The Electrical Century

The Bioelectrical Century: Bioelectrical Engineering and the "Inside Story" of the Electrical Century

I. Introduction

Although in this series of articles the twentieth century is being called "The Electrical Century," an argument could perhaps be made that it is "The Medical Century." There have been remarkable advances in our ability to diagnose and treat disease and in our understanding of life processes at the molecular and organ system levels. Almost every aspect of our lives has been affected by new pharmaceuticals, new surgical techniques, new imaging techniques, and new understandings of disease. The story of the transformation of our view of our inside selves, and its consequences, is well known to the general public. What is perhaps less well known is the role of electrical engineering in this unprecedented revolution, and we would like briefly to reveal some of this "inside story."

As in almost every field of human technological endeavor, the application of electrical engineering to medicine in the twentieth century was profoundly affected by the development of electronics, its stepchild the computer, and related mathematical advances. Biomedical engineers have been involved in the invention of instrumentation, the development of sensory aids, prostheses, and other therapeutic devices, and the applications of physics and systems theory to physiological systems, including the use of mathematical models. There are three areas of biomedical engineering, however, that uniquely involve the transmission and/or reception of electromagnetic radiation into or out of the human body itself in order to diagnose and/or treat illness—pure "electromagnetic engineering" if you will. It is on these areas, therefore, that we would like to focus in telling the story of what we would call the "Bioelectrical Century." We refer to electrophysiology, electrotherapy, and imaging.

Electrophysiology is the understanding and processing for diagnostic purposes of electromagnetic waves produced by the body itself (i.e., by the heart—electrocardiography, by the brain—electroencephalography, and by the muscles—electromyography). By electrotherapy we mean the application, for therapeutic purposes, of electromagnetic waves into the body. Medical imaging is the passing through the body of electromagnetic radiation for the purposes of obtaining a visual image of its interior. We will specifically trace the development of one manifestation of each of these areas: the electrocardiogram (ECG); the pacemaker; and X-ray computer tomography (CT).

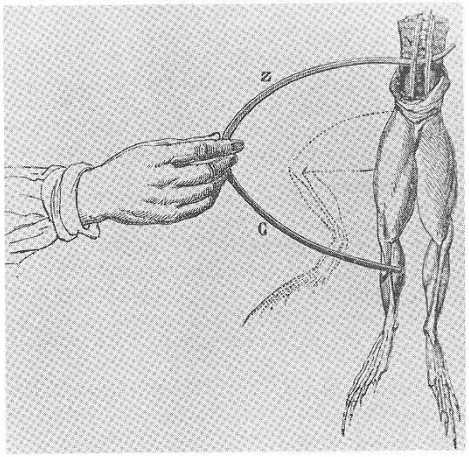

Fig. 1. Galvani's current experiment. (Courtesy of the IEEE History Center.)

II. Beginnings

Electrical activity of neurons in the brain gives rise to the electroencephalogram (EEG) on the scalp. Activity of skeletal muscle gives rise to the electromyogram (EMG) which may be detected on the skin overlying the muscle. Activity of heart cells gives rise to the ECG on the torso. The interplay of the physics, technology, biology, and medical aspects of electricity provides a fascinating history. Interrelationships have been intensive, continuing, and fertile for more than two centuries. Indeed it was a controversy between electrical pioneers, Alessandro Volta and Luigi Galvani, that helped elucidate not only the nature of bioelectricity, but that of electricity in general (Fig. 1), and led to an important technological advance, the battery.

Already in the eighteenth century, the natural scientists of the Enlightenment had seen the effects that electricity could have on living organisms. Some of them even tried to employ static-electrical machines and Leyden jars in early forms of "electrotherapy." Galvani, a professor at

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Bologna, first observed in 1786 that electricity caused a dissected frog's leg muscle to twitch and claimed he had demonstrated the existence of animal electricity. His countryman Volta argued that the electricity was artificial, arising from a potential difference when two dissimilar metals were in contact, and by 1799 Volta developed the battery.

