ACUTE COMPARTMENT SYNDROME:

ITS EFFECT ON BONE BLOOD FLOW AND BONE UNION

MARGARET M McQUEEN

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DECLARATION

This thesis has been composed by myself and all the work is my own. I have not submitted the thesis in candidature for any other degree, diploma or professional qualification.

M M McQUEEN FRCS (Ed) Orth

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Abstract

Previous work on the acute compartment syndrome has concentrated on its effect on the soft tissues. A retrospective study demonstrated an increased likelihood of delayed union in tibial diaphyseal fractures complicated by acute compartment syndrome and it was suggested that this could be due to an effect on the bone blood flow.

Bone blood flow using microspheres, bone union histologically and the strength of bone healing with biomechanical testing were examined in a series of New Zealand white rabbits after tibial osteotomy with or without an induced acute compartment syndrome. Six weeks after osteotomy bone blood flow is significantly elevated in the group with acute compartment syndrome while the tibial blood flow in the control group has returned to normal indicating a delay in the normal progression of the recovery of bone blood flow after osteotomy. This is reflected in the biomechanical testing which demonstrated significantly weaker bone union at six weeks in the compartment syndrome group. Histologically at this stage the callus in the

experimental group is less mature than in the control group.

In the clinical study data was collected on 68 patients with acute compartment syndromes. Tibial diaphyseal fractures with clinical evidence of muscle necrosis took more than twice as long to unite as those without complications and delay to fasciotomy also caused a significant increase in union times.

The clinical study also examined the use of compartment pressure monitoring and validated the use of a ▲P measurement (diastolic pressure minus compartment pressure) of less than 30mm Hg as a threshold for decompression. Continuous compartment monitoring was shown to have a highly significant influence on the reduction of complications after acute compartment syndrome.

AIMS OF THE STUDY

Following a clinical observation of delayed bone union in tibial fractures complicated by acute compartment syndrome the main aim of this study is to examine the hypothesis that acute compartment syndrome causes a reduction in bone blood flow leading to a delay in bone union in the following ways:

1. To investigate the association between raised intracompartmental pressure, muscle blood flow and bone blood flow experimentally.
2. To investigate the relationship between raised intracompartmental pressure and bone union experimentally.
3. To examine the effect of the acute compartment syndrome on bone union clinically.

There were two further clinical aims:

1. To determine a critical intracompartmental pressure threshold for decompression in the acute compartment syndrome.
2. To investigate the usefulness of continuous intracompartmental pressure monitoring.

CHAPTER 1

1.1

Historical Review

It is now well over a century since the first description of ischaemic muscle contractures was published in the medical literature. The first actual report of this condition which is now known to be the end stage of acute compartment syndrome was attributed to Hamilton in 1850 by Hildebrand (1906) but Hamilton's original description has never been found. The credit for the first full description belongs to Richard von Volkmann and in deference to this the end stage of the acute compartment syndrome is commonly termed "Volkmann's contracture".

Following a few case reports, Volkmann published a summary of his views on the nature and aetiology of the condition in 1881. He stated that paralysis and contractures appeared after too tight bandaging of the forearm and hand, were ischaemic in nature and were caused by prolonged blocking of arterial blood. He considered the ischaemic process to be identical to rigor mortis and clearly differentiated the condition from contracture of nerve origin by pointing out that in ischaemic muscle contracture the paralysis and contracture appear simultaneously, while in paralysis of nerve origin the contracture takes some time to develop. He recognised the fact that muscle cannot survive longer

than six hours with complete interruption of its arterial supply and that twelve hours or less of too tight bandaging were enough to result in "dismal permanent crippling".

Leser contributed much to the knowledge of the condition in his article of 1884. He gave clear descriptions of seven clinical cases, was the first to introduce animal models of ischaemic contracture and described the histo-pathology of the contracted muscles.

Four years later Peterson (1888) published a report of a case with two interesting features. Firstly in the absence of bandaging Peterson felt that this contracture could not be attributed to constriction by dressings. He did not however postulate a cause. He also found neurological signs with entrapment of the median nerve by scar tissue at surgery.

The first major reports appeared in the English speaking literature in the early twentieth century. Wallis in 1901 was the first to suggest that swelling after removal of tight bandaging might contribute to the contracture but postulated that it was due to the extravasation of "fibrous - tissue-forming elements", and that "hyperaemia rather than anaemia is the cause of eventual contracture". This opinion is reflected by other authors around the same time (Dudgeon 1902, Rowlands

1905) but was then developed along the lines that the ensuing fibrosis was due to a myositic process.

At this time the first suggestion that raised pressure within muscle groups could be the basic pathological mechanism appeared. Hildebrand (1906) hypothesised that after injury or tight bandaging an "oedematous saturation" of muscles occurred which caused raised pressure in the area. Since this pressure was not initially sufficiently high to occlude the major arteries, it still allowed blood to continue to flow into the area and eventually the major vessels were compressed causing a reduction in flow and death of muscles.

Bardenheuer (1911) published a remarkably similar account of the sequence of events to that which is known today. He described the presence of fascial compartments and differentiated between acute ischaemia caused by major vessel rupture, acute ischaemia caused by "subfascial tension" without major arterial damage, the late stage of ischaemic contracture and the separate concept of nerve involvement. He was the first to describe the incision of fascia or fasciotomy to relieve pressure and pointed out that this should not be delayed until the pulse disappears or cyanosis develops. These views were repeated by Murphy in 1914 who stressed the importance of prophylaxis, particularly by fasciotomy performed within

24 - 36 hours. Still, however, the majority of Murphy's article was devoted to the treatment of the established contracture rather than to prevention or early recognition of the acute condition. He also stated his belief that the condition was due to venous rather than arterial obstruction.

This is a recurring theme over the next few decades. Brooks (1922) performed a large series of animal experiments and concluded that Volkmann's ischaemic contracture could only be explained on the basic of acute venous obstruction. He appreciated the presence of swelling in each case but did not relate this to the condition. Jepson (1926) was the first to consider seriously the possibility of preventing deformity occurring. He performed a series of animal experiments and showed that decompression prevented the development of contractures. He concluded that no one factor was responsible for the production of the typical deformity in Volkmann's ischaemic contracture but that venous obstruction, extravasation of blood and serum, and swelling of the tissues could all be implicated. He recommended the value of early drainage in the prevention of deformity.

Unfortunately during the 1940's attention was directed away from these sound conclusions by several authors. Griffiths (1940) stated that he had conclusive proof that

ischaemic contracture was caused by arterial injury or spasm with concurrent reflex collateral spasm. However he based this conclusion mainly on embolectomy cases and was in fact describing what is known today to be acute compartment syndrome following relief of arterial obstruction. His successful results from excision of the damaged artery are undoubtedly due to the fact that fasciotomy was carried out simultaneously. Griffiths' views are supported by Foisie (1942) and Sirbu et al (1944). An unfortunate legacy of these statements persists today in the still surprisingly widely held but dangerously mistaken view that an acute compartment syndrome cannot exist in the presence of normal peripheral pulses.

These beliefs were prevalent until the middle of the 1960's. Seddon in 1966 published the first major report on lower limb ischaemic contractures although Thomson and Mahoney in 1951 had pointed out the occurrence of ischaemic contracture after fracture of the femur in children. Seddon's paper was the first to hint that not all ischaemic contractures were caused by arterial injury. He noted that in all cases there was early and gross swelling requiring prompt fasciotomy and that 50% of his cases had palpable peripheral pulses. He was unable to explain the presence of muscle infarcts at the same level as the injury on the basis of arterial damage. He recommended early fasciotomy as treatment of ischaemia

occurring at the same level as the injury and arterial repair if injury proximal to the level of ischaemia was present.

In their classic paper published in 1968 McQuillan and Nolan discussed the nature of ischaemia complicating injury. They clearly differentiated between injuries complicated by ischaemia caused by major vessel disruption and those complicated by "local ischaemia". They described the vicious circle of increasing tension in an enclosed compartment causing venous obstruction and subsequent reduction in arterial inflow. They reported fifteen cases of local ischaemia or acute compartment syndrome in which local arterial rupture was present only in four. Their most important conclusion was that delay in performing a fasciotomy was the single cause of failure of treatment.

These two papers were the forerunners to the current concepts of the pathogenesis of acute compartment syndrome.

1.2

Current concepts

Although the concept of increased tissue pressure had been suggested intermittently in the preceding century it is only in the last twenty years that the current concepts of the pathogenesis of the acute compartment

syndrome have evolved.

Foremost in this process of evolution has been the work of Matsen. In 1975 he published his unified concept of the condition which he renamed compartmental syndrome. He defined compartmental syndrome as a condition in which the circulation and function of tissues within a closed space are compromised by increased pressure within that space and noted that the main susceptible tissues are muscle and nerve. He pointed out that the underlying features of all compartment syndromes are the same irrespective of aetiology or location. In so doing he clarified much of the confusion regarding the terminology caused by the use of many varying names for this condition (Volkmann's ischaemic contracture, anterior compartment syndrome, local ischaemia, phlegmasia cerulear dolens etc).

Three years before Matsen's paper Rorabeck and his co-authors published a clinical and experimental review of anterior tibial compartment syndrome suggesting a rise in interstitial pressure as the common cause for their four main types. These were: Type I idiopathic or exertional; Type II post-traumatic; Type III post-embolic; and Type IV after relief of acute arterial insufficiency. They concluded that the only effective way of treating the condition is by rapid and thorough decompression of the overlying fascia.

In the last twenty years raised tissue pressure within a closed osteo-fascial compartment has been universally accepted as the basic pathogenic mechanism giving rise to the acute compartment syndrome (Matsen and Clawson 1975, Rorabeck and Macnab 1975, Karlstrom et al 1975, Whitesides et al 1975, Sheridan and Matsen 1976, Mubarak et al 1976, Matsen et al 1981, Heppenstall et al 1988, Bourne and Rorabeck 1989). Debate during this time has instead been centred on various topics including the patho-physiology of raised tissue pressure, its effect on muscle and nerve function, monitoring of compartment pressures, the pressure threshold for decompression, fasciotomy and more recently on the effects of treatment of tibial fracture on intra-compartmental pressures.

1.2.1

Pathogenesis of the acute compartment syndrome

Mechanism of muscle blood flow reduction

Regardless of the general agreement on the underlying cause debate continues over the postulated mechanism of reduced flow at the small vessel level, and over whether closure occurs at arteriolar, capillary or venous levels. The early theory of major arterial spasm (Griffiths, 1940, Foisie 1942, Sirbu et al 1944) as a cause of compartmental syndrome has now been entirely refuted mainly because of the commonly observed presence of intact distal pulses (McQuillan and Nolan 1968,

Rorabeck and Macnab 1975, Matsen et al 1977, Matsen 1980, Bourne and Rorabeck 1989). Furthermore arteriography in compartment syndrome has shown no evidence of arterial spasm (Matsen 1980).

Having excluded the arterial spasm theory there remain four theories as to the mechanism of shutdown of blood flow to muscles. It should be noted however that these theories although much debated are not entirely mutually exclusive.

Theory I - critical closing pressure

This theory is based on the hypothesis put forward by Burton in 1951. He considered the forces involved in the equilibrium of blood vessel walls, and pointed out that the intravascular pressure which tends to expand a vessel is opposed by the surrounding tissue pressure which tends to constrict the vessel. The difference between the two is the transmural pressure, which represents the total force expanding the vessel. The transmural pressure (PTM) is balanced by a constricting force (Tc) constituting the elastic and active (or smooth muscle contraction) tension.

The equilibrium between the expanding and constricting forces is expressed in a derivation of Laplace's law: PTM = Tc/r where r is the radius of the vessel. Burton then postulated that if the transmural pressure drops to

a level such that the elastic fibres are no longer on the stretch and can no longer contribute any elastic tension then there will be no further automatic decrease in the radius. Then any further decrease in transmural pressure will result in an imbalance in the Tc/r equilibrium equation. Tc/r becomes greater than PTM, the constricting force is greater than the expanding force and active closure of the vessel will occur.

Nichol and his co-authors (1951) verified this concept in a subsequent paper using microscopic observation of small vessels in frog mesentery and pressure/flow measurements in the perfused frog hind limb. This was further supported by experiments on pressure/flow relationships in human local vascular beds (Burton & Yamada 1951, Yamada 1954, Roddie and Shepherd 1957, Ashton 1962). Ashton in 1975 was the first to relate these findings directly to compartment syndromes and concluded that whatever the cause of the raised tissue pressure blood flow will be decreased and may temporarily cease altogether as a result of a combination of active arteriolar closure and passive capillary compression depending on vasomotor tone and the height of the total tissue pressure.

The concept of critical closing pressure has been challenged by several authorities. Similar experiments to those cited above have found no evidence for the

presence of a critical closing pressure (Folkow and Lovfing 1956, Read et al 1957, Hinshaw and Day 1959, Hochberger and Zweifach 1968). It is suggested by Hinshaw and Day that positive closing pressures at zero flow are produced by elevated tissue pressure resulting from varying degrees of oedema while Matsen (1980) doubts the possibility of maintaining arteriolar closure in the presence of ischaemia which is a strong local stimulus for vasodilatation. Ashton (1962) noted that flow resumes after 30 - 60 seconds of maintained tissue pressure and attributes this to vessel reopening possibly because of an accumulation of vasodilator metabolites (Folkow and Lovfing 1956) reducing the ability of the smooth muscle to contract.

Theory 2 - arteriovenous gradient

Matsen (1980) is the main proponent of this theory as a mechanism of reduction of blood flow in the compartment syndrome. According to this theory increases in local tissue pressure reduce the local arteriovenous pressure gradient and thus reduce blood flow. When flow diminishes to less than the metabolic demands of the tissues (not necessarily to zero) then functional abnormalities result.

The relationship between arteriovenous gradient and local blood flow is summarised in the equation: $LBF = \frac{Pa - PV}{R}$ where LBF is local blood flow, Pa is local arterial

pressure, Pv is local venous pressure and R is the local vascular resistance. Ryder and co-authors in 1944 and Kjellmer in 1964 pointed out that veins are collapsible tubes and therefore the pressure within them can never be less than local tissue pressure. If tissue pressure rises as in the compartment syndrome then the local venous pressure must also rise thus reducing the arteriovenous gradient (Pa - Pv) and tending to reduce blood flow. To a certain extent this reduction can be compensated for by changes in local vascular resistance (R) but this compensation is relatively ineffective at low arteriovenous gradients (Henriksen 1974). Local blood flow is then primarily determined by the arteriovenous gradient. As tissue pressure rises the local blood flow is reduced to a level whereby it is unable to meet the metabolic demands of the tissues and ischaemia and compartment syndrome ensue. Similar theories implicating collapse of soft walled capillaries have been suggested by Hinshaw and Day (1959), Zelis et al (1974) and Ashton (1975). Matsen and his co-authors (1980) presented results on human subjects showing that elevation of the limb reduces the arteriovenous gradient and correlated this with previous studies (Matsen et al 1979a) showing reduction in muscle Po_2 in normal human limbs subjected to compression and elevation.

Theory 3 - tidal wave theory

Dahn et al (1967) examined the effect of external

pressure and venous stasis in human muscles and noted that blood flow ceased when external applied pressure equalled diastolic pressure or when venous pressure equalled systolic pressure. They postulated that external pressure equal to diastolic pressure was sufficient to obliterate flow because systolic pressure could only expand the first part of the "collapsible tube" ie. the capillary-venous system. During diastole a reversal of flow occurred and they named this the tidal wave effect. However no further evidence has been advanced to substantiate this theory.

Theory 4 - microvascular occlusion theory

Hargens and his associates (1978) postulated that capillary occlusion is the main mechanism reducing blood flow in the compartment syndrome. Measurement of capillary pressure in dogs with normal tissue pressures revealed a mean level of 25mm Hg. The authors suggest that a tissue fluid pressure of similar value is sufficient to reduce capillary blood flow. They then envisage a vicious circle of increasing oedema due to increased capillary membrane permeability to plasma proteins in the presence of muscle ischaemia and obstruction of lymphatic drainage by the raised tissue pressure. Hargens and his co-authors admit in their discussion that this theory is conjectural and point out that reactive hyperaemia and vasodilatation both tend to raise the critical pressure level for microvascular

occlusion. This theory is also criticised by Matsen (1980) who points out that since capillaries are collapsible tubes, their intravascular pressure ought to rise in the presence of raised tissue pressure by the same mechanism as occurs in veins (Ryder et al 1944, Kjellmer 1964). He considered that Hargen's and his co-authors' work was performed in the presence of normal tissue pressure and cannot be extrapolated to the situation in which tissue pressure is elevated.

Reneman and his co-workers (1980) however have demonstrated that simultaneous elevation of venous and total intramuscular pressure results in cessation of muscle capillary blood flow in the presence of arteriolar dilatation. They concluded that arterioles are not the limiting factor in the muscle blood flow disturbances in compartment syndrome but that the changes occur at capillary level.

Regardless of the theoretical aspects of the mechanism of vessel closure there is now a considerable body of evidence to demonstrate the effect of vessel closure on muscle blood flow, oxygenation and neurological function.

1.2.2

The Effects of Raised Intracompartmental Pressure on Tissues Within the Osteofascial Compartment.

Increased pressure in the osteofascial compartment may cause damage to any or all of the contained tissues. This includes muscle, nerve and bone.

Muscle

The effects of raised tissue pressure on muscle have been extensively studied using several techniques. In 1972, Rorabeck and his associates studied muscle blood flow in dogs with experimentally raised compartment pressure by measuring the rate of clearance of a radioactive isotope. They demonstrated a profound reduction in muscle blood flow. Since then muscle blood flow has been measured in experimentally induced compartment syndromes by various methods and by several authors (Sheridan and Matsen 1975, Clayton et al 1977, Rorabeck and Clarke 1978, Matsen et al 1979b, Reneman et al 1980, Matsen et al 1981). There is universal agreement that increasing compartmental pressure results in decreasing muscle blood flow, with an abrupt drop occurring when the pressure reaches 60 mm Hg even for a short time. At 80 mm Hg all authors agree that muscle blood flow becomes undetectable. Clayton et al (1977) have studied muscle blood flow in the clinical setting in patients at risk of developing acute compartment syndrome. They found

that muscle blood flow reduced as the difference between compartment pressure and diastolic blood pressure reduced. This implies that muscle blood flow is dependent on both the systemic blood pressure and the compartment pressure.

Muscle blood flow is also dependent on the length of time for which pressure has been applied. After eight hours of applied pressure of 40 mm Hg in a canine model Rorabeck and Clarke (1978) noted a rapid decrease in muscle blood flow. However regardless of the pressure applied or the time elapsed (up to 12 hours), muscle blood flow returned to normal within two hours of fasciotomy.

Matsen et al (1981) demonstrated that factors other than the magnitude and duration of the applied pressure may affect the muscle blood flow. In the presence of hypotension, hypoxia, arterial occlusion or halothane anaesthesia the tolerance of muscle circulation for increased compartment pressure was reduced.

It has therefore been demonstrated clearly that muscle blood flow is decreased by a variety of factors in combination with raised tissue pressure. However muscle blood flow measurements are merely an indirect measurement of the nutrition being supplied to meet the metabolic demands of the muscle tissue. In recent years

more direct methods of measuring tissue nutrition have become available.

The partial pressure of oxygen in tissue is one determinant of the adequacy of tissue perfusion. Sheridan et al (1977) measured skeletal muscle oxygen tension in experimentally induced compartment syndromes in rabbits and found that the extent of tissue hypoxia was related to the magnitude of the applied pressure. Using a similar method, Nicholas and Miller (1978) demonstrated a reducing muscle PO_2 and a rising PCO_2 over a six hour period of pressurisation at 50 mm Hg in the presence of normal systemic arterial PO_2 and PCO_2. They also measured increased serum lactate and pyruvate levels which indicated that anaerobic metabolism had replaced aerobic metabolic processes in the affected muscle. A falling PO_2 and rising PCO_2 in the presence of raised tissue pressure has also been documented by Matsen et al (1979b and 1981). The application of phosphorus nuclear magnetic resonance spectroscopy (Heppenstall et al 1988) has provided an insight into the physiological effects of raised tissue pressure on cellular metabolism. The high energy phosphate profile and mean intracellular pH are both considered to be sensitive indicators of anaerobic metabolism. Both parameters were found to deteriorate as the difference between mean arterial blood pressure and compartment pressure ($\blacktriangle P$) dropped to less than 40 mm Hg in the

muscles of the canine hind-limb subjected only to raised intracompartmental pressure. With added trauma to the muscle itself there was a significant decline in the bioenergetic state by the eighth hour of compression. Recovery after fasciotomy performed at eight hours was evident in all but the muscles subjected to compartment pressure within 10 mm Hg of mean arterial pressure. This work has been expanded (Schneck et al 1990) to recognise three metabolic stages of the acute compartment syndrome which correlate well with ▲P measurements. Two metabolic thresholds were identified, the first indicating the onset of bioenergetic compromise and the second being characterised by the dramatic onset of metabolic collapse. The authors hypothesise that the second threshold corresponds to the point where cellular oxygen tension approaches zero.

Muscle enzymes were measured by Rorabeck and Clarke (1978) as an indication of the degree of muscle damage in an experimental model of the compartment syndrome in dogs. Values for creatinine phosphokinase (CPK) and total lactic dehydrogenase (LDH) began to rise immediately following the introduction of pressure but despite an upward trend the absolute value did not bear any relationship to the amount of pressure introduced and maintained.

The end point of the assessment of the effect of raised

tissue pressure on muscle is the quantification of muscle function. Mortensen and his co-authors (1985) measured strength and endurance of muscle contraction electrophysiologically after an experimentally induced rise in compartment pressure in dogs. They demonstrated a reduction in these parameters two days after pressurisation of a muscle compartment to 40mm Hg for eight hours. However full recovery had ensued by one week, despite evidence of muscle necrosis at two days. Thus for this magnitude and time of pressure elevation functional recovery is possible in the experimental animal.

The end point of the untreated acute compartment syndrome is muscle necrosis, the quantity of which determines the ultimate functional recovery. The microscopic and ultrastructural changes in muscle subjected to raised interstitial pressure have been well documented (Sheridan & Matsen 1975, Hargens et al 1981, Heppenstall et al 1986, Hoffmeyer et al 1987). Sheridan and Matsen (1975) described the histological appearances of muscle subjected to raised compartment pressure at varying levels for twenty-four hours. They noted inflammatory necrosis at pressures of 50 to 60mm Hg and ischaemic necrosis without inflammation at pressures over 70mm Hg. There was considerable variation of the histological pattern within a muscle which they attributed to a lack of uniformity of the pressure elevation within that

muscle. Earlier studies of the histology of the established contracture (Bowden & Gutmann 1949) after presumed increases in compartment pressure showed scattered foci of necrosis and patchy interstitial fibrosis also reflecting the nonhomogeneity of muscle changes.

Ultrastructural changes in muscle in the acute compartment syndrome are dominated by mitochondrial abnormalities (Hoffmeyer et al 1987, Heppenstall et al 1988) and parallel the gross histological changes. The ultrastructural abnormalities reflect intrinsic metabolic alteration due to ischaemia. Hargens and his associates (1981) have combined a qualitative description of the histological changes in muscle in the acute compartment syndrome with an attempt to quantify the extent of tissue injury using 99m TC stannous pyrophosphate scanning in a canine model. They found a quantitative relationship between the extent of muscle damage and intracompartmental pressures at pressures higher than 30mm Hg. This has potential application in the assessment of ultimate functional outcome after acute compartment syndrome.

Raised compartment pressure clearly reduces muscle blood flow. The magnitude of the reduction is directly related to the amount and duration of pressure applied and indirectly to the perfusion pressure (mean or

diastolic blood pressure) of the individual. This results in reduced tissue nutrition, the institution of anaerobic metabolism and ultimate metabolic collapse. These cellular events are paralleled by histological muscle necrosis and ultimate loss of muscle tissue and function.

Nerve

The effects of raised tissue pressure on neurological tissue has also been well documented. Most investigators have induced raised intracompartmental pressure in animals or humans and then measured either nerve conduction velocity or action potential amplitude at varying times and pressures. The reduction in action potential amplitude is generally attributed to a reduction in the numbers of functioning motor units (Matsen et al 1977) and is therefore a quantitative measurement while nerve conduction velocity is a qualitative measurement of functional integrity of the nerve.

There is little dispute about the effect of raised tissue pressure on neuromuscular function. All investigators (Sheridan et al 1977, Matsen et al 1977, Hargens et al 1979, Matsen et al 1979b, Matsen et al 1981, Gelberman et al 1983) note a loss of neuromuscular function but controversy exists about the level and duration of applied pressure which causes irreversible damage.

Neuromuscular abnormality has been observed after eight hours of applied pressure at 30mm Hg (Hargens et al 1979), after four hours at 40mm Hg (Gelberman et al 1983), after six hours at 40mm Hg (Sheridan et al 1977) and after five hours at 60mm Hg (Matsen et al 1979b), Matsen et al (1977) are the only authors to report on the effects of raised pressure on peripheral nerve function in human subjects. They noted considerable variation of pressure tolerance which could not be attributed to differences in systemic blood pressure or any other identifiable factor. The lowest threshold was 50mm Hg before neuromuscular functional deficit became apparent. Recommended pressure levels for decompression vary from 30mm Hg (Hargens et al 1979) to 50mm Hg (Gelberman et al 1983) in normotensive patients to prevent permanent neuromuscular deficit.

