Acta orthop. Scandinav. 43, 421–437, 1972

Department of Orthopaedic Surgery, Århus County Hospital,
University of Århus.

THE EFFECT OF ELECTRIC CURRENT ON THE HEALING TIME OF CRURAL FRACTURES

TORBEN EJSING JØRGENSEN

Accepted 15. v. 72

Wolff (1892) set up the classical law about the influence of loading on bone structure and on the growth of bone. The effect of this law is partially unknown, but investigations during the last 20 years make it probable that bioelectrical currents and potentials may form part of the effector mechanism.

The initial work concerning this was started by Fukada & Yasuda (1957), who demonstrated that mechanical loading of a bone produced electrical potentials in bone tissue. The potentials were proportional to the loadings and were negative where the tissue was under compression and positive where the tissue was under tension. The phenomenon was explained by piezo-electrical potentials in the crystalline substance of the bone tissue (grammophone pick-up principle).

Basset et al. (1963, 1964) maintained that the potentials could not be piezo-electrical only, as the potentials were delayed and retained during the loading. The phenomenon was then explained by means of the theory about semi-conductors (electrical semi-conductors).

Shamos et al. (1964) showed by measurings on bones and on crystalline structures that the potentials might after all be of piezo-electrical origin.

Lang (1966) also found it possible that a pyro-electrical effect might be a partial cause of the potentials.

Jahn (1968) discussed the theoretical importance of the potentials to live tissue and concluded "that organic matrix and apatite constituents behave as amphoteric ion exchangers," which by means of difference of potential might accelerate the migration of inorganic ions. Based on the various speeds of ionic migration in an electrical

---

Aided by a grant from the Foundation of P. Carl Petersen.

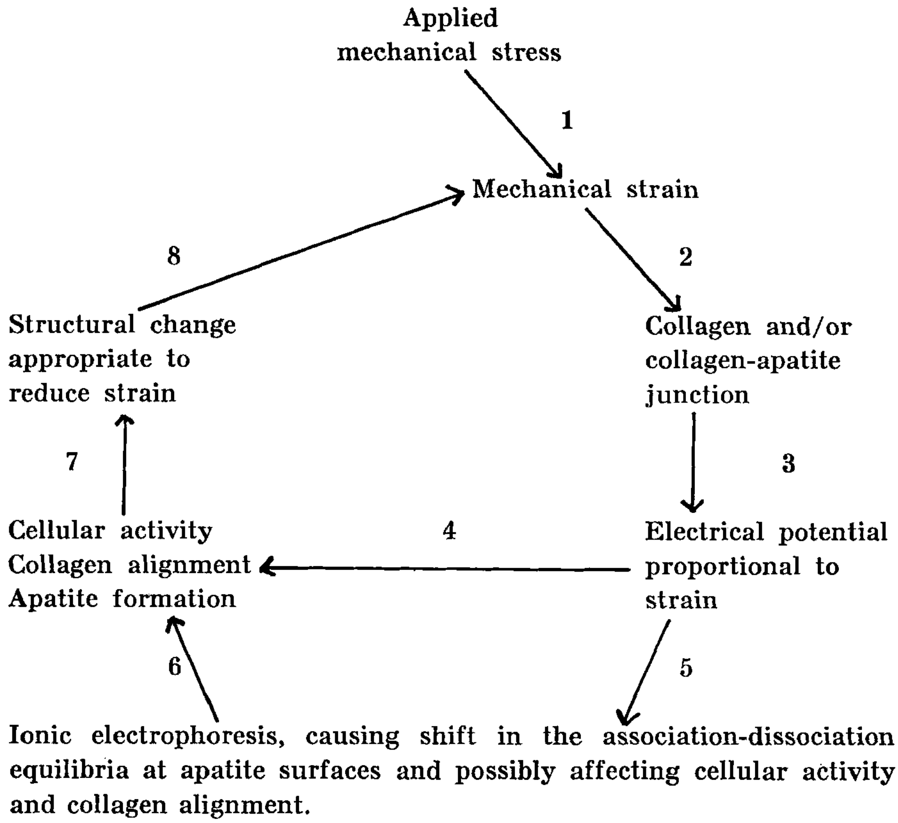

Figure 1. Steps in the operation of Wolff's law (1892). Arrows 1 to 4, 7 and 8 and all the intervening steps, except apatite formation, are modified from Basset (1966). Arrows 5 and 6 and the step between them are added on the theorem of Jahn (1968). Cellular activity, collagen alignment and apatite formation occur simultaneously, and all three may be influenced by ionic electrophoresis.

field, calcium and phosphate ions will migrate towards the cathode and sodium and chloride ions towards the anode. In theory the same ion migration might take place in a low-frequency alternating field. Jahn put forward the hypothesis in Figure 1, based on Wolff's law and on Basset's theory (1966).

It is well known that bioelectrical differences of potentials exist in tissue, and that these potentials may be related to the activity in the tissue and thus to the metabolism (Cater & Phillips 1954). Neurotransmission potentials and muscular potentials are well known in the clinic.

