CHAPTER 4

BASIC ECG CONCEPTS AND THE NORMAL ECG

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LEARNING OBJECTIVES

Upon completion of this chapter, the reader will be able to:

1. Identify standardized components of the ECG, such as the ECG paper, paper speed, voltage calibration, and the 12-lead printout.
2. Calculate heart rate from the ECG by three different methods: the dark line method, the 1500 method, and the 6-second method.
3. Understand the development of the bipolar limb leads in the frontal plane and the chest leads in the horizontal plane.
4. Discuss the use of the hexaxial reference system in the determining path of depolarization of the myocardium.
5. Ascertain the waveforms and key intervals of the cardiac cycle.
6. Determine axis deviation by vector calculation and the two-lead method.

KEY TERMS

1500 method
6-second method
atrial kick
axis deviation
Bazett's formula
dark line method
Einthoven's triangle
electrocardiogram (ECG)
hexaxial reference system
left axis deviation (LAD)
mean QRS axis (vector)
PR interval (PRI)
precordial leads
P wave
QRS complex
QT interval

right axis deviation (RAD)

ST segment

T wave

U wave

unipolar limb leads

INTRODUCTION

The heart produces electrical activity through the generation of action potentials upon receiving a signal from the sinoatrial (SA) node. As in any action potential, there is depolarization and repolarization of cells; in this case, the myocardial cells within the heart. An **electrocardiogram (ECG)** records the electrical potentials via electrodes placed on the chest wall. An ECG rhythm strip or 12-lead ECG can be printed to view and measure the electrical activity of the heart. This chapter will focus on the elements necessary for effective and accurate ECG interpretation as well as the development of the ECG leads and what is considered a normal ECG. The acronym EKG (from the German *elektrokardiogramm*) is used synonymously with ECG.

ECG STANDARDIZATION

Accuracy is essential when evaluating ECGs. In order for the ECG interpretation to be accurate, a standardized system is vital. In other words, certain checkpoints along the way need to be followed to enable comparisons between serial ECGs.

ECG PAPER

Most ECG machines use a thermal printer to print an ECG onto paper. ECGs are usually printed on paper that has preprinted grid lines. Some machines will print the grid lines and the ECG at the same time. Understanding the grid system is imperative for calculating heart rates and accurately measuring wave amplitudes as well as essential intervals.

- The grid lines are evenly spaced 1 mm apart horizontally and vertically.
- Commonly, the grid lines are thin and light with every fifth vertical and horizontal line being thicker and darker. Thin or light lines make up "small" boxes within the grid; thick or dark lines make up "large" boxes within the grid (**Figure 4-1**).
  - o Each small box is 1 square millimeter (1 mm^2); that is, 1 mm high and 1 mm wide.
  - o Each large box is 25 square millimeters (25 mm^2); that is, 5 mm high and 5 mm wide.
- Measure vertically in millimeters when measuring amplitudes of waveforms and elevation or depression of segments on the ECG (Figure 4-1).
  - o If there is no electrical activity at that time during a heartbeat, there would be no deflection above or below the baseline. The ECG at that point is said to be *isoelectric*.

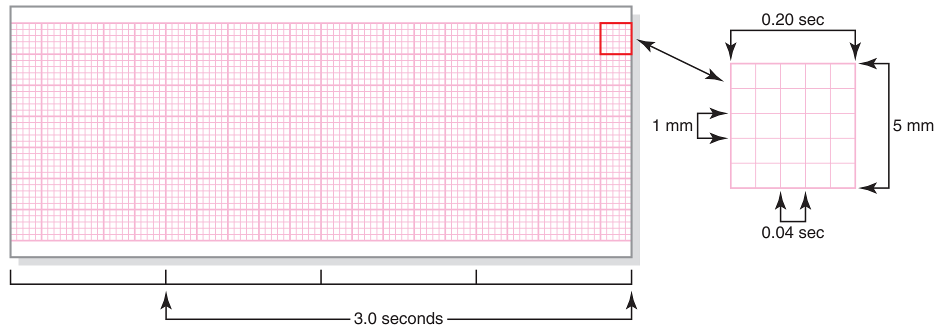

Figure 4-1
ECG paper.

  - o *Positive deflection* is above the baseline and represents electrical activity from the base to the apex of the heart. It is in line with movement from the negative pole to the positive pole of the lead and is aligned with the axis of the heart (discussed later).
  - o *Negative deflection* is below the baseline and represents electrical activity from the apex to the base of the heart and opposite to the axis of the heart. It is in line with movement from the positive pole to the negative pole of the lead (discussed later).
  - o *Biphasic deflections* are continuous waveforms that have both a positive and negative deflection. If the waveform is equally positive and negative, the waveform is said to be *equiphasic*.
- When measuring horizontally the width of intervals, waveforms, complexes, or segments, we measure in time (Figure 4-1). The time of each small box is 0.04 seconds (40 ms, or 1/25 of a second) and each large box is 0.2 seconds (200 ms, or 1/5 of a second). For example, when measuring the interval from the beginning of the P wave to the beginning of the QRS complex, if the width is 4 small boxes, then the actual measurement is 0.16 seconds. If the width was 7.5 boxes, then the measurement is 0.3 seconds. The meaning of these measurements will become evident by the end of the chapter.

ECG PAPER SPEED

To know what paper speed the ECG was recorded at is also essential for accuracy. Every ECG machine has two speeds available for printing. It is imperative to check the speed setting prior to interpreting the ECG. Most 12-lead ECGs will print the speed at the bottom of the printout.

- Standard paper speed is 25 mm/s. All measurements taken horizontally recorded at 25 mm/s are as measured. No adjustments are necessary.
- In some instances when waveforms are "cramped" together, the second speed setting, 50 mm/s, can be used to "spread out" the ECG to make it easier to measure. In this case, all measurements must be cut in half to achieve the natural measurement in

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standardized form. For example, if a QRS complex is measured at 0.06 seconds while recorded at 50 mm/s, the true measure would be 0.03 seconds.

CALIBRATION OF THE ECG

A calibration signal should also be seen on each 12-lead ECG printout. It can be seen at the beginning or the end of each recording.

- The calibration signal is typically 10 mm high and 0.20 seconds long (1 large box). The 10 mm signal represents 1 mV of electricity (**Figure 4-2a**). The calibration signal can be doubled or cut in half if needed to better interpret the ECG (**Figure 4-2b**).
  - o If the QRS complexes are too big and run into each other on a 12-lead ECG, it is advantageous to reduce the calibration signal to 0.5 mV, making the signal 5 mm high. If an R wave is measured at the half calibration, you must double the measurement to achieve the natural value. For example, if an R wave was measured at 22 mm at 0.5 mV, the actual measurement would be 44 mm.
  - o If the QRS complexes are too small, it is advantageous to double the calibration signal to 2 mV, making the signal 20 mm high. If an R wave is measured at 36 mm at 2.0 mV, the actual measurement would be 18 mm.
- If the calibration signal box is 0.40 seconds wide instead of 0.20 seconds, this may be an indication that the paper speed is set to 50 mm/s.

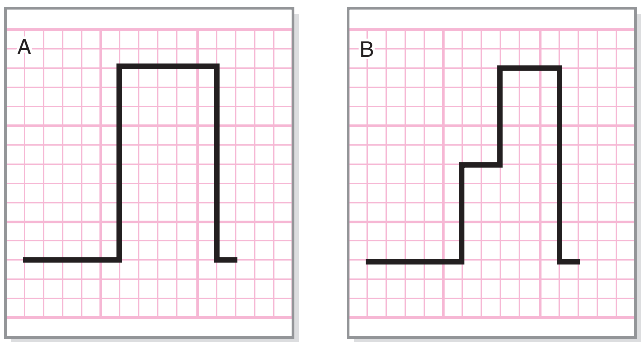

Figure 4-2
A) Standard calibration 1mV = 10mm. B) Half calibration 0.5mV = 5mm.

STANDARD 12-LEAD PRINTOUTS

A full 12-lead ECG printed at 25 mm/s and using the standard calibration signal of 1 mV/10 mm will be 12 seconds long. All 12 leads are seen on each ECG printout. **Figure 4-3** displays the standard format for the leads on a 12-lead printout. The classic presentation is three lines of four leads horizontally (I, aV_R, V_1, and V_4 on the first line; II, aV_L, V_2, and V_5 on the second line; and III, aV_F, V_3, and V_6 on the third line). The four leads across are separated by lead dividers that should not be considered in the interpretation, even if a cardiac cycle falls on a divider. While this is the classic presentation, the natural way to read the 12-lead ECG is to read down

Clinical Tip

Wave Amplitudes and Automated Blood Pressures

If a patient's QRS complexes are very small, it is helpful to double the calibration signal to 20 mm in height. Most ECG machines can be easily adjusted to reflect this calibration signal. It is even more important to do this if trying to use an automatic blood pressure machine during exercise or at rest.

- Automatic machines typically use the R waves to determine the rate.
- If the R wave deflection is not sufficient, the rate will not be read, and the blood pressure recorded will be inaccurate.
- Sometimes when the calibration signal is doubled the R wave is still insufficient to determine the rate, so blood pressures must be taken manually at rest and during exercise. If possible, the same technician should take both blood pressures.

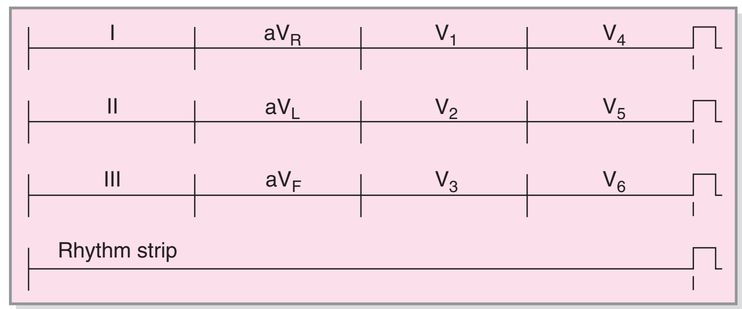

Figure 4-3
Standard 12-lead ECG printout.