There is speculation also about the mechanism of damage to neurological tissue. Damage may result from either ischaemia, ischaemia plus mechanical compression, toxic effects or the effects of acidosis. This problem has yet to be resolved.

Bone

Despite the fact that bone is contained within the osteofascial compartments of the leg, the effects of raised compartment pressure on osseous tissue has largely been ignored. The only author to consider bone ischaemia

was Nario (1938). He considered that Volkmann's disease was due to obliteration of the "musculo-diaphyseal" system of blood vessels which affected both the muscular body and the diaphysis. He postulated that the frequent incidence of pseudarthrosis after bone shortening as late treatment of this disease could be explained "as a trophic problem, dependent on a unique lesion of the hard and soft elements of the affected limbs ....".

Following Nario's work, only occasional comments on the concept of bone involvement have appeared. Karlstrom et al (1975) noted a high incidence of delayed or non-union in a series of cases with contracture of the muscles of the deep posterior compartment which they considered attributable to poor circulation in the adjacent muscles during the period of fracture healing. Delee and Stehl (1981) noted a considerably higher rate of non-union in open tibial fractures associated with compartment syndrome although they mainly attributed this to soft tissue disruption and fasciotomy allowing muscles to "hang" off the tibia and compromise bone circulation.

1.2.3

Bone healing

Bone is a unique tissue in the human body because its repair process results not in the formation of scar but in the formation of tissue which closely resembles normal bone. It is not surprising therefore that the mechanisms

which achieve this are complex and poorly understood.

The morphological stages have been known and extensively described over the years (Urist and Johnson 1943, Ham and Harris 1971, McKibbin 1978, Brand 1979, Frost 1989, Buckwater and Cruess 1991). The usual model described is fracture of the diaphysis of a long bone with three main phases - inflammation, repair and remodelling.

The phase of inflammation starts at the moment of fracture. Bleeding occurs from the bone ends and the local soft tissues show typical changes of acute inflammation with vasodilatation (Wray 1964) and the appearance of polymorphs, histiocytes and mast cells. Increased cell division becomes evident about eight hours after injury and peaks about sixteen hours later. Because of the disruption to the blood supply the bone ends themselves are dead and within 24 hours osteocyte degeneration becomes obvious (Enneking 1948). Phagocytes appear and remove necrotic tissue and debris including bone.

The stage of repair does not follow in a linear time scale but overlaps the initial inflammatory stage and achieves the formation of callus and its subsequent transition to mature bone. Proliferation of the pluri-potential mesenchymal tissues in the periosteum is seen as early as 16 hours, rapidly spreads to the adjacent

tissues and endosteum and persists for several weeks (Tonna and Cronkite 1961). At the same time the periosteal and medullary blood vessels proliferate, starting at two to three days and becoming marked at seven days, with the more displaced fractures showing a predominance of periosteal vascular hypertrophy (Rhinelander and Baragry 1962). Ingrowth of new capillaries plus fibroblasts results in the formation of a bed of granulation tissue. Within the next few days nests of cartilage cells, new osteoid tissue from endosteal cells (Enneking 1948) and periosteal new bone formation (Rhinelander and Baragry 1962) become evident and by the end of the first week callus is recognisable histologically as a mass of new vessels, fibrous tissue, cartilage and bone. The ends of the fractured bone gradually become enveloped in a collar of callus. At the same time as these changes are taking place, ossification begins at some distance from the fracture line with intramembranous bone formation originating from the deep layers of the periosteum and endosteum (Urist and McLean 1941). This new bone eventually replaces the collar of callus with spongy bone. The amount of cartilage formed within the callus is very variable for a number of reasons summarised by McKibbin (1978). He implicates the mechanism of fracture healing in lower animals, excessive movement and low oxygen tension as factors increasing the amount of cartilage formed.

In the meantime a variable amount of new bone formation is occurring in the medullary region. This is the principal method of union in cancellous bone but can also contribute in tubular bone, particularly if the fracture ends are offset (McKibbin 1978).

The final stage of healing is remodelling, characterised by a slow change in the shape of the bone and restoration of normal strength. In more modern literature this phase is split into the remodelling and modelling stages. Remodelling does four things (Frost 1989): it replaces mineralised cartilage with woven bone, replaces the latter with new lamellar bone, aligns lamellar bone parallel to the local strains and stresses and removes callus plugging the marrow cavity. The modelling process on the other hand uses bone formation and resorption mechanisms to recontour the gross shape of the bone towards normal. This process can reach completion in young children but never in adults.

Bone healing can be modified by mechanical changes in the environment of the fracture and the best known example is the phenomenon of primary bone healing. This only occurs when the fracture is stable, aligned and its surfaces closely apposed. It has been demonstrated in fissure fractures through spongy bone (Sevitt 1981), and in compression arthrodesis (Charnley and Baker 1952) also through cancellous bone. Primary cortical bone union is

best known in association with compression plating (Anderson 1965, Olerud and Danckwardt-Lilliestrom 1968, Rahn et al 1971). Rigid fixation abolishes all movement at the fracture site and this inhibits periosteal callus. The stability allows easier restoration of medullary circulation across the fracture and permits medullary osteogenesis to cross the fracture readily. In such conditions intra-cortical healing also occurs by longitudinal osteoclastic tunnelling of the cortical bone followed by ingrowth of vessels and osteogenic cells. These histological studies however were carried out in experimental conditions and Sevitt (1981) did not observe primary cortical union in six human tibial shaft fractures treated by compression plates.

Medullary reaming and intramedullary nailing also change the morphology of fracture healing. Reaming and nailing destroy the intramedullary vessels and stimulate periosteal osteogenesis. Thus the medullary nailed fracture heals predominantly by periosteal callus formation (Danckwardt - Lilliestrom 1969, Sevitt 1981).

It is important however not to regard the different types of bone union as separate entities. They are all part of the spectrum of bone healing with relative proportions being modified by differing conditions.

The control of bone healing

Perhaps the greatest contribution of recent research on fracture healing has been the expansion of our knowledge beyond the morphology of the healing fracture. Formation of granulation tissue and callus and beginning the remodelling and modelling activities requires activation of previously dormant local precursor cells which then begin to make new cell populations. Some of these new cells then differentiate and organise into the many components of fracture healing. These activation - differentiation - organisation processes control where bone healing occurs in addition to its timing, quantity, speed and endurance (Frost 1989). All of these activities are dependent on the local mediator mechanisms which include priming, mutagenic, differentiating and organising agents. Table 1.1 lists some of these which are known to affect bone healing.

A clear resumé of current knowledge is detailed in Hulth's (1989) article on the current concepts of fracture healing. He considers that the central event in fracture repair is the formation of fracture exudate which contains bone morphogenetic signal substances and growth factors from the broken bone. Urist and his co-authors (1983) state that bone morphogenetic protein (BMP) irreversibly induces differentiation of perivascular mesenchymal type cells into osteoprogenitor cells and that growth factors then stimulate DNA

synthesis. The size, duration and biochemical activity of the fracture exudate is critical for the rate and success of fracture healing.

Table 1.1

Prostaglandins PGE_1 + PGE_2
Bone morphogenetic protein (BMP)
Epidermal growth factor
Fibronectin
Interleukin 1 (1L1) and 2 (1L2)
Platelet derived growth factor (PDGF)
Tumour necrosis factor
Osteoclast activating factor
Bradykinins
Transforming growth factor (TGH-beta)
Hyaluronate

Agents affecting bone healing

Early weight bearing (Chapman 1987) and axial micromovement (Kenwright et al 1991) are the only two external factors proven to stimulate fracture healing and are thought to stimulate the production of growth factors and PGE_2. It been suggested (Hulth 1989) that PGE_2 brings about the necessary inflammation that results in migration of cells and sprouting of vessels.

Hulth also points out the importance of the soft tissues

in fracture healing. Soft tissue injury can result in avascular fragments of bone which may impede the efficacy of the osteogenic signals. The injured muscles impair the ingrowth of vessels and the subsequent extensive phagocytosis may cause the emission of disturbing molecular signals from the macrophages which hypothetically produce growth factors and cytokines promoting fibroplasia instead of bone formation.

Molecular research is increasing rapidly and it seems likely that this will link the hitherto separate fields of biomechanics and biochemistry and promote a better understanding of fracture healing processes for both clinician and scientist.

1.2.4

Bone blood flow

In order to understand the changes which take place in the blood supply of a long bone after injury it is first necessary to know the vascular pattern of the normal resting long bone. This has been extensively described both in animals (Branemark 1959, Gothman 1960a, Brookes 1971, Rhinelander 1972) and humans (Nelson et al 1960, Crock 1967).

All authorities have long agreed that the blood supply of long bones is threefold from the nutrient artery, the metaphyseal-epiphyseal arteries and the periosteal

arteries. Functionally the principal nutrient artery and the metaphyseal arteries are considered by Brookes (1971) to make up the nutrient system of the resting long bone, supplying at least the inner two thirds of the cortical bone (Rhinelander 1972). This is the opinion of most authors (Nelson et al 1960, Gothman 1960a, Trueta and Cavadias 1964, Crock 1967) although Brookes and Harrison (1957) are the exception in that they found that the periosteal arteries play no part in the vascularisation of compact bone in the adult rabbit. Rhinelander (1972) felt that the periosteal vessels supply the outer third or quarter of the cortex only at areas of fascial or ligamentous attachments. He classified the normal blood vessels into afferent (nutrient, metaphyseal and periosteal supply) and efferent (venous channels including vena comitans of the nutrient artery, the cortical venous channels and the periosteal capillaries) systems. He and Brookes (1971) concluded that the normal direction of blood flow is centrifugal.

Following fracture of a long bone all components of the affected vascular system become enhanced. Most authorities (Wray and Lynch 1959, Cavadias and Trueta 1965, Macnab and de Haas 1974, Trueta 1974) believe that the relative importance of each part of the afferent system changes and to this is added a new supply - the extraosseous supply. Gothman (1960b) was the first to describe vessels reaching the fracture site from the

surrounding muscle. In 1962 he noted these as early as four days after fracture. At seven to ten days the vascular reaction was even more marked with most vessels which reach the fracture site being derived from the soft tissues. This reached a maximum at two weeks after injury but by three to four weeks, although still prominent, had started to diminish while the medullary vascularity had started to increase. This change continued until at six weeks most of the fractures studied had re-established continuity of the medullary vessels at the fracture line. The regional circulation in the medullary cavity reached its peak about two months after fracture. The periosteal vessels only contributed in a minor way throughout. Thus the extraosseous blood supply of healing bone acts in a transitory fashion to maintain supply to the bone and callus until damaged medullary flow is reconstituted. The direction of flow under these circumstances is also reversed to become centripetal. This was demonstrated by Strachan et al (1990) when ligation of the nutrient artery two weeks after osteotomy failed to reduce cortical flow significantly implying recruitment of blood supply from extraosseous sources and a centripetal direction of flow. In recent work, Triffitt and his co-authors (1993) performed osteotomies in rabbits using tissue exclusion techniques. When the soft tissues were excluded there was no increase in cortical flow at 2 weeks while the expected increase was seen in the group where reaming was used to exclude the marrow. The

authors concluded that their results lent support to the hypothesis of recruitment of extraosseous flow in bone healing.

Variations from the above account in bone blood flow after fracture are usually due to surgical interference and are usually variations in relative proportions of blood supply. With rigid compression plating the primary importance of medullary flow has been demonstrated by Rhinelander (1974). He reports the recruitment of extraosseous flow only where a fracture gap or offset remains. Medullary reaming and nailing (Gothman 1960b, Danckwardt - Lilliestrom 1969) causes destruction of the medullary vessels and an exaggerated and prolonged response from the extraosseous supply. However Rhinelander (1974) reports regeneration of medullary vessels along the grooves of a tight fitting intramedullary nail at four weeks.

It would seem that there is fairly universal agreement about the importance of the extraosseous vascular supply in the early stages of fracture healing. By implication then the state of the soft tissues is of crucial importance.

1.2.5

The effect of soft tissue injury on bone blood flow and bone union.

In view of the importance of the extraosseous blood flow derived from the soft tissue in early fracture healing it would seem logical that soft tissue injury of any type leading to muscle ischaemia could reduce bone blood flow after fracture and thus retard healing. Indeed this is one possible explanation for increasing delay in bone union clinically with increasing severity of a fracture (Gustilo 1982, Oestern and Tscherne 1984, Court-Brown et al 1990a, Court-Brown et al 1990b).

Zucman (1960) and Whiteside and Lesker (1978a) both demonstrated the importance of the vascular connection between muscle and periosteum in the survival of muscle after induced ischaemia or muscle injury. Holden (1972) was the first to suggest that devascularisation of muscle should be considered as a significant cause of delay in bone union. He demonstrated delay in bone union in stable experimental osteotomies of the rabbit radius after ligation and subperiosteal stripping of muscle groups. He noted that the muscle ischaemia recovered (at three weeks after surgery) by revascularisation from muscle not included in the ligatures, from skin or from the main neurovascular bundle. It was only after this that the extraosseous circulation started to develop.

Whiteside and Lesker (1978b) also demonstrated the importance of the soft tissues. In a group of animals with trauma to muscle in the form of transection, bone healing was significantly delayed compared to a group without muscle injury.

Acute compartment syndrome as a cause of muscle injury has not previously been studied as a possible cause of delayed bone union. Karlstrom et al (1975) noted delayed union in fifteen of twenty-three patients with ischaemic contractures after tibial fractures and pointed out the importance of preserving circulation in adjacent muscles during fracture healing. De Lee and Stiehl (1981) noted delayed union in all of a small group of patients with open tibial fractures complicated by acute compartment syndrome and attributed this to the amount of soft tissue injury and to fasciotomy. The possibility of delayed union being caused by acute compartment syndrome was first suggested by Court-Brown and Hughes (1985). They noted that in a series of patients with tibial fractures treated with external fixation delay in bone union was more common in those whose clinical course was complicated by acute compartment syndrome and subsequent fasciotomy. This observation prompted a retrospective study on acute compartment syndrome and time to union of closed and grade I (Gustilo and Anderson 1976) open tibial fractures. This study was published in 1987 (Court-Brown and McQueen 1987).

1.2.6

A retrospective study of the effect of acute compartment syndrome on time to bone union.

Material and methods.

In the period from 1963 to 1983 approximately 3,000 tibial fractures were admitted to the Orthopaedic Trauma Unit of the Royal Infirmary of Edinburgh. Of these, thirty patients developed an acute compartment syndrome in association with a closed or type 1 open diaphyseal fracture and underwent fasciotomy. Compartment syndromes associated with metaphyseal fractures, knee or ankle pathology and major vessel disruption were excluded from the series.

In two patients information was inadequate and twenty-eight patients were therefore available for study. All were male with a mean age of twenty-five years (range 12 - 70 years). Twenty patients had been involved in road traffic accidents, ten being pedestrians and ten motorcyclists. Of the remaining eight, six were sports injuries, one resulted from a fall and one from a boating accident.

Diagnosis of an acute compartment syndrome was made clinically with the presence of inappropriate pain and pain on passive stretch of muscle groups. Compartment monitoring was not available during the period of the

study, but all diagnoses were confirmed by escape of muscle groups described at fasciotomy. The time between hospital admission and fasciotomy was recorded. On review of the case histories, delay was deemed to be due to surgical error rather than delay in onset. It was therefore felt to be reasonable to use the recorded hospital admission time as the assumed onset time of the acute compartment syndrome. The tibia was considered to be united when the patient could mobilise free of external support.

A matched group of 50 patients with uncomplicated closed and type I open tibial fractures was also studied retrospectively for purposes of comparison. The groups were matched for age and mode of injury.

Statistical analysis was performed using the Student t-test or by calculating the product moment correlation coefficient.

Results

The average time to bone union in the compartment syndrome group was 27 weeks. This was affected by the age of the patient (Table 1.2). The adult group consisting of those over 18 years of age had a longer time to union than the younger group and seven of the adults required bone grafting to achieve final union while none of the younger patients required this

procedure. In the matched uncomplicated group the mean time to union was 11 weeks in the younger group, a significant difference from the mean of 18 weeks in the compartment syndrome group ($p < 0.05$). The difference was even more marked in the adult group with the average union time in the matched uncomplicated group being 15 weeks, again significantly different from the mean of 34 weeks in the compartment syndrome group ($p < 0.001$). Only one of the adult patients in the matched group required bone grafting.

Over the period of this study most of the fractures were treated with a cast after fasciotomy was performed. In the later years however some fractures were internally or externally fixed. Table 1.3 shows that the method of treatment did not significantly affect the union time in either age group.

The effect of delay in performing the fasciotomy was also examined (Table 1.4). The fastest time to union was obtained in those younger patients who were decompressed within six hours of admission and the longest time in the adult group where fasciotomy was delayed for more than 24 hours, although the figures do not reach statistical significance.

Although it is now standard practice to perform a four compartment fasciotomy, 14 of these patients had subtotal

fasciotomy based on the surgeon's clinical judgement. There was no difference in the union times between the groups with total and subtotal fasciotomies.

Table 1.2

Age (yrs)	Compartment syndrome		Matched group		p
	No	Union time	No	Union time	
< 18	11	18	25	11	<0.05
≥ 18	17	34	25	15	<0.001

Average time to union (weeks) in the compartment syndrome and matched uncomplicated groups.

Table 1.3

Age (yrs)	Cast		Fixation		p
	No	Union time	No	Union time	
< 18	8	16	3	22	NS
≥ 18	10	35	7	33	NS

Comparison of average time to union (weeks) of tibial fractures complicated by compartment syndrome depending on treatment method.

Table 1.4

	Delay to fasciotomy (hours)					
	<6		6-24		>24	
Age (yrs)	No	Time	No	Time	No	Time
< 18	3	13	3	21	5	30
≥ 18	4	26	9	32	4	46

The effect of delay to fasciotomy on union times (weeks) of tibial fractures complicated by compartment syndrome and fasciotomy.

Discussion

The results from this retrospective study confirm that in the clinical situation acute compartment syndrome and fasciotomy can delay union of closed and grade I tibial fractures. A review of the literature shows union times in closed and type I tibial fractures in adults ranging from 12 weeks to 19.7 weeks (Batten et al 1978, Van der Linden and Larsson 1979, Bostman and Hanninen 1982, , De Bastiani et al 1984, Kay et al 1986, Court-Brown et al 1990a). The average union time of 27 weeks in the compartment syndrome group is considerably longer than both the matched group in this series and the world literature.

There is a likely association also between delay in surgical decompression and time to union. Both young and adult patients showed a marked increase in time to union with increasing delay. Delay of 18 hours (from 6 hours to over 24 hours) results in the youngest group in an average increase of 17 weeks to union and in the adult group in an average increase of 20 weeks.

Prompted by these results this study was undertaken in order to explore the possible connection between bone blood flow, bone union and the acute compartment syndrome both with experimental and clinical studies.

CHAPTER 2

Experimental Study

2.1

Verification of the animal model

Prior to the main study an initial study was undertaken in order to identify a method which consistently simulated a clinical compartment syndrome.

2.1.1

Materials and Methods

A modification of the animal model described by Sheridan and Matsen (1975) was used in this study. Thirty-one adult female New Zealand white rabbits weighing over 3kg were anaesthetised using intramuscular Hypnorm (5mg/kg body weight) and intraperitoneal Valium (2.5 mg/kg body weight). When anaesthesia was established both hind legs were shaved. In a sterile fashion a one centimetre incision was made over the anterior compartment at the level of the tibial tuberosity. A latex balloon attached to plastic tubing was inserted deep to the fascia and the tubing brought out through a stab wound at the ankle. The balloon on one side was then inflated to a pre-determined pressure using a sphygmomanometer and the tubing occluded with two ties (Fig.2.1). A latex balloon had previously been inflated using this technique in the laboratory and was shown to maintain the initial pressure within the balloon for forty-eight hours. The balloon on the opposite side was left uninflated. The

proximal wound was sutured in two layers. The pressure in the inflated balloon was maintained for a pre-determined time. The balloons in six rabbits were inflated to 60 mm Hg for four hours (group A), in seven to 60 mm Hg for 24 hours (group B) and in four to 90 mm Hg for 24 hours (group E). A further nine rabbits had balloons inflated to 60 mm Hg for 30 minutes and then 90 mm Hg for 30 minutes (group C). Five rabbits also had balloons inserted into both the anterior and posterior compartments and inflated to 60 mm Hg for 30 minutes then 90 mm Hg for thirty minutes (group D). In all these animals the tibia was left intact. The groups are summarised in Table 2.1.

Table 2.1

Group	No. of Rabbits	Balloon compartment(s)	Pressure (mm Hg)	Time (hrs)
A	6	anterior	60	4
B	7	anterior	60	24
C	9	anterior	60 then 90	½ ½
D	5	anterior & posterior	60 then 90	½ ½
E	4	anterior	90	24

Plan for pilot study to verify animal model.

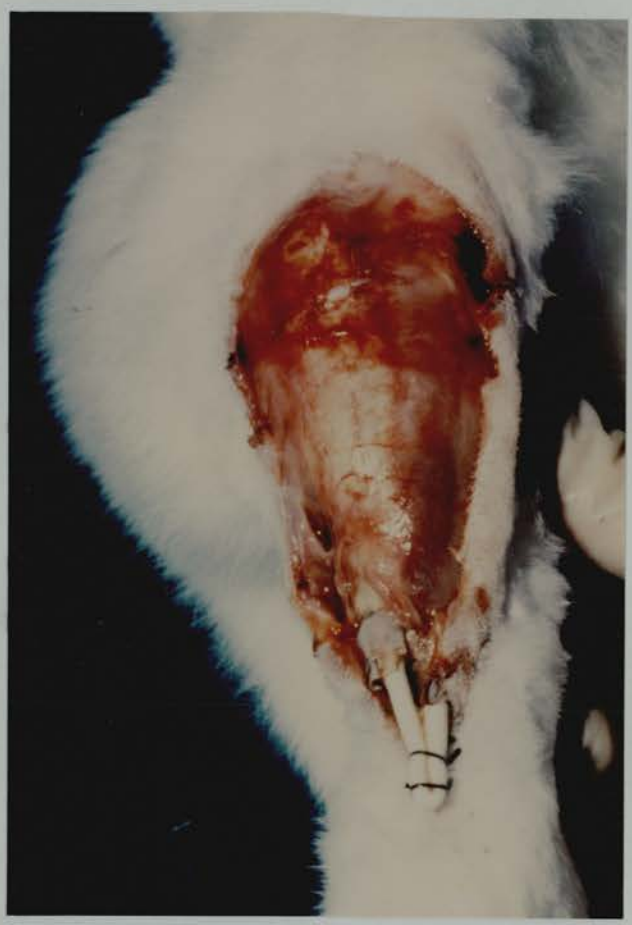

Figure 2.1
A post mortem specimen with the inflated balloon lying deep to the deep fascia and the tubing occluded by two ties. The large incision is for excision of muscle and tibia.

After the period of pressurisation the animals were either anaesthetised as before or the study was continued under the same anaesthetic depending on the elapsed time. The left carotid artery was isolated and cannulated and the cannula was passed through the aortic valve into the left ventricle. The right brachial artery was also isolated and cannulated. 250,000 15μ Co^{57} labelled microspheres per kg of body weight were

slowly injected into the left ventricle and the cannula was flushed with normal saline. Thirty seconds before injecting the microspheres blood was withdrawn from the brachial artery into a syringe at a rate of 0.852 mls/min for a total of two minutes. The syringe was considered as a reference organ. In group D Sn^{113} labelled microspheres were used for a second estimation of blood flow. The animal was then sacrificed using an intracardiac barbiturate injection. Both tibialis anterior muscles were removed for counting of radioactivity using an automatic sample scintillation counter and for histological examination. In the rabbits with posterior compartment balloons flexor hallucis longus muscle was also removed.

Both tibiae were excised and stripped of soft tissue. The metaphyses were removed and the medullary contents collected. The diaphysis was then divided into three equal parts. After weighing, the diaphyseal segments and marrow were submitted for counting of radioactivity.

Bone and muscle blood flow were calculated from the formula:

$$\text{Tissue blood flow (mls/min/100g)} = \frac{\text{microsphere activity in tissue}}{\text{microsphere activity in reference blood}} \times \frac{\text{withdrawal rate of reference blood}}{\text{tissue weight}} \times 100$$

After counting, the muscle specimens were prepared for

histological examination by setting up blocks for routine paraffin histology with haematoxylin and eosin staining. The sections were examined under a light microscope.

Statistical analysis was performed using a paired Student t - test.

2.1.2

Results

Blood flow

There were no significant differences between the mean muscle blood flow in the experimental legs and the control legs at an inflating pressure of 60 mm Hg for four hours or 24 hours (Tables 2.2 & 2.3). When 60 mm Hg was applied for 30 minutes and blood flow measured there was a lower mean flow in the experimental tibialis anterior of 6.4 mls/min/100g compared to 9.1 mls/min/100g in the control tibialis anterior muscles, although this did not reach statistical significance. There was a greater difference between the two at 90 mm Hg for 30 minutes (3.4 mls/min/100g in the experimental muscle compared to 14.6 mls/min/100g in the control muscle) and this was statistically significant ($p < 0.01$). These results are summarised in Table 2.4. Adding a balloon in the posterior compartment did not reduce muscle blood flow further (Table 2.5). When an anterior balloon was inflated to 90 mm Hg for 24 hours the mean blood flow in the experimental muscle was 8 mls/min/100g compared to 15

mls/min/100g in the control muscle (Table 2.6). This did not quite reach statistical significance.

