BioRadio® 110 Lab Book
Student Edition
Fundamentals of Physiological Monitoring
BioRadio Laboratory Manual

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Contents: Laboratory 1 covers a basic introduction to human biopotentials. The lab will explain what a biopotential is, how they are measured, and what they are used for. The lab will discuss the basic origins of human biopotentials including how they arise from ionic currents, the Hodgkin-Huxley model of the giant squid axon, resting and active ion channels, and Nernst’s potential. In addition, different types of electrodes used to measure biopotentials are reviewed.

Lab 2 – Introduction to Data Acquisition and the BioRadio pp. 21-33

Contents: Laboratory 2 covers material that is needed to complete the rest of the laboratories in this book. Basics of data acquisition are covered including instrumentation amplifiers, sources of noise in biopotential measurements, and sampling theory. Finally, the lab discusses how to configure and use the BioRadio to monitor and record physiological signals. Students will record a signal from the BioRadio test pack, export the data to ASCII, and plot and analyze the signal.

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Contents: Laboratory 4 covers the electroencephalogram (EEG). The anatomy and topographical organization of the brain will be reviewed. The origin of the EEG signal will be explained and related to normal brain activity. The alpha, beta, theta, and delta waves will be discussed including their signal characteristics, anatomical locations, and information content. Abnormalities in the EEG signal will be related to epilepsy. Students will apply gold cup electrodes to a subject’s scalp to measure and record EEG. Students will attempt to record alpha waves. Testing will be completed under various conditions including the eyes open and closed and limb movements. Typical problems with recording the EEG signal will be discussed. Data analysis will include signal processing, noise analysis, and spectral analysis of the EEG signal that they record.
Lab 5 – The Electromyogram

Contents: Laboratory 5 covers the electromyogram (EMG). The basis for a skeletal muscle contraction will be reviewed from the efferent neurotransmitter release until the insertion of the myosin head. Different types of muscle fibers will be reviewed including fast, slow, oxidative, and glycolytic. Recruitment properties of the muscle including spatial and temporal summation will be reviewed along with how twitches sum to form tetanic contractions. The characteristics of the EMG signal will be reviewed with its relation to the output force of a muscle. Students will record EMG from the biceps and triceps while holding different weights. Data analysis will expose students to signal processing techniques of the EMG signal including rectification, high and low pass filtering, bin integration, and RMS. Trade offs between high and low pass filtering with EMG as a control source will be analyzed.

Lab 6 – The Electro-oculogram

Contents: Laboratory 6 covers the electro-oculogram (EOG). This laboratory will review the dipole formed by the cornea and the retina and how the electric field changes as a result of eye movement. It will illustrate to students how the EOG can be used to detect eye blinks and eye movement. Students will learn how the electrodes can be setup to differentiate between up, down, left, and right movement.

Lab 7 – Signal Processing and Artifact Removal

Contents: Laboratory 7 monitors EEG, EMG, and EOG while a subject chews and talks. This lab will illustrate to students the difficulty in separating EMG, EEG, and EOG signals. Spectral analysis of the signals will be performed. Students will attempt to design filters that will allow them to extract specific information.

Lab 8 – Polysomnography

Contents: Laboratory 8 covers a polysomnograph (PSG) study. Students will use the experience that they have gained in previous labs to complete an overnight sleep study on a subject. Several sleep disorders will be reviewed. Students will measure 2 channels of EEG, 2 channels of EOG, ECG, and chin EMG. In addition, students will be exposed to using mechanical sensors to record physiological signals. These will include a respiratory effort belt that uses a resistive element and a nasal and oral thermocouple cannula to detect breathing. Data analysis will give students some experience with sleep staging and typical problems that occur with PSG studies.

Lab 9 – Sports and Exercise Lab

Contents: Laboratory 9 allows students to perform a sports analysis. Several physiological measurements will be made during three experiments. These experiments are designed to illustrate concentration and coordination in activities and how these parameters can be monitored through biopotentials to improve performance.

Lab 10 – Student Designed Lab

Contents: Laboratory 10 allows students to design their own experiments. Students will be asked to make a hypothesis about a biological system. They hypothesis should be one that they can answer using the BioRadio 110 Lab Kit. Students will then use the methods that they have learned throughout the book to measure and record the desired physiological signals. They will then use these results to test their hypothesis. Some example of hypotheses may be to determine when an athlete is “in the zone”, biofeedback and meditation, or efficiency of work.
Appendix A – Exporting Files from BioRadio to ASCII pp. 147-154

Contents: Appendix A contains information on how to open files with the BioRadio software and then export the file to ASCII. It illustrates how whole files or portions of BioRadio files can be exported to ASCII files. In addition, it illustrate examples of how these ASCII files can then be imported into Excel and MATLAB.

Appendix B – BioRadio DSP Toolbox Software pp. 155-161

Contents: Appendix B contains information on using the BioRadio DSP Toolbox software that is included on a CD with this laboratory kit. This software is imports ASCII files that were exported by the BioRadio Capture software. This software has features for spectral analysis, filtering, and processing of data that are not possible with the BioRadio Capture software.
Lab 1

Introduction to Biopotentials
Introduction

The human body is beautifully complex consisting of mechanical, electrical, and chemical systems that allow us to function. An example of a mechanical system is the actin and myosin filaments found in muscles that allow them to contract. Chemical systems include the neurotransmitters that are released by neurons for communication with other cells. Finally, electrical systems include the electrical potentials that propagate down nerve cells and muscle fibers. These potentials are responsible for brain function, muscle movement, cardiac function, eye movement, sensory function, and many other events in the body (Figure 1.1). These electrical potentials are created by the flow of ions in and out of cells. The flow of these charged ions creates potential differences between the inside and outside of cells. These potential differences are called biopotentials. Biopotentials are measurable with electronic devices and give insight into the functioning of various systems of the body.

Figure 1.1: The body produces many different types of biopotentials. Sources of this potential include skeletal muscle, the brain, the heart, and the eye. Each of these organs produces electrical activity that can be recorded on the surface of the skin.
Background

**Human Biopotentials**

A typical nerve cell is made up of a cell body, an axon, and dendrites (Figure 1.2A). The cell body contains the nucleus or command center of the cell, the axon responsible for transmitting the action potential along the cell, and the dendrites responsible for receiving inputs to the cell in the form of neurotransmitters. Nerve and muscle cells in the body communicate with each other via action potentials. Action potentials are voltage impulses that propagate along a nerve or muscle and may cause neurotransmitter release when the action potential reaches a specific area of the nerve cell. A typical action potential recorded from a muscle is shown in Figure 1.2B. These voltage impulses arise from tiny currents in the nerve and muscle cells. These currents are a result of charged ions flowing in and out of voltage-gated channels in the membrane of the cells. You should remember from basic circuits that $V=IR$, where $V$ is a measured voltage, $I$ is a current, and $R$ is a resistance. The membrane of the cell has a specific resistance. Therefore, the ionic currents flowing through the membrane of the cell create a voltage i.e., a biopotential.

![Typical nerve cell](image1)

**Figure 1.2**: A) A typical nerve cell. B) A typical muscle action potential, with resting potential at -70 mV.

The membrane of a cell is a layer of lipids. The lipid membrane separates the inner structures of the cell from the rest of the body. There are specific concentrations of ions inside and outside of the cell. Examples of these ions are sodium (Na$^+$), potassium (K$^+$), and chloride (Cl$^-$). These ions are either positively or negatively charged. Therefore, a separation of charge exists across a cell membrane. The standard convention used in neurology is that the potential of the cell is the relative potential inside the cell with respect to the outside of the cell. All along the cell membrane there are openings or channels made of proteins. These channels allow ions to flow in and out of the cell. Each channel is specific to a specific ion. For example, there are sodium ion channels, potassium ion channels, etc. There are two types of channels that transverse the cell membrane, resting channels and gated channels. Resting channels are open all of the time and along with active ion pumps are responsible for maintaining the resting membrane potential of a cell. The gated channels will be discussed later in this laboratory.
There are two major forces that determine how ions will flow in and out of a cell at rest. One is a chemical force and the other is an electrical force. When a cell is at rest there is a high concentration of sodium outside of the cell and a low concentration of sodium inside the cell (Figure 1.3). On the other hand, there is a high concentration of potassium inside the cell and a low concentration outside of the cell. Therefore, a chemical concentration gradient exists for each ion. For example, consider the potassium ion. Since there is a high concentration inside the cell and a low concentration outside, the potassium ions inside the cell begin to move through the resting potassium channels to the outside of the cell. These ions are positively charged. Therefore, as they move out of the cell, the outside of the cell becomes more positive than the inside and a potential difference develops across the cell membrane. This separation of charge across the membrane creates the second major force involved in the resting potential, the electrical force. When this electrical force is equal to the chemical force of the concentration gradient, a steady state potential will be reached. However, sodium is also important in the nerve cell. The same process occurs with sodium as with potassium. Sodium ions flow into the cell due to the concentration gradient. The flow of positively charged sodium flowing into the cell balances the flow of positively charged potassium out of the cell and a steady state potential is maintained.

**Figure 1.3:** The resting potential of a cell is determined by the resting ion channels, the concentration of ions inside and outside of a cell, and the potential difference across the cell membrane. The concentration gradient causes positively charged potassium to flow out of the cell and causes the outside of the cell to become more positive.
The potential that is created can be determined by Nernst’s equation. Nernst’s equation describes the relationship between the concentration of an ion outside and inside of a cell and the cellular potential \( V \). Nernst’s equation is:

\[
V = \frac{RT}{zF} \ln \frac{[X_{ext}]}{[X_{int}]}
\]

Where \( R \) is the gas constant, \( T \) is temperature in Kelvin, \( F \) is Faraday’s constant, \( z \) is the valence of the ion, \([X]\) is the ionic concentration, externally and internally.

In addition to the passive process described above, there is an active process that occurs in the cell to maintain its steady state potential. If the passive process were allowed to continue with no intervention the ionic concentrations would begin to dissipate, i.e. most of the potassium would eventually flow out of the cell and a large amount of sodium would flow into the cell. Therefore, a sodium-potassium pump also exists in the cell. This pump acts to force sodium and potassium ions against their concentration gradients and hence maintain proper concentration of ions in the cell without disturbing the steady state resting potential. A cell at rest is therefore not really at rest, but the potential difference across the membrane is in a steady state condition.

The cell membrane is not always at rest. During the action potential, the membrane of a cell is very active, voltage-gated channels begin to open and allow large fluxes of ions in and out of the cell. This causes a large change in the potential difference across the membrane of the cell. An action potential can occur when dendrites receive neurotransmitters from another cell. These neurotransmitters cause voltage-gated channels to open and ions to start flowing. If the neurotransmitter release was strong enough, an action potential can result. The following will explain voltage gated ion channels and how the action potential arises.

In the early 1950’s, two scientists from Britain, Alan Hodgkin and Andrew Huxley discovered how the action potential was generated using a giant squid axon and later received the Nobel Prize for their work. This giant squid axon is a very large nerve cell that they manipulated using a voltage clamp instrument. A voltage clamp instrument uses feedback circuitry to fix the potential of a cell or neuron at a desired potential. As stated earlier, the membrane of nerve cells also contains voltage gated ion channels. As the potential of the inside of the cell changes with respect to the outside of the cell it causes these gates to open and ions to flow. As ions flow in and out, it further depolarizes the cell and causes more gates to open. This in turn causes a greater change in potential and even more channels to open. As you can see, this process would keep occurring until all the possible channels were opened. However, since the voltage clamp instrument uses feedback circuitry to apply sufficient current in the opposite polarity, the voltage on the cell does not change and is therefore “clamped”. Researchers determined the membrane ionic current through ion channels at specific potentials by measuring the amount of current required by the voltage clamp to maintain the cell at a specific potential.

Hodgkin and Huxley concluded that the depolarization (the inside of the cell becoming more positive with respect to the outside) associated with the action potential was related to the permeability of \( \text{Na}^+ \) and the repolarization (the inside of the cell returning to its original potential with respect to the outside of the cell) with the permeability of \( \text{K}^+ \). To test this,
Hodgkin and Huxley used the voltage clamp to create various step potentials and measured the current of the various ionic channels through the cell membrane. In order to record one specific type of ion channel (either K+ or Na+), drugs were used to block the other channels. Hodgkin and Huxley discovered that sodium channels created a sharp inward current during the beginning action potential while later in the action potential potassium channels created a current that flowed out of the cell. At the start of the action potential the voltage-gated sodium channels quickly open and sodium ions flow into the cell. These ions are positively charged, therefore, the inside of the cell becomes more positive. Since the potential increases, more sodium channels open and the cell is further depolarized. This cycle continues until the peak of the action potential is reached. At this point, the slower potassium channels open, allowing positively charged potassium ions to flow back out to the extracellular solution, causing the repolarization of the cell. The currents and conductances of sodium and potassium can be seen in Figure 1.4 as a function of a step change in the membrane potential.

