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A METHOD OF MEASURING THE CHANGE IN COMPRESSION APPLIED TO LIVING CORTICAL BONE

by

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with the technical assistance of V. Geret and M. Klebl

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INTRODUCTION

Continuously changing mechanical stress seems to be essential for the maintenance of the functional internal architecture of a bone. If a living bone is protected from functional stress osteoporosis may develop. The physiological range of forces which cause the bone to follow **Wolff's** law of adaption to functional demand is not known. There is much confusion about the effect of different kinds of load (dynamic or static) on bone. Relatively small dynamic pressure changes may engender bone resorption. These forces may be developed by a growing aneurysm for instance or by a foreign body anchored to bone undergoing passive movement (**Perren et al.**). The effect of static load is not the same. **Key** and **Charnley** have shown that osteotomised cancellous bone fixed under static pressure will quickly unite by new bone formation.

Little, however, is known about the reaction of living cortical bone to different amounts of static load and what circumstances lead to a condition such as «pressure necrosis» (**Rustizky**). Rigid fixation, of necessity, depends on inducing areas of pressure* between bone and metal and between bone fragments. Since bone and metal have high moduli of elasticity even a small loss of bone due to pressure would instantly eliminate the pressure areas and thus result in loss of rigidity.

It seemed important therefore to determine how compression might decrease over a long period when a static load was applied to live cortical bone. For this purpose a system of load-sensitive compression plates has been designed. The application of these to normal or osteotomised diaphyseal bone was intended to provide continuous or intermittent pressure recording over a period of several weeks. The object of this paper is to describe the construction of this plate, the technique of pressure recording and the information obtained from preliminary experiments.

It would have been attractive to use the ferromagnetic device of **Willenegger** and **Straumann** with the prospect of real telemetry, but this presented difficulties due to tissue reaction to the material and the need to compensate for bending and torque.

MATERIAL AND METHOD

As figure 1 shows bone may be put under longitudinal compression by applying an internal fixation plate using a compression clamp (compressor). The amount of the axial compression of the bone is equal to the axial tension in the plate (Fig. 2) if weight-bearing and muscle contraction are eliminated.

* In the sequel we use the words pressure and compression synonymously although strictly speaking the word pressure should be reserved for a state of three dimensional hydrostatic pressure.

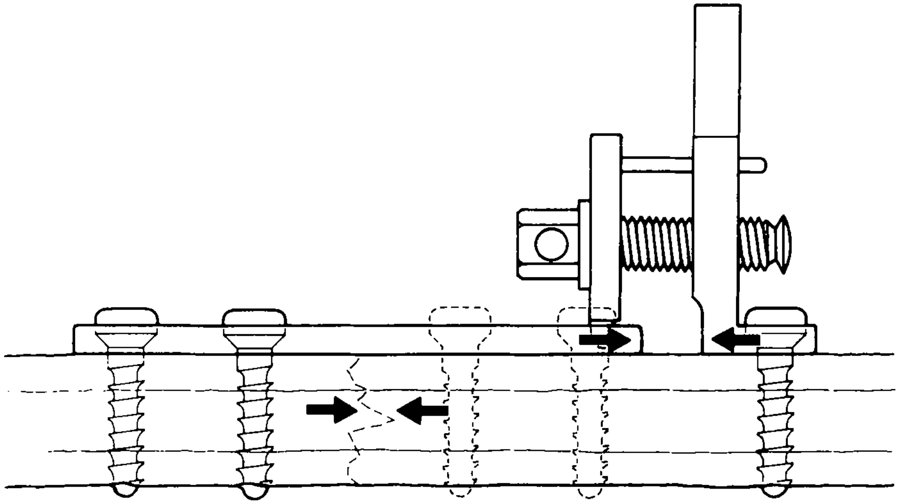


Fig 1. The AO* compressor is used to apply the AO*-plate under tension. The compressor is removed after driving home the middle screw on the right hand side of the fracture.

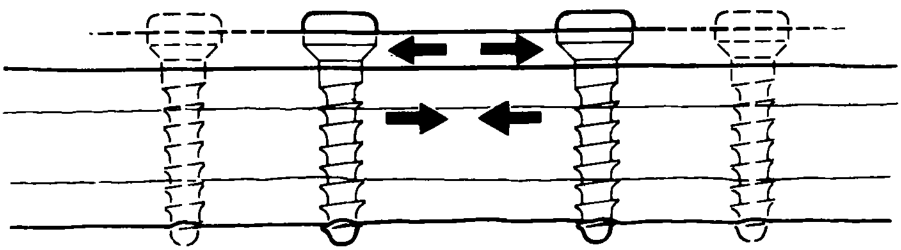


Fig. 2 Cortical bone is compressed longitudinally by an internal fixation plate applied under tension. The amount of traction in the plate equals the amount of compression of bone if external forces resulting from weight-bearing or muscle contraction are avoided.

A gauge plate has been constructed. It is a modification of the AO* plate as developed by **M. E. Müller** (Fig. 3). The plate is made of type 316 L stainless steel of which the ultimate tensile strength is about 90 Kp**/mm^2 and the Young's modulus 19 000 Kp**/mm^2. The original AO* screw with standard thread and recessed head and made of the same material as the plate is used. The holes for the screws in the bone are drilled and tapped and the plate applied with the special compressor (Fig. 1) exactly as described by **M. E. Müller, Allgöwer** and **Willenegger.** Located between the two middle screw holes of the plate (Figs. 5 and 6) is a strain gauge compartment which is made of the same piece of metal as the plate. The gauge plate is constructed to satisfy the following requirements:

* or ASIF
** Kp = Kilopond = Kilogram force

Fig. 3

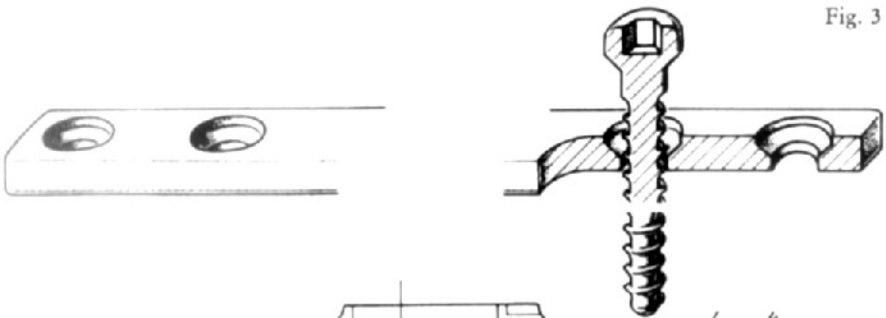


Fig. 4

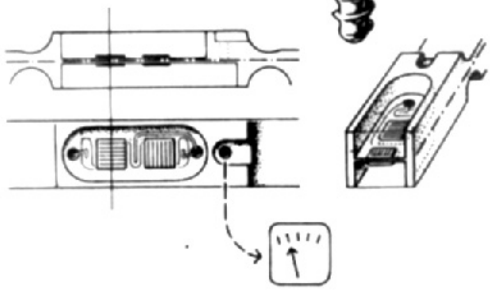


Fig. 5

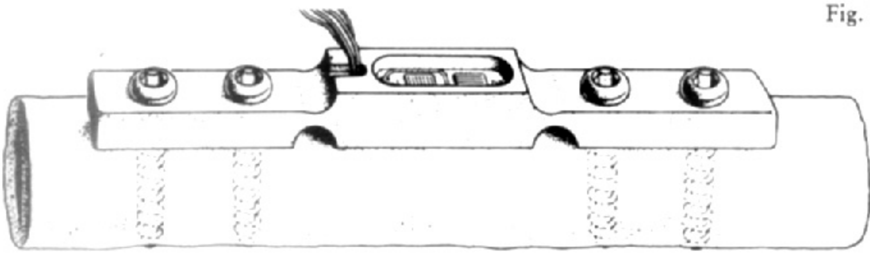


Fig. 3—5. A small four-hole AO*-plate is modified (Fig. 3) providing it with a strain gauge compartment (Fig. 4), to measure longitudinal stress in the plate. The plate is fixed to the bone as shown in Fig. 5 using the compressor (Fig. 1).

1. to permit recording of longitudinal stress in the plate
2. to permit stable internal fixation of two diaphyseal fragments produced by osteotomy or fracture
3. the device must be well tolerated by the tissues

The strain-sensitive device in the plate (Fig. 4) is constructed using strain gauges, which alter their electrical resistance in proportion to forces applied in the long axis of the plate. The resistance changes of the strain gauges are measured by a special carrier frequency bridge (Peekel WE 6002, precision bridge or Tepic Indikator IT 1). Metallic foil strain gauges (Frischen MFS-FG: $R = 120$ Ohms, $K = 2$) are preferred to semiconductor gauges as the latter are not yet considered sufficiently temperature stable.

* or ASIF

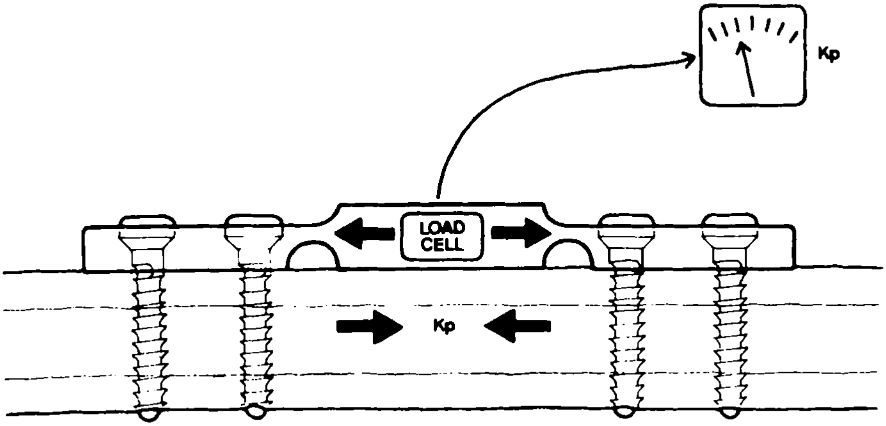


Fig. 6. The load cell incorporated in the plate permits continuous recording of longitudinal traction in the plate and thus measurement of compression in the osteotomy.

When using strain gauges in such a load cell, care must be taken to:

1. compensate for temperature changes
2. prevent plastic deformation of the load cell
3. compensate for bending moments
4. ensure good insulation
5. prevent errors due to resistance changes in the electrical leads.

1. Temperature

Temperature changes affect the strain readings due to:

a) thermal expansion of the underlying metal
b) thermal changes in the resistance of the gauges.

Thermal expansion of the underlying material may be easily compensated for by the use of appropriate gauges. Temperature effects on the gauges' resistance may be compensated for by the use of twin gauges which are both at the same temperature level, but only one of which is under strain. In the present system, temperature compensation is achieved by the use of a pair of identical gauges, one of which is in the long axis of the plate, the other at 90^0 to it.

2. Deformation

The relationship between stress and strain is linear only if the metal beneath the gauges is stressed within its own elastic limits. To prevent any overload due to bending and torque the chamber is provided with weakend segments to prevent plastic deformation of the load cell (Fig. 4).

3. Bending

There remains a possibility of some elastic deformation by bending. Two pairs of temperature compensated strain gauges are located equidistant from the neutral axis of bending. They are connected to a Wheatstone bridge circuit, the balance of which is affected only by axial forces acting on the load cell and not by temperature changes or bending forces. This arrangement is simpler to achieve than using one pair of strain gauges placed exactly in the neutral axis of bending (Figs. 5—7).

4. Insulation

Any failure of insulation would shunt the strain gauges. Insulation defects may be asymmetrical thus imitating a change of the resistance of the gauge and thereby producing a false reading. To avoid such errors, the resistance of the gauges versus the plate is measured regularly and plates with insulation defects are discarded.

5. Leads

Changes in the resistance of the leads would also imitate changes in the gauge resistance. By connecting the strain gauges within the plate to each other to form a Wheatstone bridge the system is much less sensitive to changes in the lead resistance.

To test the gauge mounting for possible «creep» a constant load of 100 Kp was applied to 6 plates and strain recordings were taken during 1 week. In one of these plates strain was recorded during 10 weeks.

To find out to what extent stress relaxation due to inelastic deformation of the plate or screw would affect the «plate on bone» system, in 2 experiments a gauge plate was applied to a steel tube and an initial load near 100 Kp was installed. Strain recordings were then taken during 8 weeks. From these recordings an upper bound on the amount of stress relaxation to be expected in the «plate on bone» system was estimated. The estimate was made from a simple model which included in an approximate way the effects of material and geometrical properties of the plate and the material beneath. A value for the Young's modulus of a sheep tibia was measured in a simple compression test and found to be 2100 Kp/mm^2. The calculated rate of elongation of the gauge plate was 1μ/100 Kp. On this basis the elastic deformation of bone was estimated to be between 10μ and 20μ depending upon the assumed stress distribution.

Before use each plate was tested in a special machine (Fig. 8a). The testing procedure included the following steps:

1. The relation between measured strain and axial load was plotted over a range from 0—100 Kp (Figs. 8a, 9 and 10)
2. The influence of temperature was tested in a saline bath at temperatures of 27^0, 37^0 and 47^0 C. (Figs. 8a and 9).
3. The influence of bending and torque was measured, applying a constant moment of 20 cm · Kp (Figs. 8d, 8e and 10)
4. The insulation of the gauges was tested and plates with an insulation resistance $<10^8$ Ohms were discarded.

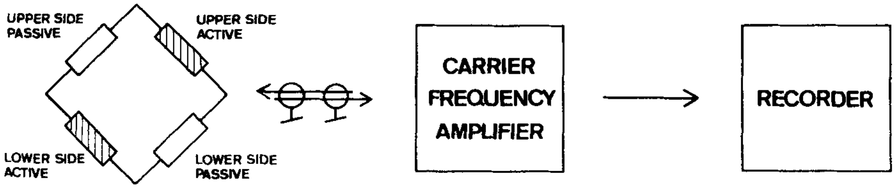


Fig. 7. The load cell contains 4 strain gauges forming a Wheatstone-bridge which compensates for temperature and bending influences. The gauge plate is connected to a carrier frequency amplifier which drives a recorder.

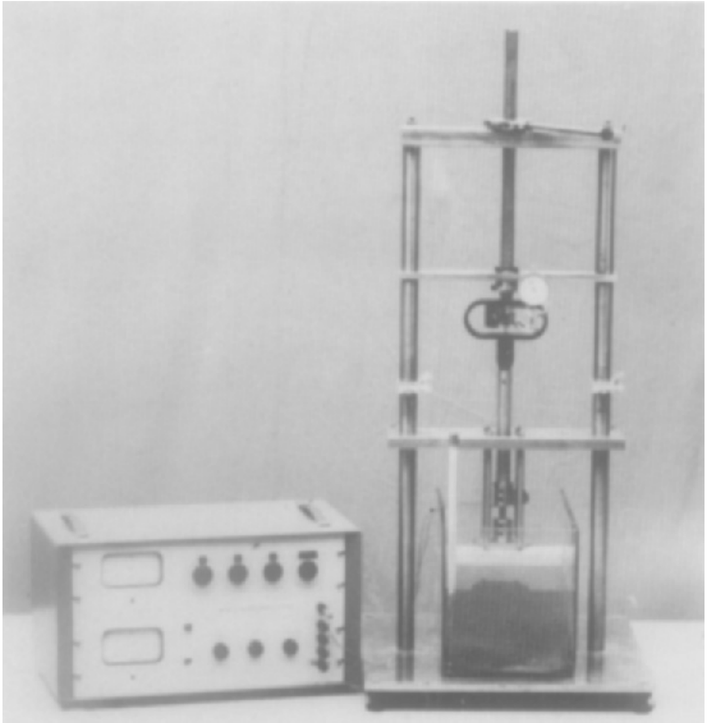


Fig. 8a. Test rig shown ready to calibrate indicated strain versus longitudinal traction at different levels of temperature. The gauge plate, placed in a temperature controlled bath of saline, is loaded by the use of a Jack-Screw. The applied load is measured with a dynamometer (Fig. 8b) while the precision bridge at left permits reading of indicated strain.

