiology, prevention and treatment of pin track infection

As previously noted, pin track infections have been associated with loosening of the pin (Mahan *et al.* 1991). Loosening can be reduced by under-drilling the initial hole, thereby ensuring a tight fit, and so radially preloading the pin (Hyldahl, Pearson, Tepic *et al.* 1991). Radially preloading reduced micromotion at the pin/bone interface, and reduced the possibility of high local stresses at the interface, which can cause bone lysis.

Thermal necrosis of the bone can also predispose to infection of the pins (Green 1981). Temperatures of 89^0C have been recorded within 0.5mm of a drill hole (Eriksson, Albrektsson and Albrektsson 1984). It has been shown that water-cooling the drill, predrilling a smaller hole or the use of new drill bits, can reduce the maximum temperature (Matthews and Hirsch 1972).

Other factors thought to predispose to infection include abscess formation around the pin, and the presence of excessive motion between the pin and the adjacent tissues (Green 1981). This may be due to the development and accumulation of fluid around the pin/bone interface (Clasper, Cannon, Stapley *et al.* 2001). Excess motion may be the reason for the higher rate of infection reported with the use of transfixion pins (Clifford *et al.* 1987), which in many cases had to pass through muscle and other deep tissues. Pins should ideally be inserted into the subcutaneous surface of a bone.

Despite all these precautions pin track sepsis can still occur, and this will have a significant effect on the outcome of secondary IM nailing. It is likely that in the military fracture pin track infection will be more common, due to more extensive contamination and limited resources.

Further work is needed to investigate the contamination of military fractures, as well as define the role of pin sepsis, and to determine if any therapy can reduce the infection rate after secondary nailing.

There is little controversy surrounding the treatment of a pin track infection (Green 1981; Edwards 1986). The pin should be assessed for clinical evidence of loosening. If the pin is loose it should be removed, replacing it with a pin in a different location if necessary. If the pin is not loose, the skin around the pin should be incised to allow drainage, adequate pin care should be ensured, and the patient should be started on an appropriate oral antibiotic if significant cellulitis is present. Any weight-bearing should be discontinued, and the patient instructed to elevate and rest the limb.

Most infections will resolve with this management, but if the problem persists the patient should be admitted to hospital for strict bedrest, elevation of the limb and intravenous antibiotics. If the pin track infection still fails to resolve, the pin should be removed, and this will usually cure the problem. A persisting infection, after removal of the pin, is an indication of chronic osteomyelitis of the track, and requires surgical débridement.

4.2.4 Contamination of military fractures

One factor that has not been considered is the possibility that an external fixator pin may be inserted through a contaminated area, and so may carry infected material into the medulla of the bone. This will have disastrous consequences if secondary IM nailing is carried out. The possibility of inserting a pin into a contaminated area is particularly relevant to the military casualty, especially with high-energy transfer wounds where extensive cavitation may have occurred. This may be the reason for the high pin track infection rate after external fixation of military fractures, and must be considered prior to any widespread use of secondary IM nailing in management of a military fracture. This will be investigated in the next chapter.

4.3 Aims

The initial aim of this research is to develop an *in vitro* model of a ballistic fracture to study the dissemination of contamination. If it can be demonstrated that external fixation can be carried out without introducing pins through contaminated areas, secondary IM nailing may be suitable for the military casualty. In addition an animal model of secondary IM nailing will be developed, to attempt to mirror the clinical finding of a high implant infection rate after IM nailing when a known pin track infection is present. Using standard methods of treatment it may be possible to prevent implant infection, and this will also be studied in a second group of animals.

5. Contamination of Ballistic Fractures: An *In vitro* Model

5.1 Aim

The aim of this work was to study the fracture pattern and extent of contamination in an *in vitro* model of a ballistic fracture. This would help to determine if initial external fixation followed by secondary IM nailing is a realistic option in the management of military fractures.

5.2 Material and Methods

The study was carried out using a sheep model of a long bone fracture. Three separate groups were studied: In groups 1 and 2 sheep femora were used, in group 3 a complete hindleg was used, with the fracture created in the tibia.

5.2.1 Direct fracture group (n=7)

All soft tissues were removed, and the bones were individually suspended in a 20% gelatin solution (Croda Colloids Ltd, Widnes, Cheshire. U.K.) to form blocks measuring 30 cm in length with a cross-section of 15x15 cm^2. The blocks were made 48 hours in advance of their use and all experiments were carried out at room temperature (16° C). Ball bearings (diameter 7.94 mm and mass 2.1 g), were used as projectiles and fired using a standard 7.62 mm cartridge. The barrel was connected to a Mann pressure housing, and was remotely fired by an electrically activated 24V DC solenoid (local manufacture). This assembly was supported by a V block (local manufacture and assembly). A laser-sighting device was used to ensure the missile actually struck the bone.

In order to assess the contamination of the fracture site, gauze soaked with 1ml of fluorescein solution (Martindale Pharmaceuticals Ltd Romford) was placed on the outer surface of the gelatin block, and the missile passed through the gauze prior to striking the bone (Figure 5.1). Direct fractures were produced by aiming at the centre of the lateral cortex in the transverse mid-diaphyseal plane. The entrance velocity of the ball bearing was measured using an electronic sensor (Skan chronoscope® MK7 DRSC, Reading, UK).

Figure 5.1 – Experimental setup for the direct fracture group

5.2.2 Indirect fracture group (n=17)

The experimental setup was similar to that described above. In this group, however, the missile was aimed 5mm posterior to the bone. This resulted in a reproducible indirect fracture.

Following the creation of a fracture the gelatin blocks and bones were dissected under ultraviolet light to assess the spread of fluorescein.

5.2.3 Clinically relevant fracture group (n=5)

In the 2 previous groups assessment of the extent of contamination and comminution was greatly aided by the transparent nature of the gelatin. The models, however, are not truly representative of the clinical situation. In order to make the *in vitro* model clinically representative, a further group was studied.

The left hindleg of 5 adult sheep were obtained at post-mortem. These animals were involved in a separate project that did not involve this limb. The leg was disarticulated at the hip joint, the skin was shaved, and the limb was suspended from a stand with a metatarsal

clamp. A sheet of cotton, which had been presoaked in fluorescein dye, was placed over the midshaft of the tibia (Figure 5.2). All legs were shot to produce a high-energy wound involving bone. The experiments were carried out within 4 hours of death to minimise the effect of post-mortem changes.

A 7.62mm bullet (NATO 7.62 x 51 L2A2 ball ammunition) was fired at the midshaft of the subcutaneous surface of the tibia from a distance of 2.3m. The 9.4g bullet was fired through a rifled barrel (RSA Enfield UK) mounted in a Whitworth rest, using a laser aiming device.

Antero-posterior and lateral radiographs of the leg were taken, and the extent of bony involvement was measured. This was expressed as a percentage of a pre-operative radiograph of the intact tibia. After the radiograph was taken, the leg was removed from the stand, and the wound track was formally explored. The entry and exit wounds were measured, and based on the surface appearance an estimation of the macroscopic extent of traumatised skin was made. The area of this wound was calculated using the formula:

$A = \pi ab/4$ where a and b were the 2 long axes of the ellipse.

All skin from the leg was excised by dissection in the subcutaneous plane, and the wound in the deep fascia was measured. In addition, the subcutaneous spread of fluorescein was measured under ultraviolet light. Finally the periosteal spread of fluorescein was measured, and related to the extent of the fracture, both at dissection and on the radiograph.

5.3 Results

The mean velocity of the rounds in groups 1 and 2 was 599 ms^{-1}. In group 3 it was approximately 840 ms^{-1}.

5.3.1 Direct fracture group

A multifragmentary fracture was produced in all bones, with a mean of 8.3 fragments (range 4 –12, Figure 5.3). These fragments varied greatly in size (2 x 1mm to 35 x 15mm). In all cases widespread contamination of the wound track, by fluorescein, was present including the medullary cavity of the bone. In addition, bony fragments were found in the wound track in all specimens. The mean spread of fluorescein along the periosteal surface of the bone

was 4.1 cm (range 2.0-5.0) proximally and 3.3 cm distally (range 0 – 5.0). The results are presented in table 5.1.

Figure 5.2 – Experimental setup for the clinically relevant group

Figure 5.3 – Direct fracture

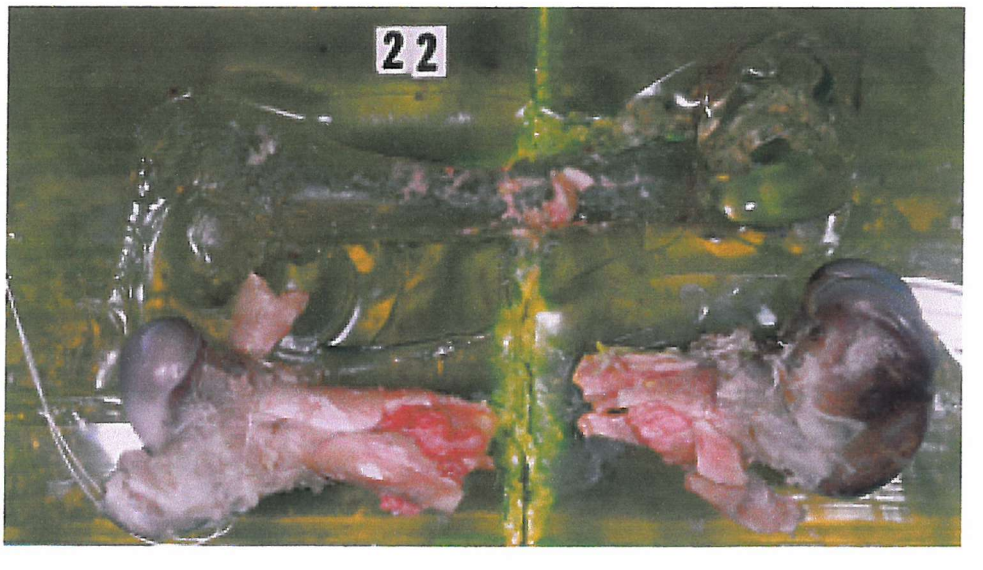


Table 5.1 – Summary of data from direct fracture group

Bone Number	Number of Fragments	Proximal Spread (cm)	Distal Spread (cm)	Medullary Contamination	Fragments in Wound Track
1	6	4.0	5.0	Yes	Yes
2	12	4.0	3.0	Yes	Yes
3	11	5.0	4.0	Yes	Yes
4	4	5.0	3.0	Yes	Yes
5	7	4.0	3.0	Yes	Yes
6	6	5.0	5.0	Yes	Yes
7	12	2.0	0	Yes	Yes
Mean	8.3	4.1	3.3		

5.3.2 Indirect fracture group

Group 2 – A fracture resulted in only 14 of the 17 bones, and the 3 intact bones were excluded from further analysis. Of the remaining 14, a simple 2 part fracture was produced in 9, there was 1 additional fragment in 4, and 2 additional fragments in 1 bone. Only 3 of the 14 bones had evidence of medullary contamination, and there were no bony fragments in the wound track (Figure 5.4). The mean spread of fluorescein along the periosteal surface of the bone was 1.6 cm (0-5.0) proximally and 2.2 cm distally (0-6.0). The Kolmogonov-Smirnov test was used to compare the 2 groups, as it was not certain if the data had the same distribution. There was a significant difference in the spread of fluorescein, along the periosteal surface, between the 2 groups ($p=0.002$). The results are presented in table 5.2.

Table 5.2 – Summary of data from indirect fracture group

Bone Number	Number of Fragments	Proximal Spread (cm)	Distal Spread (cm)	Medullary Contamination	Fragments in Wound Track
1	1	0	0	No	Yes
2	1	2.0	4.5	No	No
3	0	0	0	No	No
4	0	4.0	4.0	No	No
5	0	0.3	0	No	No
6	0	0.1	0	No	No
7.	0	0	0.5	No	No
8	1	5.5	5.0	Yes	No
9	0	0	0.5	No	No
10	0	3.0	6.0	Yes	No
11	0	0	0	No	No
12	0	0	0	No	No
13	1	2.0	5.0	No	No
14	2	5.0	5.0	Yes	No
Mean	0.4	1.6	2.2		

5.3.3 Clinically relevant group

An entry and exit wound was produced in all legs, together with a multifragmentary fracture (Figure 5.5). At dissection widespread contamination of the soft tissues was noted. This was greater than the macroscopic appearance suggested. The extent of the soft tissue wound and contamination is presented in table 5.3. The area of the exit wounds was significantly greater than that of the entry wounds ($p=0.004$, Kolmogonov-Smirnov Test). However there was no significant difference between the subcutaneous contamination of the entry and exit wounds.

A direct fracture was produced in all legs, as demonstrated by the wound track passing through the middle of the fracture site. The extent of the fracture and bony contamination is presented in table 5.4.

Figure 5.4 – Indirect fracture

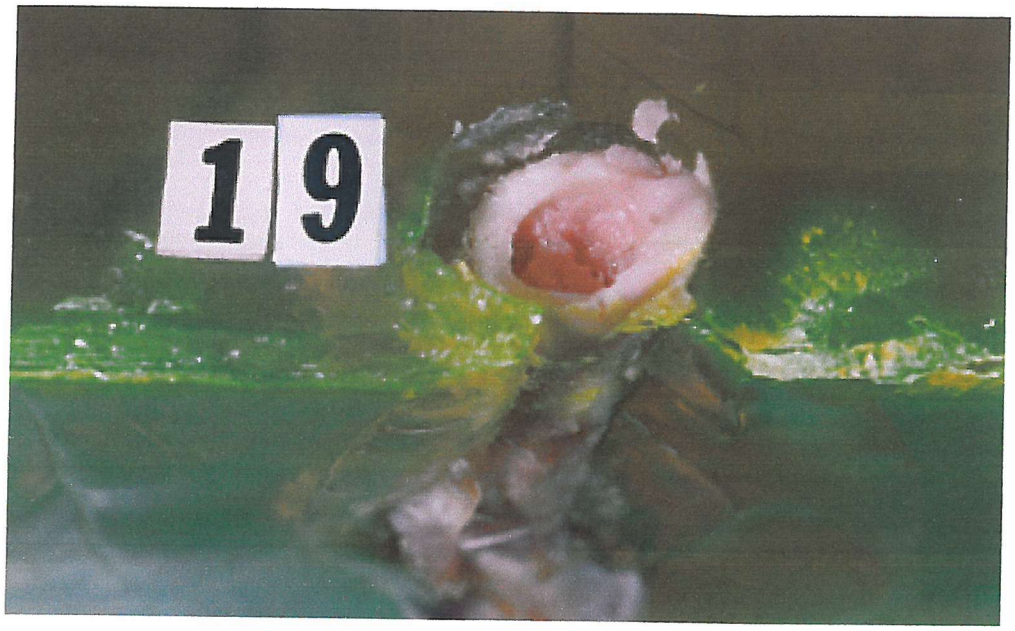


Figure 5.5 – Fracture in clinically relevant group

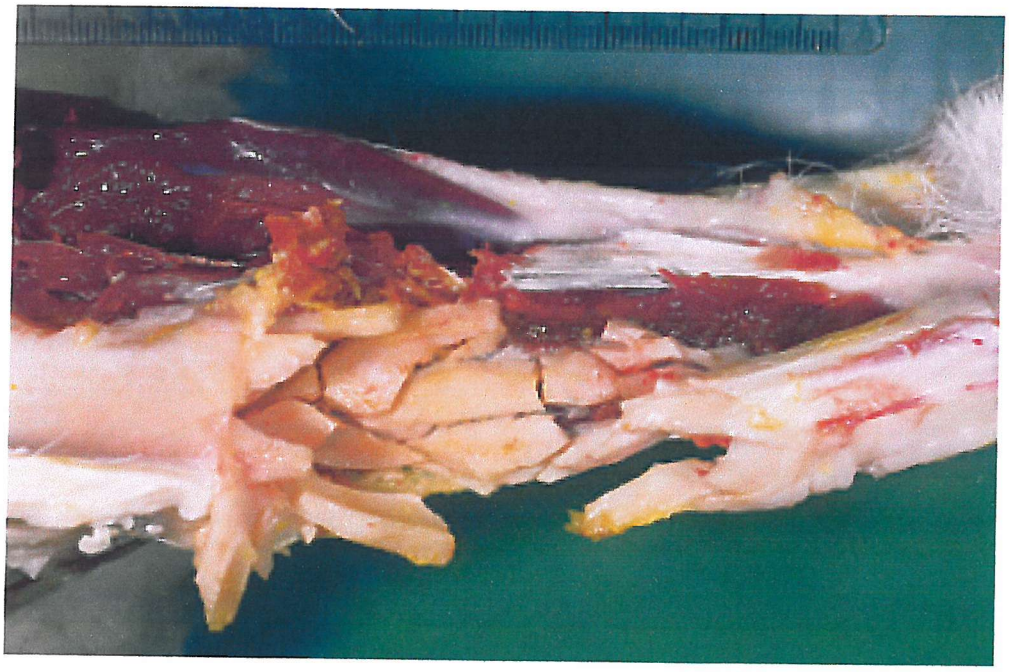


Table 5.3 - Gross tissue damage and soft tissue contamination in clinically relevant group

Entry Wound	**Mean (mm^2)**	**Range (mm^2)**
Area of Entry Wound	70	43-95
Area of Contamination of Deep Fascia	1650	687-2120
Exit Wound		
Area of Exit Wound	636	126-2136
Area of Contamination of Deep Fascia	1531	687-5891

Table 5.4 - Extent of fracture comminution and bone contamination in clinically relevant group - expressed as a % of the length of the intact tibia

	Mean	**Range**
Extent of Comminution	42%	34-52%
Extent of Contamination	45%	34-55%

The data for individual limbs is given in appendix 1.

5.4 Discussion

Although this was an *in vitro* study, a number of observations can be made, and these can be applied to the clinical situation. The multifragmentary nature of the fractures is consistent with those reported clinically. Rose *et al.* in a retrospective review reported that with high-energy weapons, such as military or hunting rifles, all fractures were complete, and comminuted (multifragmentary). For low-energy weapons, such as handguns, 60% of the fractures were incomplete, and only 22% were multifragmentary (Rose *et al.* 1988).

Further confirmation that high-energy injuries were associated with greater bony damage came from an *in vitro* study from Ragsdale and Josselson (1988). They reported that increasing pre-impact velocity was associated with an increased cavitation effect and increased fragmentation. For a handgun with a pre-impact velocity of approximately 200

ms^{-1}, there were 2 fragments. However, for a military rifle with a pre-impact velocity of nearly 1000 ms^{-1}, there were 33 fragments. In the current study the entrance velocity for group 1 of nearly 600 ms^{-1}, and for group 3 of 840 ms^{-1} would be expected to produce a multifragmentary fracture.

In addition, as discussed in section 2.3, a fracture may also result despite the missile not actually striking the bone. These indirect fractures are thought to be due to the cavitation effect, with the acceleration of bone away from the track of the missile. This type of fracture is usually only seen with high-energy transfer wounds, and the fracture is usually simple rather than the multifragmentary pattern seen when the missile hits the bone (Shephard 1981). This is consistent with the results in group 2, and demonstrates that our model can be compared to the clinical situation. Although in groups 1 and 2, the bones were embedded in gelatin, this has been shown to have the same drag co-efficient has human soft tissue, and is widely used as a soft tissue substitute (Janzon and Seeman 1985).

Although group 3 was an *in vitro* study, it was made as realistic as possible. All soft tissues were retained, and the tibia rather than the femur was used. This permitted an intact joint above and below the injured bone to be maintained, allowing the soft tissue envelope to be optimized. All the legs were shot within 4 hours of death, and most were shot within 1 – 2 hours to minimise post-mortem changes. The projectile measured 7.62 x 29mm, and as discussed in section 2.2, the small entry wounds indicate that relatively little energy was lost as it passed through the skin (Figure 5.6). The much larger exit wounds, together with their star-like appearance are highly suggestive of a high-energy transfer wound (Janzon *et al.* 1997, Figure 5.7). This is confirmed by the radiographic appearance (Figure 5.8). In 2 of the legs, a much greater transfer of energy appears to have occurred, as the exits wounds were much larger than in the other legs, and metallic fragments are visible on the radiograph.

