Electrifying Biology

By DIETRICK E. THOMSEN

Electricity may be good for you — in homeopathic doses. It may, in fact, be part of what makes exercise beneficial. Very minute currents (in the microampere range) produced naturally in bone and connective tissue appear to play an important role in maintaining the health of those tissues.

Researchers are still trying to understand the origins of these signals to relate them "to specific mechanisms well known in physics," says Wendell S. Williams of the University of Illinois at Urbana-Champaign. Nevertheless, clinical applications are already under way. Says Eiichi Fukada of the Institute of Physical and Chemical Research in Wako, Japan: "The clinical applicability of DC, AC or pulsing electric current for the treatment of nonunion [failure of the ends of a fractured bone to unite] and pseudoarthrosis [formation of a false joint by a fractured bone] has been established."

Biological cells and tissues are much more complex systems than physicists are used to studying, yet these researchers, who might be called biophysicists, have reached "a degree of unity ... to set the stage for providing a model to understand some of these effects," according to Abraham R. Liboff of Oakland University in Rochester, Mich. A symposium at the recent meeting in Baltimore of the American Physical Society featured their recent achievements.

Minute electric currents are produced in bone when it is stressed, and one example of unity among researchers in the field is the attribution of that electricity to two sources. To quote Fukada, whom the others regard as a pioneer in the subject, "Stress-induced electricity in bone is caused by both piezoelectricity in collagen and streaming potential in microcanals in bone." Or, in other participants' words: piezoelectricity for dry bone, streaming potential for wet bone.

Piezoelectricity is induced by pressure that slightly deforms crystals in the material, causing a separation of electrical charges, that is, polarization. This will make an electric current flow. Streaming potential results from the behavior of liquid in microtubules in the bone. As bone is stressed, this liquid is forced to flow in the microtubules. The flow carries with it charged ions, and consequently a current.

"This stress-induced electricity is believed to affect the metabolic activity of osteocytes [certain bone cells] in living bone," Fukada continues. "Application of piezoelectric polymer films around the femurs of animals induces new bone formation."

In biological tissues the kind of piezoelectricity that investigators deal with is mainly shear piezoelectricity, polarization caused by bending the material. Fukada, whose work in the field goes back three decades, says the study of shear piezoelectricity in biological samples started with wood cellulose, silk fibroin (the protein that forms silk filaments) and bone collagen. Over the years the effect has been found in "several cellulose derivatives, chitin and amylose, which are polysaccharides; collagen in tendon, skin and teeth; keratin in wool, baleen and horn; fibrin in blood clot; myosin and actin in muscles, which are proteins; DNA; several kinds of synthetic polypeptides; and optically active polymers...."

Williams speaks of a recently developed polymeric device that responds to an electric field by bending or produces an electric field when bent. (Piezoelectric effects work backward as well as forward.) He remarks: "It is interesting that biological tissues, which have been on earth for millions of years, utilize this same feature — displaceable bound charge — for generating unusually large electric fields."

In living bone the streaming-potential current, induced by the flow of slightly charged liquids, becomes important. (In fact it shorts out part, but not all, of the piezoelectric current.) Both currents arise from slight bending of the bone under loads, and both depend on the rate at which the mechanical stress is applied. It follows, therefore, that impulse loading, as in running, should produce a larger signal than slow deformation, as in swimming.

Williams cites a recent study of osteoporosis, a bone deterioration disease that tends to affect postmenopausal women. It found that gravity-related activity (running, for example) is more beneficial in reducing the rate of bone loss than is activity that doesn't involve impacts. At the University of Illinois Williams and co-workers immobilized the hind limbs of some rabbits and found that they became osteoporotic in a few months. The researchers then stimulated some of the limbs with minute electrical currents, and "substantial amounts of new bone were produced, though loss of cortical bone was still noticed." His tentative conclusion from all this is that electrical currents are necessary "to sustain the activity of the bone cells that produce new bone (the osteoblasts) to keep pace with the activity of bone cells which tear down existing bone (the osteoclasts)." In healthy, active bone the two procedures are in balance, and the bone tissue continually turns over, gaining new cells while losing old.