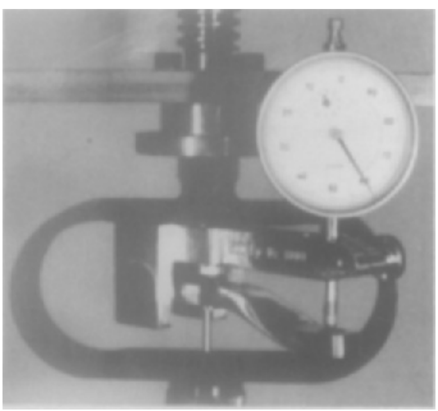
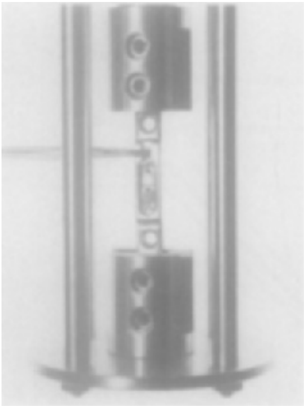


Fig. 8b. Precision dynamometer to measure longitudinal traction applied to the plate.

Fig. 8c 

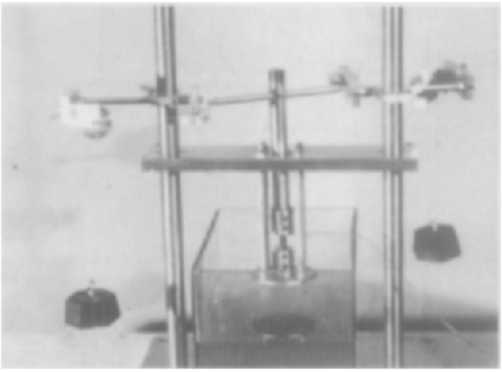


Fig. 8d

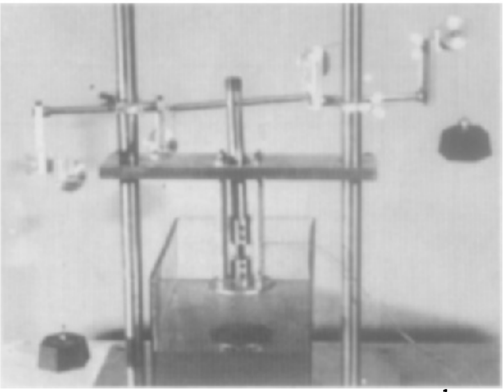


Fig. 8e

Fig. 8c. The gauge plate is mounted with the use of two clamps.

Fig. 8d. Calibration of indicated strain versus torque (20 cm · Kp).

Fig. 8e. Calibration of strain versus bending. A constant moment over the whole length of the plate is applied (20 cm ·Kp).

RESULTS

The curve made by plotting axial force against measured strain is shown in figure 9. In the same figure the error due to temperature changes is also plotted. The calibration curve is linear and the influence of temperature is small.

The errors due to bending forces in two directions and due to torque are indicated in figure 10. The influence of these forces is negligible.

The strain recording of the plate with a constant load acting, demonstrated that the creep of the strain gauge mounting was very small.

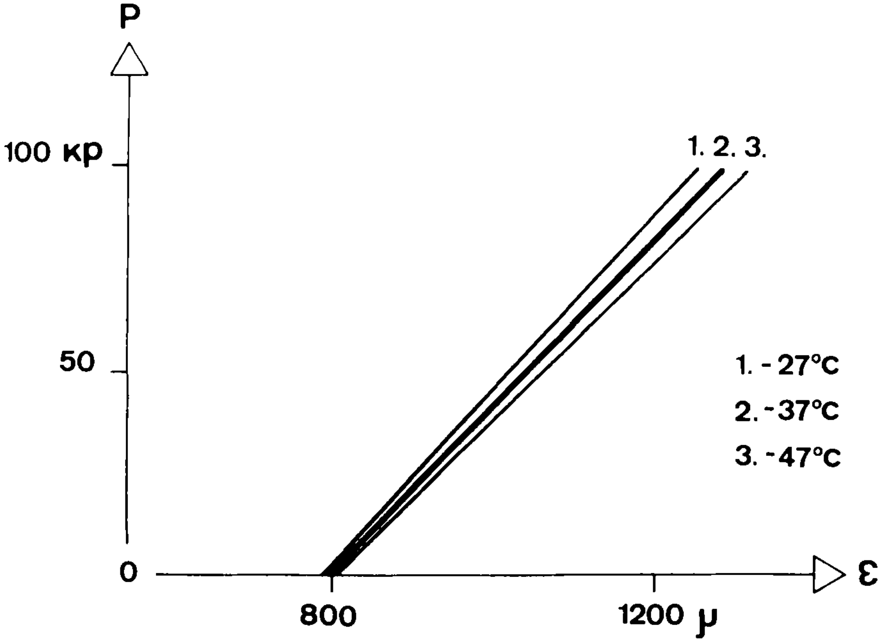
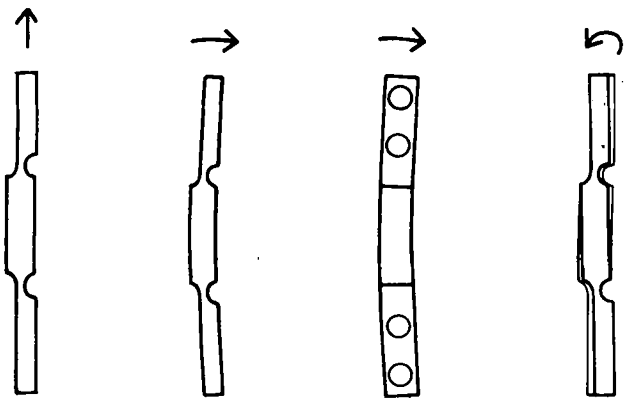


Fig. 9. Calibration curve plotting applied load versus indicated strain at different temperatures. The relation is linear and the temperature influence small. The strain is expressed in μm/m.



Force acting on the plate	Tension	Bending 20 cm · Kp	Bending 20 cm · Kp	Torque 20 cm · Kp
Indicated strain μm/m	500/100 Kp*	— 1.5 ± 3	+ 4.0 ± 3	— 0.3 ± 4

Fig. 10. Indicated strain versus different kinds of forces. Mean values and standard errors of a group of 6 plates are listed.

* each plate is calibrated according to figure 9.

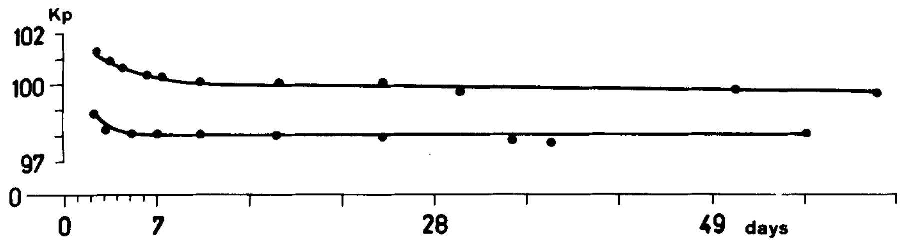


Fig. 11. Estimated change of compression in the bone due to inelastic deformation of the plate and the screws.

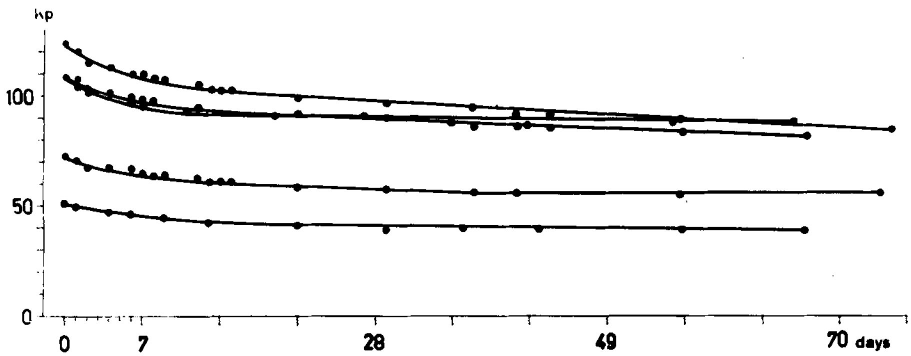


Fig. 12. Pressure recording with gauge plates on sterile dead bone at 37° C and high humidity. Note the initial fall of pressure due mainly to viscoelastic properties of bone.

Figure 11 shows the estimated change of compression in the bone due to inelastic deformation of the plate and screws. On the basis of a simplified model of the system, this deformation was estimated to be less than 0.2μ.

Figure 12 shows the decrease of compression in intact dead bone in a temperature controlled environment of high humidity. Here an initial steep decrease is followed by a very slow decrease. The total loss of compression over 8 weeks is of the order of 20% of the initial value.

DISCUSSION

The gauge plate has proved to be useful in recording the change of axial compression of bone. In preliminary experiments the strength of the plate and the tissue tolerance were found to be adequate. Very little creep has been encountered in the strain gauge mounting. Furthermore the experiment with plates on steel tubes revealed little stress relaxation due to inelastic deformation of the plate and the screws.

The experiment using freshly removed tibiae has shown a decrease of the order of 20% which cannot be accounted for by biological processes. This decrease occurs in the first few days and is followed by no appreciable long term decrease. It most likely results from the viscoelastic properties of bone itself **(Sedlin).**

In the «plate on bone» system a total load of 100 Kp results in an elastic deformation of only 10—20μ. Since small changes in the length of the system will result in large changes in force, the gauge plate is suitable for measuring the small changes in bone length which might be caused by creep, resorption or failure of fixation.

As a whole, the method now seems to be ready for use in living animals. Results on the behaviour of intact living bone and osteotomised living bone will be reported below.

SUMMARY

The reaction of bone to compression is of primary importance in the internal fixation of fractures. Any induction of «pressure necrosis» and consequent bone resorption would result in total loss of rigidity. A gauge plate has been developed to study, **in vivo**, the reaction of bone to compression by recording the change of load in the bone with time. The method permits detection of minute changes in bone length due to creep, resorption or instability. It is therefore a valuable tool for investigating the quality of a fixation over extended periods of time.

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THE REACTION OF CORTICAL BONE TO COMPRESSION

by

S. M. Perren, A. Huggler, M. Russenberger, M. Allgöwer, R. Mathys, R. Schenk, H. Willenegger and M. E. Müller

with the technical assistance of V. Geret and E. Frey

THE REACTION OF CORTICAL BONE TO COMPRESSION

INTRODUCTION

Rigid internal fixation by necessity depends on the production of local pressure areas between implant and bone or between bone ends. Wherever «pressure necrosis» and consequent bone resorption occurs, there will be a loss of stability. It is vital, therefore, to understand precisely the reaction of bone to static compression*.

Clinical experience shows that bone can withstand a considerable static load without «pressure necrosis» becoming apparent (**Lambotte, Danis, Lane, Hicks, M. E. Müller, Allgöwer** and **Willenegger**). Quantitative information however is lacking about the type and magnitude of forces which will promote functional adaptation of bone structure to stress according to **Wolff's** law.

There are two ways of measuring the change in pressure applied to bone. One employs a system with a comparatively high deformability while the other uses a system of very low deformability:

— **In highly deformable systems** the use of ordinary springs permits the determination of load continuously (**Burri**) or at the beginning and at the end of the experiment (**Friedenberg & French**). This method cannot detect small amounts of bone resorption as compression depends mainly on the deformability of the spring rather than of the bone. Furthermore such a system can become unstable at low pressures.

— **In systems of low elastic deformability** load-sensitive metal plates are fixed to the bone. Here the deformability is infinitesimal compared with systems using springs. These systems thus are able to detect small changes in bone length due to e. g. creep or resorption.

Straumann designed a measuring plate that employed ferromagnetic material and this was used in animals by **Willenegger**. Telemetric readings of tension acting on such a plate were obtained by inserting the limb into a magnetic field. Accurate measurements were difficult however because of the effects of torque and bending, and precise positioning of the plates in the magnetic field was impossible when using living animals. The ferromagnetic materials hitherto available also corroded badly in the tissues.

In view of these facts a four-hole AO** compression plate of **M. E. Müller's** design was modified to incorporate strain gauges and thus to act as a compression plate and load cell at the same time. This plate allowed long term pressure recordings to be made unaffected by temperature changes and bending stresses. The plate itself was well tolerated by the tissues. Its precise specifications have been described above (p. 14).

* In the sequel we use the words pressure and compression synonymously although strictly speaking the word pressure should be reserved for a state of three dimensional hydrostatic pressure.

** or ASIF

It is the purpose of this paper to report the reaction of the living tibial diaphysis of the sheep to known amounts of pressure load, comparing the normal to the osteotomised tibia. Changes in load are the main demonstration of physical alterations occurring in the bone and are related to the histological appearance.

MATERIAL AND METHOD

To apply static compression to the bone, four-hole plates with built-in strain gauges were used as described previously (p. 9). The gauge plate, compensated for bending moments and temperature variations, gave either continuous or intermittent recordings. The plates were applied under tension to exert compression as described by **M. E. Müller, Allgöwer** and **Willenegger.**

Sheep, 2—4 years old, were used as experimental animals. They were anaesthetised with Fluothane®[1]) **(Hutzschenreuter & Perren).** The tibia was approached from the medial side, preserving the proximal nutrient artery. When the tibia had been exposed subperiostally the gauge plate was fixed to the bone. The electrical leads were brought through the skin above the femoral trochanter to prevent retrograde infection. One of two procedures was then followed:

In 6 sheep of group A the plate was applied to the intact bone while in 9 sheep of group B an osteotomy was performed using a very fine saw that cleanly removed 0,1 mm of bone **(Willenegger et al.)** Continuous irrigation with Ringer's solution and slow movements of the saw prevented any thermal damage. To prevent splitting of the bone during osteotomy a special bone clamp was used. As the operated leg of the animal takes full weight soon after the operation, two plates were applied at right angles to each other.

At the end of the operation the wounds were irrigated with Polybactrin®[2]) (solution containing Bacitracin, Neomycin and Nebacetin) and the skin closed with one layer of 4—0 dermalon®[3]) sutures using **Allgöwer's** technique. The suture was then protected by Nobecutan®[4]) Spray and no dressing was applied. Negative pressure drainage was maintained for 24 hours using a disposable vacuum generator (Protevac®[5]) attached to the animal.

The amount of strain placed on the plate was measured while the compressor was being tightened until the required level was reached. The first base line reading was taken no sooner than 3 hours after operation to ensure that temperature equilibrium had been reached and the initial stress relaxation of bone had diminished.

Pressure readings were taken as described above (p. 9). A few animals were followed continuously, but in most of them recordings were made at weekly intervals. X-rays* were taken in a. p. and lateral projections every three weeks.

The sheep were kept as long as measurements were technically possible and were sacrificed only when the leads broke, which in group B (osteotomised tibia) occurred between 3 and 12 weeks after operation while in the group A (intact tibia) breakage occurred between 7 and 12 weeks. In some animals not listed here, measurements after 16 weeks were possible. Specimens were removed and embedded in Acrylic after fixation with 40% alcohol and staining with alkaline

* OSRAY® Film Agfa-Gevaert AG Basel

1) P. Geistlich AG, Wolhusen
2) Pharmacalmic SA, Zürich
3) Ulrich & Co., St. Gallen
4) Globopharma AG, Zürich
5) Protek AG, Bern
6) Opopharma AG, Zürich

Fuchsin. The bone segments were then cut into thin slices and ground to 50 without decalcification. All animals had received 500 mg of Aureomycin®[6]) intravenously at various intervals after operation and remodelling of the bone could be studied by fluorescent microscopy.

It must be emphasized that many preliminary experiments were required to define long term measuring techniques in live animals. Difficulties arose from failure of insulation, retrograde infections and bending deformations in some early gauge plates. Animals with any of these failures are excluded from this report whereas on occasion of broken leads the animals were sacrificed but the results are included.

RESULTS

The pressure readings in group A (intact bone) are shown in figure 1. There is a gradual decrease of pressure over 12 weeks after a somewhat steeper decrease in the first few days.

