STARS: ELECTROCARDIOGRAPHY

Editor's note: *This month we continue a series of reprints from the IEEE Global History Network's STARS articles.*[1] *STARS is an online compendium of invited, peer-reviewed articles on the history of major developments in electrical and computer science and technology. Some light editing has been done, along with the addition of a few illustrations, to make the article more suitable for a journal publication.*

The development of electrocardiography, a painless noninvasive technology which is invaluable in the medical world today, is a result of a continual collaboration between cardiologists and engineers.

Because heart disease, along with cancer, is at the top of the list of public health concerns, electrocardiography, which provides vital information about the functioning of a heart, is one of the most important of all medical technologies. This technology grew out of investigations beginning in the late 18th century of electrical phenomena in living systems.

I. GALVANI TO WALLER

In 1791, Luigi Galvani reported his observations that an electric spark could cause the muscle of a frog leg to twitch.[2] This report initiated the study of bioelectricity, which made great progress in the 19th century through the efforts of numerous investigators, often with ingenious experiments. They found that muscle and nerve cells are electrically active and that electric activity propagates along muscle and nerve fibers. (In a sense, the electric battery was an offshoot of bioelectricity: Alessandro Volta suggested that a voltage arose in the path Galvani was studying due to a contact potential between dissimilar metals, and Volta went on to use this idea to invent the battery.)

Since body tissues conduct electricity, currents and electric potentials (voltages) are produced in the surrounding medium. In some cases, the potentials are large enough to be detected at the body surface. The measurement of bioelectric potentials nonetheless would pose a major challenge to researchers. The heart's signals are small in amplitude, on the order of millivolts. The time course often exhibits rapid changes. In many cases, the signals are pulsatile in nature. Many ingenious instruments were developed to measure bioelectric potentials. In a number of cases, these instruments themselves advanced the state of the art.

The study of the spread of currents in body tissues is called the volume conductor problem. In 1853, Hermann von Helmholtz developed the physics of the volume conductor problem in a remarkable paper. In the second half of the 19th century, some researchers experimenting on animals believed that these signals could provide important clinical information for each of the three muscle types—skeletal, smooth, and cardiac. Etienne Jules-Marey first recorded electric activity in skeletal muscles and named the electromyogram in 1890, for example, and the electrogastrogram, research on which began in 1885, reflects electric activity of the smooth muscles of the stomach. Of greatest immediate clinical significance was the realization that an electrocardiogram could provide information about the heart's condition.

In 1856, R. A. von Kölliker and Heinrich Müller of the University of Würzburg discovered that a frog's heart generates an electric current and that it varied in time with the beating of the heart. Recording this signal proved difficult. It is intriguing to note that the investigators used the sciatic nerve in a frog's leg to perform their measurement. Thus, wires attached to the surface of the heart were led to the frog muscle. Von Kölliker and Müller observed that every time the heart beat, the muscle twitched.

Augustus D. Waller of St. Mary's Hospital, London, first recorded a human electrocardiogram (ECG or EKG) in 1887. Waller used a sensitive detector of electricity, Gabriel Lippmann's capillary electrometer (Figs. 1 and 2). He captured a time record of the voltages by photographing the shadow of the meniscus (the top

[1]Please refer to the STARS website for additional information and to view the full article: http://www.ieeeghn.org/wiki/index.php/STARS:Electrocardiography#cite_ref-0.

[2]It should be pointed out that Galvani's experiment dealt with electric stimulation of muscle, and stimulation of muscle, especially of the heart, is an important medical topic on its own. This topic, which includes the development of pacemakers and defibrillators, is outside the scope of this article.

