EXTERNAL FIXATION OF THE TIBIA

BASIC CONCEPTS AND PROSPECTIVE EVALUATION

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External fixation of fractures of the leg may give uneven results and a high rate of complications. We postulate that three basic principles can govern the optimal use of these devices. The external fixation frame should avoid damage to vital anatomical structures, it should allow access to the injured area and it should meet the mechanical demands of the patient and the injury.

From 1978 to 1981 these principles were evaluated prospectively in 75 consecutive cases of complex tibial injury treated with an external frame. Most were open fractures. The study confirmed that the principles were safe and effective; they have general application and do not depend on the use of a particular frame or device. By following them we have eliminated the majority of complications seen after traditional methods of external fixation.

After a century of doubt regarding the safety and the proper indications for external fixation, it has recently gained acceptance as the preferred method of stabilisation for severe open fractures and some closed ones. There has been a proliferation of new and improved fixator designs, with a decade of controversy about the ideal geometrical and mechanical properties of the frame (Burny 1972; Vidal *et al.* 1976; Hierholzer *et al.* 1978).

Much of this discussion has focused on the leg, the site of application of most fixators. Following Hoffmann (1938), some authors, including Burny (1972) and Edge and Denham (1981), have favoured one-plane unilateral or half frames (Fig. 1), as their low rigidity seems to induce a large amount of fracture callus. Vidal *et al.* (1976) have suggested that these frames are too weak to stabilise severe tibial fractures; they and others (Karlström and Olerud 1975; Hierholzer *et al.* 1978; Edwards *et al.* 1979) have promoted the use of more rigid one-plane and two-plane bilateral frames (Fig. 1). Both approaches claim improved clinical results, but both have serious limitations, and can have high complication rates.

Traditional half frames are safe and provide excellent wound access, but are not rigid enough to hold unstable fractures, to deal with heavy limbs, or to permit early weight-bearing (Schmidt and Rorabeck 1983). Loss of reduction has been reported in 7% of cases by Burny (1972), in 15% by Schmidt and Rorabeck (1983) and in

23% by Edge and Denham (1981); while malunion was found in 37% by Court-Brown and Hughes (1982) and in 55% by Edge and Denham. Pin-track infections occurred in 27% of Court-Brown and Hughes' series and in 42% of those treated by Edge and Denham.

UNILATERAL FRAMES

BILATERAL FRAMES

Fig. 1

The four basic configurations of external fixation frames.

Bilateral frames rarely allow loss of reduction, but malunion occurred in up to 39% of cases (Kimmel 1982), refracture in 8% (Lawyer and Lubbers 1980) and 21% (Tolo 1983), and pin-track infection in 30% (Edwards *et al.* 1979) and in 50% (Kimmel 1982; Tolo 1983). These frames often interfere with the opposite leg, making partial weight-bearing difficult and full weight-bearing almost impossible. Despite their current popularity, bilateral frames are not safe; insertion of transfixion pins has caused compartment syndromes and injury to the

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anterior tibial vessels, or to branches of the peroneal and saphenous nerves (Raimbeau, Chevalier and Raguin 1979; Green 1981; Kimmel 1982). Transfixion of the ankle and foot dorsiflexors more distally may lead to permanent ankle stiffness. Emerson and Grabias (1983) followed up tibial fractures immobilised with bilateral frames and found that "the most frequent complaint was ankle and foot stiffness".

By 1978 we had recognised that the application of external fixation according to set patterns could not do justice to the clinical and mechanical demands of each particular case and could cause iatrogenic injury. An external fixation frame should be safe, non-obstructive, adaptable to a wide variety of injuries and stiff enough to maintain alignment. It should allow full weight-bearing, and have a low rate of serious complications. A review of the literature and our own experience with a number of different devices and frames suggested that these goals could be attained by adherence to three basic principles. In order of decreasing importance, these principles are: that the frame should not damage vital anatomical structures; that it should provide sufficient access for debridement and secondary procedures; and that it should fulfil the mechanical demands of the patient and the injury.

BASIC CONCEPTS

Limb anatomy. The safe soft-tissue corridor for pin insertion is determined by the anatomy. Cross-sections of the leg (Eycleshymer and Jones 1925) show that in the proximal tibia pin placement is safe within a 220° arc from the posteromedial border of the tibial plateau to the tibiofibular joint, excluding a small rectangular area overlying the patellar tendon (Fig. 2). Below the tibial tubercle this anteromedial corridor decreases to 140° and is therefore unsafe for transfixion. Posterior pin exit areas may injure the posterior tibial neurovascular structures. In the distal third, the anterior tibial vessels are vulnerable along the lateral tibial cortex (Raimbeau *et al.* 1979). Whenever possible, pin insertion should be limited to the subcutaneous areas of the tibia.

