Glaser #2121

ELECTROMAGNETIC RESPONSE IN BONE

Miles F. Buchman

The form of the bone being given, the bone elements place or displace themselves in the direction of the functional pressure and increase or decrease their mass to reflect the amount of functional pressure.

Julius Wolff

A BONE WILL GROW to relieve the load placed upon it. Prolonged periods of inactivity result in loss of mass and strength of bones. Conversely, increased physical activity yields heavier, stronger bones. Wolff's Law, published in 1892 as "the Law of Bone Transformation," was the first detailed description of this relationship between mechanical stress and bone structure.

A long bone fracture in a child need not be set in perfect alignment. About a year after the fracture has healed, the bone will have remodeled itself, straightening its alignment at the old fracture site to best bear the loads imposed upon it. In all cases of bone modification, some mechanism, dependent on stress, regulates the adsorption of old bone and growth of new bone. This stimulus-response system may be analyzed by control-system theory. The basic biological control system is negative feedback in which an initiating environmental stimulus is converted to a biological response by a biological transducer. Figure 1 is a schematic representation of such a mechanism. In the particular case of Wolff's Law response of bone, the environmental stimulus is mechanical stress and the response is the stress oriented bone growth and remodeling.

Work by many investigators since the early 1950's has evolved a possible transducer mechanism. The bone, under a mechanical stress, produces a measurable electrical potential. This potential may be the significant biological signal that activates a second transducer to induce bone remodeling. Experiments have led to three theories, all or none of which may describe the actual mechanism.

TRANSDUCER THEORIES

The first theory is that the highly crystalline nature of bone causes it to be a piezoelectric material. Thus it produces an electric current upon deformation and conversely, deforms upon application of an electric field. Many researchers have shown that bone does indeed fit this phenomenological definition of a piezoelectric material.

The second theory postulates a semi-conductor junction of the p-n type. Classical p-n junctions produce electrical current upon deformation. The p-n junction in bone is

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This is Mr. Buchman's first article for the TRIANGLE.

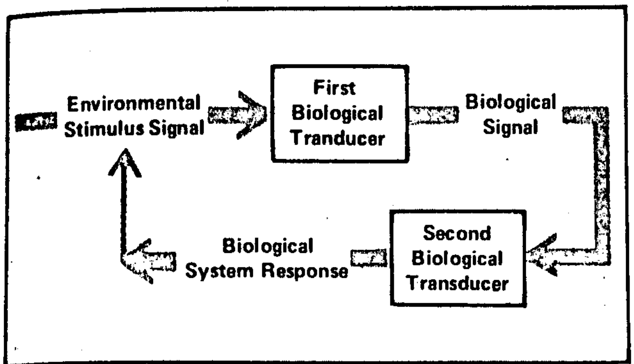

Figure 1. Schematic diagram of a biological response system in which a transducer mediates environmental stimuli with a biological signal which leads, via a second transducer to a systemic response.

thought to be the interface between a collagen molecule (the long chain triple helix protein that composes bone, skin, cartilage, and nail) and a crystal of hydroxyapatite (the calcium bearing compound giving bone its strength and hardness) oriented upon it. One researcher determined the diode voltage-current characteristic for the bone p-n junction although others who tried to duplicate this experiment failed.

The third theory is known as a streaming potential, which basically involves the displacement of charged ions in solution in moist bone (the natural state). The small cavities in the bone matrix are filled with ionic fluid. As the bone is elongated in deformation, the volume of these cavities increases and more fluid rushes in to fill the cavities. When the load is removed, the bone returns to its initial configuration, the cavities return to their initial volume, and some fluid is displaced from the matrix. The resulting motion of charged ionic fluid results in a stress induced "streaming" potential in moist bone.

