Lesson 6
ELECTROCARDIOGRAPHY II
Bipolar Leads (Leads I, II, III)
Einthoven's Law
Mean Electrical Axis on the Frontal Plane

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I. INTRODUCTION

Willem Einthoven developed a "string galvanometer" in 1901 that could record the electrical activity of the heart. Although it was not the first such recorder, it was a breakthrough in that it was accurate enough to duplicate the results on the same patient. Einthoven's work established a standard configuration for recording the ECG and won him the Nobel Prize in 1924. Since then, the ECG has become a powerful tool in diagnosing disorders of the heart. [It should be noted that the clinical interpretation of the ECG is quite empirical in practice, and has evolved from a long history of reference to and correlation with known cardiac disorders.]

The electrical activity of the heart begins in the sinoatrial (SA) node, and spreads throughout the atria and to the AV node (see Lesson 5 ECG I for details). The spread of signal causes a negative charge to occur, which induces depolarization. This depolarization of the atria is recorded as the P wave of the ECG. At the AV node, the electrical signal is slowed. Then, the electrical signal conducts down the AV bundle and down the left and right bundle branches, following the interventricular septum. The depolarization continues down the septum spreading through the ventricles via the Purkinje fibers. The depolarization of the ventricles is recorded as the QRS complex in the ECG. Following complete depolarization of the ventricles, the ventricles start the process of repolarization, which is recorded as the T wave.

Because the current spreads along specialized pathways and depolarizes in sequence, the electrical activity has a spatial orientation or electrical axis. Because the amount of electrical signal generated is proportional to the amount of tissue being depolarized, and the ventricles make up the majority of the mass, the largest potential difference reflects the depolarization of the ventricles. Furthermore, since the left ventricle is larger than the right, more of the QRS complex reflects the depolarization of the left ventricle.

The body contains fluids with ions that allow for electrical conduction. This makes it possible to measure electrical activity in and around the heart from the surface of the skin (assuming good electrical contact is made with the body fluids using electrodes). This also allows the legs and arms to act as simple extensions of points in the torso. Measurements from the leg approximate those occurring in the groin, and measurements from the arms approximate those from the corresponding shoulder.

Ideally, electrodes are placed on the ankles and wrists for convenience to the subject undergoing the ECG evaluation. In order for the ECG recorder to work properly, a ground reference point on the body is required. This ground is obtained from an electrode placed on the right leg above the ankle.
To represent the body in three dimensions, three planes are defined for electrocardiography (Fig. 6.1).

![Diagram of body showing transverse, sagittal, and frontal planes](image)

**Fig. 6.1**

The term "lead" is defined as a spatial arrangement of two electrodes on the body. One lead is labeled "+" (positive) and the other "-" (negative). The electrode placement defines the recording direction of the lead, which is called the lead axis or angle. The axis is determined by the direction when going from the negative to positive electrode. The ECG recorder computes the difference (magnitude) between the positive and negative electrodes.

A good mathematical tool for representing the measurement of a lead is the vector. A vector is defined as an arrow whose head points in the positive direction. The length of the arrow is proportional to the magnitude of the lead.

**Einthoven's Triangle** is defined as a configuration of three leads, with the polarity shown in Fig. 6.2: Lead I goes from right to left shoulder, Lead II from right shoulder to groin area, and Lead III from left shoulder to groin area. To simplify calculations, the triangle will be assumed to be an equilateral triangle. Since the legs and arms act as simple extensions of points in the torso, we can also re-define the leads as follows:

<table>
<thead>
<tr>
<th>Lead</th>
<th>Right Arm (RA) &quot;-&quot; electrode</th>
<th>Left Arm (LA) &quot;+&quot; electrode</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lead I</td>
<td>Right Arm (RA) &quot;-&quot; electrode</td>
<td>Left Arm (LA) &quot;+&quot; electrode</td>
</tr>
<tr>
<td>Lead II</td>
<td>Right Leg (LL) &quot;-&quot; electrode</td>
<td>Left Leg (LL) &quot;+&quot; electrode</td>
</tr>
<tr>
<td>Lead III</td>
<td>Left Arm (LA) &quot;-&quot; electrode</td>
<td>Left Leg (LL) &quot;+&quot; electrode</td>
</tr>
</tbody>
</table>
The direction of the lead must be paid attention to. This lead configuration is called the standard bipolar limb lead.

Einthoven's Law is stated mathematically as follows: Lead I + Lead III = Lead II. Therefore, if any two leads are known at a given time, the third lead can be determined mathematically.