There were no significant differences in bone blood flow in the intact tibia.

Table 2.2

	Experimental ± S.E.	Control ± S.E.	P
Muscle	13.2 ± 5.9	16.6 ± 5.5	NS
Proximal diaphysis	11.8 ± 4.9	11.5 ± 5.9	NS
Middle diaphysis	5.1 ± 2.4	5.8 ± 2.5	NS
Distal diaphysis	7.9 ± 3.0	5.7 ± 22	NS
Whole diaphysis	8.3 ± 3.3	7.7 ± 3.3	NS
Marrow	51.4 ± 17.2	57.2 ± 21.9	NS

Mean blood flow (mls/min/100g) for Group A (60 mm Hg for 4 hours)

S.E. = standard error
N.S. = non significant

Table 2.3

	Experimental ± S.E.	Control ± S.E.	P
Muscle	5.6 ± 1.1	7.9 ± 1.6	NS
Proximal diaphysis	4.0 ± 1.2	4.1 ± 1.1	NS
Middle diaphysis	3.9 ± 1.8	3.0 ± 1.2	NS
Distal diaphysis	3.4 ± 1.0	4.5 ± 2.1	NS
Whole diaphysis	3.8 ± 1.2	3.8 ± 1.3	NS
Marrow	33.1 ± 11.1	35.1 ± 11.5	NS

Mean blood flow (mls/min/100g) for Group B (60 mm Hg for 24 hours)

S.E. = standard error
N.S. = non significant

Table 2.4

		Experimental ± S.E.	Control ± S.E.	P
Muscle	60	6.4 ± 1.9	9.1 ± 2.6	NS
	90	3.4 ± 1.3	14.6 ± 3.7	<0.01
Proximal diaphysis	60	3.9 ± 0.9	4.3 ± 1.1	NS
	90	4.3 ± 0.8	4.8 ± 0.8	NS
Middle diaphysis	60	2.1 ± 0.7	2.1 ± 0.5	NS
	90	1.9 ± 0.5	2.7 ± 0.7	NS
Distal diaphysis	60	3.2 ± 1.4	2.4 ± 0.8	NS
	90	2.5 ± 0.1	2.6 ± 0.6	NS
Whole diaphysis	60	3.0 ± 0.9	3.0 ± 0.8	NS
	90	3.0 ± 0.6	3.6 ± 0.8	NS
Marrow	60	34.8 ± 8.5	34.1 ± 8.1	NS
	90	38.7 ± 1.1	30.8 ± 5.1	NS

Mean blood flow (mls/min/100g) for Group C (60 mm Hg for ½ hour then 90 mm Hg for ½ hour)

S.E. = standard error
N.S. = non significant

Table 2.5

		Experimental ± S.E.	Control ± S.E.	P
Anterior muscle	60	3.6 ± 1.1	7.6 ± 3.9	NS
	90	1.3 ± 0.8	12.1 ± 6.6	NS
Posterior muscle	60	6.3 ± 2.9	7.0 ± 3.6	NS
	90	8.9 ± 0.6	12.5 ± 7.3	NS
Proximal diaphysis	60	3.5 ± 0.4	4.4 ± 0.7	NS
	90	5.0 ± 1.9	6.2 ± 1.9	NS
Middle diaphysis	60	1.8 ± 0.3	2.0 ± 0.5	NS
	90	2.2 ± 0.7	2.3 ± 0.6	NS
Distal diaphysis	60	2.4 ± 0.3	3.5 ± 0.7	NS
	90	4.6 ± 1.6	6.1 ± 1.8	NS
Whole diaphysis	60	2.7 ± 0.3	3.3 ± 0.4	NS
	90	4.0 ± 1.3	4.8 ± 1.4	NS
Marrow	60	17.1 ± 4.3	22.2 ± 6.3	NS
	90	37.5 ± 14.9	40.9 ± 17.1	NS

Mean blood flow (mls/min/100g) for Group D (anterior and posterior balloons 60 mm Hg for ½ hour, 90 mm Hg for ½ hour)

S.E. = standard error
N.S. = non significant

Table 2.6

	Experimental ± S.E.	Control ± S.E.	p
Muscle	8.0 ± 4.8	15.0 ± 7.2	NS
Proximal diaphysis	5.5 ± 1.8	5.4 ± 2.1	NS
Middle diaphysis	2.5 ± 0.7	3.0 ± 0.9	NS
Distal diaphysis	2.0 ± 0.3	2.6 ± 0.7	NS
Whole diaphysis	3.3 ± 0.9	3.5 ± 1.1	NS
Marrow	38.9 ± 14.2	52.3 ± 15.5	NS

Mean blood flow (mls/min/100g) for Group E (90mm Hg for 24 hours)

S.E. = standard error
N.S. = non significant

Histology

No histological abnormalities were found in groups A, C or D apart from a few cases with minor superficial inflammatory change which was thought to be due to mild trauma during insertion of the balloon.

In group B where 60 mm Hg was applied for 24 hours two of the seven animals had gross inflammatory changes throughout the muscle of the experimental leg with swelling of the fibres and inflammatory infiltrates between the fibres. The other five showed no histological abnormality.

In group E where 90 mm Hg was applied for 24 hours more consistent histological abnormalities appeared. All four experimental muscles showed extensive necrosis with added inflammatory change between the fibres (Figure 2.2). The control muscles had a normal histological pattern.

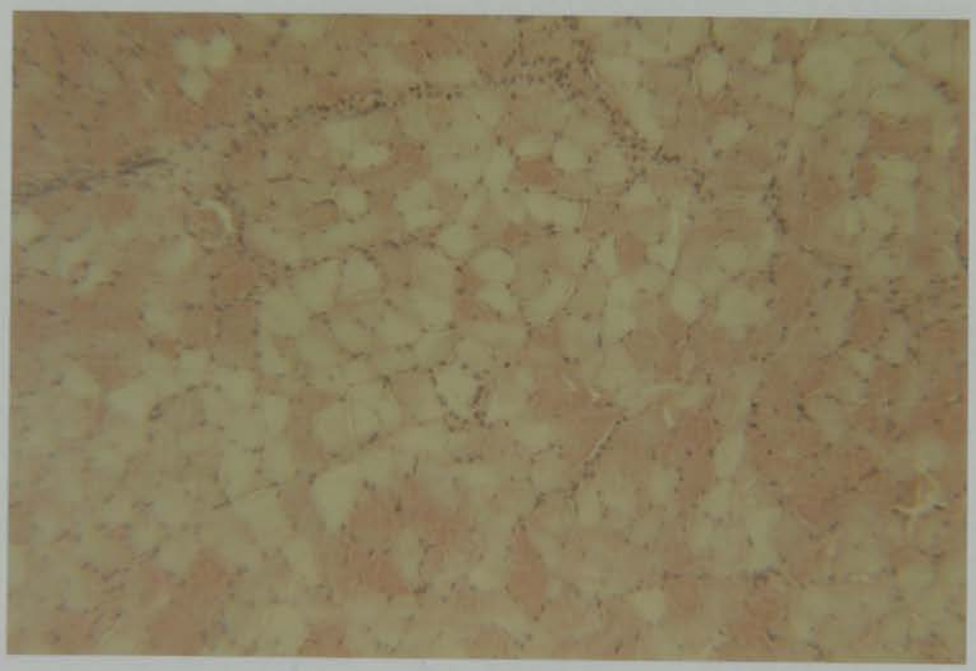

Figure 2.2
Histological section (x100) of muscle subjected to 90mm Hg pressure for 24 hours. There is extensive necrosis with inflammatory infiltrates.

2.1.3

Discussion

In this pilot study the attempt at compromising muscle blood flow in order to simulate an acute compartment syndrome proved very inconsistent both in terms of blood flow and histologically at a pressure of 60 mm Hg for

either four or twenty-four hours. The rabbits' mean blood pressure varied between 70 and 90 mm Hg and it may be that 60 mm Hg only produced significant compromise of muscle blood flow if the rabbit became hypotensive. Little swelling is seen in these specimens because the pressure in the balloon was not released before sacrifice, thus not allowing time for post-ischaemic swelling, which takes 2 - 4 hours to reach its maximum (Sanderson et al 1975).

At higher pressures for a short period of thirty minutes there was a consistent and significant reduction of muscle blood flow. At higher pressures for 24 hours there was still a marked reduction in blood flow which corresponded with histological evidence of ischaemic necrosis in the muscle.

A pressure of 90 mm Hg for 24 hours was chosen for the main study because although the reduction in blood flow did not reach statistical significance the drop in flow was sufficient to cause ischaemic necrosis of the muscles. A time period of 24 hours was also felt to simulate the clinical situation most closely.

Since the intact tibia depends mainly on the nutrient artery and metaphyseal vessels for its blood flow (Brookes 1971, Rhinelander 1972), it is not surprising that there is little effect on bone blood flow in these

experiments. In particular in group E, the group chosen for the main study the tibial blood flow remained within normal limits despite the changes in the soft tissues.

2.2

Main Experimental Study

The aim of the main study was to examine experimentally the effect of raised compartment pressure on bone blood flow and bone union in the osteotomised rabbit tibia.

2.2.1

Materials and Methods

Thirty-six skeletally mature female New Zealand white rabbits weighing from 3.0 kg to 4.3 kg were used. The rabbits were anaesthetised as in the pilot study. Under sterile conditions a short incision was made over the subcutaneous border of the tibia in its middle third. The tibia was exposed subperiosteally without disturbing the muscle compartments. A straight transverse osteotomy was created in the middle third of the tibia just distal to the tibiofibular junction using a powered saw (Figure 2.3). Through a separate longitudinal incision on the medial side of the patellar tendon and without displacing the osteotomy, three threaded Kirschner (K) wires were inserted into the medullary canal across the fracture site and engaged in the subchondral bone of the distal tibia. The K wires were cut short deep to the patellar tendon and the skin wounds were closed with subcuticular

dexon. A latex balloon was inserted into the anterior compartment as described for the pilot study and in half of the animals inflated to 90 mm Hg. The balloon was left uninflated in the remaining animals. Plaster of Paris was then applied immobilising the knee and ankle in order to control rotation at the osteotomy site. The balloon tubing was left protruding to facilitate removal. No procedure was undertaken on the opposite leg.

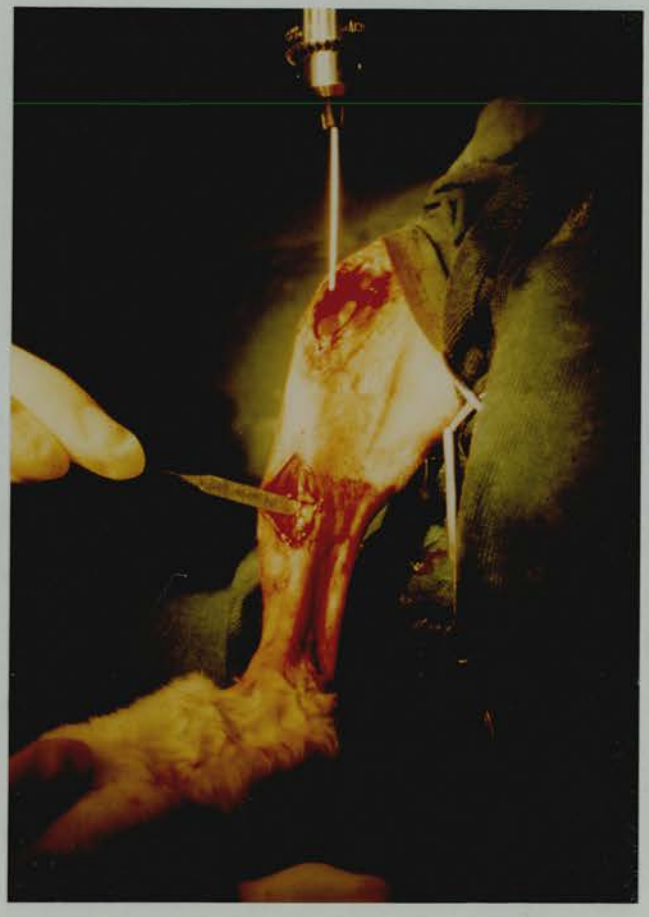

Figure 2.3
An osteotomy made in the middle third of the tibia. The K wire is being introduced at the proximal end.

The animals were divided into three groups. The first group (group F) contained twelve animals, six with inflated balloons and six with uninflated balloons, with equal proportions of left and right tibiae used. Twenty-four hours after the initial surgery these rabbits were anaesthetised by the technique already described. With the balloon still inflated and the plaster of Paris intact radioactive labelled microspheres were injected and blood withdrawn using a technique identical to that used in the pilot study. These rabbits were then killed with an intracardiac barbiturate injection.

There were twelve rabbits in the second group (group G), six with inflated balloons and six with uninflated balloons, with equal numbers of right and left tibiae in each part. Twenty-four hours after initial surgery the balloon was deflated if appropriate and removed without disturbing the plaster. The animals were allowed to move freely in cages for two weeks after which they were sacrificed after microsphere injection.

The third group (group H) contained 12 rabbits, six with inflated and six with uninflated balloons again with equal numbers of right and left tibiae. Their balloons were also removed at 24 hours. One rabbit in the experimental group died four days later of snuffles. Eleven rabbits therefore survived for six weeks and were sacrificed after microsphere injection. One rabbit in

the control group died as the microspheres were injected. There were therefore five animals available in the experimental group for examination. In the control group there were five animals available for bone blood flow estimation and six for torsional testing and callus estimation.

After sacrifice both tibialis anterior muscles were removed for radioactive counting and histological examination as before. Both tibiae were dissected free of soft tissue and removed. In group F the tibiae were divided and prepared as in the pilot study for counting of radioactivity.

Bilateral tibiae from groups G and H were stripped of soft tissue and immediately frozen before any drying occurred. They were stored in polythene bags at - 4° C and allowed to thaw at room temperature for twenty-four hours and the K wires removed before biomechanical testing. The fibula was divided just proximal to the tibio fibular junction in order to eliminate any stabilising effect. The mechanical properties of the bones were measured using a technique developed in Edinburgh for the torsional testing of long bones. A specially designed jig was used to hold a mounting cup at either end of the bones. The bones were positioned central to the torsional axis using two pairs of alignment screws on each cup and Wood's metal was used to

secure the bone ends in the cups. The cups were then clamped into the testing machine. The machine held one cup stationary in a torque transducer while it turned the other at a constant speed of six degrees per second (Figure 2.4). The torque was measured every 0.5 degree.

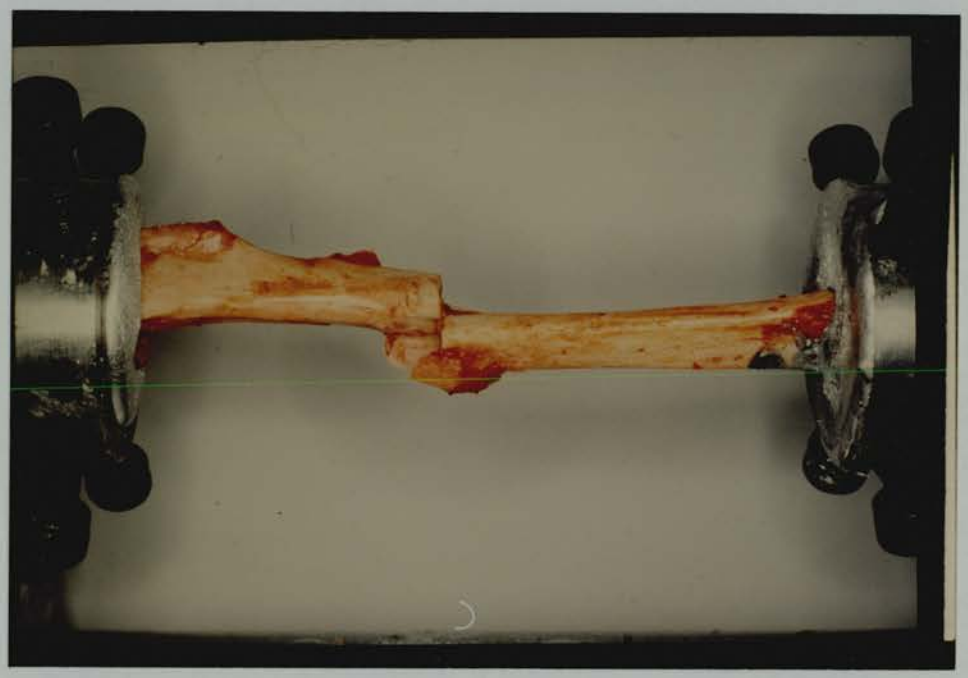

Figure 2.4
Torsional testing of an osteotomised tibia. The tibia has failed partly through the osteotomy and partly through the diaphysis.

After the test was complete the data was analysed to give values for the torsional stiffness, the maximum torque (torsional strength), the angle to maximum torque, the energy to maximum torque and the total energy to failure. To minimise any deleterious effect on the properties of

the bone caused by freezing or differences in bone size between animals the measurements from each pair of bones were converted into a ratio of osteotomised to contralateral tibia.

After torsional testing the experimental tibiae were reconstructed and embedded in paraffin wax. The middle third of the diaphysis was then cut in 1 mm sections. Slab radiographs were prepared on Kodak 4415 technical pan film using a Faxitron soft x-ray unit. Callus and cortical area on each section was then measured using a Joyce Loebl image analysis system. Callus area was expressed as a ratio of periosteal area to cortical area to minimise variation in tibial size between animals.

Statistical analysis was performed using the Wilcoxon rank sum test on the ratios of the experimental to normal legs and the paired Wilcoxon test for comparing control and experimental legs.

2.2.2

Justification of methods

Choice of the animal model

Three main types of animal model for simulation of the acute compartment syndrome have been described. Sheridan and Matsen (1975) described the technique of inserting a latex balloon into the anterior compartment of the rabbit hindleg and obtained consistent muscle ischaemia above

60 mm Hg for a period of 24 hours.

Other methods previously described include external compression (Matsen et al 1979b, Reneman et al 1980) and infusion of autologous blood (Rorabeck and Clarke 1978) or plasma (Hargens et al 1979). The main difficulty of applying these methods is that they require restraint of the animal which is not permitted in the U.K. The method of Sheridan and Matsen (1975) was modified in this study by ligating the balloon tubing thus removing the necessity of attaching it to a column of saline. This allowed the animals to move freely but still gave consistent muscle ischaemia at higher pressures.

Infusion of fluid would not have been suitable for this study as relief of the pressure is achieved only by fasciotomy. It was felt that adding fasciotomy to the surgical insult would result in unnecessary complications in interpreting the results although it is recognised that fasciotomy may have a separate effect on bone blood flow.

Adult female New Zealand white rabbits were used as the experimental animals. Maturity was essential to eliminate the possible effect of open epiphyses on bone blood flow and bone healing. All the animals had been successfully quarantined prior to use, implying they were in good health.

Sevitt (1981) points out that differences occur between bone healing in man and small animals, with particular reference to the speed of healing. He points out that the larger the animal the larger the gap that has to be bridged to achieve union. The cells involved however are of equal size in all the species thus explaining why fractures in small animals unite more quickly than in man. Morphologically however many workers have demonstrated close similarities between fracture healing in small animals (Urist and McLean 1941, Enneking 1948, Trueta and Cavadias 1955, Gothman 1961, Olerud and Danckwardt-Lilliestrom 1968, Rahn et al 1971) under differing conditions.

The rabbit is suitable also for studies on bone blood flow as Brookes (1971) and Gothman (1961) have described in detail the pattern of the blood supply to the rabbit tibia. The tibial nutrient artery enters bone posteriorly just proximal to the tibiofibular syndesmosis and therefore neither a balloon in the anterior compartment or osteotomy distal to the fibular junction will compromise the nutrient flow.

The response of the vascular system of the tibia to fracture has also been shown by several authorities to be similar in small animals to that in man (Wray and Lynch 1959, Trueta 1974, Macnab and de Haas 1974). Indeed

the first description of the extraosseous supply (Gothman 1960b) was on the basis of experiments with rabbit tibiae. The rabbit therefore provides a close simulation to man for the experiments carried out in this study.

Choice of the operative method

The operative methods were chosen in order to minimise disturbance to the muscle compartments and nutrient blood supply. The osteotomy was performed subperiosteally to avoid compromise to the collateral circulation of the muscle by extraperiosteal dissection (Whiteside and Lesker 1978a, Zucman 1960). This also avoided opening the muscle compartment and the possible risk of dissipation of the applied pressure.

Intramedullary fixation was chosen as the method of fixation which least disturbs the muscle compartments and extraosseous flow but provides better stability than plaster fixation alone. This also simulates the clinical study in which the majority of the tibial fractures were treated with closed reamed intramedullary nailing. The rabbit tibiae however were not reamed thus minimising the disturbance of medullary flow.

Choice of mechanical test

Torsional testing was chosen as the most appropriate method of assessment of fracture healing. Burstein and Frankel (1971) consider that five criteria should be met

in judging the most suitable loading criteria of bones.

These are:

1. The loading configuration should produce fractures similar to clinical fractures.

2. The loading configuration should subject the bone to uniform loading conditions along its length in order to identify weak sections.

3. The loading mode must not be critically dependent on bone geometry especially length.

4. The loading configuration must allow control of the rate of load application.

5. The loading configuration should require simple inexpensive equipment.

Burstein and Frankel also stated that torsion is the only configuration which satisfies all of these criteria. Paavolainen (1978) considers torsion to be suitable because it exerts simultaneous tensile, compressive and shear forces.

The torsional testing was designed to be as uniform as possible. Both body weight and the transverse dimensions of the bone were shown by Paavolainen (1978) to have a significant influence on the maximum torque moment and

the torsional rigidity of the rabbit tibia. In order to eliminate these variables the results were expressed as a ratio of the intact to contralateral tibia. Paavolainen also demonstrated right to left differences of 7.1% in torsional rigidity and 6.3% in maximum torque although these figures lacked statistical significance. The numbers of right and left tibiae were equal in each group in this study in order to remove any possible influence of dominance on the results.

Measurement of bone and muscle blood flow

Radioactive labelled microspheres were used in this study for the measurement of both bone and muscle blood flow. The underlying principle of this technique is that microspheres will become trapped in patent vessels of the appropriate diameter and thus the blood flow can be assessed by recording the level of radioactivity. It has distinct advantages over other techniques for measuring blood flow to bone and marrow (Gross et al 1981). Bones required for study need no surgical preparation, several measurements of blood flow are possible in one animal using different radioactive labels, total and regional blood flow to any bone can be measured and experiments can be performed on conscious animals. The first three advantages applied particularly to the experiments in this study. Gross and his co-authors cite three main disadvantages: the inability to detect transient change in flow over a few seconds, limitation of the number of

measurements possible in one animal and the impossibility of the use of the technique in humans. None of these disadvantages apply to this study.

In order to obtain valid measurements several criteria have to be met in the technique: the microspheres must mix adequately with arterial blood, must be extracted in one pass through bone, should not cause significant haemodynamic effects on the general circulation and in bone, must not distort regional blood flow within bone or marrow and their gamma emissions must not be attenuated by the dense cortical bone. These criteria are all met by the technique and size of microspheres employed in this study.

The use of radioactive labelled microspheres has been validated for skeletal muscle. Kane and Grim (1969) found close correlation between microsphere distribution and ^{42}K clearance in both skeletal muscle and bone and Marcus and his co-authors (1981) showed that skeletal muscle blood flow measured with microspheres closely approximated timed venous outflow. It was therefore felt that the microsphere method was also appropriate for the measurement of skeletal muscle blood flow.

In this study it was assumed that the bone blood flow to both hindlimbs in the rabbit is similar under normal conditions. This assumption was confirmed by Court-Brown

(1984) who found less than 2% difference in the bone blood flow of rabbit hindlimbs using the microsphere technique and by Li and his co-authors (1989) who found no difference in bone blood flow between paired dog hindlimbs.

2.2.3

Results

Blood flow - 24 hours

The results for this group (group F) are summarised in table 2.7 and detailed individually in appendix tables 6 and 7.

The mean muscle blood flow in the experimental half of group F is 3.6 mls/min/100g in the osteotomised legs compared to 11.1 mls/min/100g in the opposite intact legs. This difference just fails to reach statistical significance. In the control half of group F, mean muscle blood flow in the osteotomised legs is 4.6 mls/min/100g compared to 4.7 mls/min/100g in the opposite normal legs. There are no significant differences in muscle blood flow on comparing the ratios of osteotomised to normal legs for the experimental and control groups.

Bone blood flow was examined using paired Wilcoxon tests for the control and experimental groups combined. There was a significant reduction in the whole diaphysis ($p < 0.05$) and the marrow ($p < 0.01$) as would be expected at

twenty-four hours after osteotomy.

When the experimental and control groups are compared using the ratio of osteotomised to control legs there are no significant differences in bone blood flow between the two groups although the E/N ratios for the cortex are all considerably lower in the experimental group showing a trend towards a reduction in bone blood flow.