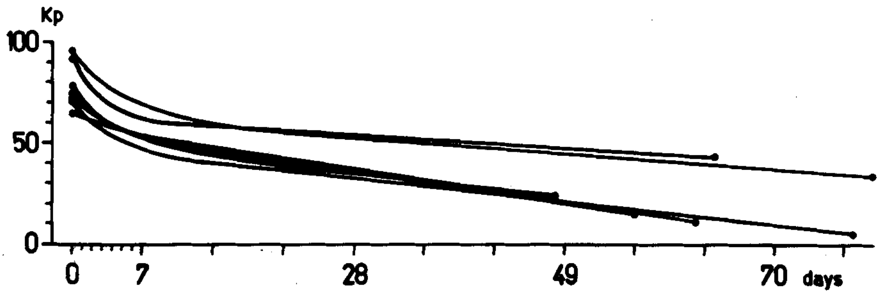

Fig. 1. Pressure recording of group A where the plate was applied to intact bone. The pressure decreases gradually over 12 weeks after a steeper initial fall.

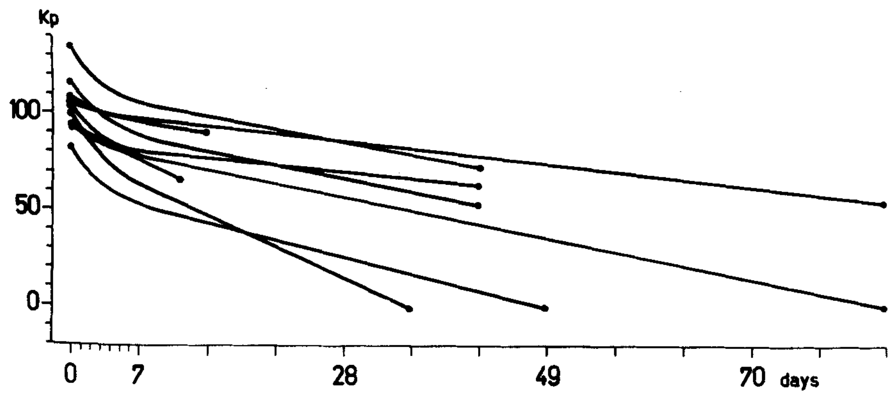

Fig. 2. Pressure recording in group B where the tibia was osteotomised. The rate of change of pressure is similar with or without osteotomy (fig. 1).

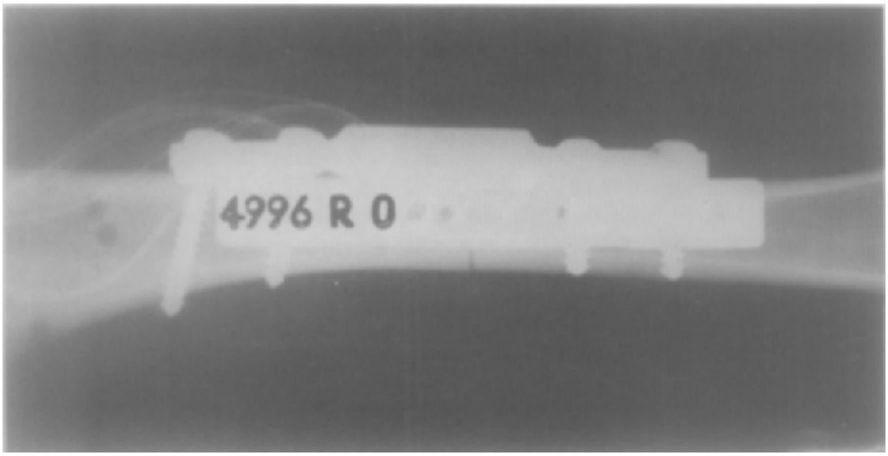

Fig. 3. X-ray taken immediately after operation. The positioning of the two plates placed at right angles may be seen bridging the transverse osteotomy of the tibia.

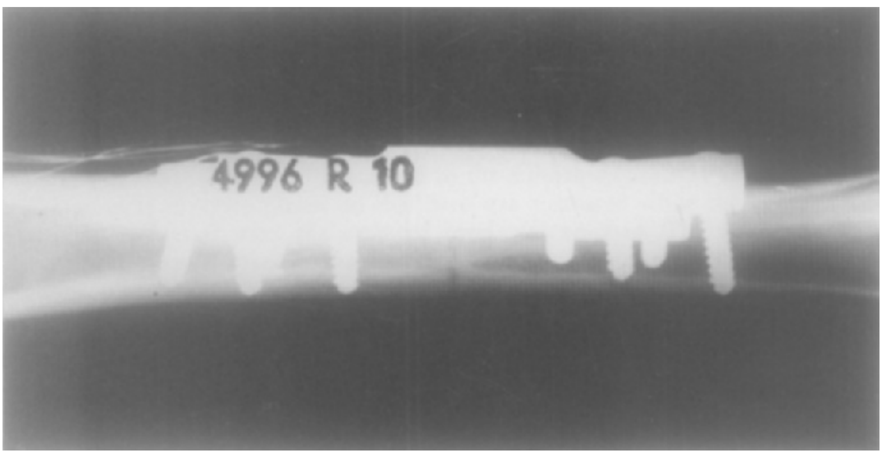

Fig. 4. X-ray taken at 10 weeks after operation. In spite of full weight-bearing very little callus can be seen. Bony union has occurred.

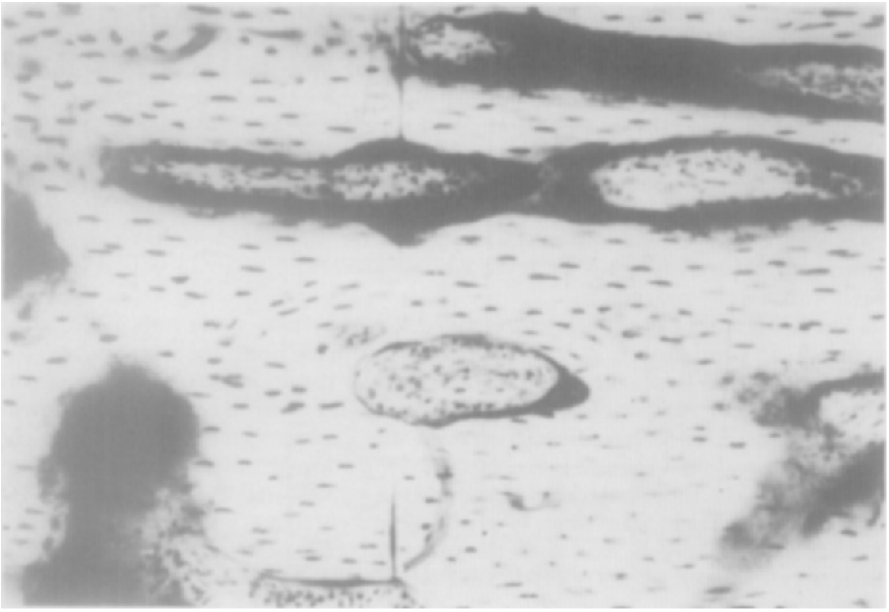

Fig. 5. Histology of the cortex beneath the plate, 12 weeks after operation. Primary fracture healing is seen in spite of full weight-bearing. No specific resorption of the compressed surfaces is visible.

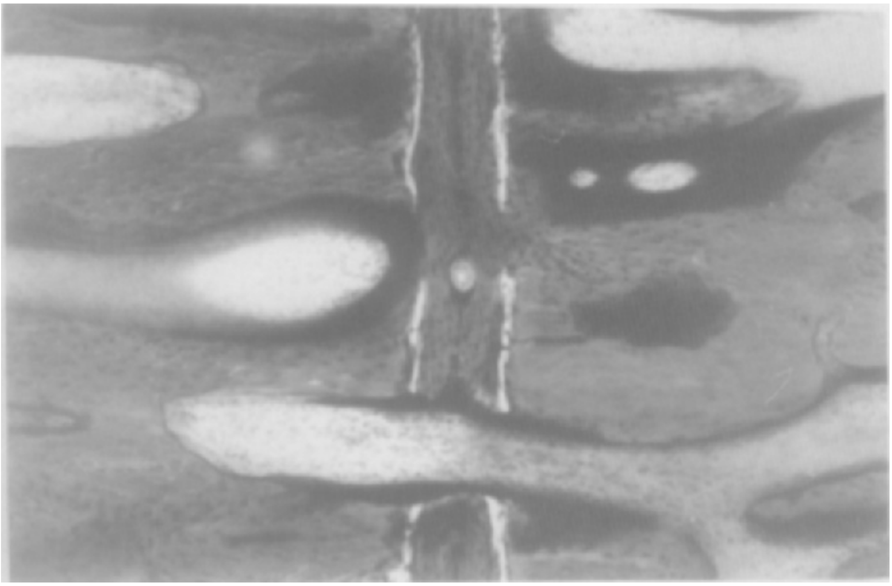

Fig. 6. Histology of the opposite side to the plate. The gap between the fragments is first filled by lamellar bone («transverse osteon») which in turn will be remodelled later in axial direction. Fluorescent label given 3 weeks after operation is found in such a «transverse osteon». The animal was sacrificed at 12 weeks.

The pressure readings in group B (osteotomised bone) are shown in figure 2. The same initial decrease of pressure as in intact bone is seen. After this initial decrease the rate of change of pressure is similar to the one in intact bone. The rate of decrease of pressure does not depend on the initial level of pressure.

Typical radiographs of an osteotomised tibia are shown in figures 3 and 4. In figure 3 the transverse osteotomy of the tibia is seen fixed by two gauge plates. A part of the wire connection between the implanted gauge plate and the measuring bridge outside the animal is visible.

In figure 4 the radiograph taken 10 weeks after the operation shows the osteotomy gap bridged directly by bone while no external callus is seen in spite of early full weight-bearing.

The histology of the specimen removed 12 weeks after osteotomy is shown in figure 5. It confirms the X-ray finding of «primary bone healing». In no case is there any development of interposed fibrous tissue or cartilage. This shows that, in spite of full weight-bearing, the osteotomy is bridged by direct Haversian remodelling. It can be seen that in the cortex which is in contact the plate the new bone spanning the osteotomy is formed mainly in the long axis of the tibia. In the osteotomy of the cortex opposite to the plate the osteons are first laid down transverse to the long axis of bone but later remodelling takes place in the long axis as in the other cortex. The tetracycline label administered three weeks after operation is found in the transverse osteon (Fig. 6).

DISCUSSION

After application of compression there is no sudden drop of pressure. This statement applies to intact as well as to osteotomised bone under compression of 60—140 Kp. The system is sensitive to very small changes in length (a few micra) and the pressure would have decreased to zero if there had been a loss of substance of 10—20μ due to resorption. This resorption could occur either at the compressed interfaces of the osteotomy (Fig. 7a) or of the screw thread (Fig. 7b). Minute changes of length due to instability would also cause sudden changes of pressure (Fig. 7c).

The data indicate that, at pressure levels of group A (intact bone) and B (osteotomised bone) namely at pressure levels of 60—140 Kp no «pressure necrosis» is present. If a layer of bone as thin as 2—3 red cells disappeared at the compressed bone surface a complete loss of compression would result. In fact, resorption of the compressed interfaces is not even observed at the small area of compressed bone at the screw site where a total pressure of 140 Kp results in a specific pressure exceeding 400 Kp/cm^2. Regardless of the initial pressure there is an identical rate of change.

From the results it is reasonable to conclude that rigid fixation was maintained since any movement of the two fragments (even in the range of a few micra) would have resulted in a sudden change of pressure and, most probably, in a complete loss of compression. The fact that the pressure recordings permit conclusions about long term stability of fixation has interesting potentialities in testing new devices for internal fixation (see p. 45).

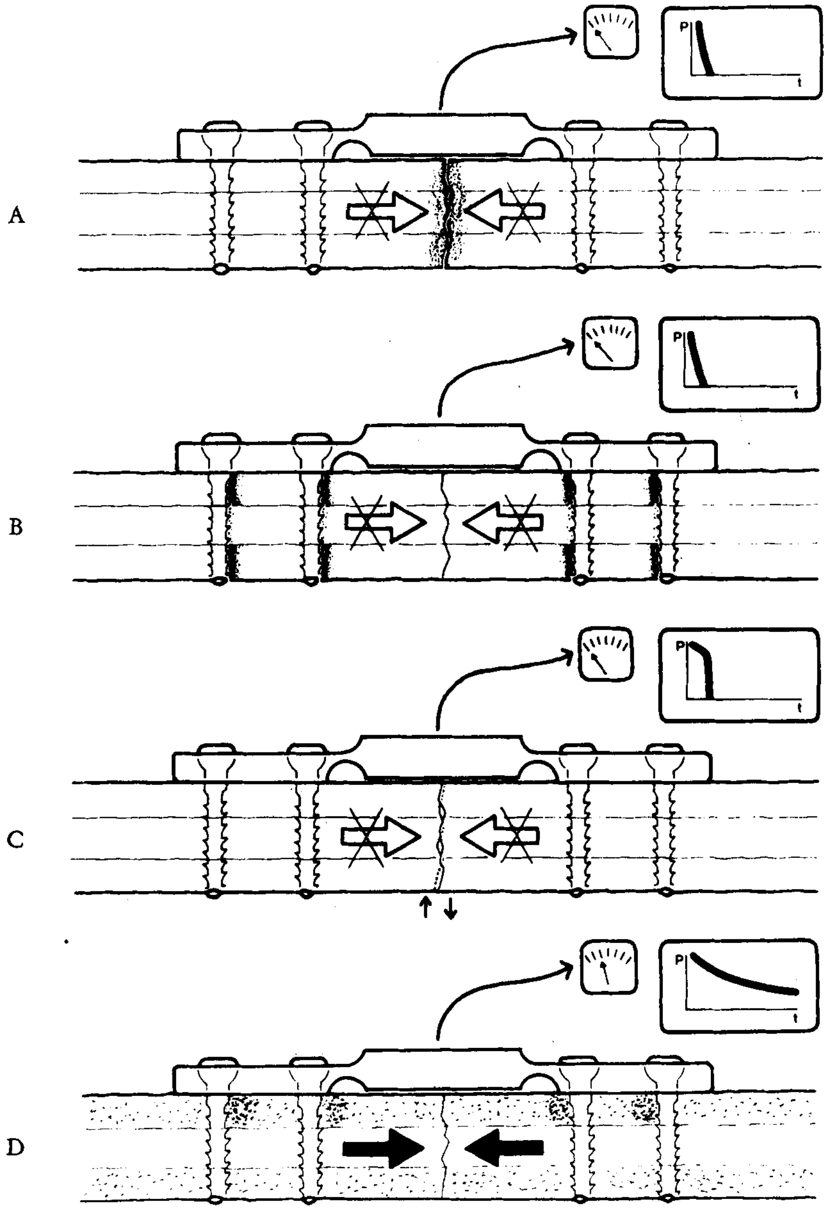

Fig. 7. The effect of various forms of bone resorption and instability on applied pressure in internal fixation.
Minute amounts of bone resorption at the compressed bone surface either at the osteotomy (A) or at the screw thread (B) would lead to a steep fall of pressure. By a similar mechanism minute amounts of instability (C) would result in a sudden change of pressure. Longitudinal resorption of bone (Haversian remodelling) explains the slow and gradual fall of pressure (D) as seen in our experiment (Fig. 1 and Fig. 2).

The second observation is the slow, but continuous reduction of the pressure in the intact as well as in the osteotomised tibiae. When the gauge plates are fixed to a steel tube, there is an initial pressure drop which, when corrected for bone would be about 2%. On dead bone, there is a loss of about 20% of the originally applied load (see p. 15), occurring mainly in the first week probably due in part to viscoelastic behaviour of the bone (**Sedlin**). A pressure loss above 20% should therefore be attributed to the response of living bone reacting to load conditions. The pressure does in fact fall to 50% within 2 months and the experiments which could be followed over a longer period indicated a further decrease of pressure reaching a new equilibrium near zero in 3—5 months.

