This article is a review of the history of the string galvanometer and of the electrocardiogram (ECG) on the occasion of the centennial of the instrument. Einthoven most likely developed the string galvanometer prior to 1901, the date of the first publication. The galvanometer made electrocardiography practical creating a new branch of medicine and even a new industry. In 1791 Galvani, in 1842 Mateucci and in 1855 Kolliker and Muller recorded, using the nerve muscle preparation, contraction of injured muscle, contraction of muscle when laid across a beating heart, and occasionally two contractions. In 1872 Lippmann introduced the capillary manometer. Using the capillary manometer Waller recorded for the first time from body surface voltage changes generated by the heart. Einthoven and Lewis dominated the early years of electrocardiography. The former made his contributions by 1913 while Lewis continued the studies of arrhythmias until 1920. The period following 1920 was influenced largely by Wilson. None did as much to advance ECG knowledge as did Wilson. The interest shifted to the theory of the ECG, abnormalities of wave form and of ECG leads. A major contribution of the ECG is in evaluation of ischemic heart disease and cardiac arrhythmias.

Issues facing electrocardiography in the year 2000 include a shortage of experienced electrocardiographers, the advent of new noninvasive procedures and, paradoxically, wide acceptance of the ECG by the medical profession. The role of the computer in analysis of the clinical ECG is limited. The technique, while reasonably reliable for analysis of the normal tracing and some ECG waveforms, has serious limitations when applied to arrhythmias. The early hopes for “stand-alone” programs are yet to be realized. (J Am Coll Cardiol 2000;36:1737–45) © 2000 by the American College of Cardiology

The time is at hand, if not already come, when an examination of the heart is incomplete if this new method is neglected.
—Thomas Lewis (Heart 1912;3:279.)

In 1895 Einthoven published his classic article on the “Form of the Human Electrocardiogram,” and by 1900 he had developed the string galvanometer, with a preliminary report in 1901. He showed that his mathematically predicted form of the electrocardiogram (ECG) derived from the capillary manometer agreed well with the one recorded with the string galvanometer (1). He published these results in 1904 in the Proceedings of the Royal Netherlands Academy of Arts and Sciences. The invention of the string galvanometer and, thus, the electrocardiograph by Einthoven has drastically and lastingly changed the practice of medicine (2,3). “It literally created a new branch of medicine, and even produced a new industry” (4).

See page 1746

Of necessity, this is a rather brief review highlighting the progress in the development of the clinical ECG and focusing on some of the individuals who made this progress possible with the understanding that many who contributed could not be included because of space constraints.

The ECG is not only the oldest but, in fact, 100 years after its introduction, continues as the most commonly used cardiovascular laboratory procedure. It is interpreted by cardiologists, internists and to various extents by primary care physicians, specialized nurses and more and more by computers. It is noninvasive, simple to record, highly reproducible and can be applied serially. The equipment and the cost of recording are minimal. Furthermore, it is the only practical, noninvasive method of recording the electrical activity of the heart, and, importantly, it is the first laboratory test performed in a patient with chest pain, syncope or presyncope, the two major markers of potential cardiovascular catastrophe. Electrocardiography serves as a gold standard for the clinical, noninvasive diagnosis of cardiac arrhythmias (5).

Some would suggest that the large volume recorded annually at a cost of billions attests to the importance of the procedure. Others would point to its versatility, its role in diagnosis, decision-making and risk-stratification, critical knowledge for the appropriate care of patients with and without heart disease.

The reason for the unique endurance of the ECG as a laboratory procedure is the fact that it makes concrete and perceptible through pathologic and epidemiologic correlations about the status of the underlying cardiac...
anatomy and electrical functioning essential for clinical decision making.

CARDIAC ELECTRICAL ACTIVITY

The earliest studies of cardiac electricity can be traced to the year 1791 (6). In that year, Galvani placed the nerve of a nerve-muscle preparation on an injured muscle and noted contraction of the muscle of the nerve-muscle preparation. Some 50 years later, Matteucci (7) observed that if the nerve of the Galvani nerve-muscle preparation was laid across a beating heart, the muscle of the nerve-muscle preparation contracted in synchrony with the beating heart. In 1856, Kolliker and Muller (8) placed the nerve of the Galvani nerve-muscle preparation on the beating heart and noted that not only did the muscle contract synchronously with the contraction of the heart but on occasion, two contractions were evident. The first contraction of the muscle of the nerve-muscle preparation occurred just before the cardiac systole, comparable to the R wave, and this was followed by a second feeble late diastolic twitch comparable to the T wave.