QUANTITATIVE MEASUREMENTS

The Biomaterials group at the University of Pennsylvania is currently conducting a series of experiments to resolve the controversy and determine the transducer that produces the stress induced potential. A significant breakthrough was attained by Jonathan Black in a series of experiments recently completed. He was able to design a complex testing apparatus and use procedures to keep bone samples alive and moist during the measurement of stress induced voltages. The resulting data is the first quantitative measurement of the bone tranducer's effect as it presumably operates in a living individual.

A second series of experiments is being planned by the author to determine the actual mechanism of the transducer. The various components of bone thought to produce the electro-mechanical response will be individually removed or modified and the remaining bone will be tested for transducer behavior. It is hoped that this method will isolate and finally quantify the source of the response.

These results will be applied to the electrically induced fracture healing studies presently underway by a team headed by Dr. Carl J. Brighton of the Orthopaedic Research Department. The normal electrical response of bone will be coupled with the already proven electrical induced fracture healing to give medicine a valuable new tool.

STATIC AND DYNAMIC POTENTIALS

The total electrical potential in bone can be broken down into two parts, the static potential and the dynamic potential. The dynamic potential is the constantly varying time dependent phenomenon discussed above as being induced by stress. It is thought to be responsible for bone maintenance and remodeling as evidenced in the effects described in Wolff's Law. Since the dynamic potential can be thought of as responsible for bone maintenance, various bone diseases and atrophy of old age can be interpreted as degradation of the transducer. Through a knowledge of the transducer, the dynamic current could be increased by an external source to combat osteoporiosis and other bone diseases.

The static potential in bone is the constant voltage present in live bone which is not subjected to a load. Work in the University of Pennsylvania Medical School by Drs. Friedenberg and Brighton in 1966 indicated that this potential varies along the length of a long bone. At the ends (which are growing), the voltage was negative, gradually increasing to isopolarity in the middle. These measurements agree with a more general observation that areas of cellular proliferation in living tissues tend to be electronegative with respect to surrounding tissues.

When the bone was fractured, the whole bone became more negative, with a greater negative voltage at the ends and a secondary increase in the negative potential at the fracture site. This increase in current due to the fracture prompted studies on the effect of an applied voltage on facture healing.

RABBIT STUDIES LEAD THE WAY

Early studies on fracture of rabbit tibias indicated that the optimum current to form new bone is between 5 and 20 microamperes, with new bone forming at the cathode. A larger series of studies was then conducted by Drs. Friedenberg, Roberts, Didizian, and Brighton on the actual placement of the electrode around the fracture.

The tests were performed on 60 New Zealand white rabbits whose left and right fibulae were surgically cut. Electrodes were placed near the fracture as indicated in Figure 2, either at the fracture site itself or 5 millimeters away. The polarities were reversed and group number 5 had one electrode distant from the bone just below the surface of the skin. The electrodes were placed in both legs, but only those on the left were connected to the 10 microampere constant current power supply; the right acted as a control.

Eighteen days after the fracture, the rabbits were sacrificed and the degree of healing was analyzed by the amount of bone formation at the fracture and the strength of bone (measured on an Instron Universal testing machine). Only groups 3 and 5 exhibited a higher degree of fracture healing in the current treated leg bone. It was therefore concluded that fracture healing was induced when the cathode was placed in the fracture site with the anode hearby. Further studies on rabbits over a ten year period showed bone and soft tissue destruction at the anode for currents of 20 microamperes or greater.

HUMAN FRACTURE HEALING

The latest and by far the most interesting series of experiments now being conducted at the University of Pennsylvania is a clinical study on fracture healing with electrical potentials in humans. The research team headed by Dr. Brighton includes Drs. Friedenberg, Steinberg, Black, Pollack, and Korostoff. Only a few cases have been tried to date, with one success in the first five attempted. All human cases consisted of old fractures that had not healed. These non-union cases would normally require a surgical bone graft, which in some cases would result in loss of normal motion in the limb or joint. The successful patient was a 51 year old female with a hair line fracture of the ankle which had not healed in 14 months. A teflon-coated stainless wire with the end exposed was inserted into the fracture site under local anesthesia. The anode was applied to the skin on the lower leg. The 10 microampere constant current power supply was connected and a cast applied over the entire device (Figure 3). After 9 weeks, the cast was removed and x-rays indicated that the fracture had healed.

