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MECHANICAL EFFECTS OF METAL PLATE FIXATION

In Vitro Investigation on Intact and Osteotomized Human and Rabbit Tibiae

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In order to study the *in vitro* stress-protecting effect on intact bone, and the rigidity of plate fixation on osteotomized bone, human and rabbit tibiae were tested in three-point bending in an Instron testing machine. Intact tibiae were loaded in the elastic range before and after metal plate application. The deformation was measured with a linear voltage differential transformer. In the human specimens a median stiffness increase of 31 per cent was obtained in the plated bone segment after application of a tibial plate (140 × 12 × 4 mm) and of 43.8 per cent after application of a femoral plate (140 × 16 × 5 mm). In the rabbit specimens a median stiffness increase of 31.9 per cent was obtained after application of a thin plate (45 × 5 × 1 mm).

In osteotomized human tibiae with tibial plate fixation, a median elastic stiffness of 51.4 per cent of the intact bone was found, compared to 40.4 per cent in osteotomized rabbit tibiae plated with the thin plate. There was good agreement between the results in human tibiae plated with a tibial plate, and rabbit tibiae with the small plate. In previous studies of the stress-protecting effect of internal plate fixation on rabbit tibiae more rigid plates have been used. These plates seem to have been overdimensioned. In further studies in rabbits plates of similar size as the one tested in this study should be applied.

Key words: cortical bone stiffness; fracture fixation; internal fixation plates; stress protection

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Internal fixation with metal plates is widely used in the treatment of diaphyseal fractures. The stability of the fixation has been improved by the introduction of compression technique and more rigid plates, mainly due to the research work of the AO-group (Müller et al. 1965, Perren et al. 1969). However, rigid plates lead to bone loss because of reduction in normal bone stress. This stress-protecting effect of rigid plates has been shown in man (Refior et al. 1975), and in various animals (Matter et al. 1974, Uhthoff & Dubuc 1971, Tonino et al. 1976, Strømberg & Dalen 1976, Paavolainen et al. 1978, Låftman et al. 1980). The extent of the bone loss depends on the stiffness of the plate, since less marked structural alterations have been found after the use of less rigid plates (Akeson et al. 1976, Tonino et al. 1976, Moyen et al. 1978).

Following plate application on intact rabbit tibiae, a reduction in bone strength of as much as 50 per cent has been found after plate removal (Paavolainen et al. 1978, Låftman et al. 1980). This great strength reduction might be due to use of plates with a comparatively greater stress protecting effect than that of tibial plates on human tibiae. It seems that no research work has been published on the important matter how the dimensions of metal plates used in animal studies should be to obtain stress protection corresponding to that of human tibiae after plating.

Furthermore, there is scant information concerning the rigidity of plate fixation of experimental diaphyseal osteotomies, both in human and animal bones.

The object of this study was to investigate the following problems:

1. To what extent is the stiffness increased in the intact human tibial shaft after application of femoral and tibial plates?
2. What plate dimensions give a stiffness increase in the rabbit tibia corresponding to that obtained by the commonly used plates in the human tibia?
3. How rigid is plate fixation of osteotomies of the human and rabbit tibial shaft?

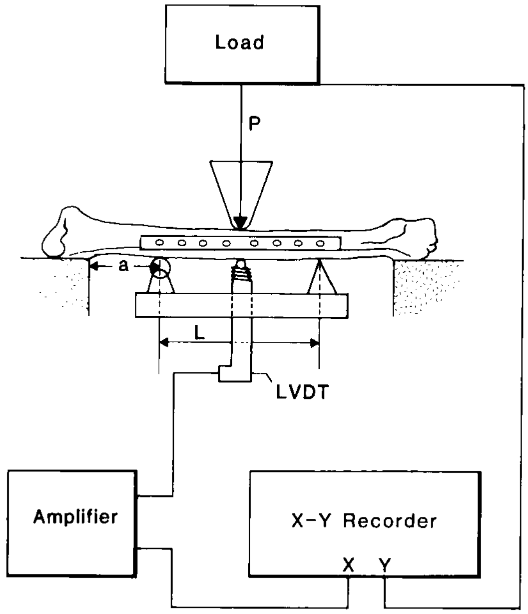

Figure 1. The test model shows a plated tibia loaded in three-point bending, and the test equipment with Instron, LVDT, amplifier and X-Y recorder. The distances L and a are indicated.

