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A History of the Origin, Evolution, and Impact of Electrocardiography

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The invention of the electrocardiograph by Dutch physiologist Willem Einthoven in 1902 gave physicians a powerful tool to help them diagnose various forms of heart disease, especially arrhythmias and acute myocardial infarction. The discovery of x-rays in 1895 and the invention of the electrocardiograph 7 years later inaugurated a new era in which various machines and technical procedures gradually replaced the physician's unaided senses and the stethoscope as the primary tools of cardiac diagnosis. These sophisticated new approaches provided objective information about the structure and function of the heart in health and disease. This review summarizes the origins and development of electrocardiography and addresses its role in defining cardiology as a specialty.

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There is no denying the prominent role of technology in contemporary medical practice. Technology has changed the way doctors evaluate their patients, and it has changed the way patients view their doctors.[1] Our enthusiasm for medical technology, despite its cost and complexity, results from our conviction that it contributes significantly to the diagnosis and treatment of disease.[2] Earlier generations of doctors and patients shared our fascination with new diagnostic instruments and embraced the new technologies of their day.[3]

Reflecting on "the development of the science of diagnosis," Johns Hopkins physician Lewellys Barker[4] declared in 1917, "a physician that went to sleep in 1890 and woke up yesterday would find himself a disoriented Rip Van Winkle in diagnosis, with utterly antiquated ideas and information. The diagnostician that sleeps longer than eight or nine hours at a stretch in these days runs a risk!" Barker's Rip Van Winkle would have slept through the discovery of x-rays, the invention of the electrocardiograph and the sphygmomanometer, the development of many serologic tests, and the introduction of a multitude of other diagnostic techniques.

Today, no medical specialty is more dependant on various types of technology than cardiology. This reliance on technology (in its broadest sense) as an aid to cardiac diagnosis can be traced to 1819, when French physician René Laennec invented the stethoscope.[5] By the end of the 19th century, physicians with a special interest in heart disease also used the sphygmograph and the x-ray machine to help them evaluate their patients' complaints and physical findings.

The invention of the electrocardiograph by Dutch physiologist Willem Einthoven in 1902 represented a major advance in the methods available for the diagnosis of heart disease.[6] Moreover, the electrocardiograph heralded a new era in which various machines and technical procedures gradually replaced the physician's unaided senses and the stethoscope as the primary tools of cardiac diagnosis. This transition continues because doctors and patients alike value the objective and accurate analysis of the heart's structure and function that contemporary imaging and physiologic techniques provide.

This review will focus on the direct antecedents of electrocardiography and the subsequent development of the technique. Of necessity, I will consider only the most significant discoveries and observations that led to our current knowledge of electrocardiography. Many of the persons mentioned spent years, occasionally decades, pursuing the research or making clinical observations that ultimately resulted in an important discovery. The greatest advances in the science and practice of electrocardiography occurred during the first half of the 20th century, and this essay focuses on that era. Besides summarizing the development of electrocardiography, I will examine its role in helping to define cardiology as a specialty.

CARDIAC ELECTROPHYSIOLOGY IN THE 19TH CENTURY

Although Luigi Galvani, Alessandro Volta, and other scientists made important contributions to our knowledge of electricity during the late 18th and early 19th centuries, the origins of modern cardiac electrophysiology can be traced to the 1840s.[7,8] Italian physicist Carlo Matteucci showed in 1842 that an electric current accompanied each cardiac contraction. The following year German physiologist Emil DuBois-Reymond, the founder of electrophysiology, described an "action potential" that accompanied muscular contraction. He also confirmed Matteucci's discovery of electrical activity in the frog heart.

In 1856, continental physiologists Rudolph von Koelliker and Heinrich Müller first recorded a cardiac action potential, thereby proving that an electric current accompanied each contraction of the heart. During the next 4 decades several European scientists including Frans Donders, Theodor Engelmann, Richard Marchand, Étienne Jules Marey, and John Burdon Sanderson extended these pioneering studies on cardiac electrophysiology. The invention of several instruments of precision expedited their efforts and made it possible to measure and record graphically a variety of physiologic phenomena.[9]

French physicist Gabriel Lippmann invented a capillary electrometer in the early 1870s that British physiologists John Burdon Sanderson and Frederick Page used to record the heart's electrical current. They reported in 1878 that each cardiac contraction was accompanied by an electrical variation consisting of "two phases, viz., of an initial disturbance of short duration, in which the apex becomes positive, and of a much longer second phase, in which the apex tends to negativity." This was the first description of ventricular depolarization and repolarization.[10] Six years later Burdon Sanderson and Page published several tracings of the heart's electrical activity recorded with a capillary electrometer. The undulations they registered were later termed the QRS complex and the T wave. Enthusiastic about the capillary electrometer's potential role in studying the heartbeat, they claimed it was "of the simplest possible character" and noted that it was available "in most physiological laboratories."[11]

About this time Augustus D. Waller began a series of experiments at St. Mary's Hospital Medical School in London that culminated in his recording the first human electrocardiogram. By connecting electrodes attached to the front and back of a man's chest to a capillary electrometer, Waller showed that each heartbeat was "accompanied by an electrical variation." He also proved that the electrical activity *preceded* the heart's contraction, thus excluding the possibility that the recording was an artifact caused by "a mechanical alteration of contact between the electrodes and the chest wall caused by the heart's impulse." As historian Robert Frank, Jr. showed in an insightful summary of early cardiac electrophysiology, Waller spent more than a year pursuing his studies of the human electrocardiogram before reporting his results in the Autumn of 1887.[12,13]

As one would expect of a physiologist, Waller focused his attention on the theoretical aspects of the electrocardiogram—he showed little interest in using the technique clinically. Indeed, while he acknowledged the capillary electrometer's "convenience as an instrument of research," he concluded that "the technical difficulties are such as to prohibit its use as a clinical instrument."[14] Nevertheless, Waller's studies were critical for the subsequent development of electrocardiography. One of his more interesting observations was that it was unnecessary to apply the electrodes to the subject's chest. Waller explained: "if the two hands or one hand and one foot be plunged into two dishes of salt solution connected with the two sides of the electrometer, the column of mercury will be seen to move at each beat of the heart, though less than when the electrodes are strapped to the chest."[12]

WILLEM EINTHOVEN AND THE STRING GALVANOMETER

Willem Einthoven saw Waller demonstrate his technique of recording the heart's electrical impulse at the First International Congress of Physiologists held at Basel in 1889. Waller's demonstration stimulated Einthoven and a few other physiologists to pursue this line of investigation. William Bayliss and Edward Starling of University College, London, published the results of their research on the electrical activity of the heart using the capillary electrometer 3 years later. Improvements in the apparatus, including the use of an electric arc light and a more powerful projecting microscope, allowed them to distinguish 3 separate deflections (later known as the P, QRS, and T waves) in their tracings while Waller had identified only 2.[15]