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each column (separated by the lead dividers). Column one contains the bipolar limb leads I, II, and III. Column two contains the unipolar limb leads aV_R, aV_L, and aV_F. Column three contains the chest leads V_1, V_2, and V_3; while column four contains the chest leads V_4, V_5, and V_6. Usually a rhythm strip of one or more leads appears just below the 12-lead printout. Usually, lead II is the lead exhibited.

- Each horizontal lead strip is 3 seconds long and separated by lead dividers.
- The rhythm strip line across the bottom is 12 seconds long and can be used to determine the rate and rhythm. It is best not to use the lead strips to determine rate or rhythm.
- The rhythm strips are coordinated, meaning that the strips above and below are showing electrical activity of the heart at the same time as the compared rhythm strip.

CALCULATION OF HEART RATE

Three methods are available for determining heart rate (HR) from an ECG printout. Two are used when the HR is regular (i.e., the RR intervals line up) and one is used when the HR is irregular. To determine regularity of the HR, line up calipers on two consecutive R waves and then rotate the calipers down the strip. If all the R waves line up, the HR is regular. Depending on the method used, HR calculations can be extremely accurate or a close estimate.

DARK LINE METHOD

The **dark line method** can only be used when the HR is regular. This method can be a very accurate way to determine HR or to generate a close estimate.

- On a rhythm strip, find one R wave that falls directly on a dark thick line. The subsequent dark thick lines each have an associated HR. In order, the HRs are 300, 150, 100, 75, 60, 50, 44, and 38 beats per minute (bpm). There is no need to go any lower than 38! Find the next R wave (**Figure 4-4a**).
- If the first R wave after the starting point is exactly on the first dark thick line, the HR is 300 bpm (60 s/min divided by 0.20 s/beat); on the second dark thick line, the HR is 150 bpm (60 s/min divided by 0.40 s/beat); on the third dark thick line, the HR is 100 bpm (60 s/min divided by 0.60 s/beat); on the fourth dark line, the HR is 75 bpm (60 s/min divided by 0.80 s/beat, **Figure 4-4b**), and so on.
- If both R waves fall directly on dark thick lines, this method is extremely accurate. If the second R wave falls between dark lines, the HR can quickly be estimated. For example, if the second R wave falls between the third and fourth dark lines, the HR is somewhere between 75 and 100 bpm.

THE 1500 METHOD

Like the dark line method, the **1500 method** can only be used when the HR is regular. The 1500 method is considered the most accurate way to calculate HR from the ECG.

- Find two consecutive R waves on the rhythm strip and count the number of small boxes between them (**Figure 4-5**).
- Divide 1,500 (60 seconds divided by 0.04 s/small box = 1,500) by the number of small boxes counted.
  - o Thus, for 17 small boxes counted between two consecutive R waves: 1,500/17 = 88 bpm.

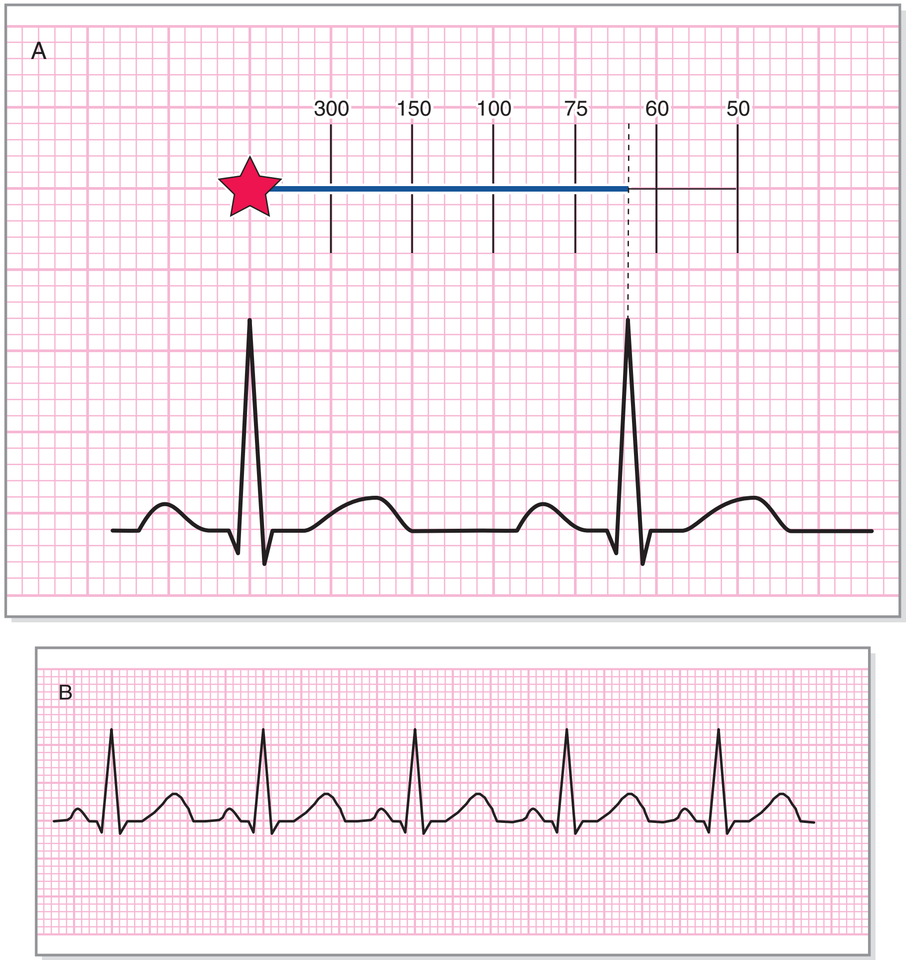


Figure 4-4
A) The dark line method of heart rate determination. B) The second consecutive R wave falls on the fourth dark line; therefore, HR = 75 beats per minute.
Reproduced from *Arrhythmia Recognition: The Art of Interpretation*, courtesy of Tomas B. Garcia, MD.

Clinical Tip

Quick Check Method

The dark line method serves as a great quick check for exercising cardiac rehabilitation patients.

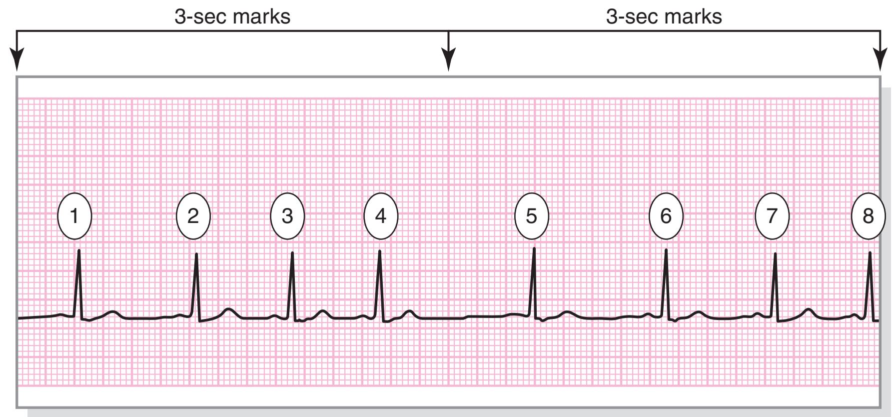
- If the patient's target HR for exercise is 96–102 bpm, it is very easy to see if he or she is in range.
- If the second R wave falls at least two small boxes before the third dark line, then the HR is faster than 102 bpm. This becomes evident if the patient is complaining of symptoms.
- If the second R wave falls at least two small boxes after the third dark line, then the HR is slower than 96 bpm, and as long as the patient is symptom free, the workload can be adjusted as needed.

THE 6-SECOND METHOD

The **6-second method** is used when the RR intervals are irregular (**Figure 4-6**).

- First, determine a 6-second period: 6 seconds = 30 large boxes or the distance between three 3-second marks at the top or bottom of the rhythm strip.
  - o 6 seconds divided by 0.20 s/box = 30 boxes
- Count the number of cardiac cycles in that 6-second period.

Figure 4-5
1500 Method of HR Calculation
There are 17 small boxes between two consecutive R waves; therefore, 1,500/17 = 88 beats per minute.
Reproduced from *Arrhythmia Recognition: The Art of Interpretation*, courtesy of Tomas B. Garcia, MD.



There are 8 cardiac cycles within this six-second strip. Therefore, the HR = 80 bpm (8 cycles × 10 seconds)

Figure 4-6
6-Second Method of Irregular Heart Rate Calculation
This 6-second strip shows eight cardiac cycles; therefore, heart rate = 80 beats per minute. (bpm) (8 cycles × 10 seconds).

- Multiply the number of cycles by 10 to estimate HR.
- A 3-second strip (15 large boxes) may also be used to determine the HR for 30 seconds. Just double the calculation to determine the HR in beats per minute.

DEVELOPMENT OF THE 12 LEADS

The heart produces electrical activity, and the ECG is the means for measuring that activity. In order to measure the electrical activity, electrodes must be placed at specific points on the body and chest wall. Dr. Willem Einthoven, the Dutch physician who created the ECG, developed the lead system at the beginning of the 20th century and standardized lead placement. Ten electrodes are placed on the body to record a 12-lead ECG. These 12 leads are divided into 6 limb, or extremity, leads (3 bipolar and 3 unipolar), and 6 precordial, or chest (ventral), leads.

