THE INFLUENCE OF INDUCED MICROMOVEMENT UPON THE HEALING OF EXPERIMENTAL TIBIAL FRACTURES

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Although it has been well established that fracture healing is influenced by the mechanical environment, the optimal parameters have not yet been established. In two groups of sheep an experimental tibial diaphyseal fracture was created, and stabilised using external skeletal fixation. In one group rigid fixation was maintained throughout fracture healing; in the other group controlled axial micromovement, with a loading regime known to be osteogenic in intact bones, was applied for a short period daily.

A significant improvement in healing was associated with the application of controlled micromovement. Data from these experiments provide the basis for improving the conditions for fracture healing and may assist in the prevention of delayed union.

It has been shown both clinically and experimentally that the pattern of fracture healing in long bones is dependent upon the prevailing mechanical environment (Sarmiento et al. 1977; McKibbin 1978; Rahn 1982). However, the precise influence of each mechanical variable has neither been fully established nor quantified. Consequently, it has not yet been possible, in clinical practice, to predict and select the optimal mechanical environment when planning a treatment programme for a given fracture. This difficulty is particularly apparent when choosing a fixation technique for those fractures of the tibial diaphysis in which there is a high risk of delayed union (Nicoll 1964; Rosenthal, MacPhail and Ortiz 1977) and, therefore, where the correct mechanical environment is probably of considerable importance.

The recent clinical trend has been toward less rigid methods of fixation, using non-metallic bone plates, flexible external skeletal fixation, or functional braces. Little information, however, has been reported on the precise relationship between the degree of micromovement these systems allow and the rates and patterns of fracture healing.

Experimental studies using strain gauges attached to bone surfaces in vivo have shown quantitatively that, for intact bones, the physiological stimulus experienced by the bone cell population is intermittent cyclical deformation, usually associated with locomotor activity (Lanyon et al. 1975; Goodship, Lanyon and McFie 1979). It has also been shown that appropriate known loading regimes applied experimentally to intact bones for very short periods each day can result in stimulation of osteogenesis (Goodship et al. 1978; Lanyon et al. 1982; Rubin 1982).

When a fracture occurs the normal mechanical stimulus to which the bone cells respond is reduced markedly, and the degree to which this stimulus is restored will be influenced largely by the method of fracture fixation.

The present study was designed to investigate the influence of a controlled mechanical regime, known to be osteogenic in intact bone, upon fracture healing.

MATERIALS AND METHODS

Twelve skeletally mature female Clun sheep were randomly divided into two groups. Under general anaesthesia and aseptic conditions an Oxford Mk II external skeletal fixation frame was applied to the right tibia, using guides to maintain constant geometry. The geometrical configuration chosen had been shown to give a high degree of rigidity of osteotomy fixation when tested on post-mortem specimen tibiae in the laboratory (Harris et al. 1980).

After application of the fixation frame the periosteum was cut and at the same level a transverse osteotomy was made in the midshaft of the tibia, using a Gigli saw with guides to ensure a constant osteotomy position in relation to the fixation screws and frame. The bone fragments were distracted and a 3 mm gap (measured with a gauge) produced at the experimental fracture site. The fixation system was then locked and a metal spacer placed between the most distal clamp on the proximal fragment and the most proximal clamp on the
distal fragment in order to prevent any interfragmentary movement. In Group 1 this rigid configuration (Fig. 1) was maintained throughout the healing period of 12 weeks.

In Group 2 a controlled mechanical stimulus was applied axially to the experimental fracture for a period of 17 minutes (500 cycles at 0.5 Hz) each day by means of a pneumatic cylinder attached to the column of the fixation system. At all other times in this second group the pneumatic cylinder was removed and the fixator locked in the rigid configuration to provide the same conditions for fracture healing as experienced by the first group of sheep.

The daily intermittent mechanical stimulus applied axially to the experimental fractures in Group 2 sheep had the following characteristics.
1. A maximum initial longitudinal axial displacement of 1 mm, this being 33% strain at the onset of stimulation. Higher strains might have caused tissue damage.
2. A constant low force of 360 N was used throughout so that the fatigue stress limit of the bone–screw interface was not exceeded (Pope and Evans 1982).
3. A frequency of loading of 0.5 Hz, which is approximately that of physiological walking.
4. An initial strain rate of $30 \times 10^3 \mu \text{e/sec};$ this strain rate is at the upper end of the physiological range and had been found to be osteogenic in experimental studies with intact bone.
5. Five hundred cycles per day (applied continuously over 17 minutes) which was similarly at a value within the range found to be most osteogenic when stimulating intact bone.

The intermittent application of micromovement was started one week after osteotomy and continued daily throughout the healing period of 12 weeks. There was no evidence of discomfort experienced during the mechanical stimulation and in both Groups 1 and 2 the sheep walked freely, weight-bearing upon the osteotomised leg from the first postoperative day.