Friedenberg & Brighton (1966) showed by measuring rabbit bones that a characteristic potential pattern could be measured on tubular bones. The metaphysis was negative in relation to the epiphysis, which in relation to the diaphysis was isoelectrical or slightly negative. In potential measurings on skin above diaphyseally fractured humane tibia, it was found that the diaphysis was negative in relation to the epiphysis. Shortly after the occurrence of a diaphyseal fracture, the metaphyseal potential was strongly negative and a marked negative potential measurings on skin above diaphyseally fractured human the potential slowly increased towards normal values. Thus a negative potential should indicate increased cellular activity.

On the basis of the above-mentioned observations and theories several research workers have induced electric current in bone tissue.

Basset et al. (1964) implanted iridium electrodes on dog femurs. Through the electrodes a small direct current was induced. Thus it was found that when the current was 10 to 100 μ A (microamperes) an extensive callus formation occurred within a fortnight around the cathode (negative). In the same way rapid osteogenesis was found around the cathode, so that 21 days after the stimulation was initiated a homogeneous field of complete bone fibres was found. Around the anode (positive) a shell of a brownish homogeneous material was found, which probably consisted of denaturated protein. There seemed to be a realiable increase around the cathode in the absolute number of young mesenchymal cells and osteoblasts.

Cieszynski (1963) experimented on rabbits where both forelegs were fractured and immobilized in plaster. In one of the plasters a metal shield was built in as a skin pole, while the other skin pole was a metal electrode on the back of the animal. Thus it was possible to influence the fractured leg either by positive or negative potentials. Stimulation was administered for 3 to 7 days, and the current varied within 250 to 4000 μ A. The result of the examinations was that positive potential on the electrode on the back caused a subcutaneous mineral tumour. Positive potential on the fractured leg increased the breaking strength of the fracture by 1.5 compared with the breaking strength of the control fracture within 24 days. Negative potential does not seem to improve healing.

In 1964 Cieszynski published the only known paper on electrical stimulation of human fractures. The fractures were stimulated through skin electrodes, partly by negative and partly by positive potentials. Furthermore, the fractured legs were treated with various electrical saline baths. The material was very small and very difficult to estimate as the fractures described and the treatments varied a good deal.

Minkin et al. (1968) implanted platinum-iridium electrodes in the distal femoral epiphyses and metaphyses of eight-week-old rabbits. The epiphyseal electrodes acted as cathodes while the metaphyseal electrodes acted as anodes. In one group of animals the electrodes were connected to an active stimulator delivering 70 μ A, while in the other group of animals the electrodes were connected with a non-active stimulator. Three weeks later the bones were examined and it was found that exostosis occurred in the actively stimulated bones. The same phenomenon, less pronounced, was observed in the metaphyseal electrodes on the non-stimulated bones. In the greater part of the stimulated bones a bending occurred on the side where the electrodes had been placed. This was assumed to indicate that electrical current depressed the growth of the bone. Both the stimulated and the non-stimulated bones showed increase of the breadth of the metaphysis, while the content of fat-dry material in the bone decreased. This was explained either by active resorption of inorganic substance or by delayed ossification.

The experiments described are all performed by low direct current, which must be regarded as unphysiological in relation to the original theory concerning varying potential in bone tissue. The reason for this is probably that it is technically difficult to use low-frequency alternating current in animal experiments.

The object of the present paper is to examine, by means of previously described measurings of stability (Jørgensen 1972 a, b, c, d), whether a slow pulsating asymmetrical direct current may promote the healing of human crural fractures.

METHODS AND MATERIALS

Fracture Treatment

The fractures of the material are all treated with the Hoffmann apparatus, because this apparatus fulfils the mechanical and electrical demands required for electrical stimulation of crural fractures. These demands are: (1) a solid mounting of a stimulator capable of working for months; (2) electrical electrodes in the bone proximally and distally to the fracture; these electrodes have to be insulated one from the other (Figure 2); (3) it must be possible to measure the fracture stability.

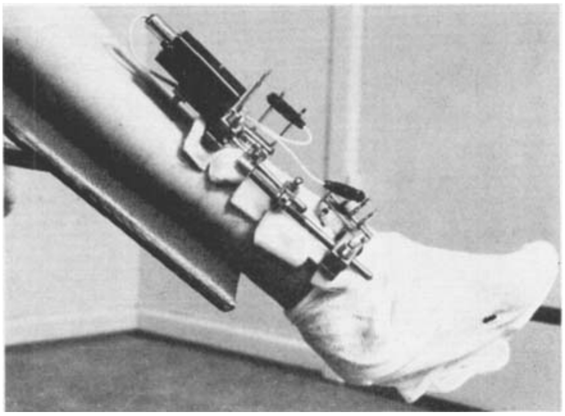

Figure 2. The electrical stimulator mounted the Hoffmann apparatus. The ball joint grips are manufactured with insulating clamp plates, which insulate the screws in the bone electrically.

The Stimulator

The demands for the stimulator used here are as follows:

1. It must yield an alternating potential of approximately 1 cycle per second (1 Hz) corresponding to the frequency of normal walking speed.
2. Besides the alternating current the fracture must be exposed to a direct current of approximately 20 to 100 μ A.
3. The patients must not feel the current impulses.
4. The apparatus must be secured so that an electrical fault cannot cause an overdose of electricity.
5. It must be possible for the patients quickly to switch off the stimulator.

