

# 15

---

## Basic ECG Theory, Recordings, and Interpretation

---

ANTHONY DUPRE, MS, SARAH VINCENT, MS,  
AND PAUL A. IAIZZO, PhD

### CONTENTS

THE ELECTROCARDIOGRAM  
THE ECG WAVEFORM  
MEASURING THE ECG  
SOME BASIC INTERPRETATION OF THE ECG TRACE  
LEAD PLACEMENT IN THE CLINICAL SETTING  
ECG DEVICES  
SUMMARY  
SOURCES  
ON-LINE SOURCES

---

### 1. THE ELECTROCARDIOGRAM

An electrocardiogram (ECG; in German, the *elektrokardiogramm*, EKG) is a measure of how the electrical activity of the heart changes over time as action potentials propagate throughout the heart during each cardiac cycle. However, this is not a direct measure of the cellular depolarization and repolarization with the heart, but rather the relative, cumulative magnitude of populations of cells eliciting changes in their membrane potentials at a given point in time; it shows electrical differences across the heart when depolarization and repolarization of these atrial and ventricular cells occur.

The human body can be considered, for the purposes of an ECG, a large-volume conductor. It is basically filled with tissues surrounded by a conductive ionic fluid. You can imagine that the heart is suspended inside of that conductive medium. During the cardiac cycle, the heart contracts in response to action potentials moving along the chambers of the heart. As it moves, there will be one part of the cardiac tissue that is depolarized and another part that is at rest or polarized. This results in a charge separation, or dipole, which is illustrated in Fig. 1.

The dipole causes current flow in the surrounding body fluids between the ends of the heart, resulting in a fluctuating electric field throughout the body. This is much like the electric field that would result, for example, if a common battery were suspended in a saltwater solution (an electrically conductive medium). The opposite poles of the battery would cause current flow in the surrounding fluid, creating an electric field that could be detected by electrodes placed in the solution. A similar electrical field around the heart can be detected using electrodes attached to the skin. The intensity of the voltage detected depends on the orientation of the electrodes with respect to that of the dipole ends. The amplitude of the signal is proportional to the mass of tissue involved in creating that dipole at any given time. Using electrodes on the surface of the skin to detect the voltage of this electrical field is what provides the electrocardiogram.

It is important to note, as might be expected, that because the ECG is measured on the skin, any potential differences within the body can have an effect on the electrical field detected. This is why it is considered important for diagnostic purposes that, while recording an ECG from an individual, the individual should remain as still as possible. Movements require the use of skeletal muscles, which then contribute to the changes in volt-

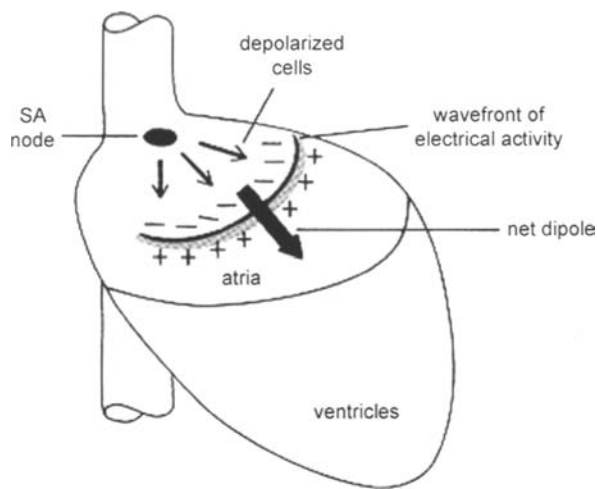


Fig. 1. After conduction begins at the sinoatrial (SA) node, cells in the atria begin to depolarize. This creates an electrical wavefront that moves down toward the ventricles, with polarized cells at the front, followed by depolarized cells behind. The separation of charge results in a dipole across the heart (the large black arrow shows its direction). Modified from D.E. Mohrman and L.J. Heller (eds.), *Cardiovascular Physiology*, 5th Ed., 2003. Reproduced with permission of the McGraw-Hill Companies.

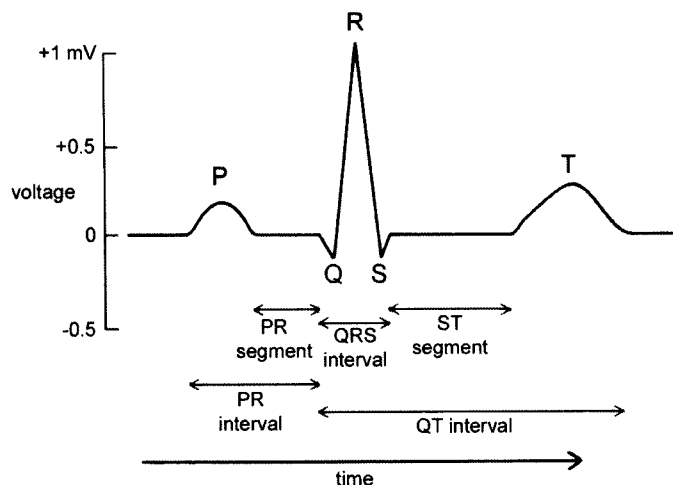


Fig. 2. A typical ECG waveform for one cardiac cycle measured from the lead II position. The P wave denotes atrial depolarization, the QRS indicates ventricular depolarization, and the T wave denotes ventricular repolarization. The events on the waveform occur on a scale of hundreds of milliseconds. Modified from D.E. Mohrman and L.J. Heller, (eds.), *Cardiovascular Physiology*, 5th Ed., 2003. Reproduced with permission of the McGraw-Hill Companies.

ages detected using electrodes on the surface of the body. When the monitored patient is essentially motionless, it is considered a “resting ECG,” the type of ECG signals discussed in the majority of this chapter.

## 2. THE ECG WAVEFORM

When an ECG is recorded, a reading of voltage vs time is produced, which is normally displayed as millivolts (mV) and seconds. A typical lead II ECG waveform is shown in Fig. 2. For this recording, the negative electrode was placed on the right

wrist, and the positive electrode was placed on the left ankle, giving the standard lead II ECG (explained in Section 3.1.). It shows a series of peaks and waves that corresponds to ventricular or atrial depolarization and repolarization, with each segment of the signal representing a different event associated with the cardiac cycle.