The next important contribution to the evolution of the ECG was the capillary manometer introduced by Gabriel Lippmann in 1872 (9). With this instrument it was possible to record from the body surface voltage changes generated by the heart. The instrument consisted of a finely drawn glass tube filled with mercury and immersed in sulfuric acid. The surface of the mercury moved as the potential difference between the mercury and sulfuric acid changed. This motion was magnified and recorded on photographic paper (Fig. 1).

Einthoven constructed a mathematically derived curve based on the capillary manometer tracing and that proved nearly identical to the ECG (Fig. 2). However, because of its poor frequency response, the use of the Lippmann manometer was short lived. After 29 years, it was replaced by the string galvanometer but only after Waller, in 1887, successfully recorded from the body surface voltage changes generated by the human heart (Fig. 3) (10). According to Einthoven, Waller also coined the term electrocardiogram.

The beginning of human electrocardiography and the major role played by Waller is discussed in some detail in an article by Howard B. Burchell published in 1987 on the occasion of the centennial of the first human ECG. Burchell concluded his discussion of Waller and his contribution by stating, “All in all, the name Augustus Desire Waller belongs in an electrocardiographic hall of fame. Waller was a pioneer in human electrocardiography, a physiologic investigator and stimulating teacher. His range of interests was wide in the physiologic world and his contributions manifold (11).”

WILLEM EINTHOVEN

It should be pointed out at the onset that the commentary on Einthoven and his contribution to medicine are also of necessity brief. Numerous articles and books have been published about Einthoven, the string galvanometer and the ECG. The titles of some of the more recent articles are included in the bibliography (12–15).

Although there is some difference of opinion as to whether Einthoven modified the string galvanometer developed by Ader for use with transatlantic cable, increasing its sensitivity and applied to recording of electrical activity of the heart or actually developed the instrument (16), the current consensus is that Einthoven developed the instrument (17). A preliminary report by Einthoven describing the instrument appeared in 1901 (18) and a more detailed description including ECG tracings in 1903 (19). The instrument weighed 600 lb and was operated by five individuals. Electrodes consisted of jars of saline in which the extremities were immersed (Fig. 4). Einthoven discussed the theory of the ECG and its application to the study of heart disease in two classic articles, “Le Telecardiogramme” published in 1906 (20) and “Weiteres uber das Electrocardiogramm” published in 1908 (21). He was interested in the ECG not only as a tool for the study of

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**Abbreviations and Acronyms**

AMI = acute myocardial infarction
ECG = electrocardiogram

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Figure 1. The Lippmann electrometer (1872) and the ECG recorded by Waller in 1887 shown below. “e” represents the electrocardiogram, “h” represents the chest wall motion and t time in 0.05-s intervals. (Reprinted from: Waller AD. A demonstration on man of electromotive changes accompanying the heart’s beat. J Physiol 1887;8:229, with permission.)
physiology but also in its potential application to clinical cardiology. To tap into clinical material, the galvanometer housed in the physiology laboratory in Leiden was connected by telephone wires to the clinic at the Academic Hospital located more than a mile away. Einthoven's contribution was widely recognized and in 1924 he was awarded the Nobel prize. In 1993, the Royal Post Office of the Netherlands issued stamps to commemorate three Dutch Nobel laureates, one being Einthoven (Fig. 5).

**SIR THOMAS LEWIS**

With the development by Einthoven of a practical galvanometer for recording ECGs, considerable interest in electrocardiography followed. The ECG attracted some of the brightest minds interested in the genesis of arrhythmias and spread of excitation.

One of the leaders, if not the leader, during that period was Sir Thomas Lewis (Fig. 6). Lewis, successor to Einthoven and Wilson's teacher, made many important contributions to our understanding of mechanisms of arrhythmias and spread of excitation. He did this between the years 1908 to 1920 while at the University College in London (Fig. 7) (22,23). His contribution was acknowledged by Einthoven who in his Nobel lecture stated, “It is my conviction that the general interest in the ECG would certainly not be so high nowadays if we had to do without his work, and I doubt whether without his valuable contribution I should have the privilege of standing before you today” (2).