Table 2.7

	Experimental Group			Control Group			
	E ± SE	N ± SE	Mean Ratio E/N	E ± SE	N ± SE	Mean Ratio E/N	P
Muscle	3.6 ± 1.5	11.1 ± 4.4	1.6	4.6 ± 1.1	4.7 ± 1.8	1.3	NS
Proximal 1/3	0.7 ± 0.5	5.8 ± 2.1	0.1	0.6 ± 0.3	2.5 ± 1.4	0.2	NS
Middle 1/3	0.5 ± 0.3	3.5 ± 1.2	0.1	1.4 ± 1.1	1.1 ± 0.6	1.3	NS
Distal 1/3	0.06 ± 0.004	1.7 ± 0.7	0.03	0.1 ± 0.1	0.6 ± 0.3	0.5	NS
Whole diaphysis	0.4 ± 0.2	3.8 ± 1.4	0.1	0.7 ± 0.5	1.4 ± 0.8	0.6	NS
Marrow	3.7 ± 1.6	46.3 ± 15.9	0.2	2.8 ± 1.6	21.4 ± 15.6	0.2	NS

Mean blood flow (mls/min/100g) for group F (unilateral balloon and osteotomy, 24 hours survival)

E = experimental leg N = normal leg
SE = standard error NS = non significant

Blood flow - 2 weeks

The results for this group (group G) are summarised in table 2.8 and detailed in appendix tables 8 and 9. At two weeks after surgery there is a marked hyperaemia in the muscle of the osteotomised legs in the experimental group (18.8 mls/min/100g) compared to the normal legs (3.9 mls/min/100g). This difference is less in the control group where the mean muscle blood flow in the osteotomised legs is 7.5 mls/min/100g compared to 5.2 mls/min/100g in the normal legs. On comparing the ratios of experimental to control legs for the two groups there is a statistically significant increase in muscle blood flow in the experimental group ($p < 0.05$, Wilcoxon rank sum test).

Bone blood flow is significantly increased in the whole diaphysis in both groups by a factor of seven ($p < 0.01$, paired Wilcoxon test). This is particularly marked in the middle third of the diaphysis in both groups. Marrow flow however has returned to normal by this time with no significant differences in either group between the osteotomised and intact legs.

On comparing the ratios of osteotomised to normal legs for the two groups there are no statistical differences in bone blood flow.

Table 2.8

	Experimental Group			Control Group			
	E ± SE	N ± SE	Mean Ratio E/N	E ± SE	N ± SE	Mean Ratio E/N	P
Muscle	18.8 ± 8.1	3.9 ± 1.0	4.4	7.5 ± 2.9	5.2 ± 1.3	1.3	<0.05
Proximal 1/3	8.3 ± 4.4	3.2 ± 0.8	2.0	8.7 ± 2.9	3.2 ± 1.5	3.4	NS
Middle 1/3	21.0 ± 8.0	1.9 ± 0.9	14.1	22.3 ± 7.5	1.6 ± 0.5	21.4	NS
Distal 1/3	9.9 ± 5.7	1.5 ± 0.8	6.4	9.8 ± 4.3	2.6 ± 0.9	3.6	NS
Whole diaphysis	14.0 ± 6.2	2.0 ± 0.9	9.2	15.1 ± 5.6	2.2 ± 0.7	7.0	NS
Marrow	12.8 ± 6.4	11.2 ± 2.6	1.0	8.8 ± 2.6	15.1 ± 4.7	1.0	NS

Mean blood flow (mls/min/100g) for group G (unilateral balloon and osteotomy, two weeks survival)

E = experimental leg N = normal leg
SE = standard error NS = non significant

Blood flow - 6 weeks

The results for this group (group H) are summarised in table 2.9 and detailed in appendix tables 10 and 11.

In the muscle blood flow there is a persistent hyperaemia in the osteotomised legs in the experimental group of

21.7 mls/min/100g compared to 8.7 mls/min/100g in the normal legs but this difference does not reach statistical significance.

The mean muscle blood flow in the osteotomised legs in the control group has dropped to 3.9 mls/min/100g, which is less than the normal legs in this group. The mean ratio for the osteotomised to normal leg is 2.6 in the experimental group and 0.9 in the control group. This suggests a trend for persistent hyperaemia in the muscle subjected to elevated pressures but is not statistically significant.

Mean blood flow in the whole diaphysis of the tibia remains significantly elevated in both groups compared to their intact legs ($p < 0.01$, paired Wilcoxon test) with a mean flow of 15 mls/min/100g in the osteotomised leg and 1.4 mls/min/100g in the intact leg in the experimental group and a more modest increase in the osteotomised legs in the control group (4.2 mls/min/100g) compared to the intact legs (1.2 mls/min/100g) ($p < 0.05$).

On comparison of the ratios for the two groups using the Wilcoxon rank sum test there is a statistically significant increase in blood flow in the whole diaphysis ($p < 0.05$) and in the proximal third ($p < 0.05$) in the experimental group.

Table 2.9

	Experimental Group			Control Group			
	E ± SE	N ± SE	Mean E/N	E ± SE	N ± SE	Mean Ratio E/N	P
Muscle	21.7 ± 9.8	8.7 ± 2.0	2.6	3.9 ± 1.5	4.8 ± 1.8	0.9	NS
Proximal 1/3	8.5 ± 1.7	2.1 ± 1.0	8.5	3.5 ± 2.0	1.7 ± 0.8	1.9	<0.05
Middle 1/3	17.3 ± 3.4	1.3 ± 0.3	14.0	5.3 ± 2.6	0.8 ± 0.3	6.6	NS
Distal 1/3	7.4 ± 3.5	0.5 ± 0.1	14.2	2.1 ± 1.3	4.0 ± 3.7	9.0	NS
Whole diaphysis	15.0 ± 4.4	1.4 ± 0.5	11.5	4.2 ± 1.8	1.2 ± 0.6	3.7	<0.05
Marrow	24.4 ± 6.2	21.8 ± 3.9	1.1	13.7 ± 6.9	8.9 ± 3.1	2.9	NS

Mean blood flow (mls/min/100g) for group H (unilateral balloon and osteotomy, six weeks survival)

E = experimental leg N = normal leg
SE = standard error NS = non significant

Muscle histology

None of the control group muscles showed any histological abnormalities either in the 24 hour, two week or six week survival groups.

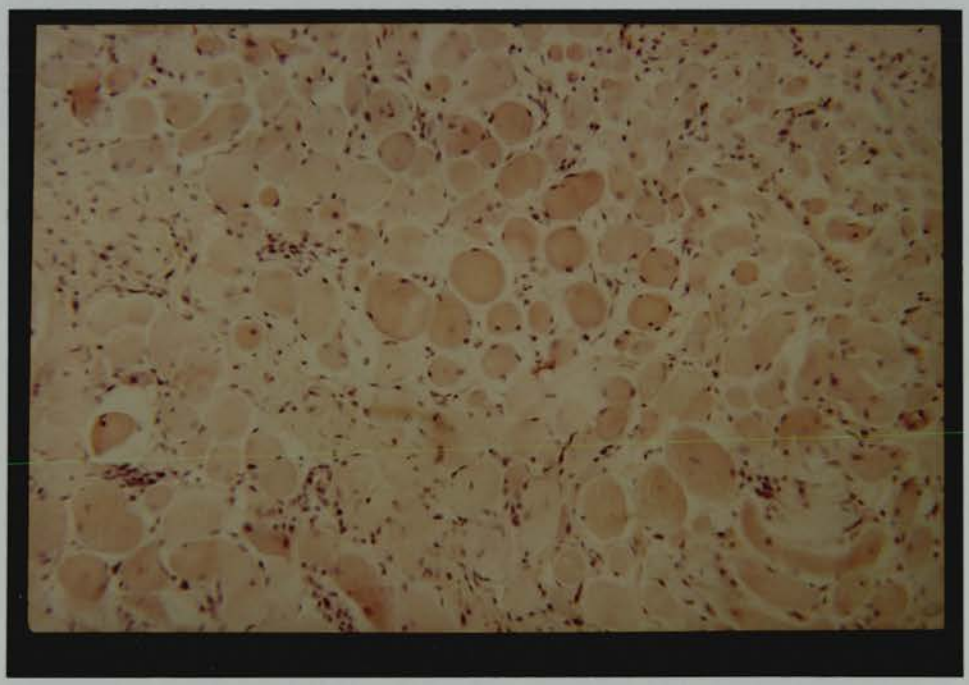

Figure 2.5
Histological section (x100) of muscle two weeks after pressurisation at 90 mm Hg for 24 hours. There is extensive ischaemic necrosis with early fibrosis.

In the experimental group there were histological abnormalities in all the muscle specimens from the osteotomised legs. At 24 hours there were predominantly inflammatory changes with ischaemic necrosis evident in that many fibres although retaining their pyknotic shape had no nuclei. There was occasional patchy swelling of fibres. These changes were very similar to those in the pilot study for the same pressure and time (Figure 2.2).

At two weeks all the preparations showed extensive ischaemic necrosis with one showing residual inflammatory change and the other five showing early fibrosis with invasion by phagocytes and fibrocytes (Figure 2.5). At six weeks there was universal extensive fibrosis replacing the muscle tissue (Figure 2.6).

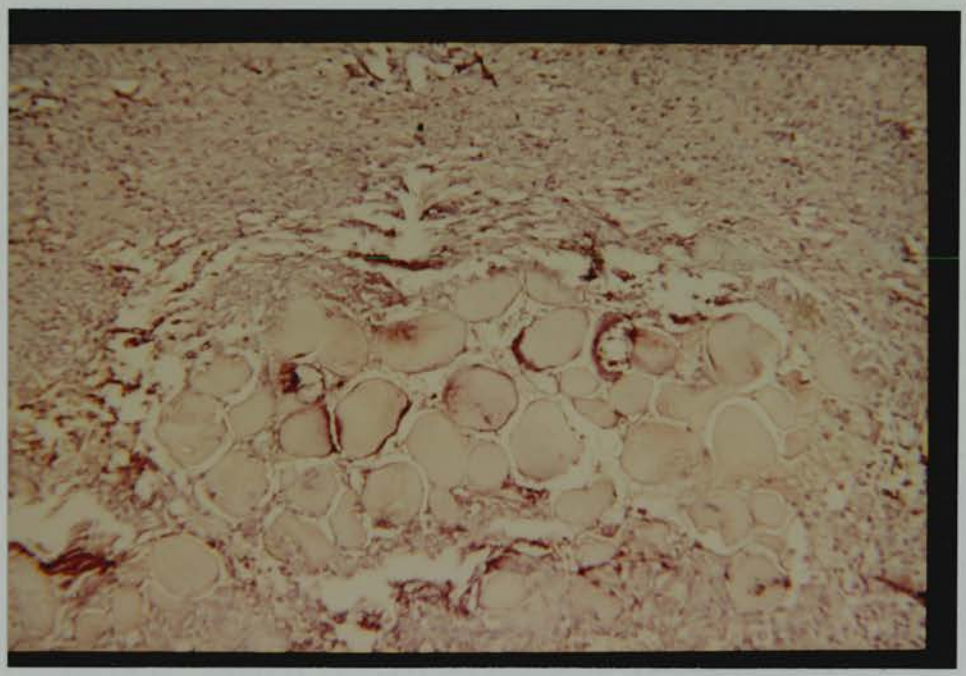

Figure 2.6
Histological section (x100) of muscle six weeks after pressurisation at 90 mm Hg for 24 hours. There is extensive fibrosis.

Testing of mechanical strength

The results for group G are summarised in table 2.10 and detailed in appendix tables 12 and 13. The results are expressed for statistical analysis as ratios of the values for the osteotomised tibiae compared to the opposite intact tibiae. This is to eliminate any changes

due to variation in the size of the animals or the normal strength of their tibiae. The weights of the animals in the two week control group ranged from 3.0 kg to 3.7 kg with a mean weight of 3.4 kg. In the two week experimental group their weights ranged from 3.0 kg to 4.1 kg with a mean of 3.4 kg. It can be seen from appendix tables 12 and 13 that there is a considerable variation in the mechanical strength of the intact tibiae.

Although at two weeks there is a tendency for the experimental tibiae to be weaker in all tests (Table 2.10) only the difference for maximum torque moment reaches statistical significance ($p < 0.05$, Wilcoxon rank sum test). However two of the experimental group (Appendix table 13) were too weak to test formally. All the osteotomised tibiae in both the control and experimental groups failed through the fracture site.

In contrast, in the six week experimental group the weights of the rabbits ranged from 3.7 kg to 4.2 kg with a mean weight of 3.9 kg. The control group was very similar with a mean weight of 3.8 kg (range 3.4 to 4.3 kg). From appendix tables 14 and 15, it can be seen that animals in the experimental group have slightly stronger normal tibiae in terms of maximum torque moment and torsional stiffness than those in the control group.

On comparison of the control and experimental groups (Table 2.11) some differences can be seen to emerge. At six weeks the control group have regained 0.9 of their normal torsional stiffness while the experimental group have only regained 0.6. This difference is significant ($p < 0.01$, Wilcoxon rank sum test). For maximum torque moment, the control group have regained 0.9 of their strength compared to 0.5 in the experimental group ($p < 0.05$, Wilcoxon rank sum test). For the other measurements of strength the experimental group is weaker but none of the results reach statistical significance.

Table 2.10

	Control Group	Experimental Group	P
Max torque moment	0.2	0.1	<0.05
Max angular deformation	1.1	0.5	NS
Total energy	0.5	0.3	NS
Energy to fracture	0.2	0.1	NS
Torsional stiffness	0.3	0.2	NS

Mean ratios for biomechanical tests of osteotomised to normal tibiae in Group G (2 week survival)

NS = not significant

Table 2.11

	Control Group	Experimental Group	P
Max torque moment	0.9	0.5	<0.05
Max angular deformation	0.9	0.9	NS
Total energy	0.9	0.6	NS
Energy to fracture	1.0	0.5	NS
Torsional stiffness	0.9	0.6	<0.01

Mean ratios for biomechanical tests of osteotomised to normal tibiae in Group H (6 week survival)

NS = not significant

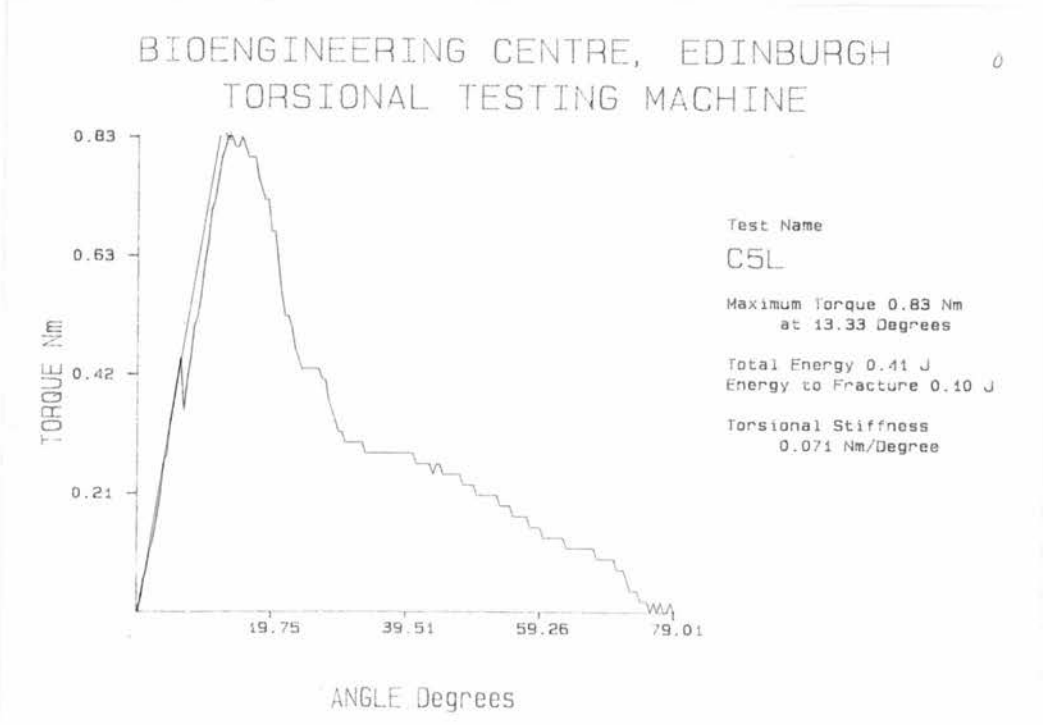

Figure 2.7
Torsional testing of an experimental osteotomised tibia at six weeks. There is a low stiffness, rubbery pattern of failure.

Three osteotomised tibiae in the experimental group failed through the osteotomy site at six weeks, two with a low stiffness rubbery pattern of failure (Figure 2.7). The remaining three failed partly through the diaphysis with a hard tissue pattern. In contrast none of the control group failed completely through the osteotomy, two failed in part through the osteotomy and four failed through the distal third of the diaphysis with no relation to the osteotomy site. All demonstrated a high torque and small angular deformation associated with high stiffness (Figure 2.8).

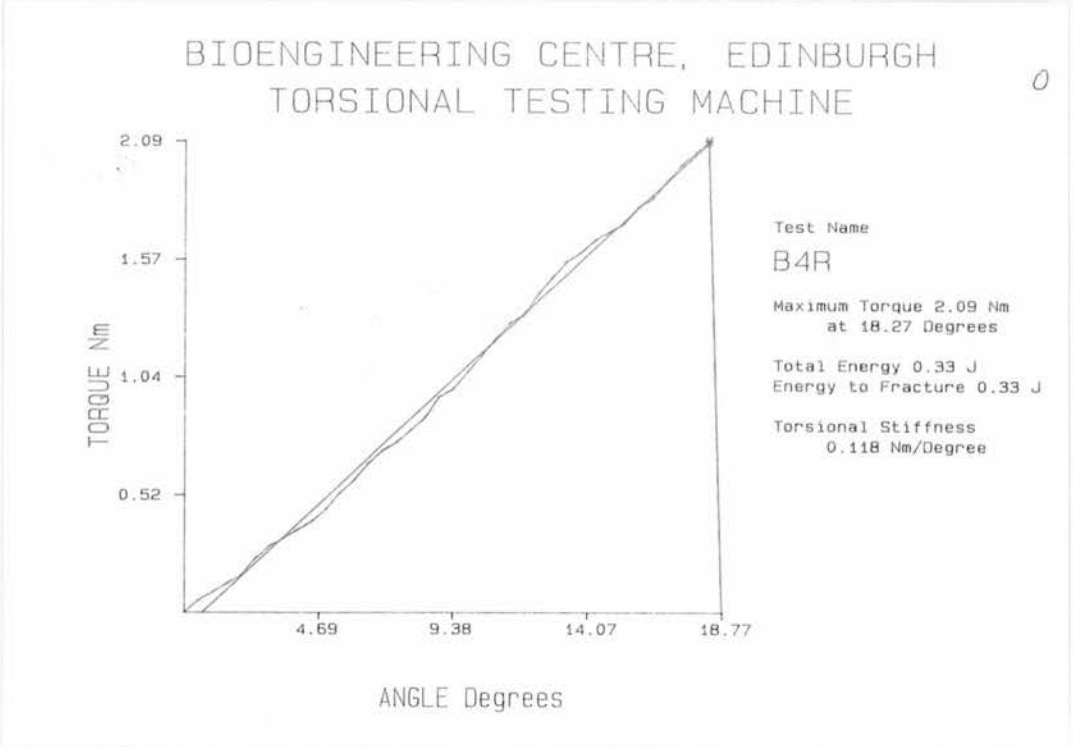

Figure 2.8
Torsional testing of a control osteotomised tibia at six weeks. There is a high stiffness pattern of failure.

Table 2.12

No.	Control Group P/C	Experimental Group P/C
1	3.81	0.31
2	3.22	3.01
3	3.67	2.78
4	2.90	2.64
5	3.18	3.17
6	2.13	3.38
Mean ± SE	3.15 ± 0.25	2.55 ± 0.46
P	NS	

Ratios of periosteal callus area to cortical area (P/C) for experimental and control groups G (2 weeks survival)

NS = non significant SE = standard error

Table 2.13

No.	Control Group P/C	Experimental Group P/C
1	0.74	1.81
2	2.08	2.06
3	1.54	2.53
4	1.49	2.67
5	1.30	5.02
6	1.49	-
Mean ± SE	1.44 ± 0.18	2.82 ± 0.57
P	<0.05	

Ratios of periosteal callus area to cortical area (P/C) for experimental and control groups H (6 weeks survival)

SE = standard error

Measurement of callus area

The results for group G (two week survival) are summarised in Table 2.12 and detailed in appendix tables 16 and 17. At two weeks the mean ratio of periosteal callus area to cortical area in the control group is 3.15 compared with 2.5 in the experimental group. Despite the apparently smaller amount of callus in the experimental group this difference is not statistically significant.

The results for group H (six week survival) are summarised in table 2.13 and detailed in appendix tables 18 and 19. The ratio of periosteal callus area to cortical area in the control group is 1.44 compared to 2.82 in the experimental group. This difference is statistically significant ($p < 0.05$, Wilcoxon rank sum test). The callus in each group was examined histologically. In the experimental group the callus was immature with a much larger proportion of cartilaginous callus. In contrast in the control group all the specimens showed evidence of remodelling with replacement of callus by mature cortical bone.

2.2.4

Discussion

The experimental study has demonstrated a clear relationship between experimentally induced acute compartment syndrome and delay in tibial union.

The compartment syndrome model has been validated in combination with osteotomy by the findings of reduced muscle blood flow at 24 hours, muscle hyperaemia at two and six weeks and necrosis and fibrosis histologically. Although the model is not identical to the clinical situation because of absence of direct trauma to the muscle itself, this would diminish rather than falsely exaggerate any difference in the results (Whiteside and Lesker 1978a). Muscle ischaemia has been induced by this method although its extent is not quantifiable.

The main evidence for a delay in bone union lies in the results of the torsional testing. This is a clinically relevant observation since one of the main functions of bone is to carry load. The individual results for the intact tibiae differ slightly from those published by Paavolainen (1978). This may be due to a slightly different rate of loading or to the effect of freezing in this study. Sedlin (1965) states however that the physical properties of cortical bone are not altered by freezing at -20°C. Since all of the specimens in this study were frozen this should not significantly affect the results.

There were no statistical differences in the strength of healing at two weeks. This is not surprising since healing at this stage is very weak and differences are likely to be less than the method error, reported as 6.3%

using a similar method (Paavolainen 1978). The specimens all failed with a low stiffness, rubbery pattern and this corresponds closely to stage I of fracture healing as described by White and his colleagues (1977). The elapsed time from fracture also corresponds in this study as White et al describe stage I as being within 21 days of fracture.

At six weeks after osteotomy clear differences are seen in the strength and pattern of healing. The osteotomies which were subjected to an induced compartment syndrome are an average of 39% weaker in terms of torsional stiffness than their contralateral tibiae while the control group have regained normal torsional stiffness allowing for method error. Measurements of maximum torque moment show similar differences with the experimental group only having regained 52% of its normal strength. The patterns of failure again correspond closely to White et al's stages of fracture repair. In the experimental group two osteotomies had not progressed beyond stage I of fracture healing, failing through the osteotomy site with a low stiffness, rubbery pattern which ought to disappear at 21 days. One tibia corresponded to stage II, failing through the osteotomy with a high stiffness, hard tissue pattern and the remaining three fell into stage III failing partly through the osteotomy site and partly through intact bone. In contrast, healing as defined by these stages

was much more advanced in the control group with the pattern of failure in two tibiae corresponding to stage III and the remaining four falling into stage IV by failing through a site unrelated to the original osteotomy. These factors taken together demonstrate both a qualitative and quantitative delay in bone union at six weeks in the presence of an experimentally induced compartment syndrome.

Interpretation of the assessment of callus area mirrors the mechanical results. There is an apparent reduction in the total amount of callus at two weeks in the experimental group but as with the mechanical testing this does not reach statistical significance. Presumably at this stage healing is too early and callus volumes too small to show changes taking into account all the variables.

At six weeks however there is a larger callus area in the experimental group which is histologically less mature than the control group. The smaller volume in the control group shows histological characteristics of remodelling with some cortical reconstitution. This confirms the biomechanical testing, since the majority of the control group at this stage had the characteristics of normal cortical bone. This study has therefore demonstrated a delay in the evolution of callus in experimental osteotomy associated with an experimentally

induced compartment syndrome.

In the retrospective study on the effect of acute compartment syndrome (Court-Brown and McQueen 1987) it was suggested that the clinically observed delay in bone union was due to reduction in bone blood flow and this study was designed to test this hypothesis. Bone blood flow in this study is clearly affected by raised intracompartmental pressure with a relative bone ischaemia appearing in the experimental group at 24 hours and a hyperaemia at six weeks after osteotomy.

The accuracy of the bone blood flow measurements is validated by achieving the normal vascular response to experimental osteotomy with an increase in flow peaking at two weeks. (Rhinelander 1968, Paradis and Kelly 1975). Furthermore the absolute measurements of flow in the intact tibiae are similar to those quoted by other authors both in the same laboratory (Court-Brown 1984, Strachan et al 1990, Wallace et al 1991) and elsewhere (Paradis and Kelly 1975, Gross et al 1981, Li et al 1989, Triffit and Gregg 1990).

