

Electric Stimulation for Delayed Union and Nonunion with Direct Current and Capacitive Coupling Method

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ABSTRACT: Direct current electric stimulation was utilized in the treatment of delayed union nonunion of the bones. Semiinvasive method was used in 26 cases of delayed union and nonunion of the tibial fractures which had less muscular coverage. Those fractures were also stabilized with external skeletal fixation using methylmethacrylate. Invasive method was employed in delayed union and nonunion of the bones. Semiinvasive method was used in 26 cases of delayed union and nonunion of the tibial fractures which had less muscular coverage. Those fractures were also stabilized with external skeletal fixation using methylmethacrylate, usually fixed with internal devices and the bones had thick muscular coverage. Noninvasive electric stimulation was also instituted in 17 nonunions, 9 delayed union and 13 fresh fractures. Those bones included humerus, femur, tibia clavicle, and fibula. Stabilization of fracture site was accomplished with either cast, brace external or internal fixation. The results of studies indicated the noninvasive method was superior than the others and produced no side affects. One case of congenital pseudarthrosis of the tibia was treated with electrically stimulated periosteum graft and the result was very encouraging.

INTRODUCTION

Electrical induction of osteogenesis has attracted the interest of many orthopaedic surgeons.

The earliest report of electric stimulation for enhancement of fracture healing seems to have been made by a doctor at St. Thomas Hospital in London in 1812, just after the discovery of electric power by Volta in 1799. In this report, electric stimulation was applied for nonunion or congenital pseudarthrosis. Hortshone (1849) and Lente (1850) reported the application of electric stimulation for treatment of nonunions. However the dose of electrical current was not mentioned in

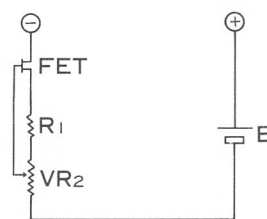
these reports.¹

Yasuda was the first to report electrical properties, piezoelectricity of bone and electrically induced callus with small amperage of direct current (DC) in 1953 and clinical application for fractures and bone diseases in 1955.^{2,3}

Similar experiments of piezoelectricity were reported by Bassett and Becker in 1962 and by Shamos and Lavine in 1963 in the United States.

Friedenberg and Brighton began the same kind of studies and reported clinical experience in 1971.⁴ Since then, numerous investigators have been studying this theme and also many clinical reports have appeared presenting successful electric stimulation for congenital or acquired pseudarthrosis or delayed union of bone in various manners.^{1,3,5-7}

Under Yasuda's instruction, in 1975 we started using a simple stimulator with 1.5 volt battery and variable resistor delivering 10-20 A direct current for the delayed or nonunion of the fracture and pathologic bone disease.^{8,9} This method is progressed from original system of unstable amperage of electric stimulation current to constant direct current circuit (Figures 1, 2). At present time, the direct current is divided into two types; one is a stimulator for semi-invasive method and the other is an implantable stimulator for totally invasive method. Semi-invasive method which has two electrodes inserted into the bone around the fracture site is for delayed union and nonunion



R_1 : 30-56Kohm, VR_2 : 200Kohm and B : 9volt battery

Fig. 1: Constant DC circuit

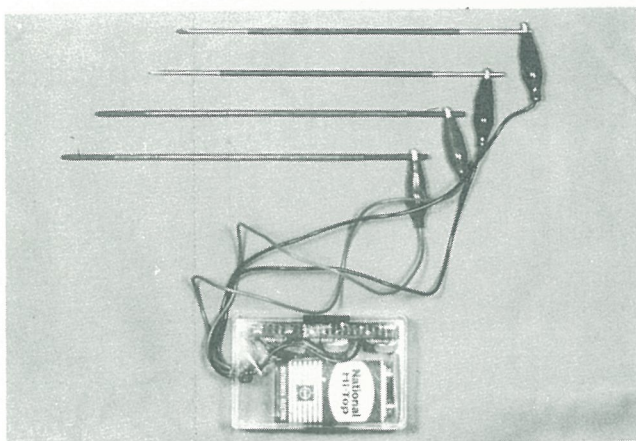


Fig. 2: Our hand made constant DC stimulator Power pack: Battery and constant DC circuit. Cathode: Stainless steel pins insulated with Teflon coating. Anode: Carbon fiber stick insulated with epoxy resin.

of tibia fracture. Totally, invasive method was used by us for the delayed union and nonunion of humerus and femur and for the fresh fracture of femoral neck. These invasive methods were very effective, but needed operations. We applied clinically pulsing electromagnetic fields therapy (non invasive method) by Bassett for nonunion of humerus and femur from 1980.⁵ Unfortunately, we could not get bone union of these three cases and gave up clinical application of this therapy.