Einthoven and Lewis dominated the early years of electrocardiography. They brought it to the bedside and applied it to clinical medicine. Einthoven made his major contributions by the year 1913. Lewis continued the study of arrhythmias until 1920. Believing that no further important information can be gained from the study of the ECG, Lewis turned his attention to peripheral vascular disease, effectively ending the period dominated by studies of arrhythmias. Lewis summarized his work with the polygraph and the ECG in a classic 1920 edition of the “Mechanism and Graphic Registration of the Heart Beat.” Of the role of graphic records as an investigative and clinical laboratory tool he wrote, “Of the immediate value of graphic methods to practical medicine, it is my desire to speak, but briefly. These records have placed the entire question of irregular or disordered mechanisms of the human heart upon a rational basis, so giving to the works the confidence of knowledge; they have influenced prognosis, rendered it more exact; they have potentially abolished the promiscuous administration of certain cardiac poisons, and have clearly shown the lines which therapy must follow. The new clinical observations have stimulated and directed a host of valuable laboratory researches, anatomical, physiological, pathological, and pharmacological. The records constitute the most exact signs of cardiac affections which we possess” (22).

During the first half of the 20th century, the ECG was the only noninvasive cardiovascular laboratory procedure capable of recording accurately physiologic phenomena and, thus, generated considerable interest not only among cardiovascular investigators but also clinical cardiologists.


The period following 1920 was influenced primarily by Frank N. Wilson and his group (Fig. 8). According to Burch and De Pasquale, although many contributed to our knowledge of electrocardiography, “... none did as much to advance electrocardiographic knowledge as did Frank N. Wilson.” The interest shifted from arrhythmias to the theory of the ECG, to ECG leads and abnormalities of waveforms. In 1934, Wilson described the unipolar leads having an exploring and indifferent electrode (24,25). He used the exploring electrode as a chest lead to follow the course of acute infarction. In 1938, the American Heart
Association and the British Cardiac Society recommended the presently used six precordial locations for the exploring electrode. Augmented unipolar limb leads were later included in the 12 leads currently in use. In 1944, Wilson and associates published an article entitled, “The Precordial Electrocardiogram” (26) describing the utility and contribution of the unipolar precordial leads to clinical cardiology, ushering in clinical electrocardiography as we know it today (27).

THE ELECTROCARDIOGRAPH

Over the years, the weight of the ECG was reduced from 600 lb to 8 lb; the number of operators necessary to make the recording was reduced from 5 to 1. It is no longer necessary to balance and photograph the movement of the string, to develop the negative and finally print it on photographic paper. Lead connections no longer require immersion of extremities in vessels of saline. Considering such limitations, it is no wonder that the early investigators had some doubt as to the potential utility of the galvanometer as a clinical tool.

The reason for selection of the letters P, Q, R, S, T by Einthoven will, according to Meijler, “never be solved because Einthoven himself never explained why he chose P, Q, R, S, T.” Each of the waveforms has a different sensitivity and specificity. For example, the low specificity and high sensitivity is characteristic of the T wave. This most common ECG abnormality, recorded in approximately 50% of all abnormal tracings and 2.4% to 4.5% of all ECGs, is also the most labile of all the ECG waveforms (28). It has been shown that abbreviating the monophasic action potential by 12 to 18 ms over an area of myocardium of only \( \leq 8\% \) will alter the T wave (29). Abnormal T waves can be present in the absence of heart disease and can reflect a number of physiologic and pharmacologic alternations. These include, from time to time, extracardiac disorders, primary myocardial disease, secondary heart disease and ischemic heart disease. Thus, the most sensitive component of the ECG is at the same time least specific. Wilson stressed the nonspecificity of the T wave in 1923 observing T-wave inversion following ingestion of cold water (30).

On occasion, limitation of specificity is applicable to the Q wave. Although myocardial infarction is the most common cause of an abnormal Q wave, abnormal Q waves may be observed with a variety of other anatomic and functional abnormalities including, from time to time, congenital heart...
disease, pulmonary disease, myocardial nonischemic disease, left ventricular hypertrophy, idiopathic subaortic stenosis, intraventricular conduction defects, coronary embolism, metabolic and neurogenic abnormalities. This is so because the ECG reflects an electrical phenomenon that can be altered identically by a variety of functional and anatomic disorders, the common denominator being altered direction of depolarization or a loss of electrically functioning myocardium, either transient or permanent.

The ECG may record subtle but clinically significant abnormalities, such as, for example, a negative U wave. The latter is rarely if ever recorded in the normal individual. While the most common cause of a negative U wave is hypertension, a negative U wave may be the only ECG abnormality in acute myocardial ischemia.

One of the most useful contributions of the ECG is in the evaluation of ischemic heart disease, especially acute myocardial infarction (AMI). It is the first test performed when infarction is suspected. Its contribution is not only to the diagnosis of infarction but also to early risk stratification and clinical management (31).