Figure 6.3 shows another way to look at Einthoven’s Triangle. You can move each axis horizontally or vertically and still have the same representation. This makes it a little easier to visualize the mean electrical axis of the heart.
The electrical activity of the heart at any instant in time can be represented by a vector. The **mean electrical axis** of the heart is the summation of all the vectors occurring in a cardiac cycle. Since the QRS interval caused by ventricular depolarization represents the majority of the electrical activity of the heart, you can approximate the mean electrical axis by looking only in this interval.

A further approximation can be made by looking only at the peak of the R wave, which makes up the largest magnitude in the cardiac cycle. To define the mean electrical axis precisely, you need to define it in three dimensions (X, Y, and Z). This is done in practice by using a standardized set of 12 Leads. Three of these leads are the ones previously defined and allow the mean electrical axis to be calculated in the frontal plane. This lesson focuses on only the frontal plane axis.

![Diagram of mean electrical axis and magnitude of R wave from leads]

Fig. 6.4

As mentioned above, one way to approximate the mean electrical axis in the frontal plane is to plot the magnitude of the R-wave from Lead I and Lead III (Fig. 6.4). To do this:

1. Draw a perpendicular line from the ends of the vectors (right angles to the axis of the Lead)
2. Determine the point of intersection of these two perpendicular lines.
3. Draw a new vector from point 0,0 to the point of intersection.

The direction of the resulting vector approximates the mean electrical axis of the heart. The length of the vector approximates the mean potential of the heart.

A more accurate method of approximating the mean electrical axis is to algebraically add the Q, R, and S potentials for one lead, instead of using just the magnitude of the R wave. The rest of the procedure would be the same as outlined above.

It is important to note that, because the body is not a perfect conductor and electrodes are not perfect attachments to the skin (among many other reasons), ECG measurements from the surface of the skin only approximate the actual activity of the heart.
II. EXPERIMENTAL OBJECTIVES

1) Record ECG from Leads I and III in the following conditions: lying down, sitting up, and breathing deeply while sitting.

2) Review the ECGs for Lead II.

3) Correlate the direction of the QRS Complex (+ or −) with the direction of the lead axis.

4) Estimate the mean electrical axis of the QRS complex using two methods.

III. MATERIALS

➤ BIOPAC electrode lead set (SS2L), Qty - 2
➤ BIOPAC disposable vinyl electrodes (EL503), 6 electrodes per subject
➤ Cot or lab table and pillow
➤ Protractor
➤ Two different colored pens/pencils
➤ BIOPAC electrode gel (GEL1) and abrasive pad (ELPAD)
  or
  Skin cleanser or alcohol prep
➤ Computer system:
  Macintosh* - minimum 68020
  or
  PC running Windows 95*
➤ Memory requirements:
  The Biopac Student Lab application needs to have at least 4MB of RAM available for its needs. This is 4MB above and beyond the operating system needs and any other programs that are running.
➤ BIOPAC Student Lab software V3.0
➤ BIOPAC acquisition unit (MP30)
➤ BIOPAC wall transformer (AC100A)
➤ BIOPAC serial cable (CBLSERA)
IV. EXPERIMENTAL METHODS

Overview

➢ As you complete the Experimental Methods (Set Up, Calibration, and Recording) and the Analysis, you may need to use the following tools and/or display options. The window display shown below is only a reference sample — it does not represent any lesson specific data. The sample screen shows 3 channels of data and four channel measurement boxes, but your screen display may vary between lessons and at different points within the same lesson.

The symbols explained below are used throughout Experimental Methods and Analysis.

Key to Symbols

📖 If you encounter a problem or need further explanation of a concept, refer to the Orientation Chapter for more details.

📅 The data collected in the step needs to be recorded in the Data Report (in the section indicated by the alpha character). You can record the data individually by hand or choose Edit > Journal > Paste measurements to paste the data to your journal for future reference.

▽ Most markers and labels are automatic. Markers appear at the top of the window as inverted triangles. This symbol is used to indicate that you need to insert a marker and key in a marker label similar to the text in quotes. You can insert and label the marker during or after acquisition. On a Mac, press “ESC” and on a PC, press “F9.”

➢ Each section is presented in a two-column format, as described below.

**FAST TRACK STEPS**

This side of the lesson (left, shaded column) is the “FAST TRACK” through the lesson, which contains a basic explanation of each step.