The cardiac cycle begins with the firing of the sinoatrial node in the right atrium. This firing is not detected by the surface ECG because the sinoatrial node is not composed of an adequately large quantity of cells to create an electrical potential with a high enough amplitude to be recorded with distal electrodes (signal amplitude is lost as it dissipates through the conductive medium). The atria then depolarize, giving rise to the P wave. This represents the coordinated depolarization of the right and left atria and the onset of atrial contraction. The P wave is normally around 80–100 ms in duration. As the P wave ends, the atria are completely depolarized and are beginning contraction.

The signal then returns to baseline, and action potentials (not large enough to be detected) spread to the atrioventricular node and bundle of His. Then, roughly 160 ms after the beginning of the P wave, the right and left ventricles begin to depolarize, resulting in what is called the QRS complex, representing the beginning of ventricular contraction, which is around 80 (60–100) ms in duration. Typically, the first negative deflection is the Q wave, the large positive deflection is the R wave, and if there is a negative deflection after the R wave, it is called the S wave. The exact shape of the QRS complex, as explained in Section 3.2., depends on the placement of electrodes from which the signals are recorded.

Simultaneous with the QRS complex, atrial contraction has ended, and the atria are repolarizing. However, the effect of this global atrial repolarization is sufficiently masked by the much larger amount of tissue involved in ventricular depolarization and is thus not normally detected in the ECG. During ventricular contraction, the ECG signal returns to baseline. The ventricles then repolarize after contraction, giving rise to the T wave. Note that the T wave is normally the last-detected potential in the cardiac cycle; thus, it is followed by the P wave of the next cycle, repeating the process.

Of clinical importance in the ECG waveform are several notable parameters (regions), which include the P–R interval, the S–T segment, and the Q–T interval. The P–R interval is measured from the beginning of the P wave to the beginning of the QRS complex and is normally 120–200 ms long. This is basically a measure of the time it takes for an impulse to travel from atrial excitation and through the atria, atrioventricular node, and remaining fibers of the conduction system. The S–T segment is the period of time when the ventricles are completely depolarized and contracting and is measured from the S wave to the beginning of the T wave. The Q–T interval is measured from the beginning of the QRS complex to the end of the T wave; this is the time segment from when the ventricles begin their depolarization to the time when they have repolarized to their resting potentials and is normally about 400 ms in duration.

An obvious observation made concerning the QRS complex is that it has a much higher peak and shorter duration than

either the P or T waves. This is because ventricular depolarization occurs over a greater mass of cardiac tissue (i.e., a greater number of myocytes are depolarizing at the same time); furthermore, the ventricular depolarization is much more synchronized than either atrial depolarization or ventricular repolarization. For additional details relative to the types of action potential that occur in various regions of the heart, refer to Chapter 9.

It is also very important to note that deflections in the ECG waveform represent the change in electrical activity caused by atrial or ventricular depolarization and repolarization and not necessarily generalized cardiac contractions or relaxations, which take place on a slightly longer time-scale (see Fig. 3). Shown in Fig. 3 are the certain points on the ECG waveform and how they relate to other events in the heart during the cardiac cycle.

One last thing that should be noted relative to the ECG waveform is the sometimes-detected potential referred to as the U wave. Its presence is not fully understood, but is considered by some to be caused by late repolarization of the Purkinje system. If detected, the U wave will be toward the end of the T wave and have the same polarity (positive deflection). However, it has a much shorter amplitude and usually ascends more rapidly than it descends (which is the opposite of the T wave).

### 3. MEASURING THE ECG

Typically, the ECG is measured from the surface of the skin, which can be done by placing two electrodes directly on the skin and reading the potential difference between them. This is possible because these signals are transmitted throughout the body. Again, as stated above, the detected waveform features depend not only on the amount of cardiac tissue involved, but also on the orientation of the electrodes with respect to the dipole in the heart. In other words, the ECG waveform will look slightly different when measured from different electrode positions, and typically an ECG is obtained using a number of different electrode locations (e.g., limb leads or precordial) or configurations (unipolar, bipolar, modified bipolar), which, fortunately, have been standardized by universal application of certain conventions.

#### 3.1. Bipolar Limb Leads

The three most commonly employed lead positions used today are referred to as leads I, II, and III. For the purposes of explaining the position of these leads, imagine the torso of the body as an equilateral triangle as illustrated in Fig. 4. This forms what is known as Einthoven's triangle (named for the Dutch scientist who first described it). Electrodes are placed at each of the vertices of the triangle, and a single ECG trace (lead I, II, or III) is measured along the corresponding side of the triangle using the electrodes at each end (because each lead uses one electrode on either side of the heart, leads I, II, and III are also referred to as the bipolar leads). The plus and minus signs shown in Fig. 4 indicate the polarity of each lead measurement and are notably considered as the universal convention. (For reasons that become clear in this chapter, the vertices of the triangle can be considered to be at the wrists and left ankle for electrode placement, as well as the shoulders and lower torso.)

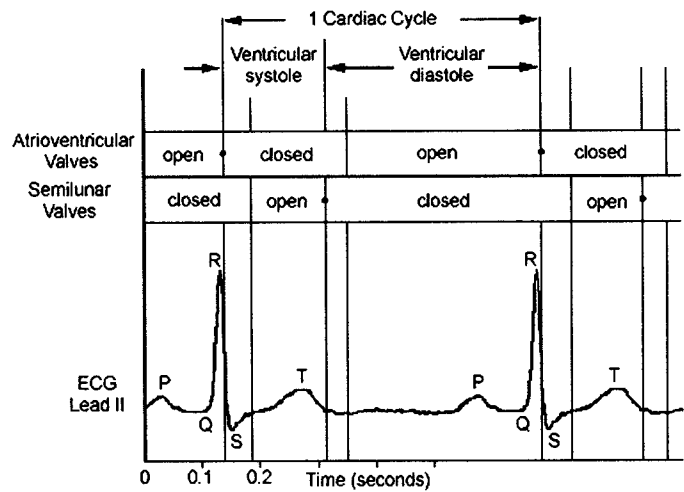


Fig. 3. A typical lead II electrocardiogram (ECG) waveform is compared to the timing of atrioventricular and semilunar valve activity, along with which segments of the cardiac cycle the ventricles are in systole/diastole.