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Timeline

1791	Luigi Galvani reports that an electric spark can cause muscle to twitch
1853	Hermann von Helmholtz develops the physics of the volume conductor problem
1856	R.A. von Kölliker and Heinrich Müller discover that a frog's heart generates electric currents
1887	A.D. Waller records a human electrocardiogram (ECG)
1901	Willem Einthoven describes the string galvanometer for recording an ECG
1905	Cambridge Scientific Instrument Company sells first commercial string galvanometer
1927	William Craib develops the theory of a dipole source in a sphere
1933	Frank Wilson relates current sources in the heart to external potentials
1938	The first standards for electrocardiographs are published
1946	Herman Burger formalizes heart vector and lead vector concepts
1949	Norman Holter invents an ambulatory ECG monitor
1953	Otto Schmitt, Richard McFee, and Ernest Frank develop vector lead systems
1963	G.M. Baule and Richard McFee measure the magnetic field of the heart
1984	Adriaan van Oosterom and Thom Oostendorp publish the first version of ECGSIM

surface of the liquid in the capillary tube) on moving paper. While the erratic quality of the recordings made Waller pessimistic about their utility, one of his demonstrations inspired Willem Einthoven. He recognized, in turn, that the ECG or EKG could be a powerful tool for learning about the function of the heart, but the challenge remained to develop an accurate amplifier and recorder of the small currents produced by the heart, and other muscles, in contraction.

II. EINTHOVEN

In 1901, Willem Einthoven (Fig. 3), a physician and physiologist at the University of Leiden, developed the string galvanometer. It had a better sensitivity and frequency response than the capillary electrometer and was much sturdier. Using this device, Einthoven made clinical electrocardiography practical. He undertook many clinical studies, which advanced the art of interpretation of the ECG, and he performed animal experiments to aid in this understanding. Finally, he presented a theoretical framework for relating the ECG to sources in the heart, work for which he received a Nobel Prize in 1924. In addition, companies in several countries began making and selling versions of Einthoven's machine.

Electrocardiograms are recorded based on the input from leads connected to the body at specific points. Einthoven proposed that the heart is an electric generator that acts approximately as a dipole; that is, as a