Throughout the 1890s, Einthoven's research centered on the heart's electrical activity. He recognized the limited frequency response of the capillary electrometer and used complex mathematic and physical approaches to enhance the quality of his recordings. Einthoven succeeded in obtaining higher frequency recordings from his refined capillary electrometer and concluded that each cardiac contraction was accompanied by 5 distinct electrical deflections. In his first paper on the subject, published in 1895, Einthoven included drawings of these deflections which he labeled P, Q, R, S, and T.[16] His choice of these letters was not arbitrary; it reflected a tradition in mathematics that can be traced to 17th century French scientist René Descartes.[17]

Despite Einthoven's attempts to improve the capillary electrometer, he concluded that the instrument's poor frequency response limited its usefulness in cardiac electrophysiology. Although he continued to use the technique and recorded electrocardiograms from several volunteers, Einthoven turned his attention to an instrument that he thought might be more suited to the task. He was familiar with the galvanometers invented independently by the French physicist Arsène D'Arsonval and the French engineer Clement Ader. Einthoven described his modification of the string galvanometer in 1901 and first reported its use in electrocardiography the following year.[18–20] This little known 1902 paper, published in a festschrift for Dutch physician Samuel Rosenstein, included the first electrocardiogram recorded with a string galvanometer.

Einthoven's instrument consisted of a thin ($< 3\mu$) silver-coated quartz filament or string stretched across a strong magnetic field generated by a massive electromagnet. If an electric current, even the heart's small current, passed through the string it caused it to move from side to side in the magnetic field. The string's oscillations reflected the current's strength and direction. Einthoven magnified these minuscule deflections with a projecting microscope and recorded them photographically. The photographic plate moved at a rate of 25 mm/s so that each 1 mm deflection on the abscissa represented 0.04 second. By adjusting the tension of the string, each 1 mm deflection on the ordinate corresponded to 10-4 V. Einthoven's format for recording these deflections became the standard that is still used today.

In 1903, Einthoven reported his early experience with electrocardiography in separate papers in German and English. These articles included tracings recorded from 6 persons.[21,22] Einthoven's fourth paper on the technique appeared in 1906. Cardiologist Henry Blackburn, who translated much of this paper, considered it "the first organized presentation of normal and abnormal electrocardiograms recorded with the string galvanometer."[23–25] This article included tracings from more than a dozen patients, several of whom had cardiac arrhythmias. In it, Einthoven published the first electrocardiographic tracings of atrial fibrillation, ventricular premature contractions, ventricular bigeminy, atrial flutter, and experimentally induced heart block in a dog. Atrial enlargement was also depicted.

Although Einthoven was a physiologist, he recognized the potential clinical use of his invention. He thought the technique would shed light on the pathophysiology of heart disease, and thereby expedite the introduction of more effective therapies. But Einthoven's massive 600-pound apparatus was located in the physiologic laboratory of Leiden University almost a mile from the university's hospital. The title of his 1906 paper on electrocardiography, "Le Télécardiogramme," reflected an innovation that permitted Einthoven to record electrocardiograms from hospitalized patients. He used a telephone cable to transmit the electrical impulses from the hearts of hospitalized patients to his laboratory where they were recorded with the string galvanometer.

According to the historian of technology John Burnett, Einthoven's string galvanometer was "probably the most sophisticated scientific instrument in existence when it was first invented, combining as it did technical ingenuity in a number of fields."[26] Its development was facilitated by generous support that Einthoven received from Leiden University. Well-equipped and staffed with talented assistants, his institute had at this time "the most advanced instrumental setup in the world," according to Robert Frank Jr.[13] Although Einthoven's machine recorded high-quality tracings of the heart's electrical activity, it was cumbersome. He warned readers of his 1906 paper that the apparatus was expensive and required special training to operate.

Einthoven recognized the commercial possibilities of his invention. As early as 1903, he discussed its manufacture with Max Edelmann, who headed a scientific instrument company in Munich, and with Horace Darwin of the Cambridge Scientific Instrument Company in London. Royalty negotiations and technical problems delayed commercial manufacture of Einthoven's string galvanometer for 2 years. Both firms eventually produced the machine, but Edelmann refused to pay a royalty to Einthoven, claiming that he had substantially improved the instrument.

A few scientists and clinicians especially interested in disorders of the heartbeat acquired an electrocardiograph because they thought it would facilitate their studies of cardiac arrhythmias. The Cambridge Instrument Company produced and sold 3 Einthoven string galvanometers to physiologists between 1905 and 1907. The first unit equipped to record human electrocardiograms was installed in Edward Schäfer's physiologic laboratory at the University of Edinburgh in 1908.[26] The following year, smaller Edelmann versions of the instrument were set up in Thomas Lewis's laboratory at University College Hospital in London and Alfred Cohn's cellar workroom at Mt. Sinai Hospital in New York.

THE ADVENT OF CLINICAL ELECTROCARDIOGRAPHY: CARDIAC ARRHYTHMIAS

Although ancient physicians palpated the pulse, most cardiac arrhythmias were poorly understood before the invention of Einthoven's string galvanometer.[27,28] Unlike the sphygmograph, which registered the waveforms of the arterial and venous pulses or the apex impulse, the string galvanometer recorded the heart's electrical activity. The ability of this new instrument to directly record the electrical activity of the heart underscored the limitations of earlier indirect techniques. Cardiologist and historian Edward Shapiro referred to the electrocardiograph as "the Rosetta stone of the arrhythmias."[29]

After visiting Einthoven's laboratory in 1909, Thomas Lewis returned to London eager to study cardiac arrhythmias using the string galvanometer.[30] He recognized the practical value of the instrument and told Einthoven, "the galvanometer is going to do a great deal for clinical medicine."[31] As much as any of his contemporaries, Lewis advanced the science and practice of electrocardiography. His many publications on the technique and his willingness to accept visitors in his laboratory catalyzed interest in electrocardiography in Europe and America.

The electrocardiogram was ideally suited for the evaluation of cardiac arrhythmias, a subject that already interested several medical scientists and physicians.[32] New York clinical investigator Samuel Meltzer claimed in 1909, the same year Alfred Cohn brought the first electrocardiograph machine to America, "...keen investigators and leading clinicians throughout the world are now paying a great deal of attention to the study of cardiac arrhythmias, and the literature on the subject has already assumed large proportions."[33]

It is easy to see why many of these clinicians turned to the electrocardiograph to help them study disorders of the heartbeat. As with Wilhelm Roentgen's discovery of x-rays, it was immediately obvious that Einthoven's electrocardiograph provided unique clinical information. Through their publications and presentations, Einthoven, Lewis, and other pioneers of electrocardiography demonstrated the power of the technique to characterize the various types of arrhythmias encountered in patients. This, in turn, stimulated more physicians and institutions to purchase string galvanometers.