The similar decrease of pressure in intact as well as in osteotomised bone indicates that the rate of change of pressure does not depend on any specific change peculiar to the osteotomy. This striking conclusion is based furthermore on the fact that the pressure recordings exclude any movement at the compressed surface of the osteotomy and that the histology (Fig. 5) does not show any surface resorption of the compressed area.

The histology gives a clue to the decrease in the compression force. It shows an intense Haversian remodelling of the compressed tibia. In their work on the dog radius **Schenk** and **Willenegger** noticed a remodelling rate of 60% within 8 weeks of osteotomy. This seems to be of the same order as that of the sheep though this animal seems to remodel at a slower rate than the dog. The physical effect of this process is the destruction of the osteons under pressure thus reducing the load bearing area of the compressed diaphysis (Fig. 7d). The loss of compression is not a linear function of the remodelling rate, because the newly formed osteons will be loaded again when further osteons disappear. The fact that about 50% of the load has disappeared 2 months after loading would correspond well with **Schenk's** observation that at this time 60% of the osteons were remodelled.

Is living bone able, apart from Haversian remodelling to alter its elasticity (as might occur by the direct dissolution of calcium apatite)? This cannot be answered from our experiment. In view of the obvious effect of Haversian remodelling, such a mechanism seems to be neither necessary nor likely.

This work shows that a static preload of 60—140 Kp on a cortical bone segment about 5 cm in length and between 1.5 and 2.0 cm in diameter does not induce rapid pressure necrosis. An osteotomy in this segment in vivo does not appreciably alter its response to static pressure as long as it is rigidly fixed. It is worth noting that «pressure necrosis» at this interface is absent and direct bridging occurs.

Two relatively short plates applied at right angles were used in our experiments as immediate weight-bearing might have thrown a bending stress on a single plate. The disadvantage of too much «stress protection» of the plated part of the bone had to be accepted. (Double plating in human fractures is rarely indicated and only then at the epiphyseal area of long bones). Two plates may prevent the major action of physiological stress and result in bone resorption prevailing over bone formation. In our experiment this effect seems to be partly offset by the comparative shortness of the plate and by the early weight-bearing.

Expressing the value of pressure per unit of area is not felt justified as the distribution of load is not uniform. Plates applied at right angles would transmit most of the load to the quadrant of bone between the plates and much less to the opposite one.

Nevertheless the highest stress of the order of about 400 Kp/cm^2 is found at the screw sites and still there is no evidence of pressure necrosis. This finding is in line with that of Charnley who found it unlikely that necrosis at a pressure level of 3000 lbs/sq. inch ($\sim$ 210 Kp/cm^2) would occur.

The pressure within the range studied by us leads to a slow loss of load due to Haversian remodelling. If Haversian remodelling takes place at any cross-sectional area in the compressed segment the pressure will decrease.

The data obtained clearly shows that static compression does not neccesarily induce pressure necrosis. It seems probable that motion (which may be regarded as being intermittent pressure reaching zero level) does induce bone resorption (**Perren et al.**) which may also be induced by infection. The observed slow decrease of compression in the present experiment is due to remodelling.

SUMMARY

A new gauge plate was used to study the change of compression applied to intact and osteotomised sheep tibiae. No steep fall of compression was seen indicating that there is neither pressure necrosis nor instability of fixation. A correlation between the slow decrease of pressure and the rate of Haversian remodelling has been established for intact and osteotomised bone. In spite of unrestricted weight-bearing primary fracture healing was seen.

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A DYNAMIC COMPRESSION PLATE

by

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M. E. Müller and M. Allgöwer

with technical assistance of V. Geret and M. Klebl

A DYNAMIC COMPRESSION PLATE

INTRODUCTION

Compression fixation of fractures and osteotomies has gained wide acceptance in recent years. **Danis** was probably the first to design a rigid longitudinal compression system using a plate screwed to the bone cortex and compressed by a device incorporated in the plate. Using this technique, **Danis** was successful in securing radiological «primary bone healing» in fractures of the forearm bones and of the tibia. The application of such a plate however is not without its difficulties. As no advantage is gained by leaving the compression device in situ, **M. E. Müller** has devised a separate compressor (see p. 8) which can be removed after the plate has been fixed to the bone. The use of rigid plates of various sizes combined with the removable compressor has been widely tested by the AO*-group and has become known as AO* compression plate technique**.

The effect of known values of different static loads on intact as well as osteotomised diaphyseal bone has been thoroughly studied (p. 17). A tension force of 60— 140 Kp exerted on a rigid AO* plate will apply a corresponding compression force to the underlying cortical bone. It has been shown that under these conditions a resorption of 10—20μ at the interface of an osteotomy or at the screw sites would result in an immediate abolition of the compression force (**Perren et al.**, see p. 25). No such phenomenon was observed. On the contrary, well apposed osteotomy surfaces in dogs and sheep united directly by a process of simultaneous resorption and osteogenesis in the axial direction. There was, however, a gradual decrease from the initial load over the course of 3—5 months until a new equilibrium near zero pressure was reached. This gradual decrease in compression was matched by the histological finding of longitudinal Haversian remodelling of the cortex. The use of this compression type plate has been evaluated by experimental work on dogs (**Schenk** and **Willenegger, Anderson, J. Müller**) and sheep (**Perren et al.**, see page 23). It has also been successfully applied to clinical cases, especially for fractures of the forearm and tibia as well as for non-unions (**Anderson, J. Müller, M. E. Müller, Allgöwer** and **Willenegger**).

The rigid compression plate with a separate compressor has some minor limitations:

1. after removal of the compressor there is an unpredictable change in the forces exerted by the screws inserted in the conical holes of the plate. Very small displacements of the screw in the plate can result in large pressure changes. Such a pressure change will occur if a screw is placed in a conical countersink with even a small amount of eccentricity

* or ASIF

** It should be emphasized that compression is not confined to the use of plates nor is compression always applied in the long axis of the bone. Wherever large and comminuted fractures are bridged by plates, compression is first exerted in a plane perpendicular to the fracture by screws crossing this plane.

2. the removal of stress influences the bone beneath a rigid plate and can lead to some osteoporosis in the cortical bone. This has been observed in plated femora and tibiae especially when two and/or massive plates were used. When such plates are removed fatigue fractures may occur through the porotic area
3. applying a separate compressor requires a wider exposure which may be difficult at some sites
4. the close conical fit between screw neck and plate countersink holds the screw at right angles to the plate. This may make it difficult to place the screw in exactly the right relation to a fracture line
5. there may be significant corrosion of AISI 316 L steel at the screw seat especially when movements occur (**Steinemann**). This applies, for example, to the tibia were considerable amounts of stress are transmitted from the screws to the plate under weight-bearing conditions

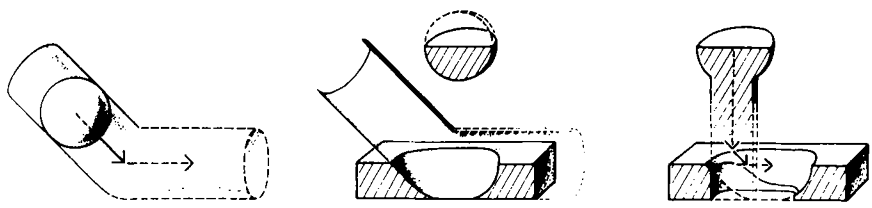

Fig. 1a—c. The new screw hole, which permits compression of the osteotomy (or fracture) when the screw is driven home, offers adequate stability and prevents any locking effect.
Fig. 1a shows how a ball (screw) is guided in a sloped cylinder (screw hole). Any movement downward will result in a horizontal displacement. No sideways movement is possible. The position aimed at is the intersection of the two cylinders. This position offers best stability without any locking effect. In the horizontal cylinder displacement towards the osteotomy is possible.
Fig. 1b. Projection of the cylinders into the screw hole, and the ball-shaped screw.
Fig. 1c. Actual shape of the hole with the slot necessary for the screw neck and thread.

It seemed desirable therefore to design a plate providing the same stability across an osteotomy or fracture as the rigid compression plate but avoiding the disadvantages listed above. Three alterations seemed essential:

a) the original conical screw hole (see p. 8) was altered to a shape which is part of the geometrical figure formed by two cylinders intersecting an obtuse angle (Fig. 1) a sloped one and one in the long axis of the plate (Figs. 1a and b). The screw entering this hole will first be guided by the sloping cylinder (Fig. 1c). A movement of the underlying bone towards the other fragment will result (Figs. 2A—D). The effect will be first to close and then to compress the fracture (see also page 48). This eliminates the need for an external compressor with the consequent need for additional surgical exposure in many cases (e. g. in undisplaced fractures). This design does not prevent the use of an external compressor if such a procedure should be desirable (e. g. in hip surgery).
The horizontal cylinder will furthermore allow the screw to move a little further towards the fracture. This is to prevent any tendency to obstruct

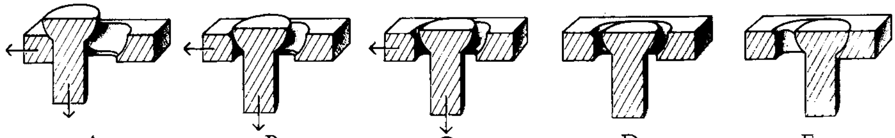

Fig. 2A—E. The osteotomy or fracture is compressed when the screw is driven home from the position A—C. Gliding movement is possible from position D. Position A results in a horizontal displacement of 1.5 mm (3 mm total if both sides are used in this position). This position is scarcely ever necessary and will not be discussed further. Positions B and C result in less displacement and less compression.
Position D «final position» offers optimum stability with three dimensional contact.
Position E at the end of gliding movement should be avoided.

the closure of the fracture. During all these movements, the screw will be maintained in optimal lateral stability which could not be achieved by previous slotted plates

b) the countersunk part of the screw (screw seat) was made spherical to fit the cylindrical shape of the screw hole
c) the Young's modulus of the plate was decreased so that more functional stress could be transmitted to bone. According to **Wolff's** law a more normal bony structure would then result. To provide the desired elastic properties and good corrosion resistance of the plate (**Hoar** and **Mears, Steinemann**), titanium was chosen.

Oval «compression holes» and plates with slots have been used before. **Eggers** devised his sliding plate to prevent deleterious gaps between the fracture surfaces. His own studies however using teleradiology showed that the bone ends rarely slid together. These plates did not regularly function as hoped because by the absence of a proper countersink fitting between the screw and plate adequate stability was achieved only by eliminating the gliding movement.

Bagby modified a Colison plate, so that a conical screw head sinking into a screw hole against a straight edge could close an osteotomy gap. Tightening the screw automatically pushed the screw towards the fracture or osteotomy resulting in adaption of the bony surfaces. He concluded that wherever good contact of osteotomised surfaces was present together with rigid fixation, union occurred regardless of the amount of compression present. However he rightly pointed out that compression increases stability. In the present work a shape of screw hole was developed which retains the desirable compression and in addition offers the optimal lateral stability that was considered to be improvable in Bagby's design.

Oblique screws do not achieve similar compression, since once the plate is in contact with bone «seating» an oblique screw will not result in any displacement of the plate relative to the bone.

The new plate, which is described in detail on page 32, offers definite advantages over the well tested AO* plate provided that rigidity is maintained. This is synonymous with maintenance of applied load.

The purpose of the present paper is to outline the construction of and to report results obtained with titanium plates similar to those mentioned above. These plates were modified by fitting them with strain gauges to measure compression forces in the osteotomy and thus to monitor the stability of fixation.

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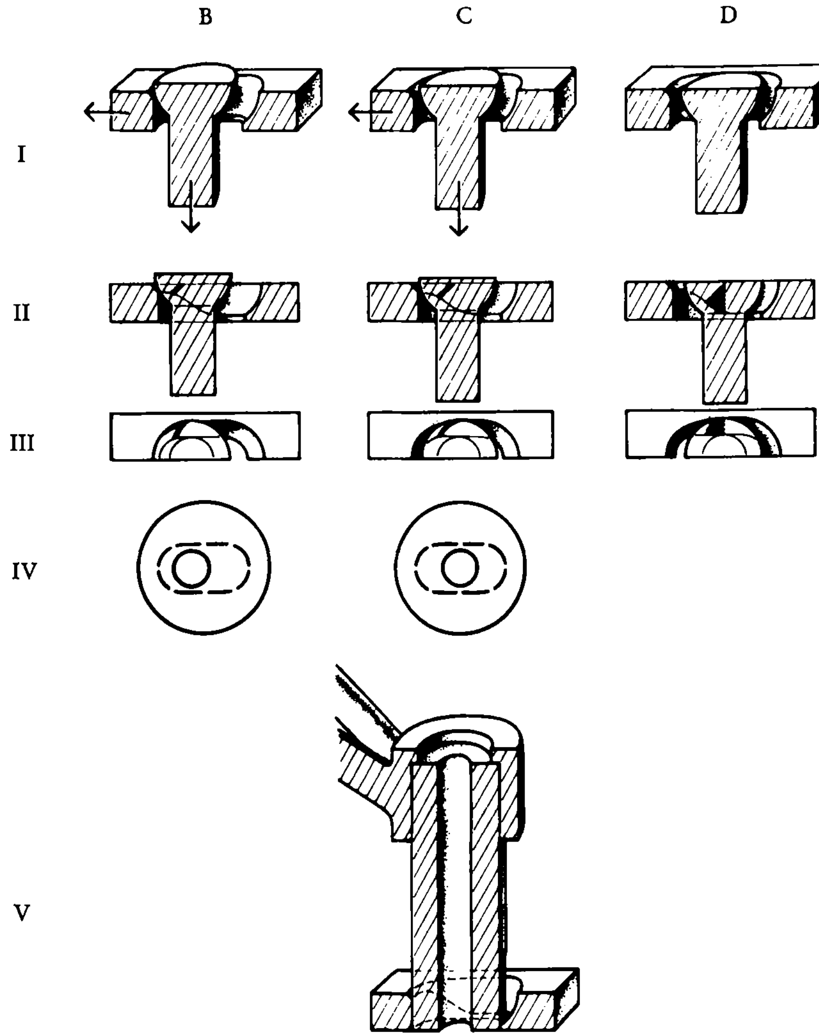

Fig. 3 B—D. **Relation of screw head and screw hole and positioning of drill guides.**
B: Positioning of the screw by the «load guide», (dislocates the bone fragment approximately 1 mm when the screw is driven home).
C: Positioning of the screw by the «neutral guide». Screw is placed near the end of the slope so that very little dislocational force results. Compression instituted by the «load guide» is slightly increased.
D: Position of screw when fully driven home.

I: Longitudinal section through screw and plate.
II: Line of contact between screw and hole seen from side.
III: Line of contact between screw and hole seen from above.
Note: Semicircular line of contact in B and C while in D the area of contact is part of sphere.
IV: Cross section of the corresponding positions of the drill guides.
B Load guide
C Neutral guide
V: Longitudinal section of the drill guide placed in a screw hole.

MATERIAL AND METHOD

The gauge plate used in these experiments was similar to the one used above, (see page 9), except for the following modifications:

1) the metal used for the plates was commercially pure titanium of which the ultimate tensile strength is about 80 Kp/mm^2 and the Young's modulus is 11 000 Kp/mm^2. The dimensions of the plate were adjusted to compensate for the somewhat smaller ultimate tensile strength of the material.
2) the load-cell was similar with respect to mechanical and electrical construction and the plate was designed to prevent any deformation of the load cell due to bending forces. The gauge compartment was arranged to leave a gap of 1 mm between the bone and the bottom surface of the compartment thus allowing tissue to grow between the bone and the plate (Fig. 4).
3) the plate has 4—6 sloping cylindrical holes so that when the screws are driven home they exert a compression force on the bone in an axial direction (Figs. 1—2). The angle of slope was chosen to eleminate any loosening of the screw due to mechanical reasons. The screw is spherically countersunk, exactly fitting the screw hole. Thus the screws have at least a semicircular line of contact with the screw in any position (Figs. 3 II & III). At the end of the slope when the screw has been fully driven home an area of contact between the screw and the hole is present, amounting to part of the sphere (Fig. 3D). This position, which offers maximum long term stability, should be achieved whenever placing a screw. To permit simultaneous adaption and compression of an osteotomy or fracture, the sloping cylinder provides a maximum horizontal displacement of 1.5 mm (Figs. 2A—D). The horizontal cylinder of the screw hole permits an additional horizontal movement of the order of 2.0 mm (Figs. 2 D and E).