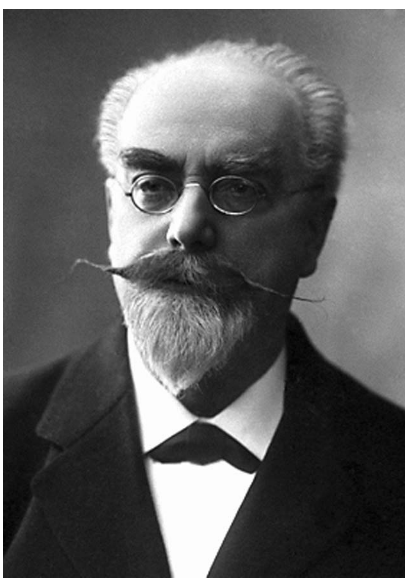

Fig. 1. *Gabriel Lippmann.*

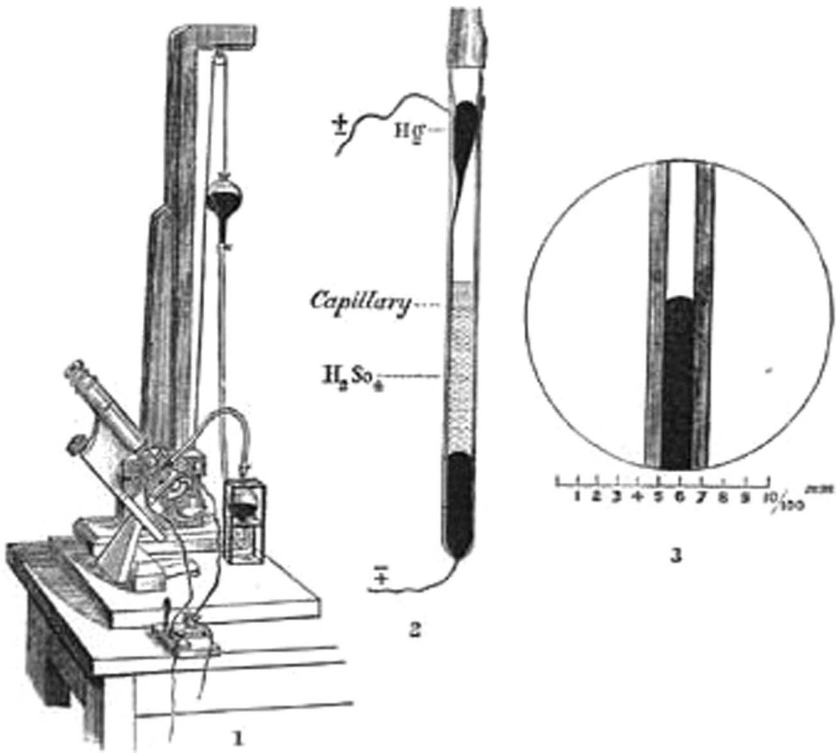

Fig. 2. *Capillary electrometer.*

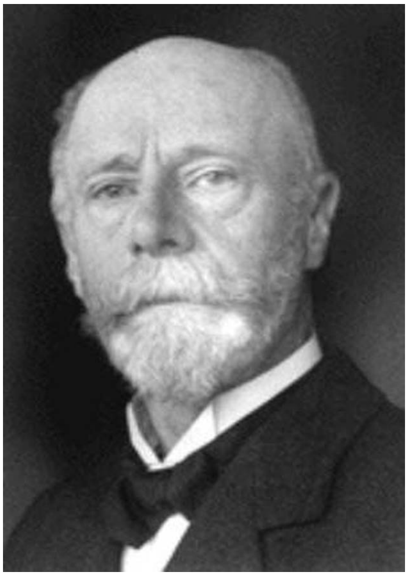

Fig. 3. *Willem Einthoven.*

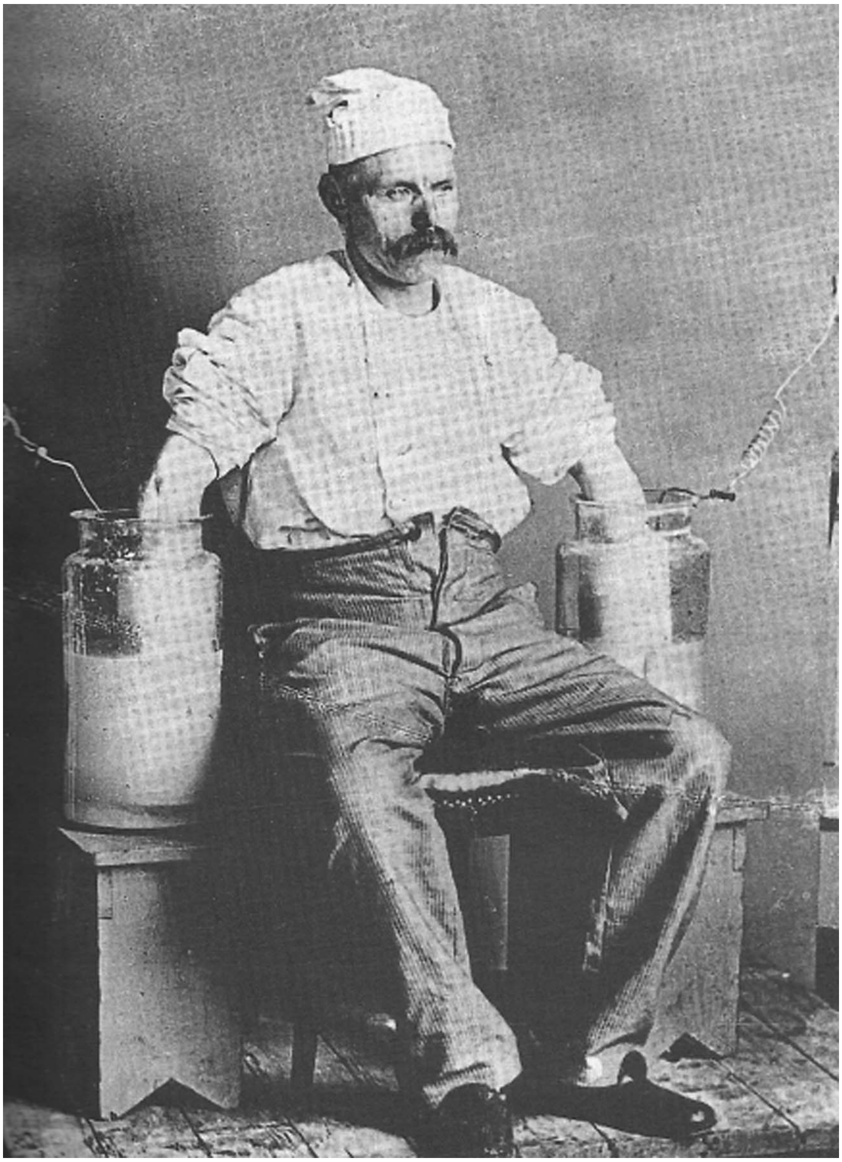

Fig. 4. *Recording of ECG from Einthoven's laboratory.*

pair of electrodes (electrical terminals) separated by a short distance. He regarded the electrical actions of the heart as quantifiable vectors consisting of a magnitude and a direction, and proposed an analytic scheme in which three vectors form a triangle, called today the Einthoven triangle.

The term "lead" has two meanings here. It can refer to an actual electrode and cable connected to the electrocardiograph. It also refers specifically in electrocardiography to the voltage difference between two or more of these electrodes. In the simplest case, a lead involves two electrodes attached to the skin. The leads used by Einthoven, called limb leads, were obtained from pairs of electrodes attached at the left leg (lead 1), the left arm (lead 2), and the right arm (lead 3) (Fig. 4). Einthoven recognized that these voltages were not independent, but that lead I + lead III = lead II, a relationship known today as Einthoven's law.

III. FROM EINTHOVEN TO BURGER

Nerve fibers and muscle fibers are cylindrical in shape. When a fiber is active, an electrical impulse, called the action potential, propagates along the cylinder with a given velocity. The impulse involves the membrane of the cell, which undergoes a rapid depolarization. The action potential produces currents which may be considered to arise from a dipole.

In cardiac muscle, the cells are interconnected in such a way that the muscle can be considered a syncytium, a cell-like structure with many nuclei. As activity propagates through the heart muscle, or myocardium, it produces a waveform on the body surface designated the QRS complex. Excitation is followed by recovery (repolarization), which produces a T-wave. These characteristic ECG forms were recognized and named by Einthoven.