Currents due to the streaming effect also occur in soft tissue, namely the cartilage attached to bone. For a long time the question of the origin of currents in cartilage — whether they are piezoelectric or from the streaming effect — has been a matter of debate. Now, Alan J. Grodzinsky and Eliot H. Frank of Massachusetts Institute of Technology have found evidence that such currents are due to streaming. For their experiments they devised an apparatus to impose stresses on calf cartilage.

The effect of electric current on the health of cartilage seems to involve an electrically charged molecule, proteoglycan, manufactured by the cartilage tissue. Other researchers' experiments show, Grodzinsky says, that in the disease osteoarthritis, "there is a heavy leach-out of this molecule." In that disease cartilage degenerates, and then the joints it protects begin to malfunction. There seems to be a connection between absence of proteoglycan and osteoarthritis. Grodzinsky and Eliot have an experiment in progress to see whether production of proteoglycan can be stimulated electrically.

If all this is so, Grodzinsky points out, it may be possible to design a diagnostic procedure that would measure the streaming-potential current in cartilage and thus show deterioration of cartilage before any arthritic symptoms appear.

Biological systems naturally produce electricity, and it seems to be important for their health

Exercise involving impacts—such as running—produces a larger electrical current in bone than does non-impact exercise such as swimming.

Electric currents can also be induced by changing electric and magnetic fields. Liboff points out that application of a pulse of strong current to coils held close to the skin also promotes bone healing. The current pulse generates varying magnetic and electric fields, and these fields would induce a current in any nearby substance capable of carrying a current (presumably in this case the bone). More than 20,000 patients have been treated this way, Liboff says, but no physical model explains what happens at the cellular level.

Certain clues have emerged from recent experiments, however. They relate to cyclically varying magnetic fields. According to Liboff, very weak magnetic fields varying at rates between 10 and 100 hertz have produced a number of biological effects, including: changes in mitotic (cell division) cycle time in slime mold; enhanced DNA synthesis in human cells; changes in mRNA production in insect cells; development problems in chick embryos; changes in metabolic activity in human lymphocytes and macrophages; and "surprisingly large" increases in activity in mouse and human cancer cells.

The threshold frequency for such effects is quite small, about 0.1 gauss per second. The effect is not dependent on dose: Increasing either the frequency of change or the amplitude of the field above threshold does not increase the effect. As the earth's field is about 0.5 gauss, the threshold is equivalent to switching the earth's field on and off over a few seconds. Indeed, Liboff relates, Carl Blackman of the Environmental Protection Agency found that the outflow of calcium ions from the brains of chicks depended on the earth's field at the locality of observation; altering the field had a strong influence.

Liboff hypothesizes that the mechanism for these effects is a cyclotron resonance. When a magnetic field is imposed, electrically charged ions in cells should begin to move in circular or helical paths. The natural frequency of revolution around the circle is different for each species of ion. If cyclic fluctuations of the magnetic field occur at a frequency that matches the natural frequency of a given ion, a condition known as cyclotron resonance will be set up, which ought to be an efficient way of pumping that ion in and out of cells.

To test this, Liboff joined two psychologists, John Thomas and John Schrot of the Naval Medical Research Institute in Bethesda, Md., to set up an experiment tuned to affect lithium ions in the brains of rats. Following exposure, "a sharp change was observed in the ability of rats to reproduce certain timing schedules for which they had been intensively trained," he says. This effect occurred when the rats were subjected to an applied magnetic field varying at 60 hertz superimposed on the local natural field of 0.26 gauss, but not when they were subjected to either the local field or the varying field alone. Liboff draws two conclusions: "First that cells may indeed be able to selectively absorb energy from weak, slowly changing [electromagnetic] fields, and secondly that behavior may be modulated to some extent by the local geomagnetic field." □