From 1982; we started another non invasive electric method, capacitive coupling which Brighton and his research group reported the result of experimental study in 1981 and 1982. Our clinical result is so good that recently we are using this method for most of cases which need electric stimulation.

Semi-invasive Method

Since 1971, the authors have been applying an external skeletal fixation with methylmethacrylate for open fracture of tibia with

severely damaged soft tissue.^{8,10,11} We applied electric stimulation for 26 cases of delayed union and non union of tibial fractures using external skeletal fixation with methylmethacrylate (Table 1). The stimulator was placed outside of the leg and the cathode and anode were inserted to the ununited bone through the skin without opening the nonunion site; (semi-invasive method).

Since the electric resistance of the bone is much larger than that of muscle and other soft tissues, both cathode and anode have to be inserted into the bone to obtain the effective electric current at the fracture site and to keep the fracture site in electrically negative potential (Figure 3). Teflon coated stainless steel wire is used for the cathode and carbon fiber insulated with epoxy resin is used for the anode to prevent corrosion which was occasionally seen in original cases with stainless steel wire anode. This method is used mainly for nonunion or delayed union of tibia because of easy application of external skeletal fixation to the tibia and electric stimulation. The power pack of the stimulator is fixed to the methylmethacrylate portion of external skeletal fixation with adhesive tape (Figure 4).

CLINICAL CASE

Case 1 (Figure 2): A 35-year-old male was hit by a car while riding a bicycle and sustained comminuted and compound fracture of right tibia. The leg was fixed with external skeletal fixation using methylmethacrylate after irrigation, debridement and closing the wound. Electric stimulation was started three months after injury because of poor callus formation. The fracture united at six months after injury (Figure 5).

Invasive Method

On the other hand, nonunion or delayed union of the femur and humerus are usually treated with intramedullary rodding or plate fixation and seldom with external skeletal fixation. Those bones are surrounded with thick muscles. In

TABLE 1
Bone Union with Direct Current Stimulation.

Fracture	Number	Average Age	Period before ES (month)	Duration of ES (month)	Bone union
Tibia	Male	20	8.1	5.8	26/26
	Female	6			

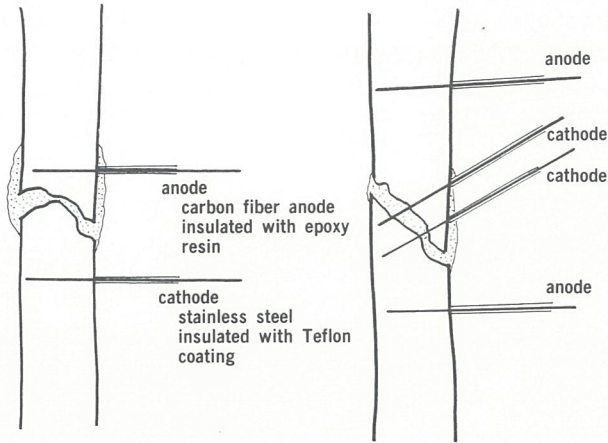


Fig. 3: Position of anode and cathode in our DC electric stimulation method.

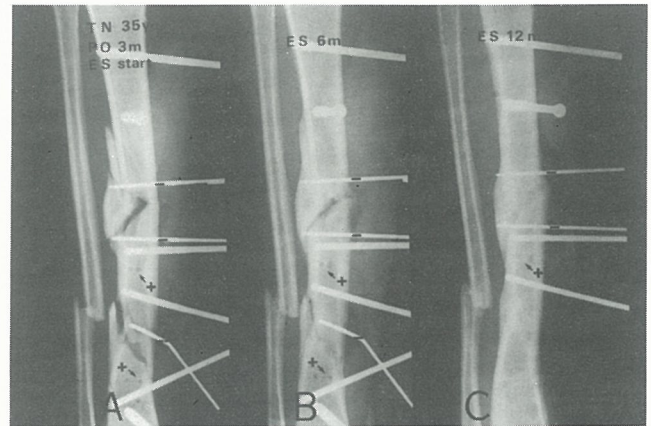


Fig. 5: Case 1. A 35 years-old male with open comminuted tibial fracture.