In 1912, Herrick described the features, of what, ultimately were shown to be due to coronary occlusion (32). He also suggested that coronary occlusion is not always fatal. In 1918, Smith, working with Herrick, described ECG changes in experimental coronary occlusion in the dog.


Figure 5. In 1995, Royal Post Office of the Netherlands issued a commemorative stamp honoring Einthoven as one of the three Dutch Nobel Laureates (courtesy of Frits L. Meijler).
model and stressed the similarities between the findings in the dog and human (33). In 1920, Pardee described ST segment elevation in leads II and III with progressive T-wave inversion over a period of time with return of the ST to isoelectric level (34). By the year 1930, the important role of the ECG in recognition of myocardial infarction was recognized and accepted by the medical profession. Current data suggest that in the course of evolution of AMI, the initial tracing may be normal in 10% to 15%, abnormal but not diagnostic of infarction in 40% to 50% and diagnostic of myocardial infarction in 50% of the patients. Several ECG tracings improve the sensitivity of the ECG for diagnosis to approximately 95%. Attention to subtle ST segment and T-wave changes, recognition of negative U waves, transient normalization in the course of evolution of the infarction, “silent” areas of infarction, masking and simulation of myocardial infarction by intraventricular conduction abnormalities and recurrent infarction enhance the diagnosis of AMI. In general, the T wave, although the most sensitive indicator of ischemia, is at the same time least specific. A new Q wave, in the acute setting, while highly specific for myocardial infarction, is less sensitive.

In the aged, the ECG is an example of an independent marker for heart disease (35). In this population, the history is often unreliable, the physical examination difficult and the ECG carries a different connotation than it does in other age groups. In fact, an ECG abnormality may be present in the absence of clinical signs of disease and the only indication of heart disease. The ECG with a pattern of myocardial infarction may fail to correlate with either symptoms or signs of coronary disease and, thus, supports the ECG change as an independent marker for heart disease.

The ECG is used widely in epidemiologic studies designed to determine the prevalence of ischemic heart disease, to identify latent heart disease and to assess physical fitness and appropriateness of employment in sensitive occupations. It is recognized, however, that the resting ECG is not a very sensitive or specific marker for occult heart disease and that the prognostic value of many ECG abnormalities is unclear. The diagnostic and prognostic implication of a given ECG abnormality differs greatly.
depending on the population studied and the reason for which the ECG is recorded.

An abnormal ECG recorded in a population with a low prevalence of cardiac disease is more likely to be a false positive while the same ECG abnormality recorded in a population with a high prevalence of heart disease is very likely to be a true positive and, thus, of considerable prognostic significance. It has been shown that an ECG abnormality identified during a clinical evaluation is associated with a two to four times greater incidence of new cardiovascular events than if the abnormality is discovered during a screening procedure (36). In the presence of heart disease, ST segment, T-wave changes and abnormal Q waves reach statistical significance as independent prognostic markers. The prognostic significance of an abnormal ST segment or T wave depends primarily on the severity of the heart disease, if any. For example, moderate T-wave inversion, when associated with a history of heart disease, has a 21% five-year mortality and only 3% when heart disease is absent.

The evidence for the ECG predicting future events such as angina, myocardial infarction, cardiovascular death and sudden death, presence or absence of clinical heart disease and severity of myocardial impairment is meager. The major contribution of the ECG in epidemiologic studies is to identify individuals with probable heart disease.

The role of the ECG in the analysis of anatomic, metabolic and hemodynamic abnormalities is limited. Only rarely such as, for example, in hyperkalemia, is an ECG change the only clue to a correct diagnosis.

**ECG AND ARRHYTHMIAS**

The role of the ECG in the diagnosis of arrhythmias is unique. It is the only *practical noninvasive* method of recording cardiac rhythm and, with some exceptions, the ECG mirrors the intracardiac events (37).

The ECG records the voltage generated by the atrial and ventricular myocardium while arrhythmias are the result of abnormal impulse formation or conduction, or both, of the specialized tissue. Since the activity of the specialized tissue is not reflected in the ECG, the diagnosis is derived by extrapolating from the temporal relationships of the waveforms generated atrial and ventricular myocardium. Initially, based on such relationships, a number of ECG mechanisms were described. Thus, the Ashman phenomenon, electrical alternans, acceleration dependent aberration, ventricular fusion, reciprocation, parasystole, exit block, supernormality and concealed conduction were defined and understood by the year 1925 (38). The basic electrophysiologic mechanisms of clinical arrhythmias include automaticity, reentry and possibly “triggered” automaticity. Rarely, however, are these mechanisms reflected as such in the surface ECG.