Of the various arrhythmias, it was atrial fibrillation that convincingly demonstrated the unique clinical value of the electrocardiograph. Although the sphygmograph had been used since the mid-19th century to record pulse waves, atrial fibrillation was not recognized as a distinct entity in humans until the early 20th century.[34] In 1899, Scottish physiologist Arthur Cushny, working at the University of Michigan, noted the similarity of arterial pulse tracings from patients with "extreme irregularity of the heart known clinically as delirium cordis" and those from dogs recorded "when the auricle is undergoing fibrillary contractions." Although Cushny[35] was reluctant to conclude that the arrhythmias were identical, he admitted, "the resemblance is certainly striking." After several more years of experiments and clinical observation using the sphygmograph, Cushny and Charles Edmunds[36] became convinced by 1906 that atrial fibrillation occurred in humans.

Although these observations were significant, they were not as compelling as those of Thomas Lewis. Using a string galvanometer to study patients with grossly irregular heart rhythms, Lewis[37] concluded in 1909 that atrial fibrillation was the usual cause of this arrhythmia and claimed it was "a common clinical condition." This discovery was a poignant example of the clinical relevance of the new technique of electrocardiography. Lewis explained, "although auricular fibrillation has been regarded by certain isolated observers as a possible phenomenon in clinical pathology, its association with anything beyond rare cases of paroxysmal tachycardia has not been seriously attempted until the last few months. The introduction of the string galvanometer as an aid to diagnosis has facilitated a much wider conclusion."[38]

Working independently, Carl Rothberger and Heinrich Winterberg, German pioneers of electrocardiography, also claimed that atrial fibrillation in experimental animals was identical to the rhythm disturbance in humans, termed delirium cordis (among many other names). They showed that electrocardiograms recorded from experimental animals and patients with what they thought was atrial fibrillation shared 3 features: a totally irregular ventricular rate; the absence of P waves; and the presence of peculiar oscillations (fibrillary waves) in the tracing.[39]

Walter James, a New York physician and clinical investigator, was one of the first Americans to use an electrocardiograph. Frustrated by his attempts to investigate cardiac arrhythmias with a sphygmograph, he declared in 1909, "the study of irregular hearts by modern means and the classification of the findings is entirely unsatisfactory." But James[40] was convinced that the electrocardiograph had played a crucial role in the recognition of atrial fibrillation in humans and was confident of the technique's potential as a clinical tool.

Thomas Lewis saw the delayed recognition of atrial fibrillation in humans as a poignant example of the value of medical technology. He told an audience at University College Hospital, "the history of the recognition of fibrillation of the auricles will impress you with the dimness of our eyes and the opacity of the obstacles which embarrass our vision. You will know how blind we have been to things which, once seen, are so apparent." Describing his recognition of the existence of atrial fibrillation in humans, Lewis claimed, "the awakening was a sudden one." He attributed his abrupt new insight to "*a new method* namely the electrocardiographic."[41] Einthoven,[42] too, thought the electrocardiogram had greatly advanced the recognition and understanding of cardiac rhythm disorders. In 1912, he claimed that arrhythmias "are always immediately recognized electrocardiographically."

Initially, Augustus Waller failed to fully appreciate the clinical relevance of the electrocardiogram. Two decades after he published the first human electrocardiogram in 1887, Waller revealed that at the time he "had no idea that the electrical signs of the heart's action could ever be utilized for clinical investigation." After visiting Einthoven's laboratory and reviewing his "extensive collection of human electro-cardiograms" in 1909, Waller conceded that electrocardiography "is capable of giving real information unattainable by any other means." Nevertheless, Waller thought the technique would have little impact on medical practice and doubted that it would ever "find any very extensive use in the hospital." Indeed, he predicted, "it can at most be of rare and occasional use to afford a concrete record of some rare anomaly of cardiac action....But for all ordinary purposes of diagnosis the finger-tips of the physician will hardly be helped by an instrument as difficult to manage and to interpret as is the string galvanometer."[43]

EARLY AMERICAN OBSERVATIONS ON THE ELECTROCARDIOGRAM

Horatio Williams and Walter James of New York also recognized the clinical potential of the electrocardiograph. After visiting Einthoven, Williams and his mechanic Charles Hindle constructed a string galvanometer that was used to record some of the first electrocardiograms in the United States.[44,45] They used Einthoven's strategy of teleocardiography to transmit electrocardiograms from Presbyterian Hospital to their string galvanometer located in the physiologic laboratory of the College of Physicians and Surgeons.

Williams and James published the first American review on electrocardiography in 1910. They claimed the procedure "gives us an entirely new point of view of the normal and morbid action of the heart and promises to throw new light upon the many problems presented by the physiology and the pathology of the organ." As an instrument of precision, Williams and James thought that the string galvanometer "leaves little to be desired." They applauded "the ease with which it may be adjusted to standard sensitiveness, and the rapidity with which the photographic records may be made." Moreover, they claimed, "little skill is required to manipulate it."

Williams and James thought the electrocardiograph was best suited for clinical research. Still, they acknowledged that optimism about the role of the machine in medical practice explained why "considerable interest has rapidly developed in electrocardiography." However, they thought the instrument's power as an aid to the senses might ultimately limit its role in clinical medicine. Once electrocardiography helped to define the pathophysiology of various "morbid phenomena," they speculated that "the clinician will no longer need this complicated apparatus to enable him to recognize and understand the conditions it has explained."[46]

Lewellys Barker, William Osler's successor as physician-in-chief of the Johns Hopkins Hospital, was one of the first Americans to use an electrocardiograph. An Edelmann string galvanometer was installed in his hospital in 1909. The following year he told members of the Association of American Physicians that the technique "has now passed the experimental stage and will doubtless form a part of the instrumental armamentarium of the larger general hospitals."[47] Barker's comments reflected changes occurring at America's hospitals as a result of the introduction of technology like the x-ray machine. Historian Charles Rosenberg identified "scientific and technological innovation" as a significant factor in the transformation of American hospitals around the turn of the century. He claimed that "by the 1920s, diagnosis had replaced dependency as the key to hospital admission."[48]

Barker published a concise account of the principles and practice of electrocardiography in 1910. In it, he rejected Waller's claim that the electrocardiograph would be of little clinical value. "Once an electrocardiographic station has been set up," according to Barker, "one can more quickly, easily and certainly analyze a cardiac arrhythmia by its use than by any other method." He declared, "the technique, once acquired is not difficult, and is far less irritating and baffling than that of making phlebograms and arteriograms (arterial pulse tracings) in difficult cases." The new technology was spreading rapidly according to Barker who claimed, "electrocardiographic outfits are being set up in the clinics of several of our larger cities."[49]

By 1913, Waller acknowledged the clinical utility of the electrocardiogram. That year he told a group of American physicians and medical scientists, "the electrocardiographic apparatus...has become a valuable adjunct to our means of making more accurate diagnoses in cases of cardiac disease or disturbance. It is no longer a laboratory toy, or an apparatus of pure scientific physiological interest, but it is an instrument of great clinical value, and one of easy application."[50] Waller changed his mind about the electrocardiograph's clinical value as many compelling reports of its usefulness appeared in the literature. Between 1910 and 1914, Thomas Lewis in England and Friedrich Kraus, Georg Nicolai, and August Hoffmann on the continent published well-illustrated books on electrocardiography that demonstrated its role in clinical medicine.[51–53]

THOMAS LEWIS AND THE DEVELOPMENT OF ELECTROCARDIOGRAPHY

In 1911, Thomas Lewis[54] published *The Mechanism of the Heart Beat*, a classic book that reflected his broad knowledge of cardiac electrophysiology. Lewis dedicated the volume to Willem Einthoven and James Mackenzie. He informed Einthoven, "the dedication is but a small recognition of the invaluable instrument and method which you have placed in the hands of *clinicians*" (emphasis added).[31] This same year the Cambridge Scientific Instrument Company of London loaned the first table model electrocardiograph it produced to Lewis for his new "Cardiographic Laboratory" established at University College Medical School.