- A: 3 months after operation, no callus formation
- B: 6 months electric stimulation, bone union progressed
- C: 12 months electric stimulation, bone defect was filled with callus.

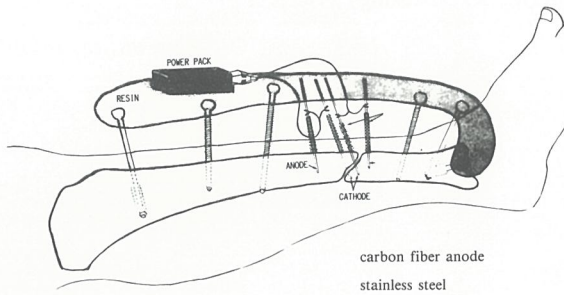


Fig. 4: DC electric stimulation with external skeletal fixation using methylmethacrylate for the tibial fracture.

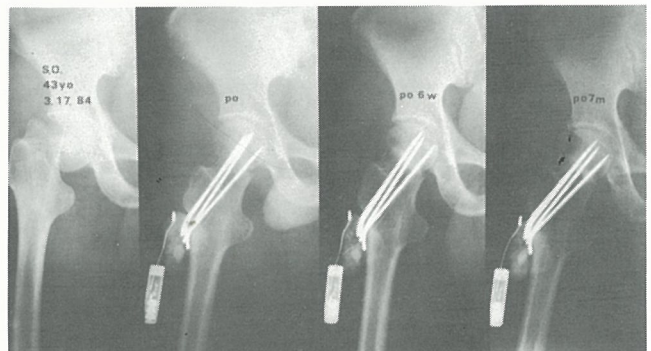


Fig. 6: Case 3. A 43-years-old male. Femoral neck fracture (Garden Stage III) closed reduction, multiple pinning with bone cement. Cathode of totally invasive stimulator was inserted into the femoral head.

these cases, totally invasive electric stimulation method is preferred. An sterilized encapsulated stimulator with a constant direct current circuit is inserted under the skin and the electrodes are placed at the fracture site for bone union.⁷

One-cathode-stimulator or two-cathode stimulator are used, and either cathode delivers 10-20 μ A of direct current. The constant direct current lasts for about 6 months. The cathode is made of stainless steel wire and the anode is made of platinum wire.

Femoral neck fracture treatment has many problems, because most of the patients are old and frequently have various medical complications. They often develop delayed or nonunion, collapse of femoral head, etc., It is controversial to treat this fracture with endoprosthesis replacement or osteosynthesis. Considering Japanese people's remarkable elongation of life span, osteosynthesis is the desirable treatment for femoral neck fractures of Garden's stage I, II and III under 75 years

old without significant medical problems disturbing rehabilitation program.

A multiple pinning with bone cement internal fixation and electric stimulator insertion were used (Figure 6). The cathode was inserted through a hall into the femoral head and the anode was placed around the subtrochanteric area. In some original cases the stimulator was placed outside of the skin as semi-invasive method and the electric wire irritated the surrounding soft tissue. Therefore, the entire stimulating system was inlayed under the skin in current method, namely invasive method.

