The heart is a muscular pump that circulates blood throughout the body. To efficiently pump the blood, cardiac contractions must be coordinated and are regulated by the heart’s electrical conduction system. For each heartbeat, an electrical signal spreads from the top to the bottom of the heart. As the signal travels, it causes contraction of the heart’s atria followed by the ventricles. This process is repeated for each heartbeat.

Disease or damage to the heart may alter how the electrical signal stimulates the heart and produces contractions. The heart’s electrical conduction system can be monitored through electrocardiography, which produces a graphic record of the electrical activity of the heart called an electrocardiogram or ECG. The ECG can provide important information as to whether the heart is beating properly and can serve to identify a number of abnormalities.

Objectives
At the conclusion of this laboratory the student will understand and be able to describe:

1. the electrical conduction system of the heart.
2. the cardiac action potential.
3. the concepts of electrocardiography.
4. the use of the ECG as a diagnostic tool.
5. how to perform and interpret an ECG.

This lab consists of one activity.

• **ACTIVITY 1. Obtain a 6-lead ECG from a resting subject**
  During this activity, students will take ECG readings from a resting subject (or subjects) and then determine the subject’s QRS axis.

VOCABULARY LIST

• **action potential** – a wave of electrical discharge propagated from one cell to another that passes along the plasma membrane.
• **AV node** – the atrioventricular node is located in the right atrium near the opening of the coronary sinus. It is part of the heart’s electrical control system of the heart and electrically connects the atrial and ventricular chambers.
• **bundle of His** – a collection of specialized heart muscle cells that transmits the electrical impulses from the AV node to the point of the apex.
• **deflection** – the movement of electrical waves from one point to another. Deflection always has a direction. • **depolarization** – the cell’s membrane potential becomes more positive (less negative).
• **ECG** – electrocardiogram (also called EKG). A graphical recording of the electrical activity of the heart by an electrocardiograph.
• **Einthoven’s triangle** – a diagrammatic representation of the three major leads. It is named after Willem Einthoven.
• **electrical axis of the heart** – this is the main direction of depolarization as it disseminates from the base of the ventricles to the apex of the heart.

• **electrocardiograph** – a device that measures electrical potentials on the body surface and generates a record of the electrical currents associated with heart muscle activity, i.e., produces an electrocardiogram.

• **isoelectric line** – the baseline reading in electrocardiography. It represents the quiescent phase.

• **lead** – this is a combination of electrodes that form an imaginary line in the body along which the electrical signals are measured. Leads are used to graph the electrical potential between two points using positive and negative electrodes.

• **P wave** – the ECG deflection representing depolarization of the atria.

• **Purkinje fibers** – these are specialized electrical conducting myocardial fibers located in the inner ventricular walls.

• **plateau stage** – period of time when the rate of repolarization slows down as Ca\(^{2+}\) ions diffuse into the cell.

• **quiescent phase** – period between the end of repolarization and the start of depolarization. During this period, there is no ion exchange across the plasma membrane in most cardiac cells.

• **QRS complex** – the ECG deflection representing depolarization of the ventricles.

• **refractory** – the state of a cell undergoing repolarization, during which it is unable to respond to stimuli. A cell cannot depolarize while it is refractory.

• **repolarization** – the cell’s membrane potential returns to the resting membrane potential after depolarization.

• **resting membrane potential** – the cell’s membrane potential when it is not transmitting or receiving electrical signals.

• **T wave** – the ECG deflection representing repolarization of the ventricles.

• **SA node** – the sinoatrial node is located in the wall of right atrium. It is also known as the pacemaker of the heart. Electrical impulses generated here set the heart rate.

**BACKGROUND AND REFERENCES**

**Electrical Conduction in the Heart**

We often think of the heart as a single muscular pump. The reality is that the heart is actually two conjoined pumps that work together to circulate blood through the entire body. One pump (the right side of the heart) is involved in pulmonary circulation where blood is pumped to the lungs and then back to the left side of the heart. The other pump (the left side of the heart) is responsible for systemic circulation where blood is pumped throughout the rest of the body and then back to the right side of the heart. Both processes involve the sequential contractions of their respective atria and ventricles, which is synchronized by the heart’s electrical conduction system.