Figure 5.6 – Entry wound

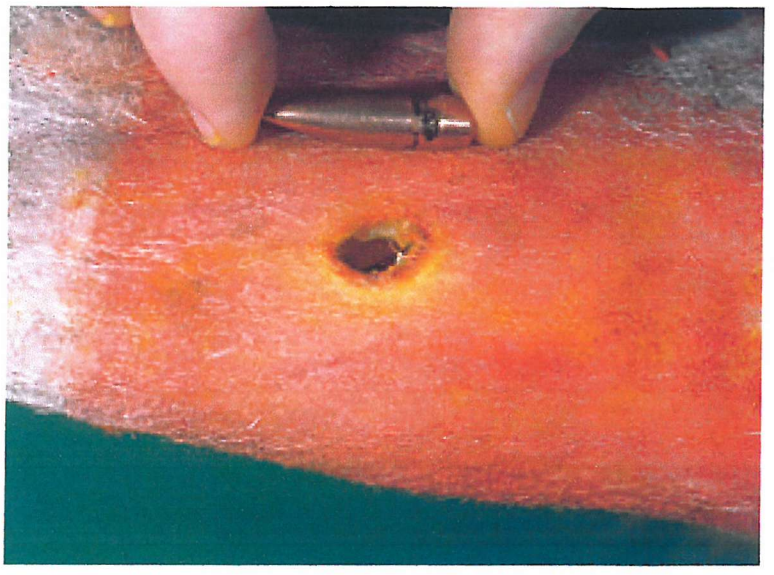
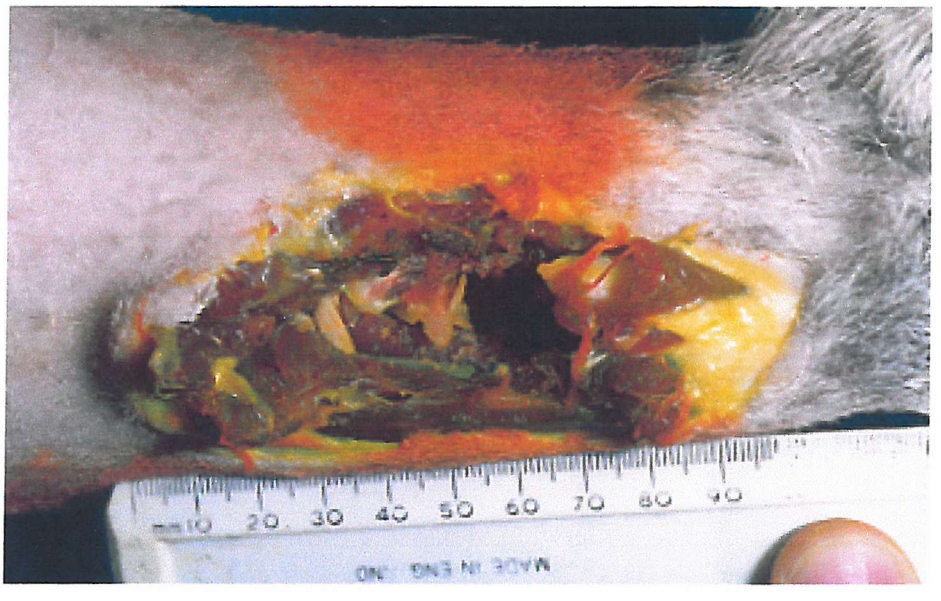


Figure 5.7 – Exit wound



Spread of contamination was greater than the skin wounds suggested, consistent with clinical observations (Strawitz *et al.*1955), but was confined to tissue planes. This may be related to shearing forces during cavitation, which may separate the tissue planes. This is particularly true for the entry site, where considerable subcutaneous contamination was present despite a very small entry wound (Figure 5.9). During débridement, therefore,

tissue planes should be thoroughly washed out. In this model intramuscular spread was limited, and therefore removal of necrotic muscle should be sufficient, during débridement, to reduce the risk of infection.

Results from all 3 groups confirm that the whole of the fracture site must be considered contaminated, and with direct fractures the contamination is more extensive. The results from group 3 would suggest, however, that there is little spread beyond the fracture site, and adequate exposure and thorough washout would be sufficient.

Whilst this is an *in vitro* study, it allows a number of observations on the spread of contamination to be made. With direct, high-energy fractures endosteal spread is universal, and the spread of infection is more extensive than with indirect fractures. As the fracture pattern is different, the extent of contamination can be estimated on radiographs prior to débridement, and it would seem sensible to recommend that radiographs be taken, prior to surgical treatment, of military fractures.

Fluorescein was used to demonstrate the contamination of the soft tissues, particularly the tissue planes. The extent of contamination was much greater than the appearance of the wounds suggested (Figure 5.9), and this is probably due to the formation of a temporary cavity as discussed in section 2.2.

This model allows recommendations to be made for the treatment of military fractures. Whilst minimal skin excision is necessary, the subcutaneous space, and all tissue planes should be thoroughly washed out. The débridement of muscle should be based on the clinical appearance, with excision of necrotic appearing non-contractile tissue. This would appear to be adequate to remove contaminated tissue. The fracture site, however, should be considered highly contaminated, and while many fragments will appear viable, the wounds must be washed out, and if necessary small fragments should be excised to minimize the risk of infection.

Figure 5.8 – Radiograph of clinically relevant group

Figure 5.9 – Subcutaneous spread of fluorescein

Of note, however, is the limited spread of contamination beyond the fracture site. This is relevant to the means of stabilisation. If the fracture site remains contaminated despite débridement, external fixator pins can be safely inserted, as long as they avoid the fracture site. As pins will be inserted into intact segments of bone, they will be sterile initially. Thus secondary IM nailing is a possibility and the aim of the next two chapters is to develop an animal model.

6. Secondary Intramedullary Nailing Following Pin Track Infection - Materials and Methods

6.1 Selection of Animal

Twelve mature, female, mixed breed sheep with a weight range 65-76kg (mean 70.4kg) were used. The animals were ex-breeding ewes purchased from a commercial flock. Six animals were used for the control group, when no treatment was given to prevent the spread of infection. A further 6 animals were used in the treatment group, when the effect of local and systemic treatment was studied. All experimental work complied with the Animals (Scientific Procedures) Act, 1986.

6.2 Selection of Bacteria

Staphylococcus aureus (ATCC 29213) was used to contaminate the external fixator pins. Staphylococci are pathogens of sheep (Buxton and Fraser 1977), and have been used previously in experimental fracture work in sheep (Hill *et al.* 1998).

6.3 Experimental Design

Anaesthesia was induced by the inhalation of 5% halothane (Zeneca Pharma, Winslow, UK), and maintained by an intravenous infusion of midazolam (Roche, Welwyn Garden City, UK), and ketamine (Parke-Davis Medical, Eastliegh, UK), titrated to effect. The animals were intubated with a cuffed endotracheal tube (Portex Ltd, Hythe, UK), and 0.9% saline solution (Animal Care Ltd, Dunnington, UK) was infused through a jugular venous catheter (Abocath, Abbot Laboratories Ltd, Queenborough, UK) as maintenance fluids. In addition a wide bore oral tube was inserted (Vygon UK Ltd, Cirencester, UK) to decompress the rumen.

The right hindleg was shaved, and the skin prepared with povidone-iodine (Seaton Healthcare, Oldham, UK). A single longitudinal skin incision was made at the lateral aspect of the subcutaneous border of the tibia, extending from the inferior aspect of the tibial tuberosity for approximately 8cm. Two external fixator pins were inserted. The proximal pin was placed approximately 2cm distal to the inferior aspect of the tibial tuberosity, and the second pin was inserted 5cm distal to the first pin. Bicortical pin placement was achieved in

all cases. A Centrafix (Military Pattern) external fixator (Central Orthopaedics Ltd, High Wycombe, UK) was used. The pins are designed to be self-drilling and self-tapping, but a 2.5mm guide hole was required as the cortex of the sheep tibia proved too hard to allow the pins to self-drill. Following satisfactory pin position the final insertion and extraction torques were recorded (RS Dial Torque wrench 575-633, Corby, UK), and all pins were connected to a single external fixator bar. Bacteriological swabs of all pin sites were taken, as was a post-operative lateral radiograph (Figure 6.1). The central portion of the wound was then approximated with 2/0 polyprolene monofilament sutures (Ethicon Ltd, Edinburgh UK).

Both pins were contaminated by placing 0.1ml of a suspension of *Staphylococcus aureus* (mean 2.4 x 10^8 colony forming units per ml) into the wound around the pin (Figure 6.2). After 1 hour bacteriological swabs were taken, a sterile, dry dressing was applied; the sheep were allowed to recover from anaesthesia and returned to their pens. Buprenorphine was administered as required, and the sheep were allowed to weight-bear as tolerated.

The dressings were removed after 24 hours, and the pin sites were left exposed. At 48 hours the pin sites were assessed clinically for the presence of infection, and graded using the classification described by Harkess *et al.* (1996 - see section 3.2.1).

Figure 6.1 – Radiograph after pin insertion

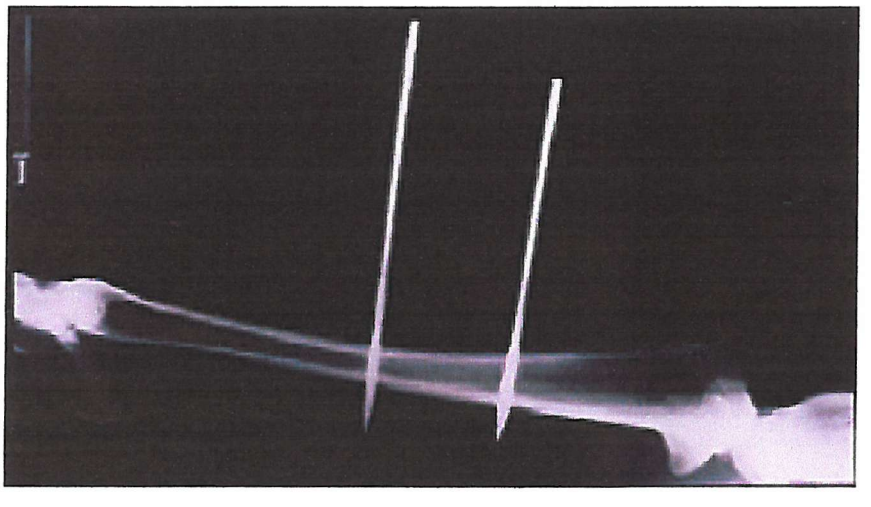
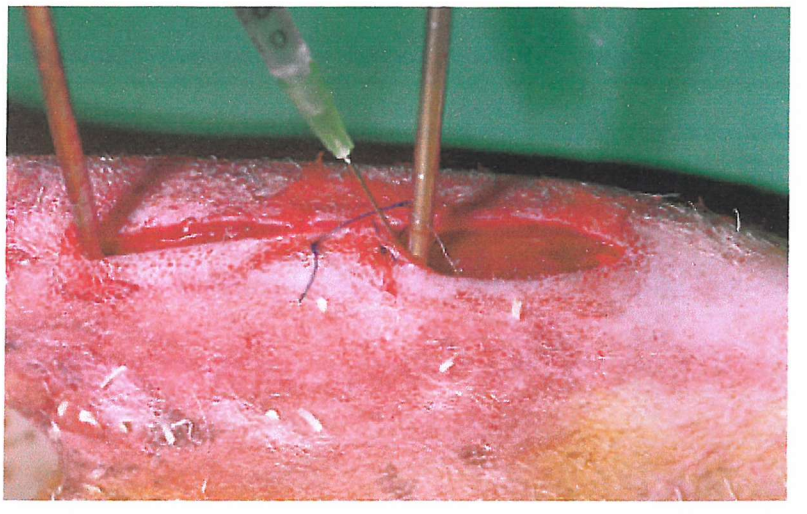


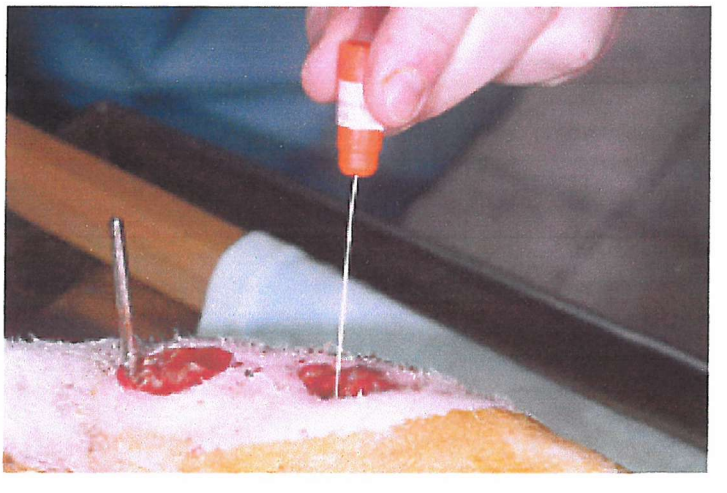
Figure 6.2 – Technique of contaminating pins



6.4 Technique of Intramedullary Nailing

Fourteen days later, the sheep were re-anaesthetised. The clinical assessment of the pins was repeated (Harkess *et al.* 1996), bacteriological swabs of each superficial pin track were taken, and a further lateral radiograph of the tibia was made. Any pin loosening was recorded using the classification of Burny (1984), and the extraction torque of each pin was measured. Both pins were then removed and swabbed, and further swabs of the medulla taken through the pin site (Figure 6.3). The tip of the pin was cut off with sterile bolt cutters and retained for further bacteriological analysis.

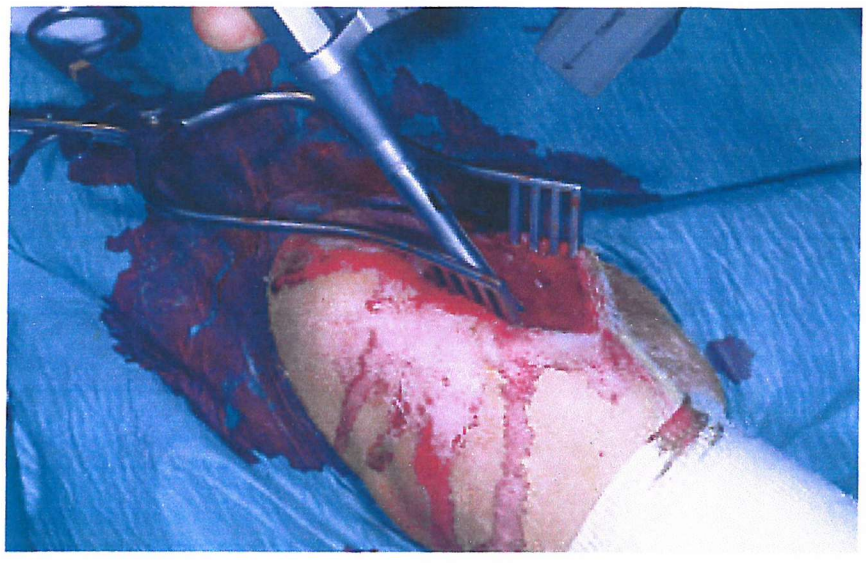
Figure 6.3 – Swabs of the medulla after pin removal



An occlusive dressing (National Veterinary Supplies, Stoke on Trent, UK) was applied over the pin sites, to prevent any contamination of the subsequent surgical wound, and the animal was taken into a clean, dedicated operating theatre.

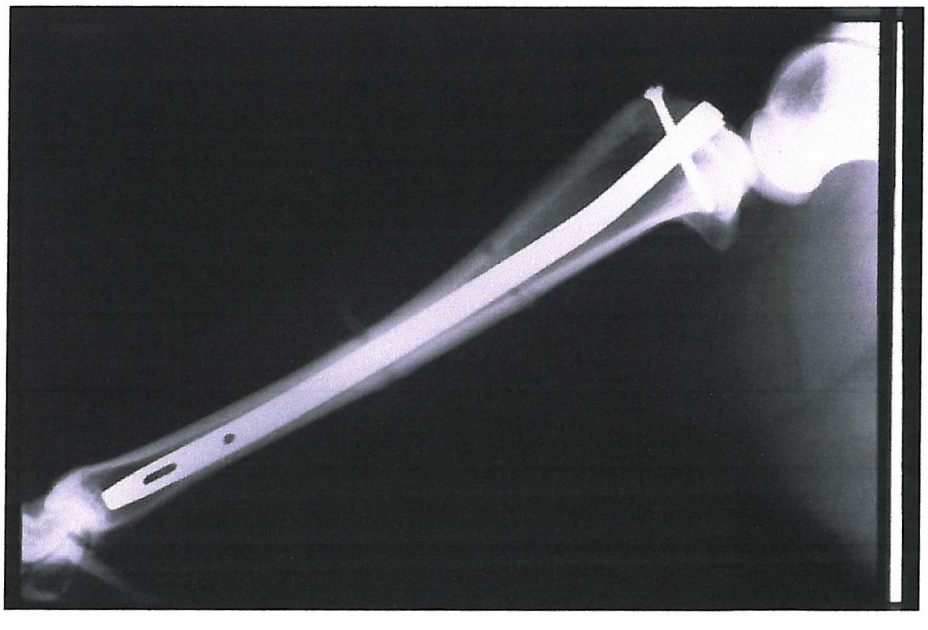
The skin of the right hindleg was prepared with povidone-iodine and disposable surgical drapes (Guardian, BDF Ltd, Girvan, UK) were applied to isolate the anterior aspect of the stifle (knee) joint as a sterile field. A 5cm medial para-patellar incision was made, and deepened onto the fat pad. A portion of the fat pad was excised for access, and the correct entry point for the nail was identified using image intensification (Siremobil 2, Siemens, Germany). An IM humeral nail was used (Smith & Nephew Richards, Memphis TN, USA) and was inserted using the recommended instrumentation (Figure 6.4). The dimensions of this implant approximate to the sheep tibia. This nail has a proximal angle, and an intra-articular starting point was required. Bacteriological swabs of the stifle joint were taken on entry. A starting hole for the nail was made with a 6mm drill (RS Components Ltd, Corby, UK), and further bacteriological swabs of the drill bit and proximal metaphysis were taken. A 2mm ball-tipped guide rod (Smith & Nephew Richards, Memphis TN, USA) was inserted into the tibia, pushed down the medulla past the pin sites, and its position in the distal metaphysis was confirmed with image intensification. The guide rod was removed, and its tip was swabbed. Using successive 7, 8 and 9mm hand reamers (Synthes pseudoarthrosis reamers, Stratec Medical Limited, Welwyn Garden City, UK), the medullary cavity was enlarged. Bacteriological swabs of all reamers were taken as they were removed, and following removal of the 9mm reamer, the stifle joint and proximal metaphysis were again swabbed. An 8mm nail of the appropriate length was inserted and a proximal locking screw was inserted using the supplied jig (Smith & Nephew Richards, Memphis TN, USA). A 20cm nail was used in all animals, in one animal however this was found to be too long, and was exchanged for an 18cm nail. Swabs were taken from both the inside and outside of the first nail on removal.

Figure 6.4 – Insertion of the nail



The final position of the implant was confirmed by image intensification, all instrumentation was removed and the wound was closed with 2/0 polyglactin (Coated Vicryl, Ethicon Ltd, Edinburgh UK), and 2/0 polyprolene monofilament sutures. A sterile dressing was applied, and antero-posterior and lateral radiographs of the tibia were taken (Figure 6.5).

Figure 6.5 – Lateral radiograph after nail insertion



The sheep were then allowed to recover and returned to their pens. Buprenorphine was administered as required, and the sheep were allowed to weight-bear as tolerated.

6.5 Examination at 2 Weeks

All surviving animals were re-anaesthetised at 14 days. The pin site wounds were assessed, and bacteriological swabs were taken if they had not healed. Radiographs were taken, and the animals were recovered and returned to their pens.

6.6 Termination of the Experiment

All experiments were terminated, the animals were killed, and a post-mortem was carried out 28 days after IM nailing. They were killed earlier if there were signs of distress, or if a purulent discharge developed. The animals were killed by an overdose of sodium pentabarbitone (Euthatal, Rhône Mérieux Ltd, Harlow, UK).

6.7 Post-mortem Technique

Bacteriological samples were obtained from the proximal and distal metaphysis and the nail, the external fixator pin tracks, and the stifle joint. In each case a separate skin incision was made with sterile instruments, after the site was prepared with povidone-iodine solution and isolated from the rest of the limb.

A transverse incision was initially made immediately proximal to the flare of the distal metaphysis, and was deepened onto the distal tibia. Using a sterile Gigli saw (National Veterinary Supplies, Stoke on Trent, UK), an osteotomy of the distal tibia was made, and the distal aspect of the nail and metaphysis were exposed. Tissue from the distal metaphysis (for qualitative bacteriology), and swabs of both the inside and outside of the implant were taken.

To expose the posterior aspect of the pin tracks, a longitudinal incision was made on the postero-medial side of the tibia, well away from the pin site wounds. The posterior cortex of the tibia was exposed at the site of the pin tracks, and samples were taken. The anterior cortex of the tibia was approached through a separate antero-lateral skin incision. A soft tissue flap was raised and reflected medially to expose the previous external fixator pin

sites, further specimens were then taken.

A medial approach to the stifle joint was made and samples of any fluid present taken for bacteriology. The top of the nail and proximal locking screw were exposed and swabbed. The screw was removed and an osteotomy of the proximal tibia was made with a second Gigli saw, and samples taken as described for the distal metaphysis. The IM nail was then removed, and placed in a sterile container for further analysis. The diaphysis of the tibia was dissected out, and prepared for histological examination.

Finally, a laparotomy was carried out to obtain biopsies of the deep inguinal lymph nodes for both bacteriology and histology, and the remainder of the carcass was then disposed of according to local regulations.

6.8 Bacteriological Analysis of Samples

All bacteriological specimens obtained from the animals were inoculated onto blood agar and MacConkey's agar plates (bioMérieux, Basingstoke, UK), and incubated aerobically at 37°C for 24 hours. In addition, inoculated blood agar plates were incubated anaerobically for 48 hours. At that stage they were analysed and sub-cultured as appropriate, and the plates re-incubated for up to 5 days to detect slow growing organisms.

All organisms obtained at primary culture were sub-cultured and identified. The presence of haemolysis on the plates was noted, and Gram staining (bioMérieux, Basingstoke, UK), oxidase testing (Bactident Oxidase test strips, Merck Ltd, Poole UK), and catalase testing (bioMérieux, Basingstoke, UK) were carried out. Final identification was made, based on biochemical characteristics, using appropriate API microbial identification systems (bioMérieux, Basingstoke, UK).

6.9 Radiological Examination

Initial pin insertion was carried out with the aid of image intensification (Siremobil 2, Siemens, Germany), and bicortical pin placement was confirmed. For the 14 day experiments (Chapters 7 & 8) lateral radiographs of the pin were taken after insertion, and at 7 and 14 days. These were taken using a mobile X-ray machine (Model R-20MO; Picker International, Ohio, U.S.A.), with the X-ray plate placed under the hindleg, with a film to

focus distance of 100 cm. All radiographs were obtained using Kodak T-MAT G/RA film, 24 x 30 cm, mounted in a Kodak X-omatic LW cassette with a Lanex Regular Screen (Eastman Kodak Company, Rochester, U.S.A.). The exposure settings remained constant for all radiographs (50 kV and 10 mAs), and films were developed immediately after exposure (Agfa-Gevaert processor model 94327131, Agfa G153 developer, G354 fixer; Agfa-Gevaert Ltd., Mortsel, Belgium). All radiographs were reviewed by a veterinary surgeon, with experience in animal radiology.

