SEVERE OPEN FRACTURE TIBIA
THE RELATIONSHIP BETWEEN EXTERNAL FIXATION AND NONUNION

BY

DR. SANUSI AZNI AB. GHANI

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Abstrak.

Satu kajian retrospektif telah dijalankan dari Januari 1997 sehingga Januari 1999 untuk mengkaji kadar ketidakcantuman fraktur terbuka yang teruk tulang tibia yang dirawat dengan fiksator eksterna.

Kajian ini melibatkan 22 pesakit yang mengalami fraktur terbuka yang teruk tulang tibia iaitu gred 11, 111A dan 111B yang telah dirawat dalam masa setahun di Hospital Universiti Sains Malaysia (HUSM), Kubang Kerian, Kelantan. Julat umur pesakit adalah dari 19 tahun sehingga 73 tahun (dengan umur purata pesakit adalah 38.2 tahun). Terdapat 19 pesakit lelaki dan 3 pesakit wanita. Penyebab kecederaaan pada 19 pesakit adalah kemalangan motosikal, satu pesakit pejalan kaki-motosikal, satu kemalangan kereta dan satu kemalangan semasa pembalakan. 2 fraktur adalah dibahagian atas, 11 dibahagian tengah, 8 dibahagian bawah dan satu melibatkan dua paras iaitu bahagian tengah dan bawah. Pemeriksaan fizikal dan filem x-ray digunakan untuk menilai kadar penyembuhan fraktur.

Dari kajian ini, masa purata dari kecederaan dan pembedahan adalah 18 jam. Jangkamasa purata pesakit memakai fiksator eksterna adalah 66 hari. Kadar penyembuhan tulang adalah 13 minggu (6 pesakit). Jangkamasa memakai fiksator eksterna dan kecederaaan ke pembedahan memasang fiksator eksterna juga tidak mempengaruhi kadar penyembuhan tulang. Fraktur pada bahagian atas sembuh lebih

cepat dari fraktur pada bahagian bawah dan tengah, walaubagaimanapun ia tidak bermakna secara statistik. Fraktur terbuka tulang tibia gred 11 sembuh lebih cepat dari gred 111A dan gred 111B. Fraktur tulang yang remuk sembuh lebih perlahan dari fraktur mudah (Winquist 4: 28 minggu), walau bagaimanapun ia tidak bermakna secara statistik.

Abstract.

A retrospective study was carried out from January 1997 to January 1999 to look into the rate of nonunion of severe open tibial fractures treated with external fixators.

This study included 22 patients with 22 severe open diaphyseal tibial fractures of grade 11, 111A and 111B seen within 1 years period in HUSM (Hospital Universiti Sains Malaysia), Kubang Kerian, Kelantan. The patients age ranged from 19 to 73 years (mean age of 38.2 years). There were 19 males and 3 females. The mechanism of injury included 19 motorcycle accidents, one pedestrian-motorcycle accident, one motorvehicle accident and one logging injury. Two fractures were at the proximal third, eleven were middle third, eight were distal third and one was segmental. Clinical symptoms and plain radiographes were used to evaluate the union rate.

The mean time interval from injury to application of external fixator was 18 hours. The mean duration of patient on external fixator was 66 days. The union rates was 13 weeks(6 patients). The duration on external fixator and time interval from injury to application of an external fixator also did not influence the union rate. Proximal third fracture healed faster than lower or middle third, however it was not statistically significant. Grade 11 open tibial fracture healed faster than grade 111A and grade 111B. Highly comminuted fracture healed slower than simple fracture (Winquist 4:28 weeks), however it was also not statistically significant.

1.0 Introduction.

The tibia is particularly prone to severe open injuries because of its location, structural anatomy and sparse anterior coverage by soft tissue. (Caudle & Stern, 1987). An open fracture of the tibia with additional severe soft tissue damage is one of the most difficult problem in traumatology. (Med. et al., 1983).

The treatment of open fractures of the tibial shaft remains controversial. (Blachut et al., 1990). The value of primary stable osteosynthesis with bone plates is questioned because of the additional damage to soft tissues and blood supply. The vast majority of authors strongly object to the use of intramedullary nails for stabilization of such fractures. Currently, the treatment of choice in these cases is external fixation.(Med. et al., 1983). It facilitates stabilization of bony and soft tissue lesions at a distance from the injury site, appear ideally suited for the initial treatment of open diaphyseal fractures.(Behrens et al.,1983).