**DETAILED EXPLANATION OF STEPS**

This side of the lesson contains more detailed information to clarify the steps and/or concepts in the FAST TRACK, and may include reference diagrams, illustrations, and screen shots.
A. SET UP

FAST TRACK Set Up

1. Turn the computer ON.

2. Make sure the BIOPAC MP30 unit is turned OFF.

3. Plug the equipment in as follows:
   - Electrode lead (SS2L) — CH 1
   - Electrode lead (SS2L) — CH 3

4. Turn the MP30 Data Acquisition Unit ON.

5. Place six electrodes on the Subject, as shown in Fig. 6.6.

Detailed Explanation of Set Up Steps

The desktop should appear on the monitor. If it does not appear, ask the laboratory instructor for assistance.

Fig. 6.5

Fig. 6.6 Electrode placement

Place six electrodes as shown in Fig. 6.6:

- two electrodes on the right ankle, just above the ankle bone
- one electrode on the left leg, just above the ankle bone
- two electrodes on the left wrist (same side of arm as the palm of hand)
6. Attach the first electrode lead set (SS2L) from Channel 1 to the electrodes, following Fig. 6.7.

- one electrode on the right wrist (same side of arm as the palm of hand).

**Note:** For optimal electrode adhesion, the electrodes should be placed on the skin at least 5 minutes before the start of the Calibration procedure.

Each of the pinch connectors on the end of the electrode cable needs to be attached to a specific electrode. The electrode cables are each a different color, and you should follow Fig. 6.7 to ensure that you connect each cable to the proper electrode.

When the electrode cable is connected properly, the LEAD I electrode configuration will be established.

![Diagram of Electrode Lead Connections (Lead I)](image)

- Lead I +
- right forearm
  - WHITE lead
- left forearm
  - RED lead
- right leg
  - BLACK lead
  (Ground)

**Fig. 6.7 Electrode lead connections (Lead I)**

The pinch connectors work like a small clothespin, but will only latch onto the nipple of the electrode from one side of the connector.

**Note:** For the two electrodes on the right ankle and the left wrist, Lead I should go to the upper of the two electrodes.
7. Attach the second electrode lead set (SS2L) from Channel 2 to the electrodes, following Fig. 6.8.

Follow Fig. 6.8 to ensure that you connect each cable to the proper electrode.

When the electrode cable is connected properly, the LEAD III electrode configuration will be established.

8. Have the Subject lie down and relax.

Fig. 6.8 Electrode lead connections (Lead III)

Position the electrode cables such that they are not pulling on the electrodes. Connect the electrode cable clip (where the cable meets the three individual colored wires) to a convenient location (can be on the subject’s clothes). This will relieve cable strain.

The Subject should not be in contact with nearby metal objects (faucets, pipes, etc.), and should remove any wrist or ankle bracelets.

9. Start the BIOPAC Student Lab Program.

10. Choose Lesson 6 (L06-ECG-2).

11. Type in your filename.

12. Click OK.

END OF SET UP

Use a unique identifier.  

This ends the Set Up procedure.
B. CALIBRATION

The Calibration procedure establishes the hardware's internal parameters (such as gain, offset, and scaling) and is critical for optimum performance. Pay close attention to the Calibration procedure.

**FAST TRACK Calibration**

1. Double check the electrodes, and make sure the subject is relaxed.

2. Click on Calibrate.

3. Wait for the calibration procedure to stop.

4. Check the calibration data:
   - If similar, proceed to the Recording Lesson Data section.
   - If different, Redo the calibration.

**END CALIBRATION**

**Detailed Explanation of Calibration Steps**

Make sure the electrodes adhere securely to the skin. If they are being pulled up, you will not get a good ECG signal.

The subject must be relaxed during the calibration procedure. The subject’s arms and legs need to be relaxed so that the muscle (EMG) signal does not corrupt the ECG signal.

The Calibrate button is in the upper left corner of the Setup window. This will start the calibration recording.

The subject needs to remain relaxed throughout calibration.

The calibration procedure will stop automatically after 8 seconds.

At the end of the 8-sec calibration recording, the screen should resemble Fig. 6.9.

![Fig. 6.9](image)

There should be a greatly reduced ECG waveform with a relatively flat baseline. If your data resembles Fig. 6.9, proceed to the Data Recording section.

If the data shows any large spikes, jitter, or large baseline drifts, then you should redo the calibration by clicking on the Redo Calibration button and repeating the entire calibration sequence.
C. RECORDING LESSON DATA

FAST TRACK Recording
1. Prepare for the recording.

Detailed Explanation of Steps
You will record two segments, one with the Subject lying down, and another with the Subject sitting up.

In order to work efficiently, read this entire section so you will know what to do before recording.