To position the screw in the hole of the DCP (dynamic compression plate) two different drill guides are used. The **load guide** (Fig. 5) places the screw in the slope as seen in figure 3 B. When driven home the head slides down the slope displàcing the underlying bone towards the osteotomy. When the fracture or osteotomy gap has been closed and only slight further compression is needed the **neutral guide** is used to place the screw near its final position on the slope (Fig. 3 C). When the screw is driven home from this position it exerts additional mild compression. In practice, the neutral guide will be used to position most of the screws and it is vital that on each side of an osteotomy or fracture, at least 2 screws are fully driven home.

The experimental animals used were sheep, from 2—4 years of age. Anaesthesia and surgery followed the procedure described above (p. 20) with these exceptions:

To obtain well standardised experimental conditions for the fixation of the osteotomy, a special drill guide was used to drill 2 holes en each side of the osteotomy. The drill guide was U-shaped and when fixed to the bone prevented splitting during osteotomy. As above, 2 plates were used to obtain enough stability for safe weight-bearing. First the four-hole plate was applied on the posterior aspect and then a six-hole plate was fixed on the medial aspect of the tibia in a similar manner, this latter plate giving about 20% higher compres-

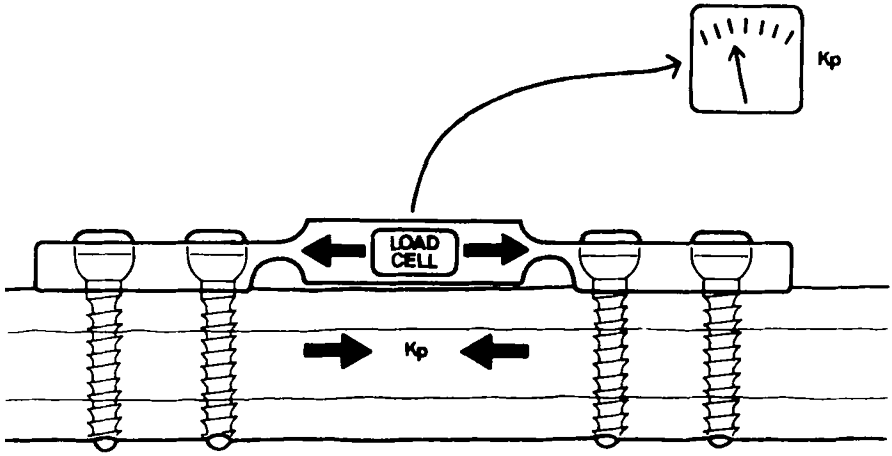

Fig. 4. Gauge plate used to control stability of fixation achieved by the dynamic compression plate. The slightest movement of the fragments due to instability results in a sudden pressure change. No such changes were recorded with the dynamic compression plate when used correctly.

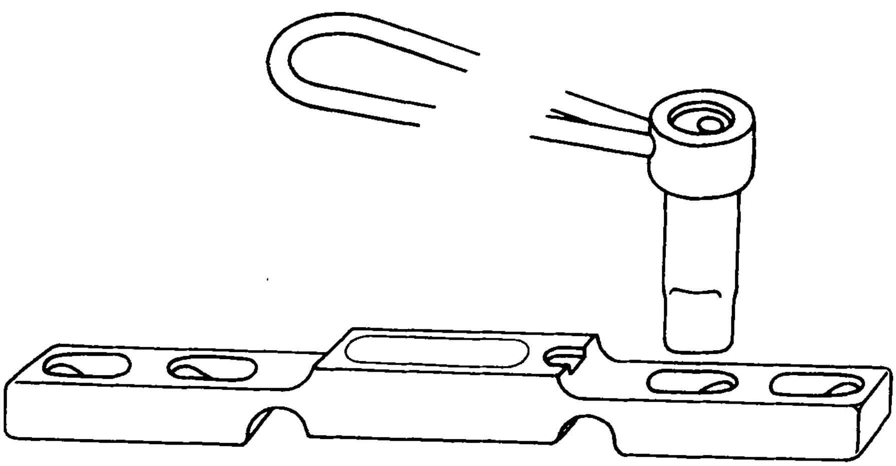

Fig. 5. Gauge plate and drill guide. Two types of drill guides permit the achievement of compression at two different levels: The load guide with an eccentrically placed hole is used as shown in Fig. 3, IV, B. Driving home the screw then results in high compression. The neutral guide with the hole in the middle is used to achieve mild compression Fig. 3, IV, C. This guide should be generally used under the condition that good adaption is obtained before.

sion than the four-hole plate. To delay weight-bearing until 3 weeks a simple tenotomy of the Achilles tendon was performed.

The plates used in animal experiments to be reported here were DCP's provided with strain gauges in a similar manner as outlined for the AO* compression plate (see p. 9). The «DCP gauge plate» is shown in figures 4 and 5. An additional simple metal clamp was employed near the plate to prevent the leads from breaking. Thus at the end of the experiment a final reading could be taken even after a lead break, by exposing the wire where it had been protected by the clamp. In this way a recalibration also could be made after removal of the plate.

The above mentioned experiment was performed on 8 sheep. An additional group of experiments was done with 4 sheep. In this group the osteotomies were performed on the metatarsus using a single plate for fixation and weight-bearing was prevented by combining ankle arthrodesis with tenotomy 3 weeks before the osteotomy. These animals were observed for 16 weeks. An additional animal with a tibia osteotomy fixed by two DCP gauge plates wes observed during 16 weeks. In this animal weight-bearing was not delayed by tenotomy. The specimens of bone were sectioned as described above (see p. 20).

RESULTS

The pressure recordings of 8 consecutive experiments which lasted two months are shown in figure 6. The pressure initially applied ranged from 70—180 Kp. As with the conventional steel plate, the pressure decreased progressively after an initial, somewhat steeper drop. In those animals which were observed during 4 months pressure gradually decreased before it approached zero with no sudden drop at any point.

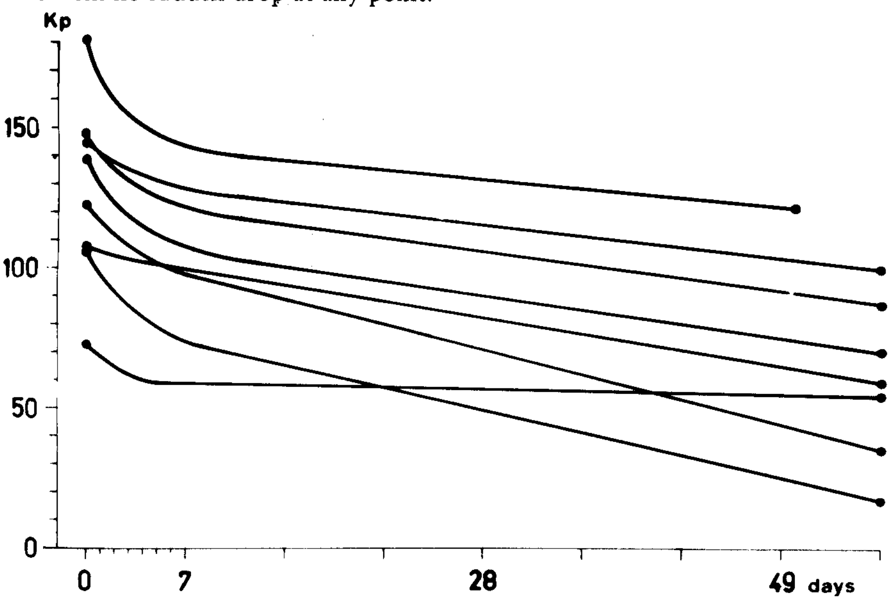

Fig. 6. Recordings of interfragmentary pressure in a group of transverse tibia osteotomies fixed by dynamic compression plates. There is no sudden fall of pressure.

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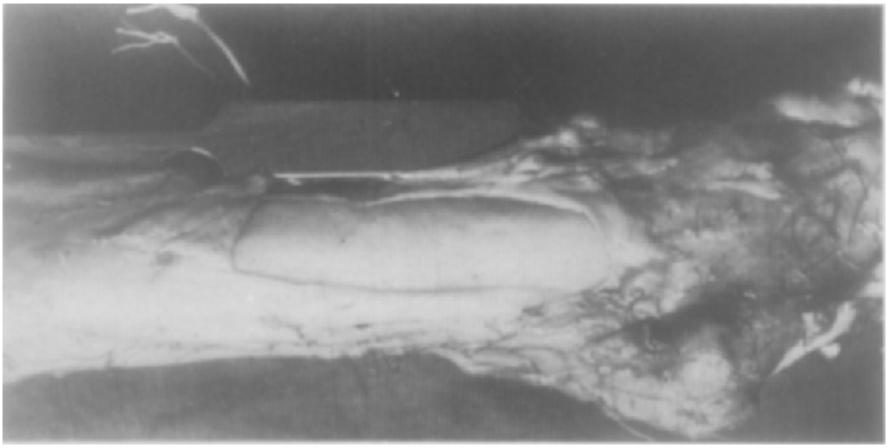

Fig. 7. Close up view of a metatarsus 16 weeks after transverse osteotomy and internal fixation with DCP gauge plate. The osteotomy is scarcely visible. There is minimal callus formation and no periosteal reaction can be detected.

Radiographic and macroscopic examinations both showed the absence of external callus formation (Fig. 7). The titanium plate provoked no visible reaction in the tissue and, in every case, a thin sheet of vascular tissue was found to be lying in contact with the metal. The bone adjacent to the plate was well vascularised. No titanium dissollution products were observed in the tissue although metal deposits sometimes are seen in human cases.

Histology revealed that the osteotomy was directly bridged by new osteons in the pressure area (Fig. 9). Beside this area of contact and pressure near the plates, there was usually a gap between the fragments on the opposite side of the osteotomy. Where there was a gap the osteotomised bone clearly did not support any pressure. Nevertheless such a gap area benefitted from the stability provided by the area which was in contact and supported pressure. Under such stable conditions small gaps were directly bridged by new osteons (Fig. 8) while larger gaps were first filled with lamellar bone and then remodelled in the long axis of bone (see p. 23 Fig. 6).

At 8 weeks remodelling was still incomplete (Fig. 8); at 16 weeks the osteotomy was healed (Fig. 9). There was no significant resorption of the osteotomy surface seen either at the «pressure side» or at the «gap side» and in no case was any cartilage or fibrous tissue detected in the gap. As seen in figure 9 there was minimal callus present in spite of early full weight-bearing in the tibia osteotomy which was observed for 16 weeks.

DISCUSSION

As **Egger** claimed, the function of an implant in internal fixation is to counteract the forces producing shear or distraction*. His plate was considered to have failed to achieve this result however, since it did not apply compression to counter distraction and did not fully prevent shear since the shape of its

* distraction is a movement which results in opening the fracture gap.

screw seat did not offer optimum lateral stability. This latter problem has plagued most other slotted plates. The key to success is congruity between screw and plate which in the present plate is produced by three-dimensional seating of a spherically countersunk screw head in a cylindrically countersunk plate. This design overcomes the chief disadvantage of the ordinary slotted plates while keeping its primary asset of preventing the plate from holding the fracture gap open.

Measurements with DCP's (dynamic compression plates) provided with strain gauges («DCP gauge plates») showed that with the DCP axial compression of the same order as with AO* compression plates with external compressor was obtained. Before use in humans, it was advantageous to determine wheter the DCP could be relied upon to maintain rigidity as long as the original AO* compression plate. It was demonstrated that with two DCP gauge plates applied to an osteotomised sheep tibia, the rate of decrease of compression measured over 8 weeks matched that obtained with the AO* plate (p. 21). Experiments with osteotomised metatarsi of sheep stabilised by DCP gauge plates showed a slow decay of pressure over 8 weeks with demonstrable compression forces up to 4 months. At no time did a sudden drop of pressure indicate the presence of instability.

The histological findings of Haversian remodelling directly bridging the osteotomy, without formation of external callus, were identical to those observed with conventional steel plates. At 8 weeks the osteotomy was bridged by some osteons but remodelling of the cortex was only partial (Fig. 8). At 16 weeks examination of the metatarsi and of the tibia showed the osteotomy to be clinically united with minimal callus formation (Fig. 9). The cortex was undergoing extensive Haversian remodelling with much osteogenesis within the canals. The DCP clearly fulfils the function of giving sufficient rigidity to allow primary healing.

The main function of the horizontal cylinder is to allow for minor displacements of the screws relative to the long axis of the plate. The present design of the screw hole permits a screw which has been positioned at the intersection of the two cylinders to move only towards the fracture gap. The major reason for allowing this kind of displacement is to prevent screws from locking during the procedure of closing the fracture gap (this procedure may involve several adjustments of the screws in order to ensure optimum fixation). An additional advantage of the allowed axial displacement is to prevent an eventual imperfect closure from being held apart. This type of design also results in a more beneficial stress distribution; in previous experiments with AO* gauge plates we have observed changes of the initially applied pressure when seating subsequent screws. In practise the DCP served the above mentioned function while maintaining a satisfactory amount of compression and stability.

The screw has a spherical seat. This shape of the screw countersink allows flexibility in directing the line of action of the screws to achieve the desired force on the fracture surfaces. It also permits to obtain a better grip in comminute fractures.

Corrosion and fatigue fractures in compression plates usually occurred in the outer screw holes or at some other highly stressed point of a plate applied to a

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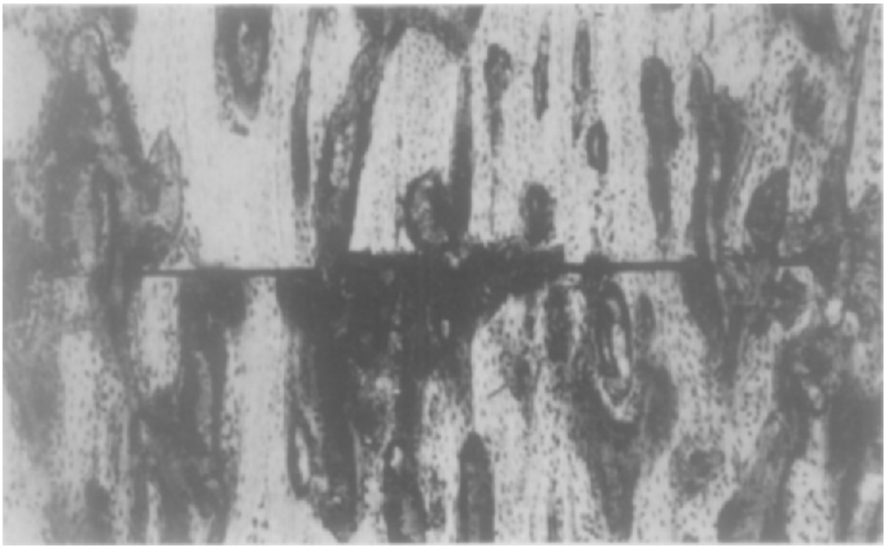

Fig. 8 Histology of a transverse tibia osteotomy 8 weeks after fixation with two DCP gauge plates. At this time the osteotomy is only partially remodelled. The gap at this particular site of the osteotomy measures about 20μ.