With the introduction of better designs and exacting postoperative management, many authors have reported high rate of success with external fixation.The fracture can be reduced and stabilised without sacrificing access to the injured soft tissues and without burying foreign material next to the fracture or under damaged skin.(Edge & Denham ,1981).

Stable external fixation of open tibial fractures promotes healing of skin and soft tissue damage, reduces the risk of infection, and facilitates the treatment of patients with multiple injury. Functional end results after a stable external fixation compare favorably with the results of internal fixation with Arbeitsgemeinschaft fur Osteosynthesefragen (AO) plates.(Karlstrom & Olerud ,1983)

However, despite many refinements in this technique, it has been associated with numerous complications, including problems at the sites of the pins, non-union, delayed union, malunion and infection.(Blachut et al.,1990). Although early removal of fixator is frequently recommended to prevent delayed union and nonunion, little or no data have been found to support this suggestion.(Thomas & Rae ,1983).

2.0 Literature review

Non union and delayed union following severe open tibial fracture is well known. The rate of non-union has been high (20 to 30 percent), reflecting the characteristics of the fracture; a high energy injury with severe loss of soft tissue and comminution.(Court-Brown et al., 1990).

Velazco et al (1983) in a prospective study of 40 consecutive patients with open type 11 or 111 tibial fractures who were treated with external fixator noted five nonunions (12 %) at 18-month follow-up which had healed after bone graft.

Kimmel (1982) in their study of severe open diaphyseal fractures of the tibial in 19 patients where 50 % were classified as grade 111. Overall, three nonunions(13%) resulted. Forty-five percent of patients required a bone graft for eventual union.

Chan et al(1984) in a retrospective study of extensive type 111 open tibial fractures, found a delayed union 60 percent and infected nonunion 30 percent.

The cause of nonunion in open tibial fracture is multifactorial.It is commonly assumed that prolonged external fixator is a cause of nonunion.However, the high incidence of nonunion noted with external fixation is not due to prolonged use of the external fixation. In fact, it is the failure of the fracture to unite that causes the surgeon to continue the use of the fixator.

Thomas & Rae (1983) in a series of 20 open tibial fractures treated with external fixators, demonstrated an association between nonunion and prolonged use of the fixator, but no cause-and-effect relation was shown. However, there was no association was found between the development of nonunion and degree of soft tissue injury, delay in fixator application, or diaphyseal versus metaphyseal fracture.

Chatziyiannakis et al.(1997) found that the type of open fracture, comminution of the fracture and extension of the original wound for satisfactory reduction, played an important role in the development of nonunion.

Aho et al.(1983) studied on the advantages of external fixation in the treatment of severe open tibial fractures (grade 11 and 111) in 79 patients during the period from 1971 to 1978 noted that the risk of delayed union or nonunion and secondary bone atrophy was due not only to the severity, comminution, soft tissue injury and/ or infection of the fracture but also to the prolonged use of the external fixators and the long nonweight-bearing time.

Rommens (1992) in his prospective study of the significance of soft tissue trauma for fracture healing on 70 severe open tibial shaft fractures observed that the more severe the soft tissue injury, the more difficult the fracture healing will be.

Augeneder et al. (1989) in their study of 50 severe open tibial fractures treated with external fixator which was published in Germany journal noted that on average, fracture healing took 6.7(4-15) months, significantly correlating with the severity of soft-tissue lesion.

With an external fixator in place in a severely comminuted fractures with defects, stable bridging callus may require a long time to form, even with repeated bone grafting.If there are no signs of beginning bony union after about 10 to 12 weeks and if the soft tissue is healed, Med et al (1983) recommended changing to internal fixation with simultaneous cancellous bone grafting.Combined secondary plate osteosynthesis and bone grafting accelerate bony union in cases of delayed healing.

Fracture healing is theoretically enhanced by anatomic reduction, preservation of blood supply, and sufficiently stable internal and external immobilization.(Philip & Jack , 1983)

Sufficient stability and adequate revascularization are essential for fracture union. The motion at a fracture site is dependent on both the load placed on it and the rigidity of the fracture fixation. The rigidity of the fracture fixation depends on both the biologic tissues present normally and those developed in the process of healing, as well as on the orthopaedic stabilizing devices used, whether a plaster cast, external skeletal fixation, or internal fixation.