It should be noted here that cardiac myocytes (muscle cells) of the atria and ventricles form two networks known as the atrial syncytium and the ventricular syncytium. Each syncytium is a network of cardiac muscle cells connected by gap junctions located in the intercalated discs, allowing coordination of the contraction of the heart’s chambers. Electrical resistance through the gap junctions is very low, which permits the free diffusion of ions. As a result, **action potentials** (large, rapid changes in the membrane potential in which the inside of the cell becomes positive relative to the
outside) propagate readily from one myocyte to the next. In terms of cardiac activity, this means that when one cell contracts, they all contract.

The electrical impulses generated by the heart’s conduction system begin in the **sinoatrial node (SA node)**, which is located in the upper wall of right atrium (Figure 1) near the entrance of the superior vena cava. Since the heart’s electrical activity begins with the SA node, it is known as the pacemaker of the heart. The SA node is actually a group of specialized cardiac myocytes that can spontaneously **depolarize** (the membrane potential becomes more positive than it is at rest). The depolarization of the SA node is followed by depolarization of the atria, which then causes contraction of the atrial musculature. The right atrium contracts slightly before the left atrium since that is where depolarization begins.

Electrical waves from the SA node are also conducted by internodal pathways (made up of specialized myocardial cells called conduction fibers) to the atrioventricular node (**AV node**) located at the base of the right atrium near the opening of the coronary sinus and the tricuspid valve. The AV node transmits action potentials slower, resulting in a 0.1 second delay in the transmission of the electrical current, which delays its arrival at the ventricles. The purpose of this **AV nodal delay** is to ensure that atrial contraction occurs before the ventricles are stimulated to contract. After leaving the AV node, the electrical current travels through the interventricular septum via conduction fibers called the **bundle of His**. From here, the action potentials are propagated through the **right and left bundle branches** and then pass from the apex of the heart up the **Purkinje fibers** in the lateral walls of the ventricles. As the action potentials spread through the ventricles, contraction of the ventricular muscle tissue occurs.

![Figure 1. Specialized conducting components of the heart include the sinoatrial (SA) node, the atrioventricular (AV) node, the bundle of His, the right and left bundle branches, and the Purkinje fibers.](credit: Openstax Anatomy and Physiology)
Cardiac Action Potential

The term “cardiac action potential” refers to a series of changes in the voltage of a cardiac contractile cell over a brief period of time. These changes include depolarization, a plateau period, and repolarization. The membrane potential is a difference in voltage or electrical potential across the cell membrane. There are more anions (negatively charged ions) than cations (positively charged ions) inside the cell, while there are more cations than anions in the extracellular fluid. The membrane potential is always given in terms of voltage inside the cell relative to voltage outside the cell. Thus, for many cells at rest (not sending or receiving electrical signals), the resting membrane potential is -70 mV, indicating that the inside of the cell is 70 mV more negative compared to the outside.

Cations and anions diffuse into and out of cells through specific ion channel proteins. Some of these ion channels are voltage-gated channels. Voltage-gated channels are normally closed (do not
allow passage of ions), but will be triggered to open by sufficient changes in the membrane potential of a cell. If a cation-specific voltage-gated channel opens, that cation will normally diffuse into the cell, resulting in a voltage decrease in the membrane potential. This voltage decrease is called depolarization. In other words, during depolarization, an influx of positive ions cause the membrane potential to become less negative and eventually positive.

The depolarization phase of a cardiac muscle action potential begins when voltage-gated sodium ion channel proteins (Na⁺ channels) are stimulated to open, allowing Na⁺ ions to diffuse into the cell (Figure 2). An action potential is a self-regenerating wave of electrochemical activity that allows excitable cells, such as cardiac cells or neurons, to carry an electrical signal over a distance. Depolarization of one cell stimulates the opening of Na⁺ channels in adjacent cells, resulting in a depolarization wave front that propagates cell by cell throughout the heart. The speed of depolarization of a given cell determines how quickly the next cell will depolarize.

Once depolarization is completed, the cell begins to repolarize (the original membrane potential is restored). It is important to realize that the cell cannot depolarize again until repolarization occurs. During the repolarization process, the cell is refractory, which means that it cannot respond to a new stimulus. The plateau stage also occurs during repolarization. This is where the repolarization rate slows down as Ca²⁺ ions diffuse into the cell and K⁺ ions move out. The plateau stage lasts about 0.20 seconds. The Ca²⁺ ions enter the cell and prevent the cell from repolarizing too quickly; thus, extending the refractory period. A long refractory period is important to allow the cardiac muscle cells to fully contract, pump the blood out, and relax before being stimulated to contract again. Cardiac muscle cells will be able to respond to a new stimulus once repolarization is finished.