**In vivo assessment of healing. Radiographic.** The external skeletal fixation frame allowed repeatable and accurate location of the fracture so that standardised radiographs could be made at two-weekly intervals during the 12-week healing period. Kodak direct exposure film was used for clear definition, with a constant exposure for all radiographs.

**Fracture stiffness.** At two-weekly intervals a strain gauge transducer was attached to the fixator bar allowing the column bending deformation to be measured in two perpendicular directions as the animal walked (Burny 1979; Evans et al. 1984). As fracture healing progressed so, for a given weight-bearing force through the affected leg, the bending deformations of the column decreased proportionally. The peak vertical ground reaction was recorded simultaneously using a Kistler force-plate. An index of fracture stiffness was then calculated by dividing the peak vertical ground force by the vector sum of the two bending strains at the corresponding time point. This stiffness index was expressed as a percentage increase in stiffness and recorded as a function of time.

**Post-mortem assessment of healing. Torsional stiffness.** At the end of the 12-week healing period post-mortem studies were performed on both tibiae in each sheep after removal of the soft tissues. Schanz 6 mm screws identical to those used in the fixation of the fracture were placed in the contralateral intact tibia using the same geometry as for the experimental limb. A non-destructive test of torsional stiffness was carried out using an Instron 1122 material testing machine and a displacement/load recording was produced. The stiffness of the osteotomised tibia was expressed as a percentage of that of the intact tibia for each sheep.

**Histology.** Standard histological sections and micro-radiographs were made of the sectioned tibiae.

**RESULTS**

**In vivo assessment of healing. Radiographic.** The development of external callus was radiographically visible two weeks after operation in all the sheep in the stimulated group (Group 2) one week after induced micromovement had been started; at this stage it was only minimal in all the rigidly fixed fractures (Group 1) (Figs 2 to 7). The pattern of callus formation was not symmetrical in relation to the bone ends in either of the two groups and this
applied throughout the 12-week healing period. In the stimulated fractures the bridging callus extended, on both proximal and distal fragments, further from the fragment ends than in the rigid group (Figs 6 and 7). There appeared to be more external callus formation at 4, 6, 8 and 10 weeks in the stimulated group but this could not be measured on the radiographs.

Fracture stiffness. The mean percentage increase in fracture stiffness of each group was recorded at two-weekly intervals during the 12-week healing period. Within the first four weeks the two groups showed similar increases in stiffness; from six weeks onwards the stimulated group increased in stiffness at a greater rate than the rigid group, but this difference was not statistically significant until the period between 8 and 10 weeks (Fig. 8). The fracture stiffness readings did not show evidence of a plateau at the end of the 12-week allotted healing period.

Post-mortem assessment. Torsional stiffness. This showed that the mean value for the stimulated group (83% ± 3.5) was significantly higher (P<0.01) than that for the rigidly fixed group (54% ± 10) (Fig. 9). Individual data points showed a high degree of variation within the rigidly fixed group, with values ranging from 30% to 80%. Values within the stimulated group were more consistent, with a range from 70% to 94%.

Histological evaluation. The histological assessment carried out 12 weeks after osteotomy showed similar tissue types in the two groups, but differences in the stage of differentiation of callus. In the rigidly fixed group those individuals with low post-mortem torsional stiffness showed less advanced differentiation of the fracture callus and the woven bone had not completely bridged the gap between the bone fragments, a line of incomplete bridging being evident in each instance (Figs 10 and 11). This correlated well with the radiological observations (Figs 6 and 7). In the stimulated group all individuals showed a high post-mortem torsional stiffness and complete bridging of the fracture callus.

DISCUSSION

Mechanical environment has been shown to influence the pattern of fracture healing both in man and in experimental models. In human diaphysial fractures treated by anatomical open reduction and plate fixation, ensuring a high degree of rigidity, healing occurs with internal remodelling (direct bone healing) and suppression of external callus formation (Schenk and Willenegger 1964). Similar fractures treated in functional casts may form proliferative external bridging callus (Sarmiento
The torsional stiffness of tibiae studied post-mortem at 12 weeks from operation. The mean value for the rigidly fixed fractures (Group 1) was 54% ± 10%. For fractures undergoing micromovement (Group 2) the mean value was 83% ± 3.5%. This difference was statistically significant \( P < 0.01 \).

Figure 9

Fig. 9—Photomicrograph showing the mature bridging callus in an osteotomy at 12 weeks in a sheep from Group 2 (with micromovement). Figure 10—Incomplete bridging callus in a Group 1 sheep (fixed rigidly) with a tibial torsional stiffness as low as 30%. These sections are taken from the same animals as shown in Figures 2 to 7.
1974). When using very rigid external skeletal fixation frames for the treatment of tibial diaphyseal fractures delayed healing may be seen (Kenwright, Harris and Evans 1980), and many investigators now conclude that perhaps the mechanical environment imposed upon the fracture in these circumstances is not optimal for osteogenesis.