In 1955 Yamagishi and Yoshimura demonstrated an association between increasing callus and decreasing stability with external skeletal fixation of fractures in rabbits. White et al.(1977) demonstrated an early increase in stiffness and a later increase in strength of externally compressed rabbit tibial fractures. The interfragmentary strain that develops during fracture healing seems to be associated with the type of tissue found at the fracture site.

Granulation tissue between the bone ends will tolerate a strain of 100 % before failure. Cartilage will fail with 10 % strain and bone with only 2 %. The greater the motion that occurs, the more likely is fibrous tissue to form. The motion between the fracture ends must be reduced to a minimum before bone tissue can bridge the fracture gap.

Fracture healing cannot occur without adequate vascularization. The injury itself produces vascular injury, both to bone and surrounding soft tissues, that must be repaired. Continued gross motion at a fracture site impedes healing process. Given these well founded principles, it is difficult to conceive of prolonged use of_external fixation causing nonunion.

Proper management of fractures by external skeletal fixation obviously includes avoidance of distraction. Removal of the external fixator and application of a plaster cast would result in a decrease in fracture site stability at a critical time in fracture healing.There is neither theory nor evidence to support the concept that decreasing fracture site stability at this critical period will enhance union.

Not only must overdistraction be scrupiously avoided, but fracture site compression should also be sought. This will avoid fracture site motion under both compressive loading and torsion.Regardless of the technique utilized, fracture site motion will be greater than with rigid internal fixation if weight-bearing is not limited. Shear displacement at the fracture site may well be best controlled by "minimal internal fixation" by interfragmentary screws or short plates, as suggested by Philip and Jack, (1983).

The other major requirement for fracture healing is adequate vascularity to supply the required energy, nutrition, and cells. In fractures that fail to heal due to excessive motion, radiographic evaluation usually reveals abundant quantities of callus surrounding each fragment but persistence of the fracture gap.

Thomas & Rae (1983) noted fractures that failed to heal were characterized by a lack of radiographic callus, supporting the concept of inadequate vascularity as a cause of nonunion rather than excessive motion.They reported their experience with the use of bone scanning to evaluate fracture healing. The static two-hour postinjection bone scan was found to be of little value. In contrast, the 7.5-15.0-minute uptake of bone-seeking isotope discriminated well between normally healing fractures, delayed unions, and nonunions. Three months after injury normally healing fractures showed a net uptake of 15 %, whereas the nonunions showed a flat line during the 7.5-15.0-minute period. The high rate of success with posterolateral bone grafting in tibial nonunions also supports this concept.

Union by a bridge of external callus has definite advantages, especially in severe injuries such as those treated using external fixation. It can bridge gaps due to missing bone or devitalised fragments, and is the most rapid variety of bone healing. (Edge & Denham, 1981).

The significance of external callus in monitoring the healing of tibial fractures treated by external fixation is supported by several recent reports.In contrast, Lawyer and Lubber (1980) proposed that union may develop without callus formation, suggesting primary union by external fixation. All of these results suggest a great need for a quantitative technique for measuring fracture healing. Bending moments rather than axial loads are more appropriate and should be measured, as well as angular deformation at the fracture site.

Thomas &Rae (1983) recommended meticulous initial debridement, irrigation, and preparation of a soft tissue envelope. Early application of rigid external fixation will expedite wound healing and decrease the development of osteomyelitis.

They also recommmend bone grafting in fractures that are unstable at four months, with or without removal of the external fixation system. Loosening of the fixation clamps allows manipulation of the fracture site and clinical evaluation of motion.

Despite all the complications, external skeletal fixation remains an ideal treatment for complicated extremity fractures in that it provides an increase in fracture site stability as compared with plaster cast technique without the increased risks associated with internal fixation.

In addition to provide adequate immobilization of the fracture, this method allows free access to the wounds and optimal care of the critical soft tissue conditions.It is also versatile and easy to apply with minimun operative trauma.

Thakur and Patankar (1991) treated 79 open tibial fractures with unilateral uniplanar tubular external fixators found that combined with early bone grafting, external fixation is an excellent method for the management of open tibial fractures.

Bach et al (1989) in their prospective study of 59 patients with Grade 11 or 111 open tibial shaft fractures compared internal and external fixation. They note that external fixation should be regarded as a primary method of stabilization for grades 11 and 111 open tibial shaft fractures compared to plate.