6.10 Histological Preparation of the Samples

All samples were initially placed in fixative containing 10% (w/v) buffered formaldehyde (Merck Ltd, Poole UK), for at least 14 days. The specimens were placed in a proprietary decalcifier (TBD-2, Shandon Scientific, Romford UK), until they could be trimmed with a scalpel. After trimming the sample, further decalcification, for approximately 2-3 weeks, was carried out in a saturated solution of ethylenediaminetetra-acetic acid (EDTA). The specimens were placed back into 10% (w/v) buffered formaldehyde, for 2-3 days to remove the residual EDTA.

Overnight processing was carried out, with alcohol dehydration followed by chloroform linked wax impregnation, using a commercially available processor (Tissue-Tek VIP - 1000 Vacuum Impregnation Process, Bayer PLC, Basingstoke, UK). Following this, the specimens were embedded in paraffin wax (Paramat, Merck Ltd, Poole UK), and after trimming, they were left to soak in hard tissue softener (glycerine - 43%, ethanol - 43%, distilled water -14%, Merck Ltd, Poole UK) for a further 7 days. Using a commercial microtome (Leica rotary microtome, Leica Microsystems Inc, Milton Keynes, UK), sections of approximately 5μm thickness were cut and stained with Haematoxylin and Eosin (Shandon Scientific, Romford, UK).

A pathologist, who was unaware of the details of the animal or the results of any radiological or bacteriological tests, examined all specimens. He was asked to determine whether a sample was infected, possibly infected or equivocal, or not infected, based on the presence of acute inflammatory changes, viable bacteria or microabscesses, and also to assess changes within the bone. Samples from both pin track as well as the diaphysis of the bone were examined.

Samples were described as infected if viable bacteria, microabscesses, or at least 5 polymorphonuclear leukocytes per high power field were present in at least 5 distinct microscopic fields. Possibly infected or equivocal was based on the presence of a number of polymorphonuclear leukocytes, but not at least 5 polymorphonuclear leukocytes per high power field, and not infected was when there was no microscopic evidence of bacteria, microabscesses, or an acute inflammatory reaction.

7. Secondary Intramedullary Nailing Following Pin Track Infection - Control group

7.1 Aim

The aim of this experiment was to assess the outcome of secondary IM nailing of an external fixator pin track infection in an animal model. No treatment was given to prevent the spread of infection.

7.2 Selection of Animal

Six mature, female, mixed breed sheep with a weight range 65-76kg (mean 69.7kg) were used.

7.3 Experimental Design

Secondary IM nailing was carried out as described in section 6.3.

7.4 Termination of the Experiment

All animals developed warm swollen stifle joints, and would not weight-bear approximately 1 week after IM nailing. All experiments were terminated, and the animals were killed, if they displayed signs of distress, or if a purulent discharge from the stiffle joint developed. Two animals were killed at 9 days following IM nailing (Animals 2 and 3 - purulent discharge), one animal was killed at 10 days (Animal 4 - abscess in stifle joint), and one animal was killed at 11 days (Animal 1 - abscess in stifle joint). The remaining 2 animals were killed at 12 days, after an abscess developed at the posterior aspect of the tibial shaft (Animals 5 and 6).

7.5 Results

7.5.1 Clinical findings at 48 hours and 7 days

The pin sites were examined 48 hours after the initial operation, and evidence of pin track infection was noted in all cases, with cellulitis present around the pins (Stage 2 - Harkess *et al.* 1996). One week following external fixation, deep infection was evident at all pin sites

(Stage 3 - Harkess *et al.* 1996).

7.5.2 Results at conversion to IM nail

7.5.2.1 Clinical findings

In 5 of the 6 animals evidence of pin track infection was still present at 14 days, with deep infection around both pins. In the 6th animal (Animal 6), although deep infection was present around the proximal pin, the distal pin did not appear clinically infected. This was despite the fact that both pins were inserted through the same skin incision, and both pins had been contaminated. In all animals, despite the presence of infection, the sutured portion of the wound, between the pins, had healed.

7.5.2.2 Pin loosening and extraction torque

All pins felt tight at the time of insertion, with no perceptible motion between pin and bone (Stage 1 - Burny 1984). After 14 days, at the time of extraction, all pins remained well fixed, with no evidence of loosening despite the presence of infection.

The extraction torque of the pins was reduced in 10 of the 12 pins (83%). The mean extraction torque of the pins at 14 days was 82% (range 63 - 100%) of the initial extraction torque.

7.5.2.3 Radiographic appearance

Radiographs taken at 14 days showed a periosteal reaction at 11 of the 12 (92%) pin sites. Bone lysis was evident at 1 of the pin sites (Animal 6 - proximal pin).

7.5.2.4 Bacteriological results at pin removal

Staphylococcus aureus was isolated from all 12 pin tracks, and in addition 7 other species of bacteria were identified.

The extraction torques, radiographic appearances and bacteriological results are presented in table 7.1.

Table 7.1 - Extraction torque, radiographic appearance and bacteriology at 14 days

Extraction torque at conversion expressed as a % of initial extraction torque

Animal	Pin	Extraction Torque at Conversion	Radiographic Appearance	Bacteriology
1	Proximal	69%	Periosteal Reaction	*Staphylococcus aureus* *Corynebacterium* *Alcaligenes faecalis*
	Distal	71%	Periosteal Reaction	*Staphylococcus aureus* *Corynebacterium*
2	Proximal	100%	Normal	*Staphylococcus aureus* *Proteus*
	Distal	73%	Periosteal Reaction	*Staphylococcus aureus* *Proteus*
3	Proximal	91%	Periosteal Reaction	*Staphylococcus aureus* *Corynebacterium* *Alcaligenes faecalis*
	Distal	100%	Periosteal Reaction	*Staphylococcus aureus* *Corynebacterium*
4	Proximal	87%	Periosteal Reaction	*Staphylococcus aureus* *Corynebacterium*
	Distal	89%	Periosteal Reaction	*Staphylococcus aureus* *Corynebacterium*
5	Proximal	79%	Periosteal Reaction	*Staphylococcus aureus* *Pasturella haemolytica* *Gemmella morbillorum* *Escherichia coli* *Pantoea*
	Distal	90%	Periosteal Reaction	*Staphylococcus aureus* *Pantoea*
6	Proximal	63%	Periosteal Reaction and Lysis	*Staphylococcus aureus*
	Distal	68%	Periosteal Reaction	*Staphylococcus aureus*

7.5.2.5 Bacteriological results after reaming

There was no bacterial growth from any of the joints on entry, or from the proximal metaphysis or guide rod. *Staphylococcus aureus* was isolated from the reamers of 3 of the 6 (50%) animals. In a further animal (Animal 5), exchange of the IM nail was required as the initial implant was too long. Although there was no bacteriological growth from any of the routine swabs in this animal, additional swabs were taken from the first nail on removal. A swab from the inside of the first nail isolated *Staphylococcus aureus.* This demonstrates that widespread contamination of the medullary canal had occurred in at least 4 of the 6 (67%) animals. These data are illustrated in table 7.2.

Table 7.2 - Results of bacterial swabs at IM nailing

Staphylococcus aureus = *S. aureus*

Animal	**Guide Rod**	**7mm Reamer**	**8mm Reamer**	**9mm Reamer**	**Proximal Tibia after Reaming**	**Proximal Locking Screw after Drilling**
1	No growth	*S. aureus*	No growth	*S. aureus*	No growth	No growth
2	No growth	*S. aureus*	*S. aureus*	*S. aureus*	*S. aureus*	*S. aureus*
3	No growth	*S. aureus*	*S. aureus*	*S. aureus*	No growth	*S. aureus* *Corynebacterium*
4	No growth	No growth	No growth	No growth	No growth	No growth
5	No growth	No growth	No growth	No growth	No growth	No growth
6	No growth	No growth	No growth	No growth	No growth	No growth

7.5.3 Post-mortem results

7.5.3.1 Clinical findings

At post-mortem 5 of the 6 animals (83%) had purulent material in the stifle joint. In addition 4 animals (67%) had a separate abscess cavity at the posterior aspect of the pin sites (Figure 7.1). Of the remaining 2 animals, 1 had a clinically infected haematoma (Animal 6), and in the other necrotic tissue was noted posteriorly (Animal 1). The nail was clinically infected in all 6 animals, with purulent material and necrotic tissue around the full length of

the implant (Figure 7.2). The superficial pin tracks appeared to be healing satisfactorily in 4 of the 6 animals. In 1 animal (Animal 5), the tissue appeared very oedematous, and in a further animal (Animal 2) there was a separate abscess cavity anteriorly. This data is illustrated in table 7.3.

Figure 7.1 – Abscess posteriorly

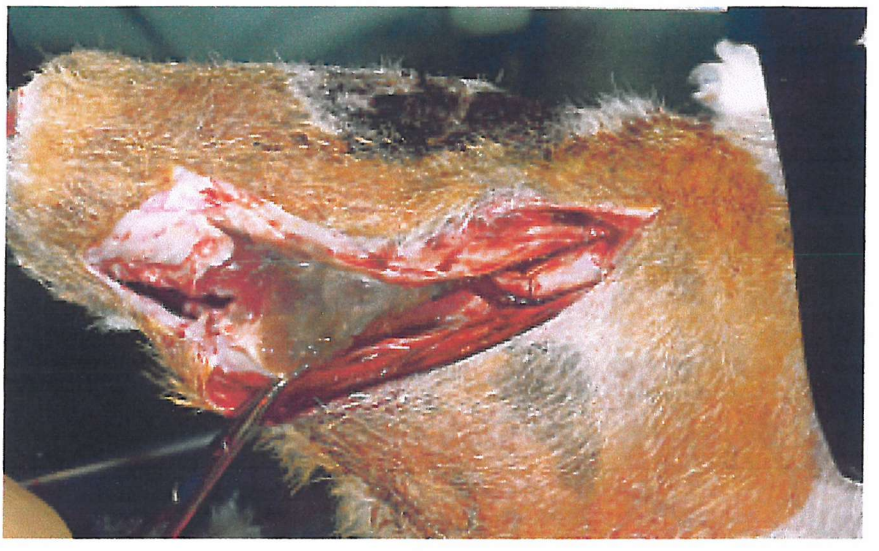
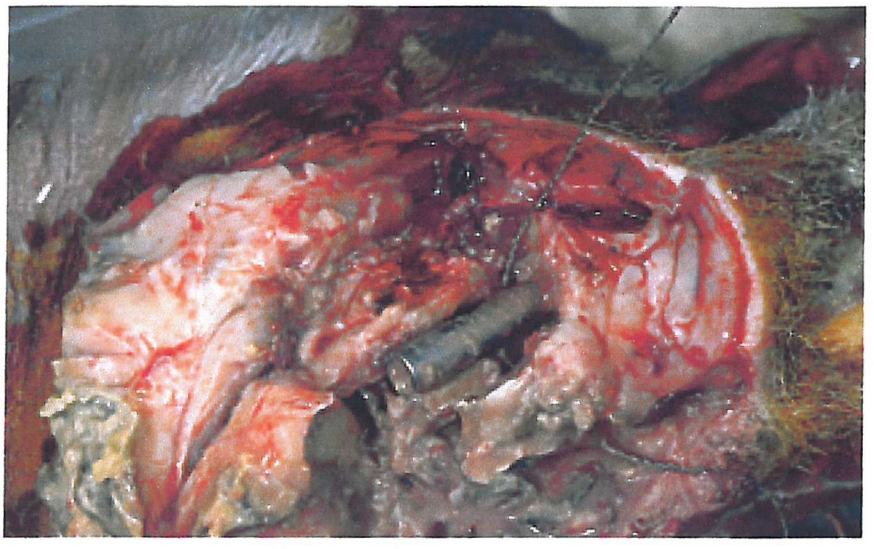


Table 7.3 - Clinical appearances at post-mortem

Animal	**Stifle Joint**	**Posterior Pin Track**	**Anterior Pin Track**	**Appearance of Implants**
1	Abscess	Necrotic Tissue	Healing	Infected
2	Abscess	Abscess	Abscess	Infected
3	Abscess	Abscess	Healing	Infected
4	Abscess	Abscess	Healing	Infected
5	Effusion	Abscess	Oedematous	Infected
6	Abscess	Infected haematoma	Healing	Infected

Figure 7.2a & b – Clinical evidence of infection along full length of implant



7.5.3.2 Radiological appearance

At post-mortem, a periosteal reaction was evident at all pin sites, and had progressed since the insertion of the nail. Bone lysis was present at 11 of the 12 (92%) pin sites, but there was no evidence of bone lysis around the nail.

7.5.3.3 Bacteriological results at post-mortem

Bacteriological results confirmed infection around the implant, within the stifle joint, and at the pin sites in all 6 animals. In addition bacteria were isolated from the inguinal nodes in 5 of the 6 (83%) animals. Only 1 of the 6 (17%) animals had the same species of bacteria isolated at both the time of IM nailing, and at post-mortem (Animal 2). Three of the 6 animals (50%) had additional bacteria isolated at post-mortem (Animals 4, 5 and 6). In 2 of the animals (33%) *Alcaligenes faecalis* was identified at IM nailing, but was not isolated from post-mortem specimens (Animals 1 and 3).

Staphylococcus aureus was isolated from the implant of all 6 animals, but was isolated from the stifle joint in only 3 of the 6 (50%) animals (Animals 3, 4 and 5). Five of the 6 (83%) animals had purulent material present, but a different organism was isolated in 3 of these animals (*Corynebacterium* spp. in Animals 1 and 6, and *Proteus* spp. Animal 2). Only 1 animal did not have purulent material within the joint, in this animal an effusion was present, from which *Staphylococcus aureus, Escherichia coli, Corynebacterium* spp. and *Staphylococcus auricularis* were isolated (Animal 5). The bacteriological findings at post-mortem are illustrated in table 7.4.

Table 7.4 - Bacteriological results at post-mortem

Staphylococcus = Staph.

Animal	**Stifle Joint**	**Implant**	**Pin Site**	**Inguinal Nodes**
1	*Corynebacterium*	*Staph. aureus* *Corynebacterium*	*Corynebacterium*	*Corynebacterium*
2	*Proteus*	*Staph. aureus* *Proteus*	*Proteus*	*Staph. aureus* *Proteus*
3	*Staph. aureus* *Corynebacterium*	*Staph. aureus* *Corynebacterium*	*Staph. aureus* *Corynebacterium*	*Staph. aureus* *Corynebacterium*
4	*Staph. aureus* *Corynebacterium* *Staph. haemolyticus*	*Staph. aureus* *Corynebacterium* *Staph. haemolyticus*	*Staph. aureus* *Corynebacterium* *Staph. haemolyticus*	*Corynebacterium* *Staph. haemolyticus*
5	*Staph. aureus* *Escherichia coli* *Corynebacterium* *Staph. auricularis*	*Staph. aureus* *Escherichia coli* *Corynebacterium* *Pepto-Streptococcus anaerobius*	*Staph. aureus* *Escherichia coli* *Corynebacterium*	*Staph. aureus* *Staph. capitus* Yeast
6	*Corynebacterium*	*Staph. aureus* *Corynebacterium*	*Staph. aureus* *Corynebacterium*	No growth

7.5.3.4 Histological results

Acute inflammatory changes were noted at all pin sites with viable bacteria and microabcess formation in a number of the samples. All histological specimens demonstrated bone lysis, and in the opinion of the pathologist all pin sites, and all samples from the diaphysis were infected (Figures 7.3 – 7.5).

Figure 7.3 – Infected pin track

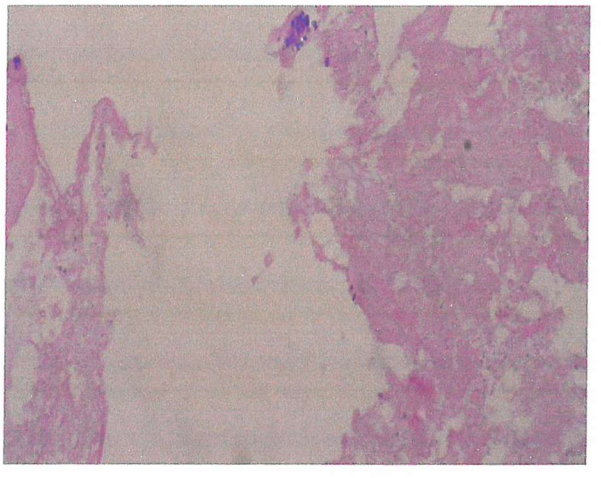


Figure 7.4 – Bone lysis

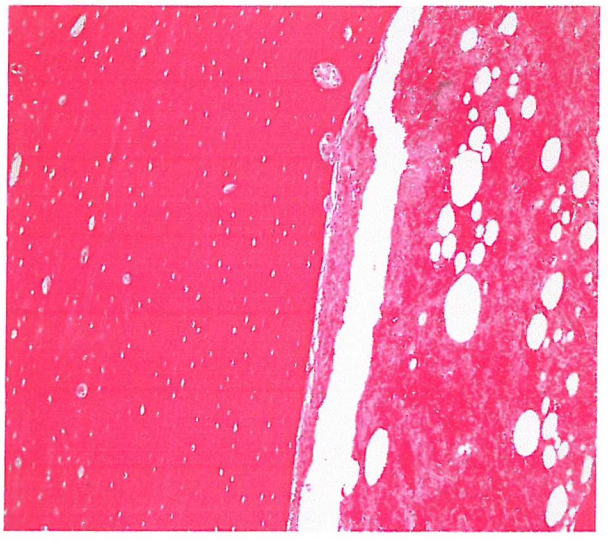
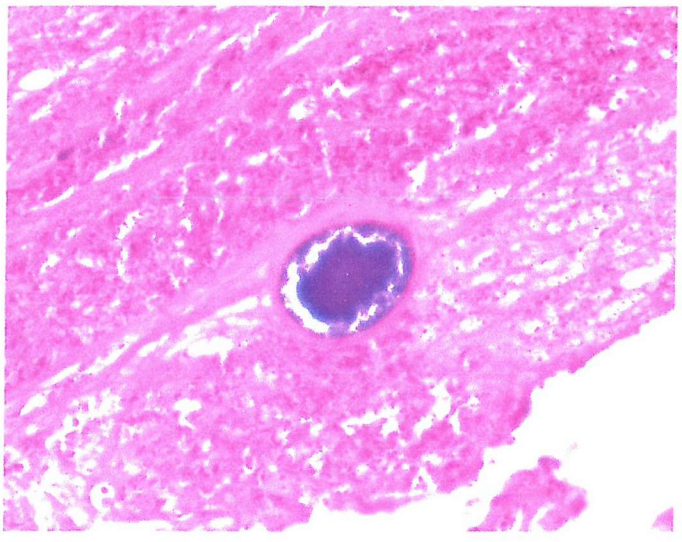


Figure 7.5 – Microabscess



7.6 Conclusion

This experiment has confirmed that widespread dissemination of infection occurs after IM nailing of an external fixator pin track infection. For early conversion to an IM nail to be accepted in the military environment, the pin tracks would have to be managed appropriately to prevent widespread infection. The effect of different treatment modalities can now be studied using this animal model.

8. Secondary Intramedullary Nailing Following Pin Track Infection - Treatment group

8.1 Aim

The aim of this experiment was to assess the effect of local and systemic treatment of a pin track infection, at the time of secondary IM nailing, on the dissemination of infection. Both local and systemic antibiotics were administered, as well as local surgical débridement.

8.2 Selection of Animal

Six mature, female, mixed breed sheep with a weight range 65-74kg (mean 71.2kg) were used.

8.3 Experimental Design

The basic surgical technique was the same as the control group described in section 6.3 but in addition, at the time of pin removal, tissue samples were taken from the posterior aspect of the tibia, at the pin tips. This was carried out through 2 small incisions at the postero-medial aspect of the tibia, and was performed to assess any spread of infection to the back of the tibia.

In addition, in this treatment group, local and systemic antibiotics were administered, as well as débridement of the pin tracks.

Antibiotic sensitivities were determined for all species of bacteria isolated in this experiment. The bacteria were cultured in the presence of antibiotic discs containing rifampicin 5μg, amoxicillin/clavulanic acid 30μg and gentamicin 120μg. Based on the appearance of the culture plate, the bacteria were classified as resistant (R), sensitive (S) or having some resistance (RS) to the antibiotic. This was based on the presence of a zone of inhibition around the disc, and the size and definition of the edge of the zone. Bacteria with some resistance to the antibiotics (RS) had a smaller zone of inhibition, and a less well defined edge than the bacteria that were sensitive to this antibiotic.

8.3.1 Local treatment of pin tracks

After removal of the external fixator, the pin sites were débrided. The skin edges and all granulation tissue were excised, and the superficial wound track was curetted (Figure 8.1). The pin tracks through bone were over drilled using a 5mm drill (RS Components Ltd, Corby, UK), and finally the wounds were lavaged with 1 litre of 0.9% saline solution (Animal Care Ltd, Dunnington, UK).

8.3.2 Systemic antibiotics

After removal of the external fixator, approximately 30 minutes prior to secondary IM nailing, intravenous co-amoxiclav 600mg (Augmentin - clavulanic acid 100mg/amoxycillin 500mg, Beecham Research, Welwyn Garden City UK) was administered. After IM nailing had been carried out, approximately 2 hours after the intravenous dose, clavulanic acid 105mg/amoxycillin 420mg (Synulox, Pfizer Limited, Sandwich, UK) was administered intramuscularly (approximately 9mg/kg). Synulox is an off-white suspension formulated for once daily administration to animals; it was administered for a total of 5 days after IM nailing.

8.3.3 Wound lavage

Conversion to an IM nail was carried as described in section 6.4, but prior to insertion of the implant, the stifle joint and intramedullary canal were washed with 1 litre of 0.9% saline containing 0.5% chlorhexidine gluconate (Zeneca, Winslow, UK). The medulla of the tibia was lavaged using a sterile disposable catheter (Pharma-Plast, Denmark) inserted down the nail track.