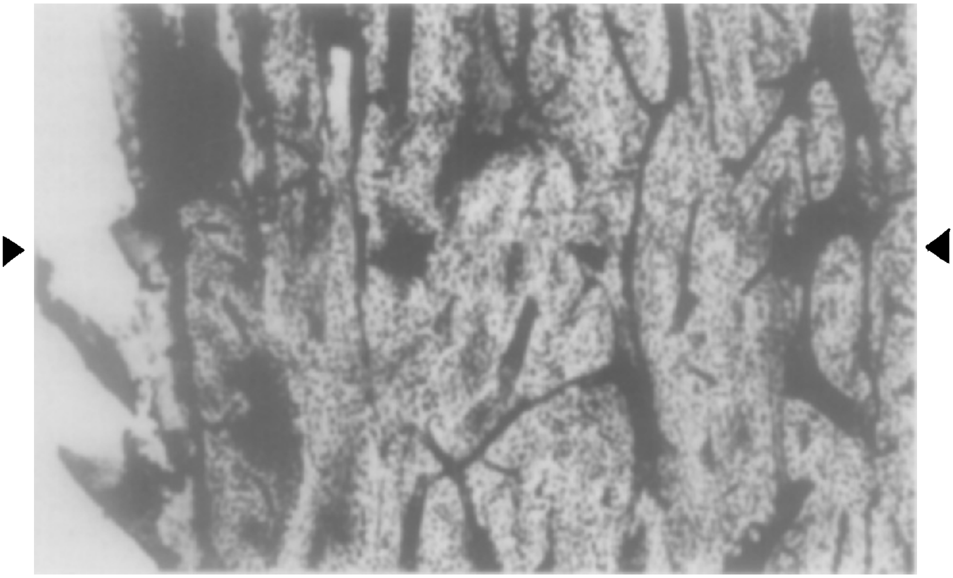

Fig. 9. Histology of a transverse tibia osteotomy 16 weeks after stable internal fixation with two DCP gauge plates; remodelling is far advanced. At this site of firm contact pressure is transmitted yet there is no sign of surface resorption. Note the minimal amount of callus at the end of the osteotomy indicating complete stability in spite of early weight-bearing.

weight-bearing bone (e. g. the tibia). Such stress concentrations may also be created by eccentric positioning of a screw in a conical seat. The present plate and screw design prevents these stress concentrations.
In our series of experiments with sheep good rigidity was maintained and prompt healing achieved in two types of experimental osteotomies. Based on these results a clinical testing program has been initiated. Preliminary results are reported in a separate paper (Allgöwer et al. see p. 45).

SUMMARY

Rigid fixation by conventional compression techniques while permitting economical primary bone healing is liable to protect bone from physiological stresses and may thus induce osteoporosis of the cortex. Furthermore there is a locking action of a screw hole with conical fitting under weight-bearing conditions.

A compression plate was constructed therefore which would provide the same amount of stability but prevent locking action of the screws and permit axial compression without the use of an external compressor.

Long term pressure recording as well as histology give evidence of maintained stability.

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CLINICAL EXPERIENCE WITH A NEW COMPRESSION PLATE «DCP»

by

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CLINICAL EXPERIENCE WITH A NEW COMPRESSION PLATE «DCP»

INTRODUCTION

Three groups of experimental findings are relevant to the clinical application of compression plates and to possible improvements in their design.

Static loads of the order of 60 to 140 Kp applied to cortical bone are found to be maintained over several months and during this time gradually diminish to near-zero pressure. There is no sudden loss of pressure due to bone necrosis. From an engineering standpoint, such a compression system therefore is able to secure maximum stability of internal fixation. Biologically it is compatible with the healing process. The gradual pressure loss mentioned above is induced by bone remodelling of the Haversian system slowly replacing the compressed osteons by new ones. There is no appreciable difference in remodelling of a cortex whether an osteotomy is present or not, provided the contact surface is rigidly stabilized. Remodelling however leads to bridging of the osteotomy gap, resulting in direct repair (**Perren et al**, see p. 23).

Such a process has been found in the osteotomised radius in the dog (**Schenk et al.**) in the tibia of the sheep (**Perren et al.**, see p. 24) and in the tibia of the rabbit (**Rahn et al.**). It has also been observed in the tibia of a human adult who died three months after internal fixation.

Endosteal or periosteal contribution to bone remodelling consists mainly of increased blood supply to the cortex. To what extent endosteal or periosteal callus formation occurs depends on the stability of the internal fixation (**Hutzschenreuter et al.**). The rationale of the rigid AO* compression system therefore is well documented and the high success rate after adequate operation is not surprising. (**Anderson, Rhinelander, M. E. Müller, Allgöwer & Willenegger**).

The rigid connection between screws anchored in the comparatively deformable bone on the one side and in the rigid plate on the other has however certain drawbacks:

— under weight-bearing conditions a rigidly plated bone undergoes a smaller elastic deformation than a bone without plate. This difference is the greater the longer the plate. A screw head at the end of a 15 cm plate will have a tendency to move towards the center of the plate over a distance of about 30μ when weight-bearing with 100 Kp is instituted. This gives rise to considerable stress at the point of contact between screw and plate and may induce corrosion and even fatigue fracture of the screw.

— in the conventional procedure using the separate compressor, compression is instituted at the beginning of the procedure and then the screws are inserted into the plate. Eccentricity in positioning of conically seated screws in such a plate will result in unpredictable alterations in the applied load and in stress concentrations

— elastic deformation of the cortex will be reduced by the locking effect of the tightly fitting screws, because the complex of bone and plate will become very rigid. The rigidly fixed plate with its high Young's modulus results in considerable «stress protection» to the plated part of the diaphysis,

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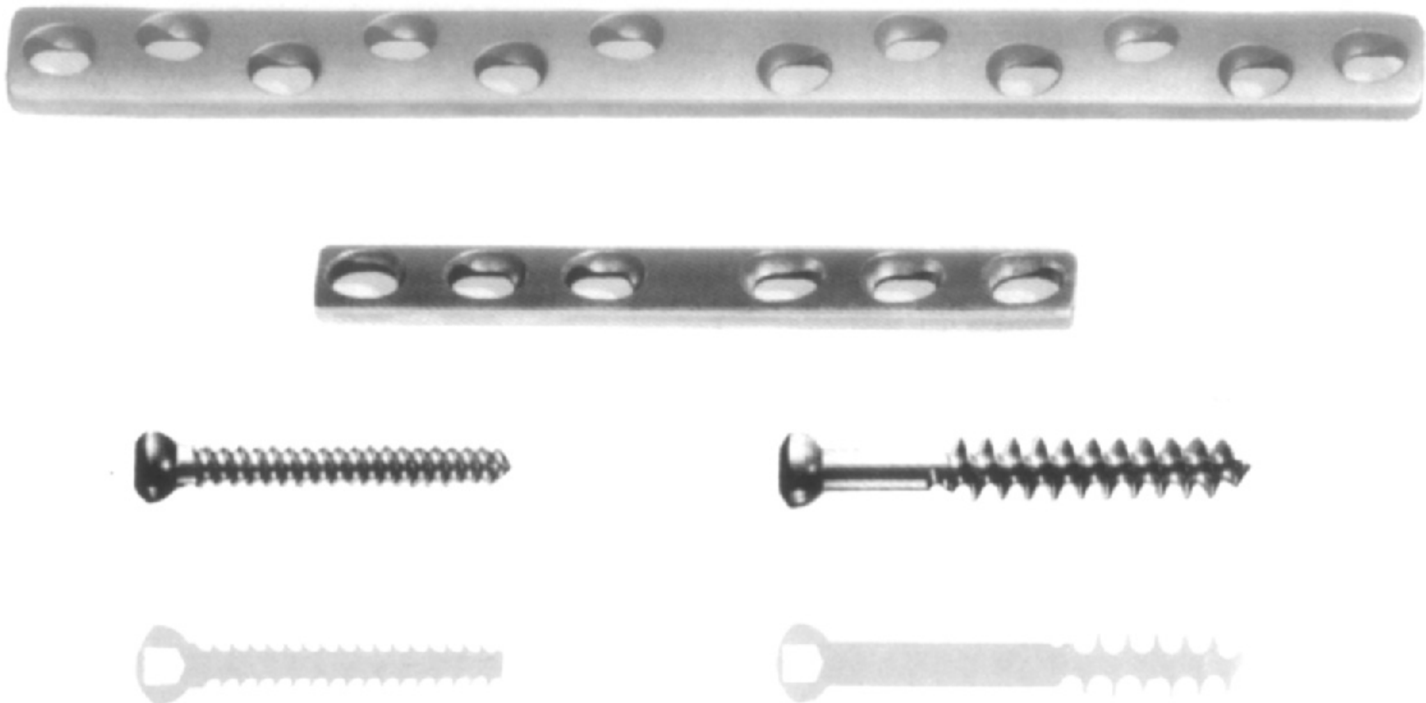

Fig. 1. **Large and small «dynamic compression plate» DCP** with cortical and cancellous screws (photograph and section), made of commercially pure titanium. Apart from the configuration of the screw holes and screw heads, the plates are similar to the conventional plates made of AISI 316 L steel described by M. E. Müller, Allgöwer and Willenegger.

especially when double plates are used. This — according to Wolff's law of adaptation to functional demand — will cause bone destruction to prevail over osteogenesis in the course of remodelling and thus lead to osteoporosis of the cortex. In turn this may give rise to fatigue fracture after removal of the implant.

The locking effect of the screws, as well as part of the «stress protection» can be eliminated by a slotted configuration of the screw holes and an increase in deformability of the plate, provided that the relative shape of the screw seat is able to protect the fracture from shear and distraction. Together with **Perren** and **Russenberger** we have been able to design a screw seat which enables a tension force to be applied to the plate by the screw head when the screw is driven home (**Perren et al.**, see p. 32). The «Dynamic Compression Plate» (DCP) has been described previously. The DCP has been proved to offer adequate stability of fixation. Its main specification will be given under «material and method». It is the purpose of this paper to report our observations in a consecutive series of clinical cases using the DCP. Apart from eliminating in most of our cases the necessity for any compression device, (thus allowing a shorter incision) this plate seems to offer definite biomechanical as well as metallurgical advantages over the conventional plates made of AISI 316 L as described previously (**M. E. Müller, Allgöwer & Willenegger**).

MATERIAL AND METHOD

The dynamic compression plate is made of commercially pure titanium treated to increase the ultimate tensile strength. The Young's modulus of titanium (11000 Kp/mm²) is markedly lower than that of stainless steel or of vitallium®. The fatigue resistance of titanium is good (**Steinemann**) and its resistance to corrosion in body fluid is excellent (**Hoar & Mears, Steinemann**) as in this fluid titanium does not show any pitting corrosion.

The over-all shape of the plate as seen in figure 1 corresponds to that of the AO* plate. The cross section of the dynamic compression plate is slightly larger than of the AO* plate. This is to allow for the somewhat smaller ultimate tensile strength of titanium (80 Kp/mm²) when compared to AO* steel (90 Kp/mm²).

The screw seat has been designed as illustrated in figures 2 and 3 in order to combine

— compression of the fracture when the screw is driven home
— firm precision fit of the screw head in the screw hole at all times
— prevention of locking effect of the screw.

The screw hole, the shape of which has been described in detail (**Perren et al.**, see p. 32) is part of the geometrical figure formed by two cylinders a sloping one and a horizontal one intersecting at an obtuse angle. The screw has a spherically countersunk head, exactly fitting the cylinders of the screw hole. The line of contact between screw and screw hole is a semicircular line. At the intersection of the two hemi-cylinders, the contact area is part of a sphere. In all other aspects the screw is identical with the AO* screw. It is not selftapping and has a hexagonal imbus. The screw holes of the plate ends will also accomodate cancellous screws with a larger thread.

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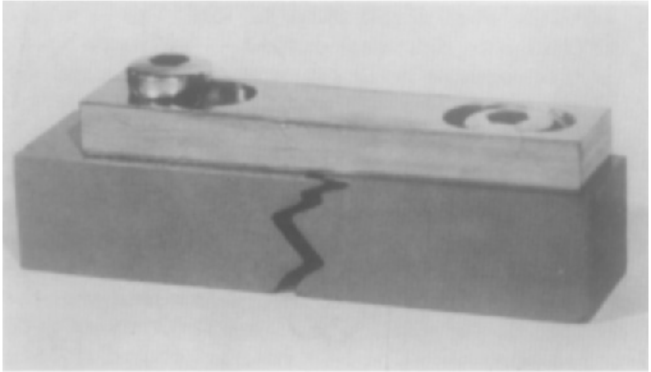

Fig. 2a

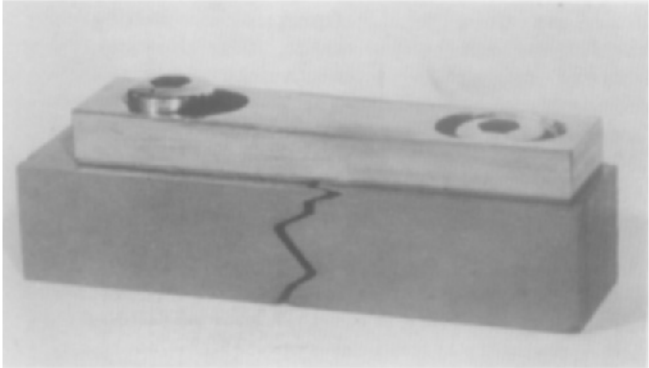

Fig. 2b

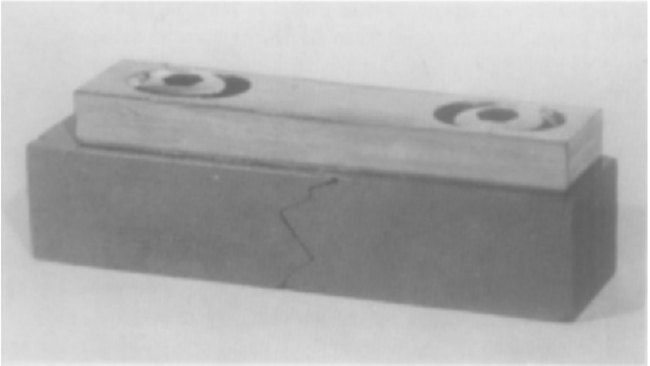

Fig. 2c

Fig. 2. Compression fixation by the DCP. Compression is obtained by the «spherical gliding principle». The spherically countersunk screw head is congruent to the hemicylindrical sloped screw hole and approximates the bone ends when driven home. At the end of the slope, the hemispherical screw head has a larger contact area with the plate corresponding to part of a sphere (see also **Perren et al.**, Fig. 1, p. 32). The screw head in figure 2c lies at the beginning of the horizontal hemicylinder of the screw hole which offers the possibility of «passive movement» of the screw.

To position the screw in the screw hole, drill guides are used (Fig. 4). Two different types of drill guide (Fig. 5) place the screw either in the middle of the sloping cylinder (load guide A) or near its lower end (neutral guide B). The use of the load guide produces a horizontal displacement of the fragments toward the fracture of about 1 mm when the screw is driven home. This guide is used to eliminate the fracture gap. The neutral guide is used when the fracture gap has been closed and put under pressure so that only slight further compression is needed.

When the screw is driven home, there remains the possibility of a passive movement of about 2 mm of the screw head towards the end of the horizontal hemicylindrical screw hole. This should prevent any locking effect of the screw, to avoid unpredictable loss of load when additional screws are inserted and to reduce the load of each screw. Thus axial stress will be transmitted to the cortex when weight-bearing is begun or muscular forces begin to act on bones such as those of the upper limb.

Up to now 300 human cases have been operated using the DCP with very gratifying results. In this first report we only include the first 60 consecutive cases done between January 1966 and February 1967, which until now have been fully followed up, namely:

— tibia: 53 fresh fractures, (two cases of non-union and one refracture)
— radius: 2 shaft fractures
— femur: 4 fresh fractures, one infected non-union
— clavicle: 1 non-union

Three patients died from coronary occlusion or pulmonary embolism in the weeks following their injury and therefore are not included in this report, although bone healing proceeded normally.