Eighty five femoral neck fractures treat-

TABLE 2
Garden's Classification and Treatment of Femoral Neck Fracture (Jan. 1976-Oct. 1984)

Garden's Classification		I	II	III	IV	Total () Failure
Treatment	Average Age					
Conservative	51	1	2	2		5
MP	63.3		1	9 (1)	3	13 (1)
MP and ES	64.7	2	1	10 (1)	4	17 (1)
Endoprosthesis	75.2			21	24	45
THR	61.2		1	2	2	5

TABLE 3
Comparison of MP vs. MP and ES for Femoral Neck Fracture (Jan. 1976-Oct. 1984)

Treatment	Number of Cases	Average Age	Garden's Classification	Period before the Sign of Bone Union (week)	Time of Weight Bearing (week)	Comments	
MP	13	63.3	I	0	14.0	15.3	One case of non union
			II	1			
			III	9 (1)			
			IV	3			
MP or Heig Nail and ES	17 (1)	63.0	I	2	7.5	13.4	One case of femoral head endoprosthesis because of collapse due to early weight bearing walking
			II	1			
			III	10 (1)			
			IV	4			

ed at our department for the last 8 years. (Table 2) The stages of Garden's classification of the cases treated with osteosynthesis were mainly III and a few of I, II and IV, and their average age was approximately 64. On the other hand the stages of the cases treated with endoprosthesis were III and IV and their average age was about 75.

Table 3 is showing the average periods before the sign of bone union at the femoral neck fracture site after the operation. The average periods are 14 weeks in the cases who were treated with only multiple pinning and 7.5 weeks in the cases who were treated with combination of multiple pinning and electric stimulation. Only one case developed collapse of the femoral neck fracture because of early weight bearing ambulation against the doctor's instructions.

In this case the femoral head was replaced with endoprosthesis. The rest of the cases were uneventful after surgery.

In regarding to humerus fracture the bone is surrounded with muscles. Therefore at the time of surgical intervention which is indicated, we prefer to

use invasive method. Five cases of humeral fractures were treated with direct current electric stimulation. Two were treated with invasive method and three were with semi-invasive method. All fractures united eventually after an average of 7.8 months of electric stimulation.

CLINICAL CASE

Case 2 (Figure 6): A 43-year-old male sustained femoral neck fracture (Garden stage III) of the previously A-K amputated leg on an epileptic seizure in March 1984. He underwent the closed reduction, multiple pinning with bone cement and also totally invasive electric stimulator was applied. The fracture showed uniting signs within 6 weeks. The fracture united within seven months.

Capacitive Coupling Method

In 1982, Brighton reported capacitive coupling using a peak to peak 5-10 volts, 60 KHZ sine wave through two skin electrodes. Since his experimental study suggested promising results of nonunion, the author started to apply the capacitive coupling

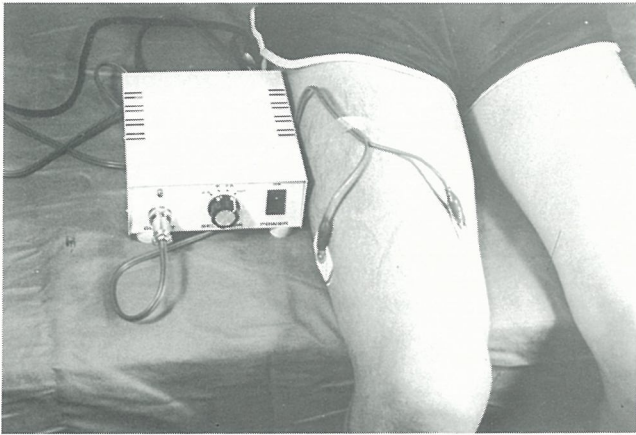


Fig. 7: Our capacitive coupling stimulator. Two skin electrodes (ECG monitor electrodes) around the fracture site were attached.

on the selected patients using our own capacitive coupling stimulator in 1982.

In USA, this stimulation method is appreciated as useful non-invasive method and a portable capacitive coupling stimulator is available for clinical cases. But the stimulator is expensive and the battery has to be replaced every day. Therefore, this is not suitable for the patient with long term treatment. Our stimulator is not portable. The power source is house electricity instead of battery. ECG monitor electrodes are used as the electrodes (Figure 7). The amount of time for treatment per day depends on the patient's condition. Since the patients of our series are not only house patients, but those attending school or working in company, the treatment period varied from 8 to 24 hours per day. Initially, nonunion or delayed union were elected for this stimulation therapy. This method was non-invasive and had no side effects. So this method was lately indicated on even fresh fractures which were expected troublesome bone union.

MATERIALS AND METHODS

Seventeen nonunions, nine delayed unions and thirteen fresh fractures were treated with capacitive coupling.

