Introduction to ECG
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Brief review of basic concepts

The electrical activity of the heart is caused by a sequence of rapid ionic movements across cell membranes resulting first in depolarization (activation) and then repolarization of the myocardial cells. This process leads to sequential changes in the cellular membrane potential and is referred to as the action potential. In the normal heart, the electrical activity associated with each cardiac cycle originates in a specialized group of cells in the high right atrium known as the Sinoatrial Node (SA Node). SA Nodal cells spontaneously depolarize at a rate that is dependent on the relative balance of sympathetic and parasympathetic tone. At rest, vagal (parasympathetic) tone predominates and the SA node spontaneously depolarizes, on average, 60-100 times per minute. During exercise, there is both increased sympathetic nervous system activity and withdrawal of vagal tone and the SA node may depolarize at a much faster rate, depending on age (220-age provides a rough approximation of maximum sinus rate in normal individuals). From the SA node the wave of depolarization propagates in an orderly timed fashion to the remaining atrial tissue, to the Atrioventricular Node (AV Node), the His-Purkinje system and then to the left and right ventricular myocardium (Figure 1). The AV Node conducts relatively slowly, thereby allowing the atrium to fully contract before ventricular contraction starts. The His-Purkinje system (also referred to as the specialized conduction system) consists of the main His Bundle and the left and right bundle branches and the diffuse fine network of intraventricular Purkinje fibers. Relatively rapid conduction in the His-Purkinje system allows for synchronized contraction of the ventricles.

Figure 1. A simplified view of the myocardial conduction system
ECG Lead Placement

The electrocardiogram (ECG) is a method for recording the summed electrical signal produced by the orderly conduction of the action potential from the SA node to the ventricles. By convention, electrodes are placed on each extremity and at six locations on the chest (Figure 2). Placement of 10 separate ECG electrodes in standard locations on the chest and extremities allows the standard 12-Lead ECG to be recorded. Remember that there are 6 “limb” leads (I, II, III, aVR, aVL, and aVF). Leads I, II and III are bipolar leads; Lead I is the potential difference between the left arm (LA) and right arm (RA) with the LA being the positive pole; Lead II uses the RA and LL with the LL being positive; Lead 3 uses the LA and LL with LL being positive. AVR, AVL and AVF are recorded by setting the respective limb leads as positive with respect to the average of the other 2 leads. Note: the RL lead is the ground and is not used to generate the 12 lead ECG. There are also 6 “chest” or “precordial” leads (V1-V6), each viewing the electrical activity of the heart from a slightly different spatial perspective. By convention, each of the chest leads is a positive pole. (The negative pole for the chest leads is the electrical average of the 3 limb leads – and for all practical purposes can be thought of as the center of the heart). By convention, when the wave of depolarization is approaching a lead, or when the wave of repolarization is receding, a positive deflection is recorded in that lead.

![ECG lead placement and Einthoven’s Triangle](image)

Figure 2. ECG lead placement and Einthoven’s Triangle are shown.
Hexaxial Reference System

Determination of the mean direction of cardiac depolarization in the frontal plane is an important aspect of ECG interpretation. One useful tool for describing the mean direction of cardiac depolarization is the Hexaxial Reference System. Redrawing the lines representing the six limb leads (Figure 2, left panel) through a center point results in Figure 3 below. Note that each of the six leads can now be associated with a specific angle in the frontal plane. By convention, Lead I is assigned an angle = 0 degrees. If, for example, a wave of ventricular depolarization is directed exactly horizontally from the patient’s right to left, exactly parallel to lead I, the mean vector of ventricular depolarization (also called the QRS axis; you will learn more about this shortly) is said to be 0 degrees.

**Figure 3.** The hexaxial reference system is derived from the 6 limb leads and provides a standardized method for describing the mean direction of cardiac depolarization
The 12-lead ECG

There are many different formats for displaying the 12 lead ECG. Figure 4 shows one common format. Something you will need to memorize is the fact that by convention, each small box represents either 0.04 seconds (horizontally) or 0.1 mV (vertically). The six limb leads are on the left side of the recording and the six chest leads are on the right. The continuous display of a single lead (or sometimes 3 leads) at the bottom of the ECG is called a rhythm strip and is most helpful in the diagnosis of arrhythmias.