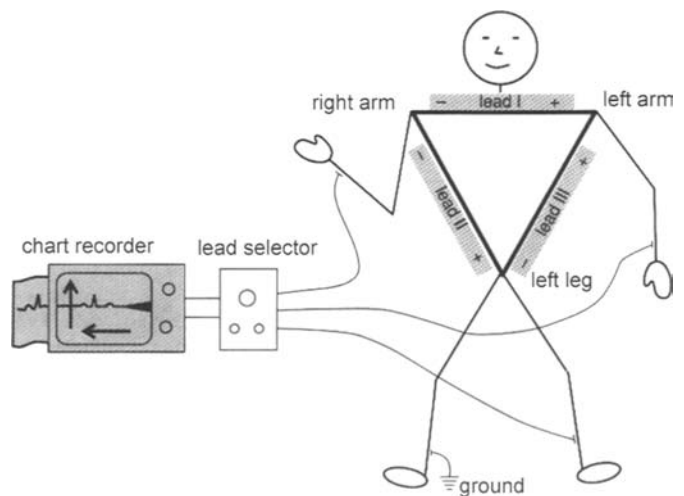


Fig. 4. The limb leads are attached to the corners of Einthoven's triangle on the body. Each lead uses two of these locations for a positive and a negative lead. The plus and minus signs indicate the orientation of the polarity conventions. Modified from D.E. Mohrman and L.J. Heller (eds.), *Cardiovascular Physiology*, 5th Ed., 2003. Reproduced with permission of the McGraw-Hill Companies.

As an example, if the lead II ECG trace shows an upward deflection, it would mean that the voltage measured at the left leg (or bottom apex of the triangle) is more positive than the voltage measured at the right arm (or upper right apex of the triangle). One notable time-point at which this happens is during the P wave. Imagine the orientation of the heart as shown in Fig. 5, with the action potential propagation across the atria creating a dipole pointed downward and to the left side of the body. This can be represented as an arrow (shown in Fig. 5) showing the magnitude and direction of the dipole in the heart. This dipole would, overall, create a more positive voltage reading at the left ankle electrode than at the right wrist electrode, thus eliciting the positive deflection of the P wave on the lead II ECG.

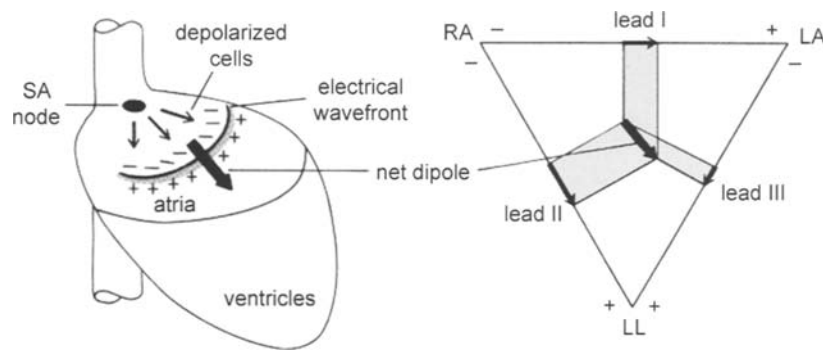


Fig. 5. The net dipole occurring in the heart at any one point in time is detected by each lead (I, II, and III) in a different way because of the different orientations of each lead set relative to the dipole in the heart. In this example, the projection of the dipole on all three leads is positive (the arrow is pointing toward the positive end of the lead), which gives a positive deflection on the electrocardiogram during the P wave. Furthermore, lead II detects a larger amplitude signal than lead III does from the same net dipole (i.e., the net dipole projects a larger arrow on the lead II side of the triangle than on the lead III side). LA, left arm; LL, left leg; RA, right arm; SA, sinoatrial. Figure from D.E. Mohrman and L.J. Heller (eds.), *Cardiovascular Physiology*, 5th Ed., 2003.

Now, imagine how that same action potential propagation would appear on the other lead placements, leads I and III, if placed at the center of Einthoven's triangle (Fig. 5, right side). Each of these lead placements can be thought of as viewing the electrical dipole from three different directions: lead I from the top, lead II from the lower right side of the body, and lead III from the lower left side, all looking at the heart in the frontal plane. In this example, the atrial depolarization creates a dipole that gives a positive deflection for all three leads because the arrow's projection onto each lead (or in other words, measuring the cardiac dipole from each lead) results in the positive end of the dipole pointed more toward the positive end of the lead than the negative end. This is why atrial depolarization (P wave) appears as a positive deflection for each lead (although wave magnitude is different in each). Ventricular depolarization, however, is a bit more complicated, as is discussed in detail in Section 3.2.; briefly, it results in various directions of the Q- and S-wave potentials depending on which lead trace is utilized for recording.

### 3.2. Electrical Axis of the Heart

The direction and magnitude of the overall dipole of the heart at any instant (represented by the arrow in Fig. 5, for example) is also known as the heart's "electrical axis," which is a vector originating in the center of Einthoven's triangle such that the direction of the dipole is typically assessed in degrees. The convention for this is to use a line horizontal across the top of Einthoven's triangle as  $0^\circ$  and move clockwise downward (pivoting on the negative end of lead I) as the positive direction. It should be noted that the electrical axis is actually changing direction throughout the cardiac cycle as different parts of the heart depolarize/repolarize in different directions. Fig. 6 shows the dipole spreading across the heart during a typical cardiac cycle, beginning with atrial depolarization. Each panel is accompanied by a diagram of the corresponding deflections on each ECG lead (I, II, and III). Keep in mind that, at certain points, the electrical axis of the heart may give opposite deflections on the various ECG leads.