Injury characteristics. Local anatomy limits the safe choice of frame to one-plane or two-plane unilateral configurations (Fig. 1), but optimal location of pins and frame is determined by the nature, size, severity and stability of the injuries. A frame must be devised individually for each injury to allow optimal access for initial care, repeated debridement, and such secondary procedures as the transfer of local and distant soft-tissue flaps or bone grafts. Within the safe corridor, the frame should leave clear both the injured area and the principal access routes, as illustrated later in this paper.

Mechanical strength. To be mechanically effective the stiffness of a fixator frame should match the forces and moments at the fracture site. Information based on the size and weight of body segments, the muscle centroids around the tibia (Fick 1911; LeVeau 1977) and gait

analysis (Zarrugh 1981) suggest that the sagittal bending moments in the leg are about two to five times larger than those in the coronal plane. This sagittal to coronal stiffness ratio can be achieved if the pins of a fixator are oriented in an anteroposterior direction (Behrens *et al.* 1983).

To counter the least favourable mechanical conditions, we consider that pins and connecting rods should be at least twice as stiff as those of the standard Hoffmann equipment (Behrens *et al.* 1983), and that advantage should be taken of experimentally confirmed methods of maximising frame stiffness. Such manoeuvres include increasing the spread of pins in each main fragment, reducing the distance between bone and longitudinal rod, attaching a second longitudinal rod to the same pins, and adding a second half-frame at an angle to the first (Evans, Kenwright and Tanner 1979; Behrens and Johnson 1983).

Fig. 2

The "safe corridor" for pin insertion in the lower leg. At level A, proximal to the tibial tubercle, pins can be safely inserted within an arc of 220°. At level B, just below the tibial tubercle, the safe arc decreases to 140°. At C, in the distal third of the leg, the safe arc remains 140°, but the anterior tibial vessels and deep peroneal nerves become vulnerable as they cross the lateral tibial cortex. At D, above the ankle joint, the safe arc is 120°. At levels E and F, pins in the tarsal or metatarsal bones may be used to splint the ankle joint if neurological or soft-tissue injuries prevent the application of an external support. The dotted area indicates where the tibia lies subcutaneously and pin insertion is safe.

Fig. 3

The basic components of the AO ASIF tubular fixator: *A*, tubular connecting rod of stainless steel (outside diameter 11 mm, inside diameter 9 mm). *B*, half pins with long thread for use in the proximal tibia, and short thread for cortical bone and the distal tibia (stainless steel, 5 mm diameter). *C*, single adjustable clamp. *D*, universal clamp. *E*, removable compression apparatus.

From November 1978, in a prospective clinical trial, we studied the validity and possible limitations of these concepts. This report therefore focuses on issues directly related to the fixator, such as injuries caused to vital anatomical structures by pins, loss of knee and ankle movement, access for primary and secondary procedures, the need for special unilateral configurations, the maintenance of bony reduction, ability to bear weight, and the rate and severity of complications.

PATIENTS AND METHODS

From November 1978 to December 1981 we studied all 80 tibial fractures and non-unions treated with an external fixator at St Paul Ramsey Medical Center. Detailed information on these cases was collected prospectively by an independent project co-ordinator (KS) who was also responsible for data storage and analysis. The two patients who died from other injuries, and three who had below-knee amputations were excluded, leaving 75 lesions in 73 patients.

There were 60 men (82.2%) and 13 women ranging in age from 6 to 67 years (median, 30 years), who had sustained 15 closed fractures and 54 open fractures; 6 cases of non-union also were treated. Of the fresh tibial fractures, 56 were caused by motor vehicle accidents, 3 by falls, 2 by firearms, 5 at work and 3 during sport. On average each patient had 2.4 associated injuries. Of all 69 fractures, 20 were single, 43 were comminuted, and 6 were segmental. Comminution involved one cortex in 18 fractures and both cortices in 25. Of the 54 open fractures, 13 had unicortical, and 4 had bicortical bone loss. These open fractures were classified according to the

severity of the soft-tissue injury (Cauchoix, Duparc and Boulez 1957).

All external fixation frames were erected from components of the AO/ASIF tubular fixator (Fig. 3). This provides stainless steel pins and longitudinal rods about two to three times stiffer than those usually employed for the erection of half frames (Behrens *et al.* 1983). To maintain the mechanical advantages of the maximal spread of the pins, universal joints were rarely used. Pin sites were pre-drilled with a 4.0 mm bit.