There remained 50 tibial fractures in 49 patients who could all be followed up fully. They constitute the main part of this report. They were contacted 6—8 months after operation by a questionnaire and one year after operation there was an individual examination of each patient. After a mean time of 69 weeks (from 45 to 100 weeks) all implants were removed according to the following procedure:

1. Distal part of scar opened, so that the distal three screws could be exposed
2. Removal of overlying tissue for histological examination
3. Color photograph of plate in situ
4. Removal of all other screws by small incisions and removal of the plate
5. Photograph of plate bed
6. Biopsy of plate bed for metallurgical and histological examination

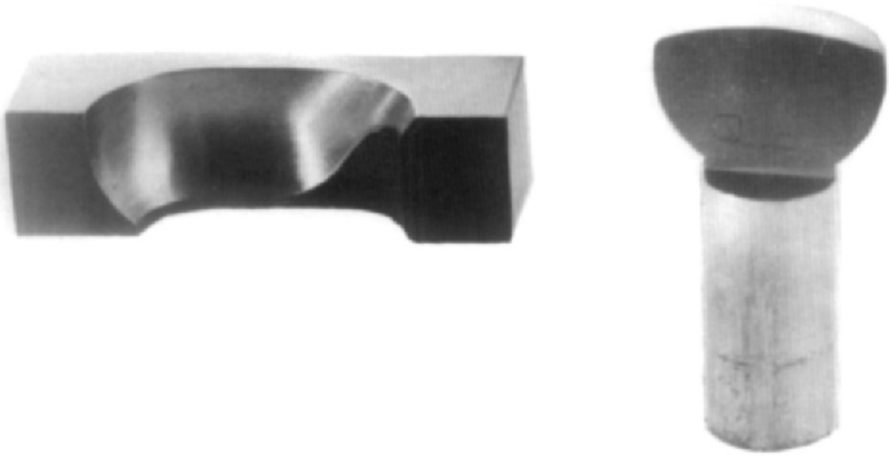

Fig. 3. **Longitudinal section through screw hole and screw head of the DCP.**
The spherical countersunk screw-head is any position congruent to the hemicylinders of which the screw hole consists.

Fig. 4. **DCP with drill guide and drill.**
The drill guide fits exactly in the screw hole and thus precisely positions the drill in respect to the sloped cylinder.

RESULTS

Tibial fractures (50 fractures in 49 patients)

The average hospital stay was 11 days. No infection occurred. Two patients showed local tenderness on premature weight-bearing, which immediately subsided when weight-bearing was discontinued. No secondary operation was required except for the removal of the plate.

During the course of healing, there was little discomfort in the operated leg, except for the cases mentioned above. On removal of the metal, 65% considered themselves completely normal, 35 % had minor complaints. Ankle and subtalar joints recovered completely.

All 50 fractures showed good **radiological consolidation** at the time of removal of the metal (Figs. 6c and d). The cortical bone appeared quite homogeneous and dense even deep to the plate. There seemed to be more evidence of endosteal callus formation than in cases plated with conventional AO* plates, but the difference seems hardly significant. The rate of so-called «primary bone healing» which means healing with no radiological evidence of callus was 50 % in this series compared to 70% in previous series with conventional AO* plates.

In 37 fractures we were able to remove all implants ourselves. In each case the tissue immediately deep to the plate was macroscopically well vascularized. The other tissues surrounding the plate showed in most cases a firm contact with the implant, so when removing the plate a thin layer of vascularized tissue adhered to the titanium implant. Of 37 fractures, 18 showed no evidence of metal deposits whatsoever, while 17 had a slight coloration of the tissue surrounding the distal part of the plate, located especially at the neck of the screws. According to **Steinemann** such a coloration corresponds to about 100 PPM of titanium in the tissue. Two cases showed significant metallic coloration of the tissue. It was interesting that visible metal deposits were not parallelled by clinical signs of irritation.

Histological examination of the tissue surrounding the plate revealed a comparatively small layer of fibrous tissue adjacent to plate (Fig. 7a). Capillaries were seen in the immediate neighbourhood of the implant (Fig. 7b). According to the macroscopic findings, in about half of the cases metal deposits were seen, the quantity of which ranged from detectable to significant deposition (Fig. 7c). Histologically, titanium deposits hardly provoked any inflammatory reaction or proliferation. This finding is consistent with other experimental findings (**Steinemann et al.**).

Of special interest was the fact that the slotted holes of these DCP's were filled with bone. The removal of the plate may thus be somewhat more difficult, than with ordinary stainless steel plates. Such a bone formation certainly indicates the good tolerance of the metal employed.

Forearm fractures and non-unions

Both our radii united without any immobilisation of the injured forearm and without any discomfort to the patient (Figs. 9 and 10). Figure 11 shows a recent

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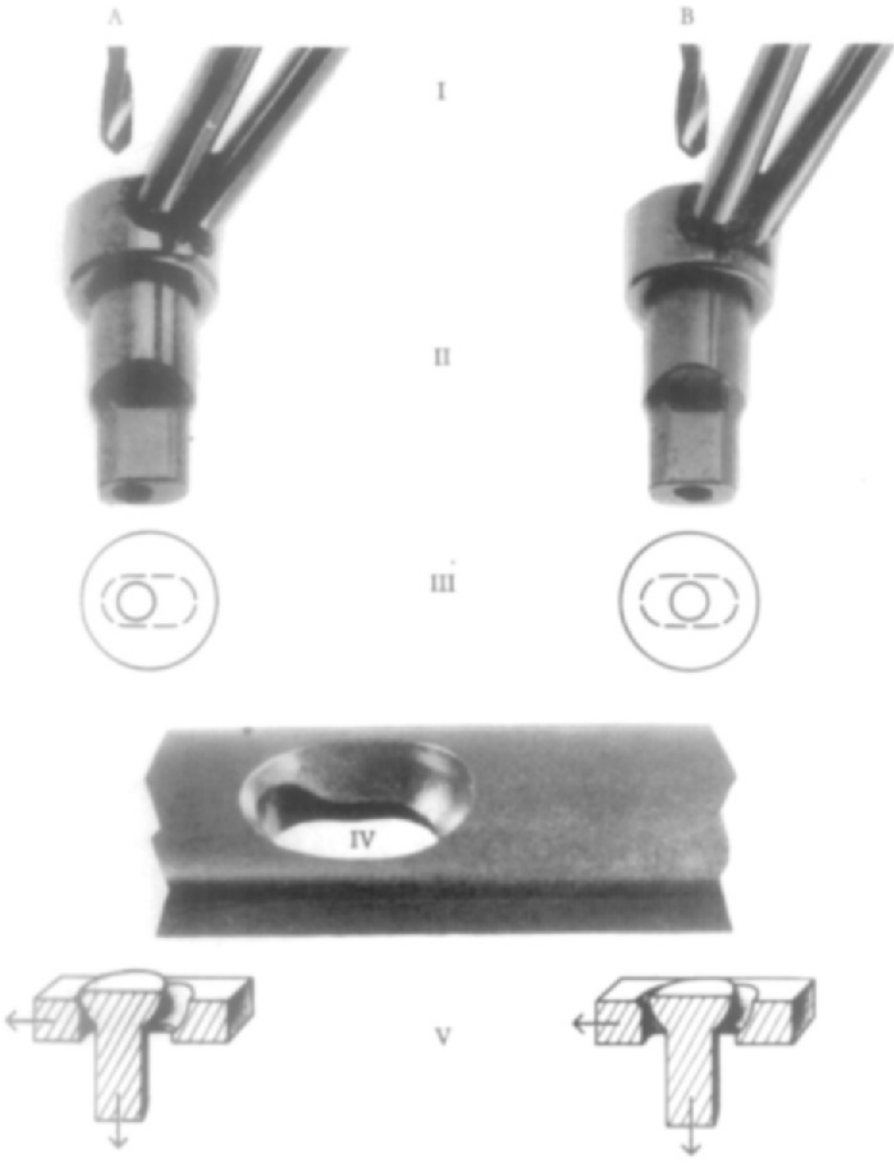

Fig. 5. **The use of the two different guides (A: load guide, B: neutral guide).**
I: Drill of 3.2 mm diameter.
II: Drill guide seen from below. (Note the eccentrical hole in the load guide (A) placing the screw on the slope of the screw hole. The neutral guide (B) places the screw near the end of the slope thus increasing compression to some extent when the screw is driven home).
III: Cross section through the drill guide. A) load guide with eccentrical hole. B) neutral guide with centrical hole.
IV: Screw hole of the plate seen from above. The drill guide fits precisely in the lower opening of the screw hole.
V: Dislocational effects of the screw when driven home.

case not included in the above mentioned series of a non-union of the forearm healing rapidly after fixation by DCP's.

The rather avascular non-union of the clavicle (Fig. 8a) was treated by compression fixation alone without any cancellous bone graft. At 50 weeks it showed good consolidation (Fig. 8b) permitting removal of the metal at this time.

The infected non-union of the femur constituted a major challenge, because of extensive cortical necrosis and bone defect which had to be replaced by cancellous bone grafts. For stabilization a double plate was required and despite the rather massive implant, bony union was surprisingly rapid and wound discharge was soon minimal. It subsided 6 months before removal of the plates. This is a most unusual observation when using other material in infected sites. Bone healing in the face of infection may occur with various metallic plates, but usually drainage continues as long as the implant is in place. In a subsequent series not reported here, we had a similar experience with other infected non-unions of the femur where the wound also healed promptly.

DISCUSSION

The rigid AO* compression plate of stainless steel facilitates the main aims in the operative treatment of fractures and non-unions, namely full functional recovery combining four principles:

— anatomical reduction
— atraumatic technique
— stable fixation
— immediate postoperative mobilisation without externel fixation.

The stability achieved is sufficient to neutralize the fracture or the non-union allowing cortical bone healing together with immediate postoperative mobilization of the injured limb. The drawbacks of the system are marked stress protection of the plated cortex by the locking action of the tightly fitting screws and unpredictable changes of compression by screws inserted eccentrically.

The question arises whether it is possible to avoid the disadvantages of the rigid compression plate without losing its advantages, namely the successful neutralization and compression of the fracture.

In osteotomised tibiae of the sheep fixed with DCPs we have indeed been able to show that the rate of pressure fall is identical to that observed with conventional AO* plates (**Perren et al.** see p. 21). This is good evidence that stability is in fact well mainained. Results in the clinical series confirm this point very well. Not one failure due to instability was encountered in the 60 cases.

The next question is whether we have really eliminated the above mentioned drawbacks of the rigid compression plates. There are some indications that this is indeed true. Cortical bone in the plated area seems more solid and more homogenous radiologically when using DCP than with ordinary AO* plates. On removal of the plate, the site appears to be distinctly better vascularized. The patients also complain less of discomfort in the lower leg fractures, but this point evidently is very difficult to quantitate.

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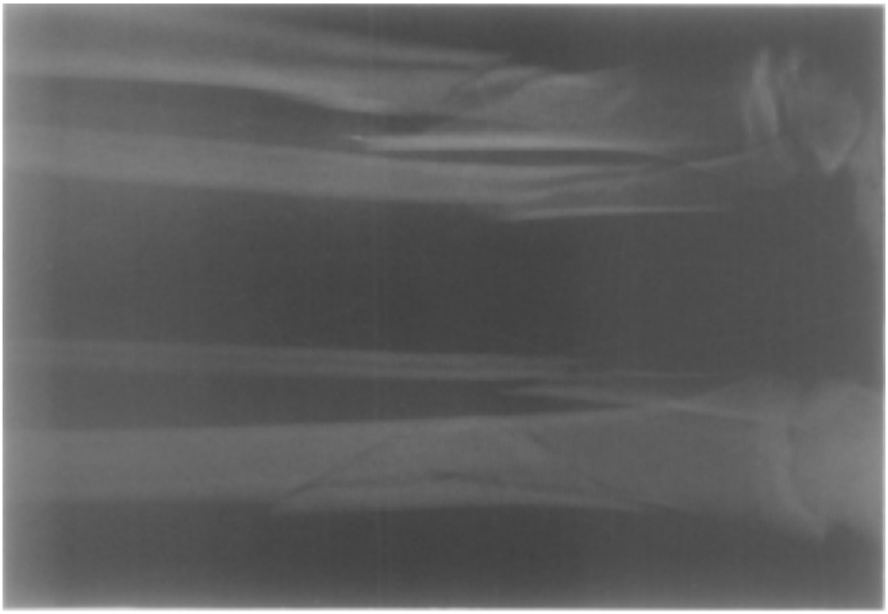


Fig. 6a

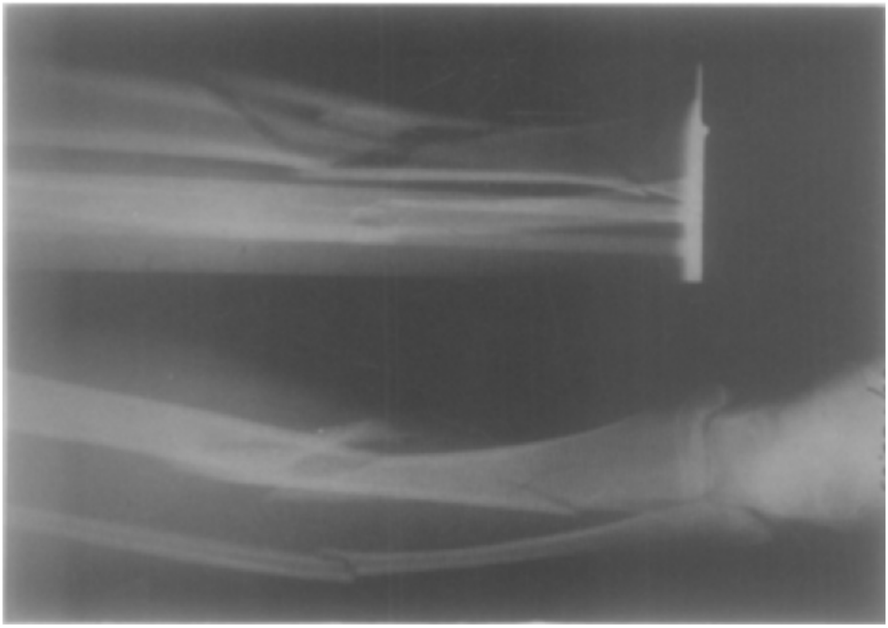


Fig. 6b

Figs. 6a and b. Fracture of both tibiae and fibulae in a 22 year old woman after accident.

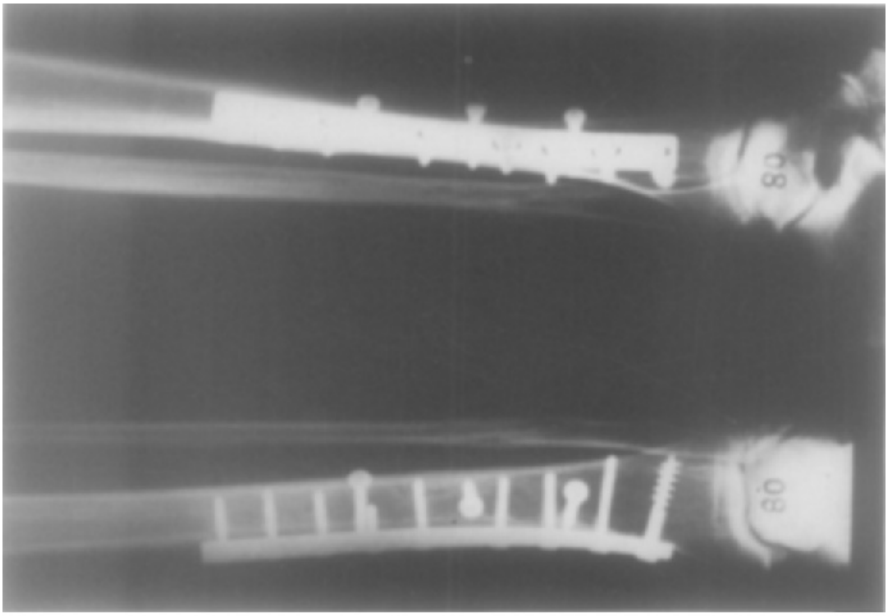


Fig. 6c

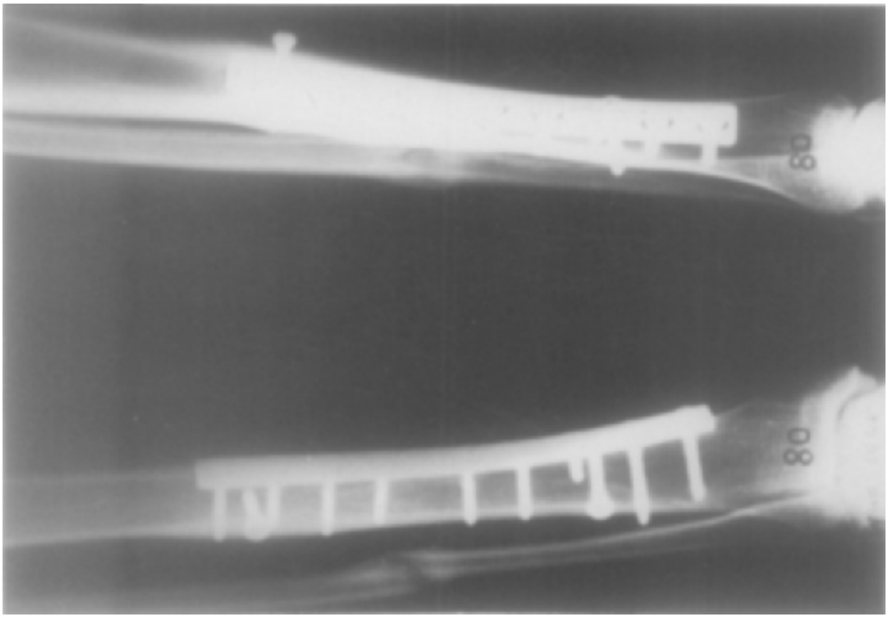


Fig. 6d

Figs. 6c and d. Fracture of both tibiae and fibulae in the same patient 80 weeks after application of DCP. Note the dense structure of bone underlying the DCP.