As can be observed in Fig. 6, depolarization begins at the sinoatrial node in the right atrium, forming the P wave. The atria depolarize downward and to the left, toward the ventricles, followed by a slight delay at the atrioventricular node before the ventricles depolarize. The initial depolarization in the ventricles normally occurs on the left side of the septum, creating a dipole pointed slightly down and to the right. This gives a negative deflection of the Q wave for leads I and II; however, it is positive in lead III. Depolarization then continues to spread down the ventricles toward the apex, which is when the most tissue mass is depolarizing at the same time, with the same orientation. This gives the large positive deflection of the R wave for all three leads. Ventricular depolarization then continues to spread through the cardiac wall and finally finishes in the left ventricular lateral wall. This results in a positive deflection for leads I and II; however, lead III shows a lower R-wave amplitude along with a negative S-wave deflection.

After a sustained depolarized period (the S-T segment), the ventricles then repolarize. This occurs anatomically in the opposite direction of depolarization. However, one must keep in mind that the arrow in Fig. 6 represents the electrical axis of the heart (or the dipole) and does not necessarily show the direction that the repolarization wave is moving. Thus, even though the wave is moving from epicardium to endocardium (the direction of repolarization), the dipole (and therefore the electrical axis) remains in the same orientation as during depolarization. This explains why the T wave is also a positive deflection on leads I and II and negative (or nonexistent) on Lead III. The ventricles are then repolarized, returning the signal to its baseline potential (value).

During the cardiac cycle, the electrical axis of the heart (viewed from the plane of the limb leads) is always changing in both magnitude and direction. The average of all instantaneous electrical axis vectors gives rise to the "mean electrical axis" of the heart. Most commonly, it is taken as the average dipole (or electrical axis) direction during the QRS complex since this is the highest and most synchronized signal on the waveform. Typically, to find the mean electrical axis, area calculations

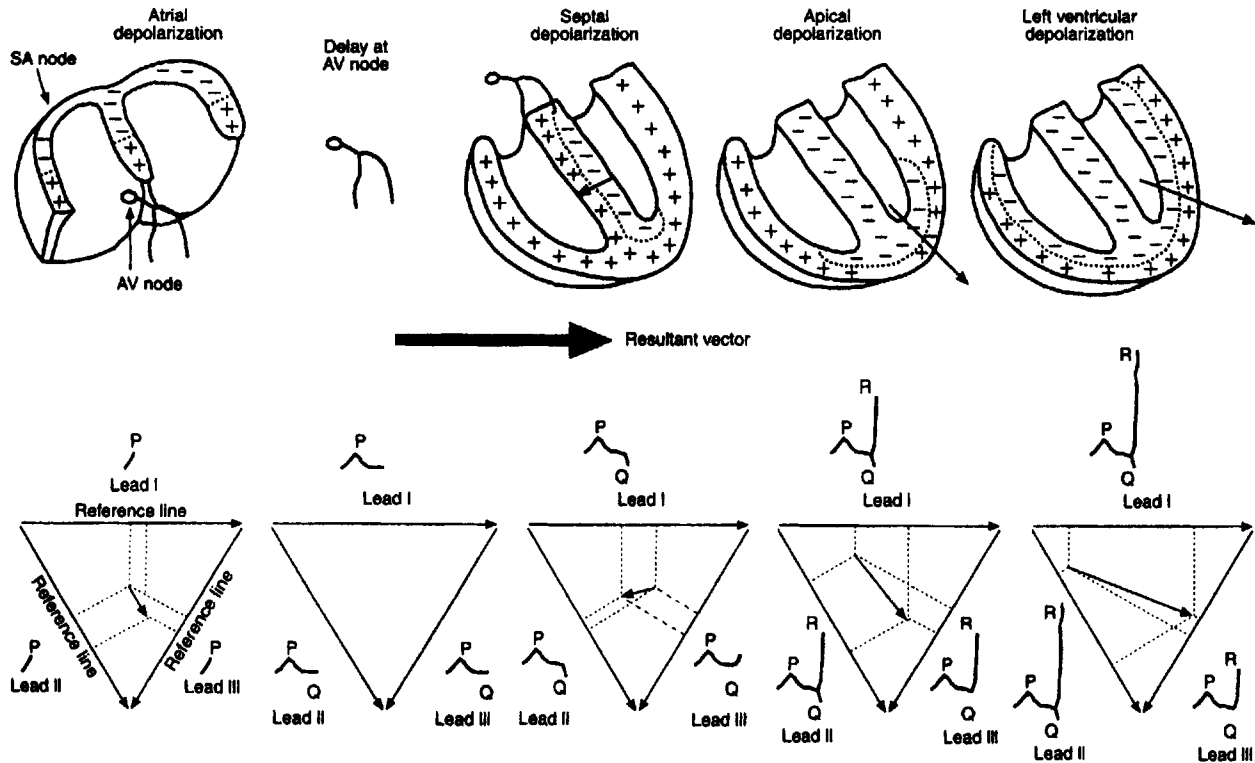
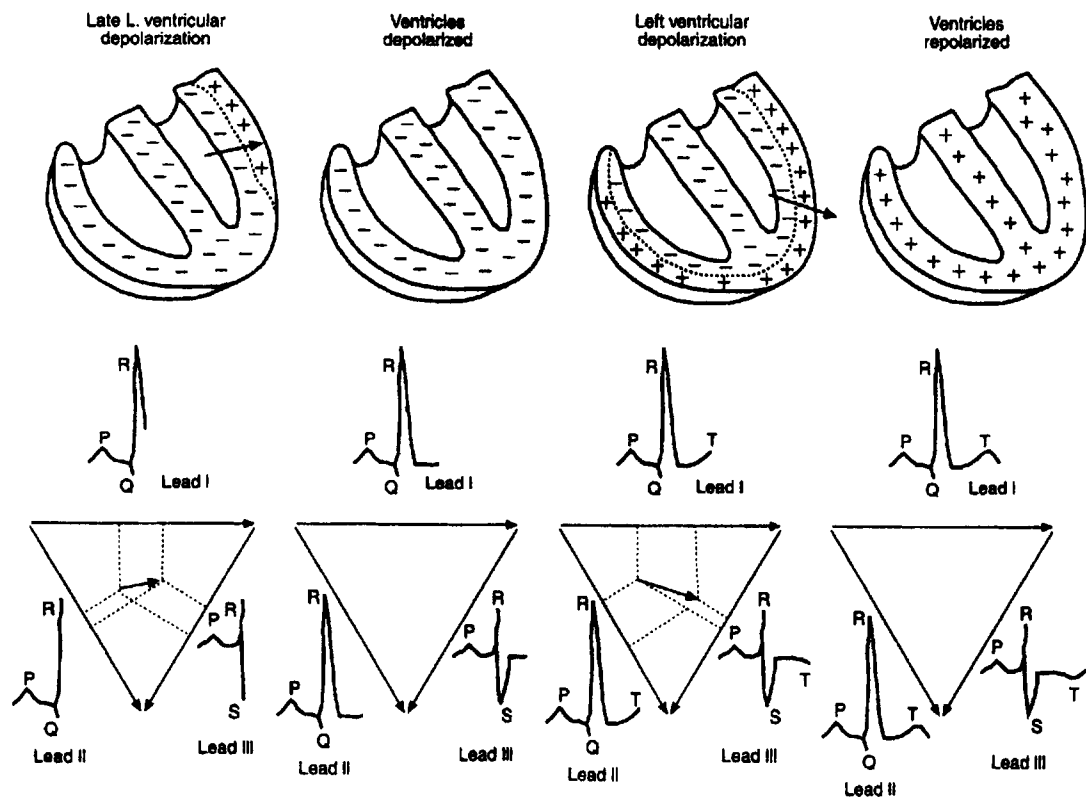
**Progression of depolarization****End of depolarization and repolarization**