BIPOLAR LIMB LEAD DEVELOPMENT (EINTHOVEN'S TRIANGLE)

Four electrodes (right arm [RA], left arm [LA], right leg [RL], and left leg [LL]) are placed either on the extremities or the torso, depending on whether a diagnostic or functional placement is needed. For a diagnostic placement, which is usually used in a physician's office during a physical examination, the electrodes are placed on the extremities (**Table 4-1**). The functional placement—the Mason-Likar[1] placement—is

Table 4-1 Electrode Placement of 10 Electrodes for 12-Lead ECG: Functional Versus Diagnostic

Electrode	Functional (Mason-Likar) Placement	Diagnostic Placement
Right arm (RA)	Right subclavicular fossa, usually at middle of right clavicle	Right arm
Left arm (LA)	Left subclavicular fossa, usually at middle of left clavicle	Left arm
Right leg (RL)	Lateral of the rectus abdominus, superior to iliac crest, inferior to the bottom rib, usually along the umbilical line on right side of torso	Right leg
Left leg (LL)	Lateral of the rectus abdominus, superior to iliac crest, inferior to bottom rib, usually along the umbilical line on left side of torso	Left leg
V_1	4th intercostal space just to right of sternum	Same
V_2	4th intercostal space just to left of sternum	Same
V_3	Midpoint between V_2 and V_4	Same
V_4	Level with V_4 or 5th intercostal space in line with midclavicular line	Same
V_5	Level with V_4 or 5th intercostal space in line with anterior axillary line	Same
V_6	Level with V_4 or 5th intercostal space in line with midaxillary line	Same

traditionally used for exercise testing because the electrodes are placed on the torso (Table 4-1) to allow for freedom of movement. Once the limb-lead electrodes are placed, the electrical activity recorded between two specific electrodes defines leads I, II, and III. Each lead has a positive pole and a negative pole.

- Lead I displays electrical flow through the heart in line with movement from the RA electrode (negative pole) to the LA electrode (positive pole). In other words, the electrical activity measured at the RA electrode is subtracted from the electrical activity measured at the LA electrode (LA – RA). The result is the waveform manifested in lead I. A positive deflection is expected in lead I.
- Lead II displays electrical flow in line with movement from the RA electrode (negative pole) to the LL electrode (positive pole). In other words, the electrical activity measured at the RA electrode is subtracted from the electrical activity measured at the LL electrode (LL – RA). The result is the waveform manifested in lead II. Lead II is normally the limb lead most aligned with the axis of the heart. The most positive deflection of the limb leads is usually expected in lead II; therefore, lead II is commonly used to record the subject's heart rate.
- Lead III displays electrical flow in line with movement from the LA electrode (negative pole) to the LL electrode (positive pole). In other words, the electrical activity measured at the LA electrode is subtracted from the electrical activity measured at the LL electrode (LL – LA). The result is the waveform manifested in lead III. A positive deflection is also expected in lead III.
- The triangle that forms from leads I, II, and III is referred to as **Einthoven's triangle** (Figure 4-7). Einthoven's triangle shows the movement of electricity from the negative to the positive pole as compared to the heart and defines the bipolar limb leads.
- The RL electrode serves as a ground and therefore is not associated with any electrical movement.

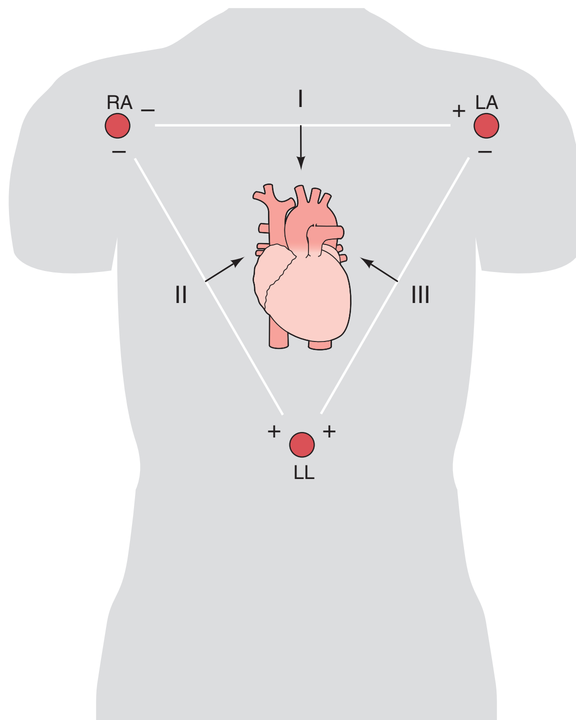


Figure 4-7
Einthoven's triangle.

Remember way back in the first grade when you learned that 1 + 2 = 3? Well, in Einthoven's world, 1 + 3 = 2. More specifically, I + III = II. This is Einthoven's equation. What this means, other than tricky math and trying to confuse students of clinical exercise physiology, is that the electrical activity in lead I plus the electrical activity in lead III is equal to the electrical activity in lead II.

- To prove this, recall that lead I = LA – RA, lead II = LL – RA, and lead III = LL – LA.
- In mathematical terms, if you add leads I and III (LA – RA and LL – LA) the LAs cancel each other out, leaving LL – RA, which is lead II.

$$\begin{aligned} \text{I} &= \boxed{\text{LA}} - \text{RA} \\ \text{III} &= \text{LL} - \boxed{\text{LA}} \\ \hline \text{II} &= \text{LL} - \text{RA} \end{aligned}$$

- So now you are wondering, "how does this help me?" The answer is that the sum of the amplitudes of the R waves in leads I and III must be equal to the height of the R wave in lead II (**Figure 4-8**). If this does not hold true, then there is usually a problem with the placement of the electrodes.

UNIPOLAR LIMB LEAD DEVELOPMENT

Unipolar limb leads are also called *augmented vector leads* because they are developed from a combination of leads. The unipolar limb leads use the RA, LA, or LL electrodes as the positive pole and the combination of the other two as the negative pole, which augments the signal strength from the measuring electrode.

Figure 4-8
Einthoven's Equation I + III = II
The R wave in I (4 mm) + the R wave in III (10 mm) = the R wave in II (14 mm).
Reproduced from Klabunde, RE. Cardiovascular Physiology Concepts: Electrocardiogram Standard Limb Leads (Bipolar). http://www.cvphysiology.com/Arrhythmias/A013a.htm. Accessed on March 16, 2014.

- The augmented vector foot lead (aV_F) is measured from the positive LL electrode to the negative electrode, which is a combination of the RA and LA electrodes.
  - aV_F shows the flow of electrical activity from the arms (negative pole) to the left leg (positive pole).
- The augmented vector left arm lead (aV_L) is measured from the positive LA electrode to the negative electrode, which is a combination of the RA and LL electrodes.
  - aV_L displays a flow of electrical activity from the LL and RA electrodes (negative pole) to the LA electrode (positive pole).
- The augmented vector right arm lead (aV_R) is measured from the positive RA electrode to the negative electrode, which is a combination of the LA and LL electrodes.
  - aV_R shows a flow of electrical activity from the LL and LA electrodes (negative pole) to the RA electrode (positive pole).
  - aV_R is a mirror image of other leads, whose orientation is leftward.
  - The QRS complex in aV_R is expected to have a net negative deflection because the axis of the lead is opposite to the flow of electrical activity through the heart.

HEXAXIAL REFERENCE SYSTEM

The **hexaxial reference system** is a diagram that shows the relationship of the six limb leads in the frontal plane and helps to determine the heart's electrical axis (**Figure 4-9**). This will become more evident in the section on the mean QRS axis and axis deviation. At this point, just get a feel for the diagram:

- Identify where the negative and positive poles of each lead lie.
- Determine what positive poles of different leads are located together in the same region.
- Identify the angle associated with the positive and negative pole of each lead. Notice that positive poles do not always associate with a positive angle. The positive pole of aV_L is located at –30 degrees and the negative pole of aV_R is at 30 degrees.

The hexaxial reference system can also be used to help determine why there are positive or negative deflections of the QRS complex in the limb leads. Three rules can be used to help determine the direction of deflections:

- *Rule 1*: If the flow of the depolarization is toward the positive pole of a specific lead, you will see a positive deflection in that lead.
- *Rule 2*: If the flow of the depolarization is toward the negative pole (or away from the positive pole) of a specific lead, you will see a negative deflection in that lead.
- *Rule 3*: If the flow of the depolarization is 90 degrees from a specific lead, you will see an equiphasic (biphasic) deflection in that lead.

Now obviously, you cannot look at patients and tell them how their heart is depolarizing. And you should not have to. The ECG is the final product, and that tells us how the heart is depolarizing, or the mean QRS axis (discussed later).

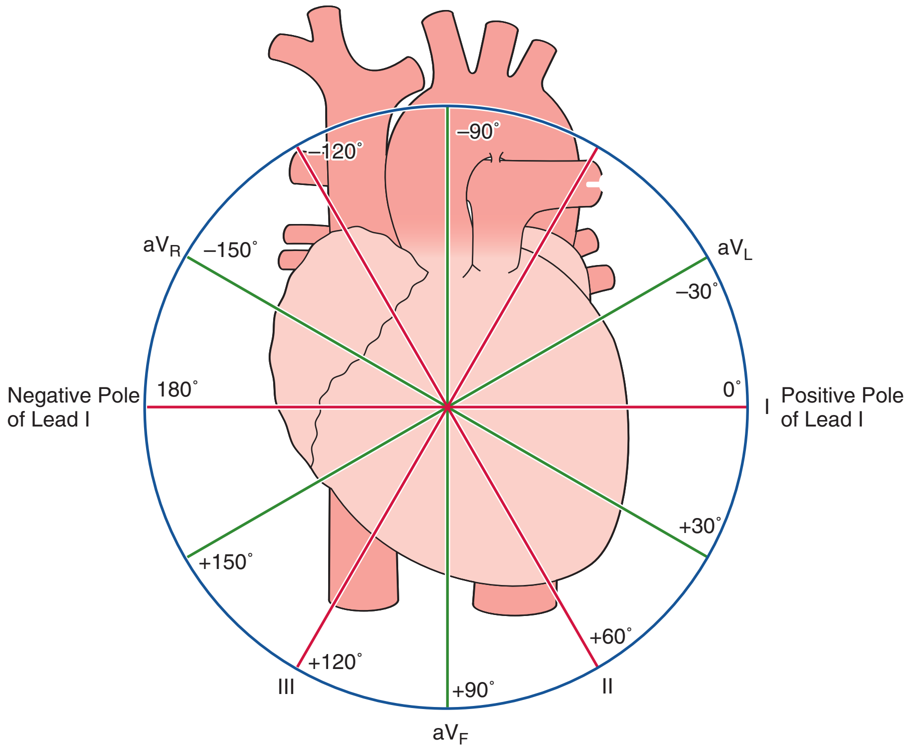


Figure 4-9
Hexaxial reference system.