![Figure 1.4](image-url)

**Figure 1.4:** A) A step change in membrane potential to depolarize the cell will cause ions to flow in and out of the cell. B) As a result of the change in potential, first the sodium channels open, creating a sharp inward Na+ current to the cell. The potassium gates open much more slowly, therefore, after the Na+ current has reached its peak, the K+ gates open and potassium begins to flow out of the cell. C) The currents that are produced are a result of the conductance of the cell to the two ions.
Another way to understand the membrane voltage and ionic current from the action potential is to look at an equivalent circuit of a nerve cell (Figure 1.5). Part of the cell membrane can be modeled as a capacitor since it separates charges on the inside and outside of the cell. At the same time, there are gates in the membrane that control the conductance of various ions. This conductance can be directly translated to resistance, since conductance is simply the inverse of resistance. So, the cell membrane is modeled as a resistor and capacitor in parallel. In addition, the cytoplasm inside the cell represents another source of resistance. The extracellular fluids and tissues present a finite resistance to the flow of action currents, creating the extracellular potential gradients that form the basis of most electrophysiological methods. However for most models, the outside of the membrane is usually represented as a shorted wire. Researchers have used this model to better understand how an action potential propagates down a nerve cell.

![Figure 1.5: Equivalent Circuit Model for the Cell.](image)

**Examples of Biopotentials**

In order to measure the potentials from a single cell, invasive recording instruments are necessary. For the purposes of the laboratories in this lab book we will be measuring electrical potentials on the surface of the skin. Electrical potentials measured on the skin are not the result of a single cell, but are the combination of a large number of cells firing together. These cells may be firing synchronously or asynchronously.

There are many different sources of biopotentials. One of the most popular electrophysiological measurements is the electrocardiogram (ECG) (Figure 1.6). As the heart pumps blood, different chambers of cardiac muscle are activated in a specific order. The ECG waveform represents the rhythmical depolarization and repolarization of each chamber of the heart. The ECG can be used to determine whether the heart is functioning properly or conduction problems exist.
Another source of human biopotentials is the electroencephalogram (EEG). EEG signals measure the electrical activity of neurons in the brain. Surface EEG from the scalp is extremely low voltage, ranging from 5 - 200 microvolts. Unlike the ECG signal, EEG recordings do not have a discernable pattern during normal waking activity. The EEG can be used to detect states of sleep and awareness. It can also be used to detect neurological disorders such as epilepsy. Shown below in Table 1.1 are the typical rhythms monitored by an EEG.

<table>
<thead>
<tr>
<th>Common EEG Activity</th>
<th>Frequency Range</th>
<th>Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alpha Rhythm</td>
<td>8 - 13 Hz</td>
<td>Quiet Resting Activity, eyes closed</td>
</tr>
<tr>
<td>Beta Rhythm</td>
<td>13 - 22 Hz</td>
<td>Awake, Attentive state</td>
</tr>
<tr>
<td>Delta Rhythm</td>
<td>0.5 - 4 Hz</td>
<td>Stressful activity or some brain disorders</td>
</tr>
<tr>
<td>Theta Rhythm</td>
<td>4 - 8 Hz</td>
<td>Deep Sleep, brain disorders</td>
</tr>
</tbody>
</table>

Table 1.1: Common frequencies found in EEG recordings and their associated conditions.

Electromyograms (EMG) are recordings of skeletal muscle potential. Just as the nerves that innervate them, skeletal muscle tissue carries action potentials. The EMG signal can be on the order of millivolts. EMG measurements are an indicator of muscle force. The amplitude of the recording is related to the amount of force generated from the muscle contraction. EMG potentials can be used to diagnose muscle disorders and also have applications in sports medicine, where muscle potentials could be recorded and analyzed to help increase an athlete’s performance.

Biopotentials can also be recorded from the eye. One popular biopotential recorded from the eye is the electro-oculogram (EOG). The eye can be modeled as a dipole with the retina and cornea acting as the two ends. To measure an EOG, surface electrodes are placed next to the eyes. As the eye moves back and forth the field generated by the dipole changes direction and hence the potential measured by the electrode changes. The EOG can effectively measure the eye’s horizontal deflection up to approximately ±30 degrees.
Electrodes

As discussed above, physiological potentials arise from ionic currents flowing in and out of a nerve or muscle cell. This creates the measurable potential difference on the surface of the skin. There are several types of electrodes that are used to record biopotentials. The type of electrode that is used depends on the biopotential that is being measured and the application. An electrode provides the interface between the ionic currents in the body and the electrical currents in the measuring device.

Two types of electrodes exist theoretically, polarizable and nonpolarizable electrodes. Electrode polarization is a function of three components. These components include an ohmic overvoltage, a concentration overvoltage, and an activation overvoltage. The ohmic overvoltage refers to the voltage potential that arises from the current flowing through the electrode-electrolyte interface. The concentration overvoltage is a result of the alterations in the local ionic concentrations around the electrode. Finally, the activation overvoltage is a function of the electrode structure changing over time. When current is passed through the electrode deposition and dissolution can occur on the electrode surface changing the electrode properties for passing current. The goal in fabricating an electrode is to minimize all of these components so that the electrode has the same characteristics over time. A perfectly nonpolarizable electrode is not possible in the real world, therefore, electrodes are designed as close to this as possible.

There are several different types of electrodes that are suited for particular biomedical applications. One of the most common types is the metal plate snap electrode (Figure 1.7). This electrode consists of a small metal disc, generally silver or silver plated with silver chloride, surrounded by foam padding with an adhesive. There is a metal snap on the other side of the electrode that connects to snap leads. These leads are then connected to an instrumentation amplifier. The silver-silver chloride electrode is considered nonpolarizable. It provides a stable output over time, it can perform DC recording, has low noise, and a small amount of drift. These snap electrodes are frequently used for ECG and EMG recordings. For EMG, the electrodes may have a less reactive metal, such as stainless steel, gold or platinum to avoid any reaction between the metal and perspiration coming from the skin. Other variations on the metal plate snap electrodes are long curved rectangular plates that can be placed flush on a limb, or metal discs that are attached with surgical tape.

Another modification to the metal plate electrode is the suction electrode. This electrode has a bell-shaped metal surface with a small rubber bulb above it. The electrode is attached by coating gel on the metal contact surface, squeezing the rubber bulb, pushing the electrode against the chest, and releasing the bulb. The suction electrode gives a better connection between the skin and the electrode. However, these types of electrodes can only be used for brief amounts of time since the suction would eventually cause some irritation on the skin of the patient.
Gold cup electrodes are frequently used for EEG recordings (Figure 1.7). They may also be used to record EOG and EMG from facial muscles. These electrodes are smaller than metal disc electrodes and are shaped like a cup. The small size of these electrodes allow easier placement on the head, since the hair would interfere with a larger metal disc electrode. Unlike the snap electrodes, which have an adhesive backing, these cup electrodes require a paste to adhere the electrodes to the skin. These electrodes are filled with a conductive paste, pressed against the scalp, and then taped to the head. Gauze may also be used to wrap the head to hold these electrodes in place.

![Snap Electrodes](image1)

![Gold Cup Electrodes](image2)

**Figure 1.7.** Snap leads can be used to measure EMG, ECG, and EOG, while the gold cup electrodes can be used for EEG recordings.

Since some locations on the body are not flat, electrodes are needed that can be deformed to fit flush against the skin. For these cases, flexible electrodes can be used. These electrodes are constructed with either a fabric that is impregnated with silver particles or a conducting rubber pad. Sometimes measurements need to be conducted below the skin. Percutaneous electrodes are used for these applications. Percutaneous electrodes usually have a deinsulated end and are inserted through the skin and into the target muscle or next to the target nerve to be monitored. These electrodes are often used for monitoring EMG from deep muscles. These electrodes allow for a highly localized recording. Since these electrodes are placed directly in the tissue to be recorded, fewer artifacts are likely and the recordings are of higher amplitude due to the proximity of the signal source. The laboratories in this book will not require the use of percutaneous electrodes.

Electrodes are not always passive devices. Electrodes may also be used to electrically stimulate tissues and nerves. Stimulating electrodes deliver a current to tissue and nerves. One application of stimulating electrodes is cardiac pacing. During cardiac pacing an implanted electronic device delivers stimulating pulses to the heart to regulate the heartbeat. In addition to cardiac pacemakers, stimulating electrodes have been used in functional electrical stimulation of paralyzed skeletal muscles in spinal cord injury patients to restore motor function. Current research also focuses on using electrical stimulation to treat neurological disorders, such as Parkinson’s disease and epilepsy, by stimulating areas of the deep brain.
Skin Preparation for Surface Electrodes

For each of the laboratories that you will be completing in this book, the surface of the skin needs to be properly prepared before placing recording electrodes on it. Properly preparing the skin allows for better conductance of the signal that is to be measured. The dead layer of skin on the surface of the skin creates a large resistance for the physiological signal to travel through and hence decreases the amplitude of the signal to be recorded. The skin surface should be abraded with a lightly abrasive scrub to remove the dead layer of skin on the surface and improve conductance. For this lab you may use Lemon Prep™ to abrade the skin. Simply use the provided cotton tipped applicators to apply the Lemon Prep™. Gently rub over the surface of the skin where the electrode is to be place with the applicator. The fine granules in the Lemon Prep™ will act to abrade the skin and remove the dead outer layer. Do not rub the skin intensely with the abrasive material so that it turns red, just lightly rub the location a few times in order to remove the dead skin cells. In addition to using an abrasive, often alcohol is used to clean the skin before electrode application. However, the surface electrodes that we are including with this kit recommend using soap and water instead. In some instances it may even be necessary to shave hair off the skin before applying an electrode. However, you should not shave anyone for these labs. For example, before recording ECG from a patient certain areas of their chest may need to be shaved before surface electrodes are applied. In addition to preparing the skin, often times a conductive gel will be placed between the electrode and the skin to further improve signal conductance. You will use a conductive gel during the EEG lab later in this course.

Discussion Questions

1. Given the table below of various ionic concentrations inside and outside the cell, find the Nernst potential of each of these ions at room temperature (25°C). Assume that for a temperature of 25°C, RT/F simplifies to 26mV. The valence of Na and K are 1, while Cl is –1.

<table>
<thead>
<tr>
<th>Ion</th>
<th>External</th>
<th>Internal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Potassium</td>
<td>120 mM</td>
<td>400 mM</td>
</tr>
<tr>
<td>Sodium</td>
<td>440 mM</td>
<td>50 mM</td>
</tr>
<tr>
<td>Chloride</td>
<td>400 mM</td>
<td>60 mM</td>
</tr>
</tbody>
</table>

2. The Nernst potential for a certain single valence ion is at –60 mV. Assuming this measurement is being done within the body (i.e. normal body temperature), find the ratio of the concentration of this ion.

3. Which ion is most responsible for the depolarization of the nerve cell? And for repolarization?
4. Sodium ion channels open much more quickly than the potassium ion channels. Why is this important? Can you hypothesize what the action potential would look like if the potassium channels opened much more quickly than the sodium channels?

5. Notice that the ionic currents for both the potassium and sodium channels don’t respond immediately to the step command from the voltage clamp. Why do you think that the response is not immediate? Hint: Think about how you would calculate current across each element in the membrane in Figure 1.5 from basic circuits.

6. What is the purpose of the voltage clamp? Explain how it is able to keep the cell at a given potential and measure the ionic current of a specific type of channel.

7. List several types of biopotentials that can be measured with surface electrodes. Give applications that each of these biopotentials could be used for.

8. The nerve cell can be modeled as an electrical circuit as shown in Figure 1.5. Explain what each of the components in the circuit represents.

9. Why are gold cup electrodes used to monitor an EEG signal instead of snap electrodes?

10. Why is it important that the electrode location on the skin is properly cleaned before electrodes are placed there? Explain the proper procedure for preparing and cleaning these electrode sites.

**NOTE: Graduate Students Should Continue and Complete the Following Section.**

**Graduate Discussion Questions**

1. The Nernst potential for a single ion is given by Nernst equation. However, as we have seen, the resting membrane potential for a typical nerve cell is governed not just one ion, but by sodium and potassium ions. The equation that governs a resting potential for more than one ion is the Goldman Equation:

\[
V = \frac{RT}{F} \ln \left( \frac{P_{X_{\text{ext}}} [X_{\text{ext}}] + P_{Y_{\text{ext}}} [Y_{\text{ext}}]}{P_{X_{\text{int}}} [X_{\text{int}}] + P_{Y_{\text{int}}} [Y_{\text{int}}]} \right)
\]

Calculate the resting potential for a cell that has both sodium and potassium ions flowing through channels in the membrane. \(P_X\) and \(P_Y\) represent the membrane permeability to the specific ion. Assume a \(P_{X_{\text{Na}}}\) of 0.02 and a \(P_{X_{\text{K}}}\) of 1.00. Assume the same concentrations as shown in the previous section of questions under question 1.

