Basic ECG Theory, 12-Lead Recordings, and Their Interpretation

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Abstract

The recorded electrocardiogram (ECG) remains as one of the most vital monitors of a patient's cardiovascular status and is used today in nearly every clinical setting. This chapter discusses the ECG as a measure of how the electrical activity of the heart changes over time, as action potentials within each myocyte propagate throughout the heart during each cardiac cycle. By utilizing the resultant electrical fields present in the body, electrodes can be placed around the heart to measure potential differences as the heart depolarizes and repolarizes. Furthermore, various techniques for obtaining ECG data are presented.

Electrocardiography has progressed rapidly since it was first employed back in the early 1900s. New instruments that are smaller and more sophisticated, as well as innovative analysis techniques, are continually being developed. The trend has been toward developing smaller, easier-to-use devices that can gather and remotely send a wealth of information to aid patient diagnosis and treatment.

19.1 The Electrocardiogram

An *electrocardiogram* (ECG) is a measure of how the electrical activity of the heart changes over time, as action potentials within each myocyte propagate throughout the heart as a whole during each cardiac cycle. In other words, the ECG is not a direct measure of the cellular depolarization and repolarization, but rather the recording of the cumulative signals produced by populations of cells eliciting changes in their membrane potentials at a given point in time. The ECG provides specific waveforms of electrical differences when the atria and ventricles depolarize and repolarize.

The human body can be considered, for the purposes of an ECG, as a large volume conductor. It is filled with tissues surrounded by a conductive medium, in which the heart is suspended. During the cardiac cycle, the heart contracts in response to action potentials moving through the chambers of the heart in a coordinated fashion. As this normally occurs, one part of the cardiac tissue is depolarized and another part is at rest or polarized. This results in a charge separation, or dipole, which is illustrated in Fig. 19.1. The moving dipole causes current flow in the surrounding body fluids between the ends of the heart, resulting in fluctuating electric fields throughout the body. This is much like the electric field that would result, for example, if a common battery was 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

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Fig. 19.1 After conduction begins at the sinoatrial 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 (with the large *black arrow* showing its direction). Modified from Mohrman and Heller (2003). *SA* = sinoatrial
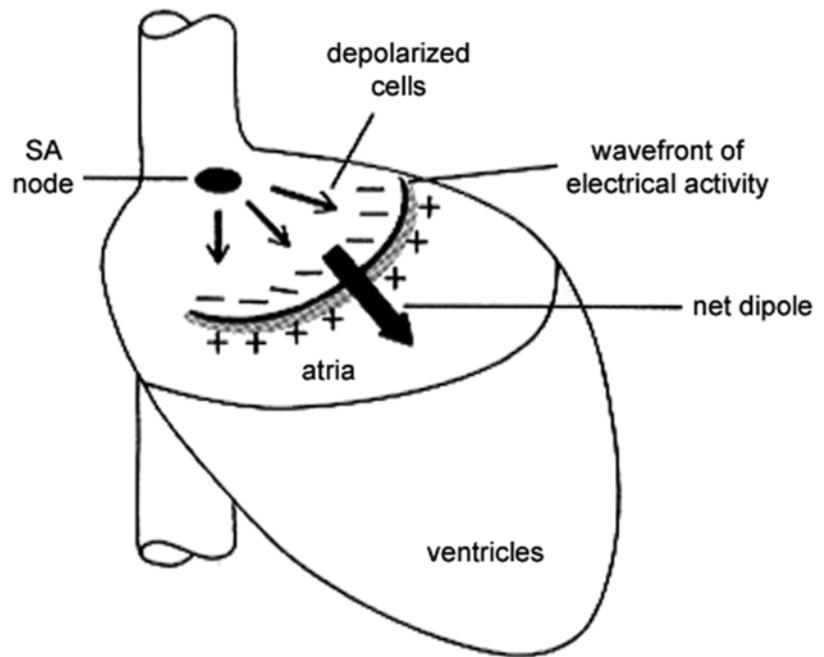
similar electrical field around the heart can be detected using electrodes attached to the skin. The intensity of the voltages detected depends on the orientation of the electrodes with respect to that of the dipole ends. The amplitudes of the signals are proportional to the masses of tissue involved in creating that dipole at any given time. Typically one employs electrodes on the surface of the skin to detect the voltages of these electrical fields, which is what gives rise to the ECG.

It is important to note that, because the surface ECG is measured from the skin, any potential differences within the body will have an effect on the resultant electrical fields that are being detected. This is why it is important, for diagnostic purposes, that patients remain as still as possible while recording an ECG. Movements from skeletal muscle activation (electromyograms, EMGs) will contribute to the changes in voltage detected using electrodes on the surface of the body. A *resting ECG* is recorded when the patient is essentially motionless; this type of ECG signal is discussed in the majority of this chapter).

19.2   ECG Devices

The invention of electrocardiography had an immeasurable impact on the field of cardiology. It has provided insights into the structure and function of healthy and diseased hearts. Thus, the ECG has evolved into a powerful diagnostic tool for heart disease, including the detection of arrhythmias, myocardial infarction, and/or hypertrophy, among others. The use of ECG has become a standard of care in cardiology, and new technological advances are continually being made.
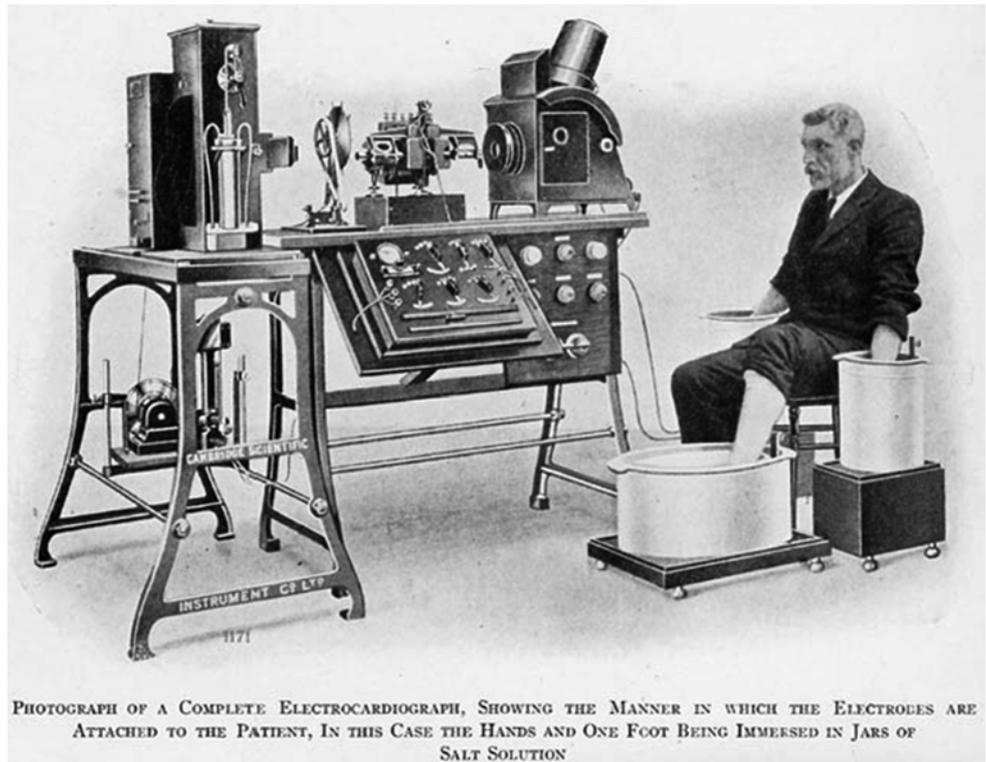
19.3   History of the ECG