Check the last line of the journal and note the total amount of time available for the recording. Stop each recording segment as soon as possible so you don’t use an excessive amount of time (time is memory).

Hints for obtaining optimal data:
To minimize muscle (EMG) corruption of the ECG signal and baseline drift:

a) The subject should not talk or laugh during any of the recording segments.

b) When lying down or sitting up, the subject should be completely relaxed.

c) When sitting up, the subject’s arms should be supported on an armrest.

d) The recording should be suspended before the subject prepares for the next recording segment.

e) The subject should breath normally during the recording to minimize EMG from the chest area.

f) Make sure electrodes do not “peel up.”
**Segment 1**

2. Click on **Record**.
3. Record for 20 seconds (Segment 1).
4. Click on **Suspend**.
5. Review the data on the screen.
   - If correct, go to Step 7.

   ![Recording continues...]

   ➤ If incorrect, go to Step 6

6. If data was incorrect, Click on **Redo**.

   You will begin to record data.

   The subject should be in a relaxed state and lying down.
   Markers are automatic.

   The recording should halt, giving you time to review the data.

   If all went well, your data should look similar to Fig. 6.10.

   ![Fig. 6.10 End of Segment 1 (Lying down)]

   The data would be **incorrect** if:

   a) the suspend button was pressed prematurely
   b) An electrode peeled up, giving a large baseline drift
   c) The subject has too much muscle (EMG) artifact

   **Note:** A little baseline drift when the subject breathes in and out is normal and does not indicate incorrect data.

   Click **"Redo"** and repeat Steps 1-5. Note that once you press **Redo**, the data you have just recorded will be erased.
Segment 2

7. Have the subject sit up in a chair, with arms relaxed.

8. Click Resume as soon as possible after the Subject sits up.

9. After 10 seconds of recording, the Subject should breathe in and out such that the breath is audible and the Recorder should insert markers:
   a) at beginning of an inhale.
      \[\text{\textquotedblleft breathe in\textquotedblright}\]
   b) at beginning of an exhale.
      \[\text{\textquotedblleft breathe out\textquotedblright}\]

10. Click on Suspend.
11. Review the data on the screen.

   ➤ If correct, go to Step 13.

   ➤ If incorrect, go to Step 12.

Have the subject sit up in a chair, with arms relaxed (on an arm rest if available).

The recording will resume. In order to capture the heart rate variation, it is important that you resume recording as quickly as possible after the subject has performed the requested task.

However, it is also important that you do not click Record while the subject is in the process of sitting up or you will capture motion artifact.

After about 10 seconds of recording, the Director should instruct the Subject to breathe in such that the inhale and exhale are audible.

Note: Subject should not breathe in too deeply as that will cause excessive EMG or baseline drift.

To insert Markers: Mac = Esc key, PC = F9 key

Note: Do not worry if you do not have time to type in the marker label while recording. This can always be entered or edited after the data is recorded.

The recording should run for about 20 seconds total.

The recording should halt, allowing you to review the data.

If all went well, your data should look similar to Fig. 6.11.

Fig. 6.11 Segment 2 (Sitting Up)

The data would be incorrect if:

a) the Suspend button was pressed prematurely.

b) an electrode peeled up, giving a large baseline drift.

c) the subject has too much muscle (EMG) artifact.

Note: A little baseline drift when the subject breathes in and out is normal and does not indicate incorrect data.
12. If data was incorrect, click on Redo.

13. Click on Done.

14. Remove the electrodes.

Click "Redo" and repeat Steps 7-11. Note that once you press Redo, the data you have just recorded will be erased.

After you press Done, a pop-up window with four options will appear. Make your choice, and continue as directed.

If choosing the "Record from another subject" option:

a) Attach electrodes per Set Up Step 6 and continue the entire lesson from Set Up Step 11.

b) Each person will need to use a unique file name

Remove the electrode cable pinch connectors, and peel off the electrodes. Throw out the electrodes (BIOPAC electrodes are not reusable). Wash the electrode gel residue from the skin, using soap and water. The electrodes may leave a slight ring on the skin for a few hours. This is normal, and does not indicate that anything is wrong.
V. DATA ANALYSIS

FAST TRACK Data Analysis

1. Enter the **Review Saved Data** mode.

Note Channel Number (CH) designations:

<table>
<thead>
<tr>
<th>Channel</th>
<th>Displays</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH 1</td>
<td>Lead I</td>
</tr>
<tr>
<td>CH 3</td>
<td>Lead III</td>
</tr>
<tr>
<td>CH 40</td>
<td>Lead II</td>
</tr>
</tbody>
</table>

2. For each of the leads, note whether the R wave is positive or negative.

3. Setup your display window for optimal viewing of Lead I and Lead III.

<table>
<thead>
<tr>
<th>Channel</th>
<th>Lead</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH 1</td>
<td>Lead I</td>
</tr>
<tr>
<td>CH 3</td>
<td>Lead III</td>
</tr>
</tbody>
</table>

4. Set up the display window for optimal viewing of the first data segment.

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**Detailed Explanation of Data Analysis Steps**

Enter the **Review Saved Data** mode.