8.3.4 Local antibiotic administration

Gentamicin was administered locally, by the use of a bio-absorbable collagen sponge (Gentacoll, Schering-Plough Ltd, Welwyn Garden City, UK). A portion of the sponge containing 33mg of gentamicin was placed in the centre of the nail prior to insertion of the implant (Figure 8.2).

Figure 8.1 – Pin sites after débridement

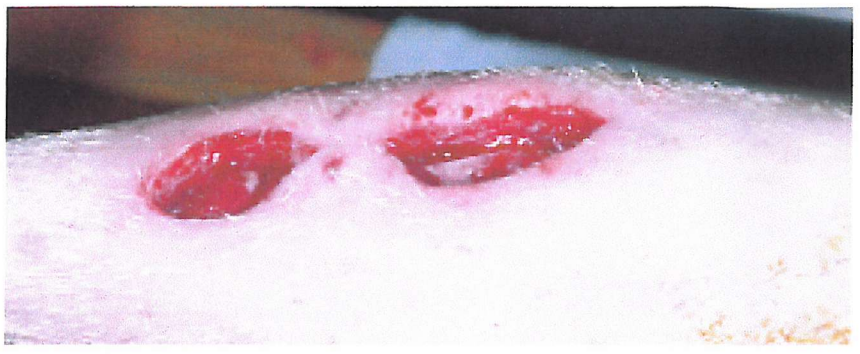
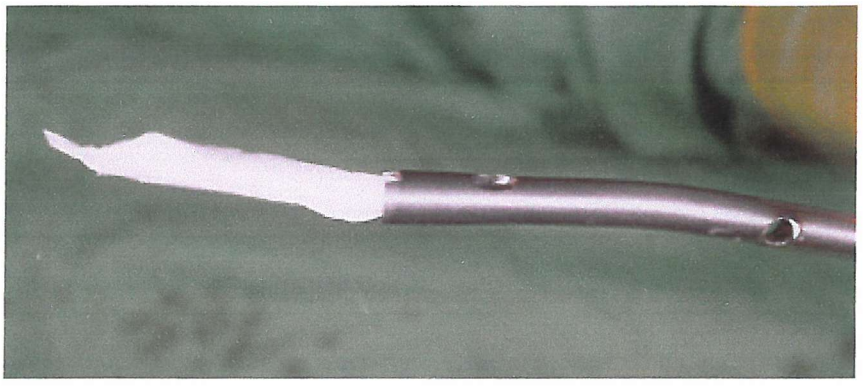
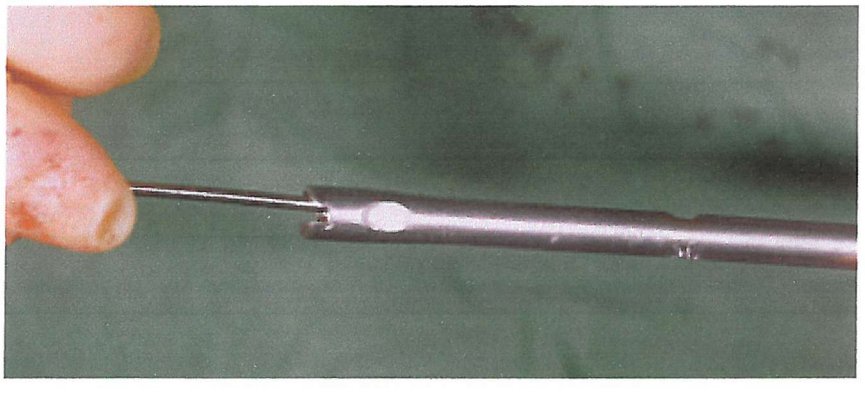


Figure 8.2a & b – Gentamicin impregnated collagen inserted into implant

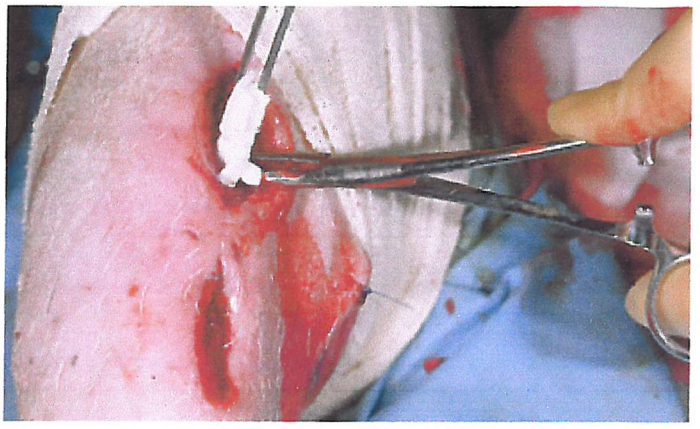




After IM nailing had been carried out, the surgical wound was sutured, and a sterile dressing was applied. The occlusive dressing over the pin sites was then removed, and further portions of the collagen sponge were inserted into the superficial wound track (Figure 8.3), and the posteromedial incision at the back of the tibia. A total of 33mg of gentamicin was administered to each of the 2 pin tracks.

A total of 100mg of gentamicin was administered locally to each animal.

Figure 8.3 - Gentamicin impregnated collagen inserted into superficial wound track

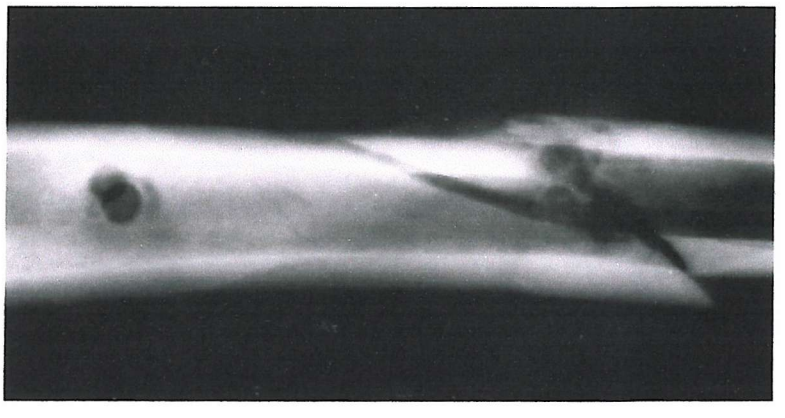


8.4 Complications

A number of complications occurred in this group of animals. In the immediate post-operative period, Animal 9 developed a large haematoma at the stifle wound that resulted in wound dehiscence. It was returned to the operating theatre for washout and resuturing. The wound subsequently healed without further problems.

Animal 10 was noted to be reluctant to weight-bear 17 days after IM nailing. This animal had previously been fully weight-bearing, had appeared well that morning, and had no clinical evidence of infection. The animal was anaesthetised, and a radiograph demonstrated a spiral fracture involving the distal pin site (Figure 8.4). It was killed at that stage, and a post-mortem was carried out.

Figure 8.4 – Radiograph of pathological fracture (after removal of implant)



Animal 7 was killed 22 days after IM nailing. This animal had always been reluctant to weight-bear, and when weighed 21 days after IM nailing, was noted to have lost approximately 10% of the original body weight (72kg to 65kg). Radiographs taken after death revealed a spiral fracture of the distal tibia. There was evidence of a periosteal reaction extending distally, and at post-mortem there was evidence of healing of the fracture; it is likely that this fracture occurred several days previously. There was no evidence of a fracture on the radiographs taken at 14 days. At post-mortem, this was the only animal of the treatment group to have widespread implant infection.

The remaining 4 animals were killed at 28 days and a post-mortem carried out.

8.5 Results

8.5.1 Results at 48 hours and 1 week

At 48 hours evidence of pin track infection was noted in all cases, with cellulitis present around the pins (Stage 2 - Harkess *et al.* 1996). One week following external fixation, deep infection was evident at all pin sites (Stage 3 - Harkess *et al.* 1996).

8.5.2 Results at conversion to IM nail

8.5.2.1 Clinical findings

In all 6 animals deep infection was still evident around both pins. Despite the presence of infection, in 5 of the 6 animals the portion of the skin wound between the pins had healed, resulting in 2 separate wounds. In the 6th animal (Animal 7), this had not occurred, and there was a single large wound.

8.5.2.2 Pin loosening and extraction torque

At 14 days, at the time of extraction, all pins remained well fixed (Stage 1 - Burny 1984), with no evidence of loosening despite the presence of infection. The extraction torque was reduced at all 12 pins. The mean extraction torque of the pins at 14 days was 82% (range 65 - 92%) of the initial extraction torque; this is similar to the mean extraction torque of the control group.

8.5.2.3 Radiographic appearance

A periosteal reaction was evident at 10 of the 12 pins (83%). There was no radiographic evidence of bone lysis in this group of animals.

Radiographs taken after the nail had been inserted showed that IM reamings had been extruded from the distal tibial pin site in 3 of the 6 animals (Figure 8.5).

8.5.2.4 Bacteriological results at pin removal

Staphylococcus aureus was isolated from all 12 pin tracks, and in addition 9 other species of bacteria were identified. The extraction torques, radiographic appearances and bacteriological results are presented in table 8.1.

Figure 8.5 – Extruded reamings from distal pin site

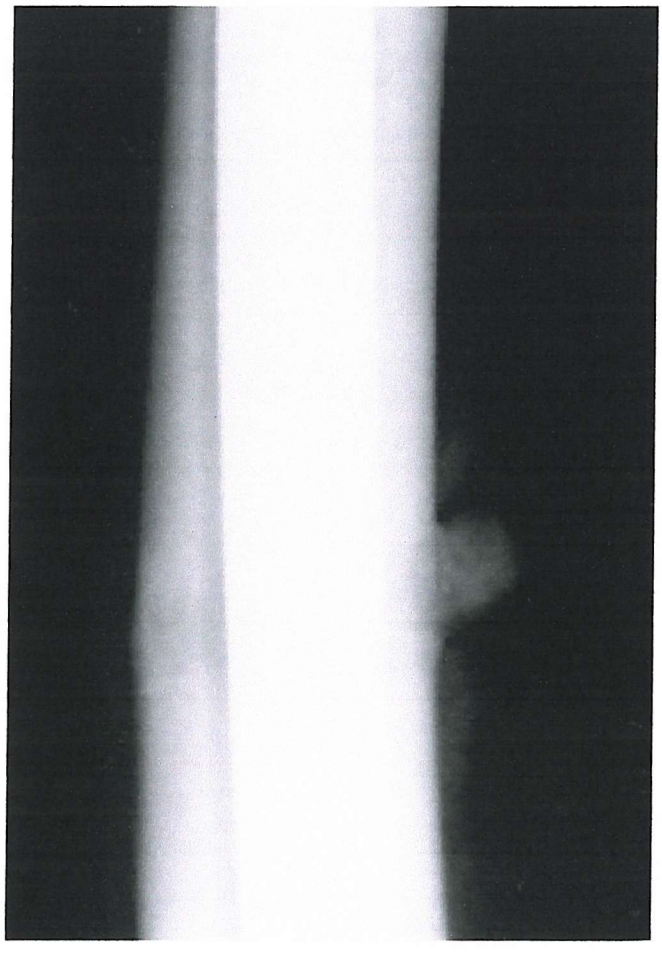


Table 8.1 - Extraction torque, radiographic appearance and bacteriology at 14 days

Extraction torque at conversion expressed as a % of initial extraction torque

Animal	**Pin**	**Extraction Torque at Conversion**	**Radiographic Appearance of Pin Track**	**Bacteriology**
7	Proximal	92%	Normal	*Staphylococcus aureus* *Micrococcus*
	Distal	78%	Periosteal Reaction	*Staphylococcus aureus*
8	Proximal	78%	Periosteal Reaction	*Staphylococcus aureus*
	Distal	91%	Periosteal Reaction	*Staphylococcus aureus* *Pasturella haemolytica* *Fusobacterium nucleatum*
9	Proximal	78%	Periosteal Reaction	*Staphylococcus aureus*
	Distal	90%	Periosteal Reaction	*Staphylococcus aureus*
10	Proximal	65%	Periosteal Reaction	*Staphylococcus aureus* *Pasturella haemolytica*
	Distal	86%	Periosteal Reaction	*Staphylococcus aureus*
11	Proximal	91%	Normal	*Staphylococcus aureus* *Escherichia coli*
	Distal	75%	Periosteal Reaction	*Staphylococcus aureus* *Escherichia coli*
12	Proximal	79%	Periosteal Reaction	*Staphylococcus aureus* *Escherichia coli* *Corynebacterium* *Gemella morbillorum* *Alcaligenes faecalis*
	Distal	80%	Periosteal Reaction	*Staphylococcus aureus* *Escherichia coli* *Staphylococcus* *chromogenes* *Corynebacterium ulcerans*

8.5.2.5 Bacteriological results after reaming

In 5 of the 6 animals (83%) there was no growth from specimens taken from the stifle joint on entry. In 1 animal (Animal 8) a single colony of *Staphylococcus aureus* was isolated from the stifle joint. There was no bacterial growth from the proximal metaphysis or guide rod in any of the animals. *Staphylococcus aureus* was isolated from the reamers of 5 of the 6 (83%) animals. This demonstrates that contamination of the medullary canal had occurred in at least 5 of the 6 (83%) animals, despite local treatment of the pin sites. These data are illustrated in table 8.2.

Table 8.2 - Results of bacterial swabs at IM nailing

Staphylococcus aureus = *S. aureus*

Animal	**Guide Rod**	**7mm Reamer**	**8mm Reamer**	**9mm Reamer**	**Proximal Tibia after Reaming**	**Proximal Locking Screw after Drilling**
7	No growth	No growth	No growth	*S. aureus*	No growth	No growth
8	No growth	*S. aureus*	*S. aureus*	No growth	No growth	No growth
9	No growth	*S. aureus*	No growth	Single colony *S. aureus*	No growth	No growth
10	No growth	No growth	No growth	No growth	No growth	No growth
11	No growth	*S. aureus*	No growth	No growth	No growth	No growth
12	No growth	*S. aureus*	*S. aureus*	*S. aureus*	*S. aureus*	No growth

8.5.3 Results at 2 weeks

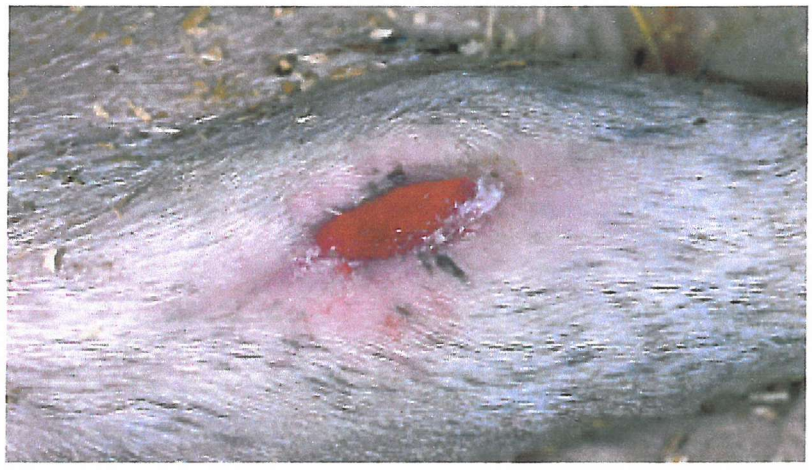
8.5.3.1 Clinical appearance

In all 6 animals the surgical wounds over the stifle joint and the postero-medial aspect of the tibia appeared to be healing satisfactorily. There was no evidence of sepsis, or effusion in the joint.

The single pin track wound in Animal 7 was healing, with contraction of the wound edges, and no evidence of infection (Figure 8.6). The remaining 5 animals had 2 separate pin track

wounds; in 1 of these animals (Animal 11) both wounds had healed, and in 2 other animals (Animal 8 and 10), one wound had healed and the other wound was healing without evidence of sepsis. In the remaining 2 animals (Animal 9 and 12) one of the wounds was healing without evidence of infection, but there was cellulitis around the second pin site.

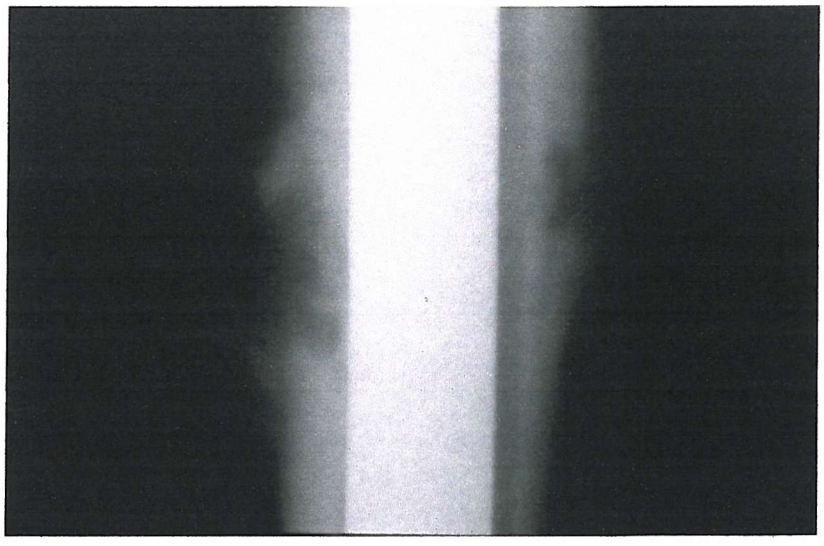
Figure 8.6 – Healing wound at 2 weeks



8.5.3.2 Radiographic appearance at 2 weeks

Radiographic changes advanced in all but one animal (Animal 11). In all other animals more extensive periosteal reaction and bone lysis were evident at all pin sites (Figure 8.7). In one animal (Animal 10) sclerosis was evident at the proximal pin site.

Figure 8.7 – Advanced radiographic features at 2 weeks



8.5.3.3 Bacteriological findings at 2 weeks

No bacteriological swabs were taken from animal 11 as the wounds had healed. In 2 other animals (Animals 8 and 10), both without evidence of infection, there was no bacterial growth. Bacteria were isolated from both animals with cellulitic pin sites (Animals 19 and 12). *Staphylococcus aureus* and *Aerococcus* spp. were isolated from the single wound in Animal 7. The clinical and radiographic appearances, and the bacteriological findings are presented in table 8.3.

Table 8.3 - Findings 14 days after IM nailing.

Animal	Pin	Clinical Appearance	Radiographic Appearance	Bacteriology
7	Proximal	Single Wound Healing	Periosteal Reaction and Lysis	*Staphylococcus aureus*
	Distal	Not Infected	Periosteal Reaction and Lysis	*Aerococcus* spp.
8	Proximal	Healed	Periosteal Reaction and Lysis	No Swabs Taken
	Distal	Healing	Periosteal Reaction and Lysis	No growth
9	Proximal	Healing	Periosteal Reaction and Lysis	*Staphylococcus aureus*
	Distal	Cellulitis	Periosteal Reaction and Lysis	*Staphylococcus auricularis* *Staphylococcus capitus*
10	Proximal	Healing	Periosteal Reaction, Lysis, Sclerotic Edge	No Growth
	Distal	Healed	Periosteal Reaction and Lysis	No Swabs Taken
11	Proximal	Healed	Normal	No Swabs Taken
	Distal	Healed	Periosteal Reaction unchanged	No Swabs Taken
12	Proximal	Healing	Periosteal Reaction and Lysis	No Swabs Taken
	Distal	Cellulitis	Periosteal Reaction and Lysis	*Staphylococcus aureus*

8.5.4 Post-mortem results

8.5.4.1 Clinical findings

The superficial pin tracks had healed in 3 of 6 (50%) animals (Figure 8.8), and appeared to be healing satisfactorily in a further 2 animals (Figure 8.9). In 1 animal (Animal 10) the distal wound had healed, but there was a serous discharge from the proximal wound. This was, however, the animal that the sustained the fracture that day.