In *Clinical Disorders of the Heart Beat*, published in 1912, Lewis summarized contemporary knowledge about cardiac arrhythmias. This book, a primer "for practitioners and students," included a summary of recent research that had helped elucidate the origin and conduction of the cardiac impulse. In it Lewis exposed physicians to new terms and ideas such as "sino-auricular node," "pacemaker," "premature contractions," "paroxysmal tachycardia," and "auricular fibrillation." He grouped arrhythmias into 6 categories: sinus arrhythmia, heart block, premature contractions, paroxysmal tachycardia, auricular fibrillation, and alternation of the pulse.[55]

This volume on cardiac arrhythmias was supplemented a year later by *Clinical Electrocardiography*. In his preface, Lewis[52] declared, "this new method of examination has become essential to the modern diagnosis and treatment of cardiac patients." Moreover, he claimed, "those cardiac patients are few, in whom an electric examination is superfluous, and in a large and increasing percentage of cases the records profoundly modify our conception of the conditions with which we deal." It is not surprising that orders for the Cambridge electrocardiograph increased dramatically after the publication of Lewis's popular book on the technique.[26]

As a result of his many publications and his role as mentor to several clinical scientists who learned electrocardiography from him, Lewis was the acknowledged authority on the technique by World War I. After Einthoven learned, in 1924, that he had won the Nobel Prize for inventing the electrocardiograph, he told Lewis, "I owe so much to you. Without your steady and excellent work to which you have devoted a great part of your life there would have been in all probability no question of a Nobel prize for me. You have given to Medicine at least as much as I have." [31,56]

While Lewis solidified his reputation as the world's leading electrocardiographer, Einthoven continued to investigate the technique's theoretical basis. The Dutch physiologist first communicated his equilateral triangle hypothesis to members of London's Chelsea Clinical Society in 1912. This hypothesis held that there was a mathematic relation between the direction and size of the deflections recorded in the 3 limb leads. He told them that the "schema of the equilateral triangle" could be used to "differentiate the real changes in the heart's action from the apparent ones, which are only caused by variations in the position of the heart." This approach also helped to identify pathologic conditions like left ventricular hypertrophy, which shifted the angle "of the most prominent peak of the QRS-group" leftward.[42]

THE EXPANSION OF CLINICAL ELECTROCARDIOGRAPHY

Following World War I, clinical electrocardiography expanded rapidly in America. Mayo Clinic physician Frederick Willius[57] wrote his 1922 book on the technique because of the "constantly increasing use of the electrocardiograph among clinicians, especially in hospitals and clinics." Doctors and hospitals were not the only ones interested in the electrocardiograph—patients were increasingly aware of the machine. In a review of Willius's book, Meyer Rabinowitz[58] observed, "the patient of today has read and heard much about the electrocardiograph, and if he suffers from heart disease is very apt to have an electrocardiographic tracing in his possession."

Already, the electrocardiograph was playing a role in distinguishing heart specialists from other physicians. It was claimed that special training and experience were necessary to interpret electrocardiograms accurately. Concerns regarding the qualifications necessary for performing and interpreting the test arose with increasing frequency as its use expanded. Stewart Hart,[59] a New York cardiologist, claimed in 1917 that "the electrocardiograph is an expensive laboratory instrument suited to the facilities of the large hospitals or the office of the consultant and cannot be included in the armamentarium of the average general practitioner."

Five years later, Philadelphia cardiologist Calvin Smith declared, "the person who undertakes to make a success of electrocardiography...must be prepared to devote all his time to acquiring and understanding of [the] art...[which] must be practiced regularly, systematically and faithfully, day after day, week after week, before proficiency is obtained. The mere possession of electrocardiographic equipment no more makes a person a cardiologist than the possession of Shakespeare's volume makes the owner a *litterateur*."

Smith acknowledged that "an electrocardiograph will never be in every physicians's office," but he admitted "with the present rate of growth, it cannot be very many years before electrocardiography is so universally established that it will be an invaluable part of the diagnostic equipment of every medical community which prides itself on progressiveness in the art of medicine." But this opinion of the potential for widespread application of electrocardiography implied that the technique could not be limited to heart specialists alone. Indeed, Smith[60] predicted that before long "the physician who cannot interpret a heart record will be deficient in a method of diagnosis that is now being taught to first year medical students."

The invention of less cumbersome electrocardiographic equipment after World War I also encouraged expanded use of the technique. By 1920, machines that could be moved to the bedside were available commercially.[61] A few years later, the Cambridge Instrument Company constructed an electrocardiograph designed to be carried rather than rolled around. Montreal cardiologist Harold Segall[62] bought one in 1927. He recalled 60 years later, "with much enthusiasm, I spoke of it to my confreres and demonstrated electrocardiograms, recorded in patient's homes or at the bedside in hospitals, when I spoke at medical meetings." Although portable, Segall's instrument was not light: it was housed in 2 wooden carrying cases, each weighing nearly 50 pounds.

In 1935, the Sanborn Company introduced a lighter machine contained in a single wooden case that weighed about 25 pounds. According to Harold Segall,[62] "this really portable model accelerated the spread of electrocardiography as general practitioners and internists attended two week courses in electrocardiography which became available after 1923 when Dr. Paul D. White began to give his special course in cardiology." Other academic cardiologists also began offering postgraduate courses in electrocardiography during the 1920s and 1930s.

THE ELECTROCARDIOGRAM AND MYOCARDIAL INFARCTION

Some historians have claimed that the electrocardiograph had no significant impact on therapeutics during the first several years it was used.[32,63] It is true that the treatment of arrhythmias did not change materially as a result of the introduction of the electrocardiograph. Digitalis and quinidine remained the mainstay of therapy until the 1950s.[34] Although these historians are technically correct, their interpretation undervalues the emphasis that physicians, then and now, place on diagnosis as an end in itself. Pioneers of electrocardiography promoted the test as a *diagnostic* tool; they did not claim that it had major implications for therapy. In a 1941 essay on "diagnosis in historical perspective," physician and historian Iago Galdston[64] identified "the function of diagnosis as essentially the definition of a clinical problem affecting a given individual to be solved therapeutically *when possible*" (emphasis added).

Patient care *was* directly affected by the electrocardiograph once its role in recognizing ischemic heart disease was appreciated. By 1920, it was apparent that the value of the electrocardiograph went beyond characterizing disorders of cardiac impulse formation and conduction and detecting atrial or ventricular hypertrophy. Clinical investigators discovered that it was possible to recognize acute myocardial infarction as a distinct syndrome with characteristic clinical *and* electrocardiographic features. This realization further stimulated interest in the technique as a clinical tool.