**Note:** Following the press of the **Done** button in the previous section, the program used Einthoven's Law to automatically calculate Lead II from Leads I and III. So from the initial two channel recording you will end up with three channels when you enter the Review Saved Data mode (as shown in Fig. 6.12).

![Image of ECG data analysis](image)

**Fig. 6.12**

This is just a visual check as to whether the R wave goes up (positive) or down (negative).

To hide a channel, click on the channel box and hold down: the “option” key on a Mac, or “Ctrl” (Control) on a PC. This will toggle between hiding and showing the data (and your screen may take some time to update).

You also have the option of showing Grids on the screen. This is activated from the “**Display Preferences**” option under the “**File**” menu.

The first data segment is the area from Time 0 to the first marker.

The following tools help you adjust the data window:

- Autoscale horizontal
- Autoscale waveforms
- Vertical (Amplitude) Scroll Bar
- Horizontal (Time) Scroll Bar
- Zoom Tool
- Zoom Previous

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Data Analysis continues...
5. Set up the measurement boxes as follows (see Fig. 6.14):

Channels | Measurement
---------|---------
CH 1     | max     
CH 3     | max     

6. Adjust the data window to display one cardiac cycle in the lying down segment.

7. Use the I-Beam cursor to select the QRS interval.

If all went well, your window should resemble Fig. 6.13.

The measurement boxes are above the marker region in the data window. Each measurement has three sections: channel number, measurement type, and result. The first two sections are pull-down menus that are activated when you click on them.

**max**: The maximum amplitude value within the area selected by the I-Beam tool (including the endpoints).

The "Lying down" segment is the one before the first marker, and represents the time when the Subject was lying down, breathing normally, in a relaxed state (Fig. 6.14).

You'll use the recorded measurements to construct the graphical estimate of the Mean Electrical Axis in the Data Report.
8. Place a marker to indicate where the QRS measurement was taken.

9. Repeat Step 5 for a cardiac cycle in the sitting up segment.

10. Repeat Step 5 for a cardiac cycle in the "breathe in" segment.

11. Repeat Step 5 for a cardiac cycle in the "breathe out" segment.

12. Set up the measurement boxes as follows:

<table>
<thead>
<tr>
<th>Channel</th>
<th>Measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH 1</td>
<td>Δ</td>
</tr>
<tr>
<td>CH 3</td>
<td>Δ</td>
</tr>
</tbody>
</table>

13. Go back to the Measurement 1 marker created in Step 7.

14. Measure and record the amplitudes of the Q, R, and S waves individually for both Lead I and Lead III.

   C

To insert Markers: Mac = Esc key, PC = F9 key

To place a marker after the data has been recorded, click in the marker region (region above the top channel). Place this directly above the selected R wave. An arrow should appear. Type in "Measurement 1."

Use the markers to find the proper data segment. Do not use a segment between the "breathe in" and "breathe out" markers.

The Delta Amplitude (Δ) measurement computes the difference in amplitude between the first point and the last point of the selected area. It is particularly useful for taking ECG measurements, because the baseline does not have to be at zero to obtain accurate, quick measurements.

Note: You must pay attention to the polarity of the Δ measurement as it is based on (first point – last point). If the point at the start of the selected area is larger than the last point in the selected area, the polarity will be positive, and vice-versa.

This was the same QRS region you used the first time you did Step 6. It represents a QRS cycle in the lying down, relaxed state.

You can use the marker arrows to the right of the marker region to go to different markers.

You will be taking a total of 6 measurements.

You may wish to look at one channel at a time by hiding the other channel(s) using the channel boxes. To measure a peak, go from the baseline (Isoelectric Line) to the peak of the wave.

Data Analysis continues...
15. Save or print the data file.

16. Exit the program.

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**Fig. 6.16 Sample measurement of the R wave peak**

You may save the data to a floppy drive, save notes that are in the journal, or print the data file.

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**END OF LESSON 6**

Complete the Lesson 6 Data Report that follows.