Figure 4. One common format for displaying a 12-Lead ECG
Waves, Intervals and Segments

Each cardiac cycle produces a series of waves, segments and intervals on the ECG that are described by standard nomenclature that you will need to memorize (Fig 5).

**Paper speed = 25 mm/sec**

--- 5 Big Boxes = 1 second ----

**Figure 5.** ECG waves, interval and segments

Before tackling the task of interpreting the entire 12 lead ECG, let’s take a very quick tour of a single cardiac cycle and relate each of the waves, segments and intervals to the sequence of cardiac depolarization and repolarization.

**P wave (atrial depolarization)**

The P wave reflects depolarization of the right and left atrium. (The cardiac cycle actually starts with depolarization of the SA Node. However, we cannot see this event on the surface ECG since the SA node is a relatively small mass of cells.) The normal atrial depolarization vector is oriented downward and toward the subject's left, reflecting the spread of depolarization from the sinus node to the right atrial and then to the left atrial myocardium.

**Key point:** It is most important to examine the P wave in Lead II where the normal P wave should be upright (positive).
PR Segment (activation of the AV node, His Bundle and Purkinje fibers)

The PR segment is measured from the end of the P wave to the first deflection of the QRS complex. The PR segment is usually isoelectric (neither above or below the baseline) since the total mass of the AV node, His Bundle and Purkinje fibers is relatively small. Generally, we do not spend much time examining the PR segment and we will not emphasize the PR segment during this course. PR segments that are depressed > 0.8 mm below the isoelectric line can be seen in a condition called pericarditis.

PR interval (onset of atrial depolarization to onset of ventricular depolarization)

The PR interval is simply the combination of the P wave and the PR interval. The PR interval is measured from the start of the P wave to the first deflection of the QRS complex. Since the PR interval may appear to be slightly different in different leads, the rule is to measure the longest PR interval on the ECG.

Key point: A normal PR interval is 0.12 – 0.20 sec (3-5 small boxes).

QRS complex (ventricular depolarization)

The term “QRS complex” generically refers to the electrical forces from depolarization of the left and right ventricles. The various deflections above and below the baseline are due to the time dependent change in the spatial direction of ventricular depolarization. If the first deflection of the QRS complex is negative (i.e. below the baseline), it is called a Q wave. The first positive deflection (above the baseline) is called an R wave. If there is a negative deflection after an R wave, it is called an S wave. If there is a second positive deflection after the S wave, it is called R’ (R prime). The exact “QRS” pattern that you see varies from patient to patient and from lead to lead. If you look at Figure 1 for example, you will see that only a few leads have all 3 waves (Q, R and S). Don’t get too confused by this.

Key point: In clinical practice, we use the generic terms “QRS” or “QRS complex” to refer to any of the ECG patterns that reflect ventricular depolarization.

ST segment

The ST segment is the interval from the end of ventricular depolarization to the beginning of ventricular repolarization, and is measured from the end of the QRS complex (called the J point) to the beginning of the T wave. The ST segment corresponds to the plateau phase of the cardiac action potential.

Key point: Like the PR segment, the normal ST segment should be isoelectric, or nearly so. However, it is usually not absolutely horizontal, but rather trends slightly upward to blend with the T wave, and it is often difficult to tell exactly where the ST segment ends and the T wave begins. Don’t worry about this. With experience, you will develop a feel for what constitutes a “normal” ST segment. The most important concept to know is that significant (usually defined as > 1 mm) elevation or depression of the ST segment from the baseline may signify cardiac ischemia.

T wave (ventricular repolarization)

T waves come in many shapes and sizes, may be upright or inverted and are affected by many different processes. A complete description of T wave morphology and the changes that can accompany disease is beyond the scope of this course. However, it is important for you to know that T wave changes can be an important sign of myocardial ischemia. Specifically, T waves which were formerly upright and become inverted are especially worrisome.