The period following repolarization and before the next depolarization is the quiescent phase. During this period, there is no ion exchange across the plasma membrane in most cardiac cells. The membrane potential during this time is referred to as the resting potential.

At some point, a leakage of ions across the plasma membrane will occur in the SA node cells. This will result in a gradual increase in the membrane potential. When the membrane potential reaches the threshold voltage, depolarization will begin again and a new action potential occurs. The ability of the heart to generate its own action potentials that trigger contractions on a periodic basis is called autorhythmicity. Although the heart has autorhythmicity, heart rate is regulated by the nervous and endocrine systems.
Figure 2: Action potential in cardiac contractile cells. (a) Note the long plateau phase due to the influx of calcium ions. The extended refractory period allows the cell to fully contract before another electrical event can occur. (b) The action potential for heart muscle is compared to that of skeletal muscle.

Credit: Openstax Anatomy and Physiology
Basic Electrocardiographic Principles and Concepts

Electrocardiography is the process of producing an electrocardiogram (ECG or EKG) with a device called an electrocardiograph. An ECG is a graphic record of the electrical activity of the heart at a given time. The electrical waves that cause the heart muscle to contract pass through the body and can be measured at electrodes attached to the skin. These electrodes are attached on different sides of the heart to measure the activity of different parts of the heart muscle. Note that the electrodes can be positive or negative. The ECG output indicates the overall rhythm of the heart as well as problems in different parts of the heart muscle. It is often considered the best way to detect and diagnose abnormal rhythms of the heart, or in some cases to identify damaged areas of the heart muscle.

Deflection and the Isoelectric Line

As electrical waves move around the heart, they are recorded as a series of deflections (movement of electrical waves from one point to another). This electrical movement produces differences in electrical potential between depolarized and polarized tissue. Changes in this electrical activity are often measured in reference to the isoelectric line or baseline. The isoelectric line represents the quiescent phase that is between repolarization and the next depolarization when no electrical activity is occurring.

ECG Waves

The ECG for one normal complete cardiac cycle (heartbeat) consists of a set of deflections referred to as the P wave, the QRS complex, and the T wave (Figure 3). The isoelectric line (baseline) represents the interval between the end of one heartbeat and the start of the next.
The **P wave** results from atrial depolarization as electrical activity moves from the SA node towards the AV node and spreads from the right atrium to the left atrium. This occurs just prior to atrial contraction. It lasts about 0.08 to 0.10 seconds.

The **QRS complex** is actually composed of the Q, R, and S waves that occur together as a result of ventricular depolarization. In fact, each of these three waves actually represents a different stage of depolarization of the ventricles. On the ECG, the QRS complex appears larger than the P wave. One reason for this is that the ventricles contain more muscle mass than the atria. The QRS complex occurs prior to contraction of the ventricles. Normally, the duration of the QRS complex is 0.06 to 0.10 seconds. A duration that is greater than 1 second may be an indication of an impairment of electrical conduction through the ventricles.

The **T wave** represents the repolarization of the ventricles. In terms of the cardiac cycle, it indicates the relaxation of the ventricles after contraction.

It should be noted that the ECG does not show a wave corresponding to atrial repolarization. This is because it occurs at the same time as ventricular depolarization and is completely hidden by the QRS complex.

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**Figure 3**: ECG tracing showing the P, QRS and T waves. Also indicated are the PR, QT, QRS, and ST intervals, plus the P-R and S-T segments.

*Credit: Openstax Anatomy and Physiology*
**Electrocardiographic Leads**

The word **lead** is used here to refer to a combination of electrodes that form an imaginary line in the body along which the electrical signals are measured. For our purposes, the wires that connect the electrodes to the computer (which is serving as our electrocardiograph) are connections and not leads.

Electrocardiographic leads are bipolar, which means they have a negative and a positive terminal. This allows them to detect changes in the electric potential between these two points.

For this reason, each lead should be considered as a graphical representation of the electrical potential between its two terminals.

There are three standard leads:

1. **Lead I** is between the right arm and left arm electrodes. The negative terminal is attached to the right arm, while the positive terminal is attached to the left arm.

2. **Lead II** is between the right arm and left leg electrodes. The negative terminal is attached to the right arm, while the positive terminal is attached to the left leg.

3. **Lead III** is between the left arm and left leg electrodes. Here, the left arm is negative, while the left leg is again positive.