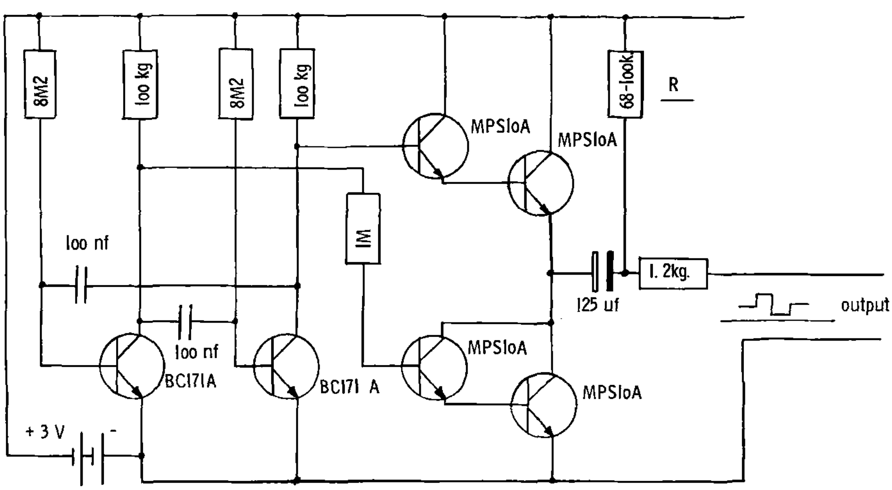

Figure 3. Diagram of the stimulator. By decreasing the resistance R the electrical pattern is changed asymmetrically.

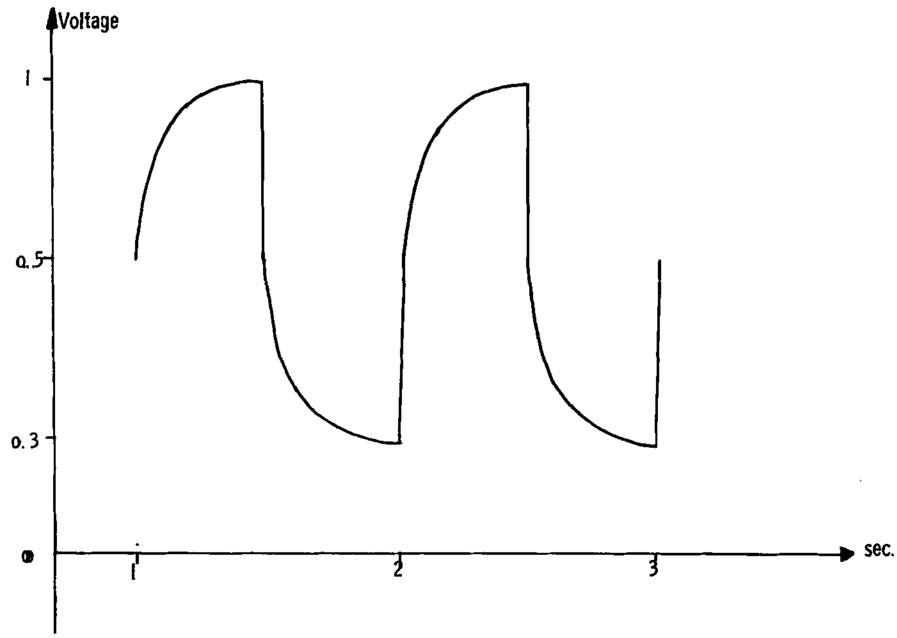

Figure 4. The potential diagram measured between the 2 bone electrodes.

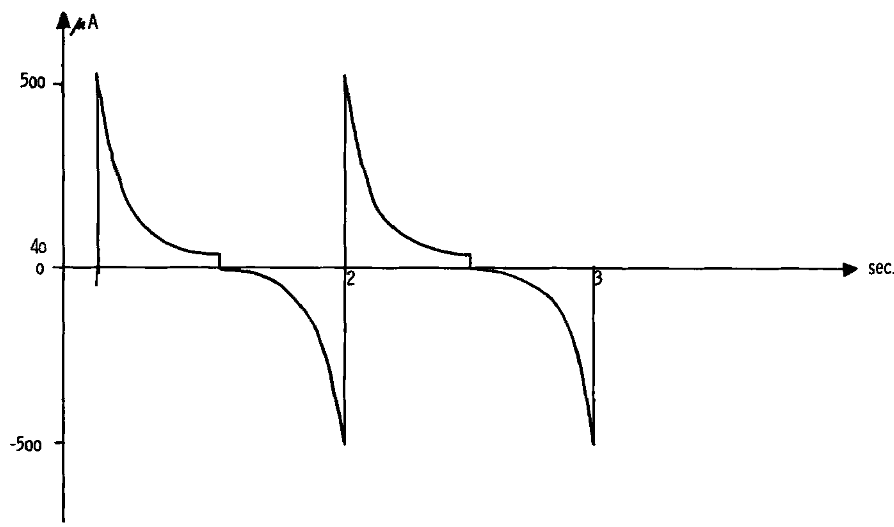

Figure 5. The current diagram measured between the 2 bone electrodes.