Figure 8.8 – Healed superficial wounds

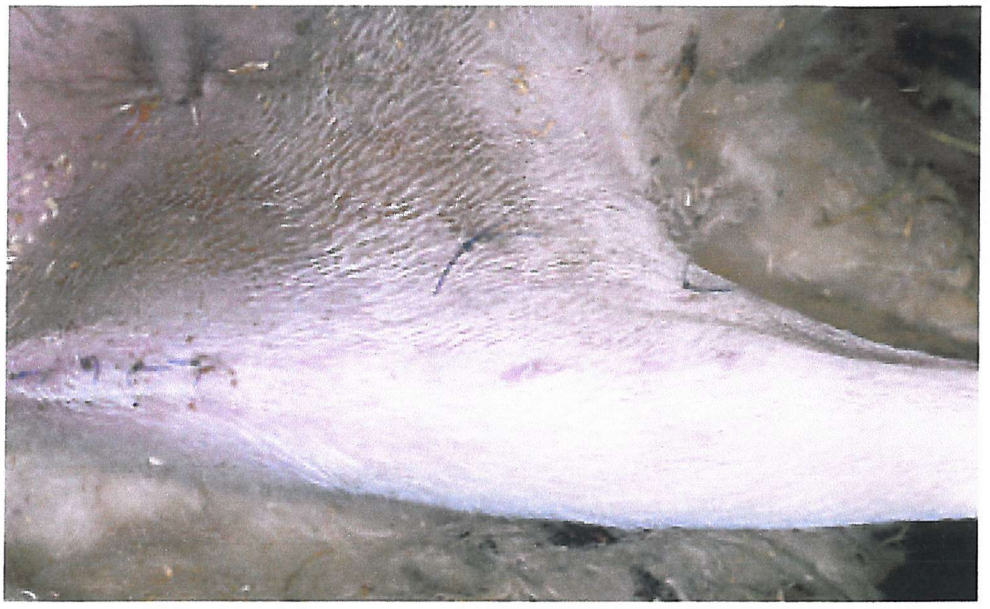
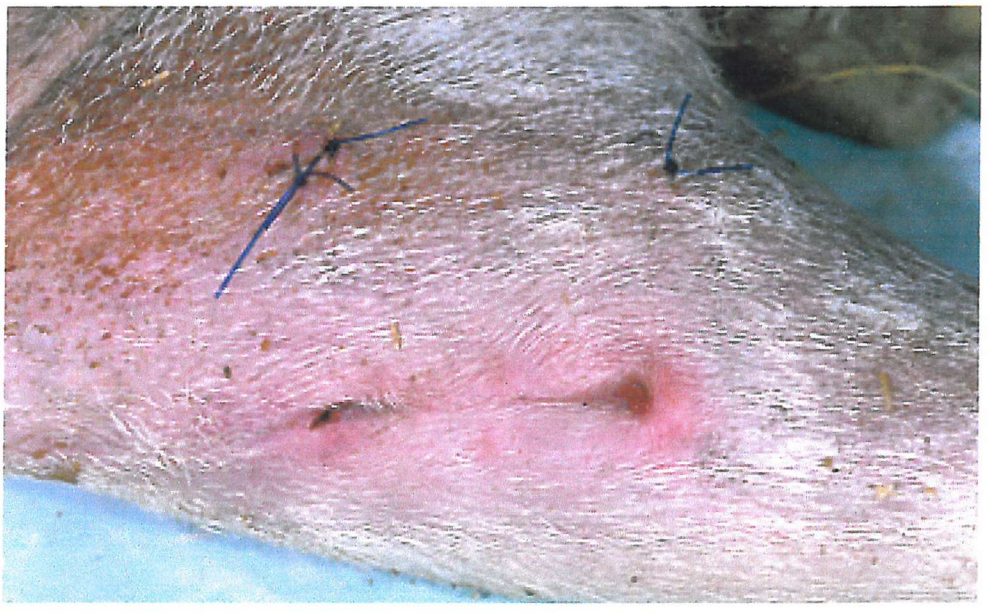


Figure 8.9 – Healing superficial wounds



None of the 6 animals had clinical evidence of infection in the stifle joint or at the posterior aspect of the pin sites (Figure 8.10). When the nail was removed from 2 animals (Animal 11 and 12) there was noted to oedematous, necrotic looking tissue on the surface of the implant. In the remaining 4 animals there was no clinical evidence of infection around the implant (Figure 8.11).

At post-mortem there was no clinical evidence of infection at the posterior aspect of the tibia of the pin sites. In all animals, however, there was oedematous tissue at the anterior aspect of the tibia (Figure 8.12). The clinical findings at post-mortem are presented in table 8.4.

Figure 8.10 – No clinical evidence of infection posteriorly

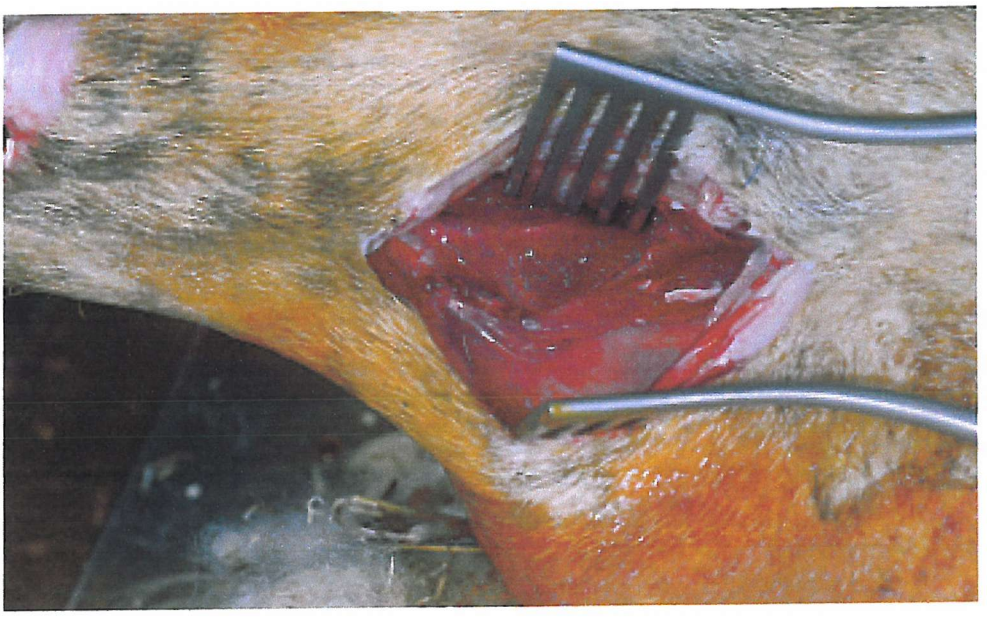


Figure 8.11 – No clinical evidence of infection around implant

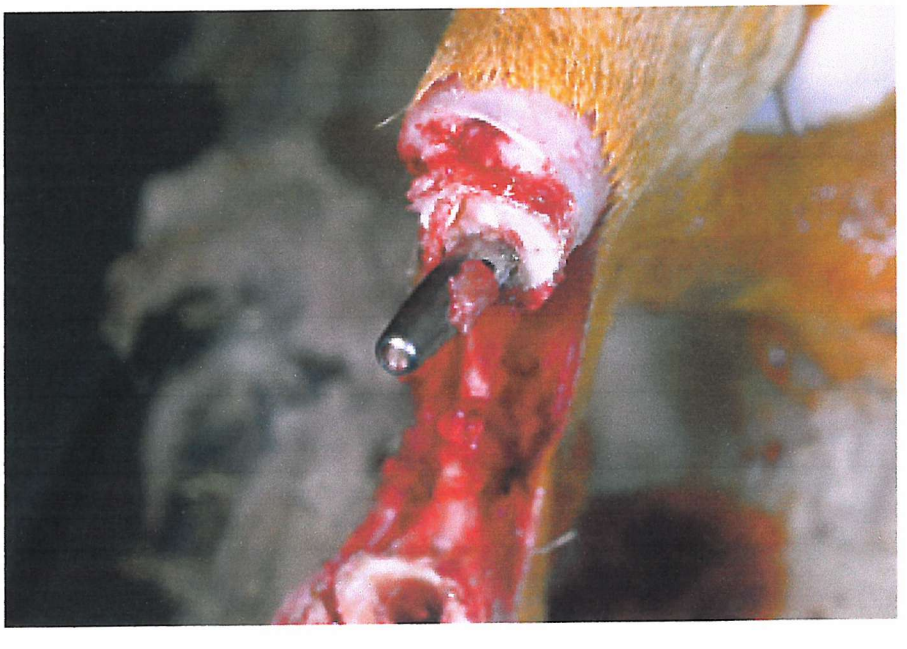


Figure 8.12 – Oedematous superficial pin tracks

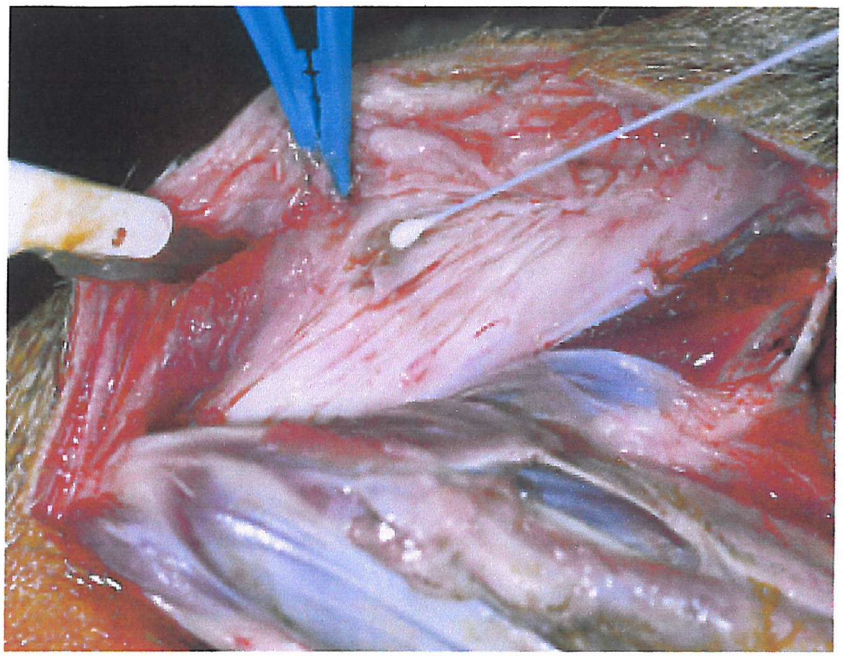


Table 8.4 - Clinical appearances at post-mortem

Animal	Superficial Wounds	Stifle Joint	Posterior Pin Track	Anterior Pin Track	Appearance of Implant
7	Healed	Not Infected	Not Infected	Oedematous ?Infected	Not Infected
8	Healing	Not Infected	Not Infected	Proximal ?Healing Distal ?Infected	Not Infected
9	Healed	Not Infected	Not Infected	Oedematous ?Infected	Not Infected
10	Proximal Discharge	Not Infected	Not Infected Fracture	Infected	Not Infected
11	Healed	Not Infected	Not Infected	Oedematous	?Infected
12	Healing	Not Infected	Haematoma	Not Infected	?Infected

8.5.4.2 Radiographic appearance

There was no radiographic abnormality around the implants in any animals. A spiral fracture of the distal tibia, involving the distal pin site was evident in 2 animals (Animals 7 and 10). In these 2 animals the appearance of the proximal pin site had not changed since the 2 week radiograph. The appearance of both pin sites in Animal 8 was also unchanged since the 2 week radiograph. There was evidence of increased bone lysis at the proximal pin site in 2 animals (Animal 11 and 12), and there was increased periosteal reaction and bone lysis at the distal pin site of animal 9.

8.5.4.3 Bacteriological results at post-mortem

There was no bacteriological evidence of infection in the stifle joint of any of the animals. Bacteria were isolated from the implants in only one animal (Animal 7); there was no growth form the swabs of the other animals, despite the clinical appearances.

Staphylococcus aureus was isolated from the posterior aspect of the tibia in only 2 animals (Animals 7 and 9). Both these animals had sustained fractures, and the organism was only isolated from the distal pin site. *Staphylococcus aureus* was isolated from the anterior part of both pin tracks from Animal 7, and from the distal pin site only in Animals 8, 9 and 10. The radiographic and bacteriological findings are shown in tables 8.5 and 8.6.

Staphylococcus aureus was isolated from the medulla of the distal tibia of Animal 12, despite the absence of growth from either the implant or the distal pin.

In addition to *Staphylococcus aureus,* a second species of bacteria was isolated from 3 of the animals at post-mortem. These organisms had not been isolated from the animals previously.

8.5.4.4 Antibiotic sensitivities

All aerobic bacteria isolated from the animals were sensitive to amoxicillin/clavulanic acid. *Aerococcus viridans* was isolated from the wounds of Animal 7, 2 weeks after IM nailing, and *Gemella morbillorum* was isolated from the proximal pin track of Animal 12 at the time

of pin removal. Both of these species were resistant to gentamicin, but neither species was isolated from the animals at post-mortem.

8.5.4.5 Histological results

Acute inflammatory changes consistent with active infection were present at all pin sites, suggesting that despite the bacteriological findings, chronic infection had persisted. The samples with the most advanced features of bone lysis were present in the distal pin tracks of the 2 animals that sustained the fractures (Animals 7 and 10). In addition microabscesses were evident at the distal pin track of Animal 9, which was also noted to have more advanced radiological features. In all 3 animals the clinical appearance also suggested that these pin sites had remained infected. Although the distal pin site of Animal 11 appeared infected on histological appearance, there was no bone lysis. This pin site did not appear clinically infected, bacterial cultures were negative, and the radiological appearances had not advanced. The histological findings, together with the clinical and radiological appearances, are shown in table 8.5.

Table 8.5 - Radiographic and bacteriological results of pin sites at post-mortem

Staphylococcus = *Staph.*

Animal	**Pin**	**Clinical Appearance**	**Radiographic Appearance**	**Bacteriology**	**Histological Appearance**
7	Proximal	?Infected	Unchanged	*Staph. aureus*	Infected - Bone Lysis
	Distal	?Infected	Fracture	*Staph. aureus* *Staph. chromogenes*	Infected - Bone Lysis and Bacteria
8	Proximal	Not Infected	Unchanged	No Growth	Infected - Bone Lysis
	Distal	Healing	Unchanged	*Staph. aureus*	Infected - Bone Lysis
9	Proximal	?Infected	Unchanged	No Growth	Infected - Bone Lysis
	Distal	?Infected	More advanced	*Staph. aureus*	Infected - Bone Lysis and Microabscesses
10	Proximal	?Infected	Unchanged	No Growth	Infected - Bone Lysis
	Distal	?Infected	Fracture	*Staph. aureus*	Infected - Bone Lysis
11	Proximal	Not Infected	Bone Lysis evident	No Growth	Infected - Bone Lysis
	Distal	Not Infected	Unchanged	No Growth	Infected
12	Proximal	Not Infected	Increased Lysis	No Growth	Infected - Bone Lysis
	Distal	Not Infected	Unchanged	No Growth	Infected - Bone Lysis

Table 8.6 - Bacteriological findings at post-mortem

Staphylococcus = *Staph.*; Proximal = Prox; Distal = Dist

Animal	**Stifle Joint**	**Implant**	**Pin Site**	**Superficial Wounds**
7	No Growth	*Staph. aureus* *Staph. chromogenes*	*Staph. aureus*	Healed - No swabs taken
8	No Growth	No Growth	Prox- No Growth Dist- *Staph. aureus*	*Staph. aureus* *Staph. simulans*
9	No Growth	No Growth	Prox- No Growth Dist- *Staph. aureus*	Healed - No swabs taken
10	No Growth	No Growth	Prox- No Growth Dist- *Staph. aureus*	Prox- *Staph. aureus* *Streptococcus acidominimus*
11	No Growth	No Growth	No Growth	Healed - No swabs taken
12	No Growth	No Growth	No Growth	No Growth

8.6 Summary of IM Nailing Experiments

The control group confirmed that widespread dissemination of infection occurred after IM nailing of an external fixator pin track infection. This has been compared with a treatment group when standard methods of infection control were utilised both before and after nailing.

In the control group, the animals were killed at a mean of 10.5 days following nailing, when widespread infection was evident, with septic arthritis, posterior abscess formation, and infection of the entire length of the tibia in all 6 animals. In the treatment group, none of the

6 animals had clinical evidence of infection in the stifle joint or at the posterior aspect of the pin sites and all surgical wounds healed without evidence of infection. When the nail was removed from 2 animals there was noted to oedematous, necrotic looking tissue on the surface of the implant, however, in the remaining 4 animals there was no clinical evidence of infection around the implant. Four of the 6 animals survived for 28 days, with the other 2 animals killed at 17 and 22 days after pathological fractures occurred.

At post-mortem, however, despite the improved clinical course, bacteriological samples were positive in 5 of the 6 animals and histological appearances demonstrated that infection was still present in all animals.

Therefore, treatment was successful at reducing, but not eliminating, infection after secondary nailing.

9. Discussion and Recommendations for Further Work

9.1 *In Vitro* Model

As discussed in chapter 5 this model can be compared to the clinical situation. The fracture pattern is consistent with clinical reports of ballistic fractures (Rose *et al.* 1988; Liu *et al.* 1988), and therefore the pattern of contamination may also be relevant to the clinical situation. This has demonstrated that external fixation can be safely carried out without the risk of inserting pins through contaminated tissue and, therefore, that secondary IM nailing is a possibility. The use of a fresh sheep tibia, with all soft tissues intact makes group 3 more clinically relevant, and further discussion on this model is given in chapter 5.

9.2 Selection of Animal for the *In Vivo* Model

Sheep have an incomplete fibula, and the tibia has a subcutaneous surface that allows external pin placement without damage to deeper structures (Getty 1975). The ovine tibia has been used as a long bone model for experiments involving external fixation (Hyldahl *et al.* 1991), IM nailing (Schemitsch *et al.* 1994), and plate fixation (Heitmeyer, Claes, Hierholzer *et al.* 1990). This is, therefore, an appropriate model to study secondary IM nailing after initial external fixation.

In this model, neither a fracture nor an osteotomy were created. With the small number of animals involved, it was felt that this may add a significant contributory factor that would make a true comparison difficult to make. In addition, the presence of an infected, potentially loose, pin with a fracture of the bone may cause unacceptable suffering to an animal.

This may be considered a major weakness of this study as instability at the fracture site has been shown to affect the infection rate following internal fixation (Friedrich and Klaue 1977). Due to the significance of instability, this experiment could be repeated with the addition of a fracture site. However as the control group of animals did badly despite the presence of an intact bone it could be considered unethical to repeat the experiment with the addition of a factor that would be likely to increase any distress to the animals. In addition despite the presence of stability, infection could not be eliminated in any animal in the treatment group and as this represents failure in a best-case scenario there would seem little indication to repeat the treatment group either.

9.3 Selection of Bacteria

In developing this model it was necessary to use a species of bacteria known to infect sheep, and therefore *Staphylococcus aureus* was used; staphylococci are pathogens of sheep (Buxton and Fraser 1977), and have been used previously in a sheep model of external fixator pin track infection (Clasper *et al.* 1999). This is a virulent bacteria, and causes external fixator pin track infections in man. Rommens *et al.* reported that 12 of 95 patients treated by external fixation developed a pin track infection, and *Staphylococcus aureus* was isolated from all 12 pin sites (Rommens, Broos, Stappaerts *et al.* 1988). In another report, virulent *Staphylococcus aureus* was the second most common bacterial species isolated from pins that were cultured at the time of removal (Mahan *et al.* 1991). Of 214 pins, 75% were colonised by bacteria, and *Staphylococcus aureus* was isolated from 37.5% of these pins (Mahan *et al.* 1991). Staphylococci are also the most common cause of implant infection and have been used previously to study infections involving IM nails (Curtis *et al.* 1995).

9.4 Selection of External Fixator Pin

The fixator used in these experiments was chosen as it was on general issue to the medical units of the British Army. The pins are designed to be self-drilling, but a 2.5mm pilot hole was required. It has been reported that the use of a pilot hole that is much smaller than the core diameter of the pin results in microfractures at the pin/bone interface (Perren, Cordey, Baumgart *et al.* 1992), and this may predispose to pin loosening or bacterial spread to the medulla. However, mechanical damage has been reported to occur irrespective of the size of the pilot hole, and the use of a 2.5mm pilot hole with a 4mm pin was not associated with a major fall in mechanical properties (Clary and Roe 1996).

9.5 Pin Loosening

All 24 pins were clinically tight at the time of removal (Stage 1 - Burny 1984), and the mean reduction in torque was the same in both groups (82% of original extraction torque). This confirms previous findings that clinical pin loosening is not necessary for a pin track infection to develop, and that, even with a well fixed pin, bacteria can spread to the medulla of the bone (Clasper *et al.* 1999). It is possible, however, that the reduction in stress at the

pin/bone interface, as a consequence of the tibia being intact, may have prevented or retarded pin loosening (Pettine *et al.* 1993).

In their paper Pettine *et al.* reported a reduction of 40% of the initial insertion torque after 40 days with an intact bone. This is similar to a clinical paper that documented a 35% reduction in torque after 45 days (Burny *et al.* 1984). There are no reports of either the measured or expected reduction of torque after 14 days, but it is unlikely that, given the above figures, there would not be a significant difference from the 18% reduction measured in this thesis.

9.6 Selection of Nail

A humeral nail was inserted, as the dimensions of this nail approximate to that of the sheep tibia. Previous reports have used a custom-built nail in the sheep tibia (Schemitsch *et al.* 1995), but the use of a humeral nail has been described (Hill *et al.* 1998). An intra-articular point of insertion was used; although a tibial nail would not normally be inserted through the knee joint, the shape of the humeral nail required a more posterior insertion point than with a tibial nail. Intra-articular insertion of an implant is required when retrograde femoral nailing is carried out, and a recent clinical report has described septic arthritis following nailing of a severe open fracture (Ostrum, DiCicco, Lakatos *et al.* 1998). The authors recommended caution when using an intra-articular entry point in the presence of severe contamination, and the findings in this study would support this view.

9.7 Control Group

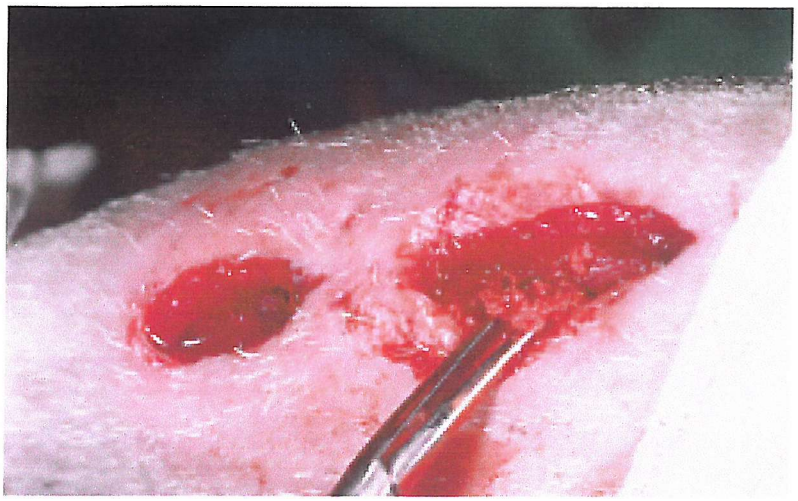
In the control group, widespread infection, with overwhelming local sepsis, developed in all animals after IM nailing. This has not been reported in the clinical situation, but this may be due to the administration of antibiotics, clinically, when the first signs of infection are evident. In addition, secondary IM nailing of an obviously infected pin track would not be carried out clinically, but was carried out in this experiment, to study the treatment of a pin track infection, at the time of secondary nailing. It has, however, confirmed the clinical finding of implant infection after secondary IM nailing with a history of pin track infection (Maurer *et al.* 1989), and allows the effect of treatment at the time of conversion to be studied.