At 24 hours after osteotomy both groups demonstrate a statistically significant reduction in bone blood flow in the whole diaphysis compared to the opposite intact tibia. In the control group however the differences are of lesser magnitude and with higher E/N ratios than

the experimental group. The addition of an experimental compartment syndrome may cause a greater degree of bone ischaemia than would be expected from osteotomy alone after 24 hours have elapsed. There is a trend towards higher blood flow in the normal legs in the experimental group but the differences are not significant. This does however suggest the possibility of a "steal" phenomenon to the opposite leg in the animals with an ischaemic muscle group. This phenomenon has been noted by Nutton et al (1984) when flow to tibiae and surrounding soft tissues was reduced by infusion of norepinephrine and the opposite control leg showed a corresponding increase in flow to these tissues. The reverse of this effect occurred when flow to the experimental leg was increased by ATP and the flow to the opposite control leg decreased. This phenomenon may be mediated by humoral mechanisms. Ischaemia is known to be a strong stimulus for vasodilatation (Matsen 1980) and this has been attributed to the accumulation of vasodilator metabolites (Folkow and Lovfing 1956).

Two weeks after surgery there is a marked hyperaemia in the muscle of the leg which was subjected to raised compartment pressure. Holden (1972) found intense hyperaemia three weeks after devascularisation of muscle and attributed this to revascularisation from adjacent healthy muscle, skin and the intact local neurovascular bundle. Hyperaemia of muscle in this study combined

with histological features of necrosis confirms the successful induction of muscle ischaemia.

At two weeks the expected rise in bone blood flow occurs and this is particularly marked in the middle 1/3 of the tibia at the osteotomy site. There are no differences between the experimental and control groups. As the muscle revascularisation has progressed in the ischaemic group presumably the extraosseous supply has also recovered and has thus been able to supply the observed increase in flow to the tibia. It is interesting to speculate when this revascularisation occurred in the preceding two weeks. In view of the possibility of relative bone ischaemia at 24 hours it may be assumed that a delay in recovery of bone blood flow occurred during the first two weeks. Experiments at shorter time intervals would be required to confirm or refute this hypothesis.

Six weeks after osteotomy hyperaemia persists in the muscles of the osteotomised legs in the experimental group while muscle blood flow in the control group remains at normal levels. Revascularisation of the ischaemic muscle is presumably continuing at this time along with continuing demand on the muscle blood vessels for recruitment of extraosseous supply. Bone blood flow in the experimental group is persistently higher in the osteotomised legs than the intact legs but this is not

the case in the control group where the bone blood flow in the osteotomised legs has returned to normal. There is significantly higher blood flow in the whole diaphysis in the osteotomised legs of the experimental group compared to the control group. Again this indicates that the vascularity of the osteotomy in the experimental group is at an earlier stage of development than in the control group, implying a delay in the normal progression of recovery of bone blood flow.

The observed delay in experimental bone union can therefore be attributed to a reduction in bone blood flow. It is likely that muscle ischaemia reduced the capacity for development of the extraosseous supply which has been shown to be of prime importance following fracture. (Wray and Lynch 1959, Cavadias and Trueta 1965, Macnab and De Haas 1974, Trueta 1974, Strachan et al 1990, Triffit et al 1993). This in turn may have a deleterious effect on the osteogenic signals from the fracture because of the presence of avascular bone (Hulth 1989). Hulth also suggests that extensive phagocytosis may cause growth factors and cytokines to promote the development of fibrous tissue rather than bone.

CHAPTER 3

Clinical study

3.1

Introduction

3.1.1

Clinical diagnosis of acute compartment syndrome

The symptoms and signs of the acute compartment syndrome can be deduced from the definition of the condition - increased tissue pressure within a limited space causing a reduction in the blood flow and function of the tissues within the space.

Inadequate blood flow to muscles causes pain which is ischaemic in nature and therefore is severe and out of proportion to what would be expected from the clinical situation. This is now recognised by most authors as being a common symptom of acute compartment syndrome in most anatomical areas (Eaton and Green 1975, Holden 1979, DeLee and Stiehl 1981, Mubarak 1983, Rorabeck 1984, Schwartz et al 1989, Bourne and Rorabeck 1989, Brostrom et al 1990, Shereff 1990, Willis and Rorabeck 1990). Rollins et al (1981) found 83% of their patients requiring fasciotomy had pain as a primary symptom. The pain is normally increased by passive stretching of the affected muscle group, although this finding may be caused by direct muscle injury rather than by ischaemia (Mubarak et al 1978). Although pain is the commonest symptom it may be unreliable as it can be very variable

in degree (Whitesides et al 1975, Eaton and Green 1975, Matsen and Krugmire 1978). Acute compartment syndrome may be painless either in association with nerve injury (Holden 1979, Wright et al 1989) or in its early stages (McQueen et al 1990). In the deep posterior compartment syndrome pain may be minimal (Matsen and Clawson 1975, Matsen and Krugmire 1978) while pain is not a useful symptom in the unconscious patient.

Sensory symptoms and signs are usually the first indication of nerve ischaemia with paraesthesiae or anaesthesia in the territory of the nerves running through the affected compartment (Matsen and Krugmire 1978, Gelberman et al 1981, DeLee and Stiehl 1981, Mubarak et al 1978, Rorabeck 1984, Bourne and Rorabeck 1989, Schwartz et al 1989, Shereff 1990, Myerson 1991). Several authors believe sensory deficit to be the most reliable sign of acute compartment syndrome (Mubarak et al 1978, Gelberman et al 1981, Shereff 1990) and its presence is reported in 42% to 100% of cases (Rollins et al 1981, DeLee and Stiehl 1981, Rorabeck 1984, Schwartz et al 1989). The anatomical location of the affected compartment can be confirmed by careful examination of the sensory deficit which will be in the area of nerve supply appropriate to the affected nerve. Nerve ischaemia progresses, if not relieved, to cause paralysis of muscles. Rollins and his co-authors (1981) found that 36% of their patients requiring fasciotomy had paralysis

of muscle and all of these patients had permanent sequelae at follow-up. Other authors have noted varying numbers of patients with motor deficit (DeLee and Stiehl 1981, Rorabeck 1984, Schwartz et al 1989) but where motor deficit was apparent full recovery was rare. Willis and Rorabeck (1990) believe that motor deficit is a late finding and is associated with irreversible damage to muscle and nerve. Paralysis however can be difficult to interpret as it may be caused by direct nerve injury, primary muscle ischaemia or may be simulated by muscle guarding because of pain (Mubarak et al 1978). Also both sensory deficit and paralysis are impossible to elicit in the unconscious patient.

A common error in the clinical diagnosis of the acute compartment syndrome is to underestimate the severity of the condition because peripheral pulses are present. Compartment pressure is only rarely high enough to occlude a major vessel and the acute compartment syndrome often occurs with pressure lower than the diastolic pressure (Whitesides et al 1975, Mubarak et al 1978, Matsen and Krugmire 1978, Gelberman et al 1981, Mubarak 1983, Bourne and Rorabeck 1989, Willis and Rorabeck 1990, Symes 1991). The only exception to this is in associated arterial injury where the absent pulse is due to arterial damage rather than high compartment pressures (Rorabeck 1984, Mubarak 1983). Distal ischaemia and absent pulses are an indication for arteriography.

Swelling or tenseness is a common sign of acute compartment syndrome provided it is possible to palpate the compartment (Matsen and Krugmire 1978, Rollins et al 1981, Mubarak 1983, Schwartz et al 1989, Shereff 1990, Brostrom et al 1990). In cases where the leg is encased in plaster or dressings or where there is marked peripheral oedema this sign may be difficult to elicit.

The early diagnosis of the acute compartment syndrome is of paramount importance. Delay in diagnosis is often due to either inexperience and insufficient awareness of the condition or to an indefinite and confusing clinical presentation. Delay in treatment can lead to catastrophic consequences including contracture, infection and occasionally amputation. McQuillan and Nolan (1968) reported on 15 cases of acute compartment syndrome in which the diagnosis was delayed by more than twenty-four hours in four patients. All four had persistent motor and sensory deficit and the authors stated that delay was the single cause of failure. This conclusion is repeated throughout the later reports on the condition (Matsen and Clawson 1975, Rorabeck and Macnab 1976, Sheridan and Matsen 1976, Matsen and Krugmire 1978, DeLee and Stiehl 1981, Rorabeck 1984) with critical times varying from six to twenty-four hours.

3.1.2

Monitoring of intracompartmental pressure

Because of the unreliability of the clinical diagnosis of the acute compartment syndrome methods of measuring intracompartmental pressure have been developed.

Whitesides and his co-authors (1975) were the first to report on the use of tissue pressure measurements in the acute compartment syndrome. They used the needle manometer method and concluded that the technique provides reliable and reproducible information. However this technique has been criticised by several authors. Mubarak et al (1976) point out that the injection of saline results in local oedema near the tip of the needle resulting in falsely high pressure readings. Reneman (1968) noted two other disadvantages of the technique: tissue pressure cannot be determined during muscle contraction and continuous measurements are impossible. Matsen and co-authors (1976) find this technique to be awkward in practice because a manometer and an air-fluid meniscus must be observed simultaneously. Inter-observer error may also lead to a lack of reproducibility. This method is now rarely used in clinical practice.

There are three other methods available for monitoring intracompartmental pressure: the continuous infusion method, the wick catheter and the slit catheter.

Matsen et al described their continuous infusion method in 1976. This technique relies on measuring the pressure necessary to infuse fluid slowly into the muscle of the compartment. They conclude that this method is simple to use and accurate to within 2mm Hg over the range from 0 to 60mm Hg. The response time was slow however being approximately 15 minutes at the recommended infusion rate of 0.7 mls per day. Rorabeck and his co-authors (1981) suggest that there is a potential risk of aggravating acute compartment syndrome by the continuous infusion. Mubarak (1983) cites the main disadvantage of this technique as being the expense of the syringe infusion pump.

The wick catheter technique was first described for the measurement of intramuscular pressure by Mubarak et al in 1976. This technique depends on braided Dexon wicks protruding from the end of an epidural catheter. This provides an extensive contact area and prevents ball-valve obstruction of the catheter tip. The authors stated that this method was accurate and reproducible and allowed continuous long term measurements. Suggested disadvantages of this technique are the risk of leaving a part of the catheter in situ after attempted removal (Rorabeck et al 1981) and possible coagulation of blood around the tip resulting in blockage of the catheter.

The slit catheter technique was described by Rorabeck and

his colleagues in 1981. This technique depends on slits being cut at the tip of the catheter resulting in a large surface area thus preventing total occlusion by muscle. Continuous infusion is therefore not required to maintain continuity between the tissue fluid and the saline in the catheter. A possible disadvantage of this technique is its susceptibility to the presence of an air bubble at the tip of the catheter which reduces catheter response to changes in intracompartmental pressure (Mubarak 1983).

Both the wick and slit catheter techniques have been shown to be accurate in experimental studies (Rorabeck et al 1981, Mubarak et al 1976, Moed and Thorderson 1993) and in humans (Koman et al 1981, Shakespeare et al 1982).

All of the above techniques are dependent on an external dome transducer and connecting manometer tubing which McDermott and his co-authors (1984) believe to have inherent problems such as difficulty in levelling the transducer with the tip of the catheter and the possibility of air in the system leading to falsely low values. They developed a catheter with a transducer incorporated in its tip which is inserted directly into the compartment and showed its accuracy to be comparable to conventional systems. This system has now been developed to provide a portable digital display of compartment pressure.

3.1.3

Tissue pressure thresholds for decompression

The normal resting pressure in muscle compartments has been measured by various authors and is found to be consistently lower than 10mm Hg (Whitesides et al 1975, Mubarak et al 1976, Shakespeare et al 1982, McDermott et al 1984, Styf 1989). Whitesides and his co-authors were the first to consider the importance of tissue pressure levels above which decompression is indicated. They stated that ischaemia begins when the tissue pressure rises to within 10 - 30mm Hg of the diastolic blood pressure. Thus patients with hypotension are more vulnerable to raised tissue pressure but conversely hypertensive patients may be relatively protected. Controversy continues however with critical levels of tissue pressure varying between 30mm Hg (Mubarak et al 1978, Hargens et al 1989) 40mm Hg (Matsen et al 1976, Koman et al 1981, McDermott et al 1984, Schwartz et al 1989) to 45 mm Hg (Matsen et al 1980a). Some of this variation may be explained by differing techniques and some by failure to take the patient's blood pressure into account. Mubarak and his colleagues (1978) performed fasciotomies in all cases with compartment pressure greater than 30mm Hg but state that some of their patients with pressures in the 30 - 40mm Hg range might well have recovered without a fasciotomy. They consider that there is no single correct pressure for all individuals. Matsen and his co-authors (1980a) consider

that a pressure greater than 45 mm Hg is an indication for fasciotomy but qualify this by pointing out that the concept of a critical pressure above which surgical decompression should be performed is of limited value because individuals vary in their tolerance for increased tissue pressure. The tissue pressure threshold for peripheral nerve function was examined by Gelberman et al (1983) who found that above 50mm Hg there was a sudden reduction in nerve function. They also demonstrated relative protection in a hypertensive subject when a pressure of 60mm Hg was applied.

Recent work by Heckman and his co-authors (1993) investigated the effect of different ▲P (the difference between the diastolic and compartment pressure) levels on canine muscle. Two weeks after pressurisation they found no abnormalities with a ▲P of greater than 20mm Hg, mild abnormality at a ▲P of 20mm Hg, scattered areas of infarction and fibrosis with a ▲P of 10mm Hg and widespread infarction and scarring where the tissue pressure equalled diastolic pressure. They concluded that fasciotomy should be carried out at a ▲P of 10 - 20mm Hg.

As yet no agreement has been reached on the tissue pressure threshold for fasciotomy.

3.1.4

Indications for pressure monitoring

A variety of indications are quoted for instituting pressure monitoring in the injured patient. The commonest reasons are in the unconscious patient (Whitesides et al 1975, Mubarak et al 1978, Matsen et al 1980a, Gelberman et al 1981, Rorabeck 1984, Hargens et al 1989, Schwartz et al 1989), in patients difficult to assess such as young children (Whitesides et al 1975, Mubarak 1983, Hargens et al 1989, Willis and Rorabeck 1990), in patients with equivocal symptoms and signs (Gelberman et al 1981) particularly in the presence of concomitant nerve injury (Whitesides et al 1975, Mubarak et al 1978, Matsen et al 1980, Wright et al 1989) and in patients with multiple injury (Bourne and Rorabeck 1989, Schwartz et al 1989, Willis and Rorabeck 1990). Compartment monitoring has also been recommended to assess the adequacy of decompressive fasciotomy (Mubarak et al 1978, Gelberman et al 1981) and in patients at risk of compartment syndrome (Brostrom et al 1990, Tischenko and Goodman 1990). Brostrom and his co-authors do not define the high risk patient but Tischenko and Goodman consider that a patient with a tibial fracture who has prolonged surgery with strong longitudinal traction is at risk of acute compartment syndrome.

The usefulness of compartment monitoring is debated by some authors. Viegas et al (1988) consider that pressure

monitoring assists but should not replace clinical assessment despite stating that clinical findings are well known to be unreliable. Shereff (1990) however feels that the clinical diagnosis of compartment syndrome in the foot is so unreliable that compartment pressure monitoring is preferred over the clinical findings for the diagnosis of acute compartment syndrome. This view is echoed by Myerson (1991). However some authors disagree and state that the use of pressure monitoring may be limited because of the infrequent occurrence of compartment syndrome, the likelihood that most surgeons would find pressure measurements cumbersome and because the need for fasciotomy is readily apparent clinically (Rollins et al 1981) Despite this statement five of their patients had sequelae of acute compartment syndrome because the diagnosis was delayed.

In summary, acute compartment syndrome is a condition in which it is difficult to make an early and accurate diagnosis on clinical findings. Delay in diagnosis however leads to serious complications. Compartment pressure monitoring has been advocated to overcome this problem.

3.2

Compartment pressure monitoring in tibial fractures.

3.2.1

Material and methods

During the period from May 1986 to December 1988, one hundred and sixteen patients with tibial diaphyseal fractures underwent continuous monitoring of their compartment pressures. There were 92 males and 24 females with an average age of 33 years (range 14 - 85). Forty-two patients had been injured playing sport, thirty-nine in road traffic accidents and twenty-nine in a fall, five of which were falls from a height of more than six feet. The remaining six had a variety of causes (Table 3.1).

Table 3.1

Mode of injury	Number
Sport	42
RTA	39
Fall	24
Fall from height	5
Assault	3
Crush injury	1
Fit	1
Stress fracture	1
Total	116

Mode of injury of the monitored tibial fractures

The fractures were classified by Tscherne's method (Oestern and Tscherne 1984) for closed fractures and Gustilo's method (Gustilo and Anderson 1976, Gustilo et al 1984) for open fractures. The distribution of types of fracture are shown in Table 3.2. Ninety fractures were treated with an intramedullary nail, fifteen with external fixation, seven in a cast and four with a plate.

Table 3.2

Classification		Number
Tscherne (T)	T O	7
	T 1	64
	T 2	22
	T 3	7
Gustilo (G)	G 1	9
	G 2	4
	G 3a	2
	G 3b	1

Classification of the types of fractures monitored

Continuous pressure monitoring was carried out peroperatively and for a period of 24 hours postoperatively or longer if indicated. The slit catheter method (Rorabeck et al 1981) was used with modification. A 20 gauge 6" central venous pressure catheter was modified by cutting two longitudinal slits of approximately 1 cm length in its tip (Figure 3.1).

Figure 3.1
A slit catheter.

This catheter was then inserted into the anterior compartment 10 cm below the level of the tibial tuberosity. The catheter was filled with normal saline and connected to a transducer via manometer tubing also full of normal saline. Care was taken to exclude air from the system. The system was then zeroed to atmospheric pressure with the transducer secured onto the leg at the level of the catheter tip. The pressure was recorded continuously on a chart recorder (Figure 3.2), during which time the patient's blood pressure was also recorded. The pressure was expressed as both the absolute pressure and the difference between the

diastolic and absolute pressures (▲P) for the first and second twelve hour periods of monitoring. The pressure for the first and second twelve hour periods was calculated by allocating a value to each hour of recording and then calculating the mean value for each twelve hour period. The delay from injury to the start of pressure monitoring and the delay to surgery were noted.

The average time to follow up was 15 months (range 6 - 59 months). Complications related to acute compartment syndrome were recorded at that time. Bone union was defined as the time at which the patient could bear weight on the unprotected leg without pain or by the presence of bridging callus radiologically.

Statistical analysis was performed using the Spearman rank correlation coefficient, the Wilcoxon rank sum test, the Kruskal Wallis test and multiple linear regression analysis.

3.2.2

Results

The mean absolute pressure for the whole group was 30 mm Hg (range 5 - 55 mm Hg) for the first twelve hours of monitoring and 25 mm Hg (range 5 - 75 mm Hg) for the second twelve hours. The mean ▲P for the first twelve hours was 52 mm Hg (range 15 - 93 mm Hg) and 56 mm Hg

(range 10 - 85 mm Hg) for the second twelve hours.

There were three acute compartment syndromes in the whole group (2.6%). The first was a 17 year old male who had been involved in a road traffic accident as a pedestrian and had a Tscherne grade 1 fracture of the tibia with ipsilateral tibial plateau and femoral condylar fractures. Compartment monitoring was instituted at time of surgery 8 hours after injury. This revealed an absolute pressure in the anterior compartment of the leg of 45 mm Hg and a ▲P of 15 mm Hg. Exploration of all four compartments revealed an extensive crush injury with widespread muscle necrosis and a through knee amputation was performed.

The second patient with acute compartment syndrome was a 24 year old male who sustained a Tscherne grade 1 tibial fracture while playing football. Immediately after admission compartment pressure monitoring was instituted and revealed a pressure of 35 mm Hg (▲ P 40 mm Hg). Fourteen hours after injury the fracture was reduced and a closed external fixator was applied. Immediately after surgery the pressure in the anterior compartment was 45 mm Hg (▲P 30 mm Hg). The patient was symptom free. Over the following 10 hours the pressure rose to 65 mm Hg (▲P 10 mm Hg) and the patient developed pain and paraesthesiae in his foot. A double incision four compartment fasciotomy was carried out. No further

complications ensued and the fracture united at 17 weeks. No complications of the acute compartment syndrome were found at final review 10 months after injury.

The third patient with acute compartment syndrome was a 19 year old male who had sustained a Tscherne grade 1 tibial fracture playing football. Six hours after injury the fracture was reduced and stabilised with an intramedullary nail and compartment monitoring was commenced. The compartment pressure immediately postoperatively was 45 mm Hg (▲P 45 mm Hg) but in the following twelve hours this gradually rose to 75 mm Hg (▲P 15 mm Hg) (Figure 3.2). The patient remained symptom free. A double incision four compartment fasciotomy was performed and the surgical findings confirmed the diagnosis (Figure 3.3). Recovery was uneventful and the fracture healed 15 weeks after injury. No sequelae of the acute compartment syndrome were found at final review 13 months after injury.

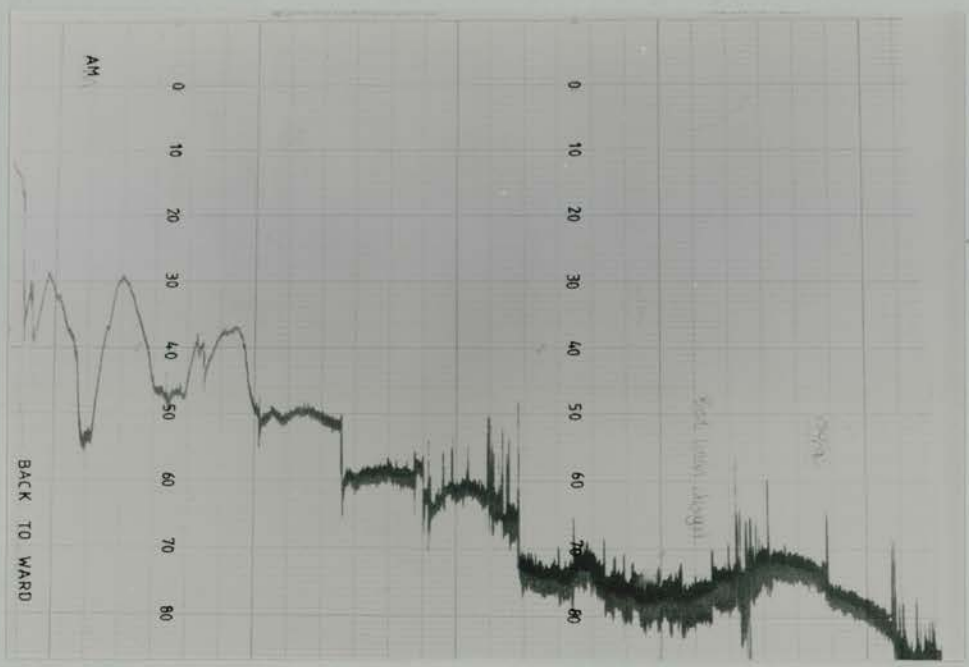

Figure 3.2
Post-operative pressure levels of the third patient with acute compartment syndrome.

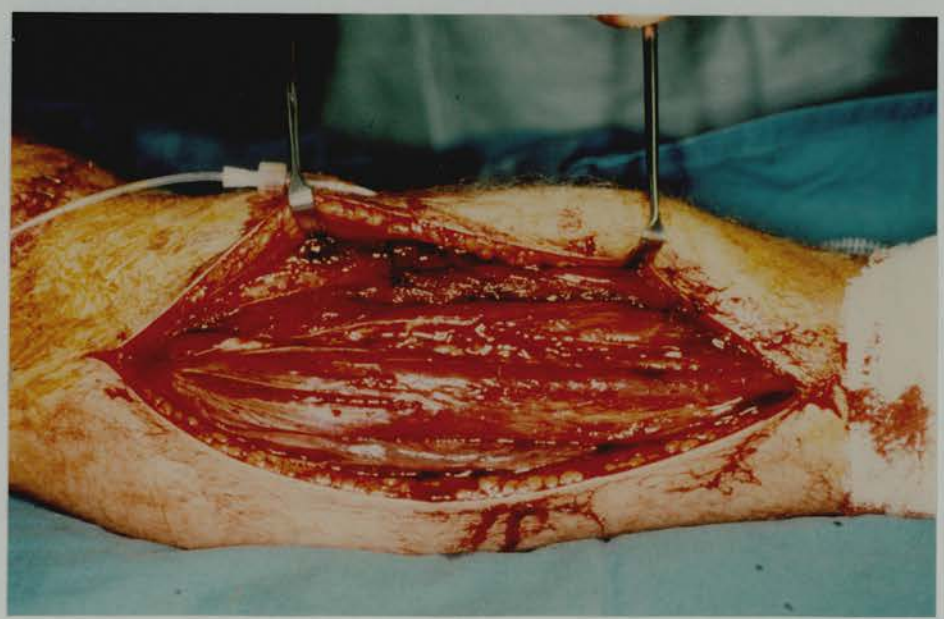

Figure 3.3
The anterior and lateral compartments after fasciotomy in the case in Figure 3.2.

Fifty-three patients had absolute pressures greater than 30 mm Hg and thirty patients had absolute pressures of greater than 40 mm Hg in the first twelve hours. Four were higher than 50 mm Hg. However only one patient had a ▲P of less than 30 mm Hg and he had a fasciotomy (see above). Six patients had a ▲P of 30 mm Hg for the first twelve hours but in all six the absolute pressure dropped and the ▲P increased over the second twelve hour period. None had any sequelae of acute compartment syndrome at final review. Twenty-eight patients had absolute pressures greater than 30 mm Hg and seven patients had absolute pressures of greater than 40 mm Hg in the second twelve hour period; all were below 50 mm Hg except two of these who required fasciotomy (see above). No sequelae of acute compartment syndrome were found at final review. No patient had a ▲P of 30 mm Hg or less in the second twelve hour period except the two with acute compartment syndrome.

