MEASURING STIFFNESS CAN DEFINE HEALING OF TIBIAL FRACTURES

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We measured fracture stiffness in 212 patients with tibial fractures treated by external fixation. In the first 117 patients (group 1) the decision to remove the fixator and allow independent weight-bearing was made on clinical grounds. In the other 95 patients (group 2) the frames were removed when the fracture stiffness had reached 15 Nm/degree.

In group 1 there were eight refractures and in group 2 there was none (p = 0.02, Fisher's exact test). The time to independent weight-bearing was longer in group 1 (median 24 weeks) than in group 2 (21.7 weeks, p = 0.02). The greater precision of our objective measurement was associated with a reduction in refracture rate and in the time taken to achieve independent weight-bearing.

We consider that a stiffness of 15 Nm/degree in the sagittal plane provides a useful definition of union of tibial fractures.

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For fractures managed by external fixation, the timing of frame removal is a particular problem. Refracture was one of the few major complications reported by De Bastiani when the Orthofix was used for tibial fractures, affecting 3% of patients (De Bastiani, Aldegerhi and Brivio 1984). Others have reported rates of 5%, 6% and 11% depending on the method of external fixation used (Steinfield et al 1988; Krettek, Haas and Tscherne 1991; Thakur and Patankar 1991). Early removal of the frame with the use of a brace to maintain alignment has been reported to give late malunion in as many as 40% of patients (Clifford, Lyons and Webb 1987).

Many attempts have been made to quantify fracture union; radiographs show the quantity of callus but not its quality (Nicholls et al 1979). Biomechanical methods of measuring union are usually based on the stiffness of the healing bone, but the traditional manual tests have low accuracy (Matthews, Kaufer and Sonstegard 1974). Deflection, produced by a known applied bending moment, has been measured by micrometers attached to the external fixation frame (Jorgensen 1972). Jernberger (1970) achieved accurate measurements in conservatively managed fractures by fixing a strain-gauged beam to the tibia under local anaesthetic. Stiffness assessed from radiographs taken under bending moments had a low accuracy (Hammer, Edholm and Lindholm 1984). The resonant frequency of the tibia has been investigated as a possible measure of healing; this correlates with the log of tibial stiffness (Benirschke et al 1993). The measurement of strain in the fixator column by strain gauges was developed by Burny et al (1978); this allows an indirect assessment by measuring the reduced stress in the fixator as healing takes place, but does not provide an objective measurement of stiffness in absolute units.

Methods of measuring absolute levels of stiffness with a removable strain-gauge unit have been developed (Churches, Tanner and Harris 1985; Evans, Kenwright and Cunningham 1988). They have been used to assess the rate of increase in fracture stiffness, for example, as an objective measure of healing in a controlled prospective study of tibial diaphyseal fractures treated by external fixation; early applied micromovement was found to speed healing by some 20% (Kenwright et al 1991). Most patients were found to achieve full weight-bearing independent of support when fracture stiffness had reached

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about 15 Nm/degree (Richardson, Kenwright and Cunningham 1992).

The present study was undertaken to determine whether 15 Nm/degree of fracture stiffness could be used to define fracture healing. We compared the incidence of refracture when external fixation was removed at this level of stiffness, with that after removal on clinical and radiological grounds.

PATIENTS AND METHODS

We reviewed a consecutive series of 219 patients with fractures of the tibial diaphysis who had been managed by unilateral external fixation and had measurements of fracture stiffness. The severity of the injuries was classified by soft-tissue damage (Gustilo and Anderson 1976) and the amount of comminution (Johner and Wruhs 1983).

Several different external fixation frames had been used, mostly the Dynabrace system (Smith & Nephew Surgical Ltd, Cambridge, UK) (57%) and the Orthofix appliance (Orthofix Srl, Bussolengo (VR), Italy) (40%). All were applied within two weeks of injury and all patients were followed for at least six months after the removal of the frame. For the first 124 consecutive patients (group 1), frames were removed when radiological and clinical findings were considered to show union. For the next 95 patients (group 2), the frames were removed and the patients allowed free weight-bearing when measured fracture stiffness had reached 15 Nm/degree in the sagittal plane.