The first description of the typical clinical features of acute myocardial infarction was published in 1910 by the Russian physicians W. P. Obrastzow and N. D. Straschesko. They emphasized 2 main findings: prolonged chest discomfort (status anginosus) and persistent dyspnea (status dyspnoeticus). After presenting cases with autopsy correlations, Obrastzow and Straschesko concluded that the condition termed status anginosus represented coronary thrombosis, especially if there was evidence of persistent cardiac dysfunction following the event.[65]

Chicago physician James Herrick was familiar with Obrastzow and Straschesko's paper. From experimental, clinical, and pathologic reports, Herrick concluded that abrupt thrombotic occlusion of a major coronary artery was not invariably fatal as was commonly believed at the time. He argued that patients sometimes survived the event and might even recover fully. In 1912, Herrick described the clinical features he thought were characteristic of coronary thrombosis. Despite this compelling report, most of Herrick's contemporaries failed to appreciate the distinction between severe attacks of angina and the syndrome of acute myocardial infarction. Extracardiac causes of chest pain caused further confusion.[66,67]

The electrocardiograph played a crucial role in the eventual acceptance of Herrick's views. Once the characteristic electrocardiographic signs of coronary thrombosis were described, physicians had a powerful tool to help them recognize acute myocardial infarction. New York physician Bernard Oppenheimer, a pupil of Thomas Lewis, was among the first to extend the scope of electrocardiographic studies beyond arrhythmias to abnormalities of the waveforms.

When Oppenheimer and Marcus Rothschild[68] reported their studies of the "electrocardiographic changes associated with myocardial involvement" at the annual meeting of the American Medical Association in 1917, New York physician Emanuel Libman commented on the problem of recognizing coronary thrombosis clinically. Although Libman accepted Herrick's concept of acute coronary thrombosis, he admitted that "there are cases in which it is very difficult to say whether the patient is suffering from a gastric condition, such as ulcer, with reflex pain in the cardiac area, or whether the patient has coronary artery disease, or possibly both." In such cases, Libman[69] thought "the electrocardiographic findings as described by Drs. Oppenheimer and Rothschild ought to be of value."

Herrick, also present for Oppenheimer's presentation, explained that he and his colleagues in Chicago were studying the electrocardiographic manifestations of experimental coronary occlusion in dogs. Herrick told the audience that he saw a similarity between the electrocardiogram recorded from one of Oppenheimer's patients with autopsy proof of coronary thrombosis and one "which we got in dogs by ligating the left branch of the coronary artery."[70]

Herrick's assistant Fred Smith[71] published the results of their study of the electrocardiographic manifestations of experimental coronary occlusion in 1918. The following year, Herrick restated his concept of acute coronary thrombosis because he thought "cases of coronary thrombosis are...of commoner occurrence than is generally supposed." This paper included an electrocardiogram recorded from a 42-year-old physician Herrick diagnosed as having had a coronary thrombosis. When the patient died of pneumonia several months later, an autopsy revealed a healed myocardial infarction and an organized thrombus in the left anterior descending coronary artery.

Herrick recognized similarities between his patient's electrocardiogram and those Smith had recorded from the dog after ligation of a coronary artery. He speculated that additional animal experiments might reveal a characteristic electrocardiographic pattern associated with occlusion of a specific coronary artery. If this were the case, Herrick argued, "may we not, when we encounter that abnormal electrocardiogram in the human being, particularly if he has had symptoms suggestive of coronary thrombosis, be able to state with a reasonable degree of certainty that the patient has had obstruction in a particular portion of the coronary system?"[72] Herrick first provided clinicians with a scientific framework for conceptualizing survival after coronary thrombosis and for recognizing the event in 1912. Now, he urged doctors to use the electrocardiogram to help them diagnose acute myocardial infarction.

Other investigators extended Herrick's observations on the role of electrocardiography in acute myocardial infarction. In 1920, Harold Pardee of New York reported dramatic ST-segment elevation in leads II and III in a patient who had a clinical event consistent with a myocardial infarction. Serial electrocardiograms obtained over the next few weeks revealed progressive T-wave inversions and the gradual return of isoelectric ST segments. Pardee concluded that these electrocardiographic changes resulted from an acute coronary occlusion followed by "muscle degeneration."

Despite Pardee's description of the electrocardiographic manifestations of acute coronary occlusion, his discussion revealed lingering confusion about what are now termed ischemic syndromes. Pardee summarized his findings: "1. A patient who had just had an attack typical of occlusion of a coronary artery showed a very remarkable electrocardiogram. 2. The patient recovered and the electrocardiogram had changed on the fourth day to a form which it retained for the four months during which he remained under observation. He lived for two years longer, and died with a typical attack of angina pectoris."[73] If Pardee had difficulty appreciating the distinction between acute coronary occlusion and an attack of angina pectoris, it is not surprising that most of his (and Herrick's) contemporaries were mystified by the various manifestations of coronary artery disease, and the problem was not limited to distinguishing various types of heart disease.

In 1924, Oppenheimer conceded, "it is often impossible even for an experienced clinician to differentiate with certainty between coronary artery disease and a variety of other conditions such as cholelithiasis, pancreatitis, peptic ulcer, gastrointestinal attack, brachial neuritis, etc." Based on a study of 100 patients who had electrocardiograms and autopsies, Oppenheimer concluded that abnormal electrocardiograms were often associated with pathologic evidence of heart disease. He concluded the test was "of considerable value as adding an objective sign in making the diagnosis of myocardial involvement." Because some patients with coronary thrombosis presented with symptoms suggesting an acute abdominal process, Oppenheimer proposed another reason to perform an electrocardiogram. "In so far as the electrocardiogram aids in making the correct diagnosis," he explained, "it is of value at times in preventing useless and even dangerous operative procedures." Oppenheimer and Rothschild[74] concluded that the test "is of distinct value in both the diagnosis and prognosis of patients suspected of myocardial disease." In this context, the electrocardiogram did more than aid diagnosis; it affected treatment.

In 1928, John Parkinson and Evan Bedford of the London Hospital published a paper describing the evolutionary changes of the electrocardiogram in 28 cases of "cardiac infarction" due to "coronary thrombosis." They recorded electrocardiograms to confirm (rather than make) the diagnosis of myocardial infarction. Most of the initial electrocardiograms were recorded 2 to 14 days after presentation. Parkinson and Bedford showed that in several cases, ST-segment shifts (some very dramatic) accompanied myocardial infarction. They termed these ST changes an "injury current" and attributed them to "a recent focal injury to the myocardium." As the ST-segment abnormalities resolved over a few days, T-wave inversions, which Pardee earlier claimed to reflect coronary occlusion, gradually appeared.[75]

Mayo Clinic physicians Arlie Barnes and Merritt Whitten[76] extended Parkinson and Bedford's observations and published a review of the electrocardiographic manifestation of "coronary thrombosis with myocardial infarction" in 1929. They claimed that this phenomenon "has come to be considered a distinct clinical entity, the diagnosis of which can be made during life with a high degree of certainty." Barnes and Whitten were especially interested in correlating the location of partial and complete coronary obstruction with the pathologic appearance of the myocardium and the electrocardiographic pattern.