MATERIALS AND METHODS

Intact tibia

Materials. Twenty human tibiae and 10 rabbit tibiae were taken after death. There were no bones with skeletal disease. The human bones were from 13 individuals, eight males and five females, in the age range 52–83 years. The rabbit bones were taken from adult or nearly adult Chinchilla rabbits weighing from 2600 to 3750 g. The bones were wrapped in towels soaked in Ringer's solution to keep them moist, and stored at −18° Celsius. Before testing the bones were thawed to room temperature. They were kept moist during testing.

On the human tibiae, dynamic compression plates (DCP) made of stainless steel were used (Zimmer, USA). Two types of plates were tested: Femoral plates (140 × 16 × 5 mm) and tibial plates (140 × 12 × 4 mm). They were fixed to the lateral aspect of the midshaft of the intact tibia with eight cortical screws of 4.5 mm diameter.

On the rabbit specimens, thin 6-hole plates of stainless steel were used (Zimmer, USA). The plates measured 45 × 5 × 1 mm, and were fixed with screws of 2.0 mm diameter. This plate was chosen according to the results of a pilot study of various types of small plates.

Bending tests. To obtain stability of the tibia, the posterior part of the epiphyseal regions were ground flat and parallel. The tibial shaft was loaded in three-point bending in an Instron testing machine (type 1123), at a constant deformation rate of 5 mm/min. The load was applied on the anterior edge of the bone.

A special measuring device was fixed with rubber bands to the posterior aspect of the bone. The deformation of the bone was measured by a Linear Variable Differential Transformer (LVDT), fixed to a bar. LVDT is an electromechanical transducer which produces an electrical output proportional to the displacement of a separate movable core. The output was connected via an amplifier to the abscissa of an X-Y-recorder (Yokogawa 30708). The load signal from the Instron machine was connected to the ordinate of the same recorder, to obtain a load-deformation diagram. The testing equipment is shown in Figure 1. The LVDT was placed exactly at the middle of the tibia. The distance (L in Figure 1) between the outer ends of the device, which was the segment of the bone where the deformation was measured, corresponded to the distance between the two outermost screws of the plate. This was 12 cm in human and 4 cm in rabbit specimens. With this method the deformation was recorded only in that segment of the bone that was stabilized by the plate.

All bones were initially tested without a plate. Then the plate was fixed to the bone without compression, and the testing performed as before. The intact human tibia was loaded up to 1471.5 N and the rabbit tibia to 98.1 N, which were within the range of elastic deformation.

In order to calculate the elastic stiffness of the bone segment covered by the plate, formulas for bending of a simple beam were used (Timoshenko & Gere 1972). The deformation (D) measured by the LVDT has two components in our test method: A deflection (d_1) due to a force (P) acting on the bone segment (L) and a deflection (d_2) in the same segment due to a bending moment (M) acting at the ends of the measuring device.

$$D = d_1 + d_2$$

$M = \frac{Pa}{2}$, where a is the distance between the measuring device and the end support (Figure 1).

$d_1 = \frac{P \cdot L^3}{48\ EI}$, where E is the modulus of elasticity, and I the area moment of inertia.

$$d_2 = \frac{M \cdot L^2}{8\ EI} = \frac{P\ a\ L^2}{16\ EI}$$

To compare bones of different lengths, the bones are considered as being leaded only in the segment L. The deformation (d_1) in such a test procedure is calculated from the above equations.

$$d_1 = \frac{D \cdot L}{L + 3a}$$

Elastic stiffness (in segment L) =

$$\frac{P}{d_1} = \frac{P\ (L + 3a)}{DL}$$

The elastic stiffness was expressed in N/mm. The increase in elastic stiffness due to plating was calculated in per cent increase in relation to the elastic stiffness of the intact tibia.

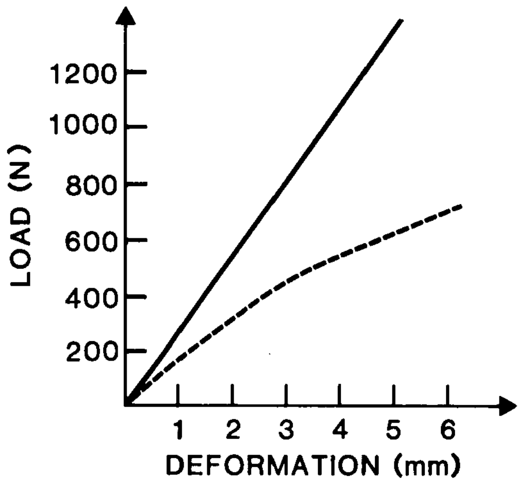

Figure 2. Load-deformation diagram from a human tibia; intact bone (continuous line) and after osteotomy and tibial plate fixation (broken line).