The discovery of intrinsic electrical activity within the heart can be traced back to as early as the 1840s. 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. 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 ECG 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 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. Waller's work was the first description of "limb leads." Interestingly, Waller would often publicly demonstrate his experiments with his dog, Jimmy, who would stand in jars of saline during the recording of the ECG.

A major breakthrough in cardiac electrocardiography came with the invention of the string galvanometer by Willem Einthoven in 1901. He reported the first ECG using his string galvanometer the following year. Einthoven's string galvanometer consisted of a massive electromagnet

Fig. 19.2 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. Reprinted with permission from NASPE-Heart Rhythm Society History Project

PHOTOGRAPH OF A COMPLETE ELECTROCARDIOGRAPH, SHOWING THE MANNER IN WHICH THE ELECTRODES ARE ATTACHED TO THE PATIENT, IN THIS CASE THE HANDS AND ONE FOOT BEING IMMERSED IN JARS OF SALT SOLUTION

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 provide information regarding the strength and direction of the electrical current. The deflections of the string were then magnified using a projecting microscope and were recorded on a moving photographic plate (Fig. 19.2). 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 waveforms.

In 1912, Einthoven made another major contribution to the field of cardiac electrophysiology by deriving a mathematical relationship between the direction and size of the deflections recorded by the three limb leads. This hypothesis became known as *Einthoven's triangle*. The standard three 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 of Einthoven and the precordial and unipolar limb leads based on Wilson's work (see the following discussion for details on these recordings).

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 obtained through recording ECGs. 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 within a dog. Einthoven was awarded the Nobel Prize for his body of work and inventions in 1924.

During this same era, 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. Importantly, Lewis was also the first to use the terms: sinoatrial node, pacemaker, premature contractions, paroxysmal tachycardia, and atrial fibrillation.

Myocardial infarction and angina pectoris were also extensively studied with ECG, using the early string galvanometer device. Numerous clinical investigators further studied the changes within ECG signals that were associated with the onset of myocardial infarction in both animals and humans. By the 1930s, characteristic features of the ECG for the diagnostic indications of myocardial infarction had been identified, and later on, the connection between angina pectoris and coronary occlusion was made. Further, while studying electrocardiographic changes accompanying angina pectoris, Francis Wood and Charles Wolferth performed the first exercise electrocardiographic stress test. Their use of exercise during ECG analyses stemmed from the observation that many of their patients experienced angina only during physical exertion. During this period, this technique was not routinely used, since it was thought to be very dangerous.

Fig. 19.3 A diagram of Cambridge Scientific Instrument Company's smaller version of the string galvanometer. Reprinted with permission from NASPE-Heart Rhythm Society History Project
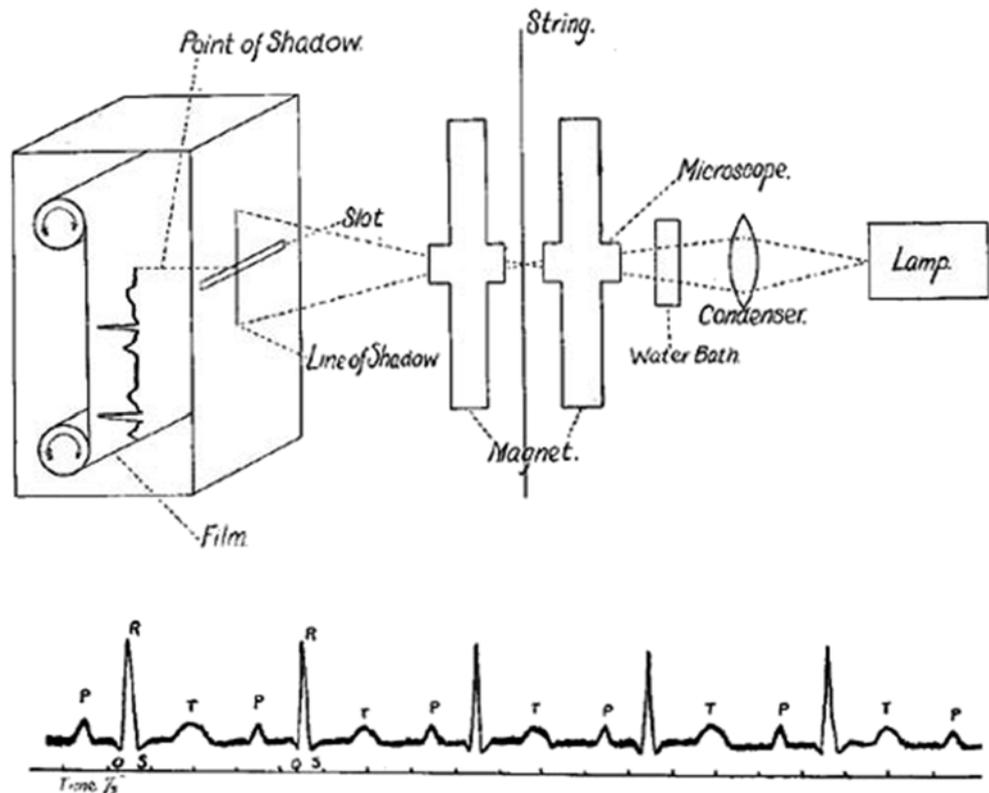
Nevertheless, with advances in protocols and technologies, the ECG emerged as an important and commonly employed diagnostic tool for physicians.