The result of the above demands was a transistorized multivibrator delivering square-wave potentials symmetrically around zero. The electrical pattern may be shifted in an asymmetric direction by means of the resistor R (68 to 100 K ohm) (Figure 3). Figures 4 and 5 show the voltage and current diagrams of the bone, when the stimulator is connected with the Hoffman screws (Figure 2).

The Correlation Between Time and the Degree of Healing of the Fracture

In a previous work (Jørgensen 1972 b) on measurements of stability on crural fractures, it was concluded that when very bendable bones were excluded it was possible to compare the stability of various crural fractures to bending, when the total deflection was above or equalled 1°. At a total deflection of 1°, a crural fracture is very close to being clinically stable, and at this time it can generally stand partial weight-bearing at quiet walking by support of two crutches.

The time when the fractures obtain a total deflection of 1° will in this paper be used as the basis of comparison for the degree of healing of the fracture.

The Grouping of the Fractures

The types of fractures in Table 1 are grouped according to the following principles.

Transversal fracture: with the bone axis the fracture line forms an angle above 45°. Comminuted fractures are regarded as transversal fractures.

Longitudinal fracture: the fracture line forms an angle of less than 45° with the bone axis.

By *middle* or *distal crural fractures* are understood fractures located on the middle or the distal third of tibia. Proximal crural fractures were not treated with Hoffmann's osteotaxis.

Demands for the Material in Table 1

Conditions prior to the experiment:

1. Only patients who previously were in good health and mobile were included in the material.
2. The patients in the stimulated group had to consent to partaking in the experiment.
3. The fractures must not be clinically infected, i.e. complicated fractures had to show primary skin healing.
4. The resetting of comminuted fractures had to be so good that X-ray nowhere revealed more than 5 mm diastasis.
5. After resetting only lateral dislocations below 5 mm were allowed.

Conditions during the experiment:

1. All patients were to be followed by the same doctor and as far as possible receive a standard treatment.
2. After the resetting and up to the defined correlation between time taken and the degree of healing of the fracture, the fractures must not have been exposed to overloadings. Nor must any delay in the healing have been found by the measurings of the stability (Jørgensen 1972 c, d).

Table 1.

No	Age	Type and localization of fracture: Un-compl. transv. middle	Compl. transv. middle	Un-compl. transv. distal.	Compl. transv. distal.	Un-compl. longit. middle	Un-compl. longit. distal.	Compl. longit. distal.	Fractures treated by el-stimu-tion	Fractures without el-stimu-lation	Month to obtain total deflection of 1 degree	Local reaction around Hoffmann-screws
1	16	+							+		1.5	+
2	16	+							+		2	++
3	21	+							+		2.5	(+)
4	22	+							+		2	—
5	23	+							+		4	+
6	69	+							+		3	(+)
7	16	+								+	1.5	—
8	17	+								+	3.5	+
9	17	+								+	5	—
10	20	+								+	1.5	—
11	21	+								+	3.5	(+)
12	22	+								+	3.5	—
13	24	+								+	2.5	—
14	25	+								+	4	—
15	28	+								+	2.5	—
16	32	+								+	6	—
17	46	+								+	5.5	—
18	55	+								+	4	—
19	16		+						+		2	+
20	17		+						+		3	(+)
21	21		+						+		3.5	(+)
22	22		+						+		2	(+)
23	39		+						+		2	(+)
24	17		+							+	1.5	—
25	20		+							+	2.5	(+)
26	20		+							+	2	—
27	26		+							+	4	+

28	34	+							+	5.5	—
29	16		+					+		3.5	+
30	17		+					+		2	+
31	20		+					+		2.5	+
32	47		+					+		2.5	(+)
33	19		+						+	2.5	(+)
34	23		+						+	2	+
35	36		+						+	2.5	—
36	72			+				+		3	—
37	21			+					+	3.5	—
38	21			+					+	4.5	—
39	55			+					+	6	—
40	72			+					+	4	(+)
41	17				+			+		2	—
42	45				+			+		1.5	(+)
43	20				+				+	2.5	—
44	26				+				+	2.5	+
45	30				+				+	3.5	—
46	41				+				+	3.5	—
47	59				+				+	3.5	—
48	26					+		+		1.5	—
49	30					+		+		2.5	—
50	57					+		+		2	—
51	58					+		+		2.5	(+)
52	65					+		+		3	—
53	22					+			+	3	—
54	50					+			+	1.5	+
55	19						+	+		2	(+)
56	16						+		+	4	—
57	44						+		+	3	—

Local reaction around Hoffmann screws: —: no reaction. (+): localised redness of skin. +: purulent secretion in screw holes. ++: bone reaction around screws.

3. At the follow-up examinations the fracture fixation had to be intact.
4. The stimulator was to work continuously during the period of treatment.

To obtain a sufficiently large material, however, it had to be accepted that minor axial deviations were corrected up to 3 weeks after the primary resetting. Transient failure of the stimulator for up to one week was tolerated.