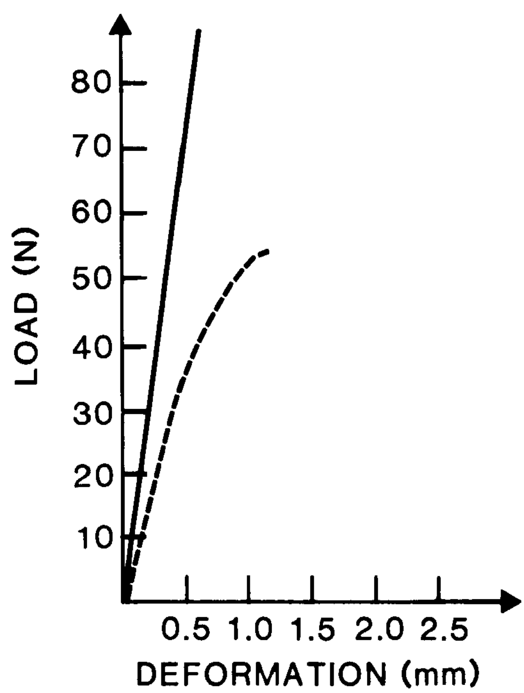

Figure 3. Load-deformation diagram from a rabbit tibia; intact bone (continuous line) and after osteotomy and plate fixation (broken line).

Osteotomized tibia

Materials. Five human and five rabbit tibiae were tested. The bones were collected and treated as described for intact bones. Bending tests were performed before osteotomy. Then a midshaft osteotomy was made with an oscillating saw, and the osteotomy was fixed with a plate on the lateral aspect of the tibia. Compression was applied in the fixation of human tibiae according to the DCP-principle, whereas no compression was used in the rabbit specimens.

The tibial plate (DCP, 140 × 12 × 4 mm) was used on human tibiae. On rabbit tibiae the same thin plate (45 × 5 × 1 mm) as in the experiments on intact tibiae was used.

Bending tests. The bones were loaded in three-point bending in the Instron testing machine. It was inconvenient to use the LVDT method in measuring deformation in osteotomized bones, and the load-deformation diagram from the Instron machine was used. The Instron cross-head displacement was at a constant rate of 5 mm/min. Before osteotomy the bones were loaded only within the elastic range. The load was applied on the anterior border of the tibia, at the level where osteotomy later was performed. After midshaft osteotomy and plate fixation the bones were tested as before, the load being applied at the same level. Curves obtained from human specimens and rabbit specimens (Figures 2 and 3) showed elastic followed by plastic deformation in the osteotomized, plated bones. As plastic deformation causes lasting damage to the tissues, it appeared to be most appropriate to perform measurements within the range of elastic deformation, which was in the range 0–3 mm for human tibiae and 0–0.5 mm for rabbit tibiae. The stiffness of the osteotomized, plated bone was calculated as the percentage of the stiffness of the intact bone.

Statistical analysis

The Wilcoxon two-sample test (two-tailed test) was used to calculate the statistical difference between human bones plated with femoral or tibial plates. Differences were considered significant at P-values below 0.05.

RESULTS

Intact tibia

The stiffness of the various intact bones varied greatly, both in human and rabbit specimens (Table 1). The median elastic stiffness was 8435 N/mm in the human tibia, and 1707 N/mm in the rabbit tibia. The intact tibiae in the femoral plate group had a greater median stiffness than those of the tibial plate group (Table 2), but the difference was not significant ($P = 0.19$). The median stiffness increase in human tibiae was 43.8 per cent after femoral plate application and 31 per cent after tibial plate application. The difference was significant ($P = 0.02$). In rabbit specimens the median stiffness increase was 31.9 per cent after plate application. There was a good accordance in elastic stiffness increase between human tibiae with a tibial plate and rabbit tibiae with the thin plate (Table 2).

Table 1. Elastic stiffness (N/mm) in the intact tibial shaft before plate fixation

	Human tibiae* $n=20$	Rabbit tibiae** $n=10$
Elastic stiffness		
Median	8435	1707
Range	4168–10900	1324–2088

* Tested in a bone segment 12 cm in length.
** Tested in a bone segment 4 cm in length.