PRECORDIAL LEADS

The **precordial leads** are produced using the horizontal plane instead of the frontal plane used for the hexaxial system. The precordial leads are the actual electrodes that are placed on the chest wall. These leads sit on the chest and record electrical activity from an imaginary negative pole in the center of the heart to the lead (positive pole). Because these electrodes are in close proximity to the heart, they directly measure the heart's activity. The chest leads are also termed *ventral* (V) leads, and are therefore named V_1, V_2, V_3, V_4, V_5, and V_6 (Table 4-1).

- V_1 is termed the first ventral, or precordial, lead and represents electrical activity from the right side of the septum.
- V_2 is the second precordial lead and represents electrical activity from the anterior side of the heart and the septum.
- V_3 is the third precordial lead and represents electrical activity from the anterior region of the heart.
- V_4 is the fourth precordial lead and represents electrical activity from the anterior region as well.
- V_5 is the fifth precordial lead and represents electrical activity from the lateral region of the heart.
- V_6 is the sixth precordial lead and represents electrical activity from the lateral region as well.

PRECORDIAL LEADS IN THE HORIZONTAL PLANE

Just as the limb leads are represented by the hexaxial reference system in the frontal plane, the precordial leads show the flow of electrical activity through the heart in the horizontal plane (**Figure 4-10**). Electrical activity will flow from a negative

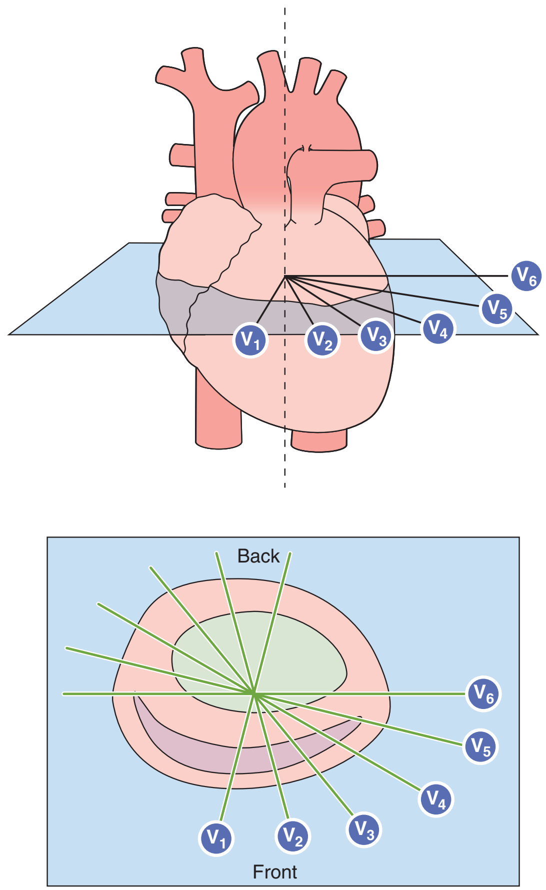


Figure 4-10
Precordial leads in the horizontal plane.

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pole around the center of the heart toward the positive pole, which is the position of the electrode on the chest wall. Additionally, like the hexaxial diagram, flow of the depolarization toward a positive pole will produce a positive deflection in that chest lead.

THE NORMAL CARDIAC CYCLE

In order to have normal sinus rhythm (NSR), the flow of depolarization through the heart must be downward and to the left. If this occurs, the flow of depolarization is in the direction of lead II and in the region of normal axis deviation. In addition, the following must be evident on the ECG:

- Every QRS complex must be preceded by one P wave (1:1 ratio).
- The P wave and QRS complex must be positive in lead II.
- The P wave and QRS complex must be negative in lead aV_R.
- All intervals must be measured within normal limits:
  - o The PR interval must be 0.12–0.20 seconds.
  - o The QRS complex must be ≤ 0.10 seconds.
- Heart rate must be 60–99 bpm.
- Normal axis deviation (NAD) must be present.
- All waveforms must have normal morphology for the leads observed and be identical in every cycle.

Standard waveforms seen in a normal ECG include the P wave, QRS complex, and the T wave (**Figure 4-11**). At times, you might see a U wave after a T wave in a normal ECG. The normal characteristics for each waveform, as well as measurable intervals, will now be discussed. Unless otherwise noted, all descriptions of waveforms in this section will represent how they would be seen in lead II.

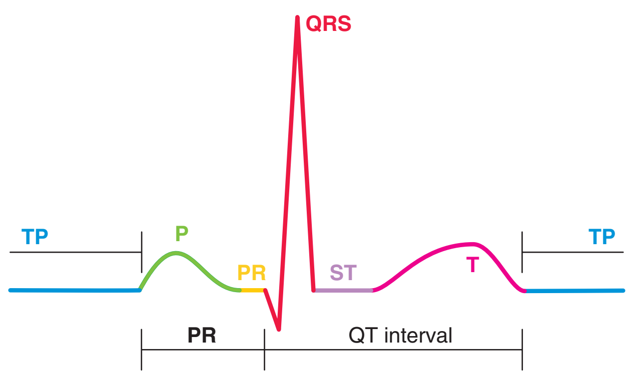

Figure 4-11
Basic ECG of the cardiac cycle.

THE P WAVE

- Generated by atrial depolarization, the **P wave** is the first positive deflection seen in a normal ECG when looking at all leads except aV_R. In aV_R, the P wave is negative (below the isoelectric line).
- Physiologically, the P wave represents conduction of electrical activity from the SA node to the AV node.
  - o The P wave occurs just prior to atrial depolarization and signifies the start of atrial systole, which produces the **atrial kick**. Atrial systole starts when the atrium contract after depolarization.
  - o Atrial kick is used to fill the ventricles with blood before ventricular systole and increases the ventricular end diastolic volume. Atrial kick helps "top off" the stroke volume.
  - o Using the Wiggers diagram as reference, one can see that the mitral valve is open and the aortic valve is closed, allowing the left ventricle to fill (**Figure 4-12**).

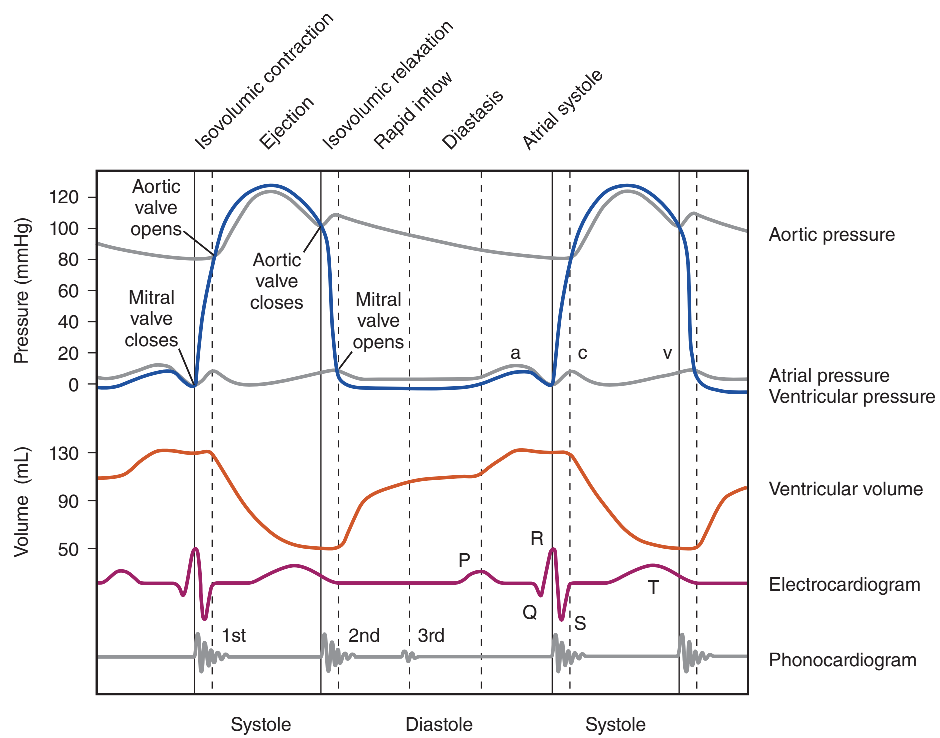

Figure 4-12
Wiggers diagram.

- The P wave should be positive in lead II and negative in aV_R. If the P wave in aV_R is positive and the P wave in lead II is negative, the rhythm originated outside the SA node. This represents what is referred to as a *junctional rhythm*.
- A P wave of varying morphology (biphasic, tall and peaked, or wide and humped) is abnormal and represents various chamber enlargements.
- Normal P wave height is ≤ 2.5 mm (2.5 small boxes) vertically. Normal P wave length is ≤ 0.10 seconds, or 2.5 small boxes horizontally at a paper speed of 25 mm/s.
- The PP interval measures the atrial rate and represents the distance/time between atrial depolarizations or consecutive P waves. The PP interval should be constant; consecutive PP intervals should be within 0.04 seconds of each other, or within 1 small box.