The absolute pressures and ▲P values for the different fracture types are shown in Table 3.3.

The mean union time for the whole group was 17 weeks with a range from 10 to 63 weeks. The union time gradually increased with the increasing severity of the Tscherne grade (Table 3.4). The Gustilo type 2 open fractures healed in a slightly longer time than the type 1 fractures, and the type 3 fractures took longest of all

to unite.

Table 3.3

Tscherne/ Gustilo grade	Absolute pressure (1st 12 hrs)	▲ P (1st 12 hrs)	Absolute pressure (2nd 12 hrs)	▲ P (2nd 12 hrs)
TO (n = 7)	35 (25-40)	49 (40-55)	30 (19-40)	53 (40-65)
T1 (n = 64)	30 (5-55)	51 (15-75)	26 (5-75)	56 (10-85)
T2 (n = 22)	26 (5-46)	56 (39-93)	21 (5-36)	61 (40-82)
T3 (n = 7)	30 (16-45)	48 (30-74)	22 (10-40)	57 (40-72)
G1 (n = 9)	32 (20-45)	50 (25-77)	27 (10-45)	55 (30-80)
G2 (n = 4)	34 (17-50)	46 (30-63)	24 (10-35)	56 (45-65)
G3 (n = 3)	14 (10-20)	59 (50-70)	8 (5-10)	65 (60-70)

Mean compartment pressures (mm Hg) (range in parentheses) for the different fracture types

Table 3.4

Fracture type	Union time (range)
T O	13 (11 - 17)
T 1	16 (10 - 60)
T 2	23 (14 - 63)
T 3	25 (17 - 32)
G 1	16 (12 - 20)
G 2	19 (16 - 22)
G 3	32 (17 - 45)

Mean union time (weeks) (range in parentheses) for the different fracture types in the monitored tibial fractures

Three patients required further surgery to achieve union. One required open bone grafting after plating, one required an exchange tibial nail, and one required conversion of external fixation to nailing. Their ▲P values were 50, 65 and 39 respectively in the first 12 hours.

Forty-four patients had injuries which were defined as being high energy injuries (road traffic accidents or a fall from a height) and seventy-two had low energy injuries. The mean absolute pressures for the low energy injuries were 31 mm Hg (5 - 55 mm Hg) in the first 12 hours and 27 mm Hg (5 - 75 mm Hg) in the second 12 hours. The equivalent ▲P values were 52 mm Hg (30 - 80 mm Hg) in the first twelve hours and 56 mm Hg (10 - 85 mm Hg) in the second 12 hours. The absolute pressures for the high energy injuries were 28 mm Hg (10 - 50 mm Hg) in the first 12 hours and 21 mm Hg (5 - 45 mm Hg) in the second 12 hours. The equivalent ▲P values were 51 mm Hg (15 - 93 mm Hg) in the first 12 hours and 56 mm Hg (30 - 82 mm Hg) in the second 12 hours.

When statistical analysis is performed there is no significant correlation between absolute pressures and either fracture grade, union time or mode of injury (high or low energy). However ▲P in the first 12 hours has a significant negative correlation (Spearman rank correlation coefficient) with both fracture grade (p

<0.02) and union time (p <0.002). ▲P in the second 12 hours also shows a negative correlation (Spearman rank correlation coefficient),with fracture grade (p < 0.001), union time (p <0.001) and a significant correlation (Wilcoxon rank sum test), between high energy injury and lower ▲P (p <0.002). However fracture grade, mode of injury and union time are all themselves highly correlated (p <0.001). When a multiple linear regression of log (▲P) is carried out on fracture grade, mode of injury and union time neither mode of injury or union time significantly predict ▲P when adjusted for grade. Thus fracture grade has the strongest influence on the ▲P values.

Seventy-two patients had surgery performed within 24 hours of injury and 44 had surgery delayed beyond 24 hours. The mean absolute pressures for the early group were 31 mm Hg (5 - 55 mm Hg) for the first 12 hours and 26 mm Hg (5 - 75 mm Hg) in the second 12 hours after surgery. The ▲P values for the same time periods were 51 mm Hg (15 - 93 mm Hg) and 55 mm Hg (10 - 82 mm Hg) respectively. In the delayed group the mean absolute pressure for the first 12 hours was 27 mm Hg (5 - 46 mm Hg) and 22 mm Hg (5 - 45 mm Hg) for the second 12 hours. The equivalent ▲P values were 54 mm Hg (30 - 75 mm Hg) and 59 mm Hg (30 - 85 mm Hg) respectively. On calculating the Spearman correlation coefficient there is no significant correlation between delay to surgery and

the absolute pressures. Neither is there correlation with the ▲P in the second 12 hours but there is a significant negative correlation between ▲P in the first 12 hours and delay time ($p < 0.05$). Thus ▲P is lower the longer the delay to surgery.

Sixteen patients had open fractures and 100 patients had closed fractures. The mean absolute pressure for the first 12 hours for the open fractures was 29 mm Hg (10 - 55 mm Hg) and for the closed fractures was 30 mm Hg (5 - 55 mm Hg). In the second 12 hours the mean absolute pressure for the open fractures was 23 mm Hg (5- 45 mm Hg) and for the closed fractures was 25 mm Hg (5 - 75 mm Hg). The ▲P for the first 12 hours for the open and closed fractures was 51 mm Hg (25 - 77 mm Hg) and 52 mm Hg (15 - 93 mm Hg) respectively. The equivalent values for the second 12 hours were 57 mm Hg (30 - 80 mm Hg) for the open fractures and 56 mm Hg (10 - 85 mm Hg) for the closed fractures. Using the Wilcoxon rank sum test, there was no statistically significant correlation between either absolute pressure or ▲P and open or closed fractures.

For the 90 patients whose fracture was treated by intramedullary nailing the mean absolute pressure in the first 12 hours was 30 mm Hg (5 - 55 mm Hg) and 25 mm Hg (5 - 75 mm Hg) for the second 12 hours. The equivalent mean ▲P values were 52 mm Hg (25 - 93 mm Hg) and 57 mm

Hg (15 - 55 mm Hg). For the patients whose fractures were treated by external fixation the mean absolute pressure in the first 12 hours was 31 mm Hg (12 - 46 mm Hg) and 23 mm Hg (5 - 65 mm Hg) for the second 12 hours. The mean ▲P value for the first 12 hours was 48 mm Hg (30 - 65 mm Hg) and 56 mm Hg (10 - 70 mm Hg) for the second 12 hours. Using the Kruskal Wallis test there were no significant differences between the pressure levels of the different treatment groups.

No patient had any sequelae of acute compartment syndrome at final review. One patient had numbness on the dorsum of her foot noted in the first week after injury having had ▲P values of 60 mm Hg in both the first and second 12 hour period. She had no contractures at final review 9 months after injury and the numbness had resolved three months after injury.

No complication occurred as a result of the use of the catheter.

3.2.3

Discussion

This study clearly demonstrates that the use of an absolute pressure measurement as an indication of the need for fasciotomy is unreliable. Had 30 mm Hg been the threshold for decompression as is recommended by many authors (Mubarak et al 1978, Hargens et al 1979, Rorabeck

1984, Blick et al 1986, Hargens et al 1989, Myerson 1991) then fifty-three of the one hundred and sixteen patients would have had a fasciotomy. One patient required a fasciotomy in the first twelve hours on the basis of his ▲P level. Two further patients required fasciotomy in the second twelve hours because of a dropping ▲P level. Thus fifty patients (43%) would have had an unnecessary fasciotomy. Even if a higher threshold pressure of 40 mm Hg had been used as an indication for decompression, twenty-seven patients (23%) would still have had a fasciotomy unnecessarily. The absence of late sequelae of the acute compartment syndrome eliminates the possibility of the syndrome having been missed in these patients. Previous authors have expressed the opinion that using a threshold of 30 mm Hg may result in unnecessary fasciotomy (Mubarak et al 1978, Blick et al 1986) but have also expressed concern that the use of a higher threshold may lead to a delay in diagnosis. Mubarak and his co-authors believe that a spectrum of critical pressures exist depending on many variables but only cite the variability of measurement techniques. Modern measurement techniques however have been shown to be comparable in their results (Matsen et al 1980a, Shakespeare et al 1982).

Much of the variability in pressure thresholds may be due to the variability in the perfusion state of the limbs in general. Whitesides and his associates (1975) considered

that the diastolic pressure was a key factor in determining the need for decompression. They quote as an example the patient with a diastolic pressure of 80 mm Hg who is likely to tolerate a tissue pressure of 30 mm Hg without ischaemia. However the same pressure would not be tolerated if the patient were hypotensive with a diastolic pressure similar to the tissue pressure. They recommend that tissue pressures should always be evaluated in association with the diastolic blood pressure. This view is also stressed by Brooker and Pezeshki (1979). Using Whitesides and his co-authors' recommendation of a 30 mm Hg gap between tissue pressure and diastolic pressure as a threshold for fasciotomy no cases of acute compartment syndrome were missed in this series. It is unlikely that the condition was overdiagnosed with an incidence of acute compartment syndrome of 2.6% which is comparable to previously reported series both locally and elsewhere (Ellis 1958, Delee and Stiehl 1981, Court-Brown and McQueen 1987, McQueen et al 1990). The highest pressure recorded not requiring fasciotomy was 55 mm Hg. This was in the presence of a diastolic pressure of 90 mm Hg and therefore a ▲P of 35 mm Hg.

Some authors feel that a lower absolute pressure persisting for several hours is an indication for decompression (Koman et al 1981, McDermott et al 1984). Twenty-eight patients in this series had persistent

elevation of tissue pressure above 30 mm Hg. Two of these had fasciotomies performed because of rising pressure and a dropping ▲P. The remaining twenty-six had no decompression and no late sequelae.

Decompression of the involved compartments should be performed if the ▲P level drops to less than 30 mm Hg. It is safe to observe relatively high tissue pressures provided there is the protection of a ▲P level of greater than 30 mm Hg. Continuous monitoring is essential until the ▲P is steadily rising and the absolute tissue pressure is dropping. In the second and third patients requiring fasciotomy there was a lag period of twenty-four and eighteen hours respectively before the ▲P values reached critical levels.

The value of continuous monitoring is also demonstrated in the third patient requiring fasciotomy by the ability to diagnose acute compartment syndrome prior to the onset of symptoms or signs. This has obvious benefit in preventing any permanent changes in the tissues. Matsen and his co-authors (1976) and Brooker and Pezeshki (1979) also believe that pressure monitoring may indicate the onset of acute compartment syndrome before the appearance of clinical symptoms and signs.

Oestern and Tscherne's classification of closed tibial fractures (Oestern & Tscherne 1984) is dependent mainly

on the severity of injury to the soft tissues. It would therefore be reasonable to assume that the compartment pressures would rise with increasing severity of the soft tissue injury. The significant and strong correlation between ▲P and the fracture grade validates the use of the Tscherne classification and relates increased soft tissue injury to lower ▲P values.

It has been suggested (Rorabeck & McNab 1976) that if the fracture is compound this will decompress the compartments and marked elevation of the intracompartmental pressure will not occur. This series disproves this statement since there were no significant differences in absolute tissue pressures or ▲P values between the closed and open fractures. Indeed two of the Gustilo type II open fractures had tissue pressures of 50 mm Hg in the first twelve hours although neither required fasciotomy. There have now been a number of reports of acute compartment syndrome complicating open fractures (McQuillan & Nolan 1968, Gershuni et al 1987, Schwartz et al 1989). Delee and Stiehl (1981) had a 6% incidence of acute compartment syndrome in 104 open tibial fractures. Blick et al (1986) quote a 9.1% incidence in 198 open tibial fractures although this may be falsely high since the diagnosis was based on tissue pressures above 30 mm Hg. 83% of their acute compartment syndromes had type III open fractures. They concluded that an open wound does not adequately decompress the

compartments.

There is no relationship between the union times and the ▲P values in this series when adjusted for grade. There were no cases of neglected compartment syndromes resulting in muscle necrosis in the series and it is likely that bone blood flow diminishes in the same way as muscle blood flow. If delayed union occurs after an acute compartment syndrome it is probable that muscle necrosis has occurred thereby reducing or eliminating the appearance of extra-osseous flow. If the muscle remains viable there is unlikely to be bone ischaemia related to raised tissue pressures.

Delaying surgery in tibial fractures does not result in reduced compartment pressures as has previously been stated. Indeed the significant negative correlation between ▲P in the first 12 hours after surgery and delay to surgery indicates the the longer the delay the more likely there is to be soft tissue swelling. However the majority (101) of these patients had surgery within 72 hours and it may be that this correlation would be lost if the time elapsed were longer. At a later stage also, the manoeuvres required to reduce a tibial fracture require more force and this may result in either further soft tissue swelling or the "fingertrap phenomenon" (Matsen & Clawson 1975) where compartment pressures increase when a tibial fracture is pulled to length.

This would account for the delay in onset in the second patient with an acute compartment syndrome in this series. Although some authors believe the cause of acute compartment syndrome to be the procedure of reaming and nailing of tibial fractures (Rorabeck & McKenzie 1985, Tischenko & Goodman 1990, Moed & Strom 1991) all of their reported fractures underwent reduction at the same time as the nailing procedure was performed. The acute compartment syndrome was more likely to be caused by reduction of the fracture than by the nailing procedure. This theory is substantiated by the fact that ▲P values did not vary depending on the method of fracture stabilisation.

3.3

Acute compartment syndromes

3.3.1

Materials and methods

In the period from January 1988 to July 1992, 68 patients with acute compartment syndrome were admitted to the Orthopaedic Trauma Unit of the Royal Infirmary of Edinburgh. There were 62 males and 6 females with a mean age of 32 years (range 13 - 83).

Clinical details were recorded at the time of injury. Pressure monitoring was carried out at the discretion of the surgeon in charge of the patient, using the same slit catheter method as described in section 3.2.1. Pressure

monitoring was either commenced immediately after admission or surgery, at the time that clinical suspicion of acute compartment syndrome arose or not at all.

The diagnosis of acute compartment syndrome was made on the basis of either elevated compartment pressures, surgical findings at fasciotomy or a combination of the two. Compartment pressures were considered to be diagnostic of acute compartment syndrome if the pressure rose to within 30 mm Hg of the patient's diastolic blood pressure (Whitesides et al, 1975). At surgery the diagnosis was confirmed by escape of muscle groups after fasciotomy such that the wound could not be closed or by the presence of compromised muscle viability.

Four patients died soon after admission and three patients were lost to follow up leaving 61 patients available for review. The average review time was 10.5 months (range 3 - 36 months). Clinical review involved examining the patients to document the presence of muscle contractures, weakness or sensory changes.

For the tibial fractures the time to bone union was assessed on the ability of the patient to weight bear without pain on the unprotected leg and by the presence of bridging callus radiographically. Closed tibial diaphyseal fractures were classified according to Tscherne's method (Oestern & Tscherne 1984). Open

fractures were classified by the Gustilo system (Gustilo and Anderson 1976, Gustilo et al 1984).

3.3.2

Results

The age/sex distribution of the whole series is shown in figure 3.4. There is the expected peak in young men but the usual second peak seen in middle-aged to elderly females in other traumatic conditions is missing. The age distribution is therefore unimodal (Figure 3.4).

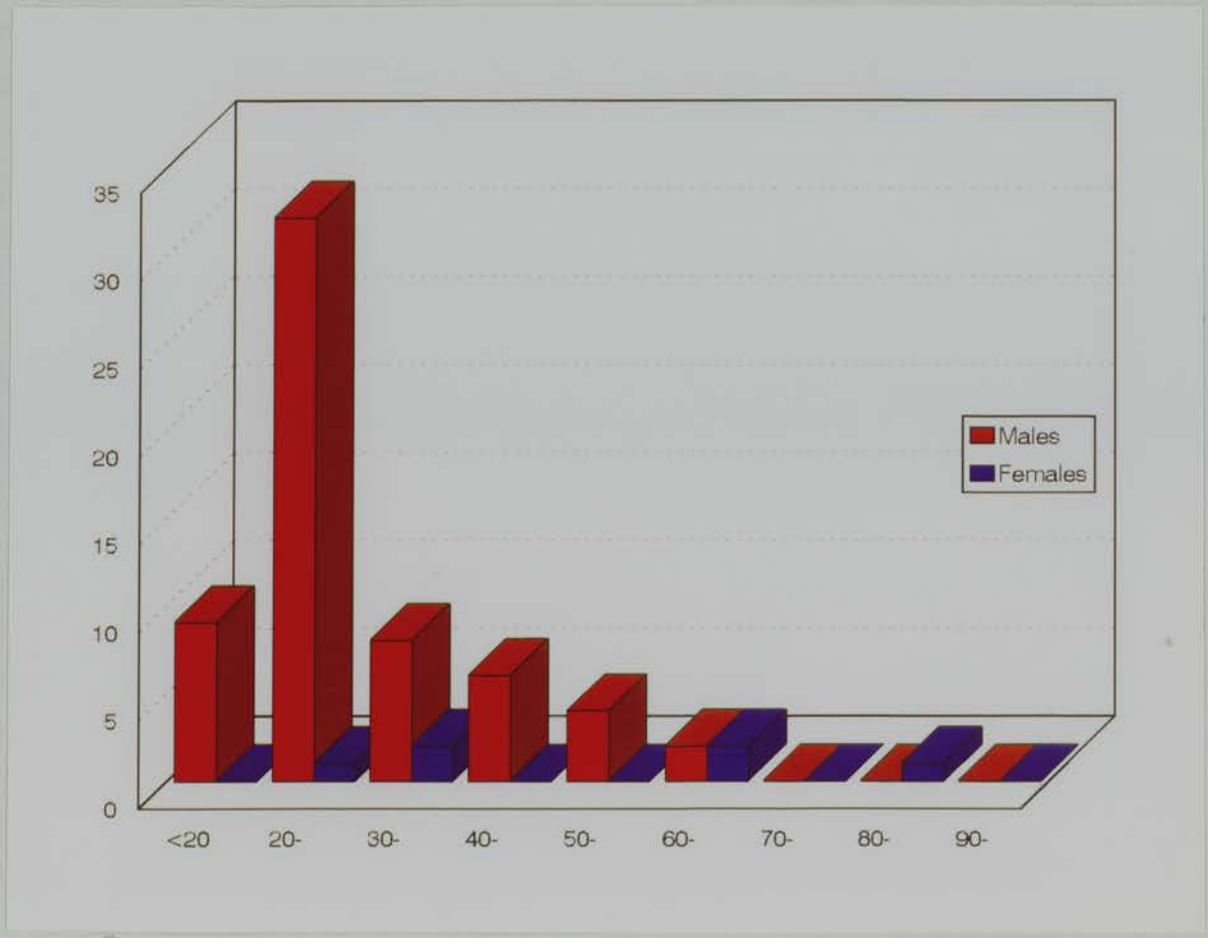

Figure 3.4

Age/sex distribution of acute compartment syndromes.

The underlying conditions causing acute compartment syndrome are shown in Table 3.5. The largest group are tibial diaphyseal fractures which constitute 37% of the whole population. Fifteen per cent are soft tissue injuries with no associated fractures and 10% are the crush syndrome all of which were drug related. Forearm fractures, distal radial fractures and femoral fractures make up 10%, 7% and 6% of the population respectively. Seventy-five per cent of all acute compartment syndromes were due to fractures.

Table 3.5

Underlying condition	Number	%
Tibial diaphyseal fracture	25	37
Tibial plateau fracture	3	4
Plateau + ankle fracture	1	2
Pilon fracture	1	2
Soft tissue injury	10	15
Crush syndrome	7	10
Forearm fracture	7	10
Distal radial fracture	5	7
Femoral fracture	4	6
Hand fractures	3	4
Foot fracture/dislocation	2	3
TOTAL	68	100

Underlying conditions in acute compartment syndrome

Thirty-two patients underwent compartment monitoring. Their mean absolute compartment pressure at the time of fasciotomy was 67 mm Hg with a range from 35 - 110 mm Hg. The mean value for the difference between the diastolic pressure and the compartment pressure (▲P) was 6 mm Hg (range - 50 to 30 mm Hg). A negative value implies that the compartment pressure was higher than the diastolic pressure. Nineteen of the 32 patients with documented pressures had compartment pressures within 10 mm Hg of their diastolic pressure. Six patients had compartment pressure higher than diastolic pressure.

The average delay from injury to fasciotomy was 29 hours with a wide range from 3 to 216 hours.

Pain was the predominant symptom in 42 patients (62%). Twenty-four patients were either unconscious or under anaesthetic at the time of diagnosis. In two conscious patients (3%) pain was absent at the time of diagnosis. One was a 21 year old male who had no underlying medical conditions and had sustained multiple metatarsal fractures in a road traffic accident. Severe swelling and sensory changes in the toes led to fasciotomy of the interosseous compartments 21 hours after injury. His postoperative course was complicated by wound infection and poor wound healing. The second patient was a 22 year old male who was otherwise healthy and had sustained a Gustilo type 1 open fracture of his radial

and ulnar shafts with no clinical evidence of concomitant neurological injury. Paraesthesiae and sensory deficit in both median and ulnar distributions developed gradually over the 22 hours after injury and volar forearm fasciotomy was carried out. Surgical findings confirmed an acute compartment syndrome. The wound was covered with a split skin graft three days later and there were no permanent sequelae.

Twenty-two (32%) of the patients had stretch pain at the time of diagnosis. This symptom was therefore present in half the conscious patients in the series.

Twenty-one (30%) of the patients had sensory symptoms prior to fasciotomy. The average delay from injury to fasciotomy in these patients was 33 hours.

Ten patients (15%) had detectable motor weakness at the time of diagnosis. The average delay to fasciotomy in these patients was 35 hours. Nine of these ten patients had permanent sequelae compared to the fifteen of the remaining fifty-eight patients without motor weakness. This difference is statistically significant ($p < 0.04$, Fisher's exact test). In all, 25 patients exhibited neurological symptoms or signs with an average delay from injury of 32 hours (range 4 - 80 hours). The average delay in the 19 patients without neurological symptoms or signs was 39 hours (range 3 - 216 hours).

There was no significant difference in the pressure attained between the two groups with and without neurological symptoms and signs. The mean pressure in the nine patients with normal neurology who had pressures measured was 66 mm Hg (range 35 - 110 mm Hg) and was 64mm Hg (range 30 - 100 mm Hg) in 14 patients with abnormal neurology and documented pressures.

Twenty-four patients had 33 sequelae of the acute compartment syndrome (Table 3.6) with the majority of complications being related to muscle weakness or contracture. The average delay from injury to fasciotomy in this group was 41 hours (range 16 - 88 hours). In the 37 patients who had no sequelae at follow up the average delay from injury to fasciotomy was 23 hours (range 3 - 216 hours). The two longest delays in this group were 144 hours and 216 hours, both in patients with a bleeding diathesis. If these two patients are excluded then the average delay in the group who had no sequelae is 14 hours with a range from 3 - 48 hours. Using the Wilcoxon rank sum test, complications are significantly related to delay ($p < 0.001$).

Sixteen patients had continuous compartment pressure monitoring from the time of admission. The average delay to fasciotomy in these patients was 14 hours (range 3 - 28 hours). One patient died of his injuries and one was lost to follow up leaving 14 available for

review. None had any complications attributable to acute compartment syndrome.

Table 3.6

Sequelae	Number
Muscle necrosis/weakness	12
Muscle contracture	10
Renal failure (rhabdomyolysis)	5
Infection	3
Sensory changes	3
TOTAL	33

Complications of acute compartment syndrome in the whole group

Fifty-two patients had no monitoring performed or had pressures recorded prefasciotomy to confirm the diagnosis. The average delay in this group was 36 hours (range 3 - 216 hours). Three patients died and two were lost to follow up leaving 47 patients available for review. Twenty-four (47%) of these had complications of the acute compartment syndrome. The difference in complication rates between the monitored and non-monitored groups was examined using a chi-squared test and found to be highly significant ($x^2 = 10.81$, $p = 0.001$). Multiple logistic regression showed that monitoring significantly affects the complication rate even after adjusting for the effect of delay ($p = 0.001$). Equally delay is significantly related to complications

after adjusting for monitoring ($p < 0.05$). When adjusted for delay and monitoring, the underlying cause of the acute compartment syndrome (soft tissue injury, tibial fracture, other fracture, crush syndrome) is not significantly associated with complications.

Table 3.7

Type of fasciotomy	Number
4 compartment leg	37
Volar forearm	15
Thigh	6
< 4 compartment leg	5
Hand interosseous	4
Foot interosseous	3
Thenar	1
Biceps	1
Deltoid/triceps	1

Types of fasciotomy performed

The largest group (49%) of fasciotomies were double incision four compartment fasciotomies of the leg (Mubarak and Owen, 1977) (Table 3.7). In two patients fasciotomy in the leg was confined to the superficial and deep posterior compartments. In one there was a soft tissue injury only and in the the other a Gustilo type 1 open fracture was complicated by injury to the posterior tibial artery. In three cases the fasciotomy was

confined to the anterior and lateral compartments. One patient had a soft tissue injury in association with anticoagulant treatment and one had a lateral tibial plateau fracture. The third patient had a Gustilo type 1 open fracture of the tibial diaphysis and fasciotomy was confined to the anterior and lateral compartments with a delay of seven hours from injury. Twenty-four hours later she was returned to theatre and exploration revealed necrotic muscle in the deep posterior compartment which required excision.