Boston cardiologist Samuel Levine's[77] 1929 book on coronary thrombosis was the first comprehensive American publication on the subject. Based on a study of 145 patients with myocardial infarction, Levine concluded that certain typical electrocardiographic signs were of great value in distinguishing coronary thrombosis from noncardiac causes of chest pain or other symptoms suggestive of myocardial infarction. He explained, "although the recognition of coronary thrombosis developed as a bedside or clinical diagnosis before the use of electrocardiography was generally made, this latter procedure has in recent years added materially to the criteria that we use in diagnosis. In fact, certain changes that occur in the electrocardiograms are now regarded as so characteristic that without any other evidence whatever a proper diagnosis might be made in some cases."

THE ELECTROCARDIOGRAM AND ANGINA PECTORIS

By 1930, many of the typical electrocardiographic features of myocardial infarction had been described. But this dramatic, often fatal event represented one end of the spectrum of symptomatic coronary artery disease. Some clinical investigators hoped the electrocardiograph might enhance the ability of doctors to diagnose angina pectoris. William Heberden's[78] classic description of angina published in 1772 emphasized that chest discomfort was typically brought on by exertion. Although other signs and symptoms might be present, it was the exertional nature of the complaint that defined it as angina pectoris.

Just as the electrocardiograph shed light on acute myocardial infarction, it also proved helpful in evaluating patients thought to have angina pectoris. Harold Feil and Mortimer Siegel[79] of Chicago reported their electrocardiographic observations on 4 patients with angina in 1928. Three of them had temporary ST-segment abnormalities during paroxysms of pain typical of angina which Feil and Siegel attributed to "transient vascular changes in the heart muscle."

In 1931, Francis Wood and Charles Wolferth of Philadelphia published the results of their study of the electrocardiographic manifestations of angina pectoris. Although the coronary theory of angina was first proposed nearly 150 years earlier by Edward Jenner and Caleb Parry, debate about its pathophysiology persisted into the 20th century.[80] Most authorities accepted the coronary theory, but a few influentials, like Clifford Allbutt of England and Karel Wenckebach of Germany, attributed angina to distention of the proximal aorta. Wood and Wolferth noted, however, that "the trend of current opinion seems to be toward the belief that the majority of cases of true Heberden's angina can be explained on a coronary basis."

The electrocardiogram provided compelling proof of the coronary theory of angina. Wood and Wolferth explained, "the main difficulty confronting this explanation has been the almost complete lack of direct evidence that the heart is primarily involved during the paroxysm." Besides studying patients with angina and "controls," Wood and Wolferth performed animal experiments to evaluate the electrocardiographic manifestations of temporary coronary occlusion. They sought to induce "temporary and rapidly reversible electrocardiographic changes analogous to those seen in our angina pectoris tracings."

Half the 30 patients thought to have angina had ST-segment and T-wave changes during an episode of chest discomfort. Six of the 15 patients had spontaneous anginal attacks, whereas 9 had angina "induced by various amounts of prescribed exertion, which was stopped at the first suggestion of pain." It is likely that only half their patients had abnormal tracings during pain because of the investigators' cautious approach to exercise and the fact that they recorded only standard limb leads I, II, and III. The unipolar limb and precordial lead systems had not been introduced, so Wood and Wolferth surely missed some electrocardiographic abnormalities that those leads would have revealed. Still, their conclusions had important clinical implications.

This was the first use of exercise electrocardiography to differentiate cardiac from noncardiac chest pain. However, Wood and Wolferth cautioned against routine use of this approach. They thought it was "dangerous to induce anginal attacks indiscriminately." Nevertheless, they acknowledged that the procedure might be of benefit "in a doubtful case, with a relatively healthy cardiovascular apparatus."[81] The clinical use of exercise electrocardiography was later popularized by New York cardiologist Arthur Master.[82] Exercise electrocardiography, a major extension of the resting technique, is beyond the scope of this review.

PRECORDIAL LEADS, AUGMENTED LIMB LEADS, AND VECTORCARDIOGRAPHY

Wolferth and Wood made another contribution to electrocardiography that greatly enhanced the clinical value of the technique. They were the first to emphasize the important information that might be obtained by recording the electrocardiogram using precordial electrodes. Although Augustus Waller used a precordial electrode to record the first human electrocardiogram in 1887, subsequent use of this technique was sporadic and confined to experimental studies. For 3 decades, physicians and researchers relied on the 3 standard (limb) leads Einthoven introduced in 1902. Whereas these leads were satisfactory for characterizing arrhythmias, they proved inadequate for evaluating patients with other manifestations of heart disease, especially myocardial infarction.[83]

Clinical and experimental studies of coronary occlusion led Wolferth and Wood to conclude that "many cases of coronary occlusion do not show characteristic changes in [the] routine electrocardiogram." They proposed that there were "silent areas" in the heart where infarction could occur but would not be accompanied by ST-segment abnormalities in the "three conventional leads." During their evaluation of a woman who presented "with a clinical picture typical of coronary occlusion, but with no electrocardiographic evidence of the presence of such a lesion," Wolferth and Wood placed electrodes on her chest and back and recorded "striking deviations in the S-T interval." A second similar case convinced them that the "anteroposterior chest lead (Lead IV) is an important adjunct to the routine electrocardiogram in the diagnosis of certain cases of coronary occlusion."[84]

During the 1930s, several workers in America and Europe confirmed these observations and advanced the technique of precordial electrocardiography. Frank Wilson of the University of Michigan published several papers on the physical principles underlying the electrocardiogram that complemented the clinical observations of Wolferth and Wood.[85] Wilson and his colleagues proposed concepts and introduced techniques that provided a scientific basis for interpreting the waveforms recorded with the precordial leads and greatly advanced the practice of electrocardiography.

Wilson first described the "unipolar lead" concept in 1931. He proved mathematically that it was possible to record the electrical activity of the heart from any site on the body and that the signals recorded by the "exploring electrode" were unaffected by the "indifferent electrode." This idea was critical for the development of the precordial leads.[86] Two years later, Wilson reported the value of using an "exploring electrode" to record "serial precordial leads" in 8 patients with myocardial infarction.[87]

According to Charles Kossmann,[88] who worked with Wilson on the development of the precordial leads, Wolferth and Wood's and Wilson's studies on the subject "had considerable impact on clinical practice, and from that time forward the usefulness of leads to record electrical events in the transverse as well as the frontal planes of the body was established." Kossmann and Franklin Johnston[89] published a paper in 1935 that described the electrocardiograms recorded from precordial leads in 30 medical students. Kossmann[88] recently claimed, with justification, "the article, though not the first on chest leads...represented the birth of a method which has prevailed for half a century."