Measurements of stiffness. Healing of the fibula may influence the measurement of tibial stiffness, but the effect is minimal if the bending moment is applied in the sagittal plane (Richardson et al 1984). The method of testing is shown in Figure 1. A manual load was applied, slightly proximal to the fracture. The bending moment applied to the fracture site (in Nm) is the product of the force measured at the heel by a load transducer and the distance from the heel to the fracture.

Angulation at the fracture site was measured in two ways. The indirect method used a removable strain-gauge unit to measure strain in the fixator column (Evans et al 1988). This allowed measurements to be made without removal of the frame, but large errors are possible if the bone screws are loose (Churches et al 1985). The direct method used a flexible electrogoniometer which was applied to the bone screws after the removal of the fixator column (Shah, Nicol and Richardson 1988). We used this method only after six weeks from injury, when clinical examination would also be appropriate. The very low stiffness of the goniometer allows valid measurements to be made even if there are loose bone screws since the transmitted loads across the screws are small. It has become our preferred method. The average time taken to perform the stiffness test was six minutes.

For both methods, the measurements of force and angle were fed into a microcomputer which calculated the fracture stiffness in Nm/degree as the ratio of applied bending moment to the resulting angular deflection.

Removal of frames. After removal of the fixator, both groups of patients were encouraged to mobilise normally without splintage, but advised to avoid sports such as football for six months.

Definitions. We defined clinical healing time as the time
MEASURING STIFFNESS CAN DEFINE HEALING OF TIBIAL FRACTURES

The rate of increase of stiffness in an individual fracture was usually exponential over the period of treatment and can be described by the equation:

\[ \text{Stiffness} = e^{mt+c} \]

where \( t \) is the time since injury and \( m \) and \( c \) are constants.

Fracture stiffness at the time of fixator removal for group 1 (clinical decision) and group 2 (removal when fracture stiffness \( > 15 \, \text{Nm/degree} \)). There were eight refractures in group 1 and none in group 2.

(Richardson et al 1992). The shape of the curve of rising stiffness in an individual case could be defined in terms of these constants, but for our study the rate of healing was more simply defined as the time taken for the best-fit exponential plot of the fracture stiffness results to reach 15 Nm/degree.

Statistics. Injury severity in the two groups was compared by the chi-squared test. Fisher’s exact test was applied to the distribution of refractures as the numbers were small. The clinical and biomechanical healing times were not normally distributed; they were compared by a non-parametric method, the Kruskal-Wallis test using the Minitab software package (Minitab, State College, Pennsylvania).

RESULTS

Numbers of patients and exclusions. Indirect fracture stiffness measurements in six patients in group 1 were unsatisfactory because of significant loosening of more than one bone screw. One other patient from group 1 moved overseas. These seven patients were excluded, leaving 117 patients in group 1. Two patients complained that the direct method was painful at six weeks, but had satisfactory tests two weeks later.

Severity of injury. The distribution of injury severity for the two groups is shown in Table I and related to the time to clinical healing in Table II. The more severe injuries were slower to heal. There was a tendency for the injuries in group 1 to be more severe but this did not achieve statistical significance on the chi-squared test \( (\chi^2 = 3.8, \, df = 4, \, \text{NS}) \). The management differed in the two groups: 69 in group 1 were treated by passive cyclic micromovement (Kenwright et al 1991) but only four in group 2.

Biomechanical stiffness measurements indicating healing were achieved in similar times in the two groups, the median times being 17.6 weeks in group 1 and 19.4 weeks in group 2 (Kruskal-Wallis test; \( H = 2.3, \, p = 0.1, \, \text{NS} \)).

Refractures and clinical healing times. In group 1 eight patients had refractures (Table III); in group 2 none (Fisher’s exact test, \( p = 0.02 \)). Refracture was caused by a variety of types of injury and ranged from the first day to four months after frame removal. All the refractures took place after a clinical decision to remove the frame was taken when the fracture stiffness was less than 15 Nm/degree (median 10.2 Nm/degree, range 3.2 to 14.6 Nm/degree, Fig. 2). In these eight patients, the median time, estimated by extrapolation, to reach a fracture stiffness of 15 Nm/degree was 20.6 weeks.