2. Why does repolarization occur slower than depolarization in the cell?
3. In addition to placing surface electrodes on the skin in order to record biopotentials, reference electrodes also need to be placed on the body. Describe what you would consider a “good” location on the body to place a reference electrode.

4. The electrical equivalent circuit shown in Figure 1.5 can be used to represent a nerve fiber. Researchers use this model to determine how action potentials propagate down a nerve fiber. Notice how the extracellular fluid side of the model is just shorted together, while a resistance is used on the intracellular side. Is this accurate in real life? Why or why not and what consequences does this have on measuring biopotentials on the surface of the skin?
References


Lab 2

Introduction to Data Acquisition and the BioRadio
Introduction

Many systems in the body can be modeled as electrical systems that interact with various organs, such as the heart, the brain, and body muscle. These systems communicate by generating electrical impulses. These impulses can often be measured by placing electrodes on the skin. Before the advent of digital acquisition, these electrodes would be connected to pen-based strip-charts. These recorders would move a pen on a moving paper chart to sketch the electrical signal recorded from each electrode.

Electrophysiological measurements can be done digitally with computers and saved on a permanent storage device. The data can be quickly analyzed and manipulated on a computer. Furthermore, this computer-based review is more efficient, since a technologist can save relevant information for later review by a physician as opposed to reviewing a whole hour-long EEG recording which may only have 2-3 minutes of clinically relevant information.

This lab will allow you to examine the contents of the BioRadio Lab Kit, review basic principles of data acquisition, and explore the features available in the BioRadio software by actually recording an electrical signal.

Equipment required:
- BioRadio 110
- BioRadio Lab Kit
- BioRadio User’s Guide
- Microsoft Excel and BioRadio DSP Toolbox
- MATLAB (Graduate Students)

Background

Noise During Recording of Biopotentials

As with any electrical measurements, noise occurs during the recording of biopotentials. Sources of this noise include other electronic laboratory equipment, lights, radios, and cell phones. Noise is an important problem in the recording of biopotentials since the amplitude of biopotentials is often much smaller than that of the noise. One of the most common sources of noise in the recording of biopotentials is 60 Hz AC power in the United States. A patient essentially acts as an antenna that receives this 60 Hz noise. The patient receives this 60 Hz noise through electrical and magnetic field coupling.

Without noise rejection circuits, this 60 Hertz signal would contaminate the electrical signal being measured, particularly if the amplitude of 60 Hz noise is much larger than the biopotentials being recorded. A differential amplifier can be used to greatly reduce this noise. Assume an
electrocardiogram (ECG) measurement was being completed. An ECG measures the electrical activity of the heart. The ECG will be explained in detail in the next lab. It can be measured by placing electrodes on the right and left wrists. Since the 60 Hz noise appears evenly on both wrists whereas the ECG signal is different on both wrists due to the potential difference created by the heart. Subtracting the two channels at the wrists will effectively cancel out the 60 Hz noise, leaving the patient’s ECG signal intact. A differential amplifier is used to perform the subtraction between the two channels. Recall the basic principles of an ideal operational amplifier:

1. The op amp is configured so that the negative and positive input voltages of the operational amplifier are kept equal by the net currents produced by the input and output voltages flowing through the external resistors
2. The operational amplifier has a high gain
3. The operational amplifier has high input impedance and zero output impedance

For our example, the $V^+$ and $V^-$ inputs would be the signals measured from the right wrist and left wrist, and $V^{\text{out}}$ would be the desired ECG signal.

![Image of a simple differential amplifier circuit](image)

**Figure 2.1:** Simple Differential Amplifier.

By the rules of operational amplifiers, we know that $V^+$ equals $V^-$. Solving for $V^+$,

$$V^+ = \frac{V_1 R_4}{R_2 + R_4}$$

Similarly, solving for $V$,

$$V^- = V_1 - \frac{(V_1 - V^{\text{out}}) R_1}{R_1 + R_3}$$

Since we know $V^+ = V^-$, we equate the two equations and solve in terms of $V^{\text{out}}$.

$$V^{\text{out}} = \frac{R_4 (R_1 + R_3)}{R_1 (R_2 + R_4)} V_2 - \frac{R_3}{R_1} V_1$$
In order for this differential amplifier to cancel out signals that are common to both inputs, the coefficients need to be equal. This is done by making $R_1R_4 = R_2R_3$. Doing so reduces the equation to

$$V_{OUT} = \frac{R_1}{R_1}(V_2 - V_1)$$

Thus, the output at $V_{OUT}$ is proportional to the difference of the inputs. So, this value of $R/R_1$ will be the **Differential Gain** of the circuit. A differential gain is a measurement of the amplification done to signals that are different between the two inputs, such as the ECG signal. If the resistance condition above ($R_1R_4 = R_2R_3$) is not met (since real-world resistors cannot be perfectly matched), there will be some gain in the common mode. That common mode gain is measured as:

$$\text{Common Mode Gain} = \frac{R_4R_1 - R_2R_3}{R_1(R_2 + R_4)}$$

Common mode gain is a measurement of the amplification done to signals that are common to both inputs, like 60 Hz noise. Circuit designers can then determine the performance of a differential amplifier by calculating the common mode rejection ratio, or CMRR, which is measured in dB.

$$\text{CMRR (dB)} = 20\log \frac{\text{Differential Gain}}{\text{Common Mode gain}}$$

Typical values for CMRR are 100 dB and higher. Ideally, if the resistors could be perfectly matched, the common mode gain would be zero, making the CMRR infinite.

One problem with the circuit above is that it does not have high input impedance for the two voltage inputs. The voltage inputs usually have sustained source impedances from the tissues and electrodes (Z in Figure 2.2), so attempts to draw a substantial current into the op-amp via low values of R1 and R2 will drag down the recordable potentials. The problem can be solved by adding voltage followers at the two voltage input sources, thus meeting the high input impedance criteria. The combined circuit is a general-purpose instrumentation amplifier (Figure 2.2), since the inputs have only unity gain. The voltage follower has unity gain for voltage, but provides a high input impedance and power gain so that reasonable values can be used for resistors R1-4.
Figure 2.2: General Purpose Instrumentation Amplifier. Note the voltage followers at the two inputs.

The BioRadio already has built-in circuits that utilize instrumentation amplifiers to remove common mode noise from the recorded signals. Some more advanced methods of removing 60-Hertz noise include using notch filters and digital filtering by the computer.

Noise can also arise from the human body itself. There are many biopotentials occurring in the body all the time and it is possible to record an undesired biopotential along with the desired biopotential. For example, electroencephalogram (EEG) (brain wave) recordings can be polluted with noise from other biopotentials. Since the EEG electrodes are attached to the scalp, not only will the electrodes record brainwaves, but it may also pick up electrical signals originating from the scalp muscle if the patient shrugs their forehead or blinks their eye. This type of noise is difficult to remove, but computerized signal processing can be done to remove some of the artifacts created by this noise. In addition, proper placement of the EEG electrodes can help diminish this noise as well.

Some sources of noise are analyzed in the frequency domain. White noise is considered noise that is evenly spread across all frequencies, whereas pink noise is noise that is distributed within a certain frequency band. Another type of noise encountered by engineers is thermal noise. All electronic components, particularly resistors and semiconductors, generate electrical noise from the random motion of electrons, depending on the temperature. Although these topics are not covered here, you should be aware that these sources of noise exist.
**Safety**

Designers of bioinstrumentation must ensure that the chances of passing current from the device to the patient are minimized. This means that biomedical instrumentation designers must ensure that the patient is never connected directly to ground. If a patient is directly connected to ground, equipment failure could lead to electrical currents passing directly across the patient and to ground. Low currents through the skin (from 1 mA to 100 mA), may cause a person to feel a tingling sensation or some moderate pain. However, if this current were to exceed 100 mA, there is a great risk of inducing ventricular fibrillation in the heart. Even lower currents introduced through implanted electrodes or catheters may be fatal. If nothing is done to restart the heart’s natural rhythm, this will quickly lead to death. Therefore, isolating the subject from ground is a paramount issue in patient safety when designing biomedical instrumentation.

For instrumentation that is connected directly to a power source, hardware designers use isolation amplifiers. These are special amplifiers that electrically separate the patient from the power supply and grounding circuitry, either using optical or magnetic (transformer) coupling. With these methods, the patient is not directly connected to any circuitry that may cause a shock hazard. The BioRadio couples the patient using battery powered RF isolation. Since the BioRadio transmits its signals using radio waves and the patient is never directly connected to earth ground, the patient is totally isolated from power and ground lines, preventing risk of shock to the patient. (Figure 2.3)

![Figure 2.3: BioRadio Isolates Patient from a Direct Connection To Ground.](image)

**Data Acquisition**

The BioRadio uses a computer interface to display and record biopotentials. The biopotentials that are recorded have a continuous range of voltages varying over time (analog signals). This means that they have an infinite amount of possible values. Because a computer is digital it cannot record an infinite number of values. Therefore, a computer samples discrete voltage levels at discrete points in time and then reconstructs the continuous signal from these discrete points. Since the computer operates with discrete units of data, we use an analog to digital converter (ADC) to convert between the two. The first step of the ADC is sampling. Sampling works by recording the voltage at a discrete point of time of the original analog signal. Once sampled, this
sample is then converted into a binary value. Typical resolutions for data acquisition are 8, 12, and 16 bits. This process is then repeated for the next sample.

When a computer goes to reconstruct the sampled data to appear as a continuous graph, it connects all the discrete samples together to form a continuous plot. There are many techniques a computer uses to reconnect the points, however they will not be discussed here.

![Analog Signal](image1.png)
![Oversampled Digital Signal](image2.png)
![Undersampled Digital Signal](image3.png)

**Figure 2.3:** When a signal is sampled at a frequency greater than 2 times its highest frequency, it can be accurately reconstructed. Sampling slower, however, leads to aliasing, for example in this case, converting a sinusoidal signal to a DC value.
Other data acquisition issues include aliasing, which according to Nyquist theory requires the sampling rate to be at least two times higher than the highest frequency of the signal being recorded. However, for most practical applications, sampling is done at least 5 times faster than the highest frequency in the signal. Aliasing occurs when the sampling rate is not high enough to appropriately represent all the frequencies in a signal, causing some higher frequency signals to incorrectly appear as lower frequencies (Figure 2.3). In this example, the bottom plot (undersampled) shows the sine wave sampled below the Nyquist rate. Arbitrarily, it sampled at the zero crossings, making what was a 2 Hz signal appear as a DC signal. However, imagine what would happen if this signal was sampled at the Nyquist rate and sampling was started at a zero crossing. The signal would still appear as a DC signal with zero amplitude! Therefore, it is important to sample at a frequency that is greater than 2 times the highest frequency in the signal.

Errors during ADC conversion can occur due to converting continuous data into discrete time data. Quantization error can be thought of as not having sufficient levels to accurately represent the data. For example, a 2-bit system can only represent 2^2 or 4 discrete values whereas an 8-bit system could represent 2^8 or 256 discrete values. The signal being measured is typically divided by the number of discrete values available. For example, imagine a 2-bit system used to measure a 0 - 3 volts signal. Since the system is 2-bit, only four discrete values could be measured. Therefore, the only values you could measure would be 0, 1, 2, and 3 volts. Anything in between these levels would be rounded off to one of these four values. Truncation is responsible for quantization noise. The more bits you have the greater the resolution of your measuring system. Values that go above the range of values that the computer will read will appear as the maximum value that the computer can read. For example, in the previous case, any values above 3 volts would appear as 3 volts. This is known as saturation of the signal. The dynamic response of the system is also an important characteristic. A recording device with ideal dynamic characteristics yields an output that is proportional to the input for all frequencies with no amplitude or phase distortion.

Clinicians are usually interested in recording more than one channel. Instead of having multiple ADCs for each channel, we can “time-share” a single ADC by sending each channel sample in a consecutive fashion. This efficient process is called multiplexing. Multiplexing can be visualized by the following. Imagine 3 channels being recorded, and this data is being sent to the computer in a multiplexed fashion. The data stream going into the computer would appear:

<table>
<thead>
<tr>
<th>Ch. 1: sample 1</th>
<th>Ch. 2: sample 1</th>
<th>Ch. 3: sample 1</th>
<th>Ch. 1: sample 2</th>
<th>Ch. 2: sample 2</th>
<th>Ch. 3: sample 2</th>
<th>Ch. 1: sample 3</th>
<th>Ch. 2: sample 3</th>
<th>Ch. 3: sample 3</th>
<th>etc…</th>
</tr>
</thead>
</table>

Once stored on the computer, the software can de-multiplex the channels and then display each channel individually.