Key point: T waves are normally upright in leads I and II and V3-V6, so an inverted (i.e. negative) T wave in these leads is always abnormal.
QT interval (total duration of ventricular depolarization and repolarization)

The QT interval is measured from the first deflection of the QRS complex to the end of the T wave. When measuring, it is best to find a lead with a very distinct T wave. Since the normal QT interval varies with heart rate (slower heart rates are associated with longer QT intervals), it is necessary to “correct” the raw QT interval measurement using a formula that includes a correction factor based on the heart rate. The resultant number is called the “corrected” QT or QTc. You are not expected to remember this formula, but you should be familiar with what the QTc refers to and why it is necessary. The QTc is usually considered abnormal when it exceeds 0.44 sec. However, the QT interval is often difficult to measure precisely and rigid adherence to a precise value for normality is not warranted.

**Key point:** A quick way to check for QT prolongation is to visually compare the QT interval to the R-R interval (the interval between 2 successive R waves). The QT interval should normally be less than 1/2 the RR interval. However, this rule only applies with normal heart rates (60-100 bpm). You may need to check the computer reading when the heart rate is abnormal.

**Summary**

At this point, you should have a basic understanding of the following:
- Cardiac action potential
- Sequence of cardiac depolarization and repolarization
- Electrode placement to record the 12-lead ECG
- Vector terminology and the hexaxial reference system
- Measurement of the various waves, segments and intervals on the 12-lead ECG

If so, you have all the basic skills you need and you are now ready to apply this knowledge to a systematic approach to ECG interpretation. It will serve you well to develop a consistent approach early in your clinical career. One such method is to analyze the ECG in a series of 7 steps. These steps are:

1. Determine the Heart Rate
2. Determine the Rhythm
3. Determine the QRS axis
4. Determine the intervals (PR and QT)
5. Check for abnormalities of the P wave
6. Check for abnormalities of the QRS complex
7. Check for abnormalities of the ST segment and T wave
Step 1 Determine the Heart Rate

Measuring heart rate is easy and can be done in a number of ways. The easiest is to count the number of large boxes between 2 successive QRS complexes. The heart rate (beats per minute, bpm) equals 300 divided by the number of large boxes between QRS complexes. Take a moment to recall that each small box represents 0.04 sec and therefore each large box represents 0.20 sec. In the example below (Figure 6) there are 2-3 large boxes between QRS complexes and therefore the heart rate is 100-150 bpm. In most circumstances it is fine to estimate the heart rate. For example, if there were between 3 and 4 large boxes between R waves, the heart rate would be 75-100 bpm. Most ECG readers learn to memorize the heart rates corresponding to the number of large boxes between R waves as shown in the figure below. One may also get a more precise estimate by measuring the number of small boxes and dividing into 1500. In figure 6 below, there are about 13 small boxes between QRS complexes and therefore the heart rate is approximately 115 beats per minute. For very irregular heart rhythms, count the number of QRS complexes in 6 seconds (30 large boxes) and multiply by 10.

Heart rate = 300 divided by number of big boxes between QRS complexes or
= 1500 divided by the number of small boxes between QRS complexes

Figure 6. Quick method to estimate heart rate

♥ Clinical correlation: Heart rates of 60-100 beats per minute are considered normal. Slower heart rates are called bradycardia; faster heart rates are called tachycardia.
Step 2 Determine the Heart Rhythm

This is the most complex of the 7 steps and there are whole chapters devoted to this topic later on in this syllabus. For now, we need to learn just those rhythms that originate from the SA node. The first is called Normal Sinus Rhythm (NSR). This is the rhythm that most of us have most of the time and is seen in Figure 4. The criteria for normal sinus rhythm are as follows:

1. One P wave before every QRS, and a QRS for every P wave
2. A heart rate between 60 and 100 beats per minute (bpm)
3. An upright (positive) P wave in lead II

Clinical correlation: When the heart rate is less than 60 bpm, or greater than 100 bpm, but the other 2 above criteria are met, the rhythms are called Sinus Bradycardia or Sinus Tachycardia respectively. Both rhythms are commonly seen in otherwise healthy individuals at rest and during exercise.