3.0 Blood supply of tibia

The blood supply of the tibial is derived from three vessels systems: Nutrient vessels, Metaphyseal vessels and Periosteal vessels.

The nutrient artery of the tibia arises from the posterior tibial artery and enters the posterolateral cortex of the bone at the origin of the soleus muscle just below the oblique line of the tibia posteriorly. The artery divides into three ascending branches and only one main descending branches, which give off smaller branches to the endosteal surface. It responsibles for the perfusion of the marrow and the inner two-thirds of the diaphyseal cortex. (Trueta J, 1974).

Periosteal vessels arise from branches of the anterior tibial artery as it courses down the interosseus membrane. It supplies the outer one-third of the cortical bone.

Metaphyseal vessels arises from the periarticular vascular plexus (i.e geniculate arteries). It provides numerous anastomoses with the branches of the nutrient artery. It is capable of maintaining the perfusion of the marrow and the inner one-half of the cortex following division of the nutrient artery.

The role of each source in fracture healing is controversial. Rhinelander (1974) believe that the periosteal blood supply plays a relatively minor role in supplying the normal adult tibial cortex. He also stated that the intramedullary vascular supply is the most important in normal bone; however, after an injury that disrupts the intramedullary vascular pattern, the periosteal blood vessels increase their contribution and become prominent in the formation of new bone.Macnab and Haas (1974) found that the periosteal vessels were especially important in the distal third tibial fractures but found no difference in intramedullary supply between proximal and distal regions.

In experimental animals the nutrient artery can be ligated or the metaphyseal anastomoses can be interrupted without any apparent circulatory deficiency. Interruption of both nutrient artery and the metaphyseal intercommunications lead to extensive necrosis of the inner two-thirds of the cortical bone. (Trueta, 1974)

Experimental studies by Rhinelander (1974) and others have shown the enormous capacity of the medullary and periosteal blood supply to regenerate after injury or osteotomy in laboratory animals.Complete revascularization of the cortex occurs relatively early in the fracture-healing process.

The two basic frame types, unilateral and bilateral, can be applied in one or two-plane configurations. The one-plane configurations are less obstructive and generally suffice for most injury situations.

Two-plane frames are more effective in neutralization multi-directional bending and torsional movements (Behren et al. 1983; Behrens and Johnson 1985). However, they are only needed when dealing with severe comminuted fracture or with bone loss (Behrens and Searls 1986), and for arthrodesis as well as osteotomies.

4.3 External fixator component mechanics.

4.3.1 *Fasteners.*

External fixation frames are fastened to bone using Schantz screws. In principle, the most significant parameter that affects the stability of an external fixation system is the radius of the screw.The bending stiffness of the screw increases as a function of the fourth power of the radius of that implant. (Burstein et al., 1972)

Care must be taken to limit the diameter of any screw hole to no greater than 30 % of the diameter of the diaphysis. To exceed this significantly weakens the bone, effectively creating an open section. It has been shown that a hole greater than 30 %

of the diameter markedly increases the risk of fracture. Burstein and colleagues (1972) demonstrated that a screw hole equal to 30 % of the diameter weakened the torsional strength of that bone by 45 %. Over 6 to 8 weeks, the bone will remodel about the implant, restoring its strength. However, upon removal of the screw, the weakening recurs until the bone has remodeled once more.(Burstein et al., 1972)

Screw design has concentrated on the development of implants with a greater core or root diameter to increase rigidity. Because of an increased rate of implant loosening, current recommendations favor stiffer, larger root-diameter screws with bicortical threads for better purchase and decreased loosening characteristics.

Bending preload technique would theoretically reduce pin loosening by allowing the elastically loaded implant to maintain three-point bending contact. Animal studies, however, have suggested that the bending preload technique actually accelerates loosening because of rapid pressure necrosis on the compression side of the preload pin. Therefore, bending preload is discouraged.(James VN, 1996)

Hydahl and coworkers (1991) recommends *radial preload* to improve screw fixation and prevent loosening. This can be achieved either by first drilling a pilot hole slightly smaller than the root diameter screw design to produce a radial preload as the screw is introduce. They demonstrated in animal studies that radial preload is preferable to bending preload techniques. (Hydahl et al., 1991)

Enlarging the shank diameter of screws has been shown to increase the overall rigidity of the implant which, in turn, results in lower bending stresses at the entry site cortex and in a diminished rate of osteolysis and loosening. (Chao & Aro, 1991)