Fifteen forearm volar compartment fasciotomies were performed, five being for distal radial fractures, seven for forearm fractures, two for crush syndrome and one for a soft tissue injury.

Tibial fractures

There were 25 patients with acute compartment syndrome associated with tibial diaphyseal fractures. Twenty-three were male and two were female. Their average age was 28 years with a range from 15 to 83 years. The majority (64%) were sporting injuries. Seven patients (28%) had been involved in a road traffic accident. One patient had simply fallen and one had fallen from a height of 30 feet.

Twenty-three fractures were closed and two were open. Their Tscherne or Gustilo classifications are shown in

Table 3.8. It can be seen that the large majority of closed fractures were either Tscherne grade 1 or 2. This distribution is similar to the normal distribution of tibial diaphyseal fractures in Edinburgh (Court-Brown et al 1990a).

Table 3.8

Tscherne	Gustilo	Number
T 0		2
T 1		12
T 2		8
T 3		1
	G 1	1
	G 2	1
	TOTAL	25

Tscherne and Gustilo classification of the tibial fractures complicated by acute compartment syndrome

Six patients had sustained injury in more than one body system. Two of these patients had injured the ipsilateral femur implying major injury to that limb.

In the period of the study there were 622 tibial diaphyseal fractures treated in the Orthopaedic Trauma Unit of the Royal Infirmary of Edinburgh. The incidence of acute compartment syndrome in tibial fractures was 4%.

There were 166 open tibial diaphyseal fractures treated during the time of the study. The incidence of acute compartment syndrome in open tibial diaphyseal fractures was 1.2%. The difference in the incidence of acute compartment syndrome in closed and open tibial fractures is not significant using the chi-squared test.

Three hundred and forty two fractures occurred in patients aged 35 years or younger and 280 in the over 35 year age group. However 22 of the acute compartment syndromes occurred in the younger group while only three occurred in the older group. All of these three had multisystem injury and one was hypotensive. Using the chi-squared test there is a significantly higher risk of developing an acute compartment syndrome in the younger age group ($p < 0.01$). This is not related to high energy injury since 43% of the younger age group sustained high energy injury compared to 55% of the older age group.

Twenty-three patients underwent compartment pressure monitoring. In 13 patients compartment monitoring was instituted within eight hours of injury and in 10 patients monitoring was only used immediately before fasciotomy to confirm the clinical diagnosis of acute compartment syndrome. With the two patients who had no monitoring performed there were therefore 12 patients who did not have early monitoring.

Twenty-three patients had double incision four compartment fasciotomy performed. One patient had fasciotomies of the anterior and lateral compartments only with no pressure monitoring of the superficial or deep posterior compartment. He had a concomitant posterior tibial artery injury with a considerable volume of blood in the deep posterior compartment. One patient had fasciotomies of the anterior and lateral compartments only with no pressure monitoring of the superficial or deep posterior compartments. Twenty-four hours later exploration prompted by pain and stretch pain of the toe flexors revealed necrosis of the muscles of the deep posterior compartment.

In all 25 patients the anterior compartment was involved. Of these, positive surgical findings were noted in all four compartments in six patients, in a combination of the anterior and lateral compartments in three and of the anterior and deep posterior compartments in four. Twelve patients therefore had isolated anterior compartment involvement.

The average delay from admission to fasciotomy was 23 hours (range 4 - 80 hours). In the 12 patients who had late or no monitoring performed this delay was an average of 32 hours (range 4 - 80 hours). In the 13 who had early monitoring the average delay from injury to fasciotomy was 16 hours (range 4 - 28 hours). This

difference was statistically significant ($p < 0.05$ Wilcoxon rank sum test). Five of this group had a documented delay of 24 hours prior to reaching a critical pressure level. The average delay from fracture manipulation and fixation to fasciotomy in the non-monitored group was 24 hours (range 4 - 64 hours) and seven hours (range 0 - 24 hours) in the monitored group.

Four patients in the monitored group had delayed onset of their compartment syndrome to 14, 16, 18 and 24 hours after surgery, all documented by pressure monitoring. Two patients had a clear association between reduction and fixation of the fracture and a rise in pressure to critical levels. One had been treated with an intramedullary nail and the other with a closed external fixator.

One patient in the non-monitored and one patient in the monitored group died of their other injuries leaving 12 patients in the monitored group and 11 in the unmonitored group for follow up examination. The average review time was 10.5 months with a range from 4 - 32 months. In the non-monitored group, 10 of the 11 patients had continuing problems following their acute compartment syndromes, with muscle weakness in six patients, muscle contractures in three patients and infection in one. One patient with muscle weakness also had a permanent sensory deficit. None of the 12 patients in the early monitored group had

any sequelae of the acute compartment syndrome. This difference is statistically significant ($x^2 = 10.36$, $p < 0.01$) (Table 3.9). On examining the two groups to compare the severity of their injury and compartment syndromes using the Wilcoxon rank sum test there were no significant differences between the monitored and non-monitored group in either fracture types or the number of compartments involved. Using multiple logistic regression the use of monitoring still significantly predicted fewer complications ($p < 0.05$) even after adjustment for delay and number of compartments involved.

Table 3.9

	Complications	No Complications	p
Monitored patients (n=12)	0	12	<0.01
Non monitored patients (n=11)	10	1	

Complication rates for monitored and non monitored patients with acute compartment syndrome after tibial fracture.

The average time to union in 23 patients was 21 weeks. The two main groups were Tscherne grade 1 fractures (11) with a mean union time of 19 weeks (range 9 - 42 weeks) and Tscherne grade 2 fractures (7) with an average union time of 23 weeks (range 12 - 29 weeks).

The average union times for the monitored fractures was 17 weeks (range 9 - 26 weeks) and for the non-monitored fractures was 25 weeks (range 13 - 42 weeks). The union times for the Tscherne grade 1 and Tscherne grade 2 fractures, split into monitored and non-monitored groups are shown in Table 3.10. Three patients in the non-monitored group required further surgery to achieve union. No fractures in the monitored group were considered to have delayed union. Using the Wilcoxon rank sum test, the use of compartment monitoring is shown to have a significant influence in reducing the union time ($p < 0.05$). Increasing the delay also increases union time significantly ($p < 0.05$).

Table 3.10

Tscherne class	All	Monitored	Non monitored
T 1 (n = 11)	19 (9 - 42)	14 (9 - 16)	29 (13 - 42)
T 2 (n = 7)	23 (12 - 29)	20 (12 - 26)	26 (18 - 31)

Average union times (weeks) for Tscherne class 1 and 2 (ranges in brackets)

Femoral fractures

Three of the femoral fractures were diaphyseal and one a condylar fracture. Of the diaphyseal fractures one was segmental and two were in association with multiple injuries. The segmental femoral fracture had a delay of 42 hours to fasciotomy and subsequently developed knee

stiffness. The multiply injured patients had short delays of four and six hours prior to fasciotomy. They had no sequelae of acute compartment syndrome.

During this period there were 372 fractures of the femoral shaft treated in Edinburgh. The incidence of acute compartment syndrome in femoral diaphyseal fractures is therefore 0.8%.

Forearm fractures

Of the seven forearm fractures complicated by acute compartment syndrome four were due to high energy injury and one fracture was open. The average delay in this group was 22 hours (range 4 - 53 hours). Two patients with delays of 24 and 53 hours had permanent sequelae with contractures in the hand. During this period there were 221 forearm fractures treated. The incidence of acute compartment syndrome in forearm fractures is therefore 3%.

Distal radial fractures

There were five distal radial fractures complicated by acute compartment syndrome. All but one occurred in males with an average age of 30 years (20 - 44 years). Four occurred due to high energy injuries. Four had delays of more than 24 hours to fasciotomy and two of these had finger contractures at final review. None had monitoring performed.

In the same period 2404 distal radial fractures were treated. The incidence of acute compartment syndrome in distal radial fractures is therefore 0.2%. Three hundred and sixty two distal radial fractures were in males under the age of 45. This incidence in this group therefore is 1.4%.

Soft tissue injuries

Ten patients had soft tissue injury with no associated fractures. Eight were male and two were female with an average age of 39 years (range 20 - 69). Eight patients had sustained a blow to the affected compartment, one had a roller injury and one had been stabbed. Two of the ten patients had a bleeding diathesis. The average delay from injury to surgery was 44 hours (range 3 - 216).

Three patients in this group had pressure measurements immediately before fasciotomy to confirm the diagnosis. The ▲P was 0 mm Hg, 35 mm Hg and -50 mm Hg in these patients. No patients had continuous monitoring carried out.

Only two of the ten patients with this injury had sequelae of their compartment syndrome despite the long delays to surgery. Both had quadriceps compartment syndromes with delays of 14 and 24 hours to surgery. The two patients with the longest delays (144 hours and 216

hours) were the two patients with bleeding diatheses. Neither had any complications.

Crush syndrome

Seven patients had developed their acute compartment syndrome following a period of altered consciousness. Six had taken an overdose of drugs and one had carbon monoxide poisoning. There were six males and one female with an average age of 32 years (range 22 - 54).

The average delay of onset of unconsciousness to fasciotomy was 47 hours (range 24 - 88). Three patients had pressure levels measured immediately prior to fasciotomy with ▲P levels of 0, 25 and 25 mm Hg.

The seven patients had a total of eight limbs and 18 compartments involved. Two patients died (29%), one of acute renal failure secondary to rhabdomyolysis and the other as a result of carbon monoxide poisoning. Five of the seven patients (71%) had renal failure due to muscle necrosis. Three lower limb amputations were performed in two patients, both of whom survived. This is an amputation rate of 38%.

3.3.3

DISCUSSION

The clinical study of acute compartment syndromes

supports the results of the experimental study in demonstrating a delay to union in the patients who had tibial fractures with sequelae of the acute compartment syndrome and therefore by implication had significant muscle necrosis. The mean union times of the Tscherne grade 1 and 2 tibial fractures is very similar to those for the larger group of monitored tibial fractures in section 3.2 and to those in a previous series from the same centre (Court-Brown et al 1990a). The Tscherne grade 1 fractures with sequelae of the acute compartment syndrome took more than twice as long to unite as those without sequelae. Clinically as well as experimentally muscle necrosis leads to delayed union in tibial diaphyseal fractures.

The 75% incidence of fractures causing acute compartment syndrome in this series is high compared with the few other series reporting incidences. In a combination of 44 children and adults with the same mean age as in this series, Sheridan and Matsen (1976) found that 30% of their cases were due to fractures. Their incidence of soft tissue injury is very similar to the Edinburgh experience but they have a 13% incidence of post ischaemic compartment syndrome. These are not included in this series since they are not treated in the Orthopaedic Trauma Unit in Edinburgh.

The incidence of crush syndrome is higher in this series

(10%) than in Sheridan and Matsen's series (4%). This may be because of the relatively large population of drug abusers in Edinburgh.

Mubarak and Carroll (1979) reviewed 55 cases of Volkmann's contracture in children and found that 70% were due to fractures. Thirty-six per cent of these however were in femoral fractures and were leg compartment syndromes due to Bryant's traction. None were thigh compartment syndromes directly associated with femoral fracture. Thus their incidence of established ischaemia directly related to the fracture was 34% with the commonest being in the upper limb. They gave no details of cases of the acute compartment syndrome which did not develop contracture.

The tibia has the highest incidence of acute compartment syndrome. This may be because tibial fractures have a higher risk of acute compartment syndrome because of the particular anatomy of the leg with its well defined compartments. The diagnosis however depends on awareness of the condition. It may be that acute compartment syndrome is under diagnosed in the other fractures because of less awareness of the condition than in tibial fractures.

This series shows that continuous compartment monitoring significantly reduced the delay to fasciotomy and

therefore the long term sequelae. The abolition of complications in the monitored group in comparison to the high rate of long term sequelae in the unmonitored group is clear in the whole population and dramatic in the tibial fracture series.

Delay to fasciotomy is widely accepted as being disastrous in patients with acute compartment syndrome. McQuillan and Nolan (1968) stated that delay to fasciotomy was the single cause of failure in their series. This view has been echoed by many others (Matsen and Clawson 1975, Sheridan and Matsen 1976, Gelberman et al 1981, Rorabeck 1984, Schwartz et al 1989). The function of compartment monitoring is to heighten awareness of the possibility of acute compartment syndrome and to confirm clinical findings. This significantly reduced delay to fasciotomy and complications especially in the tibial fractures in this series. It is recommended therefore that all tibial fractures should undergo continuous compartment monitoring when equipment is available.

It is a surprising finding that the use of monitoring alone has a significant effect on the outcome when the effects of delay are eliminated. It might be suggested that the unmonitored group had more severe fractures with more severe soft tissue injury, but the two groups have been shown to be similar in severity of fracture

type and number of compartments involved. One explanation could be that the patients who were monitored tended to be those treated by the orthopaedic trauma specialists and the direct influence of monitoring on outcome may be a reflection of better surgery.

Some authors deny the need for compartment monitoring in fracture management. Criticism includes the infrequent occurrence of the compartment syndrome combined with cumbersome methods (Rollins et al 1981), and the general reliability of clinical signs (Rollins et al 1981, Brostrom et al 1990). Despite this however reports of the condition continue to show a significant proportion of poor results due to delay (Rorabeck 1984, Schwarz et al 1989, Wright et al 1989). Currently accepted indications for compartment monitoring are the unconscious patient (Gelberman et al 1981, Mubarak 1983, Rorabeck 1984, Schwartz et al 1989), the uncommunicative patient (Matsen et al 1980a, Mubarak 1983), children (Willis and Rorabeck 1990) and those with equivocal symptoms or signs (Gelberman et al 1981). Some authors state that monitoring should be used in high risk cases but fail to define this description (Brostrom et al 1990). Myerson (1991) is the only author to state that he prefers compartment pressure monitoring to clinical symptoms and signs and recommends that pressures be measured in all crushed feet.

Establishing firm criteria for the at risk patient would help to solve some of the criticisms and allow selective use of compartment monitoring which may be a limited resource in many centres. This series has highlighted several groups of patients in whom there is a high risk of acute compartment syndrome. The first of these is the young patient with a tibial fracture. Seven per cent of this group developed an acute compartment syndrome compared to 1% in the older age group, all of whom had severe injuries and were likely to be under perfused. It is possible that the young patient is a greater risk because of a relatively large muscle volume compared to the generally more atrophic muscle in the older population.

Other at risk groups are high energy femoral diaphyseal fractures, high energy forearm fractures and young patients with high energy distal radial fractures. Bleeding diatheses or anticoagulant treatment constitute a further risk although the onset appears to be slower in these patients. Of the four patients in this category delays of 44 to 216 hours were tolerated with no sequelae.

The necessity for more objective methods of diagnosing the acute compartment syndrome is well illustrated by the unreliability of clinical symptoms and signs. Pain was the most reliable symptom in this series although it

cannot be elicited in the unconscious patient. Pain however is not an infallible symptom even in the conscious patient. Two of this series were painless acute compartment syndromes, one in the foot and one in the forearm. Other series have noted a small proportion of acute compartment syndromes without pain (Eaton and Green 1975, Matsen and Clawson 1975, Rollins et al 1981) while painless acute compartment syndrome is recognised in cases with neurological injury (Wright et al 1989). It is possible that this was the reason for the absence of pain in the patient in this series with a forearm fracture.

The slightly increased mean delay in the patients without neurological abnormality compared to those with neurological abnormality illustrates the difficulty of defining the exact time of onset of acute compartment syndrome. The time of injury is not necessarily the time of onset of the condition. This is demonstrated in the four patients in the tibial fracture group with onsets ranging from 14 to 24 hours after surgery. These patients illustrate further the "finger trap phenomenon" (Matsen and Clawson 1975) which was shown in one patient in section 3.2.

This study has demonstrated the importance of treatment before the onset of muscle weakness. Muscle weakness is associated with a poor prognosis in the form of long-

term complications. Only one of the ten patients with muscle weakness showed any recovery of muscle strength. This supports the views of others (DeLee and Stiehl 1981, Rorabeck 1984, Schwarz et al 1989, Willis and Rorabeck 1990).

Four compartment fasciotomy should always be used in the leg in the absence of compartment monitoring to avoid serious complications as illustrated in the third case of a tibial fracture which had decompression only of the anterior and lateral compartments and proceeded 24 hours later to excision of the deep posterior compartment. Limited decompression may be used in combination with compartment monitoring in experienced hands. It must be stressed that monitoring should be continued postoperatively and four compartment fasciotomy used if any doubt exists as to the adequacy of decompression.

It is of interest that the anterior compartment is consistently affected in the tibial fractures complicated by acute compartment syndrome although in leg compartment syndromes for reasons other than tibial diaphyseal fractures only 50% involved the anterior compartment. Sheridan and Matsen (1976) found that the anterior compartment was most commonly involved in a series of fasciotomies with a variety of underlying causes. Gershuni (1987) and his co-authors found that 30 of 32 tibial fractures complicated by acute compartment

syndrome had anterior involvement but did not support the diagnoses with pressure measurements. Monitoring all four compartments is cumbersome and in tibial fractures it is unlikely that pressure will not be elevated in the anterior compartment in the presence of an acute compartment syndrome. The anterior compartment was monitored in the tibial fractures in this series with other compartments being monitored if clinical suspicion of their involvement was raised.

Two of the tibial fractures were open giving an incidence of acute compartment syndrome of 1.2% in open tibial fractures. This is lower than the 6% incidence quoted by DeLee and Stiehl (1981) and the 9.1% incidence quoted by Blick and his co-authors (1986). The latter made the diagnosis on compartment pressures of 30 mm Hg or more and may have overdiagnosed the condition. Whichever is the true incidence it is clear that Rorabeck and Macnab's statement in 1976 that compounding prevents significant rises in intracompartmental pressure is mistaken.

There was a wide range of absolute compartment pressures documented immediately prior to fasciotomy. None of the group had a ▲P level of more than 30 mm Hg which supports the view that compromise of the muscle blood flow starts to occur when the compartment pressure rises to within 30 mm Hg of the diastolic pressure.

CHAPTER 4

SUMMARY AND CONCLUSIONS

From a previous retrospective clinical study it was suggested that acute compartment syndrome complicating tibial diaphyseal fracture causes a delay in union of the fracture. It was postulated that this was due to a reduction in bone blood flow related to the reduction in muscle blood flow caused by the acute compartment syndrome.

The experimental study examined the effect of raised intracompartmental pressure on the bone blood flow response and on bone healing quantitatively and qualitatively. Raised intracompartmental pressure was shown to have a significant effect in delaying bone healing both quantitatively and qualitatively. This was associated with a significant increase in the bone blood flow at six weeks, indicating a delay in the normal pattern of bone blood flow response.

These results were reflected in the clinical study. The tibial fractures which were complicated by acute compartment syndrome and long term sequelae took significantly longer to unite than those without sequelae which confirms the findings in the retrospective study.

The clinical study also examined the use of monitoring in the detection of the acute compartment syndrome. The

concept of a critical ▲P of 30mm Hg was validated and the value of compartment monitoring in preventing the serious long term sequelae of acute compartment syndrome was demonstrated.

It is concluded that acute compartment syndrome causes delayed union in tibial diaphyseal fractures mediated by a delay in the normal vascular response to fracture.

FUTURE WORK

In view of the importance of the early diagnosis and treatment of the acute compartment syndrome, future work should be concentrated on two areas:

1. Early non-invasive diagnosis of acute compartment syndrome by bedside direct measurement of muscle blood flow using the more sophisticated methods of clinical assessment of blood flow currently developing e.g. magnetic resonance imaging and ultrasonographic techniques.

2. Prevention of the acute compartment syndrome. Studies of available "oedema-reducing" substances e.g. mannitol, pentafraction and their role in reducing compartment pressures are possible both experimentally and clinically.

3. Mechanical prevention of acute compartment syndrome. The A-V impulse foot pump claims to reduce oedema by stimulation of venous flow. A prospective randomised clinical study of its effectiveness after tibial fracture is currently under way.

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APPENDIX TABLES

Rabbit No	1		2		3		4		5		6		Mean ± SE		
	I	NI	I	NI	I	NI	I	NI	I	NI	I	NI	I	NI	P
Muscle	1.2	3.8	0.4	4.0	28.5	36.5	30.2	28.7	0.2	11.8	18.8	14.6	13.2 5.9	16.6 5.5	NS
Prox 1/3	4.5	3.1	0.7	1.8	35.2	41.2	24.4	20.0	2.0	2.2	8.5	6.5	11.8 4.9	11.5 5.5	NS
Mid 1/3	0.9	2.5	1.2	0.8	9.1	18.8	17.6	10.0	0.9	1.3	2.1	3.2	5.1 2.4	5.8 2.5	NS
Distal 1/3	2.8	1.6	1.2	1.0	19.0	15.4	19.5	9.4	2.2	1.8	7.8	9.6	7.9 3.0	5.7 2.2	NS
Whole Diaphysis	2.7	2.5	1.0	1.1	21.1	25.1	20.5	13.1	1.7	1.8	6.3	6.3	8.3 3.3	7.7 3.3	NS
Marrow	17.8	21.6	14.7	7.4	106.3	123.9	104.8	147.0	9.8	11.4	87.7	72.0	51.4 17.2	57.2 21.9	NS

Appendix Table 1

Blood flow (mls/min/100g) for Group A (60mm Hg for 4 hrs)

I = inflated balloon NI = non-inflated balloon
NS = non significant SE = standard error

Rabbit No	1		2		3		4		5		6	
	I	NI	I	NI	I	NI	I	NI	I	NI	I	NI
Muscle	3.5	5.0	6.1	10.1	2.8	3.2	8.4	5.0	10.6	11.3	6.5	15.0
Prox 1/3	3.7	2.4	9.4	6.7	1.8	2.4	2.4	3.0	5.4	8.9	5.4	4.7
Mid 1/3	1.6	0.5	13.9	9.9	3.8	2.7	0.7	1.9	4.2	2.0	2.5	3.5
Distal 1/3	1.2	1.0	6.0	15.4	1.4	2.5	2.0	0.1	6.8	7.0	5.5	4.7
Whole Diaphysis	2.2	1.3	10.0	10.4	2.2	2.6	1.7	1.7	5.4	5.9	4.5	4.3
Marrow	20.9	12.5	95.9	96.9	16.7	15.1	34.4	43.3	30.6	39.9	28.6	30.0

Appendix Table 2 (continued next page)

Blood flow (mls/min/100g) for Group B (60 mm Hg for 24 hrs)

I = inflated balloon NI = non-inflated balloon

Rabbit No	7		Mean + SE -		
	I	NI	I	NI	P
Muscle	2.8	5.6	5.8 1.1	7.9 1.6	NS
Prox 1/3	0.1	0.6	4.0 1.2	4.1 1.1	NS
Mid 1/3	0.5	0.8	3.9 1.8	3.0 1.2	NS
Distal 1/3	0.6	0.5	3.4 1.0	4.5 2.1	NS
Whole Diaphysis	0.4	0.6	3.8 1.2	3.8 1.3	NS
Marrow	4.5	8.0	33.1 11.1	35.1 11.5	NS

Appendix Table 2 (continued)

Rabbit No	1		2		3		4		5		6	
	I	NI	I	NI	I	NI	I	NI	I	NI	I	NI
Muscle	16.3	13.4	6.3	10.4	5.0	4.0	.03	5.0	3.3	5.2	14.6	26.7
Prox 1/3	4.8	5.7	0.6	1.0	8.0	5.0	1.1	1.1	4.8	5.1	5.2	7.9
Mid 1/3	3.6	2.0	0.5	1.0	2.0	4.0	0.5	1.0	1.6	1.6	7.4	4.6
Distal 1/3	1.9	2.1	0	0.4	5.0	4.0	0.3	0.6	2.7	0.6	13.7	5.4
Whole Diaphysis	3.4	3.1	0.3	0.7	5.1	4.0	0.6	0.9	2.9	2.8	8.6	6.1
Marrow	71.9	53.8	22.1	28.0	70.4	52.9	10.6	11.5	28.9	23.3	36.5	36.0

Appendix Table 3a (continued next page)
Blood flow (mls/min/100g) in first half of
experiment with Group C (60mm Hg for ½ hr)

I = inflated balloon NI = non-inflated balloon

Rabbit No	7		8		9		Mean + SE −		
	I	NI	I	NI	I	NI	I	NI	P
Muscle	2.3	2.2	1.2	2.2	8.4	13.1	6.4 1.9	9.1 2.6	NS
Prox 1/3	1.2	1.4	2.4	2.0	7.0	9.8	3.9 0.9	4.3 1.1	NS
Mid 1/3	0.5	0.1	0.9	1.1	1.8	3.6	2.1 0.7	2.1 0.5	NS
Distal 1/3	0.4	0.4	0.5	1.2	4.2	6.6	3.2 1.4	2.4 0.8	NS
Whole Diaphysis	0.7	0.7	1.4	2.1	4.4	6.8	3.0 0.9	3.0 0.8	NS
Marrow	3.1	4.5	15.9	16.9	53.7	80.0	34.8 8.5	34.1 8.1	NS