In this model, strict precautions were taken to prevent infection from the superficial pin tracks contaminating the surgical field at the time of secondary IM nailing. The sterility of the

field was confirmed by the absence of bacterial growth from swabs of the stifle joint and proximal metaphysis. Only 1 colony of *Staphylococcus aureus* was isolated from 1 of the animals. Bacteriological swabs from the reamers, and at nail exchange, confirmed the widespread contamination of the bone and joint following reaming of the infected pin sites. Given the reported low sensitivity of bacteriological swabs (An and Friedman 1998), it is possible that widespread contamination occurred in all 12 animals after reaming.

Dissemination of infection occurred after reaming an infected pin track, and local abscess formation may well have been caused by the extrusion of infected reamings at the time of the procedure (Figure 9.1). In addition to extrusion of reamings out of the pin holes, reamings were pushed into the distal metaphysis, and this may have contributed to the widespread infection (Figure 9.2).

Figure 9.1a & b – Extruded reamings evident clinically and radiographically after nailing



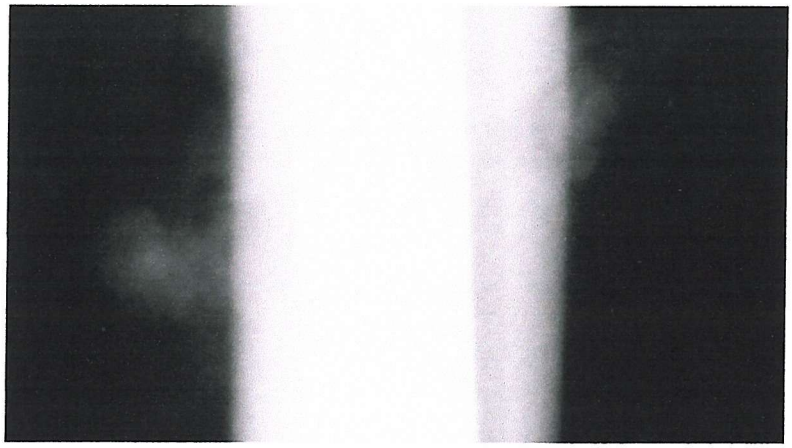
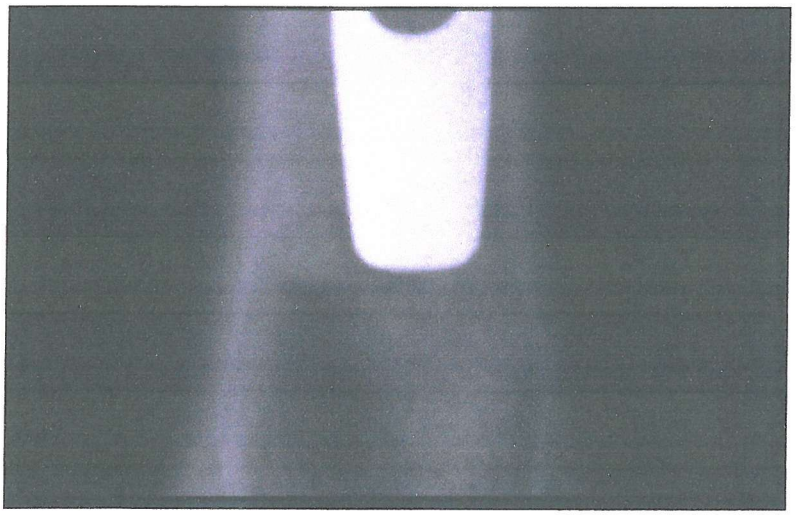


Figure 9.2 – Reamings pushed distally



In retrospect, the use of an unreamed technique may have reduced the spread of contamination proximally, but spread would have still occurred distally when the implant was inserted. Although the use of unreamed nails has been recommended for open fractures (Sanders *et al.* 1994), the use of these implants has led to specific problems. Unreamed nails are smaller, and have an increased rate of locking screw failure (Schandelmaier *et al.* 1995). In addition, a recent report on the use of unreamed nails documented that 36% of 55 implants could not be inserted without reaming, despite the measurement of pre-operative radiographs to identify the appropriate size of nail (Uhlin and Hammer 1998).

9.8 Treatment Group

Systemic antibiotics were administered prior to IM nail insertion, as recommended in the protocol for secondary IM nailing described by Blachut *et al.* (1990). Broad-spectrum antibiotics have been shown to be effective in reducing the incidence of infection after closed fractures (Boxma, Broekhuizen, Patka *et al.* 1996), and also open fractures (Patzakis *et al.* 1974). For these experiments, a combination of amoxicillin and clavulanic acid was chosen for its broad spectrum of activity, and the availability of a once daily preparation suitable for sheep. In retrospect this would appear to have been the correct choice, as all species of bacteria isolated were sensitive to this combination. The sensitivity of bacteria to rifampicin and gentamicin was also tested, as gentamicin was used locally, and rifampicin has been recommended for the treatment of implant infections (Zimmerli, Widmer, Blatter *et al.* 1998). There was some resistance to both of these antibiotics from bacteria isolated at IM nailing, but all species of bacteria isolated at post-mortem were sensitive to the antibiotics.

The use of local antibiotic therapy in addition to systemic antibiotics has been reported to reduce risk of chronic osteomyelitis after open fractures (Ostermann, Henry and Seligson 1995), and the prophylactic use of gentamicin has been reported to reduce the infection rate after joint replacement (Malchau and Herberts 1996). Gentamicin was therefore administered locally using a biodegradable collagen sponge.

Débridement of the pin tracks was carried out by overdrilling the pin tracks together with curetting and excision of infected soft tissues. Pin track débridement of both acute (Green 1983) and chronic infections (Green and Ripley 1984) has been recommended, together

with administration of systemic antibiotics. Despite local treatment of the pin tracks, at the time of reaming, *Staphylococcus aureus* was isolated from 5 of the 6 (83%) animals. This confirms that local treatment was inadequate in eliminating infection from the pin tracks, and demonstrates that lavage of the wound and antibiotics had an important role in preventing infection in the stifle joint.

Despite this débridement of pin tracks should still be considered at the time of pin removal, particularly when there is a history of infection. This may be carried out by overdrilling the pin track, or the use of a small curette introduced along the track. More extensive débridement should be considered with chronically infected pin tracks, loose pins or the presence of sclerosis on radiographs.

It is possible that the débridement of the pin tracks by overdrilling may have contributed to posterior abscess formation. However, given the radiographically visible reamings present posteriorly after reaming, it would appear more likely that this was the predominant factor.

Copious irrigation of open fractures with 0.9% saline has been recommended to reduce the incidence of subsequent infection (Gustilo and Anderson 1976), but there is no consensus on the volume of fluid required. In an experimental model, it has been shown that the addition of an antiseptic to the lavage solution increased the elimination of bacteria from the wound. The addition of chlorhexidine was noted to be more effective than hydrogen peroxide or iodine solutions (Taylor, Leeming and Bannister 1992). Chlorhexidine solution was therefore used to lavage the wounds and medullary canal prior to insertion of the implant.

It is possible, however, that this solution is toxic to bone or cartilage cells, and with a longer follow up, articular cartilage degeneration may have developed. In the absence of a fracture in these experiments, it is not possible to comment on the effect of this solution on fracture healing.

In the treatment group, at the time of pin removal, incisions were made at the posterior aspect of the pin sites. In a previous study infection was demonstrated at the posterior aspect of the tibia in only 20% of the pins (Clasper *et al.* 1999), and yet all animals in the IM nailing control group developed a posterior abscess. It was felt that this was due to the extrusion of reamings at the time of conversion, and to confirm the sterility of the posterior

tibia, additional samples were taken from this site prior to any treatment of the infected pins. There was no growth from the swabs or tissue samples from any of the 12 pin sites. It can be concluded that the posterior cortex of the tibia acts as a barrier to bacteria in the presence of a pin track infection, and that abscess formation was probably due to extruded infected reamings.

Posterior abscess formation has not been described in the clinical situation following a pin track infection, and may have developed, in this study, as a result of increased intramedullary pressure at the time of conversion. This increased pressure would be due to the intact bone; in the clinical situation, if reamings were extruded, it would be at the fracture site, and may be one cause of an infected fracture. In addition, posterior incisions were made in the treatment group to allow the insertion of gentamicin impregnated collagen sponge. It was possible to prevent abscess formation in the treatment animals, and this may have been due to the local and/or systemic antibiotics.

Infection persisted at the pin sites despite débridement. Chronic osteomyelitis of pin tracks has been reported despite removal of the pin and débridement, and these persisted in at least one third of cases despite further surgery (Green and Ripley 1984). It has been reported that chronic osteomyelitis of pin sites is usually due to retained necrotic bone (Edwards 1986), and even arthroscopic surgery has been used to allow direct inspection of the track and ensure all necrotic tissue is removed (Morgan-Jones, Burgert and Richardson 1998). It is possible, therefore, that the surgery carried out in this study was inadequate, and this contributed to the persistence of infection.

The persistence of infection is also related to the type of bone, as chronic osteomyelitis has only been reported in cortical bone, and not in cancellous bone such as found in the pelvis or calcaneus (Green 1981).

Although all 12 pin sites appeared infected histologically, the distal pins appeared to be more infected. In 2 animals fractures occurred through the distal pins, and in 2 further animals (Animals 8 and 9) clinical and histological features appeared more advanced. It has been reported that distal tibial pins are more likely to be chronically infected than proximal pins (Green and Ripley 1984), and the findings in this study would be consistent with this observation. This may be due to greater thermal necrosis when drilling thicker cortical bone. This is the reason for ensuring bicortical placement of pins, as transcortical placement is a

factor in chronic osteomyelitis (Green and Ripley 1984).

Thermal necrosis is one of the factors responsible for the bone cell death that is observed adjacent to an implant (Schatzker, Horne and Sumner-Smith 1975). This is also a factor in the establishment of infection, as bacteria must initially adhere to a susceptible surface, such as a foreign body or damaged tissue, before infection can occur (Gristina, Naylor and Myrvik 1991).

9.9 Bacteriology of Pin Track Infection

Staphylococcus aureus was isolated from all pin tracks, as well as a number of other species of bacteria. In both groups 5 of the 6 animals had additional species of bacteria isolated; only 1 animal in both groups was infected by only *Staphylococcus aureus*. In the control group 7 additional species of bacteria were isolated, compared with 9 additional species from the treatment group. This is similar to previous findings when developing the pin track infection model (Clasper *et al.* 1999). The polymicrobial nature of trauma wounds has been previously reported (Brook 1998), and this has major implications for the choice of antimicrobials.

Corynebacterium spp., a gram-positive rod, was isolated from animals in both experimental groups, and dissemination occurred in the control group after IM nailing. It is commonly isolated from the mucous membranes, gastrointestinal, and genitourinary tracks of healthy sheep, and is usually considered non-pathogenic (Buxton and Fraser 1977). Clinical problems can develop if predisposing factors produce a favourable local environment (Buxton and Fraser 1977). The infected IM nail may have produced such an environment, allowing the bacteria not only to become established, but also to become the predominant species of bacteria in some animals.

Escherichia coli, *Pasturella* spp. and *Alcaligenes faecalis* were also isolated from animals in both groups. Infection by these gram-negative enterobacteria may have been favoured by the choice of animal, or their normal living conditions, but wound infections by these bacteria has been reported in man (Robinson *et al.* 1989), particularly in the military environment (Lindberg *et al.* 1955).

It is possible that, *in vivo*, the presence of one species of bacteria allows another species to become established more easily. This could explain the presence of several different species of bacteria isolated from most samples. From one IM nail, *Staphylococcus aureus* was isolated as well *Escherichia coli, Corynebacterium* spp. and *Peptostreptococcus anaerobius* (part of the normal anaerobic ruminal flora).

9.10 Radiographic Appearance

Radiographs taken at the time of pin removal demonstrated a periosteal reaction at 21 of 24 (88%) pin sites, and bone lysis at 1 pin site. A periosteal reaction can occur in a number of pathological conditions including trauma and neoplasia, but it can be considered as an early radiographic sign of infection (An and Friedman 1998). In the control group, at a mean of 24.5 days after pin insertion, the periosteal reaction had become more pronounced, and bone lysis was visible at 11 of 12 (92%) pin sites. Bacteriological swabs confirmed that infection was still present, and suggest that a chronic infection had persisted despite removal of the pins 10 days earlier.

In the treatment group, antibiotics were administered together with débridement of the pin sites. Despite this, the periosteal reaction was more pronounced and bone lysis was present at 10 of the 12 (83%) pin sites 4 weeks after the pins were inserted. At post-mortem, although no microbiological evidence of infection was found in 5 of these 10 pins, the histological appearance did suggest that these pins were infected, consistent with the radiographic findings. The changes were, however, more florid when bacteria were isolated.

9.11 Histological Appearance

In the diagnosis of implant infection, histology has been considered as the gold standard by which other methods are compared (Atkins, Athanasou, Deeks *et al.* 1998). In animal models of implant infection, however, it has been stated that only the presence of microabscesses is definite histological evidence of infection (An and Friedman 1998). Histology is often used in combination with microbiology in the diagnosis of implant infection (Atkins, Athanasou, Simpson *et al.* 1996). The presence of a positive culture, together with acute inflammatory changes at histology, have been taken to indicate infection (Atkins *et al.* 1996). In the control group, there was no doubt about the presence of infection as clinical appearance and bacteriological findings confirmed the diagnosis. The histological

appearance was also consistent with infection, with acute inflammatory changes bacteria and in most cases microabscesses.

However, in the treatment group, histological features suggested that infection was present at all 12 pin sites at the time of post-mortem, despite no bacterial growth on cultures from 7 of the 12 pin sites. The low sensitivity of bacteriological swabs has been discussed previously (An and Friedman 1998), and even when tissue from débrided areas has been cultured, it has been reported that bacteria may not be isolated despite chronic infection (Perry, Pearson and Miller 1991). The results from the animals in this study add further weight to the belief that microbiology of chronic infection is inaccurate, and that histology is a more useful investigation (Padgett, Silverman, Sachjowicz *et al.* 1995).

9.12 Complications

Although widespread infection occurred in the control group, there were no other complications. Two major complications occurred in the treatment group, 2 animals sustained spiral fractures involving the distal pin hole. These can both be considered as pathological fractures, as bacteriological findings confirmed both pin tracks were chronically infected. Fracture of the tibia, through a chronically infected pin site, has been reported previously in man (Green 1981).

In retrospect, the use of distal locking screws through the nail may have increased the rotational stability of the bone, and would possibly prevented the fractures. A number of animal models of pin track infection have been described, but secondary IM nailing has not been reported in an animal model. It was therefore impossible to predict that this complication would have occurred in an animal model.

It is interesting to note that, in the treatment group, the only animal with widespread infection involving the implant had a fracture of several days duration. Unstable internal fixation, in the presence of bacterial contamination of the fracture site, has been shown in an animal model to increase the risk of infection (Worlock *et al.* 1994). It is possible that, in the absence of a fracture, the infection would not have become so widespread in this animal.

9.13 Future Work

9.13.1 Introduction

Despite the use of conventional methods of infection control, *Staphylococcus aureus* was isolated from 5 of the 6 animals in the treatment group, and histological features consistent with infection were present in all 6 animals. However all animals in the treatment group fared better than the control animals, as illustrated in table 9.1.

Table 9.1 - Overall comparison of control and treatment groups at post-mortem

	Control Group	**Treatment Group**
Mean Survival After Nailing	10.5 days	25 days
Infection in Surgical Wound	6 animals	0 animals
Infection Around Implant	6 animals	1 animal
Infection at Superficial Pin Track	6 animals	2 animals
Infected Pin Track Through Bone	12 pins	12 pins

The major problem with this technique is the persistence of infection in the pin tracks. This lead to pathological fractures in 2 of the animals, and if the study had been over a longer period may have lead to implant infection and possibly failure in all animals. This outcome is not good enough for the recommendation of this technique to the military casualty, and further methods of infection control must be considered.

9.13.2 Delay between removal of external fixator and secondary IM nailing

Some authors have advocated a period of time in plaster, or traction prior to secondary nailing (Blachut *et al.* 1990). This would be difficult to achieve in a sheep, although dividing the patellar tendon has been carried out to limit weight-bearing, after excessive pin loosening occurred (Gilbert, Dahners and Atkinson 1989). As pathological fractures occurred in 2 animals in the treatment group, despite the presence of an IM nail, there may be a high risk of fracture, and excessive suffering in animals managed by a delay in secondary IM nailing. In addition Törnqvist (1990) has demonstrated that secondary implant infection can occur despite a mean delay of 218 days after removal of external fixator, prior to IM nailing. This treatment protocol was, therefore, not studied in this model, and to further

develop this work it is necessary to prevent or treat an infected pin track prior to nailing.

9.13.3 Pin modification

As discussed, there are potential problems with the design of the external fixator pins used in these experiments. Different designs are available, and a different pin is now used by the British Army. The pin has a larger diameter, and 2 different thread diameters, which is designed to prevent cutting out of the thread of the near cortex when the cutting tip initially engages the far cortex. This may reduce the bacterial spread to the medulla, and future work could include an assessment of the effectiveness of the pin in this animal model.

In addition, the use of hydroxyapatite (HA) coating has been reported to improve the pin/bone interface and reduce loosening (Moroni, Orienti, Stea *et al.* 1996). There are, however, reports that HA coating may increase the risk of infection, as the positive charge on the bacteria may attract the negatively charged bacteria (Oga, Arizono and Sugioka 1993).

Recent reports have described the use of HA as a method of drug delivery for both chemotherapy (Itokazo, Sugiyama, Ohno *et al.* 1998), and antibiotics (Conceição, Martins, Goissis *et al.* 1998). The use of HA coated external fixator pins and antibiotic loaded HA could be assessed using this animal model.

The use of antiseptically coated external fixator pins in goats (Nelson, DeBerardino, Brooks *et al.* 1999), and IM nails in rabbits (Darouiche, Farmer, Chaput *et al.* 1998) has also been described recently, and it is likely that these modifications would reduce the risk of infection in this animal model. However, the optimum method of applying this coating, its durability and its shelf-life have yet to be determined (personal discussion with authors). This is vital information before the acceptance of this technique by the military.

In addition, tobramycin-impregnated polymethylmethacrylate sleeves for external fixator pins have been reported in a goat model (Voos, Rosenberg, Fagrhi *et al.* 1999). The sleeves were applied shortly after the pins were contaminated with *Staphylococcus aureus*, and prevented any of the pin sites from becoming infected. These sleeves could be applied after a pin track infection has developed, prior to secondary IM nailing. This may also reduce the risk of subsequent infection. One of the potential problems with the use of

antibiotics is the possibility of resistance developing, particularly as the antibiotic levels fall. Any of these possible options could be studied in this animal model.

9.13.4 Pinless fixation

Given that the main problem with secondary IM nailing is spread of infection from the superficial pin track infection, one possible solution is the pinless fixator, which grips, but does not penetrate the cortex of the bone (Figure 9.3). This technique would also facilitate subsequent nail insertion, as it holds the fracture in a reduced position, while the nail is inserted. Although the technique has potential in the trauma situation, a number of factors would compromise its usefulness in the military environment:

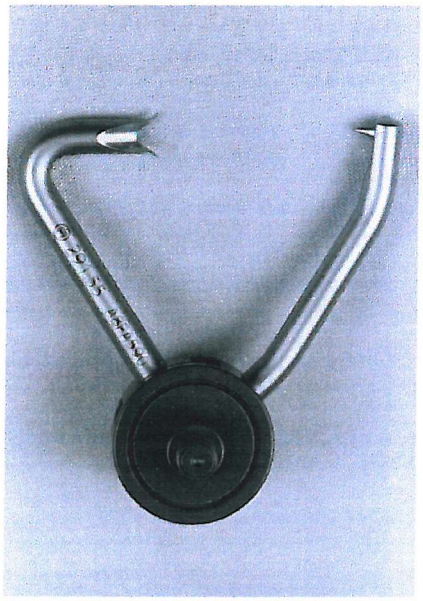
1. – The pinless fixator must only be seen as a temporary method of stabilisation, and it was not designed for the long-term treatment of fractures. With the potential logistic problems of the military environment, problems with casualty evacuation are likely to occur, particularly in a mass casualty situation. This may result in the fixator failing before definitive treatment can be instigated.

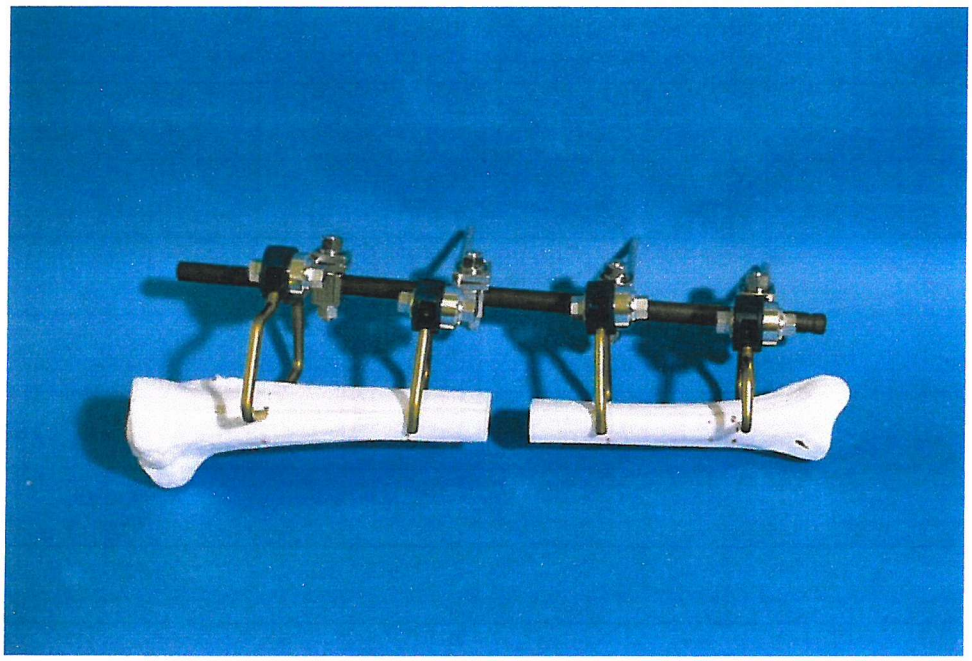
2. – The stability of the device may not be sufficient for casualty evacuation, particularly prolonged evacuation across rough terrain.