THE PR INTERVAL

The **PR interval (PRI)** is measured from the beginning of the P wave to the beginning of the QRS complex (**Figure 4-13**).

Figure 4-13
The PR Interval
The PR interval is 0.16 seconds measured from the beginning of the P wave to the beginning of the QRS complex.

- If a Q wave is present, the measurement stops at the beginning of the Q wave.
- If no Q wave is present, the measurement goes to the beginning of the R wave.

Physiologically, the PRI is the time it takes the electrical impulse to move from the SA node to the AV node and through to the Purkinje fibers.

- Specifically, the PRI is the time it takes from the beginning of atrial depolarization to the beginning of ventricular depolarization. A common misconception is that the PRI is just the time it takes for the atria to depolarize. Because the measurement goes beyond the P wave, there is more involved than just atrial depolarization.
- The normal PRI should be 0.12–0.20 seconds.
- A PRI < 0.12 seconds may represent a premature beat or beats originating from somewhere above the AV junction.
- A PRI > 0.20 seconds may represent a conduction disturbance of the impulse trying to pass through the AV junction.
- A slight delay in electrical conduction occurs when the impulse reaches the AV node.
    - This allows the atrial kick to occur. Without this delay, the atrium and the ventricles would contract at the same time, and cardiac output would be compromised.

QRS COMPLEX

The **QRS complex** is generated by ventricular depolarization. Because the left ventricle possesses greater muscle mass and is generally larger than the right ventricle, the left ventricle is electrically dominant over the right ventricle; thus the QRS complex will reference conduction of electrical activity through the left ventricle. Physiologically, the QRS complex represents the time for complete ventricular depolarization.

- The QRS complex is measured from the beginning of the complex (Q or R) to the end of the complex (R or S) (**Figure 4-14**). In some complexes, additional R or S waves may be present. These subsequent waves are referred to as R or S prime (R′ or S′) (**Figure 4-15**).
- The normal QRS complex should be 0.06–0.10 seconds (1.5–2.5 small boxes).

QRS Complex Nomenclature

The QRS complex can have many different appearances depending on the specific lead. In addition, identification of the correct waveforms in the QRS complex can help to recognize certain arrhythmias. Therefore, it is imperative to understand the nomenclature of the QRS complex.

- After the P wave, if the initial deflection is negative, it is a Q wave.
    - Q waves may or may not be seen in a normal ECG. In some leads, Q waves are normal, whereas in others they may be abnormal.
    - A Q wave of wider than 0.03 seconds or greater than one-third the amplitude of the R wave is referred to as clinically significant and is considered abnormal (**Figure 4-16**).

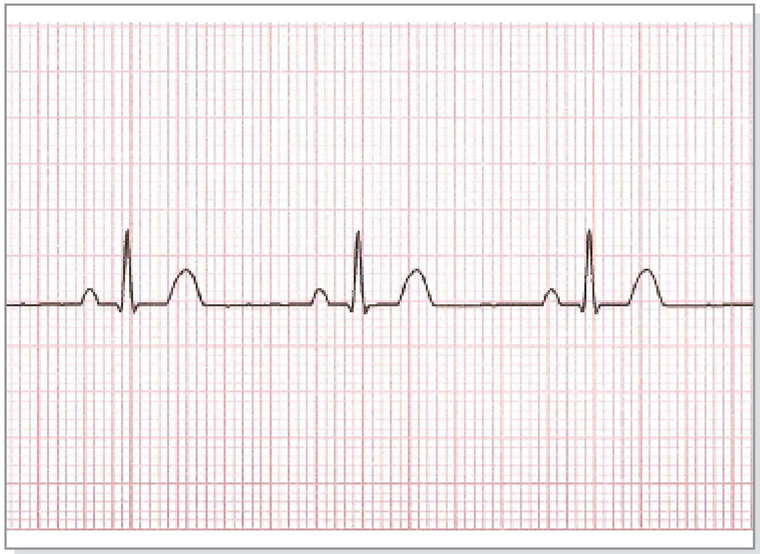

Figure 4-14
The QRS Complex
The QRS complex is 0.10 seconds from the beginning of the QRS complex to the end of the complex.

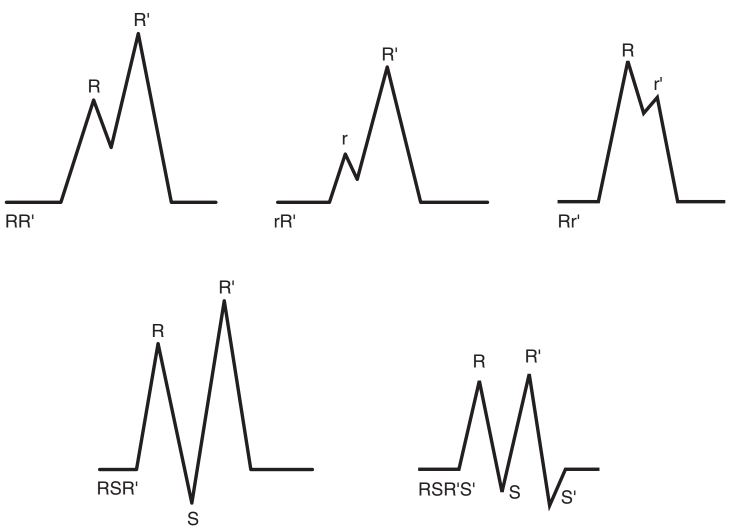

Figure 4-15
QRS Nomenclature
Reproduced from *Introduction to 12-Lead ECG: The Art of Interpretation*, courtesy of Tomas B. Garcia, MD.

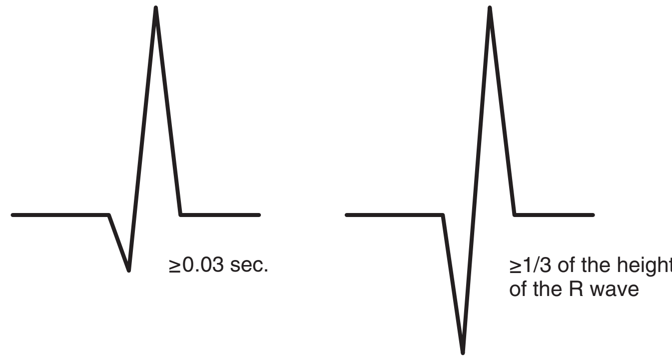

Figure 4-16
Abnormal (significant) Q waves.
Reproduced from *Introduction to 12-Lead ECG: The Art of Interpretation*, courtesy of Tomas B. Garcia, MD.

- After the P wave, if the initial deflection is positive or if there is any positive deflection after a Q wave, it is an R wave.
- Any negative deflection after an R wave is an S wave.
- Generally, just to help identify the amplitudes of waves, a lowercase letter signifies a wave of ≤ 3 mm, whereas uppercase letters identify waves > 3 mm.

The Normal QRS Complex in the Precordial Leads

Ventricular depolarization consists of two stages. In the first stage, because the left bundle branch is closer to the bundle of His, the impulse reaches the left bundle branch first, initiating septal depolarization from left to right. In the second stage, the right and left ventricles simultaneously depolarize from the inside out. However, because the left ventricle is more electrically dominant, the impulse travels toward the left ventricle.

Recall the spatial diagram of the precordial leads in the horizontal plane (Figure 4-10). Based on the rules of ECG and the flow of current in the normal heart, it can be determined what the QRS complex will look like in V_1 and V_6. During the first phase of ventricular depolarization, the septum depolarizes left to right.

- In V_1, the impulse is traveling slightly toward the positive pole of V_1; therefore, a small positive r wave (septal r) will be exhibited in V_1.
- In V_6, the impulse is traveling away from the positive pole of V_6; therefore, a small negative q wave (septal q) will be exhibited in V_6.

During the second phase of ventricular depolarization, the ventricles depolarize simultaneously from the inside out, with the impulse traveling toward the left ventricle due to its size and electrical dominance.

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- In V_1, the impulse is traveling away from the positive pole of V_1; therefore, a negative deflection (S wave) occurs. Consequently, the traditional QRS complex in V_1 is rS.
- In V_6, the impulse is traveling toward the positive pole of V_6; therefore, a positive deflection (R wave) will occur in V_6. Consequently, the traditional QRS complex in V_6 is qR or qRs.

Within the QRS complex, the R and S waves possess some attributes that should be highlighted:

- The R wave represents conduction of electrical activity through the ventricles from the Purkinje fibers to the endocardium.
- R wave peak time is the time from the start of the QRS complex to the end of the R wave (beginning of negative deflection of the S wave). This is equivalent to the time it takes for the electrical signal to spread from the endocardium (Purkinje fibers) to the epicardium.
  - o It is expected to be shorter in V_1 and V_2 (right precordial leads) because the right ventricular wall is thinner than the left ventricular wall. The left ventricle has more muscle mass than the right ventricle.
- The S wave represents conduction of electrical activity away from the apex of the ventricles to the base of the ventricles via intracardiac conduction of the electrical signal. Movement of the signal flows from the endocardium to the epicardium.
- At the end of the S wave and the start of the ST segment is the *J point*. This is where ST segment elevation or depression should be measured on an ECG.

ST SEGMENT

The **ST segment** is the period between the end of the S wave and the start of the T wave. During this time, there is no electrical activity going on in the heart. Thus, the ST segment should be at the isoelectric line, or at the baseline.

- Using Wiggers diagram to compare ventricular activity with electrical conduction, the ST segment is a time when myocardial contraction is continuing to occur and ventricular volume is decreasing as compared to diastole.
- The ST segment correlates with early systole and high ventricular systolic pressures—at the time and just after the aortic valve opens.
- The TP segment should be used to determine if the ST segment is at the isoelectric line, elevated, or depressed (**Figure 4-17**). The PR segment can also be used but must be consistent when reading all leads of the 12-lead ECG.
- With early repolarization or left ventricular hypertrophy, the ST segment may deviate in the limb leads or the right precordial leads.
- The J point is where the QRS complex ends and the T wave starts.
- It is sometimes difficult to identify a J point due to ST segment deviation.