Table 2. Elastic stiffness (N/mm) of intact tibiae, and stiffness increase (per cent) in tibiae after plate application

	Human tibiae		Rabbit tibiae
	Femoral plate $n=10$	Tibial plate $n=10$	$n=10$
Elastic stiffness			
Median	9083	7178	1707
Stiffness increase			
Median	43.8	31.0	31.9
Range	25.7–97.7	15.6–48.2	17.2–42.0

Osteotomized tibia

The stiffness of osteotomized, plated human and rabbit tibiae is given in Table 3. The median stiffness in the elastic range of deformation of human specimens with a tibial plate was 51.4 per cent of the stiffness of the intact bone, compared to 40.4 per cent in rabbit tibiae with a thin plate. Table 4

Table 3. Stiffness (rigidity) of osteotomized, plated tibiae in per cent of the stiffness of the intact bone

	Human tibiae $n=5$	Rabbit tibiae $n=5$
Stiffness		
Median	51.4	40.4
Range	41.6–59.2	34.5–53.8

Table 4. The strength of plate fixation of osteotomized tibiae (bending moment, Nm) in the transitional zone between elastic and plastic deformation (at 3 mm deformation in human and 0.5 mm in rabbit specimens)

	Human tibiae $n=5$	Rabbit tibiae $n=5$
Bending moment		
Median	32.3	0.44
Range	27.8–36.9	0.42–0.68

shows the bending moments in the transitional zone between elastic and plastic deformation (at 3 mm deformation in human and 0.5 mm in rabbit tibiae), which reflect the strength of the bone-plate preparation.

DISCUSSION

Intact tibia

As it was difficult to obtain human and rabbit bones of comparable ages, the human tibiae were taken from relatively old individuals, and the rabbit ones from relatively young animals. In addition, the shape of the tibial shaft is not identical in humans and rabbits. These differences make direct comparison of the results difficult, and the conclusions must be viewed with caution. However, our test model should give approximate values concerning the relations between the mechanical effects of plate fixation on human and animal bone.

The deformation of the bone can be measured by various methods. In conventional bending tests the deformation in the whole bone segment between the supporting ends is measured. Such tests give no information of the effects in the bone segment covered by the plate. A better method is to measure the deformation on the various bone surfaces in the plated segment by strain gauges (Diehl & Mittelmeier 1974, Cochran 1969). Another method is to measure the deformation in the whole bone segment under the plate, and for this purpose the LVDT is very suitable. The benefits of the method are that the measuring device is easily and quickly applied to the bone, and that the deformation in various segments of the diaphysis can be measured, by varying the distance between the outer ends of the device, and by placing it on different parts along the bone. The linear response characteristic is maintained over wide load range. The LVDT has a relatively small weight and size and a complete absence of friction.

The distribution of stress due to bending and direct loading around the outer surfaces of the human tibia at mid-shaft was calculated by Minns et al. (1977). Compressive as well as tensile stress act on the different surfaces, according to different positions in the walking cycle. The bending load in our model was in the antero-posterior direction, which gives compressive stress in the anterior and tensile stress in the dorsal part of the tibia. The similar stress distribution was found in two out of four positions in the walking cycle (Minns et al. 1977). Thus the load direction in our model seems adequate for situations present *in vivo.*

In calculating the elastic stiffness of the tibial segment, formulas for bending of a beam were used. This is a simplification, as the dimensions of the cross-section varies somewhat along the shaft segment. Accordingly, the values for elastic stiffness must be considered as approximate values made in order to compare various bones. However, in measurements on the same bone (unchanged L and a, Figure 1), as were done to calculate the elastic stiffness increase of intact tibiae and the rigidity of fixation of osteotomized tibiae, the beam formulas do not come into use, and so the values are correct.

In vitro mechanical tests have shown that internal fixation plates reduce the strain of underlying bone (Diehl & Mittelmeier 1974, Cochran 1969, Comtet et al. 1980). The extent of this stress-protecting effect varies, according to species, and dimensions of bone and plate. In plated femoral shafts in dogs, loaded along the weight bearing axis and measured by strain gauges, a mean strain reduction of 45 per cent was found (Cochran 1969). This resulted from a mean reduction of 84 per cent in the anterolateral surface beneath the plate, a reduction of 22 per cent over the medial surface, and of 27 per cent posteriorly. The stress-protecting effect of rigid plate fixation on bone thus seems to be greatest in the bone surface underneath the plate, but is pronounced in the whole bone segment as well. In compression and bending tests with strain gauge technique on the human tibia, Diehl & Mittelmeier (1974) found a mean strain reduction of about 75 per cent on the bone surface underneath the plate, and a mean reduction of 30 per cent on the other bone surfaces in the plated segment. Tibial plates of 4 mm thickness were used. This is the same thickness as that of the tibial plates in our experiments. We found a median stiffness increase of 31 per cent with a tibial plate, which corresponds well with the findings of Diehl & Mittelmeier (1974).