Step 3 Determine the QRS axis

Determination of the major vector of ventricular depolarization (QRS axis) is an important aspect of ECG interpretation. Fortunately, it is quite easy to determine by quick inspection of just 2 leads. But first, we must review the general concept of vectors as applied to the net direction of ventricular depolarization. Remember from your lecture on Cardiac Electrophysiology that following the early left to right activation of the ventricular septum, the major activation (depolarization) of the ventricular myocardium proceeds in a downward and leftward direction, roughly parallel to the long axis of the heart. Therefore, ECG leads with a positive pole to the patient’s left (example leads I and II) will record a QRS complex that is more positive than negative (i.e with more of the QRS above the baseline than below), while leads with a positive pole to the patient’s right (e.g. aVR) will record a QRS that is mostly negative.

By measuring the amplitude of the QRS complex in all 6 of the limb leads it is possible to determine the angle of the major vector of ventricular activation quite accurately. Although you should understand how it is theoretically possible to calculate an exact vector, it is rarely necessary to do so. In clinical practice, it is sufficient to know whether the QRS axis is normal, left or right. Textbooks differ slightly with the definition of normal, but for the purposes of this course I would like you to remember that a normal adult QRS axis is from −30 degrees to +90 degrees. From Figure 7, you will note that if the QRS is mostly positive in Lead I, the QRS axis must be between −90 degrees and +90 degrees. If the QRS is mostly positive in Lead II, the QRS axis must be between -30 degrees and +150 degrees. If both Leads I and II are positive, the QRS axis must be −30 degrees to +90 degrees (normal). This relationship provides a quick and convenient method for determining the QRS axis:

• QRS up in I and up in II = Normal axis
• QRS up in I and down in II = Left axis deviation
• QRS down in I and up in II = Right axis deviation
• QRS down in I and down in II = Right superior axis
LEAD I POSITIVE

LEAD II POSITIVE

BOTH LEAD I AND LEAD II ARE POSITIVE = NORMAL QRS AXIS

Figure 7. Determining the QRS axis using Leads I and II

Clinical correlation: an abnormal QRS axis may be a clue to the presence of certain cardiac conditions. For example, left axis deviation may be seen when there is hypertrophy of the left ventricle.
Step 4 Measure the Intervals (PR and QT)
You have already learned how to do this! To review;

• Normal PR interval = 3-5 small boxes (0.12-0.20 sec)

♥ Clinical correlation: A long PR interval (> 0.2 sec) usually indicates slowed conduction in the AV node and/or His-Purkinje system and is called **First degree AV Block**.

♥ Clinical correlation: A short PR interval (<0.12 sec) can be a clue to the presence of a congenital accessory conduction pathway linking the atria and ventricles. This condition is called **Wolff-Parkinson-White or WPW**.

• Normal QT interval = < 1/2 the corresponding R-R interval (HR = 60-100)

♥ Clinical correlation: Disease processes and medications may cause prolongation of the QT interval. When the QT interval is very prolonged, patients are predisposed to a greater risk of **ventricular tachycardia**. There is even a congenital condition known as **Long-QT Syndrome** in which individuals are prone to sudden cardiac death from ventricular arrhythmias.

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**Figure 8.** Examples of long PR and long QT segments
Step 5 Check for abnormalities of the P wave

The normal P wave is upright in lead II and you should always specifically look at the P wave in Lead II as an indicator that the rhythm originates in the SA node. As a reasonable and practical approximation, normal P waves in the limb leads should be less than or equal to 2.5 small boxes high and less than or equal to 2.5 small boxes wide.

♥ Clinical correlation: Negative (often called “inverted) P waves in Lead II are a clue that the cardiac rhythm does not originate from the SA node. Later in the course, you will see some specific examples and learn more about these abnormal rhythms.

♥ Clinical correlation: P waves that are taller and/or wider than 2.5 small boxes in the limb leads indicate possible atrial enlargement (for example, due to valvular heart disease). However, the overall sensitivity and specificity of this finding is very poor and is of limited clinical value. Echocardiography has become the gold standard for assessing atrial size. It is presented here because most computerized ECG interpretation systems still include the terms ‘left atrial enlargement” and “right atrial enlargement”.