Data acquisition can generate very large files if not carefully monitored. For example, a 10 minute 16 channel EEG recording using a sampling rate of 200 Hz and 16 bits per channel will generate a file that is

\[16 \text{ bits} \times 200 \text{ samples/sec} \times 600 \text{ seconds} \times 16 \text{ channels} = 30,720,000 \text{ bits or 3.84 Megabytes!}\]
Experimental Methods

Experimental Setup

2. Install the BioRadio Capture and Configuration Wizard software on your computer.

Procedure and Data Collection

1. Open the BioRadio Lab Kit and examine the contents. First examine the BioRadio transmitter and receiver. Then examine the universal harness that is included with the kit. The universal harness includes positive and negative connectors for eight channels in addition to two references and a ground. This harness plugs into the BioRadio transmitter as per the User Guide. Notice how the connectors are stackable, i.e. more than one connector could be attached to the same lead (Figure 2.4). Each lead is labeled. Snap leads and gold cup electrode leads can be connected to the stackable outputs from the harness (Figure 2.5). The snap leads connect to snap electrodes for monitoring potentials on the surface of the skin (Figure 2.6). In addition, many other sensors such as piezoelectric respiratory effort belts and nasal/oral airflow thermistors can be connected to the stackable leads.

NOTE: Throughout the experiments in this laboratory book the Universal Harness in these pictures will be setup in different configurations. Some of these configurations will not use all of the channel inputs. The positive and negative inputs of channels that are not used for experiments should be connected to one of the reference inputs on the harness. They should not be left floating during experiments.

Figure 2.4: The harness includes 8 channels of stackable connectors and references.

Figure 2.5: The stackable connectors can be attached to snap leads.

Figure 2.6: The snap leads can then be connected to snap electrodes for monitoring EMG, ECG, EOG, and other physiological signals.
2. Using the Configuration Wizard, setup the BioRadio to record 2 channels of data. Set both channels to record a low level signal. Set the input resolution to 16-bit resolution and note the sampling rate you use. IT IS IMPORTANT THAT YOU NOTE THE SAMPLING RATE THAT YOU USE FOR THIS AND ALL SUBSEQUENT LABS. YOU WILL NEED TO KNOW THIS SAMPLING RATE FOR THE DATA ANALYSIS. Keep the default input ranges, channel names, and RF Frequency, and save the configuration as “Lab 1 BioRadio Configuration.” After configuring the recording options, proceed with programming the transmitter and receiver as per the instructions in the User’s Guide and on the Screen.

3. Exit the Configuration Wizard and run the BioRadio Capture software. Connect the receiver to a serial port on the computer as per the User’s Guide and connect the Test Pack to the transmitter. Turn the Test Pack on. Turn the BioRadio transmitter on. Start the BioRadio Capture as per the User’s Guide. In a few seconds you should begin to view data scrolling across the computer screen. The Test Pack should output a square wave. You may need to adjust the scale or time controls to see the square wave. Verify that you see a test square wave on the screen. Save a few seconds of data to a file. When prompted, name the data file “testsignal.bd”.

4. Stop the capture software and use View mode to open the file you just saved. Export the entire file to an ASCII file. Save it as “testsignal.dat”. Exporting a data file only exports the raw data from the .bd file. Any filtering that you complete with the BioRadio software will not be included with the exported file. ONLY RAW DATA IS EXPORTED.

Data Analysis

1. Using the BioRadio Capture software open the saved data file “testsignal.bd”. The filters in the BioRadio software should be turned off for each of the channels. Print out the plot made with the BioRadio software. Change the amplitude and time scales for each channel in the BioRadio software to get a feel for how the software works. Print out plots with different amplitude and time scales of the data file.

2. Using Excel, open the data file named “testsignal.dat”. The first column in the spreadsheet will be time. Consecutive columns will be the data that was collected. Each column being a different channel. Create and print a plot of the data you collected using Excel. NOTE: Refer to Appendix A of this Laboratory Book for information on opening exported BioRadio data files with Excel.

3. Using the BioRadio Digital Signal Processing Toolbox plot channels 1 and 2 of the file “testsignal.dat” in the time domain. Make sure that all filtering is off. Print this plot. NOTE: Refer to Appendix B of this Laboratory Book for information on using the BioRadio DSP Toolbox.
4. Now select channel 1 to perform a spectral analysis on. Set the start time to 0s and the stop time to 10s. Display unit should be Vrms, Log/Linear should be set to linear, and Window should be set to none. Click on the white button labeled Spectral Analysis. Print this plot.

Discussion Questions

1. In the testsignal.dat file that was recorded, what was the sampling rate used? And based on the number of channels in the file, along with this sampling rate, how many bits per sample were used for this recording?

2. Determine the frequency of the square wave in the test signal from the plots that you made.

3. In the lab procedure, the BioRadio was programmed for 2 channels. How many bits per sample are there? (Hint: refer to the manual) What is the range of values that can be represented by each bit for both the high-level and low-level signals? Would a high number of bits per sample be better for low-level or high-level recordings? Why? In what ways would this affect the amount of data acquired?

4. Assume you are going to use the BioRadio to record two channels for 30-minutes with the BioRadio configuration given in the lab procedure. How many bytes would you expect that file to be?

5. If you wanted to determine the frequency of a rapidly changing signal. Would it be easier to measure the frequency by changing the timescale in View mode to a smaller or larger value? Why?

6. How does the BioRadio ensure that the patient is not at risk for electric shock? What are some other methods for electrically isolating the patient?

7. Assume an instrumentation amplifier has a CMRR of 100 dB and a differential mode gain of 100. What would be the amplitude at the output of the amplifier of 60 Hz noise and an ECG signal? Assume that the surrounding 60 Hz noise signal was 100 mV, and the ECG signal was 1 mV.

8. What sources of noise would you expect when recording EMG, EEG, and EOG signals besides 60 Hz from power sources?

9. If the highest frequency in a given signal is 120 Hz, how fast must the signal be sampled to prevent aliasing?

10. Where does the major peak occur in your spectrum analysis plot? Why does it occur there? What was the frequency of the test pack signal?
NOTE: Graduate Students Should Continue and Complete the Following Section.

Graduate Analysis and Discussion

1. Illustrate, either mathematically or graphically, how an analog signal is sampled. Using this, derive why the Nyquist rate must be at least twice the highest frequency in the signal.

2. The BioRadio allows you to specify the sampling rate and the amount of resolution that you can use. As the sampling rate you specify increases and more channels are used, the amount of resolution that you are allowed to use decreases. Explain this relationship in terms of bandwidth available in an RF signal.

3. Using MATLAB, import the data file “testsignal.dat” and plot the two channels of data versus time. Print this plot. NOTE: Appendix A contains information on reading .dat files into MATLAB creating plots.
References


Lab 3
The Electrocardiogram
Introduction

The body relies on the heart to circulate blood throughout the body. The heart is responsible for pumping oxygenated blood from the lungs out to the body through the arteries and also circulating deoxygenated blood back to the lungs from the body through the veins. The heart is divided into four chambers. Each chamber is responsible for a different part of the circulatory process mentioned above. Deoxygenated blood first comes into the right atrium via the vena cava, where it is then pumped into the right ventricle. The right ventricle pumps this deoxygenated blood through the pulmonary artery to the lungs, where it flows through the alveoli, receives oxygen, and then is returned to the heart by flowing through the pulmonary vein and into the left atrium. The left atrium then pumps this blood into the left ventricle, where then it is pumped out to the rest of the body through the aorta. This process of contracting the different chambers is highly coordinated. This coordination is controlled by specialized regions of the heart responsible for electrical stimulation of cardiac muscle. Like several other bioelectrical signals, these electrical impulses generated by the heart can be measured on the skin with surface electrodes.

Using surface electrodes the cardiac potential in the heart can be measured and correlated with regions of cardiac excitation. This measurement is called an electrocardiogram (ECG). The ECG can be used to evaluate cardiac function, heart rate, and arrhythmias. The electrical activation that creates the normal heartbeat can in some instances cause abnormal cardiac function. Disorders such as bradycardia (slow heart rate), tachycardia (fast heart rate), and electrical conduction problems such as bundle branch blocks can be all diagnosed from the ECG.

Equipment required:

- BioRadio 110
- BioRadio Lab Kit
- Microsoft Excel and BioRadio DSP Toolbox
- Protractor
- MATLAB (Graduate Students)
Background

Cardiac Contraction

As mentioned above, a series of events occur in a specific order during a normal heartbeat. This process is called the cardiac cycle. The cardiac cycle can be broken down into two components, systole and diastole. Diastole occurs when the heart muscle is relaxed and begins to fill with venous blood in the right atrium, and oxygenated blood in the left atrium. Systole is the time when the heart contracts. During systole the heart forces oxygenated blood out of the left ventricle and deoxygenated blood to the lungs through the right ventricle.

Deoxygenated blood first enters the heart via the superior and inferior vena cava and fills the right atrium. Contraction of the atria causes this blood to be pumped into the right ventricle. After blood fills the right ventricle, it contracts and the tricuspid valve closes, preventing backflow of venous blood into the right atrium. As the right ventricle contracts to pumps venous blood to the lungs, the pulmonary valve opens to allow the blood to flow through the pulmonary artery to the lungs. The valve then closes to prevent backflow of the blood into the right ventricle. This blood then flows to the lungs and the red blood cells receive oxygen. This oxygenated blood then returns to the heart via the pulmonary vein and fills the left atrium. As the left atrium contracts, the mitral valve opens, sending blood into the left ventricle. Similar to the right ventricle, as the left ventricle contracts, the mitral valve closes to prevent backflow into the atria, and the aortic valve opens, sending the oxygenated blood out of the heart through the aorta. After this oxygenated blood flows through the aorta, the aortic valve closes again to prevent backflow of this blood into the left ventricle.

![Diagram of the heart showing blood flow from right atrium to right ventricle, through the lungs, to the left atrium, left ventricle, and out to the body.]

**Figure 3.1:** Blood in the heart travels from the right atrium to the right ventricle and into the lungs. After receiving oxygen in the lungs, the blood travels to the left atrium, the left ventricle and then out to the body.
Special Conductive Tissues in the Heart

There are several specialized regions within the heart to initiate electrical signals that cause cardiac contraction. The primary area responsible for cardiac activation is the sinus node (also known as the sinoatrial or SA node). The SA node is located at the top of the right atrium and is the major structure responsible for pacing the heart. Connecting the SA node to atrioventricular (AV) node are the internodal pathways. These internodal pathways are located along the walls of the right atrium. The electrical signal propagates down the internodal pathways and enters the AV node. At the AV node the signal is slightly delayed. The AV node is located in the heart septum, between the right and left atrium. After the AV node, the electrical signal flows through the Bundle of His, located in the septal wall between the left and right ventricles. The Bundle of His then divides into two branches, the right branch and left branch. These branches continue along the septal wall, and then go into the Purkinje fibers, which innervate the right and left ventricular walls.

Figure 3.2: Conducting Pathways of the Heart

Origin of the ECG Signal

In normal cases, the SA node is the heart’s natural pacemaker with the autonomic nervous system to regulate its excitation. Therefore, the electrical impulse responsible for the cardiac cycle originates at the SA node. Pulses from the SA node propagate via the internodal fibers of the right atrium, and then to the left atrium, causing immediate atrial contraction. This electrical potential then travels to the AV node. At the AV node, the depolarization potential is then
delayed, allowing the atria to fully contract. This delay allows the atrium to completely empty its contents into the ventricles before ventricular contraction. After this delay in the AV node, the potential travels down the Bundle of His, which then splits into the right and left branch bundles. These bundles then innervate the ventricular walls via the Purkinje fibers. When the signal reaches the Purkinje fibers, ventricular contraction occurs sending blood from the right ventricle into the lungs and blood from the left ventricle out the aorta. This process then repeats for the next heartbeat.

Other tissues in the heart also have natural pacing rates controlled by the autonomic nervous system. The AV node, without outside stimulation, has a natural discharge rate of 40 to 60 times a minute, while the Purkinje fibers fire between 15 and 40 times a minute. This is in contrast to the SA node that fires between 70 and 80 times a minute. The reason that neither the AV node nor the Purkinje fibers are responsible for setting the heart rate is due to the discharge rate of the SA node. The SA node fires faster than the AV node or Purkinje fibers, so these other tissues are excited from the SA impulse rather than their own rhythmic rate.