Depression

- ST depression is evidence of potential CAD or old myocardial injury.
- Depression is a sign that the electrical signal is taking longer to move through the myocardium.

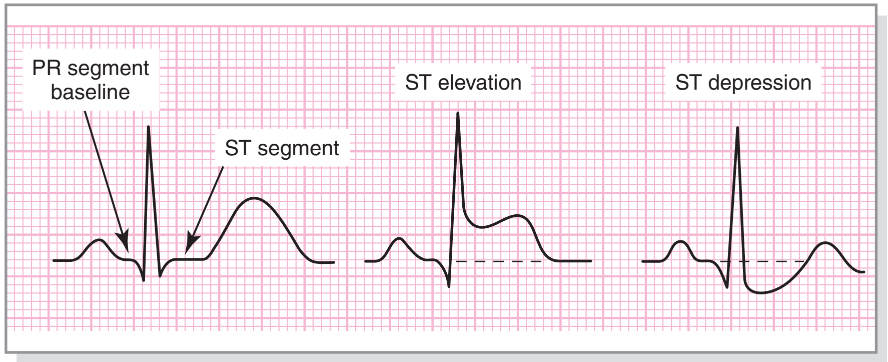

Figure 4-17
ST Segment
ST segment variations from baseline greater than 1 mm constitute ST elevation or ST depression.
Reproduced from Grauer, K. ECG Interpretation Review #34 (Acute MI - vs Nonspecific Changes - ST Elevation/Depression). http://ecg-interpretation.blogspot.com/2012/01/ecg-interpretation-review-34-acute-mi.html. Accessed on March 21, 2014.

- ST depression seen during exercise testing is evidence of possible myocardial ischemia.
- ST depression is also seen in ventricular hypertrophies and bundle branch blocks.

Elevation

- ST elevation is evidence of a recent or impending myocardial infarction.
- Elevation is a sign that the myocardium is not receiving blood to supply oxygen and other needed nutrients.
- Elevation can be seen in aV_R in right bundle branch block and is expected to be seen if the right bundle branch produces ST depression in the other augmented leads and V_1–V_3.
- If ST elevation is seen due to a myocardial infarction, ST depression should be seen in reciprocal leads.
- Any ST segment elevation seen during exercise testing is cause for immediate concern, especially if a patient is symptomatic. It could represent myocardial injury or infarction and should be thought of until proven differently.

T WAVE

The **T wave** represents ventricular repolarization of the heart and the end of ventricular systole. After the T wave the heart begins to relax. Relaxation of the heart occurs during diastole and can be seen in the Wiggers diagram from the end of the T wave to the start of the next QRS complex; the ventricles are isoelectrically inactive during this time period.

- The T wave is the positive deflection after the S wave (in lead II), but it can be negative if the QRS complex is negative in that lead.
  - o The T wave should be in the same direction as the QRS complex. Repolarization of the heart occurs in the same electrical fashion as depolarization, so one would expect the T wave to be in the same direction as the QRS complex.
  - o Ventricular repolarization travels from the epicardium to the endocardium and is seen by a positive deflection in lead II. The negative repolarization signal moves toward the negative pole of the electrode, thus creating a positive deflection.
- The T wave is typically thought of as the end of systole and the start of diastole.
- The time from the end of the QRS complex to the peak height of the T wave is the *absolute refractory period*. The *relative refractory period* is the time from the peak height of the T wave to the end of the T wave.
- Normal T waves are asymmetrical, with the upstroke being slow and the down stroke being fast (**Figure 4-18**).
- T waves are important indicators of different pathologies. One can describe T waves by symmetry, skewness, ascending and descending limb slope, and subintervals.
  - o Symmetrical T waves may be normal variant, but they are often pathologic.
  - o Tented, or peaked, T waves are a sign of hyperkalemia. The ascending and descending limb slopes of the T wave are highly positive (ascending) or negative (descending), thus the tent shape of the T wave.

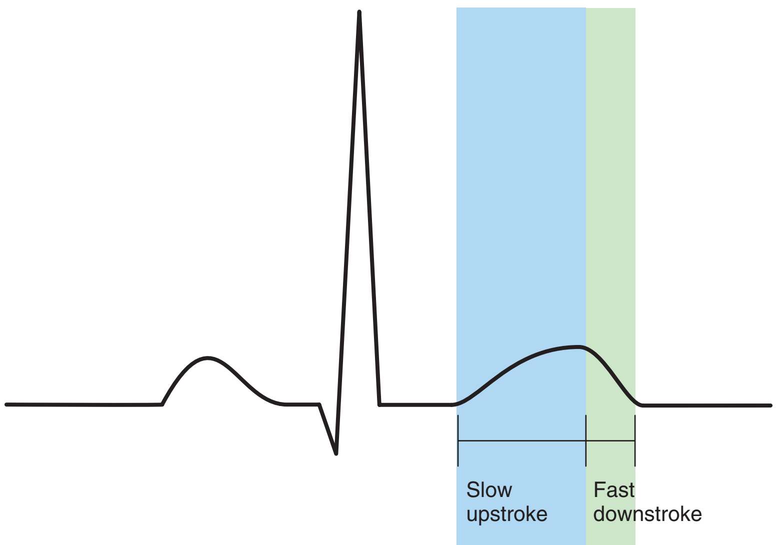

Figure 4-18
T wave.
Reproduced from *Introduction to 12-Lead ECG: The Art of Interpretation*, courtesy of Tomas B. Garcia, MD.

- An inverted T wave is clinically significant if seen in more than one lead (i.e., coronary ischemia, left ventricular hypertrophy). Commonly seen in aV_R, it can also be seen isolated in leads III, aV_F, or aV_L.

U WAVE

The **U wave** is rarely seen in a normal ECG. If seen, it is the last small, rounded, upward deflection in lead II. It represents the last stages of ventricular repolarization and could signify the repolarization of the Purkinje fibers or papillary muscles.[2] The U wave is typically not seen in a normal ECG and can be fused with the previous T wave. It can be misclassified as a second T wave (i.e., T1, T wave; T2, U wave).

QT INTERVAL

The **QT interval** is the time period between the start of QRS complex and the end of the T wave. If there is no Q wave present in the QRS complex, the QT interval nomenclature is still used to describe this time interval. The QT interval will vary depending on heart rate; slower heart rates typically have a longer QT intervals.

- The QT interval can be corrected for heart rate. This is represented by QTc.
- **Bazett's formula** is normally used to calculate QTc:[3]
  - o QTc = QT interval/Square root of RR interval
- Updated formula from Sagie and colleagues:[4]
  - o $QT_{LC} = QT + 0.154(1 - RR)$
- Normal QTc is < 0.44 seconds. It should also be less than half the RR interval.
  - o Some consider a normal QTc to be ≤ 0.45 seconds in men and ≤ 0.47 seconds in women.
- Elongated QT intervals increase risk for sudden death and are seen in those with a history of ventricular tachyarrhythmias.
- Serial ECGs can be done to compare QT intervals if there is suspicion of varying QT intervals. Holter monitors are also useful in performing a QT interval analysis over the course of 24 or 48 hours.

AXIS DEVIATION

Axis deviation is used to determine the direction of ventricular depolarization. The atrial axis can be used to determine the flow of atrial depolarization; the largest P wave identifies the general flow of atrial depolarization.

- It is important to determine whether the axis is normal. An abnormal axis can be an indication of an underlying disease state or previous cardiovascular event.
- The axis of the heart can also change depending on whether a patient is seated, standing, or supine.

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CALCULATION OF THE MEAN QRS AXIS

Because it is not possible to just look at a patient and externally determine the direction of the ventricular depolarization **(mean QRS axis)**, the mean QRS axis can be calculated by using the hexaxial reference system and the limb leads (I, II, III, aV_R, aV_L, aV_F) from a completed ECG.

- The hexaxial reference system (Figure 4-9) and the rules presented in the section on the hexaxial reference system can be used to determine the mean QRS axis.
  - Look at the limb leads and find the QRS complex that is equiphasic (equally above baseline and below baseline; e.g., where lead aV_L is 5 mm positive and 5 mm negative).
  - If no leads are equiphasic, the limb lead that is the most equiphasic is used (e.g., if lead II has an 8 mm R wave and a 6 mm S wave and lead aV_F has a 5 mm R wave and a 4 mm S wave, then aV_F is the most equiphasic).
  - Find the equiphasic lead on the hexaxial reference system.
  - Based on rule 3, identify the lead 90 degrees from that lead (e.g., lead II is 90 degrees from aV_L) and look at the ECG.
  - Based on rule 1, if that lead's QRS complex is positive, go toward the positive pole of that lead—the QRS axis is the corresponding degrees.
  - Based on rule 2, if that lead's QRS complex is negative, go toward the negative pole of that lead—the QRS vector is the corresponding degrees.
  - **Figure 4-19** provides examples of this method.
- **Table 4-2** identifies axis deviation by calculating the mean QRS axis.
  - Normal axis deviation (NAD) is indicated when the QRS axis is 0 to 90 degrees ± 15 degrees in either direction (i.e., –15 to 105 degrees).
  - If the mean QRS axis is > 15 degrees negative (–15 to –90 degrees), the ECG reveals **left axis deviation (LAD)**.
  - If the mean QRS axis is > 105 degrees, the ECG displays **right axis deviation (RAD)**.
  - If the mean QRS axis is between –90 degrees and +180 degrees, the axis is understood to be indeterminate. The terms *extreme left axis* and *extreme right axis deviation* are also commonly used.