Fig. 6. The net dipole of the heart (indicated by the arrow) as it progresses through one cardiac cycle, beginning with firing of the sinoatrial (SA) node and finishing with the complete repolarization of the ventricular walls. Each heart shows the charge separation inside the myocardium, along with a corresponding Einthoven's triangle diagram below it, which displays how the net dipole is deflected by each of the bipolar limb leads. Notice the change in direction and magnitude of the dipole during one complete cardiac cycle. AV, atrioventricular. Modified from L. R. Johnson (ed.), *Essential Medical Physiology*, 3rd Ed., 2003. With permission of Elsevier.

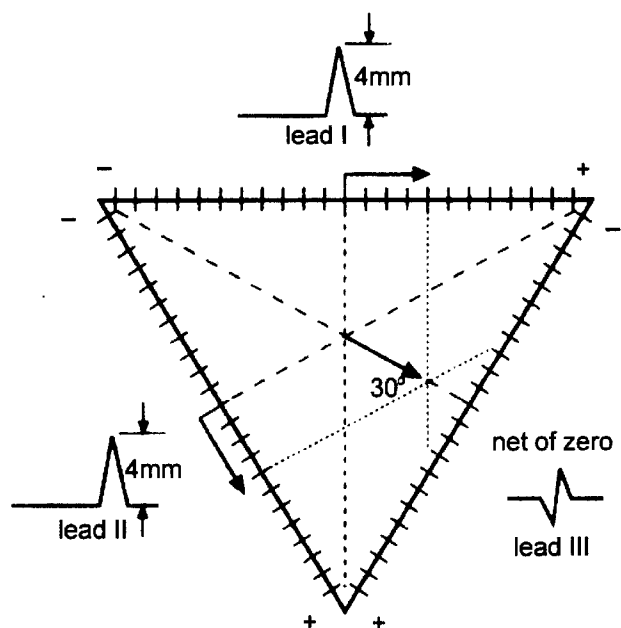


Fig. 7. The amplitudes of the lead I and II R waves are plotted along the corresponding leg of Einthoven's triangle starting at the mid-point and drawn with a length equal to the height of the R wave (units used to measure the amplitude can be arbitrary because the direction, not the magnitude, of the axis is important). The direction of the plot is toward the positive end of the lead if the R wave has a positive deflection and negative if it has a negative deflection. Perpendiculars from each point are then drawn into the triangle and meet at a point. A line drawn from the center of the triangle to this point gives the angle of the mean electrical axis. Because the normal activation sequence in the heart generally goes down and left, this is also the direction of the mean electrical axis in most people. The normal range is anywhere from  $0^\circ$  to  $+90^\circ$ . Modified from L.R. Johnson (ed.), *Essential Medical Physiology*, 3rd Ed., 2003.

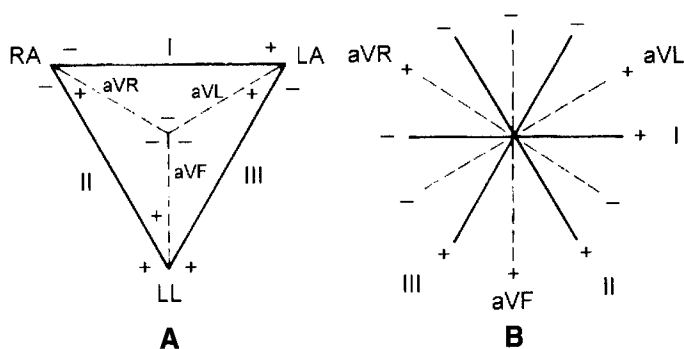


Fig. 8. (A) The augmented leads are shown on Einthoven's triangle along with the other three frontal plane leads (I, II, and III). (B) The hexaxial reference system for all six limb leads is shown, with solid and dashed lines representing the bipolar and unipolar leads, respectively. aVL, voltage recorded between left arm limb lead and neutral reference lead; aVF, voltage recorded between left leg lead and neutral reference lead; aVR, voltage recorded between right arm limb lead and neutral reference lead; LA, left arm; LL, left leg; RA, right arm. Modified from D.E. Mohrman and L.J. Heller (eds.), *Cardiovascular Physiology*, 5th Ed., 2003. Reproduced with permission of the McGraw-Hill Companies.

from under the QRS complexes from at least two leads are needed. However, it is easier and more commonly determined by an estimate using the deflection (positive or negative) and height of the R wave. Figure 7 shows a simple example of using leads I and II to find the electrical axis of the heart. It should be noted that, in the normal human heart, the electrical axis of the heart roughly corresponds to the anatomical orientation of the heart (from base to apex).