Seventeen nonunions included six humeri, three femurs, three tibias, one clavicle and one fibula. Among these 17 nonunions, seven were treated without surgical invasion to the non-union site but immobilized with cast, brace or external skeletal fixation. In the other ten cases the nonunion sites were opened and osteosynthesis and or bone grafting were carried to ensure the bone

union. And then capacitive coupling was applied. The average period between injury and capacitive coupling stimulation was 25 months in the former seven cases and 37.3 months in the later ten cases.

In addition to nonunions, nine delayed unions and 13 troublesome fresh fractures were also treated with capacitive coupling.

RESULTS

Six out of seven nonunions which did not have any additional surgical invasion united (86%). The average period of stimulation was 4.2 months. All of ten nonunions which had surgical invasion to the nonunion site united (100%). The average period of stimulation was 5.4 months.

Eight out of nine delayed unions united, one failed and two are still stimulated. The average stimulation period was 3.2 months. Twelve out of thirteen fresh fractures united and one is still under stimulation. The average period of stimulation was 3.4 months.

CLINICAL CASE

Case 4 (Figure 8): A 60 year-old male had comminuted fracture of tibia and fibula hit by a huge tree falling on his leg in February 1985. The tibia had open reduction and internal fixation with Kuntscher nail and transfixing two screws a few days after injury. The tibia was getting united gradually. But he developed pain at the fracture site of the fibula in August 1985. Because of the continuous pain, capacitive coupling was applied 12 hours per day for 5

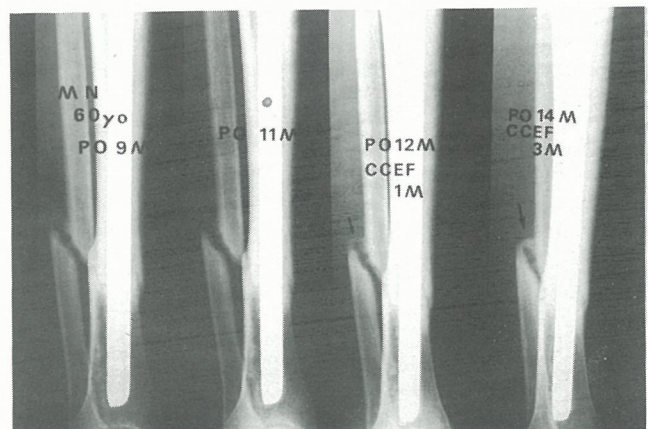


Fig. 8: Case 4. A 60-year-old male, sustained comminuted fracture of tibia and fibula. Six months after injury, he developed pain at the nonunion site of the fibula. Eleven months after injury, capacitive coupling was started for 5 weeks and the pain was relieved by bridging callus.

weeks starting eleven months after injury in January 1986. The fibula showed bridging callus and the pain was relieved.

Electrically Stimulated Periosteum Graft for Congenital Pseudarthrosis of the Tibia

Congenital pseudarthrosis of the tibia is a rare condition. The affected tibia shows segmental weakening or dysplasia of bone with failure of normal bone formation in its distal half, and complicates anterior angulation and pathologic fracture.

Conservative treatment always fails. After repeated failures of surgical intervention, amputation often becomes the final treatment. Recently electric stimulation has been applied to the congenital pseudarthrosis of the tibia. Paterson treated the Congenital pseudarthrosis by electric stimulation with the Osteostim (invasive method), and he reported that the rate of union was 67 per cent.

Bassett classified congenital pseudarthrosis of the tibia into three types according to the X-ray findings, and he reported the result of each type treated with pulsing electromagnetic fields.

Type I lesions are those in which bowing of the tibia is accompanied by significant sclerosis of the medullary canal at the apex of the lesion and usually with a simple transverse fracture line.

Type II lesion includes all cases in which a cystic or lytic lesion is present in the medullary space with or without bowing.

Type III is characterized by a significant gap and atrophic, spindled bone ends. Malalignment of the tibia and fibular involvement are universal in Type III lesions. Healing rate of type III lesion is 20 per cent and is the worst prognosis among three types (Figure 9).