It took until almost the middle of the nineteenth century for Galvani's successor at Bologna, Carlo Matteucci, to determine that living organisms did indeed produce a small but definitive electric current and therefore, as was known by then, a magnetic field. Efforts began both to understand how these signals were produced and also to improve instrumentation for detecting and recording them, attracting the attention of such leading electrical scientists as Hermann von Helmholtz (who in 1894 was made an Honorary Member of the AIEE, for that and other work). Prompted by his interest in the propagation of impulses in nerves, he began to consider the physics of bioelectric potentials. In 1853 he published a remarkable paper laying out important aspects of the physics of the volume conductor problem. The relationship between muscle motion, nerve cells, and electrical activity gradually came to be understood. As early as 1875, the electrical activity of the brain in the absence of muscle motion was observed, but owing to instrumentation problems, EEG was not to be developed for another 50 years.

The heart, meanwhile, as an active muscle with somewhat stronger signals, was closely studied in this regard, though initially with animal experimentation. The instrumentation to measure even these relatively weak signals noninvasively was developed rather slowly. Then, in 1878, Theodore Wilhelm Engelmann in Utrecht produced the first plot of a primitive ECG, and ten years later the Englishman Augustus Desir Waller recorded the first plot of a human ECG from the body surface. Ironically, neither Engelmann nor Waller saw the clinical potential of what they had; they were pursuing pure biophysics. It was left to Willem Einthoven to leap medical science forward at the dawn of the Electrical Century with the publication in 1900 of his paper "On the Normal Human Electrocardiogram and on the Capillary—Electrometer Examination of Several Cardiac Patients."

III. Electrocardiography in the Twentieth Century

The EEG and the ECG are time-varying potential fields on the body surface which can be recorded with the aid of electrodes and amplifiers. One can look at these potentials alternatively as a set of time-varying voltages or a set of body surface potential distributions. Study of the voltage waveforms often involves signal processing techniques, with consideration of waveform recognition, data compression, and signal averaging for noise reduction. Study of the distribution of potential brings field theory into play and involves the relationship of sources in cell membranes to the currents they produce in the volume conductor which is the body.

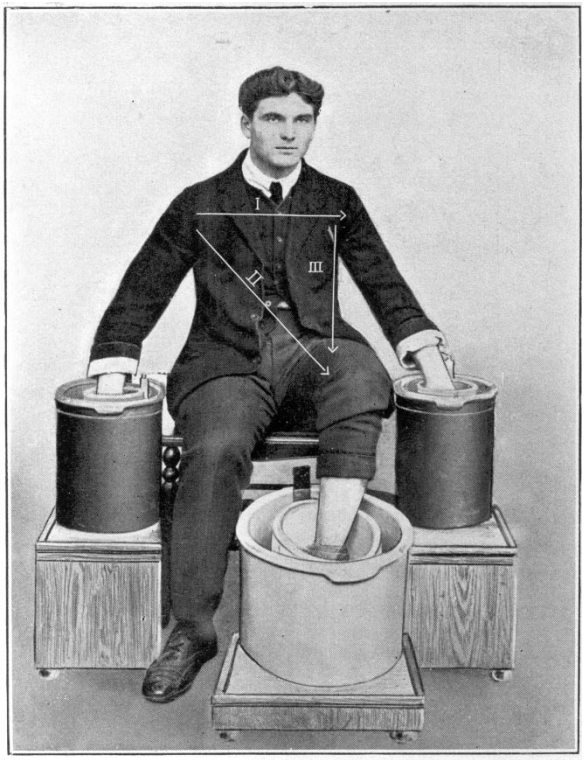

Fig. 2. Early electrocardiography setup. (Courtesy of the Bakken Museum and Library.)