In the control group 10 patients had to be omitted: 3 because of infection around the Hoffmann screws, 4 because the fractures were overloaded, and 3 because of insufficient fracture fixation.

In the treated group 4 patients had to be omitted: 2 because of infection around the screws, 1 patient overloaded the fracture, and 1 patient did not dare continue the experiment because of a feeling of pain and heat in the leg.

The Distribution of the Patients in the Material (Table 1)

As far as possible every second patient in the fracture groups was treated by electrical stimulation. To keep the average age fairly uniform in the stimulated and the non-stimulated group, a certain selection as to age was made. (Figure 6). There was no selection regarding sex.

Practical Procedure of the Experiment

When the patient was selected for electrical stimulation, the treatment was initiated 2 to 10 days after the fracture had occurred. At this time the patient

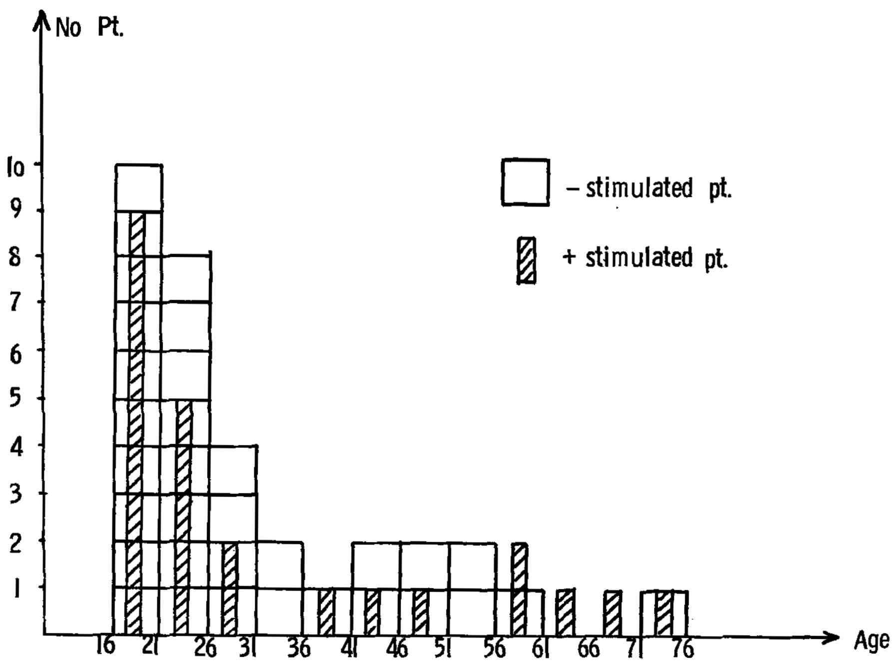

Figure 6. The distribution of age in the material in Table 1.

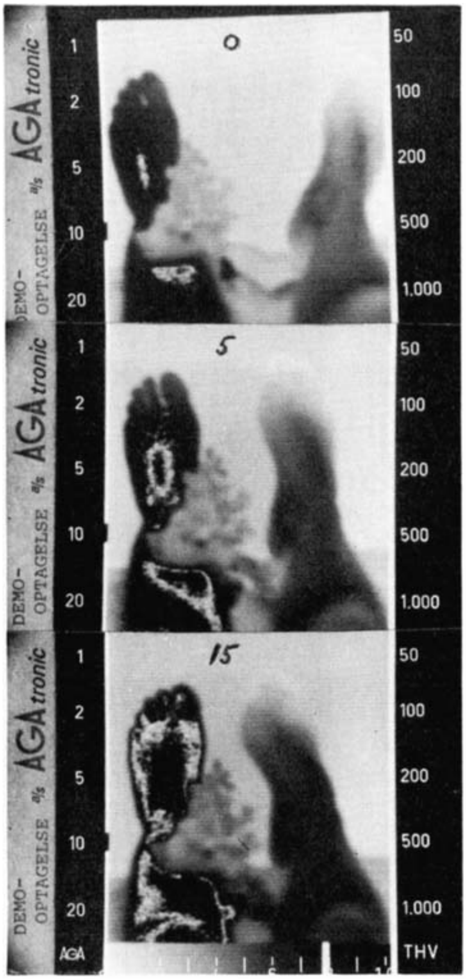

Figure 7. Thermovision recordings of crus just before initiating the stimulation, 5 and 15 minutes after the start. The white lines are isothermal lines.

was in hospital, and thus information as to pain was easily obtained. If pain occurred, the stimulator was changed so that the output voltage was less asymmetric. Generally the pain then vanished within few hours.

After the discharge from hospital the patients in both groups were followed as out-patients every week or every other week. At these follow-up examinations the stimulator was checked and the poles were reversed. The skin surrounding the Hoffmann screws was checked for redness and secretion. The fracture fixation was inspected, and when the fracture stability was sufficiently good, the deflection was measured. When the total deflection was 1° the stimulator was removed and the patient was then allowed partial weight-bearing with two crutches. The follow-up examinations were continued till the removal of the Hoffmann apparatus when the fractures could tolerate full weight-bearing.