In the 1920s, the South African William H. Craib studied the field of muscle preparations in a spherical conductor. In a famous experiment, he showed that the potential produced by a strip of muscle was that of a dipole. This helped validate Einthoven's concept of the heart as a dipole, with the distance between the pair of electrodes small in comparison with the distance from the heart to the skin. Theoretical work by investigators in various countries advanced the understanding of the biological phenomena behind the ECG. For example, in the United States in 1933, Frank N. Wilson of the University of

Michigan related current sources in the heart to external, unipolar, potentials, and in The Netherlands, Herman C. Burger formalized the concepts of heart vector and lead vector 13 years later.

IV. PRECORDIAL LEADS

The refined understanding of the electrophysiology of the heart and body led to more, and more complex, ECG leads involving several electrodes. In 1932, Charles Wolferth and Francis Wood proposed recording from electrodes on the chest over the heart, using the right arm as a reference. The American Heart Association (AHA) and the Cardiac Society of Great Britain and Ireland established the standard locations and circuits for six precordial, or chest, leads in an electrocardiogram in 1938. In 1934, Wilson introduced what is now called the Wilson central terminal (WCT), in which he connected resistors of equal value between the three limb electrodes and a central point in the Einthoven triangle, and averaged their potentials. Wilson called these the unipolar leads, which he designated VL, VR, and VF. These three leads together with leads I, II, and III constituted the limb leads. Ten years later, Wilson used the WCT as a reference for the six standard precordial leads, V1-V6. Together we have a total of 12 leads, which constitute the standard ECG.