A diagrammatic representation of these three leads is called **Einthoven's triangle** (Figure 4), named after Willem Einthoven, the Dutch physiologist who first described this relationship and also invented the first practical electrocardiograph.
The ECG is a graph centered on zero over two axes. The vertical axis represents changes in electrical potential as measured in millivolts. The horizontal axis indicates the time period during which these changes occur and is measured in seconds. Because of the centering of the graph at zero, an electrical potential that is greater towards the positive electrode will be graphically represented by an upward deflection. On the contrary, if an electrical potential is greater toward the negative electrode, it will be shown as a downward deflection.

It should be noted that the right leg is not included as part of Einthoven’s triangle. Instead of having a positive or negative electrode, it has a ground electrode. The ground electrode helps the electrocardiograph eliminate noise.

**ECG Intervals and Segments**

It was mentioned that there were two axes that are represented in an ECG. While the vertical axis portrays millivolt changes in electrical potential, the horizontal axis indicates the time period (in seconds) over which these events occurred. These events are indicated as ECG intervals and segments (Figure 3). Intervals usually begin with a complete ECG wave, while segments do not. There are several ECG intervals and segments, including:

1. The **PQ or PR interval** is the period of time from the beginning of the P wave (onset of atrial depolarization) to the beginning of the QRS complex (onset of ventricular depolarization). It is a measure of the time of conduction from the SA node through the AV node. Therefore, it indicates the period from atrial systole to ventricular systole. It is usually 0.12 to 0.20 seconds long. Since the Q wave is sometimes absent, this interval is often called the PR interval.

2. The **QT interval** is the period between the start of the QRS complex and the end of the T wave. It covers the period from the beginning of ventricular depolarization to the end of ventricular repolarization or the onset of ventricular systole to end of ventricular diastole. The normal duration of the QT interval ranges from 0.30 to 0.44 seconds.
3. The R-R interval is the time between two consecutive R waves. The heart rate can be determined from the ECG by dividing 60 by the R-R interval. Heart rate = 60/(R-R interval)

The TQ segment is measured from the end of the T wave to the beginning of the next Q wave. This is the period from the end of ventricular repolarization to the beginning of ventricular depolarization, which represents ventricular diastole.

**Checkpoint:**

1. What is a lead?

2. Which ECG interval or segment can be used to determine the heart rate?

**A Diagnostic Tool**

The ECG is an important tool for the evaluation of cardiac function and identification of possible problems. Below is a list of only a few examples where electrocardiography would be useful in a diagnostic sense.
P wave – Changes in the shape and duration of the P waves may be indications of atrial enlargement.

PR interval – The PR interval represents the time from the onset of atrial depolarization to the onset of ventricular depolarization.
- If the PR interval is prolonged (greater than 0.2 seconds), it may be an indication of a first-degree AV block, which is due to a problem with the AV node or with the His/Purkinje system.
- On the other hand, a very short PR interval may an indication of disorders like Wolff-ParkinsonWhite (WPW) syndrome. WPW syndrome is a condition where the ventricles are prematurely stimulated; it is a pre-excitation disorder. Such disorders are due to abnormal electrical conduction in the heart.

QRS complex – Evaluation of the QRS complex is useful in diagnosing a number of heart problems, including cardiac arrhythmias, conduction abnormalities, ventricular hypertrophy, and myocardial infarction. For example, an elongated QRS duration (greater than 0.12 seconds) may be an indication of a problem with the Purkinje fibers. Changes in the morphology of the QRS complex are also important.
- For example, Q waves greater than 1/3 the height of the R wave may indicate a myocardial infarction.
- A split in the R wave often indicates that the ventricles are depolarizing at different times. This may be due to bundle branch damage or due to poor blood supply to the heart.

PLEASE NOTE
Your lab instructor is not qualified to make medical evaluations. In most cases, any “abnormal” ECG results in lab are simply due to poor or incorrect electrode attachment. You should always consult with a properly qualified and licensed physician if you have concerns about the ECG results that you obtained in this lab exercise.

EXPERIMENTAL PROCEDURES
You will be working in groups of four. Each group will obtain and analyze two ECGs. Please follow the procedures for setup and data acquisition. Once your data for all three leads has been acquired, save the data to a disk so that you can analyze it later. To save to a disk, return to the Main Menu and select Data File/Disk commands.