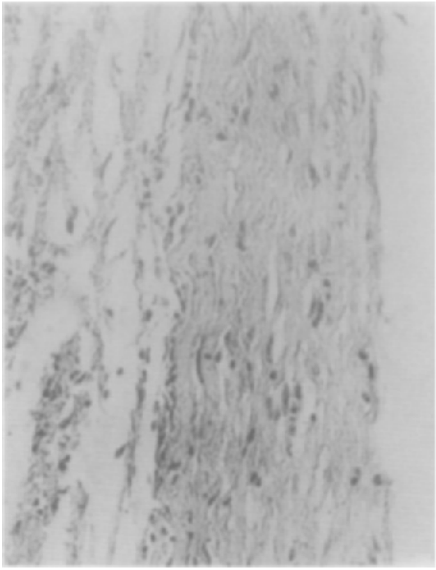


Fig. 7a

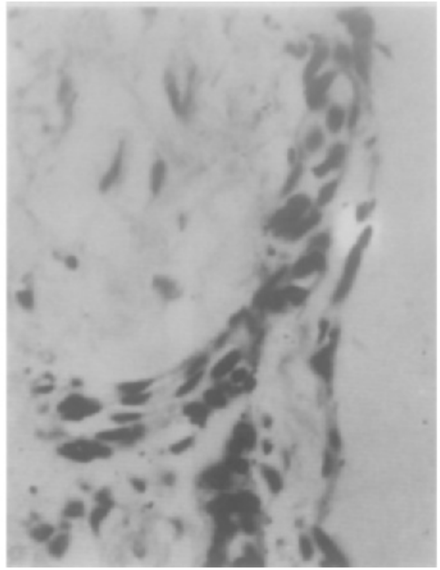


Fig. 7b

Fig. 7c

Fig. 7. **Histology of tissue adjacent to the plate.**
a) Loose connective tissue immediately adjacent to the plate, which shows no detectable proliferation or inflammatory reaction.
b) **Capillary immediately adjacent to the plate.**
c) **Deposit of titanium in tissue at removal of implant (56 weeks after internal fixation).**
Absence of inflammatory reaction around metallic deposit. Since using anodically oxidized titanium plates no further metal deposits have been observed.

Fig. 8b

Fig. 8a

Figs. 8. a and b. Non-union of collar bone. 18 months after fracture the non-union was treated by a DCP and one additional lag screw (Fig. 8a) without any additional cancellous bone transplant. The x-ray taken at 50 weeks after operation (Fig. 8b) shows bony union.

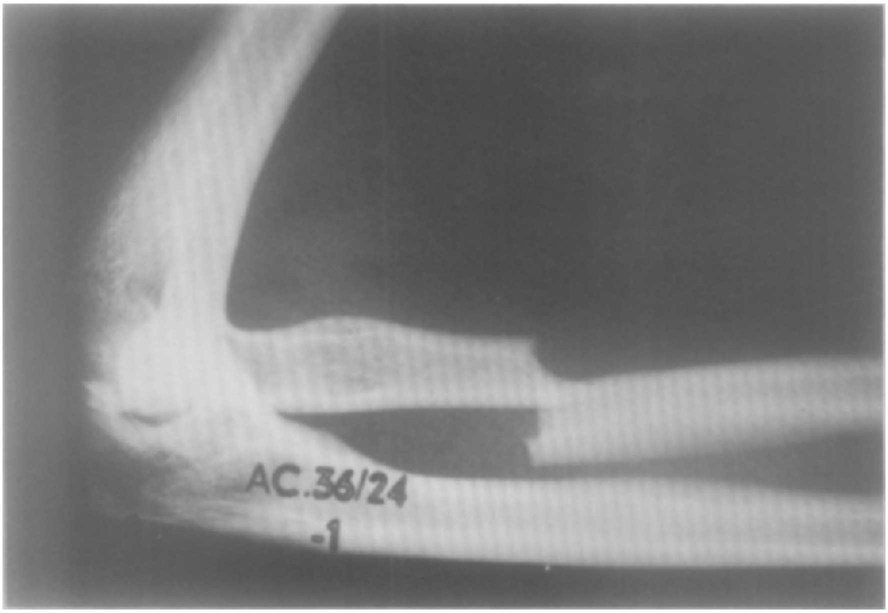


Fig. 9a. Transverse radius fracture fixed by a six-hole DCP and treated without any external fixation, showing full functional recovery one month after operation.

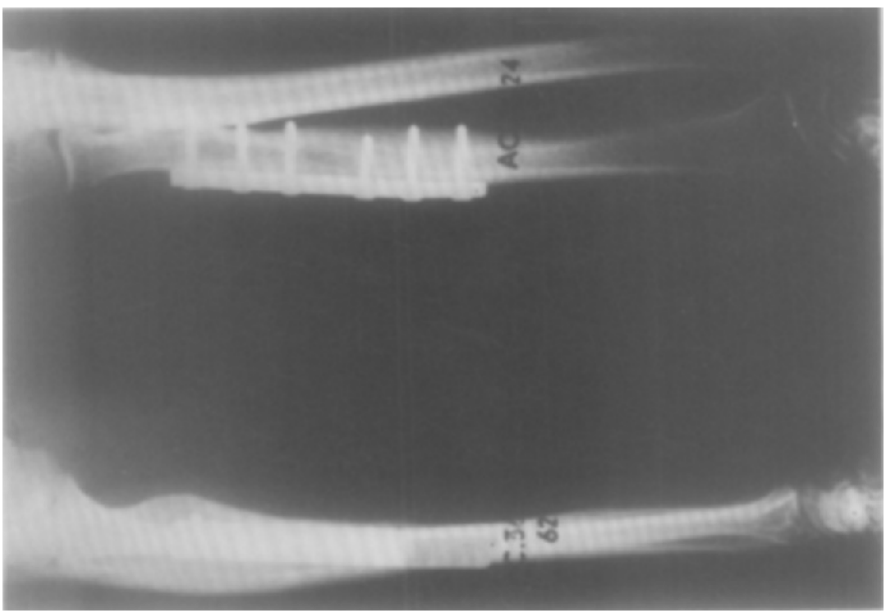


Fig. 9b. Result after 62 weeks.

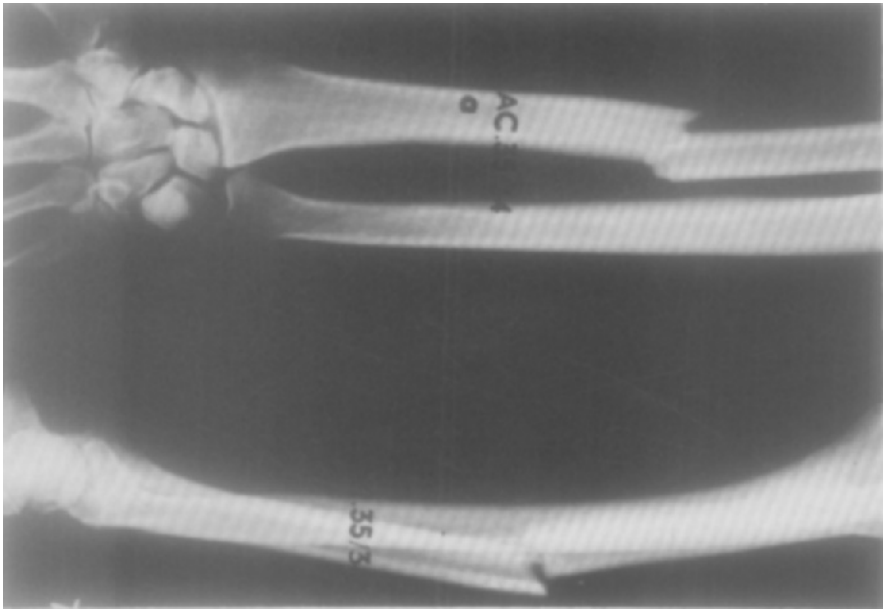


Fig. 10a. Transverse radius fracture fixed by a six-hole DCP and traeted without any external fixation, showing full functional recovery one month after operation.

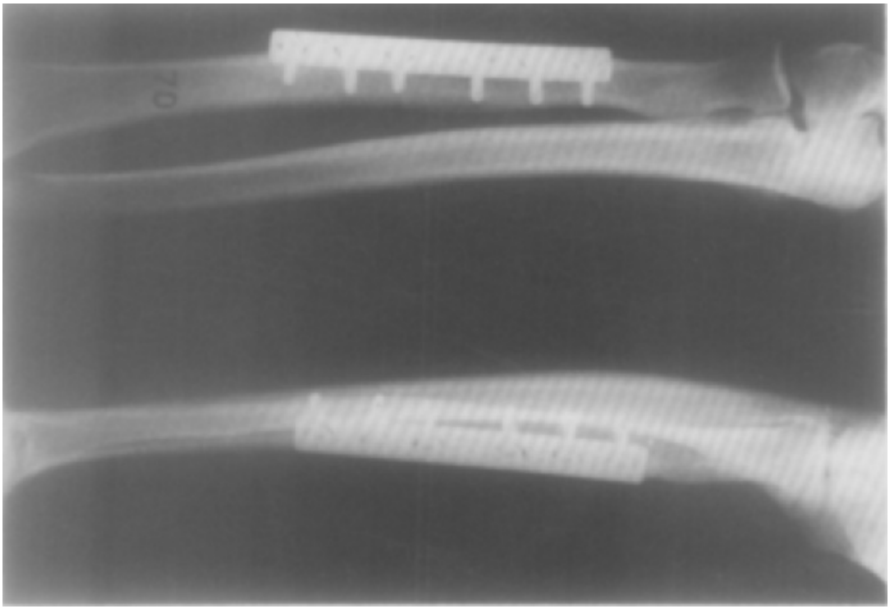
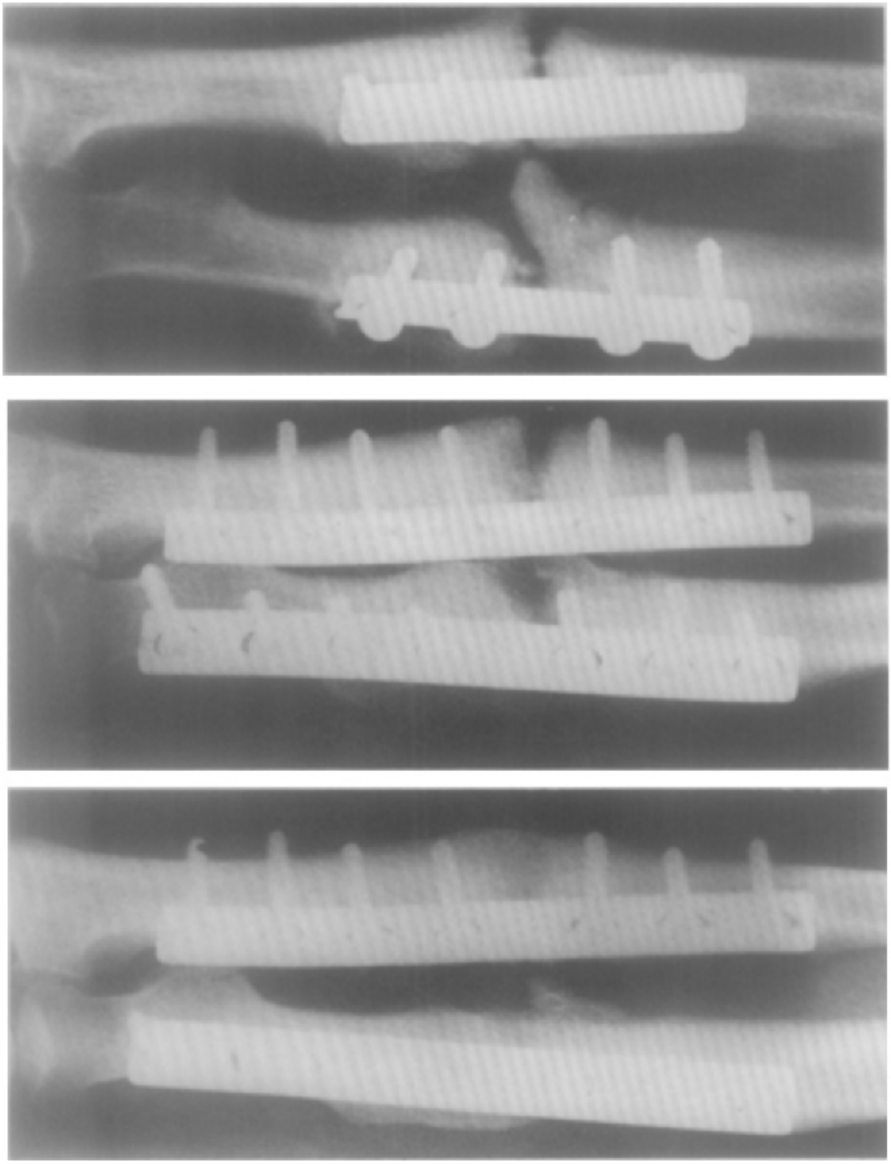


Fig. 10b. Result after 70 weeks.

Since we are introducing two changes simultaneously — configuration of the screw hole and change of metal — we are not quite sure which has played the greater role in this respect. Titanium however seems to be surprisingly well tolerated and the increased deformability of the DCP certainly did not compromise the results.



Figs. 11, a - c. a) Non-union after inadequate fixation of a forearm fracture.
b) X-rays taken after $1^1/_2$ months.
c) X-rays taken after 8 months showing bony union almost completed.

Pitting corrosion is no problem with titanium. The metal deposits present in about half the cases of this series stemmed probably from pickling. The had apparently little clinical signifiance and did not induce tissue reaction (Figs. 7a—c). Using anodically oxidized titanium plates we have not observed metal deposits in a further clinical series of 300 cases not reported here.

It is well known that **Eggers,** as well as **Bagby** advocated the use of slotted plates. An internal fixation achieved by the use of the **Eggers'** plate does not resist distraction nor shear. The lateral support of **Bagbys'** plate was not considered to be optimal. From our previous observations in the experimental animals and now in clinical cases, we may conclude that it is possible to use self-compressing plates if care is taken that lateral stability and axial compression are as well maintained as with a conventional compression plate. This plate (DCP) combining the practical benefit of requiring less exposure with a more physiological stress transmission to the bone cortex, therefore may offer some distinct advantages.

SUMMARY

The dynamic compression plate (DCP) has been succesfully applied in fresh fractures as well as in infected and non infected non unions. Detailed instructions for its application are given. The DCP is well tolerated by the tissue and offers advantage of less exposure and more adaptability to the individual case. The experimental prove of continuous stability as reported in an earlier paper is born out by clinical experience.

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