Figure 9. In the left panel, the patient has left atrial enlargement, with a very wide (>2.5 boxes) P wave in lead II. In the right panel, the patient has right and left atrial enlargement, with a tall (> 1.5 box) positive component and a very wide and deep terminal negative component of the biphasic P wave in lead V1.

Step 6 Check for abnormalities of the QRS

Step 6 involves looking for abnormalities of the QRS and is the most complicated. It is best approached by breaking the step into four smaller tasks; a) search for pathologic Q waves, b) measure QRS duration, c) assess QRS voltage, and d) evaluate R wave progression across the precordium. Each of these topics will now be discussed.
Pathologic Q waves

Whenever the first deflection of the QRS complex is negative, it is called a Q wave. “Normal” Q waves are a frequent finding on the ECG (except in leads V1-V3) and reflect activation of the ventricular septum. They are normally less than 1 small box wide. However, certain Q waves are considered abnormal or “pathologic” and may be markers of myocardial infarction, which you will learn more about later in this course. So what is a pathologic or abnormal Q wave?

Q waves are considered abnormal if;

• Present in leads V1-V3 or
• Are greater than or equal to 1 small box wide* or
• Are greater than 25% of the amplitude of the corresponding R wave*

*An exception to this rule is in lead III, where the Q wave sometimes slightly exceeds these limits. However, when we use pathologic Q waves to diagnose myocardial infarction, we need to see them present in more than one lead, so an isolated abnormal Q wave in lead III seldom causes concern.

QRS duration

The normal QRS is less than or equal to 2.5 small boxes (0.1 sec). It is measured simply from the start to the end of the complex, no matter what the configuration. QRS durations from 0.10 – 0.12 sec are considered moderately prolonged and are not as significant clinically as QRS durations > 0.12 sec., which usually indicate significant pathology, such as bundle branch block, which you will learn more about later in this syllabus. Below are rhythm strips showing examples of normal and prolonged QRS durations (Figure 10).

![Figure 10. Normal (Top, ~ 0.08s) and wide (Bottom, prolonged, ~ 0.2s) QRS intervals](Image link)
QRS voltage

The term QRS voltage refers to the amplitude of the QRS complex. When the QRS is upright (mostly positive), it is measured from the baseline to the top of the R wave. When it is mostly negative, it is measured from the baseline to the bottom of the S wave. The QRS voltage is affected by many factors. One obvious factor is that if the wave of depolarization is headed directly at a particular lead, the R wave will be larger than if the wave of depolarization approaches a lead from an angle. Look back at Figure 1. The R wave in lead I is taller than the R wave in lead aVL, because the QRS axis is closer to 0 degrees than it is to -30 degrees. Another factor is how much heart muscle is being depolarized. Patients with ventricular hypertrophy or enlargement of the ventricles may have increased voltage. Another important determinant of QRS voltage is what lies between the heart and the ECG lead. For example, very obese patients may have low QRS voltage (the converse is also true). Another example is patients with emphysema (air is a poor electrical conductor). For the above reasons, the amplitude (voltage) of the QRS has a wide range of normal limits, depending on the lead, the age of the individual and other factors such as those mentioned above. It is also important to note when individuals have very small QRS voltages (called low voltage). This is usually defined as a total QRS voltage \((R+S) < 5 \text{ mm in all limb leads and } < 10 \text{ mm in all precordial leads}\). One classic condition where low QRS voltage may be a clue to the diagnosis is pericardial effusion, which you will learn about later in the course.