There is one more addition to Einthoven's arrangement that completed the contemporary complement of 12 leads in an ECG. In 1942, Emanuel Goldberger pointed out that the unipolar leads could be enhanced 50% by simply opening a resistor in the WCT. Thus, for the VL, the WCT is modified by opening the resistor to the left arm. This is designated an augmented lead, AVL. In a similar way, we get AVR and AVF.

V. BIOPHYSICAL STUDIES

Einthoven's concepts led investigators to consider several problems. First, how can surface potentials be calculated given a current dipole source in a bounded-volume conductor? This is called the forward problem. Second, how can the heart dipole be estimated from skin potentials, a question known as the inverse problem. Third, how accurate is the single dipole approximation?

The investigators named above tried to put the theory on a firm physical basis, with the earliest work being done by Burger. Since there were no digital computers available, the investigators resorted to a physical analog to relate a dipole source, representing the heart, to skin potentials. The analog, called a phantom, was a surface representing the human torso. A dipole source in the heart region was energized, and potentials on the surface were measured. In this way, the problem of relating skin potentials to a dipolar cardiac source was solved.

The inverse problem involved determining the characteristics of the heart dipole from voltages measured at the skin. Several investigators came up with schemes for doing this, relating the measurements made at a small number of skin electrodes to the characteristics of the dipole.

The third question is how good an approximation is the heart dipole. A definitive answer was provided in 1956 by Ernest Frank, an electrical engineer at the University of Pennsylvania. Frank built a phantom that was a plaster cast of a particular individual, which he could equip with leads and then measure electrical behavior. He found rather good agreement between the actual behavior of the heart and the behavior of a dipole source, thus validating the approach.

With the advent of electronic digital computers it became possible to solve the forward problem without the use of a phantom. The team of H. Gelernter and J. C. Swihart at IBM, and Roger C. Barr and subsequent investigators elsewhere began pioneering this approach in 1964.

VI. RELATION TO CELLULAR ACTIVITY

The forward problem can be solved for a given source distribution. For many years, emphasis was on the current dipole as discussed above. At the same time, there was interest in relating the source distribution to cardiac cell activity. There was evidence that the wavefront separating resting heart cells from those that had undergone depolarization was a surface dipole layer. This activation layer would move through the heart during the cardiac cycle. So researchers regarded the cardiac activity as the motion of this double layer, which could be approximated as a single dipole.

Investigators studied animal hearts to try to determine the spread of activation. Many electrodes were placed in the heart and the voltage recorded. As activation passed an electrode, the recorded voltage changed abruptly. Dirk Durrer of the University of Amsterdam reported results from a resuscitated human heart in 1970. In this way, a picture emerged of the spread of activation in the heart. These studies also gave information about the repolarization or recovery phase of the heart, which occurs more gradually.

In 1973, Walter Miller and David Geselowitz published a simulation of the ECG which gave very good results for the normal heart as well as for several examples of infarction and ischemia. Their result has been referred to as the Miller–Geselowitz model. The heart was represented by 23 dipoles. It incorporated reported results of the sequence of activation and the cardiac action potential. A digital computer solution was used for calculating potentials at electrode sites on a realistic torso. Subsequently, Adriaan van Oosterom and Thom Oostendorp of the Radboud University Medical Center in Nijmegen published a more sophisticated simulation called ECGSIM (Fig. 5) in 1984.