ECG equipment has come a long way since Einthoven's string galvanometer. Of interest, the Cambridge Scientific Instrument Company in London was the first to manufacture this instrument back in 1905; it was massive, weighing in at 600 pounds. A telephone cable was used to transmit electrical signals from a hospital over a mile away to Einthoven's laboratory. A few years later, Max Edelman of Cambridge Scientific Instrument Company manufactured a smaller version of the instrument (Fig. 19.3). However, it wasn't until the 1920s that bedside machines became available. A few years later, a "portable" version was manufactured in which the instrument was contained in two wooden cases, each weighing close to 50 pounds. In 1935, the Sanborn Company manufactured an even smaller version of the unit that only weighed about 25 pounds.

Interestingly, the use of ECG in a nonclinical setting became possible in 1949, with Norman Jeff Holter's invention of the *Holter monitor*. The first version of this instrument was a 75-pound backpack that could continuously record the ECG and transmit these signals via radio. Subsequent versions of such systems have been dramatically reduced in size and now use a digital recording of the signal. Today, miniaturized systems (Fig. 19.4) allow patients to be monitored over longer periods of time (usually 24 h) to help diagnose any problems with rhythm or ischemic heart disease.

Fig. 19.4 A version of the Holter monitor that is used currently. The one seen here is manufactured by Medical Solutions, Inc. (Maple Grove, MN, USA)

19.4 The ECG Waveform

As an ECG is recorded, signals of voltage versus time are produced, which are normally displayed in millivolts (mV) versus seconds. A typical Lead II ECG waveform is shown in Fig. 19.5. For this recording, the negative electrode was placed on the right wrist and the positive electrode placed on the left ankle, a standard Lead II ECG. As such, one can observe a series of peaks and waves that correspond to ventricular or atrial depolarization and repolarization, with each segment of the signal representing a different event within the cardiac cycle.
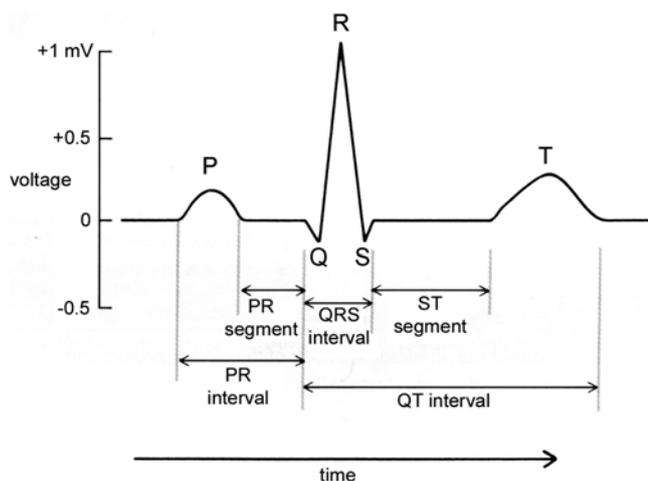
Fig. 19.5 A typical ECG waveform for one cardiac cycle, measured from the Lead II position. The P-wave denotes atrial depolarization and the QRS ventricular depolarization, and the T-wave denotes ventricular repolarization. The events on the waveform occur on a scale of hundreds of milliseconds. Modified from Mohrman and Heller (2003)

The normal cardiac cycle begins with the firing of the sinoatrial node, located within the right atrium. This initial firing is not detected by a typical ECG, because the sinoatrial node is not composed of an adequately large quantity of cells to create a detectable electrical potential, i.e., a signal with an amplitude high enough to be recorded with distal electrodes. The depolarization of the sinoatrial node is then conducted rapidly throughout the right and left atria, giving rise to the P-wave; this represents the depolarization of both atria and the onset of atrial contraction, and the P-wave is normally around 80–100 milliseconds (ms) in duration. As the P-wave ends, the atria are thus depolarized and this relates to their contraction. The signal then returns to baseline while action potentials (not large enough to be detected) spread through the atrioventricular node and bundle of His. Then, roughly 200 ms after the beginning of the P-wave, the right and left ventricles begin to depolarize resulting in the recordable QRS complex, which is approximately 100 ms in duration. The first negative deflection (if present) 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. As the QRS complex ends, the ventricles are completely depolarized and are contracting. Importantly, the exact shape of the QRS complex depends on the placement of electrodes from which the signals are recorded.

Simultaneous with the QRS complex, atrial contractions have ended and the atria are repolarizing. However, it is important to note that the effects of this global atrial repolarization are sufficiently masked by the much larger amount of tissue involved in ventricular depolarization, and thus, it is not normally detected in the ECG. Toward the end of ventricular contraction, the ECG signal returns to baseline. The ventricles repolarize after contraction, giving rise to the T-wave. 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.

It is clear that the QRS complex has a much higher and shorter duration peak than either the P- or T-waves. This is due to the fact that ventricular depolarization simultaneously occurs over a greater mass of cardiac tissue (i.e., a greater number of myocytes depolarizing at nearly the same time). 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, the reader is referred to Chap. 13. It is important to note that deflections in the ECG waveforms represent the changes only in electrical activity and have different time courses of generalized cardiac contraction or relaxation which take place on a slightly longer time scale. Figure 19.6 details certain points on the ECG waveform and how they relate to other events in the heart during the cardiac cycle.

Lastly, the recorded ECG waveforms in some individuals may elicit a potential referred to as the U-wave. Its presence is not fully understood, but is considered by some to be caused by late repolarizations within the vast 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 typically has a much shorter amplitude and ascends more rapidly than it descends (which is the opposite of the T-wave).

19.5 Measuring an ECG

The ECG is typically measured from electrodes placed on the surface of the skin; this can be done by placing a pair of electrodes directly on the skin and then monitoring the potential difference between them, as these electrical signals are transmitted throughout the body. The detected waveform features depend not only on the amount of cardiac tissue involved but also the relative orientation of the electrodes, i.e., with respect to the major dipoles in the heart. Recall that ECG waveforms will look different when measured from different electrode positions, and typically an ECG investigation is obtained using a number of different electrode locations (e.g., limb leads or precordial) or configurations (unipolar, bipolar, modified bipolar) which have been standardized by universal applications of certain conventions.