Precordial R wave progression

In the normal ECG, the R wave gets progressively larger from V1 to V6 (except that V5 is often slightly larger than V6). This is referred to as normal R wave progression. Look back again at Figure 4. Note that the R wave gets progressively larger until the R wave is larger than the S wave in V4. The point at which the R wave is greater than or equal to the S wave is called the precordial transition zone and should occur in leads V2, V3 or V4. When the transition zone does not occur by lead V4, this is called “poor R wave progression” or sometimes “delayed R wave progression”. Poor R wave progression is not a specific diagnosis by itself, but can be a sign of pathology (or faulty lead placement in normal subjects), so is important to recognize. Poor R wave progression can be seen in association with chronic lung disease, left ventricular hypertrophy, left anterior fascicular block and anterior myocardial infarction.
Step 7 Check for abnormalities of the ST segment and T wave

ST segment

We have already covered the essential points of Step 7. Remember that the normal ST segment should be isoelectric or nearly so (need a reminder; it is best to look at the segment between the end of the T wave and the beginning of the next P wave to identify the isoelectric line). There are lots of causes for relatively minor degrees of ST segment elevation or depression (< 1mm, called non-specific ST change) and usually changes of this sort do not generate clinical concern. However, it is very important to be aware of the association between greater degrees of ST segment elevation or depression and myocardial ischemia and infarction. When evaluating the ST segment, it is critical to carefully consider the clinical scenario. Even small amounts of ST segment change may be important in a patient with chest pain or other signs of myocardial infarction, particularly if the degree of ST segment deviation is changing over time. Figure 11 below shows normal and abnormal ST segments.

![Figure 11](image_url)

**Figure 11.** Examples of normal ST segment (top), ST elevation (middle), and ST depression (bottom).
T wave

T waves come in many shapes and sizes, but are normally upright in leads I and II and V3-V6, so an inverted (i.e. negative) T wave in these leads is always abnormal. New T wave changes (compared to a prior ECG) may also be an important sign of myocardial ischemia or infarction. Some interesting examples of abnormal T waves are shown in Figure 12 below.

**Figure 12.** Shown are examples of abnormal T waves. In the left panel, very tall “peaked” T waves are seen in a patient with hyperkalemia. Similar peaked T waves may also be seen in the earliest stages of myocardial infarction. In the right panel, giant negative T waves are seen in a patient with cerebral hemorrhage. Similar T waves may also be seen in patients with hypertrophic cardiomyopathy and severe myocardial ischemia.

This concludes your introduction to ECG interpretation. Most if not all of the above material will be reinforced in later tutorials in this handbook. Have fun!
Bullet Point Review

Step 1 Determine the Heart Rate
- Normal = 60-100; < 60 = bradycardia; > 100 = tachycardia
- Use rule of 300 for regular rates < 150
- Use rule of 150 for regular rates > 150
- Irregular rhythm; use averaging (number of R waves in 6 sec times 10)

Step 2 Determine the Heart Rhythm
- Normal Sinus Rhythm
  - One P wave before every QRS, and a QRS for every P wave
  - Heart rate 60-100 (< 60 sinus bradycardia; > 100 sinus tachycardia)
  - Upright (positive) P wave in lead II

Step 3 Determine the QRS axis
- QRS up in I and up in II → Normal axis
- QRS up in I and down in II → Left axis deviation
- QRS down in I and up in II → Right axis deviation
- QRS down in I and down in II → Right superior axis

Step 4 Measure the Intervals (PR and QT)
- Normal PR interval = 3-5 small boxes (0.12-0.20 sec)
  - PR interval > 0.2 sec = First degree AV Block.
  - PR interval < 0.12 sec; one cause is Wolff-Parkinson White (WPW).
- Normal QT interval = < 1/2 the corresponding R-R interval (HR 60-100)
  - Long QT can predispose to ventricular tachycardia.

Step 5 Check for abnormalities of the P wave
- Normal P wave is upright in lead II

Step 6 Check for abnormalities of the QRS
- Pathologic Q waves (sign of myocardial infarction) if
  - Located in leads V1-V3 or
  - ≥ 1 small box wide (OK in lead III)
  - > 25% of the corresponding R wave amplitude (OK in Lead III)
- Normal QRS duration < 2.5 small boxes (0.1sec)
- Large QRS voltage may indicate ventricular hypertrophy
- Normal precordial transition zone is V2-V4

Step 7 Check for abnormalities of the ST segment and T wave
- Look for ST segment elevation or depression
- Look for inverted T waves leads I, II, V3-V6, or new T wave changes

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