VII. STANDARDS AND SAFETY

An important group advancing the state of electrocardiography was the AHA Committee on Electrocardiography. This committee proposed standards for leads, electrode placement,

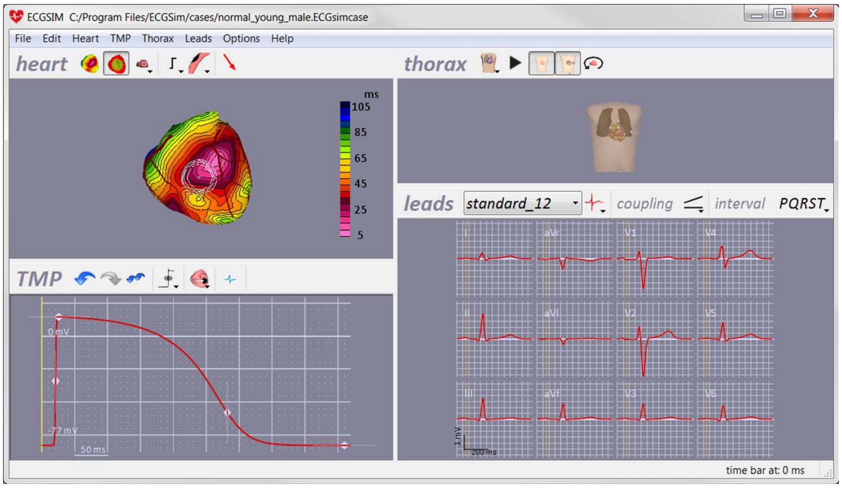

Fig. 5. ***ECGSIM's main windows (courtesy of ECGSIM).***

axis conventions, and nomenclature. Three activities of this committee were standards for electrocardiographs, for electric safety, and for computer interpretation of arrhythmias. When Hubert Pipberger, a cardiologist with the Veterans Administration in Washington, DC, became chairman of the committee in the mid-1960s, he appointed a subcommittee of biomedical engineers to address instrumentation problems. Later engineers became full members of the committee.

The electrocardiograph is powered from the mains. Because impedance (a measure of opposition to current) is relatively small at the electrode-skin interface, the electrocardiograph acts a current source driving current into the body. The key to the electric safety standard is to specify the limit on this leakage current, which has a direct path to the heart through the body.

A modest number of experiments had been performed to try to determine the threshold for causing the heart to fibrillate, which is the danger of small currents. These experiments led the committee to adopt a leakage-current limit of 10 μA. There had been a study in 1936 to determine safety limits for electric currents with regard to workers in the vicinity of high power lines. Published in the journal *Electrical Engineering*, this study identified the important concept of the vulnerable period, an interval during the cardiac cycle when a current pulse could cause fibrillation.

The earliest standards for electrocardiographs were published in 1938. They have been revised several times. Pipberger instituted the policy that no member of the committee could have any connection with industry. The question was raised whether the committee lacked knowledge about the design and engineering of the devices. This contingency was handled by the committee holding periodic open meetings where they presented their current thinking. Manufacturers could then provide feedback.

VIII. ECG MONITORING AND OTHER TOPICS

The ECG is monitored routinely in the operating room. It is monitored on patients in coronary care units, often with a wireless connection to the nurse's station. With a routine ECG, a rhythm strip of the order of ten seconds is recorded to detect arrhythmias. Researchers have found, however, that this duration is often inadequate. Norman Holter developed an ambulatory monitoring device, the Holter monitor, which records the ECG over a period of 24 h to detect arrhythmias which occur more infrequently. Systems have been developed to transmit the ECG over a telephone line to a central station where a report will be sent to the physician. If an emergency situation is detected, help can be sent to the patient. At present, the telephone transmission is activated by the patient, but schemes are under development for the patient to be continuously monitored and if a critical event is detected the transmission will be automatic.