19.5.1 Bipolar Limb Leads

Today, the three most commonly employed lead positions are referred to as Leads I, II, and III. Imagine the torso of the body as an equilateral triangle as illustrated in Fig. 19.7. This forms what is known as *Einthoven's triangle* (named for the

Fig. 19.6 A typical Lead II 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. *ECG = electrocardiogram*
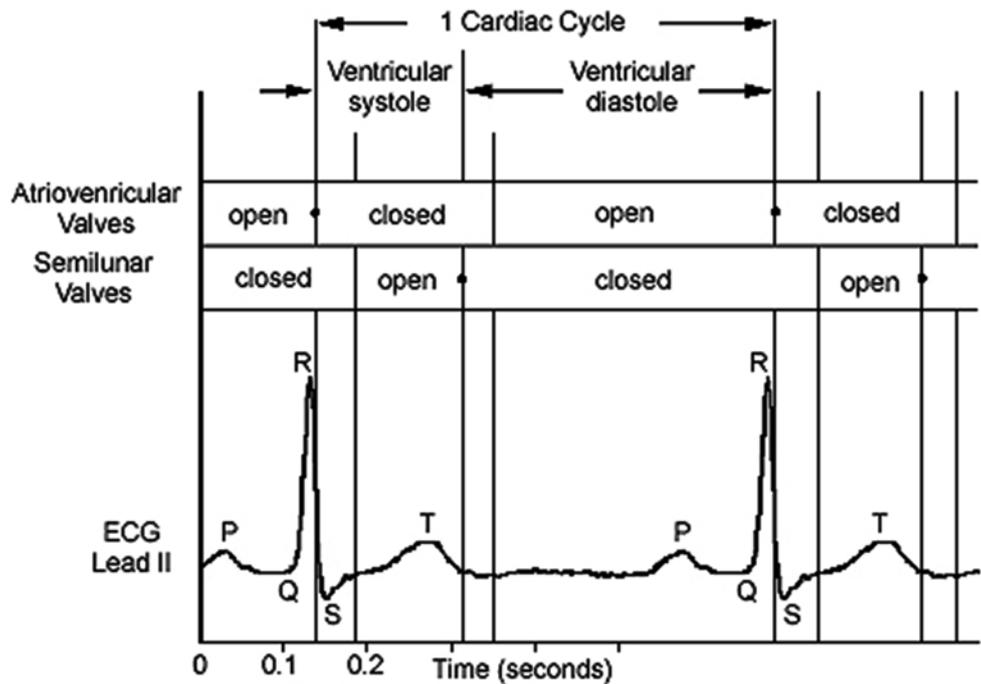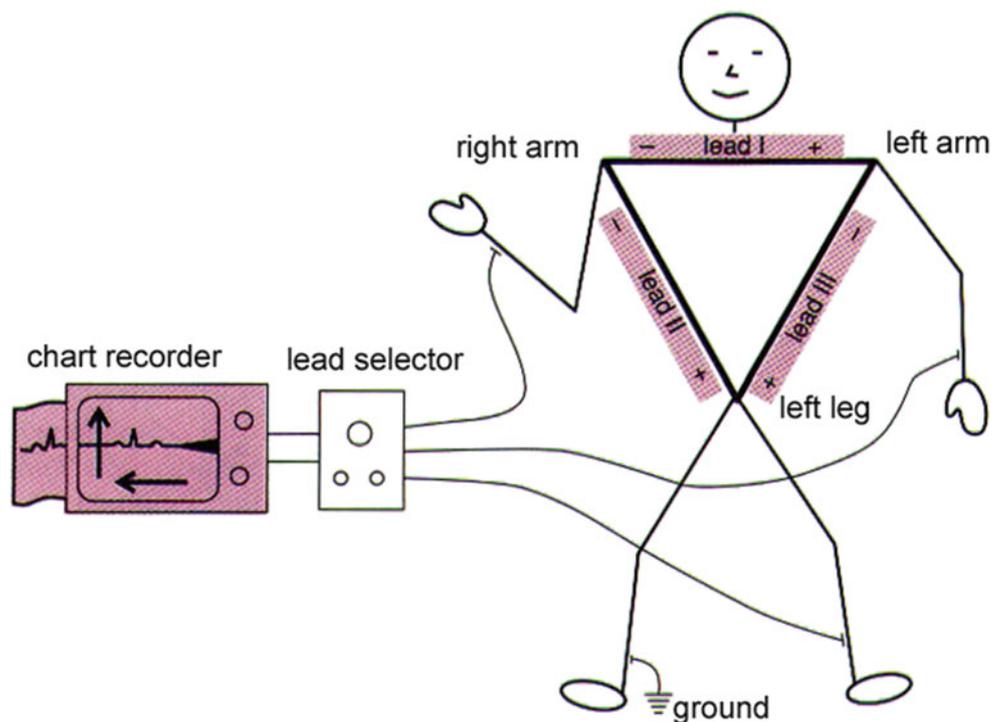
Fig. 19.7 The limb leads are attached to the corners of Einthoven's triangle on the body. Each lead uses two of these locations for a positive and negative lead. The "+" and "−" signs indicate the orientation of the polarity conventions. Modified from Mohrman and Heller (2003)

Dutch scientist who first described it). Electrodes are placed at each of the vertices of the triangle, and three ECG traces (either Lead I, II, or III) are measured along the corresponding sides of this 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 as the bipolar leads. The positive and negative signs shown in Fig. 19.7 indicate the polarity of each lead measurement, which are viewed as the universal convention. 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.

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 time point where this happens is during the P-wave. Imagine the orientation of the heart as shown in Fig. 19.8, with the action potential propagating across the
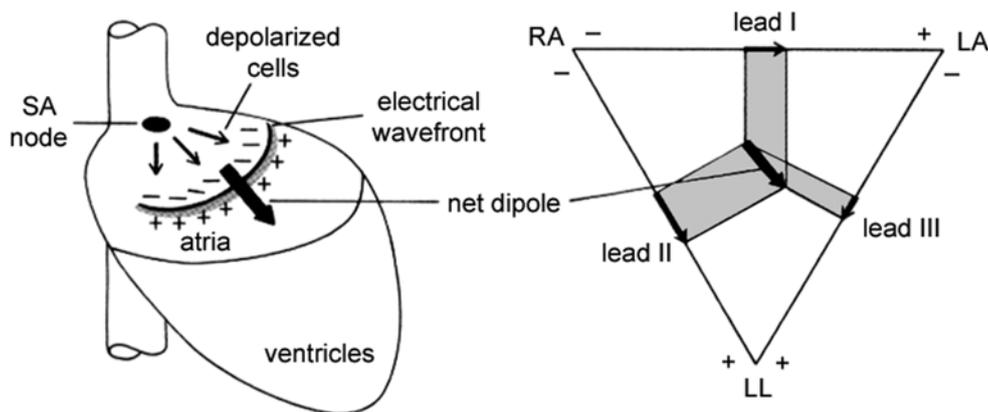
Fig. 19.8 The net dipole occurring in the heart at any one point in time is detected by each lead (I, II, and III) in a different way, due to the different orientations of each lead set relative to the dipole in the heart. In this example, the projection of the dipole on all three leads is positive (the *arrow* is pointing toward the positive end of the lead), which gives a positive deflection on the ECG 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). ©2003, Cardiovascular Physiology, 5th ed., Mohrman D and Heller L, with permission of McGraw-Hill Education. *LA* = left arm, *LL* = left leg, *RA* = right arm, *SA* = sinoatrial

atria, creating a dipole pointed downward and to the left side of the body. This can be represented as an arrow (Fig. 19.8) 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.