4.3.2 *Reduction.*

The composite stability of the bone-fixator construct is the most important factor in treating fractures with external fixation. Fracture configuration and reduction profoundly affect stresses at the screw/bone interface. End-on-end transverse or other stably reduced fracture constructs maintained with external fixation have been shown in both in vitro and in vivo testing to reduce stresses at the screw/bone interface.This results in decreased rates of pin loosening. As demonstrated by Chao and Aro (1991), bone-fixator constructs without bone-end contact, and those with very oblique(unstable) fracture patterns, tend to have increased rates of screw loosening and a longer healing time when compared with stably reduced transverse fractures with good bone-end contact.

4.3.3 *Insertion technique.*

The insertion technique may have mechanical effects on the initial screw purchase as well as a profound biological influence on the maintenance of the implant-bone interface. The insertion of self-drilling screws has been associated with microfracture and high temperatures at the bone implant interface. Thermal necrosis often the end results. To reduce the potential for both thermal necrosis and the premature loosening associated with it, an alternative technique that involves predrilling pilot holes for all screw sites is now recommended to minimize microfracture and avoid excessive increase in bone temperatures.(Matthews et al., 1984).

4.3.4 *Screw/Pin Materials.*

Chao and Aro (1991) advocate the use of high modulus materials in screw design to minimize bending and thereby decrease loosening. Others, however, believe that using more isoelastic materials, such as titanium alloy, improves loosening rates. This issue remains controversial.

Previous metals, such as gold and silver, have long been known to inhibit bacterial growth. It has been suggested that coating fixator screws with gold or silver might prevent pin-track infection. Limited laboratory and clinical studies have indicated decreased pin-track infection rates when coated pins are used. However, such implants are not clinically available.

4.3.5 *Threaded Versus Smooth Fasteners.*

Smooth implants may allow bone to translate on fixator pins. Fixation with a smooth implant is therefore less stable than fixation with a threaded implant of the same diameter. (James VN, 1996)

4.3.6 *Number of Screws/Pins/Wires*

In any system of external fixation, stability is improved by increasing the number of fixation devices to bone. Ideally, to achieve maximal effect, these additional screws should be evenly distributed across the greatest possible area of the major fragments to be stabilized. Many larger body/frame external fixation systems can achieve more than adequate stability for most applications by using two closely set screw clusters that are remote from the fracture to be stabilized.

4.3.7 *Frame geometry.*

Traditional early bar and clamp fixators, such as the ASIF or Hoffmann-Vidal-Adrey systems, offer considerable versatility in exchange for stability. For simple fracture patterns with good fracture reduction, the simple uniplanar frame geometry of these systems provides adequate stability. Any unilateral application can be made more resilient to the forces experienced in any one direction or plane by applying a like frame that opposes that plane of instability. When the frames are connected, they may constitute a so-called "delta configuration" or triangular frame. Comparative stability studies have shown that larger unilateral systems offer a degree of stability comparable to the more complex multiplanar configurations of more traditional systems.

Excessive rigidity can have a negative influence on healing.Inherently stronger large-body unilateral systems should almost never be applied in multiplanar configurations for routine fractures because they may inhibit callus formation.

4.3.8 *Bone Frame Distance*

Another technique used to significantly increase the stability of any given construct involves placing the frame component as close to the bone as clinically possible. The closer the frame is to the bone, the more stable the construct will be. This principle can also be used by clinicians who choose to produce cyclic dynamization in a frame by moving the fixator bars or body further out on the fixation pins or screws. This creates a more flexible construct. This method of decreasing frame rigidity while maintaining reduction was one of the earliest techniques of dynamization.

4.3.9 *Implant-Clamp Fixation.*

In half-screw fixator systems, implants are held by individual or grouped coupling clamps that affix screws to the frame. To improve fixation of the half-pins to the frame, screw coupling clamps can be made wider to achieve broader, more stable fixation to the shaft of the half-screw. Fixators with smaller single-coupling clamps can be used to achieve similar stability by "double stacking" them. This is another way to broaden the fixation of the screw to the frame and improve construct stability.

4.3.10 *Biomechanics: summary.*

In summary, an "ideal" degree of osseous stability for managing each clinical situation treated with external fixation is ill defined. Any fixation technique should attempt to match the biomechanical requirement of the clinical situation with the stability of the overall construct.