In normal conditions, the SA node is the natural pacemaker of the heart. However, sometimes the AV node or Purkinje fibers begin pacing faster than the SA node. This condition is known as an ectopic pacemaker. An ectopic pacemaker occurs when electrical activation of the heart is initiated elsewhere than the SA node.

Another condition that can lead to an ectopic pacemaker is when the signals from the SA node are prevented from conducting to the rest of the heart. This usually occurs when the signal is blocked at the AV node or AV fibers that innervate the ventricles. In this instance, the SA node fires at its own normal rate, but these signals do not conduct down to the ventricles. Since the Purkinje fibers do not receive these impulses from the SA node, they begin to fire at their own intrinsic rate, between 15-40 times a second. This leads to a very slow contraction rate of the ventricles, failing to pump blood. If this continues, the brain may become deprived of oxygen, and the person may faint.
Correlation of ECG to Physiological Events

The ECG signal (Figure 3.3) illustrates the electrical depolarization and repolarization of the heart during a contraction. As described above, the depolarization of the cardiac muscle cells in the atrium occurs first. Therefore, the first wave in the ECG signal corresponds to the depolarization of the atrium. This is known as the P wave. Similarly, the start of ventricular contraction is the QRS wave. The ventricles stay contracted for a few milliseconds until ventricular repolarization occurs, which is seen as the T wave. Atrial repolarization typically occurs between 0.15 to 0.20 seconds after the P wave. However, this is the same time when the QRS complex occurs. The QRS complex is of much greater amplitude than atrial repolarization so it dominates the signal.

Typical Duration and Amplitudes

The voltage of the ECG signal can vary depending on the location of the electrodes placed on the body. If the electrodes are located close to the heart, the recorded potentials can be as high as 5 mV. However, if the electrodes are placed further apart, such as at the wrists, a typical value is 1mV. Both of these measurements, however, are small compared to electrodes placed directly in contact with the heart muscle membrane. Here the potential can range as high as 110 mV. Typical amplitudes are around 1mV for the top of the Q wave to the bottom of the S wave, 0.1 - 0.3 mV for the P wave, and between 0.2 - 0.3 mV for the T wave.
The PQ interval (also known as the PR interval) is the amount of time from the beginning of the P complex to the QRS complex. This represents the amount of time between the beginning of atrial contraction and the beginning of ventricular contraction. The normal duration is approximately 0.16 seconds. Similarly, the QT interval is the time between ventricular contraction and ventricular repolarization. This is measured from the beginning of the Q wave to the end of the T wave and typically lasts 0.35 seconds. The heart rate can be determined directly from the ECG. The heart rate is the inverse of the time between similar segments in the ECG recording. For example, if the time measured between two QRS complexes is 0.8 seconds, then the number of beats per second is the inverse, 1.25 beats/second. In order to obtain the heart rate per minute, you would simply multiply by 60 seconds/minute. This would yield 75 beats per minute.

**Electrode Configuration**

There is a standard placement of electrodes when performing ECG recordings called a standard bipolar limb lead. A lead refers to the potential difference between two electrodes. For this lab, lead placement involves three leads, which are placed on right arm (RA), left arm (LA), and left leg (LL). The electrodes can be attached to the wrists and inner ankle, but for clinical applications are usually attached to the chest for a more accurate signal. Leads I, II, and III constitute the standard limb lead ECG connected as follows:

<table>
<thead>
<tr>
<th>Lead</th>
<th>+</th>
<th>-</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>LA</td>
<td>RA</td>
</tr>
<tr>
<td>II</td>
<td>LL</td>
<td>RA</td>
</tr>
<tr>
<td>III</td>
<td>LL</td>
<td>LA</td>
</tr>
</tbody>
</table>

**Table 3.1.** Standard bipolar limb lead ECG configuration.

In the table, the positive and negative signs denote the polarity of the leads. So, the positive end of Lead I connects to the LA, while the negative end of Lead I connects to the RA. Using these three leads, we can form what is called Einthoven’s Triangle. This is a representation of vectors demonstrating the formation of the ECG signal. In interpreting these measurements, each lead is assumed to be equivalent to measurements taken across all sides of an equilateral (Einthoven’s) triangle, which is superimposed over the chest, as shown below:
With Einthoven’s Triangle, there is an equation that relates all three vectors. Graphically, Einthoven’s Law says that if the potentials of the first two leads are known, then the third lead can be found by adding the two vectors together. Mathematically, Einthoven’s law states that for the potentials on each lead:

\[ \text{Lead I} + \text{Lead III} = \text{Lead II} \]

Some may notice that this equation is similar to Kirchoff’s Voltage law, which states that all of the voltages in a loop must equal zero. Using this equation, we only need to record two of the leads. The third lead can be determined mathematically, provided that the two leads were measured simultaneously. Einthoven’s Triangle also allows us to determine the mean electrical axis of the heart. This mean electrical axis is the vector representing the summation of all the vectors that occur in a cardiac cycle. This electrical axis can be thought of as a dipole. The dipole illustrates the strength and direction of the heart’s polarization during a cardiac cycle. There are two ways of determining the mean electrical axis. Lead I measures lateral voltage and the other two measure from top to bottom. One method is to measure the magnitude of the R complex along Lead I and Lead III, and to extrapolate the vector of Lead II, which would give the magnitude and angle of the vector. A more accurate way of measuring the mean electrical axis would be to add the Q, R and S potentials for the two leads, instead of only the R wave. The QRS potentials are measured along Lead I and III, added together, and then the mean electrical axis can be computed by finding the magnitude and direction of the vector representing Lead II. If a complete measurement of the mean electrical axis is desired, twelve leads are required, since the mean electrical axis is precisely defined in three dimensions, x, y, and z. In this lab, we will only focus on the frontal plane mean electrical axis. In normal conditions, the mean electrical axis of the heart is typically around 60 degrees.
Vector Analysis of the Electrocardiogram

The ECG signal that is recorded can be derived from the Leads I-III vectors. When the ECG signal is recorded, the vector values for each of the leads changes as the atria and then ventricles contract. For example, as the QRS wave occurs, the lead I vector has a very small magnitude. This describes the slow upward growth of the lead I ECG recording. As depolarization sweeps across the atria and into the ventricles, the lead I vector begins to increase, causing the fast growth in the lead I ECG signal that is typical of the QRS complex. Then, as more of the ventricles depolarize, the lead I vector starts becoming smaller since all of the ventricular muscle has become depolarized, causing the lead I vector to have zero or slightly negative magnitude, causing the negative slope of the ECG signal in lead I. A similar analysis can be performed on the other leads and can also explain how repolarization sweeps across the heart when the T wave occurs.
Abnormalities in the ECG

As stated previously, ECG recordings can be used as a diagnostic tool to determine abnormalities in cardiac function, or it can be used to visualize the effects of cardiac tissue damage. Abnormalities in the QRS complex indicate problems in the ventricles or ventricular conduction. A normal QRS complex lasts between 0.6 - 0.8 seconds, times longer than this indicate a change in ventricular conduction. One cause is ventricular dilation or hypertrophy. In this case, the ventricles are larger than normal, causing the impulse to take longer to conduct through the tissue, elongating the QRS complex. In these cases, the QRS might last between 0.9 to 0.12 seconds. Another cause for lengthened QRS complexes are conduction blocks in the Purkinje fibers. As described above, these fibers conduct the impulse from the Bundle of His node into the ventricles. If a complete block of the Purkinje fibers occurs, the QRS complex can be lengthened to 0.14 seconds or more.

Conduction from the SA node can also be blocked. In this case, the signal from the SA node is blocked before it ever reaches the atria, causing the sudden disappearance of the P wave, meaning the atria fail to contract. Since the ventricular tissues have their own rhythm, the AV node creates the QRS-T complex, but at a slower rate.

Blocks and conduction delays can also be found in the AV node. One type of block that comes from AV conduction problems is indicated by an elongated P-R (or P-Q) interval. The normal time from the beginning of the P wave until the beginning of the QRS complex is 0.16 seconds. A first-degree block occurs when that time is greater than 0.20 seconds. In first-degree block, the QRS is delayed, and not actually blocked. When the PR interval begins to grow longer to 0.25 to 0.30 seconds, some impulses may not be strong enough to pass through the AV node. This leads to dropped beats where the QRS complex disappears, even though there is a preceding P wave. These cases are called second-degree block. A second-degree block can cause the heart to develop an asynchronous 2:1 rhythm. In this case, there are 2 atrial contractions for each ventricular contraction.

Third degree block occurs when the signal from the SA node never reaches the ventricles due to complete block of the AV node. In this case, the ventricles never receive the cardiac impulses and begin to beat at their own natural rate, which is much slower than the rate from the SA node. Consequently, the relation between P waves and QRS complexes disappear. The P wave will be regular, but QRS-T complexes will appear at a much slower rate.

In a normal ECG, the T wave is of positive amplitude, denoting the repolarization of the ventricles. In some abnormal ECG, the T wave can be inverted, having negative amplitude. One reason for this is slow conduction of the depolarization wave. In this instance, the conduction delay occurs in the left ventricle due to left bundle branch block. Consequently, the right ventricle depolarizes first, then the left ventricle depolarizes, causing a shift of the mean QRS vector to point to the left. Then, as repolarization occurs, the right ventricle repolarizes before the left ventricle, causing the mean axis for the T wave to shift to the right, which is opposite of the QRS complex in the same measurement. So, with delay of the conduction of the depolarization wave in the ventricles, the inversion of the T wave occurs. Another cause for inverted T waves is delayed depolarization. In this case, repolarization does not occur at the same place as it normally does.
Instead of repolarization occurring at the apex of the heart, delayed depolarization causes the base of the ventricles to repolarize before the apex, causing the vector to point from the apex to the base of the ventricles which is opposite to the repolarization vector in normal cases, inverting the T wave. The most likely cause for this type of depolarization delay is mild ischemia of the heart tissue, which can be caused by coronary occlusion or coronary insufficiency that may occur during exercise.

Coronary ischemia caused either by myocardial infarction or other damage to the heart muscle can cause changes to the ECG signal. Since ischemia means a loss of blood flow to the muscle tissue, there is a loss of nutrients due to decreased blood flow, a lack of oxygen, and a buildup of carbon dioxide. Consequently, ischemic cardiac muscle is unable to repolarize, and remains depolarized so long as the muscle is ischemic. Since this muscle remains depolarized at all times, current flows between this injured depolarized muscle and the normal polarized areas during the cardiac cycle. This is known as a current of injury. When cardiac tissue is consistently depolarized, it affects the ECG by causing a deflection in the graph due to a strong current of injury. Using vector analysis, a physician can use the ECG to determine the location of this ischemic tissue by looking at the polarity of the current of injury.

Abnormal rhythms can be analyzed using ECG recordings. Rhythm disorders, such as tachycardia and bradycardia are quite evident. Tachycardia is when the heart rate exceeds 100 beats per minute, and is usually caused by increased body temperature, stimulation by the sympathetic nervous system, or chemical stimulation of the heart tissue. Bradycardia is when the heart rate slows to less than 60 beats per minute. Bradycardia is not always harmful, some athletes demonstrate bradycardia due to the fact that their heart has become extremely efficient at pumping blood. This reduces the need for a faster heart rate. But bradycardia can also be a result of vagal stimulation, which has an inhibitory effect on heart rate.

**Experimental Methods**

**Experimental Setup**

For this laboratory, the BioRadio will use four channels. The first channel will be used to record a standard bipolar lead configuration on the clavicles and the remaining three channels will be used to record using Einthoven’s Triangle. Using the BioRadio Configuration Wizard, create a new configuration. Select 4 channels to be recorded all using low-level signals. Choose a medium or high input resolution, and note the sampling frequency used. Keep the default input ranges. Name channel 1 “Bipolar”, channel 2 “Lead I”, channel 3 “Lead II”, and channel 4 “Lead III”. Save this BioRadio configuration as “ECG Lab”. Program the BioRadio transmitter and receiver to the “ECG Lab” Configuration.
Remember that the electrode needs to have good contact with the skin in order to get a high quality recording. The surface of the skin should be cleaned with alcohol prior to electrode attachment. For the best recordings, it is best to mildly abrade the surface with pumice or equivalent to minimize contact resistance by removing the outer dry skin layer.

For this laboratory you will need to use seven snap electrodes from the BioRadio Lab Kit. Attach one on the palmar side of the right wrist, one on the palmar side of the left wrist, one on the left leg, and two on the right leg a few inches apart. **NOTE:** The electrodes on the arms can be placed at the wrists and the electrodes on the legs can be placed near the ankles. Also attach one electrode on the surface of the skin above the right clavicle and another on the surface of the skin above the left clavicle. These two electrodes will be used for a bipolar recording.