As mentioned, the pioneering work was done by the end of the nineteenth century, notably by von Helmholtz and then Einthoven, but the great advances were to take place almost 50 years later (Fig. 2). At the end of World War II, a number of investigators trained as engineers or physicists turned their attention to the ECG and subsequently to the EEG. We now have a good picture of how body surface potentials are related to cellular activity at the membrane. Models of the cell membrane incorporating the kinetics of ion movement have been developed to aid our understanding of the electric activity of the heart. Considerable effort is being devoted to the inverse problem of determining cardiac activity from the surface ECG. Most of these efforts have been devoted to reconstructing potentials on the epicardial surface of the heart. In the last half of the century investigators have turned their attention to the magnetic field generated by the heart and brain outside the body.

The measurement of bioelectric potentials has challenged the state of technology since the eighteenth century, and this challenge has led to many improvements in instrumentation and, arguably, in digital computers through the development, supported by the National Institutes of Health, of the LINC computer as a laboratory (personal) computer. Electrocardiography became clinically feasible with the invention of the string galvanometer by Einthoven, who was prompted by his need for a suitable instrument for studying the electrocardiogram. He proposed a physical model of the ECG, i.e., a dipole source in a volume conductor, which continues to dominate thinking in the field.

Einthoven received the Nobel Prize for his contributions to electrocardiography.

The electrocardiograph is undoubtedly the medical diagnostic device which has received the earliest and most intensive study from the standpoint of standardization. Recommendations published over a period of 45 years have addressed such questions as performance specifications such as frequency response, common mode rejection, input impedance, and electric safety. Electric safety is important because the electrocardiograph (as well as other devices) may introduce power line currents into the heart causing it to fibrillate, and it is essential to establish limits on these currents. It is interesting to note that the first paper to identify the vulnerable period of the heart to alternating currents appeared in *Electrical Engineering* in 1936. Newer stand-alone devices almost invariably utilize digital signal processing and have forced a re-examination of the standards which were developed for direct writing analog devices.

The ECG was evidently the first diagnostic signal to be studied with the goal of automating interpretation with the aid of a digital computer. Computer programs are now incorporated into microprocessors built into portable electrocardiographs. There are two aspects to these programs. One is the analysis of the heart's rhythm. The other is the analysis of the waveform to determine whether, for example, injury to the heart muscle has occurred. Patient monitoring devices feature automatic alarms and provide trend data on certain parameters of interest. To assess arrhythmias in patients, Holter tape recorders accumulate 24 h or more of continuous ECG signals. Equipment for scanning Holter tapes, which are typically played back at a speed 60–240 times normal, include computer programs for recognition and analysis of the waveforms. Somewhat as a byproduct, digital recording has had a major impact on the problem of archiving and retrieving records.

IV. Pacemaking in the Twentieth Century

Meanwhile, new advances throughout the nineteenth century in electrical science and engineering were constantly tested for their effects on the human body (Fig. 3), and electrotherapy continued to grow in popularity, often leading to quack devices. A lecture by Nikola Tesla to the AIEE in 1891 about the heat caused by high-frequency current where he mentioned its possible impact on a living organism led to the field of diathermy. Diathermy, the treating of internal tissue by heating without burning the skin, through means of electromagnetic radiation, continued to develop through the twentieth century, with various shorter and shorter frequencies being applied. Tumors were one illness treated locally in this way, and in the case of infection the whole body could be heated. The popularity of diathermy began to wane after World War II with the widespread introduction of antibiotics, improved surgical techniques, and other competing therapies, although the development of radar eventually led to microwave diathermy being a recognized treatment.