As might be expected, a significantly greater stiffness increase was found after plating with the more rigid femoral plate than with the tibial plate. In animal studies it has been found that less rigid plates cause less osteoporosis (Akeson et al. 1976, Tonino et al. 1976, Moyen et al. 1978). However, there are no reports of experimental work on the important matter of how rigid plates should be used in animals to obtain a stress-protecting effect corresponding to that obtained in clinical cases. Ideally, the plate used in animal studies should cause the equivalent stiffness increase in the animal bone, as the commonly used plates do in the corresponding human bone. The purpose of our testing of plate fixation on the intact rabbit tibia was to find such a plate. One of the least rigid plates commercially available (45 × 5 × 1 mm) was chosen. The bending tests gave a good accordance between the mechanical effects of these plates on rabbit tibiae and tibial plates on human tibiae. In previous studies on rabbit tibiae, much more rigid plates have been used. Paavolainen et al. (1978) used a plate of 2 mm thickness and Strømberg et al. (1980) used plates of 36 × 6 × 2 mm. The rigidity of these plates are several times greater than that of the plates used in this study. It seems that overdimensioned plates have been used and this might be the reason why strength reduction up to 50 per cent was found after plate removal. An *in vivo* study of the stress-protecting effect of our thin plate on rabbit tibia is in progress, and we hope thereby to give a more adequate estimate of what effects can be expected in human bone by metal plate fixation.

Osteotomized tibia

It is well known that rigid metal plates give an adequate fixation for healing of diaphyseal fractures. Müller (1963) declared that the stability of the fragments must be sufficient to prevent movement even of microscopic degree at the site of fracture. Such rigid fixation can hardly be obtained in internal fixation using one plate. How rigid is, in fact, this fixation?

In our study the median bending stiffness of plated human tibial osteotomies was 51.4 per cent in relation to that of intact bone. In torsional tests on sheep tibial midshaft osteotomies fixed with a 8-hole AO dynamic compression plate, a torsional stiffness of about 60 per cent of the intact tibia was found (Hayes & Perren 1971). The plate seems to have been somewhat overdimensioned, as the sheep tibia is a smaller bone than the human tibia. In bending and torsion tests on osteotomized human tibiae fixed with plates of various stiffness, all bone-plate systems showed elastic followed by plastic deformation (Laurence et al. 1969), as was also found in our experiments.

Laurence et al. (1969) estimated that the bending moment in the human tibia was about 80 Newton metres upon quiet walking, and about 10 Newton metres upon unresisted straight leg raising. In the elastic and early plastic range of deformation the most rigid plate in their series could resist a bending moment of 24 Newton metres. This corresponds well with the results of plate fixation in our study on human tibiae, as we found a median bending moment in the upper elastic deformation range of 32.3 Newton metres. The somewhat greater strength in our tests can partly be explained by the fact that different plates were used, and partly because we loaded the bone-plate preparation in a plane perpendicular to that containing the screws, while Laurence et al. (1969) loaded the preparation in its weakest attitude, which is in such a direction as to open the fracture. These experimental studies confirm the clinical experience that the rigid plates used in internal fixation today, give an adequate stiffness and strength of the fracture fixation to tolerate straight leg raising, muscle training and restricted weight-bearing. However, the fixation is not strong enough to tolerate unrestricted weight-bearing.

In the osteotomized rabbit tibia fixed with the thin plate, a median stiffness of 40.4 per cent in relation to that of the intact bone was found, and this corresponds well with the findings in the human specimens. The somewhat greater relative rigidity obtained in human specimens can partly be explained by the fact that compression was applied, while no compression was used in rabbits. In studies of fracture healing in rabbit tibiae a plate of equivalent rigidity to the plate tested in this study should be used to obtain a rigidity of the fixation that is comparable to that acieved by plate fixation of fractured human tibiae. In previous studies in rabbits, (Paavolainen et al. 1979, Greiff 1979, Rahn et al. 1971) more rigid plates have been used, which seem to be overdimensioned.

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