Frames were applied in accordance with the clinical and mechanical demands of the injury, and pin seating and fracture alignment were checked radiographically. Injured limbs were often placed temporarily in balanced suspension with a sling supporting the calf muscles, and the ankle joint held in 5° to 10° of dorsiflexion (Fig. 4). Passive and active exercises of the knee and ankle joints were followed by walking with crutches, and partial weight-bearing as soon as this could be tolerated by the patient. Pin-entry sites were cleaned daily and covered with povidone-iodine or an antibiotic ointment. While they were still in the hospital patients were encouraged to become fully responsible for the care of their pin sites and fixator frame, and for their programme of rehabilitation (Searls *et al.* 1983).

RESULTS

All wounds healed and became free of infection. Healing time to bony union was defined as that to unsupported weight-bearing (Table I). Three cases are illustrated in Figures 5 to 13, 14 to 18 and 19 to 26. Our recommendations for the configuration of frames are summarised in Figure 27.

Fixator frames and fracture alignment. Fixators were applied within the first 72 hours of admission in 77% of cases (range 1 to 23 days). They were in place from 11 to 367 days (median, 101 days). A one-plane unilateral frame (Fig. 27A and B1) was used for 62 (82.7%) of the

Fig. 4

The early postoperative management of an open tibial fracture. The limb is suspended, the calf is supported, and the ankle joint is splinted in 5° to 10° of dorsiflexion.

Table I. Time to bony union of 75 fractures and non-unions of the tibia treated by external fixation

Lesion	Number	Per cent	Days to union (median)
Open fracture	54	72	211.5
Closed fracture	15	20	176
Non-union uninfected	4	5	116
infected	2	3	328.5
All lesions	75	100	186.0

75 lesions, and the others had a two-plane construction (Fig. 27 B2, C, D and E). In three fresh fractures angulation of from 10 to 17° developed after removal of the fixator and during further immobilisation in a cast. In no case did shortening exceed 5 mm while the limb was held in a fixator.

Access. During the use of an external frame, access was needed to the injury site for a total of 337 procedures, that is 4.5 per tibia. These included 214 debridement operations, 10 tendon and vascular repairs, 44 skin grafts, 19 muscle-pedicle flaps, and 50 bone grafts. Only

once was it necessary to change the configuration of a fixator to improve access. Figures 5 to 13 show a case in which excellent access was available for muscle, skin and bone grafting.

Joint movements. The ranges of active knee and ankle movement 6 to 12 months after bony union are given for various sub-groups in Tables II and III, where they are compared with the range in the normal joint on the opposite limb using the Wilcoxon signed rank test for matched pairs. This test was used because the recorded values did not demonstrate normal distribution and equal variance (Snedecor and Cochran 1980). Of the cases with open tibial fractures 13 had associated open fractures of the distal femur or ligamentous and bony injuries involving the knee joint. These patients lost an average of 23.1° of knee movement, while the 40 other patients with open fractures lost an average of 1.4° ($P < 0.001$).

Weight-bearing. Decisions about weight-bearing and frame removal were made individually for each patient by his surgeon (Table IV). Partial weight-bearing with the fixator in place was started after a median period of 36 days in 65 patients with 67 lesions (89.3%). Six

Fig. 5

Fig. 6

Fig. 7

Fig. 8

Fig. 9

Fig. 10

Fig. 11

Fig. 12

Fig. 13

A gunshot wound involving the lateral aspect of the proximal tibia with severe loss of soft tissue and bone. Figure 5—Initial appearance from the lateral side. Figure 6—Stabilisation by an external fixator placed on the medial side. Figure 7—The soft-tissue defect covered by a lateral gastrocnemius flap; there is no interference from the fixator frame. Figures 8 and 9—Radiographs at this stage. A split skin graft was used to cover the muscle flap. Figure 10—Elevation of the healed gastrocnemius flap to allow the skeletal defect to be bone-grafted. Figure 11—At five months the fracture has healed; the patient has been fully weight-bearing for four weeks. Figures 12 and 13—Radiographs one year after the injury.