The following frame characteristic have been shown to increase the stiffness of an applied frame and to diminish motion at the fracture site:

1. Increasing the diameter of the schanz screws.
2. Increasing the number of schanz screws in each bony fragment.
3. Increasing schanz screw spread within each main bony fragment.
4. Using multiplanar fixation.

5. Placement of the principal frame in the sagittal plane.
6. Reducing the distance between fixator frame and bone.
7. Predrilling all half-pin screw sites whenever possible, and irrigating drills and implants on insertion with a cool saline solution to avoid thermal necrosis and associated premature loosening.
8. Applying radial preload techniques to half-screw fixation.
9. Preloading of schanz screws-automatically done by slightly oversizing (+0.2 mm) the core.
10. Improving fastener-frame fixation with improved clamp technology or double stacking.
11. Reducing fractures with fragment contact improving stability and permitting "off loading" of implants (without use of adjunctive lag screws).
12. Dynamizing frames when possible to allow for bone-end contact, a reduction in screw stress and decrease in the tendency to loosen.

4.4 **Clinical indication of external fixation.**

External fixation is usually relegated to the stabilization of more severe complex injuries, especially those with associated soft-tissue wounds that are not amenable to other techniques. In instances of severe intra-articular fractures, external fixation may be used as a portable traction device, offering a means of reduction and stabilization through ligamentotaxis. Finally , external fixation can be an alternative method for temporary stabilization of long bone and pelvic injuries in multiply traumatized patients when the blood loss and operative time associated with definitive internal fixation are considered undesirable.

4.5 Principles of external fixation.

To be safe and effective, an applied fixator should have a low rate of serious complications, be nonobstructive, be stiff enough to maintain alignment under adverse loading situation, facilitate full weight-bearing, and be adaptable to a wide variety of injury and patient conditions.

Experience accumulated over the past decade has shown that these are best achieved by adhering to four basic principles(Behrens and Searls, 1986) which demand that the applied frame optimally accomodates the vital limb anatomy, access for debridement and secondary procedures, mechanical demands of patient injury, and patient comfort.

4.6 Fracture healing following external fixation.

There are basically two types of fracture healing- union through *external periosteal callus* and *primary bone healing* also known as in situ fracture remodelling.

Fracture callus forms in reaction to the disruption of the periosteum and endosteum combined with the interfragmentary strain or motion associated with bone injury.

Callus bridges the fracture fragments and acts as both a stabilizing structural framework and the biological substrate that provides the cellular material for union and remodelling.

Rigid fixation will not only preclude the development of callus; it will also typically result in a protracted, biomechanical dependency of the bone-hardware construct on the fixation system itself before adequate remodelling of the bone allows for safe removal of the implant. This principle has an important bearing on the external fixation technique.

In an attempt to reproduce plate-like stability, early external fixation systems stressed the need for increasingly rigid frames in multiplanar configurations. Adjunctive interfragmentary screws were often used to increased construct stability. Although these rigid constructs did occasionally yield an anatomic rtestoration, it is now known that these techniques may have actually delayed or prevented union. While early treatment algorithms taught that external fixators were to be removed 6 weeks after application to avoid the complication of pin-track infection, the early shift from a rigid fixator construct (promoting primary healing) to a cast or brace presupposed that the fracture would have the intrinsic stability to sustain functional load bearing of the limb.

Because of the absence of callus formation, primary bone healing, whether promoted through rigid plating or rigid external fixation, requires the fracture to be supported and protected until the bone achieves sufficient strength to prevent refracture or angulation when it is once again subjected to functional stress. Before adequate fracture remodelling, refracture may occur with a loss of reduction. A rigid external fixator that eliminates micromotion must be kept in place longer and necessarily requires prolonged maintenance of the fixator pin/bone interface.

At the time any external fixator is applied, a "race" begins between fracture healing and fixator pin failure (due to infection, loosening, etc.) External fixation depends, of course, on proper fixation of the screws to the bone. Techniques that rely on frame constructs that are too rigid, and therefore require prolonged pin fixation and frame maintenance, will often fail because the fracture cannot adequately remodel by the time the pins loosen and the fixator must be removed.

In light of contemporary interfragmentary strain theories about fracture healing, current external fixation systems have been designed to allow micromotion at the fracture site to promote callus formation. Stable yet less rigid systems of external