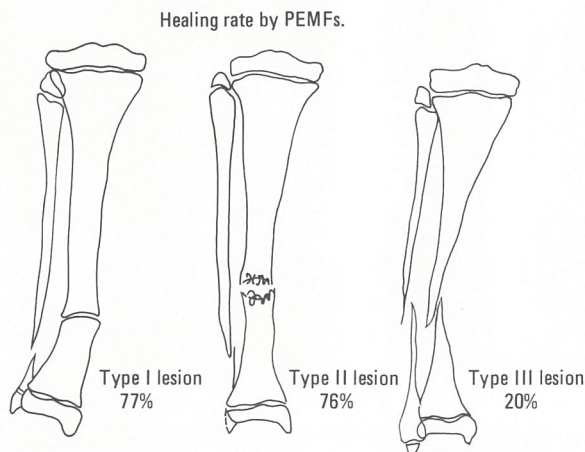


Fig. 9: Classification of congenital pseudarthrosis from Bassett C.A.B.

We treated a case of the congenital pseudarthrosis of the tibia by grafting with electrically stimulated periosteum following the principle of our basic work with rats.

CLINICAL CASE

The patient sustained right lower leg fracture in playing soccer at the age of seven. Plaster cast was applied for one month by a local doctor at the time.

The X-ray film showed a pathological fracture at this moment and the fracture was failed to unite. Then open reduction and internal fixation with plate was performed by local doctor in March 1980.

Eight months after the surgery, the plate was removed, but there was no bone union. Another surgical reduction and internal fixation with a plate was instituted. The fracture failed to unite when the plate was removed ten months after the second operation.

The patient was treated with plaster cast or brace for one year and 9 months without weight bearing of the limb till he visited our clinic at the age of ten. It was three years and 4 months after injury, and he had already undergone three surgeries by that time.

The X-ray film shows the figure of typical congenital pseudarthrosis and this is classified as type III lesion according to Bassett's report (Figure 10).

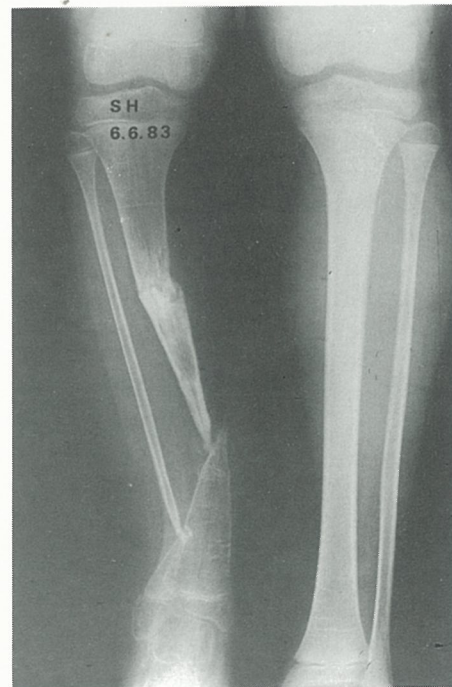


Fig. 10: A 10-year-old male. Congenital pseudarthrosis classified as type III lesion according to Bassett's report, showing double pseudarthrosis.

Physical examination disclosed Von Recklinghausen's disease. Many cafe au lait spots were on the body and soft tumors were on the right affected tibia, thigh and upper arm.

Treatment

The tibia shows double pseudarthrosis. Primarily, the angulation deformity was corrected manipulatively and the fracture was fixed with external skeletal fixation with methylmethacrylate. The patient was permitted to walk with partial weight bearing. Then electric stimulation with 20 A constant direct current was applied to the pathologic fractures area where the electrodes were inserted per cutaneously at two fracture sites and electric stimulation of semi-invasive method was indicated for about one year. The proximal pseudarthrosis united in five months, but the union of the distal pseudarthrosis did not progress in spite of one year electric stimulation (Figure 11).

Bone scan revealed no accumulation of Technetium at the distal fracture site which is indicated with a lower arrow (Figure 12). At this time, we decided to perform new technique, electrically stimulated periosteum graft on this patient.

Six cathodes were inserted into normal left proximal tibia percutaneously. 20 μ A direct current was applied to each cathode for one month to stimulate periosteum. Skin electrodes were used for anodes. The six cathodes were fixed externally with methylmethacrylate and malleolar screw to prevent falling off. After one month stimulation,

slight callus formation was noted at the stimulated site. The thickened periosteum was grafted to the site of pseudarthrosis (Figure 13).