Required Equipment
PC computer IWX/214
data unit
IWX/214 power supply
USB cable
C-AAMI-504 cable with leads
Alcohol swabs
Disposable ECG electrodes
Equipment Setup
1. Connect the IWX/214 data unit to the computer using the USB cable to connect the computer to the USB port on the rear panel of the unit.

2. The student should make sure that all jewelry from his/her wrists and ankles has been removed.

3. Use an alcohol swab to clean a spot on each wrist and ankle that has little or no hair. Make sure these areas are dry before attaching the electrodes (in the next step).

4. Remove the plastic covering from five disposable electrodes and apply an electrode to the scrubbed area on one wrist. Repeat this for the other wrist and both ankles. Please note in step 5 (below) that two electrodes will be attached to the right wrist.

5. Attach the C-AAMI-504 cable with leads on the end of the gray patient cable to the Isolated Channel 1 & 2 input of the IWX/214 unit: **DO USE THE NON-ISOLATED CHANNEL 1 OR CHANNEL 2 INPUTS** (Figure 5).

6. Attach the five color-coded electrode cables to the ground and Channel 1 inputs on the lead pedestal and snap the other ends onto the disposable electrodes, so that the:
   
   a. red cable is attached to the right wrist.

   b. black cable is connected to the left wrist.

   c. white cable is connected to the right wrist.

   d. brown cable is connected to the left ankle.

   e. green cable (the ground) is connected to the right ankle.

7. The student should sit quietly with their hands placed in their lap.
**Start the Software**

1. Click the LabScribe icon on the Desktop.

2. When the program opens, select Load Group from the Settings menu.

3. When the dialog box appears, select IPLMV3.iws. Click Load.

4. Click on the Settings menu again and select the SixLeadECG settings file.

After a short time, LabScribe will appear on the computer screen as configured by the SixLeadECG settings

**Activity 1. Obtain a 6-Lead ECG from a Resting Subject**

The aim is to record a 6-lead ECG from a resting subject and determine the QRS axis of the subject.

**Procedure**

1. Click Start, then click AutoScale on all the channels. If the R wave on Channel 1 or 2 is inverted, click Stop and check to see which electrodes the lead wires are attached to. Check the Equipment Setup section of this experiment. If a larger signal is required, the electrodes should be moved from the wrists to the skin immediately below each clavicle.

2. When you have a suitable trace, type “<Subject’s Name> resting ECG” on the comment line to the right of the Mark button. Press the Enter key on the keyboard to attach the comment to the data.

3. Click Stop to halt recording. Your data may look something like Figure 6.

4. Select Save As in the File menu and type a name for the file. Choose a destination on the computer in which to save the file (e.g. the iWorx or class folder). Click the Save button to save the file (as an *.iwd file).

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**Figure 6: 6-lead ECG generated by recording Leads I and II on Channels 1 and 2, respectively.**
Data Analysis

Figure 7: The LabScribe toolbar.

1. Click the 2-Cursor icon (Figure 7) so that two blue vertical lines appear over the recording window.

2. Drag the lines left and right so that four complete heartbeat cycles are located between the two blue lines.

3. Click the Analysis icon (see Figure 7) to open the Analysis window.

4. All eight channels will be displayed. Select any channel by clicking on its name in the Display Channel list on the left side of the Analysis window. Select additional channels by holding down the Control key and clicking.

5. Use the mouse to click and drag the cursors around the Analysis window to measure the:
   a. amplitude (V2-V1 from onset of Q to peak of R) of three adjacent R waves on each of the six ECG leads (Figure 8).
   b. amplitude (V2-V1 from onset to peak of P) of three adjacent P waves on each of the six ECG leads.
   c. amplitude (V2-V1 from onset to peak T) of three adjacent T waves on each of the six ECG leads.

6. Enter your results in the ECG Data Tables.
Figure 8: Cursors placed at the onset of the Q wave and at the peak of the R wave for measurement of the R wave amplitude.

7. Data can be entered into the Journal by either typing the titles and values directly or by using the right-click menu while in the Analysis window. Place the cursors to take measurements, and then select Add Title to Journal or Add Data to Journal from the right-click menu to add the measurements to the Journal.

8. From your Lead II data, measure and record the following in the ECG Data Tables.

   - PR interval
   - QT interval
   - QRS duration

9. Measure and record for three separate beats (RR intervals) and record below. Average these values and calculate the heart rate using the appropriate units. Also, record the heart rate in the ECG Data Tables.

   a. Time 1
   b. Time 2
   c. Time 3
   d. Heart rate