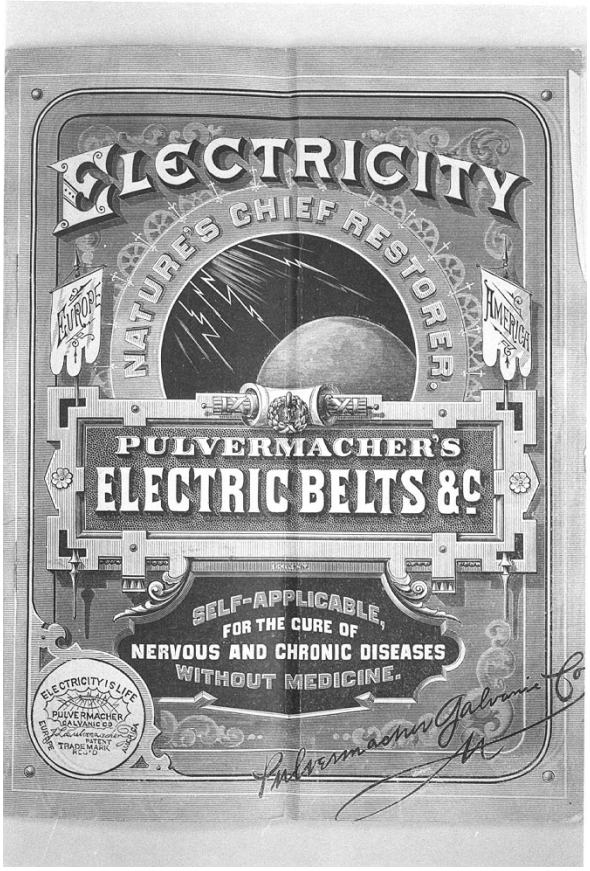

Fig. 3. Nineteenth century ad for an electrotherapy device. (Courtesy of the IEEE History Center.)

That the heart, too, responded to electricity was known for some time. In 1933 William Kouwenhoven, an electrical engineer working with a team of physiologists, proved that an electric shock can restore a fibrillating heart to normal rhythm. At about the same time, it was first observed that the application of smaller periodic pulses of dc current to the chest could cause the heart's own beat to accelerate to match the rate of the pulse, and it was suggested that this phenomenon could be used to treat bradycardia—slow heart rate.

It was Albert Hyman who, in 1918, realized that if small pulses could be supplied directly to the correct area of the heart, whether through needle electrodes or catheters, then the heart, once restarted from cardiac arrest, could be kept beating until other therapies could be employed, and he coined the term "artificial pacemaker." Owing to advances in electronics, heart surgeon Clarence Lillehei and engineer Earl Bakken were able, by 1958, to solve the problems of stable circuitry, long-lasting battery, and suitable electrodes, and to produce a completely portable and wearable pacemaker. This advance in turn led eventually to the wholly implantable pacemaker (Fig. 4), and the concept that an individual whose heart would otherwise not beat effectively could lead a relatively ordinary life.

Pacemakers are now available which can sense electric activity in both the atria and ventricles of the heart as

Fig. 4. Early implantable pacemaker, circa 1960. (Courtesy of the IEEE History Center.)

well as stimulate these chambers independently. Sophisticated algorithms are available for interpreting the sensed signals and delivering an appropriate sequence of pulses to achieve proper functioning of the heart. Features have been added to recognize and terminate life-threatening arrhythmias, including ventricular fibrillation. Pacemakers can sense physiologic parameters which indicate when the heart output is inadequate, for example, during increased activity, and adjust their rate accordingly. The dual-chamber pacemakers generally have the capability of programming many parameters of the pacemaker function. Design of pacemakers requires an intimate knowledge of cardiac electrophysiology.

A second major advance in the treatment of arrhythmias is catheter ablation. This technique involves inserting an electrode into the heart and delivering a pulse of RF current to destroy a region of heart muscle, thus disrupting a path causing an arrhythmia. The site to ablate is determined by extensive mapping of electric activity from sensing electrodes introduced with catheters into the heart. Display systems showing the patterns of electric activity tied to the heart anatomy have been developed. These maps provide another view inside the body.