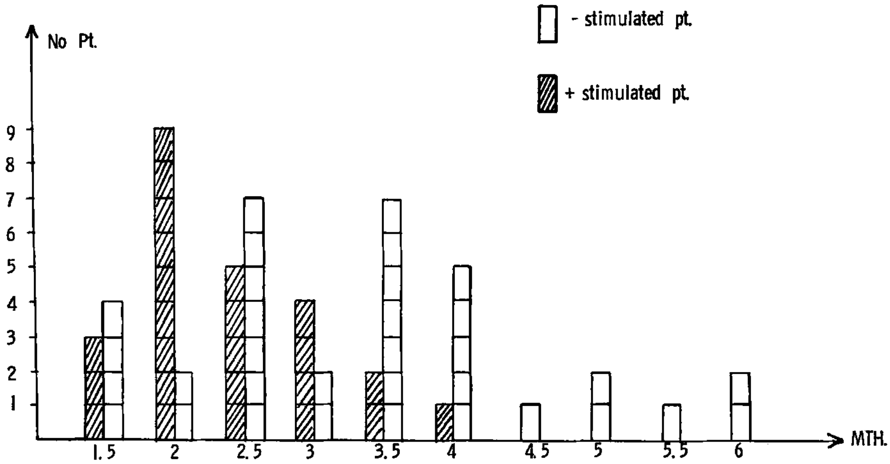

Figure 8. The distribution of the material in relation to the time required for obtaining a stability corresponding to a total deflection of 1°.

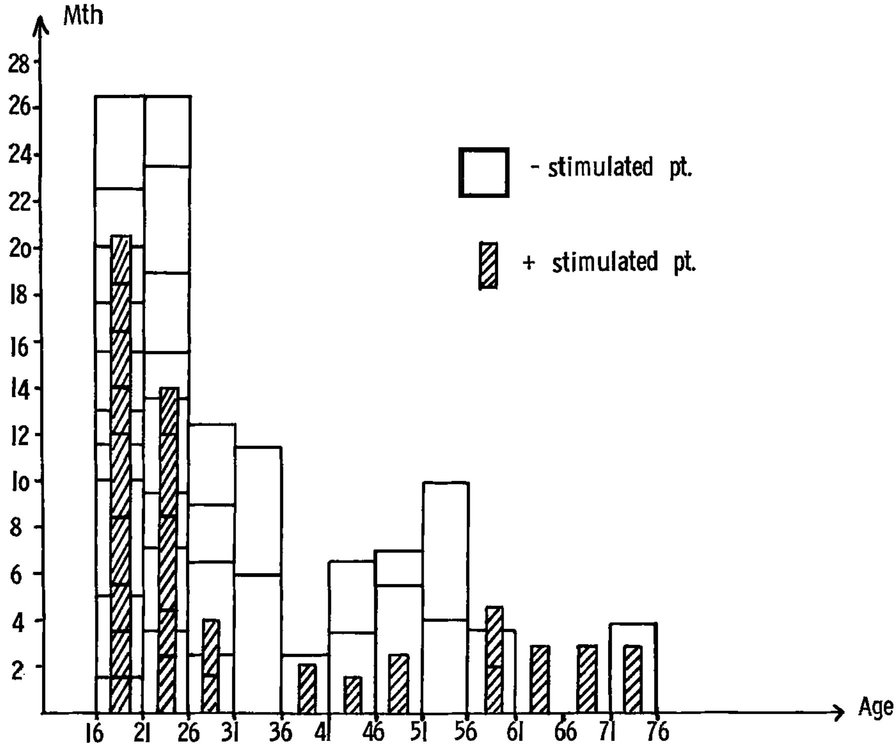

Figure 9. Distribution of age in the material in relation to the time required for obtaining a total deflection of 1°.

Patient no. 2 in Table 1 failed to appear at one follow-up examination and thus the poles were not reversed in the stimulator for 3 weeks. This caused an osteitic reaction around the positive electrode. The reaction was, however, localized and not attended by inflammation in the surrounding tissue, and thus curetting of the bone was postponed till the fracture had healed.

Thermographic examinations were performed on 2 patients before the stimulation was initiated, and then 5 minutes and 15 minutes after the start (Figure 7).

Statistic Analysis of the Material in Table 1 and in Figures 8 and 9

The problem suggests the following one-sided alternative test (Guenther 1964).

Group 1: stimulated. Group 2: control.

$H_0 : \mu 1 = \mu 2$ $H_1 : \mu 1 < \mu 2$

In the F-test: $H_0 : \delta 1 = 2$ $H_1 : \delta 1 \neq \delta 2$

The statistic: $F_{32,23} = \frac{s_2^2}{s_1^2} = \frac{1.64}{0.4565} = 3.592$ is significant at the p-level < 0.0005.

So the statistic to be used is $t_\nu = \frac{\bar{x}_1 - \bar{x}_2 - (\mu 1 - \mu 2)}{\sqrt{\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}}}$

which is approximately distributed as t_ν with degrees of freedom:

$$\nu = \frac{(s_1^2/n_1 + s_2^2/n_2)^2}{\frac{(s_1^2/n_1)^2}{n_1 - 1} + \frac{(s_2^2/n_2)^2}{n_2 - 1}} - 2$$

If the two populations are normal the degrees of freedom are $\nu = 48$.