### 3.3. The 12-Lead ECG

Leads I, II, and III are the bipolar limb leads discussed thus far. There are three other leads that use the limb electrodes; these are the unipolar limb leads. Each of these leads uses an electrode pair that consists of one limb electrode and a "neutral reference lead" created by hooking up the other two limb locations to the negative lead of the ECG amplifier. In other words, each lead has its positive end at the corresponding limb lead and runs toward the heart, the location of its "negative" end, directly between the other two limb leads. These are referred to as the *augmented unipolar limb leads*. The voltage recorded between the left arm limb lead and the neutral reference lead is called lead aVL; similarly, the right arm limb lead is aVR, and the left leg lead is aVF (Fig. 8).

The remaining 6 of the 12 lead recordings are the 6 chest leads. These leads are also unipolar; however, they measure electrical activity in the traverse plane instead of the frontal plane. Similar to the unipolar limb leads, a neutral reference lead is "created," this time using all 3 limb leads connected to the negative ECG lead, which basically puts it in the center of the chest. The 6 positive, or "exploring," electrodes are placed as shown in Fig. 9 (around the chest) and are labeled V1 through V6 (the V meaning voltage). These chest leads are also known as the *precordial leads*. Figure 9A shows a simple cross-section (looking superior to inferior) of the chest, depicting the relative position of each electrode in the traverse plane. Figure 9A also shows a typical waveform obtained from each of these leads. The 3 bipolar limb leads, 3 unipolar limb leads, and 6 precordial leads make up the 12-lead ECG.

### 4. SOME BASIC INTERPRETATION OF THE ECG TRACE

The ECG waveform and mean electrical axis are quite useful in the clinical setting. The ECG is considered one of the most important monitors of a patient's cardiovascular status and is commonly used for measurements as basic as the heart rate. Most ECG monitoring devices used today include automated systems that detect changes in durations between subsequent QRS complexes (i.e., the duration of one cycle).

Simply, determination of the PR intervals provides information regarding whether a patient may have heart block. Elongated PR intervals (longer than  $\sim 0.21$  s) serve as a good indication that conduction through the atrioventricular node is slowed to some degree (first-degree heart block). Conduction in the atrioventricular node may even intermittently fail, which would elicit a P wave without a subsequent QRS complex before the next P wave (second-degree heart block). An ECG trace showing P waves and QRS complexes beating independently of each other indicates the atrioventricular node has ceased to transmit impulses (third-degree heart block).

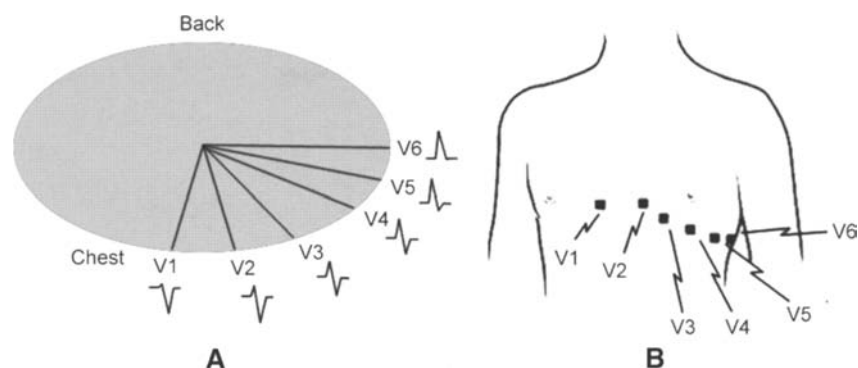


Fig. 9. (A) A cross-section of the chest shows the relative position of the six precordial leads in the traverse plane, along with a typical waveform detected for ventricular depolarization. (B) An anterior view of the chest shows common placement of each precordial lead, V1 through V6.

Prolonged Q–T intervals (which are normally no more than 40% of the cardiac cycle length) are normally an indication of delayed repolarization of the cardiomyocytes, possibly caused by irregular opening or closing of sodium or potassium channels. More important, though, is the elevation of the S–T segment, which typically indicates a regional ventricular ischemia. The S–T segment elevation (or depression) can also be used as an indication of many other abnormalities, including myocardial infarction, coronary artery disease, and pericarditis.

The electrical axis is also a helpful diagnostic tool. For example, in the case of left ventricular hypertrophy, the left side of the heart is enlarged with greater tissue mass. This could cause the dipole during ventricular contraction (and therefore the mean electrical axis) to point more towards the left.

Much more can be said about specific interpretations of the intervals and segments that make up the ECG waveform. For more details on changes in ECG patterns associated with various conditions or abnormalities, refer to Chapter 9.

## 5. LEAD PLACEMENT IN THE CLINICAL SETTING

In a clinical setting, not all 12 leads are displayed at the same time, and most often, not all leads are measured simultaneously. A common setup used is a five-wire system consisting of the two arm leads, which are actually placed on the shoulder areas, two leg leads placed where the legs join the torso, and one chest lead. This arrangement allows display of any of the limb leads (I, II, III, aVR, aVL, and aVF) and one of the precordial leads, depending on where the chest electrode is placed. Figure 10 shows the positioning of these five electrodes on the patient's body.

Nevertheless, the exact anatomical placement of the leads is very important for obtaining accurate ECG traces for clinical evaluations; moving an electrode even slightly away from its so-called correct position could cause dramatically different traces and possibly lead to misdiagnosis. A slight exception to this rule is the limb leads, which do not necessarily need to be placed at the proximal portion of the limb as described in the preceding paragraph. However, the limb leads for the most part need to be equidistant from each other relative to the heart (i.e., for determination of the electrical axis to be accurate).

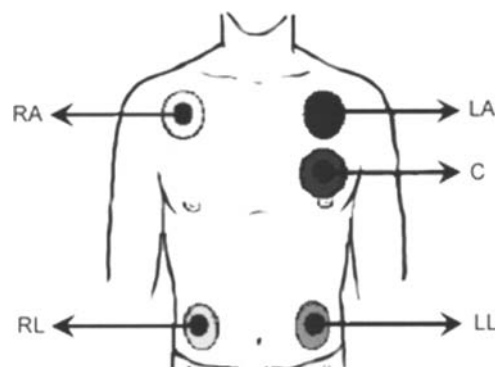


Fig. 10. Placement of the common five-wire electrocardiogram electrode system leads on the shoulders, chest, and torso. The chest electrode is placed according to the desired precordial lead position. C, chest; LA, left arm; LL, left leg; RA, right arm; RL, right leg.