V. X-Ray Tomography in the Twentieth Century

The final thread of bioelectrical engineering we wish to discuss is almost wholly a twentieth-century phenomenon, although it saw tremendous activity in just the last five years of the nineteenth century. In 1895, Wilhelm Conrad Röntgen (Fig. 5) announced the discovery of a new, penetrating form of electromagnetic radiation that was a byproduct of cathode ray tubes, which he termed "X rays." They could be used in conjunction with a photographic plate to produce a shadow image of physical structures of mixed density. Röntgen had immediately realized the medical application of his discovery: in fact, his first report

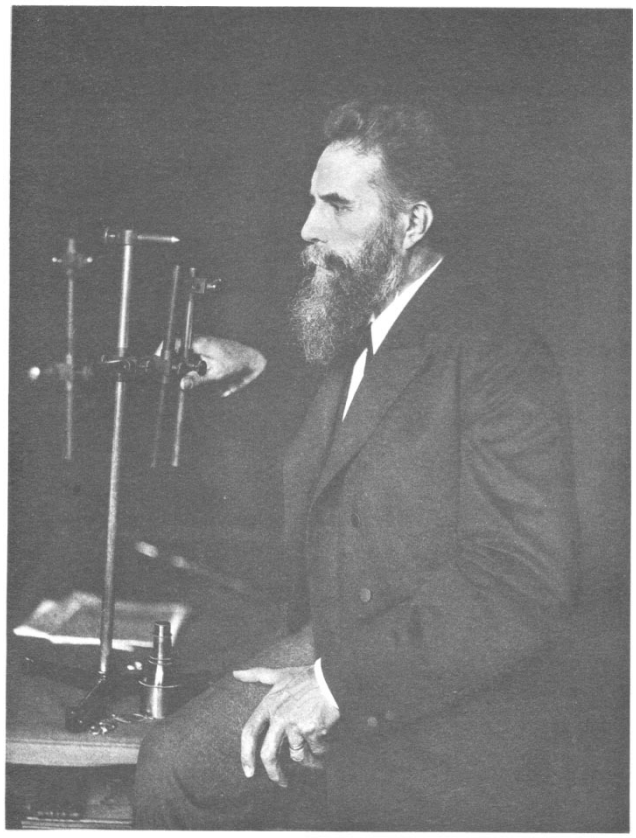

Fig. 5. Röntgen with his apparatus. (Courtesy of the IEEE History Center.)

was to the Physical Medical Society of Würzberg and included an X-ray image of his wife's hand. The world, medical and otherwise, quickly grasped the importance of the discovery. Within two months an X-ray photograph was admitted into a Canadian court as evidence and led to a shooting conviction in a case where the bullet was still lodged in the leg. Within a year, the article "The Clinical Application of the Röntgen Rays" appeared in the *American Journal of Medical Science*.

The physical appearance of the interior of the human body could now be observed noninvasively. A field then began whose mission was to increase resolution, stability, and flexibility while improving safety (for example, reducing exposure times) and decreasing cost (for example, making a more robust tube). The first big breakthrough came in 1913, when William D. Coolidge of the GE Research Laboratory in Schenectady, NY, perfected the modern tungsten-target X-ray tube. This advance was to have almost immediate impact with the outbreak of the World War I in 1914. Radiography was an ideal diagnostic tool for the battlefield surgeries of twentieth century. Nobel Laureate Marie Curie herself, aided by her daughter, future Laureate Irène Curie, worked for the French military transforming automobiles into mobile X-ray vehicles and oversaw their installation and the training of their operators. The war and its aftermath spurred further research into new contrast agents, new films, and other ways of improving the process so that various

Fig. 6. CT scanner, circa 1978. (Courtesy of the IEEE History Center.)

internal organs could be viewed with greater and greater precision.