Remove seven electrode snap leads from the lab kit. Using the picture above as a reference (Figure 3.6), connect a snap lead to the electrode over the right clavicle and the other end of the snap lead to the negative side of channel 1 on the universal harness. Connect a snap lead to the electrode over the left clavicle and the other end of the snap lead to the positive side of channel 1
on the universal harness. Connect snap leads to the remaining eight snap electrodes. Connect the
snap lead from the electrode on the left wrist to the positive side of channel 2 on the universal
harness. Connect the snap lead from the electrode on the right wrist to the negative side of
channel 2 on the universal harness. Connect the snap lead from the electrode on the left leg to
the positive input for channel 3 on the universal harness. Connect the negative side of channel 3 from
the universal harness and connect it to the negative input of channel 2 on the universal harness.
This lead should already have the snap lead from the right wrist connected to it. The connectors
extending from the universal harness are stackable. Therefore, more than one input on the
connector can be connected to a single snap lead. Connect the positive input of channel 4 on the
universal harness to the positive input of channel 3 on the universal harness. This connector
should already have the snap lead from the electrode on the left leg connected to it. Connect the
negative input of channel 4 on the universal harness to the positive input for channel 2 on the
universal harness. This connector should already have the snap lead from the electrode on the left
wrist connected to it. Finally, the snap electrode from one of the electrodes on the right leg to the
input connector on the universal harness labeled ground. Then connect the other snap lead from
the right leg to one of the input connectors on the universal harness labeled reference. Connect
the universal harness to the BioRadio transmitter and turn the transmitter on.

**Procedure and Data Collection**

1. Run the BioRadio Capture software.

2. The first part of the lab will record normal resting ECG with the subject sitting up and
   laying down. It is important that the subject is relaxed and still during this procedure in
   order to prevent EMG artifacts from contaminating the ECG signal.

3. For the first test, have the subject lie down on the floor or a cot. Begin viewing the four
   channels of data with the BioRadio capture program. The subject’s ECG should begin
   scrolling across the monitor. You may need to adjust the amplitudes and time scales of
   the plots. Instruct the subject to relax then click on the save button and record data for
   approximately 10 seconds. Name the data file “layingECG.bd”.

4. Stop the capture software and use View mode to open the file you just saved. Check to
   make sure you have obtained an ECG signal. Export the entire file to an ASCII file. Save
   it as “layingECG.dat”. **NOTE:** Refer to Appendix A of this Laboratory Book for
   information on exporting saved BioRadio data files.

5. Now, request the subject to sit up in a chair, and place his/her arm on a table or armrest.
   Make sure the subject is relaxed and quiet. When ready, start Capture mode and monitor
   the data scrolling across the monitor. Save another 10-second segment. Name this data
   file “sitECG.bd”.

6. Stop the capture software and use View mode to open the file you just saved. Check to
   make sure that you have obtained an ECG signal. Export the entire file to an ASCII file.
   Save it as “sitECG.dat”.

7. Now, we are going to examine the effects of motion during physiological monitoring. With the subject still sitting, start Capture mode in the BioRadio software. The ECG signal should begin scrolling across the screen. Click on save file, and name it “motion.bd”. Instruct the subject to wildly move their arms about for 5 seconds, relax for 5 seconds, and then keep their arm still and flex chest muscles for 5 seconds while capture is running and you are saving data.

8. Stop the capture software and use View mode to open the file you just saved. Check to make sure that you have obtained an ECG signal. You should see a normal ECG during the time that the subject was relaxed. Don’t worry if the other two sections of data do not appear to be a normal ECG. Export the entire file to an ASCII file. Save it as “motion.dat”.

9. Lastly, request the subject to jog around the room, or perform some sort of physical activity for 5 minutes in order to raise the heart rate. After these 5 minutes start Capture and save 10 seconds of the ECG while the subject is relaxed. Name the data file “exercise.bd”. During this time also record the subjects heart rate by taking their pulse at their wrist and record this number.

10. Stop the capture software and use View mode to open the file you just saved. Check to make sure that you have obtained an ECG signal. Export the entire file to an ASCII file. Save it as “exercise.dat”.

11. Data collection is now complete. Turn the BioRadio transmitter off. Disconnect the subject from the leads. Remove and dispose of the snap electrodes on the person’s body.

Data Analysis

Using the BioRadio software, open the file “layingECG.bd”. Change the timescale to an appropriate width that will reveal several beats. Turn on the low pass filter for all channels and set the cutoff to a level below 50 Hz. Print this file out. Do the same for the recording after physical exercise “exercise.bd”.

Using Excel, import the data file “layingECG.dat”. Plot the first four beats from channel 1. Also, determine the resting heart rate of the subject based on this recording. Repeat this for the file “exercise.dat”. Label the P, Q, R, S and T segments of one beat on both plots.

Using Excel, open the file “layingECG.dat”. Einthoven’s Law stated that the sum of the potentials from all three channels should equal zero. Using this relationship, calculate what lead two should be, as if data for the first four beats was only available from leads I and III. Plot this calculated lead II, along with the measured lead II. Then, subtract the calculated lead II from the measured lead II and plot this error over time. Give a mean error between the calculated lead II and the actual lead II measurements.
Lab 3 - The Electrocardiogram

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Using Einthoven’s triangle, the mean electrical axis can be approximated by adding the vectors for leads I and III, and then computing the direction and magnitude of the lead II vector, which is the mean electrical axis of the heart.

To do this measurement, draw a figure similar to the one next to Einthoven’s triangle (Figure 3.4), except omit the line representing lead II. Use a protractor to ensure that the angle between leads I and III is 120 degrees. For both the lead I and lead III vectors, draw twenty evenly spaced tics on the vectors, ranging from 0 to 2 mV.

One way of determining the mean electrical axis is to measure the amplitude of the R wave on leads I and III. Use Excel to determine the mean amplitude of the R wave for leads I and III over three or more beats. Once known, draw a line perpendicular to the lead I and a line perpendicular to lead III vectors at the value of the R wave for the respective leads. (i.e., if the mean R wave amplitude is .8 for Lead I and .6 for Lead III, find the mark corresponding to .8 mV on Lead I, and draw a perpendicular line, and do the same for Lead III) Find the intersection of these two lines, and record the magnitude and direction of this vector. Remember that zero degrees is measured from the lead I vector. This vector we computed is the lead II vector, which indicates the mean electrical axis of the heart.

On the same graph, repeat the above steps on the file with the subject sitting up.

A more accurate method of computing the mean electrical axis of the heart is to add the Q, R, and S potentials together. Average the total net potentials over three heartbeats, and then repeat the steps above to determine the mean electrical axis.

Open the file named “arm motion”. Print out the data, marking the section where the arms are moving, and the segment when the chest muscle flexed.

Using the BioRadio Digital Signal Processing Toolkit open the file named “sitECG.dat”. Plot channel 1 in the time domain. Make sure all filtering is turned off for this channel. Perform a spectral analysis of a few beats of this data. Print this plot. Repeat this for the file named “exercise.dat”.

Discussion Questions

1. What is the heart rate of the subject laying down at rest before exercise? What is the heart rate of the subject after exercise? Why does the heart rate change during exercise?

2. After the physical exercise, did the heart rate determined from the ECG match the rate counted at the wrist?

3. Define Einthoven’s Law, explain how it relates to Einthoven’s Triangle, and explain why it is useful in cardiac recordings.
4. Explain the difference, if any, in the mean electrical axis when the subject is sitting up compared to lying down. What are possible causes for the shift of the mean electrical axis? In general, why is the mean electrical axis point along the Lead II?

5. Using the BioRadio in View mode, open the file “layingECG.bd”. Compare Lead I (Channel 2) to the bipolar lead (Channel 1). What are the differences? How can you account for those differences?


7. Why isn’t atrial repolarization seen in the ECG? Why is the amplitude of ventricular depolarization so much greater than the rest of the complexes in the ECG?

8. What considerations need to be taken when placing electrodes for an ECG measurement?

9. Why does the SA node determine the heart rate, rather than the AV node or Purkinje fibers?

10. Explain how a physician would use an ECG to determine if a patient has heart conduction problems.

11. Draw an ECG graph for a patient who has right bundle branch block. Label each of the segments of the ECG and show how the abnormal ECG reflects the clinical diagnosis.

12. Open the file with arm motion and chest flexion in the BioRadio software. Describe how the noise seen in the ECG signal is different for arm motion and chest flexing. What is the mechanism for noise when the subject moves their arms around? for chest muscle flexing?

13. On the spectral analysis of the data where do the peaks occur and why?

**NOTE: Graduate Students Should Continue and Complete the Following Section.**

**Graduate Analysis and Discussion**

1. Write a program in Matlab to compute the average heart rate of any given ECG data file collected with the BioRadio software.

2. Sketch two cycles of a typical ECG recording, labeling each of the components. Now draw ECG graphs for the following symptoms: premature ventricular contractions, SA node block, and first-degree AV node block. Correlate the ECG sketches with the physiological problem.
References


Lab 4

The Electroencephalogram
Introduction

The electroencephalogram (EEG) is a recording of the biopotentials generated by the cerebrum in the brain. More specifically, it is a recording of the action potentials and the postsynaptic potentials of cortical cells. Neurons in the brain make all the things we do, such as moving our arms, performing mental math, and dreaming, possible. The potentials of the neurons in the brain vary as a function state of the person. At first glance, EEG data may look like a very unstructured, noisy signal. However, scientists have developed signal processing techniques to separate different components of the brain waves. These separate components can then be associated with different brain functions. Current research focuses on discovering correlations between specific brain activity patterns to disease, emotional states, sleep phases, and mental health. In a clinical setting, EEG's are often used to diagnose neurological diseases such as epilepsy, monitor patients during surgical procedures, and to measure brain activity during sleep studies. In addition, it has also been shown that the EEG signal can be used for control albeit at low data rates. This could be useful in the case of spinal cord injury patients. In this lab, you will be using the BioRadio to detect the electrical activity of neurons in the cerebral cortex, and applying some simple analysis techniques to interpret the data.

Figure 4.1: The human brain is comprised of three main regions.

Equipment required:
- BioRadio 110
- Six (6) Gold cup electrodes
- Elefix gel
- Gauze, cotton balls, and wipes
- Microsoft Excel and BioRadio DSP Toolbox
- MATLAB (Graduate Students)
Background

The Brain

The human brain is a part of the central nervous systems and is comprised of more than 100 billion nerve cells connected together. The brain is connected to ascending and descending tracts of nerves by the spinal cord. These tracts contain the afferent and efferent nerves that communicate information between the brain and the rest of the body. The brain consists of three major sections known as the cerebrum, the cerebellum, and the brain stem (Figure 4.1). Various kinds of information in the form of nerve impulses are transmitted and processed in the cerebral cortex. The cerebral cortex, which is the largest part of the brain, is organized in such a way that functionally similar neurons are found in localized regions, and these regions are illustrated in Figure 4.2.

Figure 4.2: A diagram of the cerebral cortex, with the various lobes specialized for performing different functions.

For example, visual information is processed in the occipital lobe, motor planning is performed in the frontal lobe, and the temporal lobe is responsible for processing auditory information. Association of the different brain regions with specific functions was discovered by repeated experiments of monitoring the electrical activity of various brain regions while performing a specific task.
Earlier, we alluded to the fact the EEG is a produced by the postsynaptic currents of neurons in the brain. This is due to the geometry of the brain, and the organization of neurons within the brain. The action potential refers to the signal propagating through the neuron, while the postsynaptic potential refers to the changes of transmembrane potential following the release of neurotransmitters at the end of a presynaptic axon, where the signal continues to another neuron.

The action potentials and synaptic potentials of individual neurons in the brain are much too small in amplitude to be detected by electrodes placed on the scalp. An EEG recording is rather a measure of the summation of the electrical signal produced by many neurons firing over a period of time. Depending on the state of the brain and the task being performed, the neurons may be firing synchronously or asynchronously. Neurons that are firing synchronously will have their potentials rise and fall at the same times. The EEG is a summation of these signals. Therefore, the peak values will add resulting in a relatively large signal. You can visualize this by thinking of adding two identical sine waves. The amplitude will double and the frequency of the signal will remain the same. Conversely, asynchronous firing neurons may or may not have signal peaks occur at the same time. This may or may not result in an overall smaller amplitude signal. Again, visualize the addition of two sine waves, but with different phases (i.e. a time shift). There may be an increase or decrease in amplitude depending on how the signals line up in time. One signal may even cancel another (e.g. a sine wave plus a cosine wave).
Lab 4 - The Electroencephalogram
BioRadio 110 Lab Book

EEG components

As stated earlier, the EEG signal can be broken down into different components. There are four frequency ranges that have been defined as primary components of the EEG: \( \alpha \) (alpha), \( \beta \) (beta), \( \Delta \) (delta), and \( \theta \) (theta) waves. The frequencies and typical amplitudes of these components are shown in the table below.