Table II. Range of active knee movement after bony union in various sub-groups of the series, compared with the range in the normal contralateral joint

Lesion	Number of cases	Mean range (degrees)			Significance of difference*
		Normal side	Involved side	Difference	
Open fracture	53	128.2	121.5	6.7	0.02
with associated injury	13	127.8	104.6	23.1	0.01†
without associated injury	40	128.4	127.0	1.4	0.62†
Closed fracture	14	122.1	121.8	0.3	0.95
Non-union	6	124.3	118.7	5.7	0.23
All cases	73	126.7	121.3	5.4	0.20

* Significances, *P*, using the Wilcoxon signed rank test† Significance of the difference between open fractures with and without associated injuries, *P* < 0.001**Table III.** Range of active ankle movement after bony union in various subgroups of the series, compared with the range in the normal contralateral joint

Lesion	Number of cases	Mean range (degrees)			Significance of difference*
		Normal side	Involved side	Difference	
Open fracture	51	51.5	36.5	15.0	<0.001
with associated injury	17	51.8	17.4	34.4	<0.001†
without associated injury	34	51.4	46.0	5.4	0.002†
Closed fracture	14	46.4	41.4	5.0	0.33
Non-union	6				
uninfected	4	45.8	42.5	3.3	N/A
infected	2	59.0	41.5	17.5	N/A
All cases	71	50.4	37.9	12.4	<0.001

* Significances, *P*, using the Wilcoxon signed rank test† Significance of the difference between open fractures with and without associated injury, *P* < 0.001

patients remained non-weight-bearing in order to protect other injuries on the same side and two were never able to walk. Full, unsupported weight-bearing was started after a median period of 65 days in 52 patients (71.2%), while most of the others had a cast applied before they were ready to take full loads in the fixator.

Complications. These are listed in Table V. Episodes of increased drainage from pin sites occurred in a number of patients while the fixator was in place. Nine patients had pin-track infections with positive cultures between 19 and 361 days (median, 74 days) after application of the fixator; 23 of 332 pins (6.9%) were involved, six of them before the patient started weight-bearing. Most infections resolved spontaneously or with more attentive pin care; only one patient developed a ring sequestrum which presented one month after his tibial fracture had consolidated. This lesion was overdrilled and then healed satisfactorily. One debilitated 60-year-old patient and two patients who had been swimming in open water developed generalised cellulitis of the leg, which responded promptly to intravenous antibiotics. In one case refracture was caused by a minor injury two weeks after healing was considered to be complete. There were no pin-induced neurovascular injuries.

DISCUSSION

It was the purpose of this study to examine the hypothesis that safe and effective external fixation in the leg depends upon three principles; the avoidance of damage to vital anatomical structures; the provision of access to the injury for primary and secondary procedures; and the need to meet the mechanical demands made by the patient and his injury. Rigorous prospective collection of data from a series mainly comprising severe closed and open tibial fractures has shown that our results compare very favourably with published reports of more traditional methods. We used a well-made fixator of a simple unsophisticated design, but our findings, and comparable results published for other fixators used according to similar guidelines, show that success is largely independent of the device employed (Schmidt and Rorabeck 1983; De Bastiani, Aldegheri and Brivio 1984; Burgess—personal communication 1984). Our experience indicates that the three principles we have described work synergistically and may help with several problems.

For all practical purposes the insertion of all pins within the safe corridor limits desirable configurations of the fixator to unilateral frames but does prevent neurovascular lesions and the impalement of muscles or ten-

Table IV. Time in days from injury to weight-bearing with an external fixator in position (see text)

Type of lesion	Partial weight-bearing		Full weight-bearing	
	Number	Median time	Number	Median time
Open fracture	49	36	37	63
Closed fracture	12	53.5	9	81
Non-union uninfected	4	19	4	36.5
infected	2	7.5	2	64
All cases	67	36	52	65

Table V. Number and percentage incidence of complications related to the use of the fixator in 75 cases

Complication	Number	Per cent
Pin track infection	9	12.0
Infected ring sequestrum	1	1.3
Cellulitis	3	4.0
Allergic reaction to povidone-iodine	3	4.0
Loss of reduction in the fixator	1	1.3
Refracture	1	1.3

Fig. 14

Fig. 15

Fig. 16

Fig. 17

Fig. 18

A patient with hypertrophic non-union of the tibia six months after a closed fracture. Figures 14 and 15—Shortly after partial fibulectomy and stabilisation with an anterior unilateral frame. Figure 16—Clinical appearance after three weeks, at which time the patient began work as a welder, bearing full weight with the fixator in place. Figures 17 and 18—The healed fracture.

Fig. 19

Fig. 20

Fig. 21

Fig. 22

Fig. 23

Fig. 24

Fig. 25

Fig. 26

A Grade 3 open tibial fracture with bone loss in a patient with other open fractures. Figures 19 and 20—Clinical and radiographic appearance on admission. Figures 21 and 22—Stabilization of the fracture with two-plane bilateral pin configuration proximally, and three anterior pins distally. Bone grafting had been delayed for three months because of adult respiratory distress syndrome. Figure 23—At eight months, once the patient had started full weight-bearing, the frame was gradually reduced and as a last step before removal, the proximal pin was loosened. Figure 24—Just before removal of the frame at nine months. Figures 25 and 26—Radiographs one year after injury.