3. – Despite the absence of pins breaching the cortex of the bone, bacteria have been isolated from the medulla of 36% of patients treated by the pinless fixator (Winkler, Hochstein and Wentzen 1994). This would increase the infection risk if secondary IM nailing were carried out.

4. – The device is only suitable for the tibia, and only for fractures involving the shaft. With high-energy transfer wounds to the tibia significant comminution occurs, and there may be insufficient bone for pin insertion. With a conventional external fixator it is possible to bridge joints, utilising the bone above or below, e.g. inserting pins into the femur and/or foot for complex tibial fractures. This will not be possible with the pinless fixator, and further work is required to define its role in the treatment of military fractures.

Figure 9.3a & b – Pinless fixator, designed to grip rather than penetrate cortex





9.13.5 The use of electricity

It has been known for many years that electric current has an antibacterial role (Anderson and Finkelstein 1919), but also may affect the viability of bone (Friedenberg, Andrews, Smolenski *et al.* 1970). Provisional results show that it may be possible to limit bacterial spread, without affecting the stability of the pins, and further work is required in this field (Clasper 2000).

9.14 Summary

An animal model of secondary IM nailing of an external fixator pin track infection has been developed. If the pin track infection was not treated, widespread sepsis occurred in all animals after nailing, and this is consistent with the reported finding that implant sepsis after secondary nailing is due to a previous pin track infection (Maurer *et al.* 1989).

Using standard methods of treatment for a pin track infection, removal of the pin and systemic antibiotics, combined with thorough lavage and local antibiotic administration, it was possible to control the infection. Infection was eliminated in only 1 animal, but all animals in the treatment group did better than the control group.

This model of a pin track infection represents a worst case scenario. Any pin track infection developing in the military situation is likely to be less severe than in these animals, and it is unlikely that secondary IM nailing would be carried out in the presence of such clinically obvious sepsis. Despite the severity of the infection in the control animals, it could be controlled, and therefore, in the military environment, secondary IM nailing may be suitable for the treatment of ballistic fractures of the tibia, but further work is necessary.

10. Appendices

10.1 Contamination and Comminution of Ballistic Fractures (Chapter 5)

10.1.1 Leg 1

10.1.1.1 Extent and contamination of soft tissues

	Entry	Exit
Size of Skin Wounds	10 x 9mm	45 x 18mm
Macroscopic Extent of Damaged Skin	20 x 15mm	50 x 25mm
Contamination of Fascia	60 x 35mm	60 x 30mm

10.1.1.2 Extent of fracture

Length of Proximal Fragment	Length of Fracture	Length of Distal Fragment	Extent of Fracture (% of intact length)
7.5cm	8cm	4.5cm	40%

10.1.1.3 Contamination of fracture

	Proximally	Distally	Extent of Fracture Contamination (% of intact length)
Contamination of Fracture	15mm Proximal to Fracture	At Distal Extent of Fracture	48%

10.1.2 Leg 2

10.1.2.1 Extent and contamination of soft tissues

	Entry	Exit
Size of Skin wounds	9 x 7mm	16 x 11mm
Macroscopic Extent of Damaged Skin	15 x 11mm	22 x 16mm
Contamination of Fascia	90 x 30mm	65 x 30mm

10.1.2.2 Extent of fracture

Length of Proximal Fragment	Length of Fracture	Length of Distal Fragment	Extent of Fracture (% of intact length)
8cm	7.5cm	6.5cm	34%

10.1.2.3 Contamination of fracture

	Proximally	Distally	Extent of Fracture Contamination (% of intact length)
Contamination of Fracture	At Proximal Extent of Fracture	10mm Distal to Fracture	39%

10.1.3 Leg 3

10.1.3.1 Extent and contamination of soft tissues

	Entry	Exit
Size of Skin Wounds	8 x 7mm	16 x 10mm
Macroscopic Extent of Damaged Skin	18 x 12mm	24 x 16mm
Contamination of Fascia	35 x 25mm	35 x 25mm

10.1.3.2 Extent of fracture

Length of Proximal Fragment	Length of Fracture	Length of Distal Fragment	Extent of Fracture (% of intact length)
6.5cm	7.5cm	6.5cm	37%

10.1.3.3 Contamination of fracture

	Proximally	Distally	Extent of Fracture Contamination (% of intact length)
Contamination of Fracture	5mm Distal to Proximal Extent of Fracture	At Distal Extent of Fracture	34%

10.1.4 Leg 4

10.1.4.1 Extent and contamination of soft tissues

	Entry	Exit
Size of Skin Wounds	12 x 9mm	100 x 38mm
Macroscopic Extent of Damaged Skin	18 x 12mm	115 x 50mm
Contamination of Fascia	30 x 35mm	100 x 50mm

10.1.4.2 Extent of fracture

Length of Proximal Fragment	Length of Fracture	Length of Distal Fragment	Extent of Fracture (% of intact length)
6cm	9.5cm	5cm	46%

10.1.4.3 Contamination of fracture

	Proximally	Distally	Extent of Fracture Contamination (% of intact length)
Contamination of Fracture	At Proximal Extent of Fracture	At Distal Extent of Fracture	46%

10.1.5 Leg 5

10.1.5.1 Extent and contamination of soft tissues

	Entry	Exit
Size of Skin Wounds	11 x 11mm	85 x 32mm
Macroscopic Extent of Damaged Skin	15 x 15mm	95 x 42mm
Contamination of Fascia	60 x 40mm	150 x 50mm

10.1.5.2 Extent of fracture

Length of Proximal Fragment	Length of Fracture	Length of Distal Fragment	Extent of Fracture (% of intact length)
4.5cm	11.5cm	6cm	52%

10.1.5.3 Contamination of fracture

	Proximally	Distally	Extent of Fracture Contamination (% of intact length)
Contamination of Fracture	At Proximal Extent of Fracture	5mm Distal to Fracture	55%

10.2 Results of External Fixation Followed by Conversion to IM nail - No Treatment (Chapter 7)

10.2.1 Animal 1

10.2.1.1 Results up to removal of external fixator pins

Staph. = *Staphylococcus,* Torque = Nm

	Pin	
	Proximal	**Distal**
Clinical Appearance-48 hours	Superficial Cellulitis	Superficial Cellulitis
Clinical Appearance-2 weeks	Deep Infection	Deep Infection
Loosening (Burny 1984)	Stage 1	Stage 1
Initial Insertion Torque	1.3	1.4
Initial Extraction Torque	1.3	1.4
Final Extraction Torque	0.9	1.0
% of Initial Torque	69	71
Radiographic Appearance at 2 weeks	Periosteal Reaction	Periosteal Reaction
Bacteriological Results	*Staph. aureus* *Corynebacterium* spp. *Alcaligenes faecalis*	*Staph. aureus* *Corynebacterium* spp.

10.2.1.2 Bacteriological findings at IM nailing

Stifle Joint on Entry	No growth
Proximal Tibia	No growth
Guide Rod	No growth
7mm Reamer	*Staph. aureus*
8mm Reamer	No growth
9mm Reamer	*Staph. aureus*
Proximal Tibia after Reaming	No growth
Proximal Locking Hole	No growth

10.2.1.3 Results at post-mortem

	Appearance	**Bacteriological Findings**
Stifle Joint	Purulent Material	*Corynebacterium* spp.
Posterior Pin Track	Necrotic Tissue	*Corynebacterium* spp.
Anterior Pin Track	Healing	*Staph. aureus* *Corynebacterium* spp.
Implant	Infected	*Staph. aureus* *Corynebacterium* spp.
Inguinal Lymph Nodes		*Corynebacterium* spp.

10.2.1.4 Radiographic appearance

	Radiographic Appearance
Proximal Pin Track	Bone Lysis, Periosteal Reaction
Distal Pin Track	Bone Lysis, Periosteal Reaction

10.2.2 Animal 2

10.2.2.1 Results up to removal of external fixator pins

Staph. = *Staphylococcus*, Torque = Nm

	Pin	
	Proximal	**Distal**
Clinical Appearance-48 hours	Superficial Cellulitis	Superficial Cellulitis
Clinical Appearance-2 weeks	Deep Infection	Deep Infection
Loosening (Burny 1984)	Stage 1	Stage 1
Initial Insertion Torque	1.2	1.1
Initial Extraction Torque	1.3	1.1
Final Extraction Torque	1.2	0.8
% of Initial Torque	92	73
Radiographic Appearance at 2 weeks	Normal	Periosteal Reaction
Bacteriological Results	*Staph. aureus* *Proteus* spp.	*Staph. aureus* *Proteus* spp.

10.2.2.2 Bacteriological findings at IM nailing

Stifle Joint on Entry	No growth
Proximal Tibia	No growth
Guide Rod	No growth
7mm Reamer	*Staph. aureus*
8mm Reamer	*Staph. aureus*
9mm Reamer	*Staph. aureus*
Proximal Tibia after Reaming	*Staph. aureus*
Proximal Locking Hole	*Staph. aureus*

10.2.2.3 Results at post-mortem

	Appearance	**Bacteriological Findings**
Stifle Joint	Purulent Material	*Proteus* spp.
Posterior Pin Track	Purulent Material	*Proteus* spp. *Escherichia coli*
Anterior Pin Track	Purulent Material	*Proteus* spp.
Implant	Infected	*Staph. aureus* *Proteus* spp.
Inguinal Lymph Nodes		*Staph. aureus* *Proteus* spp.

10.2.2.4 Radiographic appearance

	Radiographic Appearance
Proximal Pin Track	Periosteal Reaction
Distal Pin Track	Bone Lysis, Periosteal Reaction

10.2.3 Animal 3

10.2.3.1 Results up to removal of external fixator pins

Staph. = *Staphylococcus,* Torque = Nm

	Pin	
	Proximal	**Distal**
Clinical Appearance-48 hours	Superficial Cellulitis	Superficial Cellulitis
Clinical Appearance-2 weeks	Deep Infection	Deep Infection
Loosening (Burny 1984)	Stage 1	Stage 1
Initial Insertion Torque	2.2	1.2
Initial Extraction Torque	2.0	1.2
Final Extraction Torque	1.3	1.2
% of Initial Torque	65	100
Radiographic Appearance at 2 weeks	Periosteal Reaction	Periosteal Reaction
Bacteriological Results	*Staph. aureus* *Corynebacterium* spp. *Alcaligenes faecalis*	*Staph. aureus* *Corynebacterium* spp.

10.2.3.2 Bacteriological findings at IM nailing

Stifle Joint on Entry	No growth
Proximal Tibia	No growth
Guide Rod	No growth
7mm Reamer	*Staph. aureus*
8mm Reamer	*Staph. aureus*
9mm Reamer	*Staph. aureus*
Proximal Tibia after Reaming	No growth
Proximal Locking Hole	*Staph. aureus* *Corynebacterium* spp.

10.2.3.3 Results at post-mortem

	Appearance	**Bacteriological Findings**
Stifle Joint	Purulent Material	*Staph. aureus* *Corynebacterium* spp.
Posterior Pin Track	Purulent Material	*Staph. aureus* *Corynebacterium* spp.
Anterior Pin Track	Healing	*Staph. aureus* *Corynebacterium* spp.
Implant	Infected	*Staph. aureus* *Corynebacterium* spp.
Inguinal Lymph Nodes		*Staph. aureus* *Corynebacterium* spp.

10.2.3.4 Radiographic appearance

	Radiographic Appearance
Proximal Pin Track	Bone Lysis, Periosteal Reaction
Distal Pin Track	Bone Lysis, Periosteal Reaction

10.2.4 Animal 4

10.2.4.1 Results up to removal of external fixator pins

Staph. = *Staphylococcus,* Torque = Nm

	Pin	
	Proximal	**Distal**
Clinical Appearance-48 hours	Superficial Cellulitis	Superficial Cellulitis
Clinical Appearance-2 weeks	Deep Infection	Deep Infection
Loosening (Burny 1984)	Stage 1	Stage 1
Initial Insertion Torque	1.5	0.9
Initial Extraction Torque	1.5	0.9
Final Extraction Torque	1.3	0.8
% of Initial Torque	87	89
Radiographic Appearance at 2 weeks	Periosteal Reaction	Periosteal Reaction
Bacteriological Results	*Staph. aureus* *Corynebacterium* spp.	*Staph. aureus* *Corynebacterium* spp.

10.2.4.2 Bacteriological findings at IM nailing

Stifle Joint on Entry	No growth
Proximal Tibia	No growth
Guide Rod	No growth
7mm Reamer	No growth
8mm Reamer	No growth
9mm Reamer	No growth
Proximal Tibia after Reaming	No growth
Proximal Locking Hole	No growth

10.2.4.3 Results at post-mortem

	Appearance	**Bacteriological Findings**
Stifle Joint	Purulent Material	*Staph. aureus* *Corynebacterium glucuronolyticum* *Staphylococcus haemolyticus*
Posterior Pin Track	Purulent Material	*Staph. aureus* *Corynebacterium glucuronolyticum* *Staphylococcus haemolyticus*
Anterior Pin Track	Healing	*Staph. aureus* *Corynebacterium glucuronolyticum* *Staphylococcus haemolyticus*
Implant	Infected	*Staph. aureus* *Corynebacterium glucuronolyticum* *Staphylococcus haemolyticus*
Inguinal Lymph Nodes		*Corynebacterium* spp.

10.2.4.4 Radiographic appearance

	Radiographic Appearance
Proximal Pin Track	Bone Lysis, Periosteal Reaction
Distal Pin Track	Bone Lysis, Periosteal Reaction

10.2.5 Animal 5

10.2.5.1 Results up to removal of external fixator pins

Staph. = *Staphylococcus,* Torque = Nm

	Pin	
	Proximal	**Distal**
Clinical Appearance-48 hours	Superficial Cellulitis	Superficial Cellulitis
Clinical Appearance-2 weeks	Deep Infection	Deep Infection
Loosening (Burny 1984)	Stage 1	Stage 1
Initial Insertion Torque	2.4	1.9
Initial Extraction Torque	2.4	2.0
Final Extraction Torque	1.9	1.8
% of Initial Torque	79	90
Radiographic Appearance at 2 weeks	Periosteal Reaction	Periosteal Reaction
Bacteriological Results	*Staph. aureus* *Pasturella haemolytica* *Escherichia coli* *Gemella morbillorum* *Pantoea* spp.	*Staph. aureus* *Pantoea* spp.

10.2.5.2 Bacteriological findings at IM nailing

Stifle Joint on Entry	No growth
Proximal Tibia	No growth
Guide Rod	No growth
7mm Reamer	No growth
8mm Reamer	No growth
9mm Reamer	No growth
Proximal Tibia after Reaming	No growth
Proximal Locking Hole	No growth
First Nail at Exchange	*Staph. aureus* *Escherichia coli*

10.2.5.3 Results at post-mortem

	Appearance	Bacteriological Findings
Stifle Joint	Effusion	*Staph. aureus* *Escherichia coli* *Staphylococcus auricularis*
Posterior Pin Track	Purulent Material	*Staph. aureus* *Corynebacterium* spp *Escherichia coli*
Anterior Pin Track	Oedematous	*Staph. aureus* *Corynebacterium* spp *Escherichia coli*
Implant	Infected	*Staph. aureus* *Corynebacterium* spp. *Escherichia coli* *Peptostreptococcus anaerobius*
Inguinal Lymph Nodes		*Staph. aureus* *Staphylococcus capitus* Yeast

10.2.5.4 Radiographic appearance

	Radiographic Appearance
Proximal Pin Track	Bone Lysis, Periosteal Reaction
Distal Pin Track	Bone Lysis, Periosteal Reaction

10.2.6 Animal 6

10.2.6.1 Results up to removal of external fixator pins

Staph. = *Staphylococcus,* Torque = Nm

	Pin	
	Proximal	**Distal**
Clinical Appearance-48 hours	Superficial Cellulitis	Superficial Cellulitis
Clinical Appearance-2 weeks	Deep Infection	Not Infected
Loosening (Burny 1984)	Stage 1	Stage 1
Initial Insertion Torque	2.9	2.5
Initial Extraction Torque	2.9	2.5
Final Extraction Torque	1.5	1.7
% of Initial Torque	52	68
Radiographic Appearance at 2 weeks	Bone Lysis Periosteal Reaction	Periosteal Reaction
Bacteriological Results	*Staph. aureus*	*Staph. aureus*

10.2.6.2 Bacteriological findings at IM nailing

Stifle Joint on Entry	No growth
Proximal Tibia	No growth
Guide Rod	No growth
7mm Reamer	No growth
8mm Reamer	No growth
9mm Reamer	No growth
Proximal Tibia after Reaming	No growth
Proximal Locking Hole	No growth

10.2.6.3 Results at post-mortem

	Appearance	**Bacteriological Findings**
Stifle Joint	Purulent Material	*Corynebacterium* spp.
Posterior Pin Track	Infected Haematoma	*Staph. aureus* *Corynebacterium* spp.
Anterior Pin Track	Healing	*Staph. aureus* *Corynebacterium* spp.
Implant	Infected	*Staph. aureus* *Corynebacterium* spp.
Inguinal Lymph Nodes		No growth

10.2.6.4 Radiographic appearance

	Radiographic Appearance
Proximal Pin Track	Bone Lysis, Periosteal Reaction
Distal Pin Track	Bone Lysis, Periosteal Reaction

10.3 Results After Conversion to IM Nail - Treatment Group (Chapter 8)

10.3.1 Animal 7

10.3.1.1 Results up to removal of external fixator pins

Staph. = *Staphylococcus*, Torque = Nm

	Pin	
	Proximal	**Distal**
Clinical Appearance-48 hours	Superficial Cellulitis	Superficial Cellulitis
Clinical Appearance-2 weeks	Deep Infection	Deep Infection
Loosening (Burny 1984)	Stage 1	Stage 1
Initial Insertion Torque	1.25	1.8
Initial Extraction Torque	1.2	1.8
Final Extraction Torque	1.1	1.4
% of Initial Torque	92	78
Radiographic Appearance at 2 weeks	Normal	Periosteal Reaction Reamings Extruded
Bacteriological Results from Wound Track	*Staph. aureus* *Micrococcus* spp.	*Staph. aureus*
Bacteriological Results from Posterior Tibia	No Growth	No Growth

10.3.1.2 Antibiotic sensitivities - S = Sensitive

	Rifampicin 5μg	Amoxicillin/Clavulanic Acid 30μg	Gentamicin 120μg
Staph. aureus	S	S	S
Micrococcus spp.	S	S	S

10.3.1.3 Bacteriological findings at IM nailing

Stifle Joint on Entry	No growth
Proximal Tibia	No growth
Guide Rod	No growth
7mm Reamer	No growth
8mm Reamer	No growth
9mm Reamer	*Staph. aureus*
Proximal Tibia after Reaming	No growth
Proximal Locking Hole	No growth
Reamings from Distal Pin Wound	*Staph. aureus*

10.3.1.4 Results at 2 weeks

Pin Track	**Clinical Appearance**	**Bacteriology**	**Radiological Appearance**
Proximal	Single Wound	*Staph. aureus*	Bone Lysis Periosteal Reaction
Distal	Healing, Not Infected	*Aerococcus viridans*	Bone Lysis Periosteal Reaction

10.3.1.5 Antibiotic sensitivities at 2 weeks - S = Sensitive, RS = Some resistance

	Rifampicin 5μg	Amoxicillin/Clavulanic Acid 30μg	Gentamicin 120μg
Staph. aureus	S	S	S
Aerococcus viridans	S	S	RS

10.3.1.6 Results at post-mortem

	Appearance	**Bacteriological Findings**
Superficial Wounds	Healed	No Swabs Taken
Stifle Joint	Not Infected	No growth
Posterior Pin Track	Not Infected	Proximal – No growth Distal – *Staph. aureus*
Anterior Pin Track	Oedematous tissue ?Necrotic	*Staph. aureus* Both Pins
Implant	Not Infected	*Staph. aureus* *Staph. chromogenes*

10.3.1.7 Radiographic appearance

	Radiographic Appearance	**Histological Appearance**
Proximal Pin Track	Unchanged from 2 Weeks	Infected - Bone Lysis
Distal Pin Track	Fracture, Changes more Advanced than 2 Weeks	Infected - Bone Lysis and Bacterial Colonies
Shaft		Infected

10.3.1.8 Antibiotic sensitivities - S = Sensitive

	Rifampicin 5μg	Amoxicillin/Clavulanic Acid 30μg	Gentamicin 120μg
Staph. aureus	S	S	S
Staph. chromogenes	S	S	S

10.3.2 Animal 8

10.3.2.1 Results up to removal of external fixator pins

Staph. = *Staphylococcus,* Torque = Nm

	Pin	
	Proximal	**Distal**
Clinical Appearance-48 hours	Superficial Cellulitis	Superficial Cellulitis
Clinical Appearance-2 weeks	Deep Infection	Deep Infection
Loosening (Burny 1984)	Stage 1	Stage 1
Initial Insertion Torque	1.3	1.2
Initial Extraction Torque	1.15	1.1
Final Extraction Torque	0.9	1.0
% of Initial Torque	78	91
Radiographic Appearance at 2 weeks	Periosteal Reaction	Periosteal Reaction
Bacteriological Results from Wound Track	*Staph. aureus*	*Staph. aureus* *Pasturella haemolytica* *Fusobacterium nucleatum*
Bacteriological Results from Posterior Tibia	No Growth	No Growth