<table>
<thead>
<tr>
<th>Rhythm</th>
<th>Typical Frequencies (Hz)</th>
<th>Typical Amplitude (uV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \alpha )</td>
<td>8 - 13</td>
<td>2-100</td>
</tr>
<tr>
<td>( \beta )</td>
<td>13 - 22</td>
<td>5-10</td>
</tr>
<tr>
<td>( \Delta )</td>
<td>0.5 - 4</td>
<td>20-100</td>
</tr>
<tr>
<td>( \theta )</td>
<td>4 - 8</td>
<td>10</td>
</tr>
</tbody>
</table>

Table 4.1 The typical frequencies and amplitudes of the different brainwave components are listed.

Alpha waves are generally found in the EEG when the individual is awake in a quiet, resting state. The alpha wave can be detected primarily from the occipital lobe, but also from the parietal and frontal regions of the cerebral cortex. During sleep, however, the alpha waves disappear.

Beta waves are recorded from the parietal and frontal lobes. They appear when the individual performs some specific type of mental activity or are attentive to an external stimulus. They are lower in amplitude than the alpha rhythms, but this is not due to there being less electrical activity. Instead, desynchronization, also known as alpha block, occurs reducing the amplitude of the net signal recorded from the scalp. As mentioned previously, non-synchronized potentials tend to cancel each other, resulting in a lower amplitude signal.

Theta waves occur mainly in the parietal and temporal regions. These occur sometimes during emotional stress and often in degenerative brain states. Delta waves are the very low frequency components of an EEG. Deep sleep and certain brain diseases give rise to delta waves.

EEG Electrode Placement

A method called the 10-20 system has been developed for placements of electrodes on the scalp during EEG recordings. The 10 and 20 in the name refer to the percent distances that the electrodes are from each other in proportion to the size of the head. The 10-20 system relates the locations on the scalp to the locations of the cerebral cortex. The electrode locations used in the 10-20 system are indicated with a letter followed by a number. The letters that are used include F, T, C, P, and O. These letters correspond to frontal, temporal, central, parietal, and occipital respectively. These are all lobes of the brain except for the central location. The number in the indicated position corresponds to the left or right side of the head. Even numbers are located on the right hemisphere while odd numbers are on the left. Some letters are followed by a Z instead
Epilepsy

An important application of the EEG is to diagnose neurological disorders. Epilepsy is a disease of the nervous system, and is characterized by uncontrolled activity of part or all of the central nervous system. There are different kinds of epilepsy, such as grand mal, petit mal, and focal epilepsy. Epileptic seizures are characterized by usually synchronized neural activity, resulting in abnormally large amplitude EEG activity during an attack.

Grand mal epilepsy involves neuronal discharges in all areas of the brain, including the cortex, deeper parts of the cerebrum, and even the brain stem and thalamus. Generally, grand mal attacks last anywhere from a few seconds to a few minutes. During grand mal the individual may lose control of visceral and motor control. Petit mal involves the basic thalamocortical brain activating system. Often referred to as absence epilepsy, an individual suffering from a petit mal attack will lose consciousness for up to thirty seconds, experience several twitch-like contractions in the head and neck regions, and then resume previous activities. Occasionally, a petit mal attack can initiate a grand mal attack. Focal epilepsy usually results from localized organic lesions or abnormalities such as scar tissue. These abnormalities can cause rapid neuronal discharge that spread to adjacent regions in a wave-like fashion. When the wave reaches the motor cortex, the person experiences Jacksonian epilepsy, where muscles contract progressively down the body. Multichannel EEG recordings can be used to identify the location of the earliest component of the seizure activity. Such a trigger zone may be removable by surgery to eliminate the seizure disorder.
Researchers are developing electronic devices to automatically detect these abnormal bursts, or 'spikes', of electrical activity in the brain. If the onset of a seizure could be detected early enough, then it may be possible to intervene by administering drugs before an attack occurs. A problem with this technique, however, is that these rhythmic spikes occur quite often in normal EEG's as well.

**Noise**

There are several sources of noise and artifacts in the EEG signal. One of the most common artifacts is an eye blink. Blinking causes spikes in the EEG. These spikes can be difficult to distinguish from those due to an epileptic attack. When the eye blinks, the eyelids act as a sliding potential source. Blinking is not the only source of problems when analyzing EEG information. Other sources of noise in an EEG signal include muscle contractions (EMG) of the face and neck, and eye movement (EOG). Several techniques exist for removing the artifacts generated by EMG, EOG, and blinking. These techniques include filtering the data, performing correction on the data, or just completely throwing out any data with artifact. These methods will be further explored in a later laboratory. In order to minimize noise for this laboratory, it will be important to have the subject relax their face and neck muscles and keep their eyes relatively still while recording EEG data.

**Technology**

Before computers became mainstream equipment for data recording, perhaps some 20 years ago, EEG was recorded by an old-fashioned pen-based strip chart, where a pen would move vertically depending on the amplitude of the detected signal while a long sheet of paper continuously moved under it. This of course was replaced by computer (digital) acquisition, which made it much easier for data archiving and analysis. Today, there are many commercial software packages available specifically designed for EEG analysis. It is important to note that EEG studies typically last anywhere from a few hours to a few days. Obviously, this results in massive amounts of data that have to be stored and analyzed. Researchers are finding ways to implement automated data reduction and automated extraction of relevant information to increase efficiency.

**Experimental Methods**

**Experimental Setup**

Using the BioRadio Configuration Wizard, select four channels for recording. All four channels should be set for low-level signals. Choose the medium input resolution, and note the sampling rate. You will be recording from electrode sites O1, O2, FP1, and FP2 (Figure 4.4). Name channel 1 “O1”, channel 2 “O2”, channel 3 “FP1”, and channel 4 “FP2”. Save this configuration as “Lab 4 EEG”. Program both the BioRadio transmitter and receiver to this configuration as per the User Manual.
**Figure 4.5:** Two of the six gold cup electrodes will be placed at O1 and O2 to monitor EEG.

If possible, the subject for this laboratory should be a person with shorter hair. The subject also should have their scalp free of any types of hair gel. You will need six gold cup electrodes and one snap electrode for this laboratory. Gold cup electrodes will be placed at locations O1, O2, Fp1, and Fp2 (Figure 4.4) to measure EEG and on each mastoid as references. A snap electrode will be placed on the back of the neck and used as the ground electrode. Before applying electrodes to the subject it is first important to properly prepare and clean the electrode sites. If needed, refer to laboratory 2 for information on cleaning and preparing electrode sites.

Now the gold cup electrodes can be attached. Generously fill a gold cup electrode with the provided Elefix gel allowing some gel to fill over the top of the cup. Push aside the hair and place the electrode on the back of the subject’s head at position O1. Some of the electrode gel should exude out of the electrode. Take a cotton ball and press it on top of the electrode and into the excess gel. Then tape the cotton ball and electrode down onto the head. Repeat for the other gold cup electrode at locations O2, Fp1, and Fp2. The electrode placements for O1 and O2 are illustrated in Figure 4.5 without the cotton balls. Ground and reference electrodes are also needed to measure EEG. The gold cup reference electrodes will be placed on the mastoid processes on both sides of the skull. The mastoid processes are the bony structures that you can feel behind the ears (Figure 4.6). Finally, a snap electrode should be placed on the back of the neck near the midline.

**Figure 4.6:** The mastoid processes are the bony structures located behind the ears.

Connect the lead from the gold cup electrode from O1 to the positive stackable connector of channel 1 on the universal harness. Connect the lead from the gold cup electrode from O2 to the positive stackable connector of channel 2 on the harness. Connect the lead from the gold cup
electrode from Fp1 to the positive stackable connector of channel 3 on the universal harness. Connect the lead from the gold cup electrode from Fp2 to the positive stackable connector of channel 4 on the harness. Connect a snap lead to the three snap electrodes on the forehead. The leads from the two gold cup electrodes on the mastoids should each be connected to one of the two inputs labeled “REF” on the universal harness. Connect a snap lead to the electrode on the back of the subject’s neck. Then connect the other end of the snap lead to the connector labeled “GND” on the universal harness. Connect the negative inputs for channels 1 and 2 on the universal harness should be connected to one of the reference stackable connectors. The negative inputs for channels 3 and 4 on the universal harness should each be connected to the other reference stackable connector. To avoid tangling, gently run the snap lead wires behind the subject’s ears. Finally connect the positive lead from the push button switch to the positive input for channel 5 on the universal harness and then connect the negative lead from the push button to the negative input for channel 5 on the universal harness. Connect the negative input for channel 5 on the universal harness to one of the reference connectors on the universal harness. This should already have one of the reference leads connected to it.

Procedure and Data Collection

1. Connect the universal harness to the transmitter and turn the transmitter on.


3. In a quiet room, request the subject to be seated in a chair holding the push button in one of their hands. Request the subject to close their eyes and relax. After a few minutes of the subject sitting eyes closed and relaxed, begin Capture Mode. Two channels of EEG should begin scrolling across the screen. You may need to adjust the scale controls.

4. Click on the save file button and name the file “eyesclosed.bd”. Collect about 20 seconds of data with the subject’s eyes closed. Once completed, stop saving data.

5. Stop the Capture mode and use View mode to open the file you just saved. Check to make sure that you have recorded the EEG signal. Export the entire file to an ASCII file. Save it as “eyesclosed.dat”.

6. Begin capture mode again and request the subject to open their eyes. Click on the save file button and name the file “eyesopen.bd”. Collect about 20 seconds of data with the subject’s eyes open. Once completed, stop saving data.

7. Stop the Capture mode and use View mode to open the file you just saved. Check to make sure that you have recorded an EEG signal. Export the entire file to an ASCII file. Save it as “eyesopened.dat”.

8. Someone other than the subject should write down some moderately difficult math problems that can be solved mentally. Make sure the subject is still relaxed with their eyes closed. Start Capture mode and begin saving data. Name the file “math.bd”.

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Immediately begin asking the subject these prepared mental math questions and only give them a few seconds in between each question to think of the answer. You should not give them enough time to actually finish the question in their head. The idea is that they will be continually completing mental math for about 20 seconds without a break. They should not repeat the answer aloud; just try to keep solving the problems mentally. After about 20 seconds stop saving data and stop capture mode.

9. Start capture in the BioRadio software while the subject has their eyes open. Begin saving data and name the file “noise.bd”. For the first five seconds, the subject should have their eyes open, attempting not to blink. Then tell the subject to start blinking normally about once every other second for ten seconds. After this point, have the subject stop blinking and clench their teeth for 5 seconds. Stop saving data.

10. Stop the Capture mode and use View mode to open the file you just saved. Check to make sure that you have obtained an EEG signal when the subject was relaxed. Export the entire file to an ASCII file. Save it as “noise.dat”.

Data Analysis

Analysis of eyes open and closed experiment

Using the BioRadio Capture software open the file “eyesclosed.bd”. Choose a filter setting that emphasizes the alpha and beta rhythms. Note that there are three filter cutoffs for low-pass and three cutoffs for the highpass. Therefore, the best way to see these would be to use a low pass filter with a cutoff of close to 22 Hz since alpha is 8-13 Hz and beta is 13-22 Hz. Print this file and repeat for the “eyeopened.bd” file. Identify the differences between the eyes closed and eyes open files.

Using the BioRadio software, zoom into a 1 second time view of both files. Print these plots. From the plots, estimate the frequency of the rhythms. Which brain wave was recorded while the eyes are open? Which brain wave was recorded while the eyes were closed?

Using Excel, open the data file “eyesclosed.dat”. Plot and print the imported data. Note that this print out may not be the same as the print out from the BioRadio software. Remember, the data that you exported is the raw, unfiltered data. Determine the mean peak-to-peak voltage. Repeat for the file “eyeopen.dat”. Compare these the peak-to-peak voltages to typical amplitudes for EEG recordings in Table 1.

Using the BioRadio DSP Toolbox, open the data file “eyeopen.dat”. Perform a spectral analysis of a segment of data when the eyes were open one of the occipital channels and one of the frontal channels. Print both plots. Repeat for the file “eyesclosed.dat”. Compare any differences.

Analysis of mental math experiment
Using the BioRadio Capture software open the file “math.bd”. Create a filter to emphasize the alpha and beta rhythms. Print a plot of a segment of data showing mental math. Export this section of data to a file named “math.dat”.