Table 4-2 Axis Determination Using Vectors

Axis	Degrees
Normal	–15° to 105°
RAD	105° to 180°
LAD	–15° to –90°
Indeterminate	–90° to ±180°

Table 4-3 Two-Lead Method of Axis Determination

I	aV_F	Axis
+	+	Normal
RAD	+	–
LAD	–	+
–	–	Indeterminate

TWO-LEAD METHOD OF AXIS DETERMINATION

The two-lead method is a quick method to determine axis deviation (**Table 4-3**).

- From a completed ECG, look at lead I and lead aV_F to determine whether the QRS complexes in each lead are more negative or positive. (The I and aV_F leads are used because these two leads divide the hexaxial reference system diagram into the four quadrants of axis determination.) Table 4-3 can be used to expedite the two-lead method.
- If the QRS complexes in both leads I and aV_F are more positive than negative, then the axis is normal. Refer to Figure 4-19a. Leads I and aV_F are obviously both positive complexes; therefore, NAD is indicated. Consequently, the calculated mean QRS axis of 30 degrees is confirmed.
- If the QRS complex in lead I is positive and lead aV_F is negative, then LAD is present. Refer to Figure 4-19b. Because lead I is only an R wave, it is positive. Because lead aV_F has a 4 mm R wave and an 8 mm S wave, it is considered negative. Because lead I is positive and lead aV_F is negative, LAD is indicated. Therefore, the calculated mean QRS axis of –45 degrees is confirmed.
- If the QRS complex in lead I is negative and lead aV_F is positive, then RAD is specified. Refer to Figure 4-19c. Lead I has a 3 mm QS and lead aV_F has a 3 mm R wave. Therefore, lead I is negative and aV_F is positive, and RAD is indicated. Thus, the mean QRS calculated between 120 and 150 degrees is confirmed.
- If both leads are negative, indeterminate axis is indicated.

LEFT AXIS DEVIATION

In LAD, the spread of the depolarization moves toward the left, or lateral, aspect of the heart. LAD can be nonpathologic or pathologic:

- In nonpathologic LAD, the mean electrical axis or vector can be between 0 and –30 degrees. The primary cause of nonpathologic LAD can be as simple as an athletic heart or an individual who is endurance trained.
- In pathologic LAD, the mean electrical axis or vector is usually between –30 and –90 degrees. The causes of pathologic LAD are as follows:
  - left anterior hemiblock
  - Q waves of inferior MI

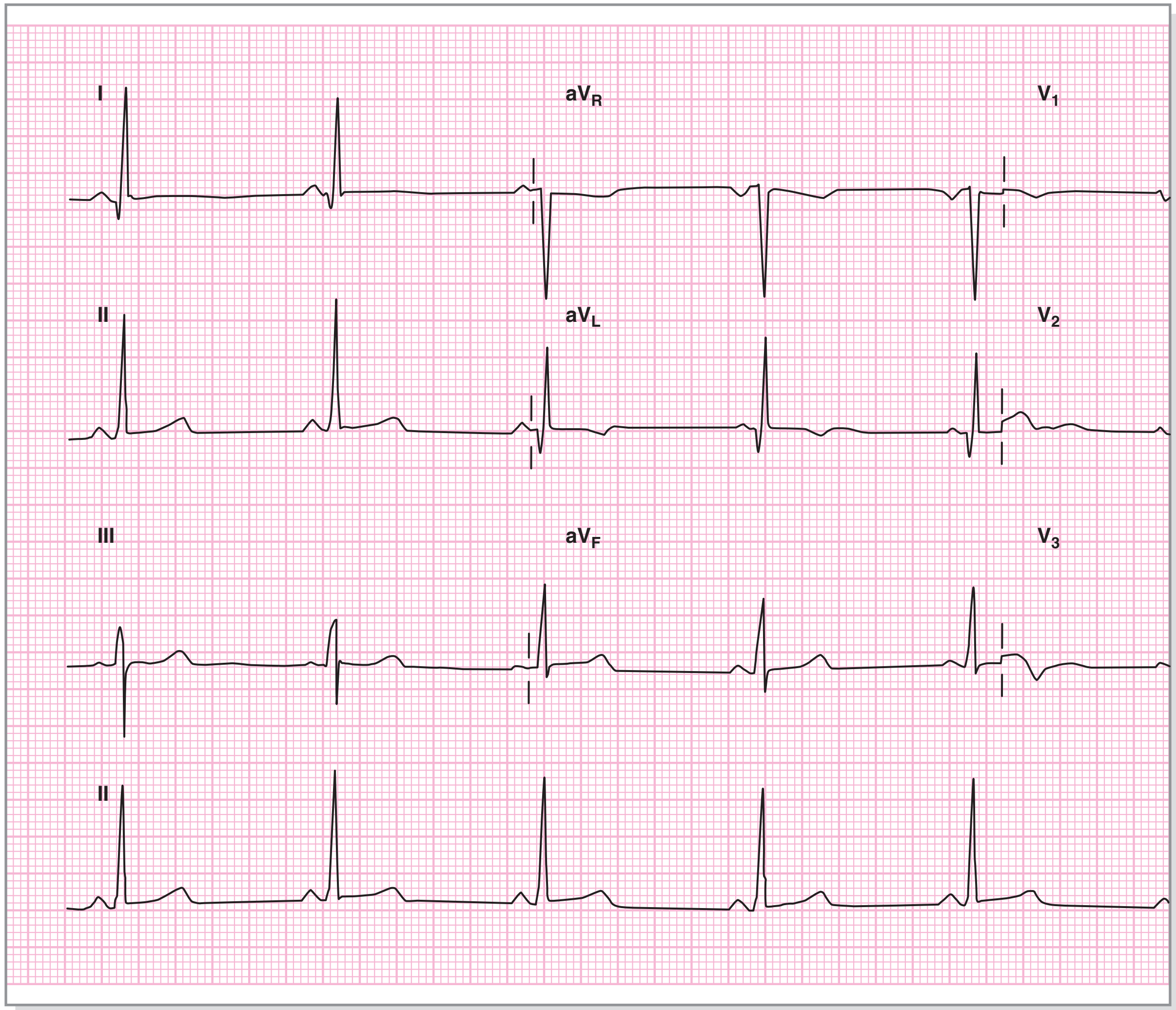

Figure 4-19

Mean QRS Calculation

(a) Example 1: Obviously, lead III is the closest to being equiphasic, so lead aV_R is the 90° lead. Because lead aV_R is negative, the direction of ventricular depolarization is toward the negative pole of lead aV_R and the mean QRS axis is determined to be 30°.

(*continues*)

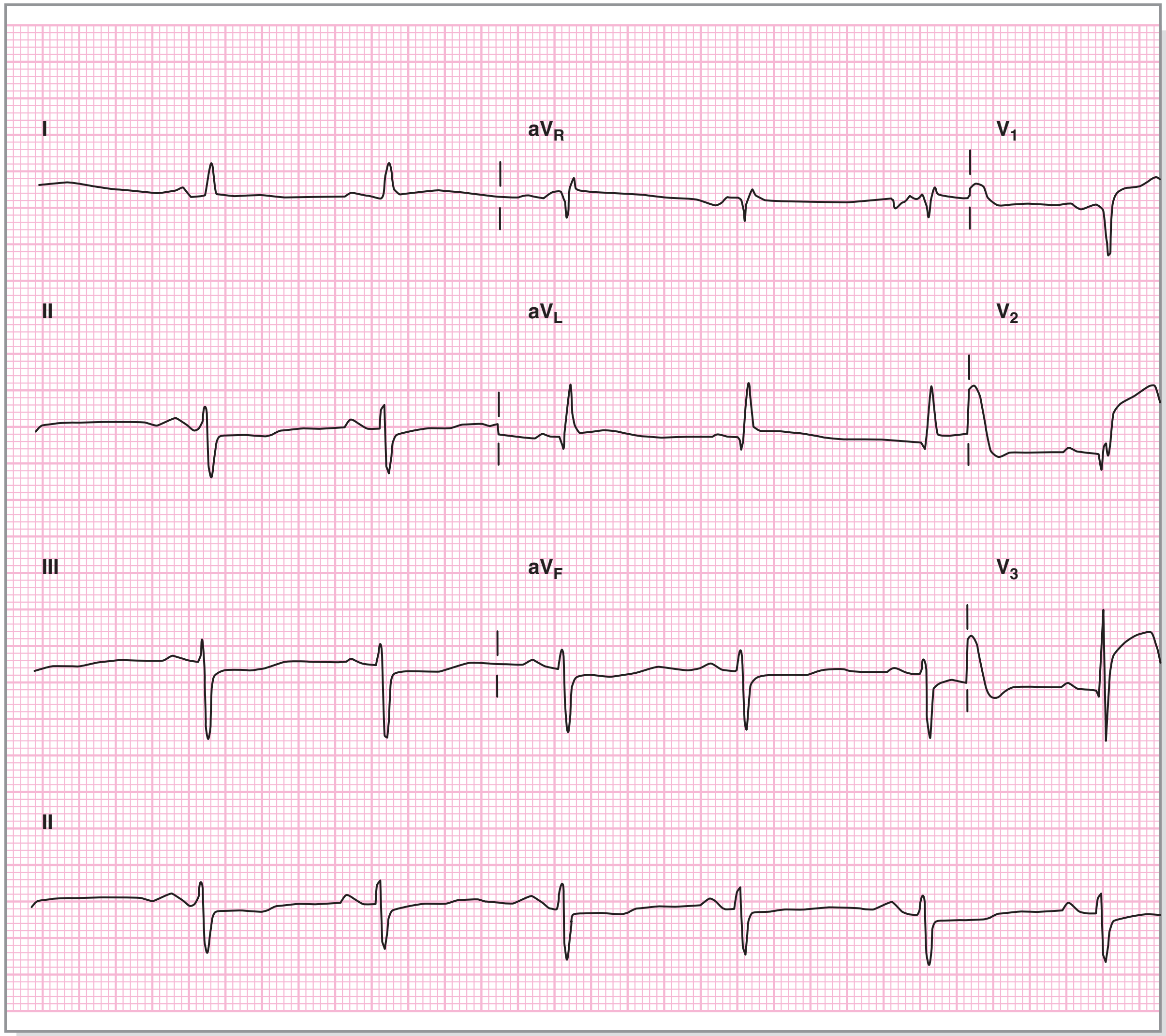

Figure 4-19 ***(continued)***
Mean QRS Calculation

(b) Example 2: There are no perfectly equiphasic leads. Two leads can be considered to be the most equiphasic. The R wave in lead II is 3 mm positive and the S wave is 6 mm negative. The R wave in lead aV_R is 3 mm positive, and the S wave is 4 mm negative. Therefore, aV_R is the most equiphasic and lead III is the 90° lead. Because lead III is negative, the direction of ventricular depolarization is toward the negative pole of lead III, and the mean QRS axis is determined to be −60°.