Only two months after grafting of the periosteum, large amount of callus was formed at the fracture site (Figure 11). Further bone union was

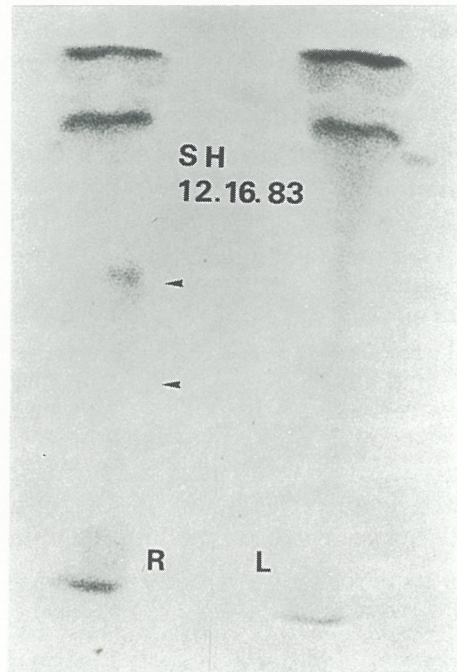


Fig. 12: Bone scan revealed no accumulation of Technetium at the distal fracture site.

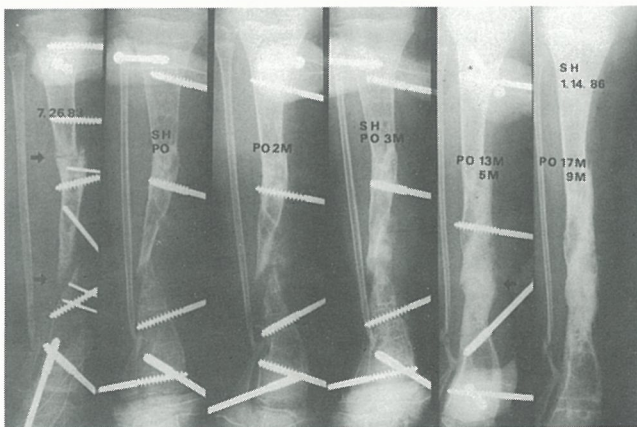


Fig. 11 A: External skeletal fixation and DC electric stimulation. Nonunion of distal pseudarthrosis after one year DC stimulation.

B: Electrically stimulated periosteal graft was performed.

C.D.E.F. : Bone union progressed.

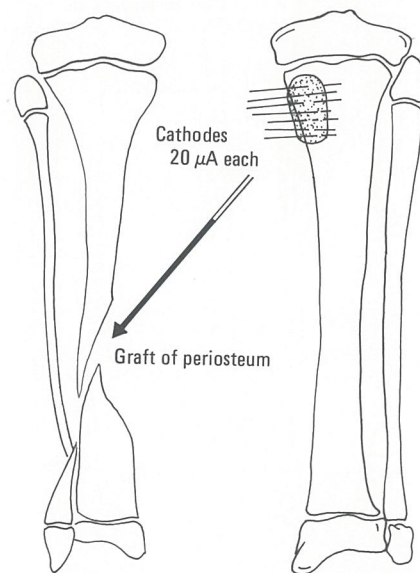


Fig. 13: Electrically stimulated periosteum graft.

progressed in three months after the grafting.

DISCUSSION

If the periosteum is grafted without electric stimulation, the grafted tissue changed not to bone tissue but to fibrous tissue. The electric stimulation causes the proliferation of primitive mesenchymal cells and their differentiation to the osteoblasts and osteocytes. When the periosteum containing the osteoblasts is grafted as a soft tissue, the grafted tissue directly differentiates to bone tissue.