## 6. ECG DEVICES

The invention of electrocardiography has had an immeasurable impact on the field of cardiology. It has provided insights into the structure and function of both healthy and diseased hearts. The ECG has evolved into a powerful diagnostic tool for heart disease, especially for the detection of arrhythmias and acute myocardial infarction. The use of the ECG has become a standard of care in cardiology, and new advances using this technology are continually introduced.

The discovery of intrinsic electrical activity of the heart can be traced to as early as the 1840s. Specifically, in 1842, the Italian physicist Carlo Matteucci first reported that an electrical current accompanies each heartbeat. Soon after, the German physiologist Emil DuBois-Reymond described the first action potential that accompanies muscle contraction. Additionally, Rudolph von Koelliker and Heinrich Miller recorded the first cardiac action potential using a galvanometer in 1856.

Subsequently, the invention of the capillary electrometer in the early 1870s by Gabriel Lippmann led to the first recording of a human electrocardiogram by Augustus D. Waller. The capillary electrometer is a thin glass tube containing a column of mercury that sits above sulfuric acid. With varying electrical potentials, the mercury meniscus moves, and this can be

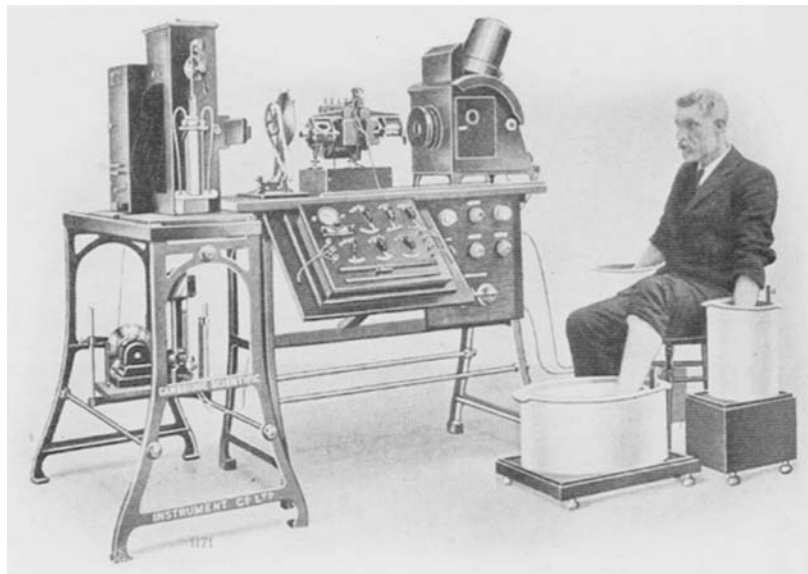


Fig. 11. Willem Einthoven's string galvanometer consisted of a massive electromagnet with a thin, silver-coated string stretched across it. Electric currents passing through the string caused it to move from side to side in the magnetic field generated by the electromagnet. The oscillations in the string provided information on the strength and direction of the electrical current. The deflections of the string were then magnified using a projecting microscope and recorded on a moving photographic plate. Courtesy of the NASPE-Heart Rhythm Society History Project.

observed through a microscope. Using this capillary electrometer, Waller was the first to show that the electrical activity precedes the mechanical contraction of the heart. He was also the first to show that the electrical activity of the heart can be seen by applying electrodes to both hands or to one hand and one foot; this was the first description of "limb leads." Interestingly, Waller would often publicly demonstrate this with his dog, Jimmy, who would stand in jars of saline during the recording of the ECG.

One of the next major breakthroughs in electrocardiography came with the invention of the string galvanometer by Willem Einthoven in 1901. The following year, he reported the first electrocardiogram, which used his string galvanometer. Einthoven's string galvanometer consisted of a massive electromagnet with a thin, silver-coated string stretched across it. Electric currents that passed through the string would cause it to move from side to side in the magnetic field generated by the electromagnet. The oscillations in the string would give information regarding the strength and direction of the electrical current. The deflections of the string were magnified using a projecting microscope and were recorded on a moving photographic plate (Fig. 11). Years earlier, utilizing recordings from a capillary electrometer, Einthoven was also the first to label the deflections of the heart's electrical activity as P, Q, R, S, and T.

In 1912, Einthoven made another major contribution to the field of electrophysiology by deriving a mathematical relationship between the direction and size of the deflections recorded by the three limb leads. This hypothesis is known as Einthoven's triangle (described in Section 3.1). The standard 3 limb leads were used for three decades before Frank Wilson described unipolar leads and the precordial lead configuration. The 12-lead ECG configuration used today consists of the standard

limb leads from Einthoven and the precordial and unipolar limb leads based on Wilson's work.

Following Einthoven's invention of the string galvanometer, electrocardiography quickly became a research tool for both physiologists and cardiologists. Much of the current knowledge involving arrhythmias was developed using the ECG. In 1906, Einthoven published the first results of ECG tracings of atrial fibrillation, atrial flutter, ventricular premature contractions, ventricular bigeminy, atrial enlargement, and induced heart block in a dog. Einthoven was awarded the Nobel Prize for his work and inventions in 1924.

Thomas Lewis was one of the pioneering cardiologists who utilized the capabilities of the ECG to further scientific knowledge of arrhythmias. His findings were summarized in his books *The Mechanism of the Heart Beat* and *Clinical Disorders of the Heart Beat*, published in 1911 and 1912, respectively. He also published over 100 research papers describing his work. Interestingly, Lewis was also the first to use the terms sinoatrial node, pacemaker, premature contractions, paroxysmal tachycardia, and atrial fibrillation. For more information on arrhythmias, see Chapter 22.

Myocardial infarction and angina pectoris were also extensively studied with ECG using the string galvanometer device. More specifically, numerous clinical investigators studied the changes within the ECG signal that were associated with the onset of myocardial infarction in both animals and humans. By the 1930s, the characteristic features of the ECG for the diagnostic indications of myocardial infarction had been identified. Subsequently, the connection between angina pectoris and coronary occlusion was made. Specifically, while studying electrocardiographic changes accompanying angina pectoris, Francis Wood and Charles Wolferth performed the first







Fig. 14. A loop recorder with pacemaker and detection capabilities is shown. This model is manufactured by LifeWatch Inc. (Buffalo Grove, IL).