Now, imagine how that same action potential propagations would appear on the other lead placements, Leads I and III, if placed at the center of Einthoven's triangle (Fig. 19.8, right side). One can think of each of these lead placements 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 along 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 (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-waves) always appears as a *positive deflection*, but with different wave *magnitudes*, for Leads I, II, and III. Ventricular depolarization, however, is a bit more complicated and results in various directions of the Q- and S-wave potentials depending on which lead trace is being utilized for recording.

19.5.2 The Electrical Axis of the Heart

The direction and magnitude of the overall dipoles of the heart at any instant are also known as the heart's *electrical axis*, which can be plotted as 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 horizontal line across the top of Einthoven's triangle as 0° and move clockwise downward (pivoting on the negative end of Lead I) as the positive direction. Note that the electrical axis changes direction throughout the cardiac cycle, as different parts of the heart depolarize and repolarize in different directions. The top row of panels in Fig. 19.9 shows the dipoles spreading across the heart during a typical cardiac cycle, beginning with atrial depolarization. The bottom row shows the corresponding deflections on each ECG lead (I, II, and III). Note that, at certain points, the electrical axis of the heart may give opposite deflections on the different ECG leads.

As can be observed in Fig. 19.9, depolarization begins at the sinoatrial node in the right atrium and then spreads through the atria 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 simultaneously depolarizing with the same relative 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 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
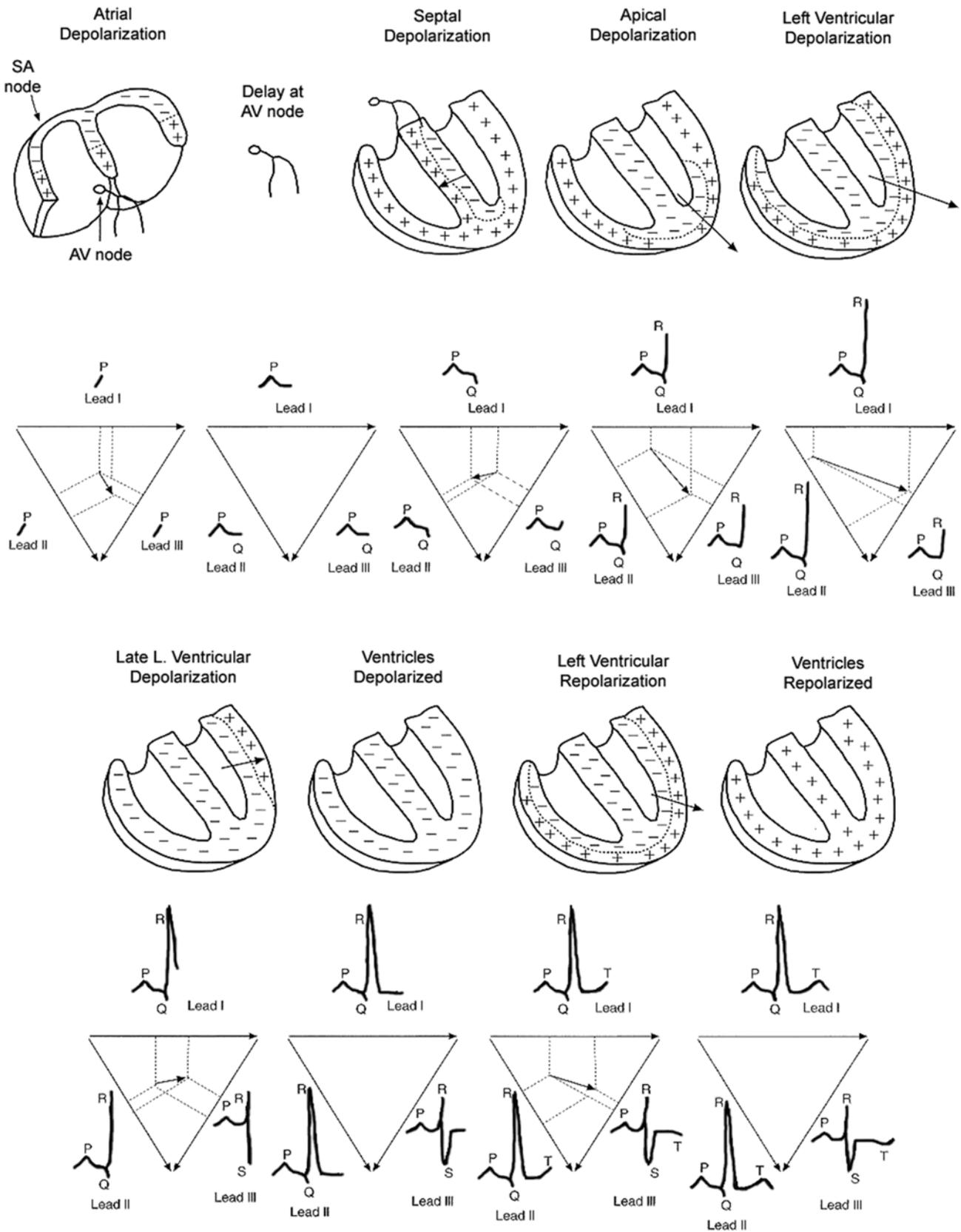
Fig. 19.9 The net dipole of the heart (indicated by the *arrow*) as it progresses through one cardiac cycle, beginning with firing of the sino-atrial node and finishing with the complete repolarization of the ventricular walls. The bottom row of panels displays how the net dipole is detected by each of the three bipolar limb Leads I, II, and III. Notice the change in direction and magnitude of the dipole during one complete cardiac cycle. Modified from Johnson (2003)

(the S–T segment), the myocytes within the ventricles then repolarize. However, this occurs in the opposite anatomical direction of depolarization, i.e., from base back toward the apex. The arrow in Fig. 19.9 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 the epicardium to endocardium, the dipole (and therefore the electrical axis) remains in the same orientation as during depolarization. Therefore, the T-wave is also a positive deflection on Leads I and II and negative (if present) on Lead III. At the end of this waveform, the ventricles are then repolarized, returning the signal to its baseline potential.