Only non-union fractures have been tried and the present technique has not yet shown positive results when soft tissue has invaded the gap in the bone. Current values and electrode design are presently being investigated for treatment of both large bones and fresh fractures involving gaps.

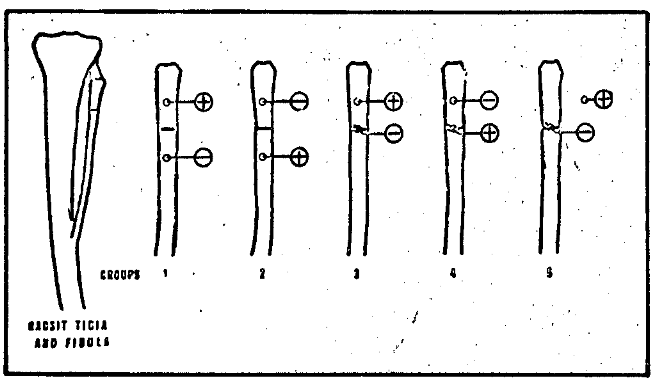

Figure 2. Drawing of the five electrode placements on the rabbit fibula. Note that in groups 3 and 5 the cathode is inserted directly into the fracture site. Groups 3 and 4 are reversed polarity from 1 and 2.

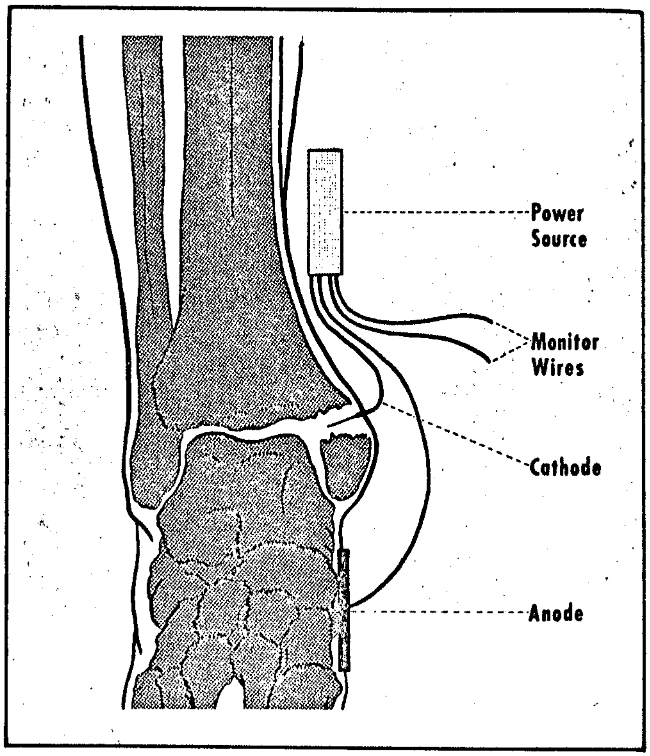

Figure 3. Sketch of the design of the current unit used on human non-union facture of the ankle. Then entire apparatus except for two monitoring wires is encased in a plaster cast.

Further case studies will be undertaken on fresh hairline fractures and other types of old non-union cases.

THE FUTURE

Once perfected, the process of inducing fracture healing with electric current might reduce healing time to about one-half (based on animal studies). Also, the ease and quickness of the procedure allow a doctor to perform the technique in his office rather then lengthy expensive bone graft surgery in the operating room. Moreover, since the limb will be immobilized for a shorter period of time, the patient will recover normal use and strength more quickly. The final result – the patient will resume his normal activities at a – smaller cost in both hospitalization and discomfort.

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