In experimental models different degrees of rigidity in osteotomy fixation have been tested, using both external and internal fixation (Yamagishi and Yoshimura 1955; Woo et al. 1976). The pattern of healing seen in these models which allow some fracture movement shows proliferative external callus formation, this callus being inhibited proportionally as the rigidity of fracture fixation is increased. There also appears to be a critical upper level of movement above which non-union will occur. Rahn (1982) has shown, in experimental hypertrophic non-union in dogs, that reducing the degree of fracture micromovement will precipitate fracture healing.

White, Panjabi and Southwick (1977) applied regimes of intermittent loading to healing experimental fractures but no consistent influence on fracture healing patterns or rates was seen.

Thus, although there appears to be an influence exerted upon fracture healing by the mechanical environment, in previous investigations this environment has not been defined. There has been little investigation of the potential effect of varying individual mechanical parameters independently, and there is still scanty information about their effects upon differentiating bone cells.

In intact bone it has long been known that the physiological stimulus that maintains normal osteogenesis is intermittent cyclical deformation. Some of the parameters of this mechanical stimulus have been investigated individually by applying known mechanical regimes to intact bone shafts. High physiological strain magnitudes and strain rates, applied even for a small number of cycles for a very short period each day, have been found to be osteogenic and to prevent stress-protection osteopenia (Goodship et al. 1978; O'Connor et al. 1981; Lanyon et al. 1982; Rubin 1982).

When a fracture occurs the mechanical influences which normally act are abolished and any treatment involving splintage will further modify and reduce the customary mechanical stimulus to the bone cells. It is possible that the rate of tissue differentiation and thus the fracture healing process might be enhanced if appropriate mechanical stimuli could be applied to the fracture site during the healing period.

In the present investigation an experimental model was chosen in order to produce a standard fracture, to be able to control and alter the mechanical environment predictably, and to make quantitative assessments of healing. The experimental fracture created was within the tibial diaphysis of the sheep, with a 3 mm fracture gap so that adverse healing conditions were produced. Control was by skeletal external fixation so that there was no interference from any implant at the fracture site. This was, however, a surgical osteotomy and not a clinical fracture with its accompanying soft tissue and vascular injury.

The response of a group of these experimental fractures subjected to axially applied mechanical stimuli of known parameters, for a short period of 17 minutes (500 cycles at 0.5 Hz) each day, applied via the external frame, has been compared to that of a group of rigidly fixed fractures. The known mechanical parameters were chosen to match the values which had been found to be osteogenic and to suppress stress-protection osteopenia when applied to intact bone in experimental conditions.

There was proliferative external callus formation at the fracture site in all the sheep undergoing induced micromovement, and this was observed within one week of starting micromovement. In the group of sheep in which such micromovement was not allowed there was a delay of a further two weeks before callus was visible on radiographs.

Radiographs taken from four weeks onwards also appeared to show greater external callus formation in the stimulated sheep, but it was not possible to make quantitative measurements of the callus from radiographs. There was an increase in fracture stiffness seen at an earlier stage in the stimulated tibiae; this became apparent at six weeks from osteotomy though the difference was not statistically significant until the 8 to 10 week period. A similar pattern of differences was seen for the post-mortem torsional stiffness of the “healed” experimental fractures, although the results here were variable for the rigidly fixed sheep. It is possible that these rigidly fixed specimens with very low torsional stiffness had not advanced sufficiently in terms of callus differentiation to complete bridging between fragments.

The proliferation or the inhibition of external callus observed at an early stage, appeared to be related to the presence or absence of the induced micromovement. It is not known, however, whether the subsequent development of earlier increase in fracture stiffness was a natural and inevitable sequel to the early callus formation or whether it was the result of a specific response to the continuing induced stimulus.

Observations ceased 12 weeks after creating the osteotomy and by this stage the fracture stiffness/time graph had not shown any plateau in either group of sheep. It is probable, therefore, that further change in mechanical rigidity of the healing fractures would occur with time and it is perhaps likely that the final mechanical integrity of the two groups would become equal after different postoperative time periods.

The intermittent mechanical stimulus embraced a number of variables and further investigation of the possible influence of each of these upon fracture healing is needed.

In patients with long bone fractures the bone is, in
the early days after injury, deprived of its normal cyclical loading as a result of the enforced immobilisation of conventional methods of treatment. It is possible that these first few days or weeks are a crucial period in which to reintroduce the normal mechanical stimulus to osteogenesis; the results of our experimental study suggest that such an effect may be achieved by the early active application of an appropriate mechanical stimulus.

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