During the cardiac cycle, the relative electrical axes of the heart are 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 this is studied as the average dipole direction during the QRS complex, being it is the highest and most synchronized signal of the overall ECG waveform. Typically, to find the mean

electrical axis, area calculations from under the QRS complex 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 19.10 shows a simple example of using Leads I and II to find the relative electrical axis of the heart. It should be noted that, in the normal human heart, the electrical axis of the heart corresponds to the anatomical (axis) orientation of the heart (from base to apex). Also see Chap. 2 for more details on the heart orientation.

19.5.3 The 12-Lead ECG

Three of the twelve ECG leads are Leads I, II, and III; the bipolar limb leads that have been discussed thus far. Of the twelve, there are three other leads that use the limb electrodes, called the *unipolar limb leads*. Each of these leads uses an electrode pair that consists of one limb electrode and a "neutral reference lead" that is created by hooking up the
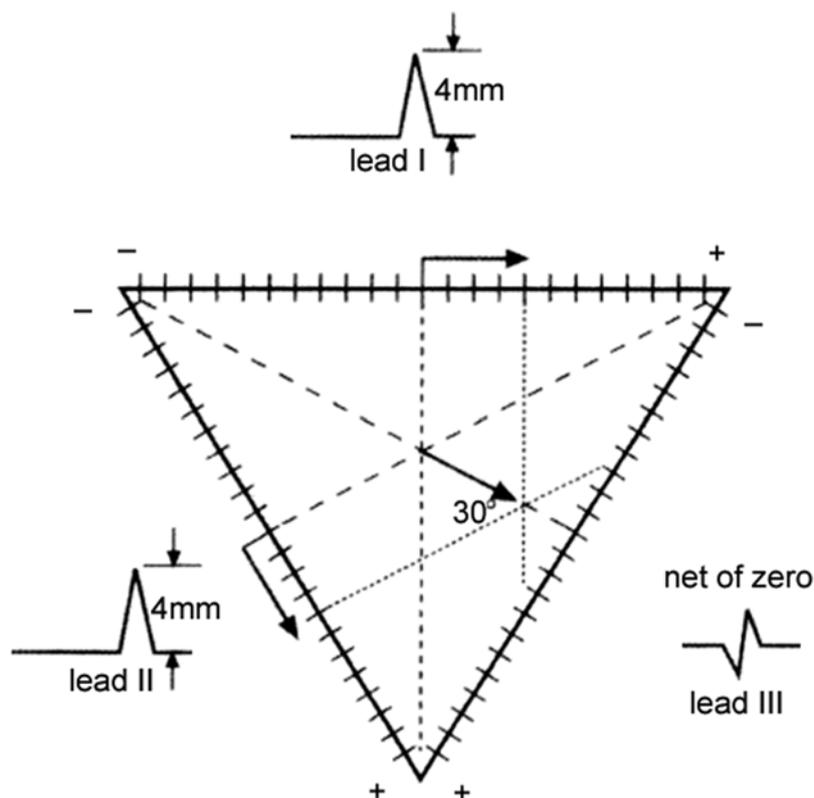

Fig. 19.10 The amplitude of the Lead I and II R-waves are plotted along the corresponding leg of Einthoven's triangle starting at the midpoint and drawn with a length equal to the height of the R-wave (units used to measure the amplitude can be arbitrary, since the direction, not the magnitude, of the 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 they meet at a point. A line drawn from the center of the triangle to this point gives the angle of the mean electrical axis. Since 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° to +90°. Modified from Johnson (2003)
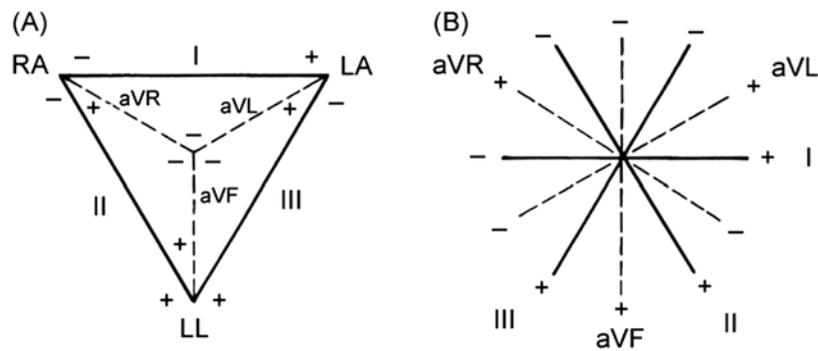
Fig. 19.11 (**A**) The augmented leads are shown on Einthoven's triangle along with the other three frontal plane leads (I, II, and III). (**B**) A hex-axial reference system for all six limb leads is shown, with *solid* and *dashed lines* representing the bipolar and unipolar leads, respectively. Modified from Mohrman and Heller (2003).

aVF = voltage recorded between left leg lead and neutral reference lead, *aVL*= voltage recorded between left arm limb 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
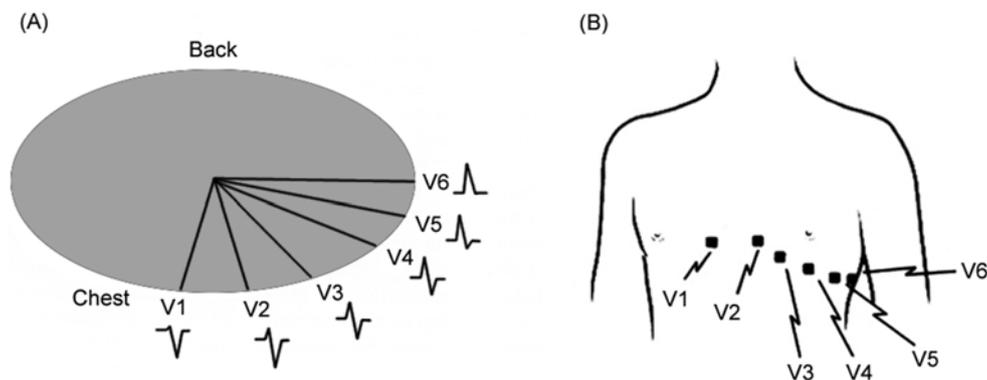

Fig. 19.12 (**A**) A cross section of the chest shows the relative position of the six precordial leads in the traverse plane, along with a typical waveform detected for ventricular depolarization. (**B**) An anterior view of the chest shows common placement of each precordial lead, V1 through V6

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 where its "negative" end is located, 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. 19.11).