In this problem $n_1 = 24$ and $n_2 = 33$, so the assumption of normality is not serious (The Central Limit Theorem).

$$t_{48} = \frac{3.35 - 2.42}{\sqrt{\frac{0.4565}{24} + \frac{1.64}{33}}} = 3.53 \qquad p < 0.001.$$

The conclusion to be drawn is to reject H_0 in favor of H_1.

If the material is divided into age groups and the above analysis is repeated, the following is found (Figures 9 and 10):

Age group 16 to 26–: $0.05 < p < 0.10$ in favour of H_1.

Age group 26 to 51 : $0.001 < p < 0.01$ in favour of H_1.

Age group 51 to 72 : $0.05 < p < 0.10$ in favour of H_1.

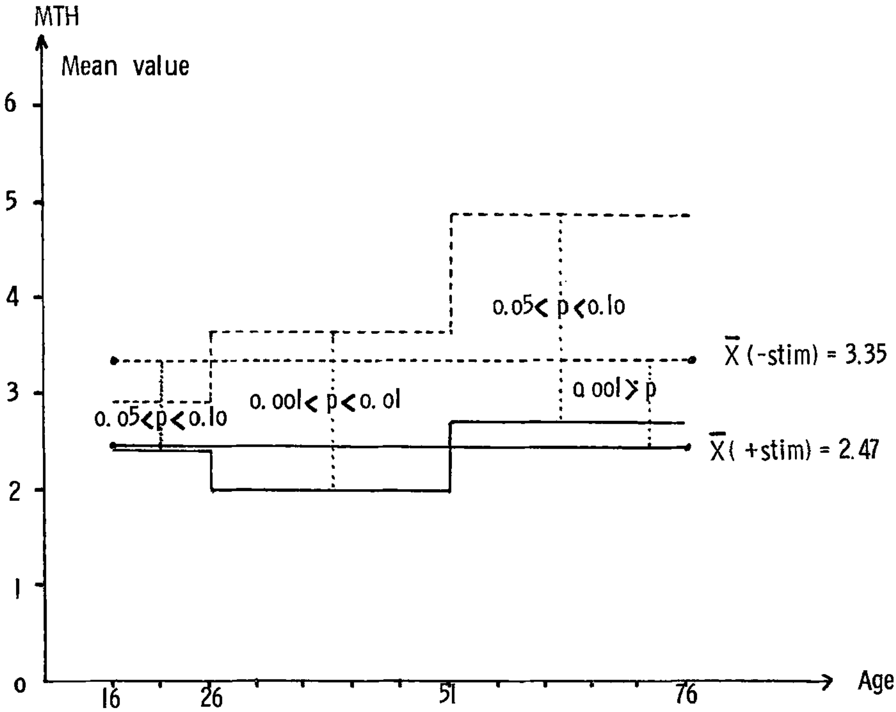

Figure 10. Graphical representation of the mean values for the time needed for obtaining a total deflection of 1°. The dotted lines represent the non-stimulated fractures. The full-drawn line represents the stimulated fractures.

RESULTS

Objective Findings

1. The average time for obtaining a certain stability of the fracture was found to be 30 per cent lower in the electrically stimulated group than in the control group (Figure 10).

2. Greater incidence of skin infection with secretion around the Hoffmann screws in the stimulated group, (29 per cent in the stimulated group and 15 per cent in the control group). The infection in the stimulated group mainly occurred around the positive electrode.

3. In one patient the poles were not reversed in the electrodes for 3 weeks causing a localized osteitis in the bone at the positive pole.

4. Increase of skin temperature occurred above the fracture down onto the foot shortly after the stimulation was initiated (Figure 7).

Subjective Findings

1. The patients declared to have a pleasant feeling of heat in the leg after the stimulation had been started.
2. Several patients had transient pain, like toothache, in the leg at the stimulation.

DISCUSSION

The analyses of the material show a distinct effect of electrical stimulation on the average healing time for crural fractures. The age distribution in the material (Figure 2) is almost identical in both groups and may hardly account for any greater shifts in the material. The material is somewhat limited regarding an analysis within age groups in Figure 10, but it seems, however, to be clearly indicated that the effect of the stimulation persists within the age groups. On the face of it, however, there seems to be an increasing effect by age, but the material is too small for an analysis of this factor.

It might have been desirable for the experiment to be performed as a blind test, but the experimental conditions did not render this possible.

A comparison between the roentgenologic picture within the 2 groups will be subjective and so unreliable that no statistically valid conclusion can be made. It was, however, the examiner's impression that electrical stimulation caused an earlier roentgenoparent fractural and periostal callus. On the other hand, there seemed to be a tendency towards osteoporosis of the distal tibial fragments.

At electrical stimulation on animal bones, Minkin et al. (1968) demonstrated, *inter alia,* that an exostosis occurred by the negative electrode. This unwanted effect is not found in these experiments where, unlike the work of Minkin et al., alternating polarity has been employed during the treatment.