Appendix Table 3a (continued

Rabbit No	1		2		3		4		5		6	
	I	NI	I	NI	I	NI	I	NI	I	NI	I	NI
Muscle	0.9	29.9	9.3	30.2	0.9	13.1	.03	4.8	3.9	11.2	9.7	26.1
Prox 1/3	4.4	5.3	1.9	4.3	7.5	4.8	0.9	0.8	4.7	5.1	5.9	8.5
Mid 1/3	1.5	4.4	2.5	4.5	1.1	1.7	0.4	1.0	1.4	1.1	5.6	7.0
Distal 1/3	2.0	2.1	0	2.0	2.9	2.2	0	0.9	2.9	2.1	9.6	6.7
Whole Diaphysis	2.9	4.1	1.5	3.6	4.3	3.0	0.5	0.9	2.9	2.7	7.0	8.8
Marrow	106.8	48.0	20.1	31.2	45.9	48.8	13.7	10.9	21.9	20.9	77.6	44.9

Appendix Table 3b (continued next page)

Blood flow (mls/min/100g) for second half of experiment with Group C (90mm Hg for ½ hr)

I = inflated balloon NI = non-inflated balloon

Rabbit No	7		8		9		Mean + SE -		
	I	NI	I	NI	I	NI	I	NI	P
Muscle	0.2	8.3	0.06	1.5	0.5	6.0	3.4 1.3	14.6 3.7	<0.01
Prox 1/3	6.0	4.8	1.5	2.0	5.6	7.5	4.3 0.8	4.8 0.8	NS
Mid 1/3	1.7	2.4	1.3	0.7	1.6	1.5	1.9 0.5	2.7 0.7	NS
Distal 1/3	2.1	3.9	0.2	1.0	2.4	2.3	2.5 1.0	2.6 0.6	NS
Whole Diaphysis	3.5	3.8	1.1	1.3	3.3	4.0	3.0 0.6	3.6 0.8	NS
Marrow	12.9	15.6	14.4	16.4	34.7	40.6	38.7 11.0	30.8 5.1	NS

Appendix Table 3b (continued

I = inflated balloon NI = non-inflated balloon
SE = standard error

Rabbit No	1		2		3		4		5		Mean ± SE		
	I	NI	I	NI	I	NI	I	NI	I	NI	I	NI	P
Muscle TA	3.0	3.0	1.9	3.0	1.7	5.7	8.0	23.0	3.3	3 .4	3.6 1.1	7.6 3.9	NS
FHL	5.0	6.0	2.6	2.4	3.0	2.4	17.8	21.3	3.0	3.1	6.3 2.9	7.0 3.6	NS
Prox 1/3	4.3	5.0	2.1	2.0	3.3	5.9	3.7	5.0	3.9	3.9	3.5 0.4	4.4 0.7	NS
Mid 1/3	1.7	1.4	2.1	2.1	1.2	1.1	1.3	3.8	2.7	1.8	1.8 0.3	2.0 0.5	NS
Distal 1/3	3.1	5.5	1.3	2.3	2.1	2.0	2.7	3.3	3.0	4.5	2.4 0.3	3.5 0.7	NS
Whole Diaphysis	3.5	4.0	1.8	2.1	2.3	3.0	2.5	4.1	3.3	3.4	2.7 0.3	3.3 0.4	NS
Marrow	15.4	10.0	16.7	16.3	40.1	43.1	33.3	46.7	7.9	18.2	17.1 4.3	22.2 6.3	NS

Appendix Table 4a

Blood flow (mls/min/100g) for first half of experiment
with Group D (anterior and posterior balloons (60mm Hg for ½ hr)

I = inflated NI = non-inflated NS = non significant
TA = tibialis anterior FHL = flexor hallucis longus

Rabbit No	1		2		3		4		5		Mean ± SE		
	I	NI	I	NI	I	NI	I	NI	I	NI	I	NI	P
Muscle TA	2.0	3.0	0.2	0.6	0	11.3	0.1	37.5	4.0	8.0	1.3 0.8	12.1 6.6	NS
FHL	6.0	7.0	0.5	0.5	3.0	9.2	32.8	40.9	2.2	4.7	8.9 6.0	12.5 7.3	NS
Prox 1/3	3.5	3.8	0.5	0.5	9.9	11.4	9.1	8.2	2.1	7.2	5.0 1.9	6.2 1.9	NS
Mid 1/3	0.9	1.3	0.3	0.3	3.0	3.0	3.0	3.8	3.8	3.1	2.2 0.7	2.3 0.6	NS
Distal 1/3	1.8	2.7	0.4	0.8	9.5	8.4	6.0	10.0	5.2	8.5	4.6 1.6	6.1 1.8	NS
Whole Diaphysis	2.2	2.6	0.4	0.5	7.7	7.5	5.9	7.2	3.6	6.3	4.0 1.3	4.8 1.4	NS
Marrow	16.1	10.8	4.4	5.7	40.1	43.1	91.3	101.9	35.5	43.1	37.5 14.9	40.9 17.1	NS

Appendix Table 4b

Blood flow (mls/min/100g) for second half of experiment
with Group D (anterior and posterior balloons (90mm Hg for ½ hr)

I = inflated NI = non-inflated NS = non significant
TA = tibialis anterior FHL = flexor hallucis longus

Rabbit No	1		2		3		4		Mean ± SE		
	I	NI	I	NI	I	NI	I	NI	I	NI	P
Muscle	1.3	5.2	21.2	32.8	8.8	21.2	0.6	2.2	8.0 4.8	15.0 7.2	NS
Prox 1/3	5.6	5.3	10.1	10.6	4.7	5.7	1.5	0.2	5.5 1.8	5.4 2.1	NS
Mid 1/3	2.3	4.1	3.9	4.3	3.3	2.8	0.7	0.6	2.5 0.7	3.0 0.9	NS
Distal 1/3	2.5	2.7	2.3	4.1	2.2	2.8	1.0	0.6	2.0 0.3	2.6 0.7	NS
Whole Diaphysis	3.5	4.0	5.6	6.0	3.3	3.6	1.0	0.5	3.3 0.9	3.5 1.1	NS
Marrow	20.5	71.8	74.6	82.8	48.4	39.7	12.2	14.9	38.9 14.2	52.3 15.5	NS

Appendix Table 5

Blood flow (mls/min/100g) for Group E (90 mm Hg for 24 hrs)

I = inflated balloon NI = non-inflated balloon

Rabbit No	1			2			3			4			5			6			Mean ± SE		Mean E/N
	E	N	E/N	E	N	E/N	E	N	E/N	E	N	E/N	E	N	E/N	E	N	E/N	E	N	
Muscle	5.5	4.1	1.3	1.9	1.0	1.9	2.9	4.5	0.6	6.0	3.4	1.8	2.9	2.2	1.3	8.2	13.1	0.6	4.6 1.1	4.7 1.8	1.3
Prox 1/3	2.1	7.7	0.3	0.01	4.0	0.002	0	0.2	0	0.03	0.1	0.3	0.1	0.4	0.3	1.1	6.3	0.17	0.6 0.3	2.5 1.4	0.2
Mid 1/3	4.0	3.6	1.1	0	4.0	0	0	0.1	0	0.001	3.0	0.0003	1.2	0.2	6	6.6	2.2	0.3	1.4 1.1	1.1 0.6	1.3
Distal 1/3	5.0	2.1	2.4	0	1.0	0	0	0.04	0	0.005	0.04	0.1	0.004	0.1	0.04	0.2	1.1	0.2	0.1 0.1	0.6 0.3	0.5
Whole Diaphysis	5.0	4.6	1.1	0	3.0	0	0	0.1	0	0.01	0.1	0.1	0.4	0.3	1.3	3.0	3.5	0.9	0.7 0.5	1.4 0.8	0.6
Marrow	1.3	4.1	0.3	1.8	4.9	0.4	2.9	10.8	0.3	0.002	7.4	0.0003	0.1	2.2	0.05	10.5	99.0	0.1	2.8 1.6	21.4 15.6	0.2

Appendix Table 6

Blood flow (mls/min/100g) for control group F

(Uninflated balloon, unilateral osteotomy, 24 hour survival)
E = experimental leg N = normal leg
NS = non significant SE = standard error

Rabbit No	1			2			3			4			5			6			Mean ± SE		Mean E/N
	E	N	E/N	E	N	E/N	E	N	E/N	E	N	E/N	E	N	E/N	E	N	E/N	E	N	
Muscle	4.0	6.2	0.6	10.0	4.0	2.5	0.3	14.7	0.02	3.1	0.6	5.2	4.1	4.1	1.0	0.1	31.4	0.003	3.6 1.5	11.1 4.4	1.6
Prox 1/3	2.0	15.2	0.1	0.2	5.6	0.04	0.2	4.2	0.05	0.4	1.5	0.27	0.004	0.7	0.006	1.3	7.5	0.17	0.7 0.5	5.8 2.1	0.1
Mid 1/3	1.1	8.9	0.1	0	2.7	0	0.1	2.9	0.03	0.2	1.7	0.1	0.05	0.4	0.1	1.6	4.6	0.3	0.5 0.3	3.5 1.2	0.1
Distal 1/3	0.3	5.0	0.06	0	2.0	0	0.003	0.2	0.02	0.0007	0.5	0.001	0.06	0.6	0.1	0.02	1.9	0.01	0.06 0.004	1.7 0.7	0.03
Whole Diaphysis	1.2	10.0	0.1	0.06	3.6	0.02	0.1	2.6	0.04	0.2	1.2	0.2	0.04	0.6	0.07	1.0	4.9	0.2	0.4 0.2	3.8 1.4	0.1
Marrow	4.7	62.1	0.08	0.7	16.8	0.04	2.9	30.4	0.1	3.1	3.4	0.9	0	16.5	0	10.8	118.0	0.09	3.7 1.6	46.3 15.9	0.2

Appendix Table 7

Blood flow (mls/min/100g) for experimental group F

(Inflated balloon, unilateral osteotomy, 24 hour survival)
E = experimental leg N = normal leg
NS = non significant SE = standard error

Rabbit No	1			2			3			4			5			6			Mean ± SE		Mean E/N
	E	N	E/N	E	N	E/N	E	N	E/N	E	N	E/N	E	N	E/N	E	N	E/N	E	N	
Muscle	9.1	8.5	1.1	0.7	3.6	0.2	3.1	3.2	1.0	16.7	5.3	3.2	15.0	9.2	1.6	0.6	1.2	0.5	7.5 2.9	5.2 1.3	1.3
Prox 1/3	9.6	4.4	2.2	6.9	1.2	5.8	6.5	1.0	6.5	22.6	6.1	3.7	2.9	2.6	1.1	3.8	3.7	1.0	8.7 2.9	3.2 1.5	3.4
Mid 1/3	38.7	3.8	10.2	20.1	0.3	67	8.6	1.5	5.7	50.9	1.6	32	6.8	1.4	4.9	8.6	1.0	8.6	22.3 7.5	1.6 0.5	21.4
Distal 1/3	10.3	5.3	1.9	6.0	1.4	4.3	3.7	0.8	4.6	30.8	5.4	5.7	3.7	1.3	2.8	4.4	1.3	3.4	9.8 4.3	2.6 0.9	3.6
Whole Diaphysis	24.0	4.0	6.0	12.6	0.9	14	6.4	1.0	6.4	37.0	3.8	9.7	4.8	1.7	2.8	6.0	2.0	3.0	15.1 5.6	2.2 0.7	7.0
Marrow	2.8	35.2	0.08	11.8	16.8	0.7	8.7	3.1	2.8	19.8	17.2	1.2	3.0	5.2	0.6	6.7	12.9	0.5	8.8 2.6	15.1 4.7	1.0

Appendix Table 8

Blood flow (mls/min/100g) for control group G

(Uninflated balloon, unilateral osteotomy, 2 weeks survival)
E = experimental leg N = normal leg
NS = non significant SE = standard error

Rabbit No	1			2			3			4			5			6			Mean ± SE		Mean E/N
	E	N	E/N	E	N	E/N	E	N	E/N	E	N	E/N	E	N	E/N	E	N	E/N	E	N	
Muscle	6.3	4.1	1.5	8.8	4.3	2.0	1.6	0.5	3.2	8.7	2.3	3.8	38.9	7.8	5.0	48.6	4.6	10.6	18.8 8.1	3.9 1.0	4.4
Prox 1/3	1.3	1.0	1.3	3.3	1.7	1.9	0.2	0.1	2.0	1.1	0.9	1.2	23.8	7.1	3.4	20.0	8.6	2.3	8.3 4.4	3.2 0.8	2.0
Mid 1/3	8.5	1.3	6.5	12.7	0.9	14.0	2.0	0.2	10.0	11.2	0.4	28.0	47.0	6.4	7.3	45.1	2.4	18.8	21.0 8.0	1.9 0.9	14.1
Distal 1/3	0.6	1.5	0.4	2.5	0.2	12.5	0.05	0.1	0.5	0.8	0.2	4.0	25.2	5.3	4.8	30.3	1.9	15.9	9.9 5.7	1.5 0.8	6.4
Whole Diaphysis	3.8	1.3	2.9	7.0	0.4	17.5	0.9	0.1	9.0	5.6	0.5	11.2	33.1	5.9	5.6	33.7	3.7	9.1	14.0 6.2	2.0 0.9	9.2
Marrow	1.0	11.6	0.09	10.5	10.2	1.0	0.6	0.5	1.2	5.3	13.1	0.4	17.0	11.7	1.5	42.1	20.3	2.1	12.8 6.4	11.2 2.6	1.0

Appendix Table 9

Blood flow (mls/min/100g) for experimental group G

(Inflated balloon, unilateral osteotomy, 2 weeks survival)
E = experimental leg N = normal leg
NS = non significant SE = standard error

Rabbit No	1			2			3			4			5			Mean ± SE		Mean E/N
	E	N	E/N	E	N	E/N	E	N	E/N	E	N	E/N	E	N	E/N	E	N	
Muscle	5 8	7.6	0.8	0.7	0.9	0.8	8.1	9.1	0.9	4.4	6.2	0.7	0.3	0.2	1.5	3.9 1.5	4.8 1.8	0.9
Prox 1/3	11.1	4.5	2.5	0.8	0.5	1.6	2.4	0.8	3.0	3.0	2.5	1.2	0.1	0.1	1.0	3.5 2.0	1.7 0.8	1.9
Mid 1/3	14 8	2.0	7.4	1.3	0.4	3.3	4.4	0.3	14.7	5.5	1.0	5.5	0.4	0.2	2.0	5.3 2.6	0.8 0.3	6.6
Distal 1/3	7.2	18.9	0.4	0.8	0.1	8.0	0.9	0.2	4.5	1.8	0.9	2.0	0.03	0.001	30.0	2.1 1.3	4.0 3.7	9.0
Whole Diaphysis	11.2	2.9	3.9	1.0	0.4	2.5	3.0	0.4	7.5	4.0	2.0	2.0	0.2	0.08	2.5	4.2 1.8	1.2 0.6	3.7
Marrow	39.4	13.8	2.9	2.1	2.3	0.9	13.6	13.6	1.0	11.6	14.4	0.8	1.8	0.2	9.0	13.7 6.9	8.9 3.1	2.9

Appendix Table 10

Blood flow (mls/min/100g) for control group H

(Unilateral uninflated balloon and osteotomy, 6 weeks survival)
E = experimental leg N = normal leg
NS = non significant SE = standard error

Rabbit No	1			2			3			4			5			Mean ± SE		Mean E/N
	E	N	E/N	E	N	E/N	E	N	E/N	E	N	E/N	E	N	E/N	E	N	
Muscle	60	11.7	5.1	10.0	4.0	2.5	17.0	6.0	2.8	6.5	15.0	0.4	15.0	7.0	2.1	21.7 9.8	8.7 2.0	2.6
Prox 1/3	7.6	5.2	1.5	4.0	0.5	8.0	12.5	0.6	20.8	6.1	0.7	8.7	12.3	3.5	3.5	8.5 1.7	2.1 1.0	8.5
Mid 1/3	23	2.4	9.6	6.0	0.6	10.0	20.4	1.7	12.0	13.2	0.9	14.7	23.8	1.0	23.8	17.3 3.4	1.3 0.3	14.0
Distal 1/3	21	0.5	42.0	0.8	0.1	8.0	6.0	0.6	10.0	3.4	0.6	5.7	5.9	0.8	7.4	7.9 345	0.5 0.1	14.2
Whole Diaphysis	17	3.0	5.7	4.0	0.4	10.0	14.7	1.1	13.4	9.2	0.8	11.5	30.0	1.8	16.7	15.0 4.4	1.4 0.5	11.5
Marrow	44	33	1.3	8.0	9.0	0.9	18.2	24.9	0.7	19.8	21.1	0.9	31.9	21.0	1.5	24.4 6.23	21.8 3.9	1.1

Appendix Table 11

Blood flow (mls/min/100g) for experimental group H

(Unilateral inflated balloon and osteotomy, 6 weeks survival)
E = experimental leg N = normal leg
NS = non significant SE = standard error

Rabbit	Maximum Torque Moment (Nm)			Maximum angular Deformation (degrees)			Total Energy (J)			Energy to Fracture			Torsional Stiffness (Nm/degree)		
	O	N	O/N	O	N	O/N	O	N	O/N	O	N	O/N	O	N	O/N
1	0.30	2.74	0.1	14.32	17.78	0.8	0.12	0.37	0.3	0.04	0.37	0.1	0.022	0.188	0.1
2	0.24	2.29	0.1	30.62	14.32	2.1	0.16	0.27	0.6	0.07	0.27	0.3	0.011	0.166	0.07
3	0.27	2.35	0.1	21 73	19.75	1.1	0.16	0.42	0.4	0.06	0.41	0.1	0.016	0.119	0.1
4	0.52	2.13	0.2	11.85	36.05	0.3	0.34	0.81	0.4	0.06	0.73	0.08	0.046	0.067	0.7
5	0.75	1.63	0.5	35.06	28.15	1.2	0.22	0.33	0.7	0.20	0.33	0.6	0.033	0.080	0.4
Mean $\pm$ SE	0.42 0.1	2.23 0.18	0.2	22.72 4.50	23.21 3.94	1.1	0.20 0.04	0.44 0.1	0.5	0.09 0.03	0.42 0.08	0.2	0.03 0.006	0.12 0.02	0.3

Appendix Table 12

Biomechanical testing of tibiae in control Group G
(Uninflated balloon, unilateral osteotomy, 2 week survival)

O = osteotomised tibia SE = standard error
N = normal tibia

Rabbit	Maximum Torque Moment (Nm)			Maximum angular Deformation (degrees)			Total Energy (J)			Energy to Fracture			Torsional Stiffness (Nm/degree)		
	O	N	O/N	O	N	O/N	O	N	O/N	O	N	O/N	O	N	O/N
1	0	2.44	0	0	15.80	0	0	0.34	0	0	0.32	0	0	0.163	0
2	0.10	2.17	0.4	82.47	12.35	6.7	0.24	0.22	1.1	0.10	0.22	0.5	0.009	0.195	0.05
3	0	4.21	0	0	17.78	0	0	0.64	0	0	0.64	0	0	0.257	0
4	0.10	4.52	0.02	11.36	24.69	0.5	0.09	0.77	0.1	0.01	0.66	0.02	0.009	0.236	0.04
5	0.56	2.09	0.2	13.83	35.56	0.4	0.24	0.73	0.3	0.07	0.69	0.1	0.042	0.067	0.6
6	0.14	1.80	0.08	7.90	28.15	0.3	0.05	0.45	0.1	0.01	0.45	0.02	0.017	0.065	0.3
Mean + SE −	0.15 0.08	2.87 0.48	0.1	19.3 12.9	22.4 3.5	0.5	0.10 0.05	0.53 0.09	0.3	0.03 0.02	0.49 0.08	0.1	0.13 0.006	0.16 0.03	0.2

Appendix Table 13

Biomechanical testing of tibiae in experimental Group G
(Inflated balloon, unilateral osteotomy, 2 week survival)

O = osteotomised tibia SE = standard error
N = normal tibia

Rabbit	Maximum Torque Moment (Nm)			Maximum angular Deformation (degrees)			Total Energy (J)			Energy to Fracture			Torsional Stiffness (Nm/degree)		
	O	N	O/N	O	N	O/N	O	N	O/N	O	N	O/N	O	N	O/N
1	3.54	2.70	1.3	21.23	17.28	1.2	0.67	0.38	2.6	0.67	0.38	1.8	0.179	0.174	1.0
2	3.24	4.43	0.7	19.26	28.15	0.7	0.58	1.08	0.5	0.58	1.08	0.5	0.176	0.177	1.0
3	2.09	1.78	1.2	18.27	14.81	1.2	0.33	0.22	1.5	0.33	0.22	1.5	0.118	0.120	1.0
4	1.43	1.83	0.8	16.79	18.77	0.9	0.20	0.31	0.6	0.20	0.30	0.6	0.089	0.107	0.8
5	1.94	4.41	0.4	14.32	24.69	0.6	0.27	1.11	0.2	0.27	0.95	0.6	0.155	0.183	0.8
6	2.97	3.53	0.8	26.17	27.16	1.0	0.69	0.87	0.8	0.69	0.85	0.8	0.123	0.137	0.9
Mean + SE −	2.53 0.34	3.20 0.51	0.9	19.34 1.66	21.81 2.28	0.9	0.46 0.09	0.66 0.17	0.9	0.46 0.09	0.63 0.15	1.0	0.14 0.02	0.15 0.01	0.9

Appendix Table 14

Biomechanical testing of tibiae in control Group H
(Uninflated balloon, unilateral osteotomy, 6 week survival)

O = osteotomised tibia SE = standard error
N = normal tibia

Rabbit	Maximum Torque Moment (Nm)			Maximum angular Deformation (degrees)			Total Energy (J)			Energy to Fracture			Torsional Stiffness		
	O	N	O/N	O	N	O/N	O	N	O/N	O	N	O/N	O	N	O/N
1	2.17	3.06	0.7	17.78	19.75	0.9	0.34	0.51	0.7	0.34	0.51	0.7	0.128	0.152	0.8
2	0.83	2.96	0.3	13.33	14.81	0.9	0.41	0.36	1.1	0.10	0.36	0.3	0.071	0.218	0.3
3	2.04	3.78	0.5	16.79	21.23	0.8	0.31	0.70	0.4	0.31	0.70	0.4	0.126	0.183	0.7
4	1.56	3.63	0.4	11.85	17.78	0.7	0.15	0.53	0.3	0.15	0.50	0.3	0.152	0.248	0.6
5	2.32	3.11	0.7	32.10	22.22	1.4	0.64	0.62	1.0	0.64	0.63	1.0	0.075	0.151	0.5
6	1.37	3.33	0.4	11.85	20.74	0.6	0.15	0.51	0.3	0.15	0.57	0.3	0.116	0.170	0.7
Mean $\pm$ SE	1.72 0.23	3.31 0.13	0.5	17.28 3.13	19.42 1.11	0.9	0.33 0.08	0.55 0.05	0.6	0.28 0.08	0.54 0.05	0.5	0.11 0.01	0.19 0.02	0.6

Appendix Table 15

Biomechanical testing of tibiae in experimental Group H
(Inflated balloon, unilateral osteotomy, 6 week survival)

O = osteotomised tibia SE = standard error
N = normal tibia

Rabbit No.	No.of fields	Area mm^2 Periosteal (P) callus	Cortical (C)	P/C
1	12	105.80	333.11	0.318
2	17	1197.36	398.38	3.006
3	16	1159.88	416.79	2.783
4	16	1039.66	393.82	2.640
5	16	1427.75	450.59	3.169
6	16	1294.02	382.41	3.384
Mean $\pm$ SE				2.550 $\pm$ 0.459

Appendix Table 16

Image analysis results for experimental Group G
(Inflated balloon, 2 week survival)

SE = standard error

P/C = ratio of periosteal callus area to cortical area

Rabbit No.	No.of fields	Area mm^2 Periosteal (P) callus	Cortical (C)	P/C
1	13	1733.21	455.10	3.808
2	15	1481.68	459.86	3.222
3	17	1613.90	440.00	3.668
4	17	1335.10	460.00	2.902
5	16	1482.44	466.63	3.177
6	16	1361.65	637.89	2.134
Mean $\pm$ SE				3.152 $\pm$ 0.245

Appendix Table 17

Image analysis results for control Group G
(Uninflated balloon, 2 week survival)

SE = standard error

P/C = ratio of periosteal callus area to cortical area

Rabbit No.	No.of fields	Area mm^2 Periosteal (P) callus	Cortical (C)	P/C
1	12	456.94	617.16	0.740
2	14	1618.20	779.10	2.077
3	13	863.95	560.39	1.542
4	16	1165.26	779.92	1.494
5	16	984.72	757.24	1.300
6	20	1260.90	843.65	1.494
Mean $\pm$ SE				1.441 $\pm$ 0.176

Appendix Table 18

Image analysis results for control Group H
(Uninflated balloon, 6 week survival)

SE = standard error

P/C = ratio of periosteal callus area to cortical area

Rabbit No.	No.of fields	Area mm^2 Periosteal (P) callus	Cortical (C)	P/C
1	15	1010.43	599.82	1.805
2	18	1527.14	742.73	2.056
3	14	1102.55	435.62	2.531
4	14	1305.31	488.62	2.671
5	17	3014.44	600.62	5.019
Mean $\pm$ SE				2.816 $\pm$ 0.573

Appendix Table 19

Image analysis results for experimental Group H
(Inflated balloon, 6 week survival)

SE = standard error

P/C = ratio of periosteal callus area to cortical area