The remaining six of the twelve lead recordings are the chest leads. These leads are also obtained as unipolar; however, they uniquely measure electrical activity in the patient's traverse plane instead of the frontal plane. Similar to the unipolar limb leads, a neutral reference lead is created, but this time using all three limb leads connected as the negative ECG lead, which basically puts it in the center of the chest. The six positive, or "exploring," electrodes are placed as

shown in Fig. 19.12 (around the chest) and are labeled V1 through V6 (V designates voltage). These chest leads are also known as the *precordial* leads. Figure 19.12a shows a simple cross section (looking superior to inferior) of the chest, depicting the relative position of each electrode in the traverse plane. Figure 19.12a also shows typical waveforms obtained from each of these leads. In summary, three bipolar limb leads, three unipolar limb leads, and six chest leads make up the 12-lead ECG.

The 12-lead ECG is widely used to evaluate overall cardiac electrical activity since it provides multiple views of how electrical conduction moves through a given patient's heart. For example, it can be used to help determine the location of many cardiac abnormalities, including (1) conduction disturbances (such as bundle branch block), (2) myocardial infarction or ischemia, (3) atrial or ventricular hypertrophy, and/or (4) electrolyte disturbances and drug effects.

19.6 Some Basic Interpretation of the ECG Trace

Analyses of the ECG waveforms and mean electrical axes are quite useful in the clinical setting. The ECG is considered to be one of the most important monitors of a patient's cardiovascular status but also can be used for basic measurements such as heart rate. Most monitoring devices used today include automated systems that detect changes in duration between subsequent QRS complexes.

Of clinical importance in the ECG waveform are several parameters (regions) which include the P–R interval, QRS interval, S–T segment, and Q–T interval (Fig. 19.5). 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 a measure of the time it takes for an impulse to travel from sinoatrial excitation through both the atria and atrioventricular node and induce the general onset of ventricular depolarization. The QRS interval measures how long the process of overall ventricular depolarization takes and is typically 60–100 ms. 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 potential and is normally about 400 ms in duration.

Determination of the P–R interval provides useful information as to whether a patient may be eliciting some degree of heart block. Elongated P–R intervals (longer than ~200 ms) 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 at all (third-degree heart block). For additional information on atrioventricular blocks, see Chap. 13.

A wide QRS complex (greater than 100 ms) may indicate conduction block or delays in electrical propagation through the bundle branches or Purkinje fibers that run through the ventricle. Delays or alterations in the conduction pathway through the ventricles can impact ventricular contraction and possibly cause dyssynchrony between the right and left ventricles. This, in turn, will negatively impact overall cardiac function and ultimately hemodynamics.

Prolonged Q–T intervals (which are usually no more that 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. Importantly, a long Q–T interval may indicate that a patient is at risk of developing a ventricular tachyarrhythmia (see Chap. 13 for more details).

Another clinically important interval is the S–T segment. Depression of the S–T segment (below the baseline) can indicate a regional ventricular ischemia. S–T segment elevation or depression can also be used as an indication of many other abnormalities including myocardial infarction, coronary artery disease, and/or pericarditis. For patients with established coronary artery disease, it is important to compare current ECG recordings to historical ones, to establish if any new regions of ischemia or infarction exist.

Estimation of the electrical axis is also a helpful diagnostic measure. 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 to shift to 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 clinical situations, the reader is referred to Chap. 13 and Chap. 28.

19.7 Lead Placement in the Clinical Setting

In a clinical setting, all 12 leads may not be displayed at the same time and, most often, not all leads are being measured simultaneously. A common setup used is a five-wire system consisting of the two arm leads (placed on the shoulder areas), two leg leads (placed low where the legs join the torso), and one chest lead. This arrangement allows one to display 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 19.13 shows the positioning of these five electrodes on the patient's body.

It should be noted that the exact anatomical placement of the leads is very important to obtain accurate ECG traces for clinical evaluations; moving an electrode even slightly away from its correct position could cause dramatic variation in the parameters of a trace 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 distal portion of the limb as described earlier. Note that the limb leads need to be, for the most part, equidistant from each other relative to the heart for determination of the electrical axis to be accurate.
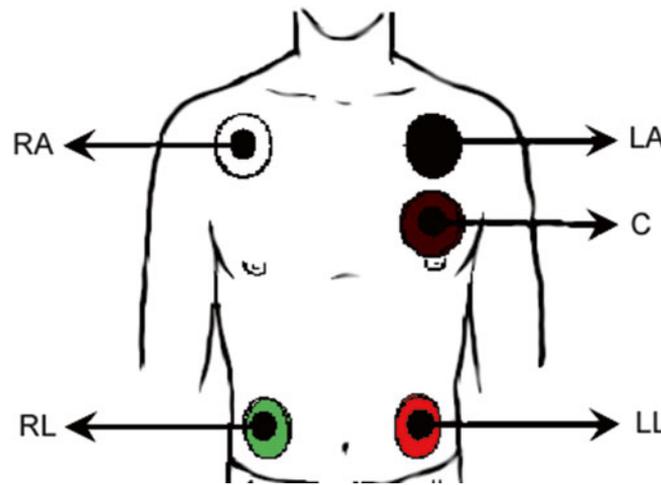
Fig. 19.13 Placement of the common five-wire ECG electrode system leads on the shoulders, chest, and torso. The chest electrode is placed according to the desired precordial lead position. *C* = chest, *LA* = left arm, *LL* = left leg, *RA* = right arm, *RL* = right leg

19.8 Computer Analyses

The use of computers for the analyses of ECG began in the 1960s. In 1961, Hubert Pipberger described the first computer analysis of ECG signals, an analysis which recognized basic abnormal activity. Computer-assisted ECG analyses were introduced into the general clinical setting in the 1970s. Subsequently, the use of computers, microcomputers, and microelectronic circuits has had a huge impact on field of electrocardiography. The size of such equipment has been drastically reduced to pocket-size or even smaller for some applications. This has allowed broader deployment of continuous monitoring of patients over much longer time periods, which has greatly helped in the diagnoses of patients with infrequent symptoms (paroxysmal).

Computer programs can also provide summaries of information recorded from the ECG including heart rate, multiple types of arrhythmias, and specific variations in QRS, S–T, Q–T, or T patterns. Additionally, there are several computer techniques that have been developed to further identify patients with cardiac dysfunction and previous myocardial infarctions that may be at risk for sudden death, e.g., signal-averaged ECGs, microvolt T-wave alternans, and/or heart rate variability. Signal-averaged ECG is a technique that uses computer analysis to identify late potentials appearing at the end of the QRS complex; these late potentials have been associated with an increased risk of ventricular arrhythmias. Microvolt T-wave alternans is another method that may be used to identify patients at risk for ventricular arrhythmias. This technique measures the presence of small changes in T-wave amplitudes that occur on an alternating beat-to-beat basis. Similarly, heart rate variability analysis measures subtle variations in ventricular rate to assess a patient's autonomic status (modulation of heart rate due to the influence of the autonomic nervous system). It is noteworthy that patients with low heart rate variability following a myocardial infarction may be at higher risk for sudden death. Studies have shown these techniques have high negative predictive value. They have been proposed as screening techniques but are not widely used in the clinical setting today due, in part, to their relatively low positive predictive value.