The infection at the positive electrode generally disappeared within a few days when the polarity was reversed. The infection could be almost eliminated if the polarity was reversed every week. However, if this was omitted for more than 2 weeks, a bone reaction occurred which on X-ray appeared as a local osteolysis around the positive pole. In all cases the infection was localized and healed spontaneously after the screw canal of the bone had been excochleated.

The cause of the effect obtained by electrical stimulation is not illustrated in this experiment. The feeling of heat and pain in the fracture as stated by the patients, compared with the increase found in skin temperature and the irritation of the tissue surrounding the positive electrodes, makes it possible that the effect may be due to an electrochemical reaction.

SUMMARY AND CONCLUSION

In a material of 57 crural fractures treated with Hoffmann's osteotaxis, 24 were treated with a pulsating asymmetric direct current through the fracture. By measuring the stability of the fractures the time for a certain stiffness of the fracture could be determined. Statistical analysis showed that the electrically stimulated group acquired a certain defined average stiffness of the fracture 30 per cent faster than the control group. The effect seems to exist in all age groups.

At the positive bone electrodes localized redness of skin or secretion frequently occurred, which in 2 to 3 weeks might cause a localized osteolysis in the bone visible on X-ray. The infection and the bone reaction could be prevented by reversing the poles of the electrodes once or twice every week.

In the stimulated group localized skin infection with secretion was found at the positive pole in 29 per cent of the cases. In the control group skin infection was found in 15 per cent.

The electrical treatment caused a feeling of heat in the fractured leg, and at thermographic examinations in 2 patients an increase in skin temperature on the fractured leg was demonstrated a few minutes after the treatment was started. One or two patients had severe pain at the treatment.

The cause of the demonstrated effect on the healing of fractures may be due to an electrochemical reaction.

If the demonstrated effect is to be used in the daily clinic, it is necessary to have a careful control programme including registration and treatment of any infections and inspection of the stimulator.

REFERENCES

Basset, C. A. L., Pawluk, R. J. & Becker, R. O. (1964) Effects of electrical currents on bone *in vivo*. *Nature (Lond.)* **204**, 652–654.

Basset, C. A. L. (1966) Electromechanical factors regulating bone architecture. *Third European Symposium on Calcified Tissues*, ed. Fleisch, Blackwood & Owen, pp. 78–89. Springer Verlag, Jena.

Becker, R. O., Basset, C. A. L. & Bachmann, C. H. (1963) Bioelectrical factors controlling bone structure. *Bone biodynamics,* ed. Frost, H., pp. 209–232, Little Brown, New York.

Cater, D. B. & Phillips, A. F. (1954) Measurements of electrode potentials in living and dead tissues. *Nature (Lond.)* **174**, 121–123.

Cieszyński, T. (1963) Studies on the regeneration of ossal tissue (2). Treatment of bone fractures in experimental animal with electric energy. *Arch. Immunol. Ther. exp. (Warsz.)* **11**, 199–217.

Cieszyński, T. (1964) Studies on the regeneration of ossal tissue (3). Influence of positive and negative electricity upon callus formation in humans. *Arch. Immunol. Ther. exp. (Warsz.)* **12**, 269–295.

Friedenberg, Z. B. & Brighton, C. T. (1966) Bioelectric potentials in bone *J. Bone Jt Surg.* **48**-A, 915–923.

Fukada, E. & Yasuda, J. (1957) On the piezoelectric effect of bone. *Jap. J. Physiol.* **12**, 1158.

Guenther, W. C. (1964) *Concept of statistical inference,* pp. 81–83, 143–150. McGraw-Hill, New York.

Jahn, T. L. (1968) A possible mechanism for the effect of electrical potentials on apatite formation in bone. *Clin. Orthop.* **56**, 261–273.

Jørgensen, T. E. (1972 a) Measurements of stability of crural fractures treated with Hoffmann osteotaxis. 1. Method and measurements of deflection on autopsy crura. *Acta orthop. scand.* **43**, 188–206.

Jørgensen, T. E. (1972 b) Measurements of stability of crural fractures treated with Hoffmann osteotaxis. 2. Measurements on crural fractures. *Acta orthop. scand.* **43**, 207–218.

Jørgensen, T. E. (1972 c) Measurements of stability of crural fractures treated with Hoffmann osteotaxis. 3. The uncomplicated, terminal phase of healing of crural fractures. *Acta orthop. scand.* **43**, 264–279.

Jørgensen, T. E. (1972 d) Measurements of stability of crural fractures treated with Hoffmann osteotaxis. 4. The complicated, terminal phase of healing of crural fractures. *Acta orthop. scand.* **43**, 280–291.

Lang, S. B. (1966) Pyroelectric effect in bone and tendon. *Nature (Lond.)* **212**, 704–705.

Minkin, C., Poulton, B. R. & Hoover, W. H. (1968) The effect of direct current on bone. *Clin. Orthop.* **57**, 303–309.

Shamos, M. H. & Lavine, L. S. (1964) Physical bases for bioelectric effects in mineralized tissue. *Clin. Orthop.* **35**, 177–188.

Wolff, J. (1892) *Das Gesetz der Transformation der Knochen.* A. Hirchwald, Berlin.

Correspondence to:

Dr. T. Ejsing Jørgensen
17 Agernvej
DK–8330 Beder
Denmark