10.3.2.2 Antibiotic sensitivities - S = Sensitive

	Rifampicin 5μg	Amoxicillin/Clavulanic Acid 30μg	Gentamicin 120μg
Staph. aureus	S	S	S
Pasturella haemolytica	S	S	S
Fusobacterium nucleatum	Not Tested		

10.3.2.3 Bacteriological findings at IM nailing

Stifle Joint on Entry	Single colony - *Staph. aureus*
Proximal Tibia	No growth
Guide Rod	No growth
7mm Reamer	*Staph. aureus*
8mm Reamer	*Staph. aureus*
9mm Reamer	No growth
Proximal Tibia after Reaming	No growth
Proximal Locking Hole	No growth

10.3.2.4 Results at 2 weeks

Pin Track	**Clinical Appearance**	**Bacteriology**	**Radiological Appearance**
Proximal	Healed	No Swabs Taken	Bone Lysis Periosteal Reaction
Distal	Healing	No growth	Bone Lysis Periosteal Reaction

10.3.2.5 Results at post-mortem

	Appearance	**Bacteriological Findings**
Superficial wounds	Proximal – Healed Distal – Healing, small scab	No Swab Taken *Staph. aureus* *Staph. simulans*
Stifle Joint	Not Infected	No Growth
Posterior Pin Track	Not Infected	No Growth
Anterior Pin Track	Proximal – Oedematous, healing Distal – Oedematous, Infected	Proximal - No Growth Distal – *Staph. aureus*
Implant	Not Infected	No Growth

10.3.2.6 Radiographic appearance and histological appearance

	Radiographic Appearance	**Histological Appearance**
Proximal Pin Track	Unchanged from 2 Weeks	Infected - Bone Lysis
Distal Pin Track	Unchanged from 2 Weeks	Infected - Bone Lysis
Shaft		Equivocal

10.3.2.7 Antibiotic sensitivities - S = Sensitive

	Rifampicin 5μg	Amoxicillin/Clavulanic Acid 30μg	Gentamicin 120μg
Staph. aureus	S	S	S
Staph. simulans	S	S	S

10.3.3 Animal 9

10.3.3.1 Results up to removal of external fixator pins

10.3.3.2 *Staph.* = *Staphylococcus,* Torque = Nm

	Pin	
	Proximal	**Distal**
Clinical Appearance-48 hours	Superficial Cellulitis	Superficial Cellulitis
Clinical Appearance-2 weeks	Deep Infection	Deep Infection
Loosening (Burny 1984)	Stage 1	Stage 1
Initial Insertion Torque	1.8	3.0
Initial Extraction Torque	1.8	3.0
Final Extraction Torque	1.4	2.7
% of Initial Torque	78	90
Radiographic Appearance at 2 weeks	Periosteal Reaction	Periosteal Reaction Reamings Extruded
Bacteriological Results from Wound Track	*Staph. aureus*	*Staph. aureus*
Bacteriological Results from Posterior Tibia	No Growth	No Growth

10.3.3.3 Antibiotic sensitivities - S = Sensitive

	Rifampicin 5μg	Amoxicillin/Clavulanic Acid 30μg	Gentamicin 120μg
Staph. aureus	S	S	S

10.3.3.4 Bacteriological findings at IM nailing

Stifle Joint on Entry	No growth
Proximal Tibia	No growth
Guide Rod	No growth
7mm Reamer	*Staph. aureus*
8mm Reamer	No growth
9mm Reamer	Single colony - *Staph. aureus*
Proximal Tibia after Reaming	No growth
Proximal Locking Hole	No growth

10.3.3.5 Results at 2 weeks

Pin Track	**Clinical Appearance**	**Bacteriology**	**Radiological Appearance**
Proximal	Healing	*Staph. aureus*	Bone Lysis, Periosteal Reaction
Distal	Swollen, Cellulitis	*Staph. auricularis* *Staph. capitus*	Bone Lysis, Periosteal Reaction

10.3.3.6 Antibiotic sensitivities - S = Sensitive

	Rifampicin 5μg	Amoxicillin/Clavulanic Acid 30μg	Gentamicin 120μg
Staph. aureus	S	S	S
Staph. auricularis	S	S	S
Staph. capitus	S	S	S

10.3.3.7 Results at post-mortem

	Appearance	**Bacteriological Findings**
Superficial Wounds	Healed	No Swabs Taken
Stifle Joint	Not Infected	No Growth
Posterior Pin Track	Not Infected	No Growth
Anterior Pin Track	Oedematous ?Infected	Proximal – No Growth Distal – *Staph. aureus*
Implant	Not Infected	No Growth

10.3.3.8 Radiographic appearance

	Radiographic Appearance	**Histological Appearance**
Proximal Pin Track	Unchanged from 2 Weeks	Infected - Bone Lysis
Distal Pin Track	Changes More Advanced than 2 Weeks	Infected - Bone Lysis and Microabscesses
Shaft		Equivocal

10.3.3.9 Antibiotic sensitivities - S = Sensitive

	Rifampicin 5μg	Amoxicillin/Clavulanic Acid 30μg	Gentamicin 120μg
Staph. aureus	S	S	S

10.3.4 Animal 10

10.3.4.1 Results up to removal of external fixator pins

Staph. = *Staphylococcus,* Torque = Nm

	Pin	
	Proximal	**Distal**
Clinical Appearance-48 hours	Superficial Cellulitis	Superficial Cellulitis
Clinical Appearance-2 weeks	Deep Infection	Deep Infection
Loosening (Burny 1984)	Stage 1	Stage 1
Initial Insertion Torque	1.6	2.9
Initial Extraction Torque	1.7	2.9
Final Extraction Torque	1.1	2.5
% of Initial Torque	65	86
Radiographic Appearance at 2 weeks	Periosteal Reaction	Periosteal Reaction Reamings Extruded
Bacteriological Results from Wound Track	*Staph. aureus* *Pasturella haemolytica*	*Staph. aureus*
Bacteriological Results from Posterior Tibia	No Growth	No Growth

10.3.4.2 Antibiotic sensitivities - S = Sensitive

	Rifampicin 5μg	Amoxicillin/Clavulanic Acid 30μg	Gentamicin 120μg
Staph. aureus	S	S	S
Pasturella haemolytica	S	S	S

10.3.4.3 Bacteriological findings at IM nailing

Stifle Joint on Entry	No Growth
Proximal Tibia	No Growth
Guide Rod	No Growth
7mm Reamer	No Growth
8mm Reamer	No Growth
9mm Reamer	No Growth
Proximal Tibia after Reaming	No Growth
Proximal Locking Hole	No Growth

10.3.4.4 Results at 2 weeks

Pin Track	**Clinical Appearance**	**Bacteriology**	**Radiological Appearance**
Proximal	Healing	No Growth	Bone Lysis, Periosteal Reaction Sclerotic Rim
Distal	Healed	No Swabs Taken	Bone Lysis, Periosteal Reaction

10.3.4.5 Results at post-mortem

	Appearance	**Bacteriological Findings**
Superficial Wound – Proximal	Discharging	*Staph. aureus* *Streptococcus acidominimus*
- Distal	Healed	No Swabs Taken
Stifle Joint	Not Infected	No growth
Posterior Pin Track	Not Infected, Fracture Distally	*Staph. aureus* – distal only
Anterior Pin Track	Infected	*Staph. aureus* – distal only
Implant	Not Infected	No growth

10.3.4.6 Radiographic appearance and histological appearance

	Radiographic Appearance	**Histological Appearance**
Proximal Pin Track	Unchanged from 2 Weeks	Infected - Bone Lysis
Distal Pin Track	Fracture	Infected - Bone Lysis
Shaft		Equivocal

10.3.4.7 Antibiotic sensitivities - S = Sensitive

	Rifampicin 5μg	Amoxicillin/Clavulanic Acid 30μg	Gentamicin 120μg
Staph. aureus	S	S	S
Streptococcus acidominimus	S	S	S

10.3.5 Animal 11

10.3.5.1 Results up to removal of external fixator pins

Staph. = *Staphylococcus,* Torque = Nm

	Pin	
	Proximal	**Distal**
Clinical Appearance-48 hours	Superficial Cellulitis	Superficial Cellulitis
Clinical Appearance-2 weeks	Deep Infection	Deep Infection
Loosening (Burny 1984)	Stage 1	Stage 1
Initial Insertion Torque	1.2	0.8
Initial Extraction Torque	1.1	0.8
Final Extraction Torque	1.0	0.6
% of Initial Torque	91	75
Radiographic Appearance at 2 weeks	Normal	Periosteal Reaction
Bacteriological Results from Wound Track	*Staph. aureus* *Escherichia coli*	*Staph. aureus* *Escherichia coli*
Bacteriological Results from Posterior Tibia	No Growth	No Growth

10.3.5.2 Antibiotic sensitivities - S = Sensitive, R = Resistant

	Rifampicin 5μg	Amoxicillin/Clavulanic Acid 30μg	Gentamicin 120μg
Staph. aureus	S	S	S
Escherichia coli	R	S	S

10.3.5.3 Bacteriological findings at IM nailing

Stifle Joint on Entry	No Growth
Proximal Tibia	No Growth
Guide Rod	No Growth
7mm Reamer	*Staph. aureus*
8mm Reamer	No Growth
9mm Reamer	No Growth
Proximal Tibia after Reaming	No Growth
Proximal Locking Hole	No Growth

10.3.5.4 Results at 2 weeks

Pin Track	**Clinical Appearance**	**Bacteriology**	**Radiological Appearance**
Proximal	Healed	No Swabs Taken	Normal
Distal	Healed	No Swabs Taken	Unchanged from Pin Removal

10.3.5.5 Results at post-mortem

	Appearance	Bacteriological Findings
Superficial Wounds	Healed	No Swabs Taken
Stifle Joint	Healed	No Growth
Posterior Pin Track	Healed	No Growth
Anterior Pin Track	Oedematous	No Growth
Implant	?Infected	No Growth

10.3.5.6 Radiographic appearance and histological appearance

	Radiographic Appearance	Histological Appearance
Proximal Pin Track	Bone Lysis	Infected - Bone Lysis
Distal Pin Track	Unchanged from Pin Removal	Infected, but no lysis
Shaft		Equivocal

10.3.6 Animal 12

10.3.6.1 Results up to removal of external fixator pins

Staph. = *Staphylococcus*, Torque = Nm

	Pin	
	Proximal	**Distal**
Clinical Appearance-48 hours	Superficial Cellulitis	Superficial Cellulitis
Clinical Appearance-2 weeks	Deep Infection	Deep Infection
Loosening (Burny 1984)	Stage 1	Stage 1
Initial Insertion Torque	1.3	2.0
Initial Extraction Torque	1.2	2.0
Final Extraction Torque	0.95	1.6
% of Initial Torque	79	80
Radiographic Appearance at 2 weeks	Periosteal Reaction	Periosteal Reaction
Bacteriological Results from Wound Track	*Staph. aureus* *Escherichia coli* *Corynebacterium* spp. *Gemella morbillorum* *Alcaligenes faecalis*	*Staph. aureus* *Escherichia coli* *Staph. chromogenes* *Corynebacterium ulcerans*
Bacteriological Results from Posterior Tibia	No Growth	No Growth

10.3.6.2 Antibiotic sensitivities - S = Sensitive, R = Resistant, RS = Some Resistance

	Rifampicin 5μg	Amoxicillin/Clavulanic Acid 30μg	Gentamicin 120μg
Staph. aureus	S	S	S
Escherichia coli	R	S	S
Corynebacterium spp.	S	S	S
Gemella morbillorum	S	S	R
Alcaligenes faecalis	RS	S	S
Staph. chromogenes	S	S	S
Corynebacterium ulcerans	S	S	S

10.3.6.3 Bacteriological findings at IM nailing

Stifle Joint on Entry	No Growth
Proximal Tibia	No Growth
Guide Rod	No Growth
7mm Reamer	*Staph. aureus*
8mm Reamer	*Staph. aureus*
9mm Reamer	*Staph. aureus*
Proximal Tibia after Reaming	*Staph. aureus*
Proximal Locking Hole	No Growth

10.3.6.4 Results at 2 weeks

Pin Track	**Clinical Appearance**	**Bacteriology**	**Radiological Appearance**
Proximal	Healing	No Swab Taken	Bone Lysis, Periosteal Reaction
Distal	Cellulitis	*Staph. aureus*	Bone Lysis, Periosteal Reaction

10.3.6.5 Antibiotic sensitivities - S = Sensitive

	Rifampicin 5μg	Amoxicillin/Clavulanic Acid 30μg	Gentamicin 120μg
Staph. aureus	S	S	S

10.3.6.6 Results at post-mortem

	Appearance	**Bacteriological Findings**
Superficial Wounds	Proximal – Healed Distal – Small Scab	No Swab Taken Distal - No Growth
Stifle Joint	Not Infected	No Growth
Posterior Pin Track	Oedematous, Heamatoma	No Growth
Anterior Pin Track	Not Infected	No growth
Implant	?Infected	No Growth
Medulla of bone	?Infected Distally	*Staph. aureus* from distal tissue

10.3.6.7 Radiographic appearance and histological appearance

	Radiographic Appearance	**Histological Appearance**
Proximal Pin Track	Bone Lysis More Advanced	Infected - Bone Lysis
Distal Pin Track	Unchanged from 2 Weeks	Infected - Bone Lysis
Shaft		Equivocal

10.3.6.8 Antibiotic sensitivities - S = Sensitive

	Rifampicin 5µg	Amoxicillin/Clavulanic Acid 30µg	Gentamicin 120µg
Staph. aureus	S	S	S

10.4 Appendix 2 - Fracture Healing

10.4.1 Introduction

The majority of long bone fractures heal with the production of new bone and subsequent remodelling to restore the original form. This is different from many other tissues where permanent scar tissue is produced after injury. Most fractures heal by indirect bone healing, when loss of contact and movement between the fracture fragments results in external bridging callus forming to immobilise the fracture site.

Under certain circumstances direct or primary bone healing can take place; this occurs when there is no movement, and virtually no gap at the fracture site, and existing cells can bridge and repair the fracture. External bridging callus formation is not required.

10.4.2 Indirect bone healing

This can be divided into 3 main stages.

Stage 1 – Inflammation

The initial event after a fracture is the formation of a local haematoma. Periosteum is stripped from the bone for a variable distance, and along with disruption of the local blood supply, results in necrosis of the bone ends. Chemical mediators including Bone Morphogenic Protein and Prostaglandins (Aaron 1996) are released and attract additional inflammatory cells. Macrophages, fibroblasts and osteoclasts are also attracted. These cells join the pool of cells in and around the haematoma. Organisation of the haematoma takes place, and granulation tissue consisting of fibroblasts and new capillaries forms. During indirect fracture healing, osteoclasts remove necrotic bone from the end of the fracture fragments.

Stage 2 – Repair

This stage is characterised by the formation of external bridging callus, composed of disorganised woven bone, which contributes to the immobilisation of the fracture site.

Cells within the granulation tissue differentiate into cartilage producing cells. The

fibrocartilage content increases until most of the haematoma has been replaced, and the mechanical stability of the fracture increases. The fibrocartilage of the callus is gradually replaced by bone, by a process of endochondral ossification, with osteoblasts producing an extracellular matrix that is subsequently mineralised.

In some areas of the fracture, bone can form by intramembranous ossification, without the need for a cartilage precursor. This takes place adjacent to the fracture site, and results in a cuff of periosteal callus The cuff forms within the first weeks of the healing process, and increases the cross sectional area of the fracture. This provides a biomechanical advantage by increasing the lever arm, and may increase the stability of the fracture (Perren 1979).

Bone can also form by intramembranous ossification at the periphery of the callus. This will not occur until the fracture has been stabilised by the external callus, and therefore, will not be evident until several weeks after the fracture.

There are several theories to explain why cartilage forms before bone in a healing fracture. One theory is based on the rigidity and tolerance to strain of the different cells (Perren 1979), another states that cartilage production is related to blood supply; cartilage rather than bone is produced in areas of low oxygen tension (McKibbin 1978). It may be that both of these theories are in part correct. Cartilage forms initially and is gradually replaced by bone as a result of biomechanical factors; these are discussed in section 13.4. This replacement requires an adequate blood supply, and therefore bone will form initially at the periphery of the zone of injury, where the blood supply is restored first.

By the end of the repair stage, the fracture is united both clinically and radiologically. Fracture callus is still evident on radiographs.

Stage 3 - Remodelling

This progresses over months, or even years. The immature woven bone of the callus is gradually replaced by mature lamellar bone. The medullary canal is restored and radiologically the bone returns to a normal appearance.

10.4.3 Direct bone healing

Direct (or primary) bone healing occurs without external bridging callus being formed. This type of repair was noted after anatomical reduction and rigid fixation of fractures, and was described as 'autogenous welding' by Danis, one of the earliest advocates of rigid internal fixation (Schenk 1982).

Direct bone healing can only occur when there is no movement at the fracture site; in practice this usually requires compression of the fracture site, often with a lag screw. Despite the anatomical reduction and compression, there will not be complete bone to bone contact at all areas of the fracture site. In areas where the two sides of the fracture are in contact, remodelling will take place. Osteoclasts remove bone as a cutter cone traverses the fracture site. This cutter cone consists of a resorption cavity produced by osteoclasts. This defect is then reossified by osteoblasts lining the defect, and a new osteon is produced, bridging the fracture gap. Radiologically this will be seen as a gradual disappearance of the fracture line.

In other areas there will not be direct bone contact, and a gap will exist between the bone surfaces. Provided there is no movement, then direct fracture healing can still take place. New bone will be produced by osteoblasts, filling the gap with osteoid. Initially the trabeculae of this osteoid are orientated at 90 degrees to the long axis of the bone, as osteoblasts are dependent on the capillary ingrowth from the overlying periosteum and soft tissue. It should also be noted that the ends of the bone fragments still consist of necrotic bone following the injury, and therefore the fracture site is still mechanically weak. As remodelling occurs, the fracture gap will be replaced by living bone. Cutter cones will cross the fracture site, and the trabeculae of the new bone will be orientated along the long axis of the bone. The mechanical strength of the fracture will increase over a period of months as the remodelling progresses.

If the fixation device is removed before complete remodelling has occurred, refracture through the necrotic bone is possible. This has been described clinically, particularly after plate fixation of the radius or ulna (Hidaka and Gustilo 1984).

10.4.4 Movement at the fracture site

A number of studies have demonstrated that altering the local mechanical environment of a fracture site can affect indirect fracture healing. It has been shown that early weight-bearing after experimental tibial fractures improved healing with increased external callus production (Sarmiento, Schaeffer, Beckerman *et al.* 1977). Studies of human tibial fractures have demonstrated that several millimetres of displacement can occur at the fracture site, if it is dynamically loaded (Sarmiento, McKellop, Llinas *et al.* 1996). When the force was removed, this displacement corrected, and the original position was restored. Over subsequent weeks the maximal displacement possible reduced, as the fracture consolidated.

Excess motion at the fracture site can result in a hypertrophic non-union, where external callus has formed, but the fracture has not united (Stirling 1939; Rosen 1991).

These findings suggest that some motion at the fracture may be beneficial for healing, but when a threshold limit is exceeded, union is delayed. This was confirmed experimentally by Kenwright and Goodship (1989), using a sheep model with a fracture gap of 3mm, and the fracture splinted by an external fixator. When the fixator design was made less rigid, more proliferative callus was evident by 3 weeks post-operatively. In a further modification, controlled axial micromotion was applied to the fracture site from 1 week post-operatively. Micromotion of 0.5mm across the 3mm gap resulted in more proliferative callus compared with no applied micromotion; whereas an applied micromotion of 2mm was found to impair healing.

The stability of the external fixator, and thus the micromotion at the fracture site, appears to have a more important role than that of weight-bearing when an external fixator is applied. Goodship *et al.* (1993) using a sheep model, demonstrated that increasing the stability of an external fixator by reducing the offset, resulted in more weight-bearing in the limb. Despite the increase in weight-bearing that was possible, the healing rate of the fracture was slower than with a less stable configuration.

Perren (1979) has investigated the role of micromotion and of microstrain at the fracture site. Strain is defined as a change in length of a structure as a result of an applied force. Bone is a rigid structure and has a low tolerance to strain, failure will occur with elongation

of only 2% of its original length (or 2000μstrain). Cartilage is less rigid and will tolerate a greater strain (10-13% elongation); granulation tissue will tolerate 100% elongation.

Perren has suggested that tissue formation, and callus production, is stimulated by interfragmentary strain. There is a threshold level of microstrain for this differentiation, and as noted above there is a limit at which tissue failure occurs. Once a tissue has formed within the fracture gap, its mechanical properties (rigidity) will further affect the mechanical environment of the fracture by reducing the microstrain. This then favours the formation of a more rigid tissue. Granulation tissue is initially produced when there is gross motion at the fracture site. The soft fibrous callus will reduce movement at the fracture, and allow fibrocartilage to form. This fibrocartilage will further reduce movement at the fracture site, and allow a rigid structure such as bone to form. If there is no motion at the fracture site, then external bridging callus will not form, as the critical strain threshold will not be achieved. Rigid internal fixation, will therefore prevent the formation of callus.

This could, potentially, result in a failure of fracture healing. If a fracture has been reduced and fixed, but not compressed, micromotion can still occur at the fracture site. This may produce a strain that exceeds the tolerance of bone tissue (2%) and prevents direct healing. If the motion at the fracture site does not reach the threshold required to induce tissue differentiation; indirect bone healing will not occur, as no external bridging callus will be produced. Bone can respond to this situation by resorption of the fracture ends to increase the fracture gap and so reduce the strain acting on individual cells (Perren 1991). This may still be insufficient to allow healing, an atrophic non-union will occur, and the implant may fail.

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