A		Most mid tibial lesions
B	1	Extensive lesions allowing only short pin-pin spreads Segmental bony defects Large limbs
	2	As above Large segmental or infected bony defects Lesions needing fixator frames for long periods of time
C		Proximal periarticular and undisplaced intra articular fractures Simple lesions Segmental comminution or bone loss Large soft tissue defects
D		Distal metaphyseal fractures Simple lesions Segmental comminution or bone loss Large soft tissue defects
E		Distal intraarticular fractures, often as temporary immobilization preceding internal fixation

Fig. 27

Diagrams to show the recommended configuration of fixator frames for different bone and soft-tissue injuries. The location and extent of the lesion is indicated, on the left, by the cross-hatched area. The preferred frame is shown, with solid bars representing the pins; on the right are the specific indications for the use of the configuration.

dons. The fact that major limitation of joint movement was only seen in cases with associated injuries shows clearly that the ankle stiffness frequently seen after the use of transfixion pins can be largely avoided by pin insertion only in the safe corridor.

The user of stiffer components and mechanically advantageous frame geometries almost eliminated pin movement, component failure and undue delay in mobilisation. A simple one-plane unilateral frame proved mechanically adequate for over 80% of our cases (Fig. 16, Fig. 27A). When a more rigid frame was needed, we used two-plane unilateral frames in the early part of our study, but we now favour sagittal one-plane frames with double rods (Fig. 27 B1) as these have similar rigidity, are less cumbersome, and allow better access to the wound. Comminuted proximal or distal periarticular fractures, with short metaphyseal or epiphyseal fragments for pin insertion often cannot be managed in one-plane unilateral frames. With simple modifications to the frame (Figs 6, 21, 22 and 27C and D), however, these lesions can easily be controlled. Distal intraarticular fractures (pilon fractures) can be held by con-

necting a talar or calcaneal pin through two rods to a set of anterior half-pins in the proximal tibia (Fig. 27E). Other investigators (Schmidt and Rorabeck 1983; Burgess—personal communication 1984) have suggested that when traditional Hoffmann or similar equipment is applied, complex tibial fractures can be reliably stabilised only with two-plane unilateral frames or one-plane configurations with double rods. The use of 6 mm pins and stiffer rods than the ones we used could, however, make one-plane unilateral frames rigid enough to hold even the most unstable tibial fracture (De Bastiani *et al.* 1984).

Early partial and full weight-bearing adds a new dimension of comfort and freedom for most patients and some have been able to return to demanding occupations with the fixator in place (Figs 14 to 18). As well as the psychological effect, the resultant increase in muscle activity and local blood flow may accelerate bone healing—as has been postulated for early weight-bearing in casts (Dehne *et al.* 1961; Sarmiento *et al.* 1977). Once the patient was bearing full weight, load transmission across the fracture was increased by gradually dis-

mantling two-plane configurations (Figs 19 to 26) or by loosening the central pin articulations in half frames (Behrens and Johnson 1983).

Apart from neurovascular injuries and permanent joint stiffness, pin-track infections have been the most serious limiting factor in the use of traditional unilateral and bilateral frames. Pin-track problems in this series and that of De Bastiani *et al.* (1984) have been virtually eliminated. This has been achieved in three ways. Firstly, by the reduction of soft-tissue irritation around the pins; this can be done by pin placement only where the tibia is subcutaneous, by using fewer, stiffer pins which have smooth shafts at skin level, and by careful correlation of the stiffness of the frame to the mechanical demands of each patient and his injuries. Secondly, by the pre-drilling of each pin track with a sharp drill bit protected by a drill sleeve (Green and Matthews 1981) which eliminates heat necrosis of soft tissues and bone, often the first event in the development of a pin-track complication. Thirdly, by effective pin and frame care, together with the transfer of the major responsibility for their care to the patient (Searls *et al.* 1983). Most of our few pin-track infections were related to insufficient care and not to weight-bearing. The most distal pin needs particular attention because the increased soft-tissue movement in the ankle area can cause irritation.

Conclusions. The excellent functional results and the low rate of complications reported in this series show that the proposed basic principles of external fixation are safe and effective. They are generally applicable, and do not depend on the employment of a specific frame or a particular device.

Since the last cases were entered into this study over three years ago, we have continued to use the same basic approach which has proved equally satisfactory for injuries elsewhere.

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