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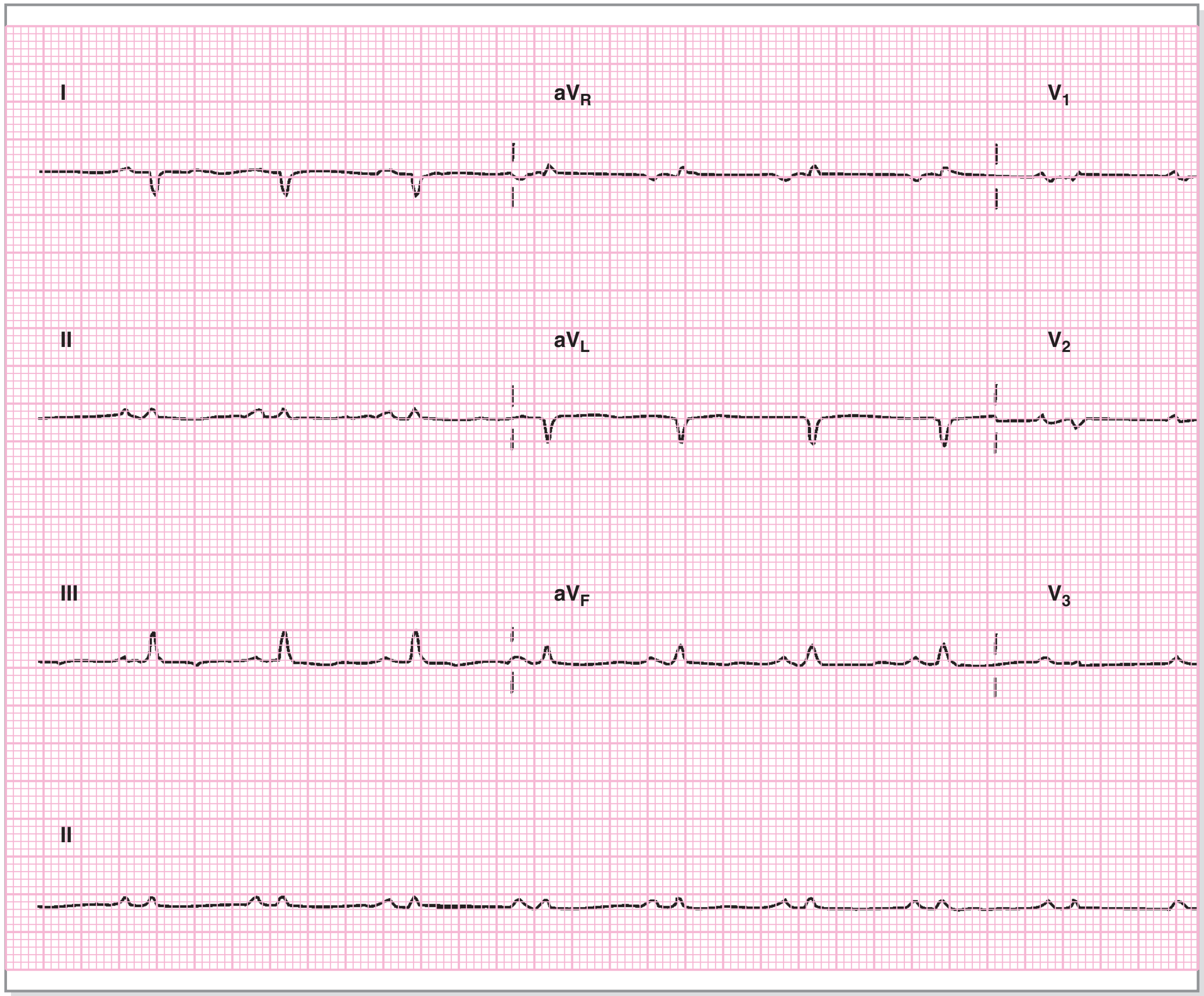

Figure 4-19 (*continued*)

Mean QRS Calculation

Example 3: Again, there are no exactly equiphasic leads. Leads II and aV_R are both 1.5 mm positive and 0 mm negative. Following rule 3, leads aV_L and III are the 90° leads. aV_L is negative and III is positive. Therefore, the mean QRS axis is between 120° and 150°.

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- pacemaker
- hyperkalemia
- Wolff-Parkinson-White right-sided bypass
- tricuspid atresia
- atrial septal defect

- Although left ventricular hypertrophy (LVH) may be an indication that LAD is present, it may or may not be a direct cause of LAD.

RIGHT AXIS DEVIATION

- In RAD, the spread of the depolarization moves toward the right ventricle. The mean electrical axis is between 105 and 180 degrees.
- RAD can be caused by the following:
  - right ventricular hypertrophy
  - left posterior hemiblock
  - chronic obstructive pulmonary disease (COPD)
  - anterior lateral MI
  - pulmonary embolism
  - Wolff-Parkinson-White left-sided bypass
  - Marfan syndrome
- Right axis deviation is typically normal in children and in tall, thin adults.

INDETERMINATE AXIS

- In an indeterminate axis, the spread of the depolarization is toward the upper right quadrant of the heart toward the right atrium. This is often referred to as a northwest axis, or "no man's land." The mean electrical QRS axis is between ±180 and −90 degrees.
- An indeterminate axis can be caused by the following:
  - emphysema
  - hyperkalemia
  - lead transposition
  - pacemaker
  - ventricular tachycardia

REFERENCES

1. Mason RE, Likar I. A new system of multiple-lead exercise electrocardiography. *Am Heart J.* 1966;71(2):196–205.
2. Pérez Riera AR, Ferreira C, Filho CF, et al. The enigmatic sixth wave of the electrocardiogram: the U wave. *Cardiol J.* 2008;15(5):408–421.
3. Bazett HC. An analysis of the time-relations of electrocardiograms. *Heart.* 1920;7:353–370.
4. Sagie A, Larson MG, Goldberg RJ, Bengston JR, Levy D. An improved method for adjusting the QT interval for heart rate (the Framingham Heart Study). *Am J Cardiol.* 1992;70(7):797–801.

KEY TERMS

1500 method Heart rate calculation method that can only be used when the heart rate is regular. It is considered the most accurate way to calculate heart rate from the ECG.

6-second method Heart rate calculation method used when the RR intervals are irregular.

atrial kick The increase in ventricular end diastolic volume before ventricular systole.

axis deviation Determination used to assess the direction of ventricular depolarization in the frontal plane.

Bazett's formula Used to calculate QTc, where QTc = QT interval/square root of RR interval. An updated formula from Sagie and colleagues is: $QT_{LC} = QT + 0.154(1 - RR)$.

dark line method Heart rate determination method that can only be used when the heart rate is regular. This method can be a very accurate way to determine heart rate or to generate a close estimate.

Einthoven's triangle An imaginary equilateral triangle formed by the right arm, left arm, and left leg electrodes. It represents the development of the three bipolar limb leads (I, II, and III) of the electrocardiogram.

electrocardiogram (ECG) A noninvasive test that records the heart's electrical activity.

hexaxial reference system Diagram that shows the relationship of the six limb leads in the frontal plane and helps to determine the heart's electrical axis.

left axis deviation (LAD) Represented by a negative lead aV_L and a positive lead I. The two forms are nonpathologic and pathologic. In nonpathologic LAD, the mean electrical axis or vector can be between 0 and −30 degrees. In pathologic LAD, the mean electrical axis or vector is usually between −30 and −90 degrees.

mean QRS axis (vector) Represents the flow of depolarization in the frontal plane. Calculated by using the hexaxial reference system and the limb leads (I, II, III, aV_R, aV_L, aV_F) of completed ECGs.

PR interval (PRI) Distance from the beginning of the P wave to the beginning of the QRS complex.

precordial leads The actual electrodes that are placed on the chest wall to produce the chest (ventral, or V) leads: V_1, V_2, V_3, V_4, V_5, and V_6.

P wave Represents depolarization of the atria.

QRS complex Generated by ventricular depolarization.

QT interval Time period between the start of the QRS complex and the end of the T wave. Represents the start of ventricular depolarization to the end of ventricular repolarization.

right axis deviation (RAD) Spread of depolarization moves toward the right ventricle. The mean electrical axis is between 105 and 180 degrees.

ST segment Period between the end of the S wave and the start of the T wave. The ST segment should be isoelectric or at the baseline.

T wave Represents ventricular repolarization of the heart and the end of ventricular systole.

U wave Rarely seen in a normal ECG. Represents the last stages of ventricular repolarization.

unipolar limb leads Leads aV_R, aV_L, and aV_F. Also called *augmented vector leads*. Developed from a combination of the right arm, left arm, and left leg electrodes.

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