In 1963, Gerhardt Baule and Richard McFee measured the external magnetic field resulting from cardiac activity (magnetocardiogram). David Cohen introduced use of a more sensitive magnetometer, called Superconducting Quantum Interference Device (SQUID). David Geselowitz worked out the theory for magnetic fields external to a volume conductor, and several laboratories have been exploring magnetocardiography, but clinical relevance is yet to be established.

Several investigators developed computer programs for interpretation of the ECG, including manufacturers who incorporated these programs in electrocardiographs. Interpretation of cardiac arrhythmia provides a particular challenge. The AHA Committee on Electrocardiography formed a group of experts to come up with a database in which representative ECGs were annotated to indicate the arrhythmia. This database could then be used to evaluate the performance of arrhythmia programs.

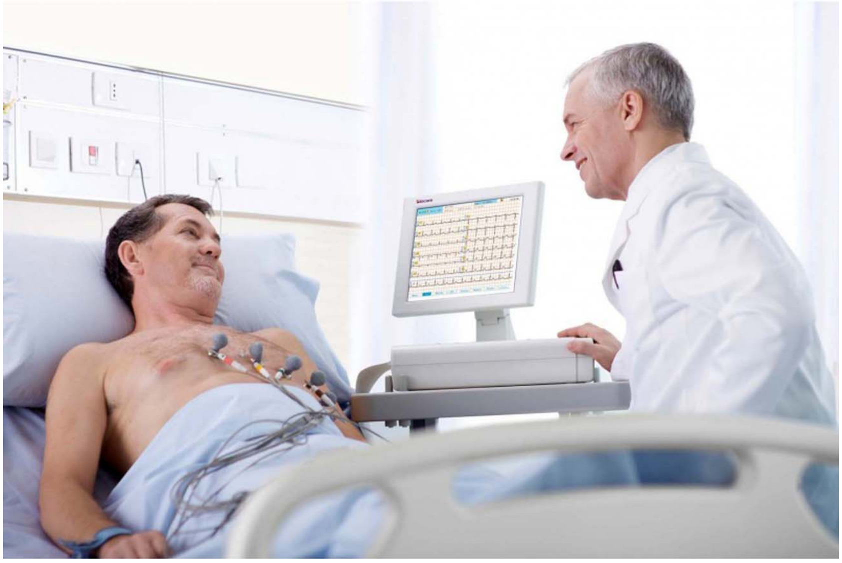

Fig. 6. *Contemporary electrocardiography (courtesy of Biocare Diagnostics).*

Another topic of interest is body surface mapping, where a large number of electrodes are attached to the skin to produce a map of ECG activity instant by instant during the cardiac cycle. Robert Lux used principal component analysis to determine the number of components necessary to extract the information present. A separate but related question is the number of leads necessary to extract the diagnostic information from the ECG.

A final topic is cardiac mapping. An electrode can be inserted into the heart and placed at various locations on the endocardial surface. Techniques are available for tracking the location of the electrode and displaying the electrograms. One very important application involves identifying the site of the origin of an arrhythmia, which can then be treated directly. This technique has proven to be quite successful. Studies have also been performed on the pattern of excitation waves during fibrillation to try to understand the mechanism of this phenomenon.

The development of the field of electrocardiography has been a continual collaboration between cardiologists and engineers. The result has been a painless, noninvasive technology that is today invaluable to medical care throughout the world (Fig. 6). ■

DAVID B. GESELOWITZ

ABOUT THE AUTHOR

David B. Geselowitz (Fellow, IEEE) is Professor Emeritus of Bioengineering and Medicine at the Pennsylvania State University. He is a Fellow of the American College of Cardiology and the American Association for the Advancement of Science, and he is a Founding Fellow of the American Institute for Medical and Biological Engineering. He served as editor of the IEEE TRANSACTIONS ON BIOMEDICAL ENGINEERING. He was elected to the National Academy of Engineering in 1989, and he received the Roger Granit Prize for contributions to bioelectromagnetism.