Excluding the refractures, the median time to independent weight-bearing in group 1 was 24 weeks, as compared with 21.7 in group 2 (Table I). This is significantly longer (\( H = 5.5, \, p = 0.02 \)), and the 95%
confidence interval for the size of the difference ranges from 5.9 to 0.6 weeks.

DISCUSSION

We have tested an objective measure of fracture healing and found it to be superior to clinical assessment. The incidence of refracture was 7% in group 1 and zero in group 2. Group 2 patients had less severe injuries, but the difference did not reach statistical significance, and it seems unlikely that the higher refracture rate in group 1 was due to the higher proportion of more severe injuries.

The measurement of fracture stiffness did not simply postpone the removal of external fixation: on average it allowed frames to be removed 2.3 weeks earlier in group 2, although there was no significant difference in the biomechanical healing times of the two groups.

Stiffness should provide a good measure of healing (Lettin 1965), since it rises throughout the process due both to the increasing quantity and to the changing quality of the repair tissues. Young’s modulus of elasticity for granulation tissue is 0.5 MN/m²; this rises to 20 000 MN/m² for mature bone, a 40 000-fold change which can be readily measured (Perren 1979).

Different methods of measuring stiffness can be compared by recalculation of the units which were used. Earlier studies have used similar levels to equate to safe healing (Fig. 3). These range from 8.5 Nm/degree (Jernberger 1970), through 12 Nm/degree (Hammer et al 1984) to a band between 12 and 20 Nm/degree (Jorgensen 1972). This comparison confirms that 15 Nm/degree is a reasonable, if slightly conservative, definition of healing for the tibia.

Our experience with the group 1 patients was valuable since it showed that many frames were removed at low stiffness levels. All the refractures occurred after removal at stiffness levels less than 15 Nm/degree; this also supports the use of this level for the safe removal of the frame.

A definition of healing based on a particular fracture stiffness can take into account differing patterns of rising stiffness and can also be related to fracture healing rates.

<table>
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<th>Injury</th>
<th>Group</th>
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<td>30</td>
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<tr>
<td></td>
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<td>25</td>
<td>27</td>
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<td>11</td>
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<tr>
<td></td>
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<tr>
<td></td>
<td>C3</td>
<td>15</td>
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</table>

* Gustilo and Anderson (1976)
† Johner and Wruhs (1983)

Fig. 3

Changes in fracture stiffness during the healing of tibial fractures showing the stiffness of a 200 mm section of normal tibia (Jernberger 1970) and the level at which independent weight-bearing was allowed in our study and by recalculation from previous reports (see text).
reported as time to achieve independent weight-bearing. The generally predictable pattern of increase in stiffness allows the detection of delays in healing and the assessment of the effects of treatment. Our patients found it helpful to see objective evidence of progress in healing. It enabled them to plan ahead and join in discussions on the management of slow healing, where for example bone grafting was being considered.

Although we took one level of stiffness as equating to healing, other variables may need consideration. A heavy patient, or one with residual angulation of the fracture, should probably await a higher level of stiffness before frame removal. It is also advisable to ensure that there is a sufficiently wide distribution of callus across the fracture, and it may also help to measure stiffness in both sagittal and coronal planes. Different anatomical sites may require different levels of stiffness for security: for example, arthrodesis of the knee, which involves a large cross-sectional area of bone, may be considered to have healed at a stiffness of 10 Nm/degree (Cunningham et al 1989).

‘Functional fixators’, which appear to allow early cyclic micromovement, have improved the outcome of fractures managed in external fixation; passive movement is associated with reduced healing times (Kenwright et al 1991) as is early weight-bearing (Richardson 1989). Axial compression after dynamisation of a fixator may be an important factor in achieving union (De Bastiani et al 1984).

External fixation frames are now usually kept in place until the fracture has healed, so that the patient can be allowed to mobilise free from the restrictions of splintage. Many of our patients in group 1 had external fixation for longer than was necessary, with an increased risk of pin-track problems. The routine measurement of fracture stiffness will allow the optimal timing for removal of external fixation after fractures and we have also found the technique valuable during callotasis and bone transport procedures.

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