19.9 Long-Term ECG Recording Devices

Currently, there are four general types of devices that are utilized in the collection of long-term electrocardiographic recordings: continuous recorders, event recorders, real-time monitoring systems, and implantable recorders.

Continuous recorders, like the Holter monitor described above, are attached to the surface of the body and continuously record signals for a predetermined duration (usually 24–48 h). Such systems record from at least three different ECG leads. When using this method, patients must also record their daily activities and the time of any onset of symptoms (e.g., were they beginning to exercise?).

Event recorders are another type of instrument used for ECG collection. There are two basic types of event recorders—a symptom event recorder and a loop memory recorder. A symptom event recorder is activated by the patient to store a recording when their symptoms appear and therefore contains a post-event ECG recording. This type of recorder can be worn continuously or can be a handheld device which records the rhythm when the unit is activated and placed on the precordium. Pre-event or loop recorders are similar to post-event recorders, but a memory loop is used to enable the recording of information several minutes before and after the onset of symptoms. Today there are many different event

recorder devices including those connected to traditional ECG wires or devices consisting of a wireless patch electrode which adheres to the skin and can store and transmit data. A patient activator to prompt recording of the ECG during symptoms can be included on the event recorder itself or as a separate device, worn like a wristwatch, for example.

Fig. 19.14 A loop recorder with pacemaker and detection capabilities is shown. This model is manufactured by LifeWatch, Inc. (Rosemont, IL, USA)

Data from event recorders can also be transmitted wirelessly for viewing of the data by the physician electronically. The trend has been toward decreasing size, maximizing information, and improving data review by physicians and perhaps patients. Examples of loop recorders are shown in Figs. 19.14 and 19.15.

The third type of ECG instrument in clinical use today is a real-time monitoring system. Data are not recorded within the device, but rather are transmitted trans-telephonically to a distal recording station. Such instruments are commonly used for monitoring of patients that have a potentially dangerous condition, so the technician can quickly identify the rhythm abnormality and make arrangements for proper management of the condition.

Finally, implantable recorders are miniaturized loop recording devices that can be implanted subcutaneously. These implantable devices can be programmed to automatically store data when fast or slow heart rhythms are detected. Additionally, the patient can also self-trigger the device to store data when symptoms are felt. The latest implantable loop recorders can be placed for up to 3 years, during which time they can be used as a diagnostic tool to help manage the medical treatment of arrhythmias. Implantable recorders have typically been used for patients that elicit infrequent symptoms (hence they remain undiagnosed) and for those in

Fig. 19.15 The SEEQ™ Mobile Cardiac Telemetry System, manufactured by Medtronic, Inc. (Minneapolis, MN), is an external, wire-free adhesive loop recorder that can be worn for up to 30 days to help detect and diagnose arrhythmias. Data from this device can be transmitted via Bluetooth and cellular connections for physician review and analysis. Reproduced with permission of Medtronic, Inc.
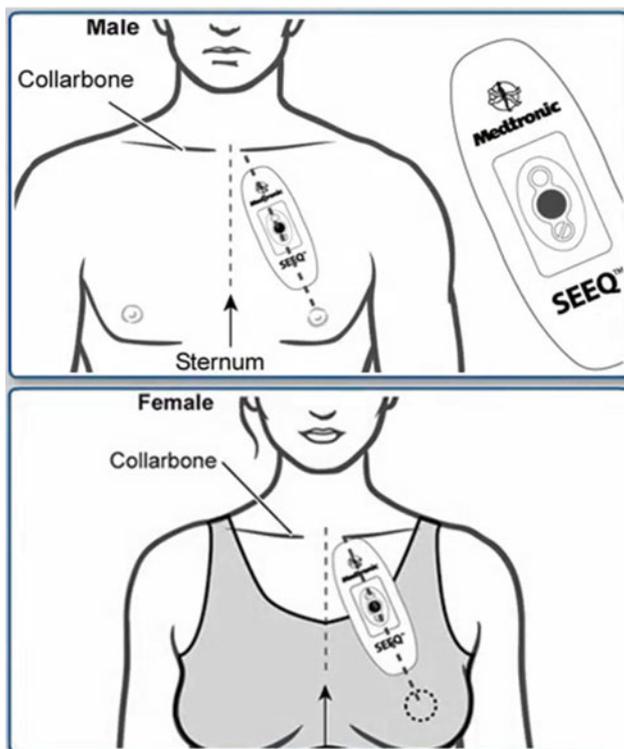
Fig. 19.16 The Reveal
LINQ™, an implantable ECG
loop recorder, is manufactured
by Medtronic, Inc.
(Minneapolis, MN, USA).
This device can be inserted
subcutaneously using an
insertion tool with an incision
of less than 1 cm. Reproduced
with permission of Medtronic,
Inc.

whom external recorders are considered impractical. Recent advances in technology have made these devices much smaller, with improved arrhythmia detection capabilities and wireless technology to facilitate transmission and viewing of the data by physicians for improved patient management. One of these devices, the Reveal LINQ™, is shown in Fig. 19.16 (Medtronic, Inc., Minneapolis, MN, USA).

19.10 Summary

As cardiomyocytes depolarize and propagate action potentials throughout the heart, an electrical 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 via atrial depolarization, the QRS complex for ventricular depolarization, and the T-wave associated with ventricular repolarization.

To date, there are twelve standard lead positions which are clinically employed to detect the ECG. Most commonly, a 5-wire system is used clinically and can be used for the three bipolar limb leads (which make up Einthoven's triangle), the three unipolar limb leads, and one 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 commonly defined as the average dipole direction recorded during ventricular depolarization (in the healthy heart this is same as the anatomical axis).

The recorded ECG remains as one of the most vital monitors of a patient's cardiovascular status and is used today in nearly every clinical setting. Yet, systems to monitor the electrocardiograph have come a long way since they were first developed in the early 1900s. New instruments that are smaller and more sophisticated as well as provide for innovative analysis techniques are continually being developed. 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 and remotely send a wealth of information to use in both patient diagnosis and treatment (telemedicine).

Additional Resources

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