These new precordial lead configurations greatly enhanced the clinical value of electrocardiography. But the approach also created problems because there was no agreement on the best placement of the chest leads. In an attempt to standardize the electrocardiographic nomenclature, a joint committee of the American Heart Association and the Cardiac Society of Great Britain published, in 1938, recommendations for recording precordial electrocardiograms from 6 locations which they termed V_1 through V_6.[90,91]

The 12-lead electrocardiogram as we know it today resulted from sequential discoveries and innovations. The final lead configuration adopted for routine use included the standard limb leads of Einthoven, the precordial leads based on the work of Wilson and his associates, and the augmented unipolar limb leads. This final lead group, a refinement of Wilson's original unipolar limb leads V_R, V_L, and V_F, was introduced by Emanuel Goldberger in 1942.[92]

Vectorcardiography can be traced to Willem Einthoven. In a 1913 study, Einthoven and his pupils A. De Waart and George Fahr[93] (an American) introduced the concept of the cardiac vector. They claimed that clinicians could use the electrical axis of the heart to help them distinguish left ventricular hypertrophy from simple changes in the heart's position: "the schema of the equilateral triangle in such a case can often provide the solution." Other researchers adopted the equilateral triangle approach and extended Einthoven's studies. Horatio Williams[94] first described cardiac depolarization as a continuous series of vectors in 1914.

Edward Carter and his associates at Johns Hopkins and Hubert Mann of Mt. Sinai Hospital in New York pursued this line of investigation. In 1920, Mann[95] published a study that described what he termed the monocardiogram, later known as a vectorcardiogram. He explained that this was "really a fusion of the three leads of the electrocardiogram into a single curve by an algebraic reversal of the process by which three leads are obtained from one heart." Although published in clinical journals, these studies included mathematic equations, numerical tables, and physical principles that few practitioners could comprehend.

Vectorcardiography gradually grew in popularity during the 1960s and 1970s, especially after a direct-writing vectorcardiograph was invented, but the technique's appeal was limited. Louis Katz and Herman Hellerstein[7] attributed this mainly to "the strangeness of the configuration of the vectorcardiogram" and a lack "of uniformity in recording and in terminology." In 1985, after spending more than 3 decades working in the field of vectorcardiography, George Burch[96] conceded "its questionable value in clinical practice." This conclusion was based on Burch's belief that "rarely has the vectorcardiogram actually shown some aspect of the electric potential from the heart that was not already clearly evident from the electrocardiogram."

THE ELECTROCARDIOGRAPH AND CARDIOLOGY AS A SPECIALTY

During the 20th century, cardiology grew in size and stature largely as a result of technologic advances that helped heart specialists diagnose and treat patients with known or suspected heart disease. In a volume on technology and American medical practice, internist and historian Joel Howell[97] claimed, "some specialists justified their expertise in a specific area of medicine by claiming a special ability to operate a medical tool, thus using medical technology to define their specialty." The dynamic relation between the electrocardiograph and cardiology as a field of specialization is an example of this phenomenon.

Recognized almost immediately as a powerful clinical tool, the electrocardiograph helped define cardiology as a special area of medical practice during the period between the First and Second World Wars. After serving as Paul Dudley White's resident in Boston and working in Ernest Starling's physiological laboratory in London, Harold Segall began practicing cardiology in Montreal in 1926. He acquired a portable electrocardiograph the following year, the first transportable instrument in Canada. Many years later, Segall[62] recalled that the electrocardiograph "did much to make the medical profession and the laity aware of the new specialty of cardiology."

New York physician Edwin Maynard Jr. "was able to learn something about reading electrocardiograms" from Stuart Hart when he was an intern and resident at Presbyterian Hospital from 1919 to 1921. Maynard set up the electrocardiographic department at Brooklyn Hospital in 1921 and discovered that his role as the hospital's electrocardiographer led other physicians to view him as a heart specialist. He viewed this as "an important benefit." Maynard[98] recalled half a century later, "when physicians on the staff began to receive my electrocardiographic reports, they called on me to ask what I thought about their patients' hearts....I was forced to tell them truthfully that I could give no opinion from the electrocardiogram alone. Whereupon I was often asked to examine their patients."

Many doctors and patients came to view expertise in electrocardiography as a significant factor that distinguished cardiologists from internists and general practitioners. But this notion created tension in the medical profession because it was acknowledged that it was impractical to restrict the interpretation of electrocardiograms to heart specialists alone. In 1932, cardiologists Albert Hyman and Aaron Parsonnet[99] alluded to this dilemma. They described 2 extremes when it came to caring for patients with heart disease. On the one hand there were doctors "who would hold the electrocardiograph and similar scientific procedures as a sort of fetish to be worshipped at the shrine of science." Practitioners who relied exclusively on traditional clinical methods were at the other extreme. Hyman and Parsonnet did not try to resolve this dichotomy and the tension it implied with respect to patient care. They simply pointed out that neither group should be "censured" more than the other.

During the 1930s, America's general practitioners anxiously witnessed a steady increase in the number of specialists. This trend had implications for their self-esteem and their income.[100] In 1932, Philadelphia internist David Riesman[101] addressed the problem. "In some respects," he contended, "it is unfortunate that diseases of the heart have become a highly specialized field of medicine. The general practitioner, unable for lack of time to cope with the intricacies of instrumental methods of study, is beginning to feel out of his depth; he is discouraged by the growing conviction that he is no longer competent to deal with cardiac cases. And yet he is the one who has the first contact with such cases." Riesman asked rhetorically, "is he really no longer competent to treat them or has he merely developed an inferiority complex which is unjust to himself and lessens his usefulness to his patients?"

The importance of the electrocardiogram in medical practice could not be denied. Samuel Levine[102] stated in his 1936 book *Clinical Heart Disease* that the electrocardiogram "has become an essential part of our methods of examination of the heart. By its use the diagnosis, prognosis and treatment of heart disease has been considerably improved." Still, he acknowledged the importance of traditional clinical skills: "An able clinician who knows nothing about the string galvanometer can still do better work than an expert in electrocardiography who has limited bedside experience and inadequate clinical judgement."

Levine hoped to demystify electrocardiography. He believed it was important for general practitioners to learn about the technique because once they gained "a clear understanding of the subject" they would be less dependent on it in the evaluation of their patients. "This sounds paradoxical," Levine admitted, "but experience shows that the more one knows about electrocardiography, the more one can predict what such tracings will show under given circumstances, so that those who are most familiar with this subject need it the least."

There were problems inherent in the widespread use of the machine by general practitioners inadequately trained to interpret electrocardiograms. North Carolina internist Frederick Taylor[103] told Boston cardiologist Howard Sprague in 1933: "I still recall your postgraduate extension lectures here with the greatest delight. During the years intervening since that time I have been pegging along in internal medicine, and am now even trying a fling at a little electrocardiography." America's few formally trained cardiologists worried about such dilettantes interpreting electrocardiograms.