Fig. 15. A loop recorder. The one pictured here is manufactured by LifeWatch, Inc.

The use of computers for the analysis of ECGs began in the 1960s. In 1961, Hubert Pipberger described the first computer analysis of ECG signals, an analysis that recognized abnormal records. Computer-assisted ECG analyses were introduced into the clinical setting in the 1970s. The use of computers, microcomputers, and microelectronic circuits has had a huge impact on electrocardiography. The size of the equipment has been drastically reduced to pocket size or even smaller for some applications. Computer programs can also provide summaries of information recorded from the ECG, including heart rates, heart rate variability, multiple types of arrhythmias, and variations in QRS, ST, QT, or T patterns. This has allowed continuous monitoring of patients over much longer time periods, which can greatly help in the diagnosis of patients with infrequent symptoms. However, there are some concerns that have surfaced with the use of computers for ECG analyses, including decreased basic training in the interpretations of ECGs and a reduction in the detection of new pattern changes associated with different disease states.

Currently, there are three general types of instruments utilized in the collection of electrocardiograms. Continuous



Fig. 16. The Reveal, an implantable electrocardiogram loop recorder, manufactured by Medtronic, Inc., Minneapolis, MN.

recorders, like the Holter monitor described earlier, are attached to the surface of the body and continuously record signals for a predetermined duration. Most such systems record from at least three different ECG leads. When using this method, patients must record their daily activities and the time of the onset of symptoms. Event recorders are another type of instrument used for ECG collection. There are two basic types of event recorders: a postevent recorder (worn continuously and self-activating when cardiac symptoms appear) and a miniature solid-state recorder (placed on the precordium to record the rhythm when symptoms appear). Today, these devices can be as small as a credit card.

A second type of event recorder available is the preevent recorder. Such devices are similar to those used for postevent recorders, but a memory loop is used to enable the recording of information several minutes before and after the onset of symptoms. Some examples of loop recorders are shown in Figs. 14 and 15. The Reveal™, a miniature version of a preevent recorder that can be implanted subcutaneously, is currently available and is shown in Fig. 16 (Usinoatrial, Medtronic Inc., Minneapolis, MN). This device is used for patients who elicit infrequent symptoms (hence, they remain undiagnosed) and for those in whom external recorders are considered impractical.

The third type of ECG instrument that is used is a real-time monitoring system. With this type of instrument, the data are not recorded within the device, but are transmitted transtelephonically to a distal recording station. Such instruments are commonly used for monitoring patients who have a potentially dangerous condition so the technician can quickly identify the rhythm abnormality and make arrangements for proper management of the condition.

## 7. SUMMARY

As cardiomyocytes depolarize and propagate action potentials throughout the heart, a charge separation (or dipole) is created. By utilizing the resultant electrical field present in the body, electrodes can be placed around the heart to measure potential differences as the heart depolarizes and repolarizes. This measurement gives rise to the ECG, normally consisting of the P wave for atrial depolarization, the QRS complex for ventricular depolarization, and the T wave for ventricular repolarization.

There are up to 12 different standard positions, or leads, available to detect the ECG. Most commonly, a 5-wire system

is used clinically and can be used for the 3 bipolar limb leads (which make up Einthoven's triangle), the 3 unipolar limb leads, and 1 precordial (chest) lead at a time. At least two lead traces are needed to calculate the heart's electrical axis, which gives the general direction of the heart's dipole at any given instant. The heart's mean electrical axis is then the average dipole direction during the cardiac cycle (or more commonly, during ventricular depolarization).

The recorded ECG remains one of the most vital monitors of a patient's cardiovascular status and is used today in nearly every clinical setting. Electrocardiography has come a long way since it was first used in the early 1900s. New instruments and analysis techniques are continually being developed. The ECG has also been used in combination with other implantable devices, such as pacemakers and defibrillators. The trend has been toward developing smaller, easier-to-use devices that can gather a wealth of information for use in patient diagnosis and treatment.

## SOURCES

- Alexander, R.W., Schlant, R.C., and Fuster, V. (eds.). (1998) *Hurst's The Heart, Arteries and Veins*, 9th Ed. McGraw-Hill, New York, NY.
- Burchell, H.B. (1987) A centennial note on Waller and the first human electrocardiogram. *Am J Cardiol.* 59, 979–983.
- Drew, B.J. (1993) Bedside electrocardiogram monitoring. *AACN Clin Issues.* 4, 25–33.
- Fye, B.W. (1994) A history of the origin, evolution, and impact of electrocardiography. *Am J Cardiol.* 73, 937–949.
- Hurst, J.W. (1998) Naming of the waves in the ECG, with a brief account of their genesis. *Circulation.* 98, 1937–1942.
- Jacobson, C. (2000) Optimum bedside cardiac monitoring. *Progr Cardiovasc Nurs.* 15, 134–137.
- Johnson, L.R. (ed.). (2003) *Essential Medical Physiology*, 3rd Ed. Elsevier Academic Press, San Diego, CA.
- Kossmann, C.E. (1985) Unipolar electrocardiography of Wilson: a half century later. *Am Heart J.* 110, 901–904.
- Krikler, D.M. (1987) Historical aspects of electrocardiography. *Cardiol Clin.* 5, 349–355.
- Mohrman, D.E. and Heller, L.J. (eds.) (2003) *Cardiovascular Physiology*, 5th Ed. McGraw-Hill, New York, NY.
- Rautaharju, P.M. (1987) A hundred years of progress in electrocardiography I: early contributions from Waller to Wilson. *Can J Cardiol.* 3, 362–374.
- Scher, A.M. (1995) Studies of the electrical activity of the ventricles and the origin of the QRS complex. *Acta Cardiol.* 50, 429–465.
- Wellens, H.J.J. (1986) The electrocardiogram 80 years after Einthoven. *J Am Coll Cardiol.* 3, 484–491.

## ON-LINE SOURCES

- <http://www.lifewatchinc.com/>  
<http://www.medcatalog.com/>  
<http://www.medicalsolutionsinc.com/>  
<http://www.naspe.org/>