Many investigators contributed to our understanding of the ECG mechanisms of complex arrhythmias. Katz, Langendorf and Pick, based on deductive reasoning, which they...
introduced, coupled with the surface ECG and electrophysiologic principles, correctly analyzed and described the ECG manifestation of complex arrhythmias. Their systematic contributions to the ECG literature over a period of more than four decades firmly established deductive analysis as an approach to the accurate diagnosis of arrhythmias (39, 40). A major contribution to our understanding of arrhythmias and the ECG of arrhythmias was made by David Scherf. He published his lifelong (1925 to 1973) studies with Schott in a remarkable, detailed 1,040-page volume entitled, “Extrasystoles and Allied Arrhythmias.” The text covers in great detail cardiac arrhythmias from the ancient days to 1973 (41).

Despite the high sensitivity and specificity of the ECG for arrhythmias, there are limitations. These include difficulty of recognizing small changes in voltage and intervals, dependence on deductive analysis and the probability of multiple diagnoses. Intracardiac studies demonstrate that changes of conduction or cycle length, in the order of a few milliseconds, may result in delay or block of an impulse. Such may not be evident from a surface ECG.

THE ELECTROCARDIOGRAM AND RESEARCH

Early electrocardiography flourished because of an exchange of ideas between the clinical electrocardiographer and the basic and clinical investigator. Electrophysiologic concepts derived by deductive analysis of the surface ECG have been confirmed in the laboratory and, similarly, concepts based on animal studies have been confirmed by the clinical electrocardiographer. As a result of such interaction, electrocardiography was placed on a firm experimental basis (42). A task force of the American College of Cardiology, Bethesda Conference on Optimal Electrocardiography, addressing intracardiac electrocardiography suggested that a “careful assessment of the surface ECG may eliminate the need for intracardiac electrocardiography” (37).

ELECTROCARDIOGRAPHY IN THE YEAR 2000

Issues facing electrocardiography in the year 2000 include a shortage of experienced electrocardiographers, the advent of new noninvasive procedures and, paradoxically, the widespread acceptance by the medical profession.

The shortage of properly trained electrocardiographers in an old issue dating back to the early days of electrocardiography. Carl J. Wiggers, in the preface to his text “Principles and Practice of Electrocardiography” published in 1919, stated “unfortunately, the training of medical manpower in the use of such apparatus and the intelligent interpretation of the electrocardiogram has not kept pace with the increased demand. Few courses in electrocardiography are included in undergraduate and postgraduate curricula in medical schools, so that opportunity for systematic instruction is decidedly restricted” (43). The issue of manpower addressed by Wiggers 80 years ago is still with us. The widespread use of the ECG is equated with many with ease of interpretation and lack of sophistication, thus, relegating interpretation to individuals with limited experience.

The large volume of tracings and the shortage of properly trained personnel stimulate a search for alternate approaches to interpretation, processing, storage and retrieval of the ECG. The computer is suggested as a partial answer. The computer is useful for epidemiologic and large-scale clinical trials. However, its role in analyses of the clinical ECG is limited. The computer programs, while reasonably reliable for the analysis of the normal ECG and some ECG waveforms, has serious limitation when applied to arrhythmias. The programs lack accuracy and reproducibility. The early hopes for “stand alone” programs are yet to be realized. Clinical ECGs must be overread by trained electrocardiographers. In fact, I would suggest that because of the availability of computer interpretation, the intellectual processes necessary to arrive at an ECG diagnosis are often circumvented and the computer may be, in fact, an obstacle to the acquisition of ECG skills. Not all ECGs can be programmed because of their complexity.

Despite the problems faced by electrocardiography in the year 2000, until a better method of noninvasive recording of electrical behavior is developed, the future of this discipline is assured. There is a renewed interest in arrhythmias, stimulated by an increased use and increased complexity of cardiac pacemakers, by implantable cardioverters and defibrillators, heart surgery, the ever-present problem of sudden death, the search for new antiarrhythmic drugs, new approaches to the surgical therapy of arrhythmias, ambulatory monitoring, telemetry, heart rate analysis, T-wave alternans and the like. Similarly, new and aggressive approaches to ischemic heart disease rekindled interest in the ECG as an anatomic, qualitative and occasionally quantitative marker of myocardial ischemia, injury and infarction—an important first step in decision-making (29).

It is proper to conclude that 100 years after its introduction, the ECG fulfills Webster’s definition of a classic. It is of recognized value, serves as a standard of excellence and is traditional, enduring and in fashion year after year (11).

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