Growing numbers of books and postgraduate courses on electrocardiography reflected the desire of America's internists and general practitioners to gain proficiency in the technique. Arthur Master[104] of Mount Sinai Hospital in New York justified publishing his 1939 book on the subject because a "large number of physicians are now taking and interpreting electrocardiograms without the study and application necessary for doing this properly." Part of the problem, in Master's opinion, was that "electrocardiographic instruments are now obtainable at quite low prices and the technique of taking the record has become very simple." A technical advance that greatly simplified recording electrocardiograms during the 1930s was the invention of direct-writing machines. These electrocardiographs used a pen to inscribe the tracing thus eliminating the need to process the records photographically.

In a pioneering study of medical technology, historian Stanley Reiser[1] argued that "an innovation influences power relationships in medicine. Developed expertness in new and accepted techniques enhances professional status." Not only did the electrocardiograph confer status on the physician who owned it, the machine could generate additional income. Frank Wilson and Paul Barker[105] explained that the University of Michigan charged $3.50 for an electrocardiogram in 1930, and acknowledged that "private patients pay somewhat more." The income produced by an electrocardiograph could be significant—if the patient could afford to pay for the test. These financial issues were especially significant during the 1930s. As a result of the Depression, the average income of general practitioners decreased from about $4,000 in 1930 to approximately $2,600/year in 1933.[106]

Gradually, patients came to expect an electrocardiogram as part of a routine medical examination. Frank Wilson[107] claimed in 1952 that "a lively interest in [electrocardiography] is now widespread among members of the medical profession and has extended to a wide circle outside it. When a prominent person is reported by the press or radio to have died suddenly of a 'heart attack' a flock of middle-aged people rush to have a cardiogram taken on the following morning." The prominent position of the electrocardiograph in medical practice seemed assured.

New technologies for evaluating the heart's structure and function introduced in the middle of the 20th century increasingly challenged the primacy of the electrocardiogram as a tool in clinical cardiology. Several techniques that permitted the visualization of cardiac structures and the assessment of hemodynamics in living humans would revolutionize cardiology practice. These approaches included cardiac catheterization (first performed in 1929 by German surgeon Werner Forssmann), angiocardiography (developed by several investigators in the 1930s and 1940s), selective coronary angiography (described by Mason Sones in 1959), echocardiography (developed by Inge Edler and Helmuth Hertz in 1954), and nuclear cardiology techniques (developed by several people beginning with Goran Liljestrand in 1939).[108] The advent of modern cardiac surgery, signaled by Blalock and Taussig's report of their pioneering operation for "blue babies" in 1945, was a potent stimulus for the development of catheterization and imaging techniques.

CLINICAL ELECTROPHYSIOLOGY

These new catheterization techniques led directly to a new era in cardiac electrophysiology. The diagnosis and management of arrhythmias changed dramatically as a result of innumerable discoveries that resulted from basic and clinical research.[109,110] In 1945, Jean Lenègre and P. Maurice of France first recorded intracardiac electrocardiograms in a human. Although others used this technique for research, its widespread application in clinical medicine began with the report of Benjamin Scherlag[111] in 1969, on a technique for recording His bundle activity in humans using intracardiac electrodes.

When the electrocardiogram was introduced into clinical medicine nearly a century ago, it was clear that the technique was of great value in the evaluation of arrhythmias. During the middle third of the 20th century, the focus shifted to the role of electrocardiography in myocardial disease and other nonarrhythmic diseases of the heart. During the final third of the century, the focus shifted back to arrhythmias. Cardiac electrophysiology emerged as a clinical discipline as noninvasive and invasive diagnostic techniques such as Holter monitoring, His bundle electrocardiography, intracardiac mapping, programmed electrical stimulation, and signal averaged electrocardiography were developed.[112] Other advances in medical care that owe their existence to the electrocardiogram include cardiopulmonary resuscitation and the coronary care unit.[113]

THE DECLINE OF ELECTROCARDIOGRAPHY: COMPETING TECHNOLOGIES, COMPUTERS, AND CONGRESS

The development of new invasive diagnostic techniques contributed to a gradual decline in traditional surface electrocardiography as a major focus of basic and clinical investigation. Dutch electrophysiologist Hein Wellens[114] expressed concern about this trend recently: "I am worried in this age of increasing use of sophisticated (and expensive) techniques, about the decreasing ability of our younger colleagues to interpret the electrocardiogram correctly. Invasive procedures, with their diagnostic (and financial) rewards have stolen the interest of the younger generation."

As a new generation of cardiologists focused their attention on other technologies, another development hastened the decline of clinical electrocardiography. Computer analysis of electrocardiograms can be traced to the early 1960s.[115] In 1961, Washington cardiologist Hubert Pipberger, a pioneer of computer analysis of the electrocardiogram, claimed that his computer program "allowed separation of normal and abnormal records with a high degree of precision." Based on his experience, Pipberger et al[116] maintained that "the physician needs to read and interpret, therefore, only those records which are recognized by the computer as being abnormal." When they were introduced into clinical practice beginning in the late 1970s, these computer techniques changed the way cardiologists interpreted electrocardiograms. The computer's "interpretation" is checked and revised as necessary by a cardiologist. Currently, more than 50 million electrocardiograms are processed by computers annually in North America.[115]

The popularity of computer-assisted electrocardiographic interpretation reflects the willingness of cardiologists to relinquish some of their control over the technology that was once so central to their professional identity. According to Charles Fisch,[117] the computer has had another effect on cardiologists: "...because of the availability of computer interpretation, the intellectual process necessary to arrive at an ECG diagnosis is often circumvented and the computer may be an obstacle to acquisition of electrocardiographic skills."

The cost of health care in America has been a matter of concern for decades. It is widely acknowledged that medical technology is a significant factor in the steadily increasing cost of health care.[118] Recent efforts by our government to control expenditures for health care included legislation that affected physicians who interpret electrocardiograms. The Omnibus Budget Reconciliation Act of 1990 included a provision that eliminated separate reimbursement for the interpretation of electrocardiograms beginning January 1, 1992. A coalition of specialty societies tried to convince Congress that this was a mistake. Although the 102nd Congress passed legislation that included a provision to restore separate payment for the interpretation of electrocardiograms, George Bush vetoed the bill in November 1992. In August 1993, Bill Clinton signed a bill passed by the 103rd Congress that restored separate payment for the interpretation of electrocardiograms. Had separate reimbursement for the interpretation of electrocardiograms not been restored, it is likely that the test would have been performed less often in the future. The elimination of reimbursement for phonocardiograms certainly contributed to the decline of that technique.

EPILOGUE

The electrocardiograph greatly advanced our understanding of various types of heart disease, most notably arrhythmias and acute myocardial infarction. Along with the x-ray machine, the electrocardiograph inaugurated an era in which the physician's traditional diagnostic approach that relied on the history and physical examination was supplemented (some would say surpassed) by complex machines that provided objective information about the structure and function of the human body in health and disease. Many researchers around the world contributed to the gradual refinement of electrocardiographic equipment and to our growing understanding of the significance of the tracings it recorded. As I have shown in this review, the electrocardiograph also played a role in the emergence of cardiology as a specialty.

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