Sofield and Millar reported a surgical procedure for congenital pseudarthrosis of the tibia (Figure 14). The procedure is fragmentation, reversal of fragments and intramedullary rod fixation. Both the proximal and distal metaphyseal areas are osteotomized and the diaphysis is removed from the limb in two pieces. The fragments are reversed so that the base of the proximal fragment is against the tibial metaphysis just above the ankle joint and the distal fragment or the bone graft is against the metaphyseal area just below the knee. The fragments are securely fixed into the distal and proximal metaphyseal areas with intramedullary rod-

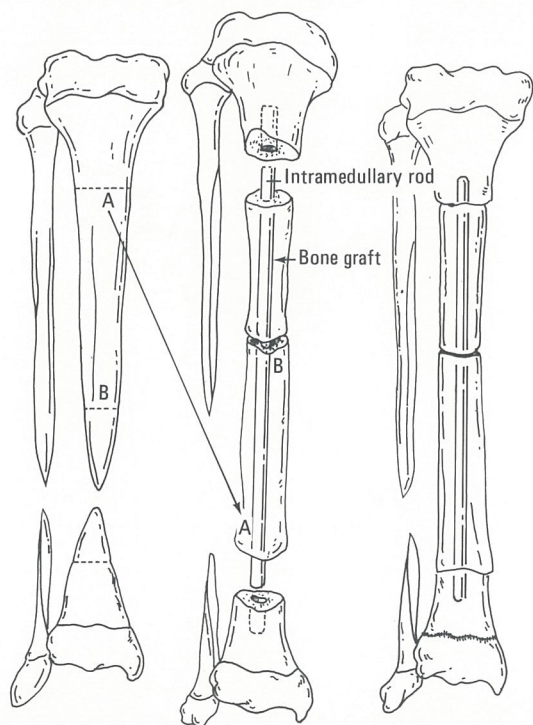


Fig. 14: Technique of Sofield and Miller Treatment of congenital pseudarthrosis of the tibia.

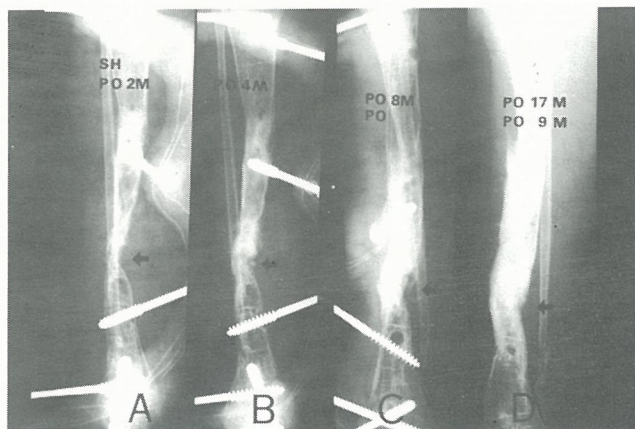


Fig. 15A: The second periosteal grafting was performed in order to obtain the thicker tibia eight months after the first periosteal grafting.

ding. In this method, bone union is expected with the aid of their healthy part of the tibia because congenital pseudarthrosis of the tibia has a segmental dysplasia of bone with local failure of normal bone formation in its distal half. However, proximal part of affected tibia is used in Sofield's method.

In our procedure, bone union is promoted with the aid of the only periosteum of opposite normal proximal tibia. Electric stimulation with capacitive coupling was also started four months after periosteal grafting. Eight months after the first periosteal grafting, the second periosteal grafting was performed in order to obtain the thicker tibia (Figure 15). The electric stimulation with capacitive coupling has been also applied for ten months in every night at his home since he was an outpatient.

The patient was successfully treated with two times of periosteal grafting from left normal tibia and with electric stimulation of capacitive coupling.

The conventional operative procedures of autogenous bone graft need large amount of bone graft, and it may cause deformity of donor site of the children.

In our method, the donor site of the periosteum was medial part of the left proximal tibia. There is no significant deformity nor bone defect at the donor site of periosteum where is stimulated electrically.

SUMMARY

Electric stimulation for fracture and bone disease should be used as followings:

1. Choose the most suitable method among the various electric stimulations for each case.

2. Non-invasive method is used more often than invasive method.

3. Electrical stimulation is not always all-mighty. Bone union is dependent on the condition of the affected bone. In the case of poor callus forming capacity of the bone, bone union does not occur with electric stimulation alone. In this occasion, we are treating with bone graft and DC

stimulated periosteae graft.

4. Using electrical stimulation for fresh fracture, will enhance easily bone union and short convalescent time is expected.

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