But the main problem facing the radiographers was how to improve the image by removing shadows of structures that existed in other planes of the body. During the war, a Polish doctor named Carol Mayer produced the first "tomogram," an image of a single plane or "slice" of the heart. After the war, a series of patents to achieve this end followed, and by 1937 the first commercial tomographs were produced. A major problem still facing the designers of X-ray equipment, however, was one that had arisen in other areas of science and engineering in the past: how does one take the interior slices and construct a three-dimensional image of the inside of a complex solid object? In 1960, William Oldendorf, who was trained as a physician but who was an inveterate tinkerer (he even belonged to the AIEE), patented an electronically based device that could image slices continuously through a solid object, but the world lacked the computational power to turn it into a single three-dimensional image. However, continued developments, both published and industrially secret, and the continued advances in computing led in 1972 to Electrical and Musical Industries Limited of London (yes, the record people) patenting and producing the first commercial "CAT" (computer-aided or computer-assisted or computed axial tomography) scanner.

Computer tomography (CT) (Fig. 6) scanners, as they came to be known, used powerful computing to take X-ray cross sections of the body and convert them into a three-dimensional image. Naturally, over the past 25 years or so, these instruments have been further refined both in their physical and computational aspects. Furthermore, engineers and physicists have been able to develop forms of tomography based on other physical effects, notably magnetic resonance imaging (MRI) based on nuclear magnetic resonance. Electrical engineers have contributed to the development of another imaging modality, ultrasound, which is extensively used in cardiology and obstetrics, and where efforts are underway to improve the resolution by going to higher frequencies.

From the very beginning, X-ray-based CT and later MRI radically changed the practice of health care and the view by physicians of the human body. The soft tissues of a living person and their state of health, from tiny tumors on the brain to damaged tissue on the lungs, could be observed by a doctor as if the person had been dissected, but completely noninvasively. Indeed, these images have aided anatomy.

In recognition of the impact of CT, the engineer responsible for the EMI project, Godfrey Newbold Hounsfield, in 1979 became the first engineer to receive the Nobel Prize for Physiology or Medicine. The world, through its most prestigious scientific prize, had recognized the convergence of electrical engineering and medicine. With the continued advances in such areas as imaging (including whole new realms such as catheterization with fiber optics), signal processing, electrical and radiation treatment, cybernetics, and laser surgery, perhaps it will be the twenty-first century that will be the true "Bioelectric Century."

David B. Geselowitz
and Michael N. Geselowitz

APPENDIX
FOR FURTHER READING

[1] G. E. Burch and N. P. DePasquale, *A History of Electrocardiography*. San Francisco: Norman, 1990 (ECG).

[2] K. Jeffrey, *Pacing the Heart. Copiague*. New York: Wexford, 1990 (Pacing).

[3] B. H. Kevles, *Naked to the Bone: Medical Imaging in the Twentieth Century.* New Brunswick, NJ: Rutgers Univ. Press, 1997 (Imaging).

[4] M. Rowbottom and C. Susskind, *Electricity and Medicine: History of Their Interaction.* San Francisco, CA: San Francisco Press, 1984 (General).

[5] For a good online resource, visit the website of the Bakken Museum and Library, an educational institution that collects material related to the history of electricity and magnetism in medicine and the life sciences: http:// www.bakkenmuseum.org.

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Limits of Semiconductor Technology	Late 2000/Early 2001	James D. Meindl, Director Microelectronics Research Center School of Electrical and Computer Engineering Georgia Institute of Technology 791 Atlantic Dr., N.W. Atlanta, GA 30332-0268 james.meindl@mirc.gatech.edu
Flat Panel Display Technology	Early 2001	Babu R. Chalmala, Senior Scientist Motorola, Inc. Flat Panel Display Division, FPD22 7700 South River Parkway Tempe, AZ 85284 chalamala@email.mot.com Bruce E. Gnade Dept. of Materials Science University of North Texas Denton, TX 76203 Frank R. Libsch IBM T. J. Watson Research Center MS 14-234 P.O. Box 218 Yorktown Heights, NY 10598

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