Using the BioRadio DSP Toolbox, open the data file “math.dat”. Set the DSP parameters to be a low pass filter for channels 1 and 2 with a cutoff of 22 Hz. Find the same section of data that you used above. Perform a spectral analysis of a segment of data during mental math. Set the display unit to Vrms, the log/linear to linear, and the window to none. Print this plot.

Analysis of noise sources

Using the BioRadio DSP Toolbox open the file “noise.dat”. Set the DSP method for channels 1 and 2 to Raw Data. Look at the data and try to create a filter that will minimize the artifacts created without sacrificing the quality of the EEG recording. The artifacts include blinking and the EMG due to clenching the teeth. You may want to do a spectral analysis of the data to try and determine the frequencies of noise.

Discussion Questions

1. Examine the plots made with the eyes open and closed during the first experiment. What differences do you observe in the EEG signal between the eyes closed and eyes opened states? What rhythm is most responsible for quiet, relaxed, eyes closed? What rhythm is most responsible for eyes open? Why do you think this rhythm changes (physiologically)?

2. Does the mean frequency measured for the eyes open and closed exercises fall into expectations?

3. For the mental math experiment, compare the measurements between eyes open and the mental math section. How does the EEG signal change as the subject begins to complete mental math? What brain rhythm would you expect to see during these states? Explain any similarities or differences. Explain the relationship between the results for mental math and the eyes open state.

4. Explain some methods for eliminating the sources of noise generated in the third recording. Some hospitals have programs for automated EEG analysis to detect seizures or spiking activity that occur during data acquisition. How might a noisy recording affect these automated programs?

5. Why are gold cup electrodes used to record EEG instead of the snap electrodes? If a more detailed and localized EEG reading is desired, explore some other options for electrode placement.

6. Where would you place gold cup electrodes on the head to measure alpha waves? Beta waves? Theta waves? Delta waves?
7. The beta rhythm typically ranges between 14-30 Hz. What particular source(s) of noise needs to be considered when analyzing the beta rhythm?

**NOTE: Graduate Students Should Continue and Complete the Following Sections.**

**Graduate Analysis and Discussion**

1. Using Matlab, create a program to filter the data into alpha and beta bands. Measure the energy of the alpha rhythm vs. time during the whole recording for channel 1 of the first experiment. Do the same for the beta rhythm. How do these energy measurements correlate with the eyes open/eyes closed states?

2. Use Matlab to show that even though a differential recording was performed 60 Hz noise can still be present in a recording. Use the data file from the first experiment.

3. Knowing that seizures generally involve slower brain rhythms, and that spiking behavior usually precedes seizure onset, suggest what factors an automated program should look for when doing automatic EEG analysis. How would noise be dealt with in this automated program?

4. There are two mechanisms responsible for creating the EEG signal. Both action potentials and post-synaptic potentials create the EEG. Explain the difference between these two mechanisms. Which of these is a graded signal and why?
References


Lab 5

The Electromyogram
Introduction

Walking around, manipulating tools, and performing any kind of activity all rely on the coordination of various muscles in the body. Humans are capable of grading the amount of force generated by our muscles. This is useful for controlling a wide range of movements that involve both large amounts of force and the agility required for precise movements. For example, a weight lifter performing squats needs to generate high muscle forces in their legs while ballet dancer uses many of the same muscles for the agility to control graceful, sweeping movements that seem to defy gravity. Fine control and precision of the hand muscles also allows the surgeon to perform delicate heart surgery and the pianist to play music.

There are three major types of muscles in the body. These include cardiac, smooth, and skeletal muscle. Cardiac muscle is found in the heart. Smooth muscle is typically found in the internal organs, such as the intestines, the stomach, and the esophagus. Smooth muscles are involuntary, meaning that they are controlled by the autonomic nervous system. Skeletal muscle, on the other hand, is under voluntary control. Skeletal muscle refers to the muscle cells that are attached to the bones in the body, allowing movement. When a person desires to move a limb for example, neural inputs from the brain travel down the spinal cord and into muscles controlling the limb. These impulses cause the muscle to contract. Since these muscles are attached to bone by tendons, movement occurs. The action potential is the mechanism responsible for muscle contraction. Electrodes placed on the skin above a muscle can monitor these action potentials. This measurement is called the electromyogram (EMG). The EMG is a summation of all action potentials occurring in a muscle at a single time.

Monitoring EMG has lead to a greater understanding of muscle properties, given insight into how muscles work together to coordinate tasks, and yielded information about neuromuscular disorders. In addition, many researchers have used EMG as a control signal for robots and the disabled. For example, a person may have had an accident that caused them to lose one of their arms from the elbow down. A scientist may be able to use recorded EMG from the subject’s biceps and triceps to control the hand grasp of a prosthetic arm. This would be considered myoelectric control of a prosthetic.

In this lab, EMG recordings from proximal muscles of the arm will be performed. You will demonstrate how the EMG relates to muscle force and explain how the EMG signal can be processed and used as a control signal.

Equipment required:
- BioRadio Lab Kit
- Snap Electrodes
- Calibrated Weights (Approximately 2.5, 5, and 10 lbs)
- Microsoft Excel and BioRadio DSP Toolbox
- MATLAB (Graduate Students)
Background

*Brain Control over Muscle Movement*

Voluntary control of skeletal muscle originates from the cerebral cortex of the brain. When a person wishes to contract a muscle to generate movement, the signal originates from the motor strip in the cerebral cortex. The motor cortex can be broken down into three areas, the primary motor cortex, the premotor cortex, and the supplementary cortex. Each area is organized topographically with different parts of the body represented in different parts of the cortical area. In fact, over 50% of the motor cortex is responsible for manipulating the hand muscles and speech. The premotor cortex is responsible for coarse movement of muscle groups. The premotor cortex prepares muscles for a specific task, such as positioning the arms and shoulder to initiate writing. The supplementary motor cortex works along with the primary cortex to create muscle movement. The supplementary motor cortex is known to provide bilateral control. Torso positioning is accomplished by the supplementary motor cortex. Recent experiments measuring blood perfusion to the brain using functional MRI have shown that the supplementary motor cortex is also responsible for mental conception of movement. Researchers have found that when a person thinks about moving their fingers increased blood flow to the supplementary motor cortex occurs, even though no action is being performed. These signals from the motor cortex are then transmitted down the spinal cord over motoneurons and activate the muscle fibers.

*Figure 5.1*: The body has over 250 skeletal muscles that are under voluntary control by the motor cortex of the brain.
Origin of the EMG Signal

To create voluntary muscle movement, an action potential must travel from the brain to the muscle. It travels from the brain, into the spinal cord, and then to an efferent nerve that connects to the muscle fiber. Each muscle fiber is innervated by a single neuron. However, one neuron innervates several hundred muscle fibers. The number of muscle fibers innervated by a single neuron is called the innervation ratio. The lower the innervation ratio, the finer the control of muscle force.

The connection between a nerve and a muscle is called the neuromuscular junction. The action potential travels down the motorneuron and causes the release of acetylcholine (Ach), a neurotransmitter, at the neuromuscular junction. As Ach is released, it travels across the neuromuscular junction and causes Ach gated receptors on the muscle fiber to open. When these gates open sodium ions flow into the cell depolarizing it. This potential change activates voltage dependent sodium channels resulting in an action potential that propagates throughout the muscle fiber. The action currents create potentials in the extracellular space that are recorded as EMG.

These action currents travel deep into the muscle fiber by means of the transverse tubule system. These currents cause a potential change that triggers the release of calcium ions from the sarcoplasmic reticulum inside the muscle fibers. Inside the muscle fiber are two filaments, actin and myosin. Actin sites are normally closed, however, in the presence of calcium these sites open. When these sites are open the myosin head can insert in the actin site. Once inserted, the myosin filament contracts to pull the actin site closer to itself, releases, and then repeats with the next actin site. Therefore, the amount of calcium that is released acts to grade the strength and duration of the muscle contraction. A fraction of a second later the calcium ions are taken back into the muscle cells, causing release of the actin and myosin elements, leading to muscle relaxation. This mechanism allows activation of a muscle fiber to occur 60 to 100 times a second.

The process described above occurs for a single action potential. A single action potential typically lasts 1-3 milliseconds, but the time of muscle contraction as a result of a single action potential will last 10-100 milliseconds. The contraction of a muscle as a result of a single action potential is called a twitch. If more action potentials come after the first one at a successive rate, the muscle does not have time to relax and the twitches begin to add. If the twitches occur with a high enough frequency the force output of the muscle will plateau. This plateau is called a tetanus response. There are two types of tetanus, fused and unfused. In unfused tetanus, the frequency of action potentials is still fairly low, and so muscle twitches can still be seen. A fused tetanus occurs when the rate of action potentials becomes much faster, so much that the effects of the individual twitches can no longer be seen.

There are two methods the body uses to recruit muscle force. These methods are temporal and spatial summation. For most muscle contractions, the firing rate of action potentials is usually higher than 8 Hz, but not usually higher than 25 Hz during times of concentrated contraction. This method of summing the action potentials to create muscle contraction is known as temporal or frequency summation. As the frequency of the neural input to the muscle increases, the force output of the muscle increases. Another method of recruiting muscle contractions is through spatial summation. Spatial summation occurs when several muscle fibers are recruited in parallel,
causing greater contractile force than the contraction of a single muscle fiber. Combining both temporal and spatial summation will lead to a strong contraction of the muscle. The force output of a muscle can be related to the amplitude of the recorded EMG signal. For weaker contractions, fewer muscle fibers are recruited, and as a result, the EMG signal is relatively small. However, for large forces, spatial summation is used to recruit more muscle fibers, and consequently the EMG signal is larger. The EMG signal is a summation of the signal produced by many muscle fibers at the same time. All of these fibers do not fire synchronously. The action potential produced by each fiber has both positive and negative components, so this summation produces a waveform that is essentially random but whose overall amplitude is related to the number, size, and frequency of recruited motor units. EMG signals are typically measured in the millivolt range (Figure 5.2).

**Figure 5.2:** A typical, high pass filtered EMG signal recorded using the BioRadio software. When a subject contracts their muscle the amplitude of the EMG signal increases.
Different Muscle Types

One skeletal muscle is comprised of many individual skeletal muscle fibers. Each of these individual fibers that make up a muscle are classified into types depending on their speed of contraction and metabolism. The three major types of muscle fibers are fast oxidative (FO), slow oxidative (SO), and fast glycolytic (FG). Each of these concepts is explained below.

Skeletal muscle fibers may be separated into fast and slow fiber types. Whole muscle groups may be comprised of both fast and slow fibers, however, they exist in different proportions depending on the muscle group. Fast fatigue muscles fibers have the ability to rapidly contract and relax and generate large amounts of force. However, these muscles will fatigue quickly. The other major muscle type is slow fatigue muscle fibers. These fibers contract slower than fast fatigue muscle fibers, however, they are more resistant to fatigue. A muscle fiber that is resistant to fatigue can output the same level of force for a longer period of time before the force output begins to decrease. Fast fatigue muscle fibers are almost twice the size of the slow fatigue muscle cells. Therefore, the brain uses what is known as the “size principle” to recruit muscle fibers in a whole muscle action. The smaller fibers are recruited first and the larger fibers are recruited last. This makes sense because the smaller fibers can perform longer for everyday tasks without a decrease in force. Larger fibers are only recruited when large amounts of force are needed since they fatigue quickly.

In addition to the speed at which a muscle fiber contracts, there are also differences in their metabolism. Two different metabolism processes can occur in a muscle. Ideally, aerobic (or oxidative) metabolism occurs in the muscle cells. This process requires oxygen to convert energy from food to ATP. ATP is required for cell metabolism. Oxidative metabolism occurs so long as oxygen is present. However, there may be times of a decreased oxygen supply to the muscles, such as during exercise. When this occurs, the body switches to anaerobic (or glycolytic) metabolism. This process metabolizes glucose molecules without the presence of oxygen. In the first stage of anaerobic metabolism, glucose is split into pyruvic acid, and energy is released to create ATP from the original glucose molecule. The second stage of anaerobic metabolism, the pyruvic acid reacts with oxygen to create even more ATP molecules. However, if oxygen is still not present, the pyruvic acid is converted to lactic acid, which then enters the bloodstream. The soreness that some people feel after intense exercise is due to this build-up of lactic acid in the muscles. This glycolytic process of metabolism is able to create ATP 2.5 times faster than the oxidative pathway, making it useful for times of intense activity, however, only for short durations. Therefore, the aerobic pathway is used for times of prolonged muscle activity, and the anaerobic pathway is utilized when large amounts of energy are briefly needed.
**Processing of the EMG Signal**

The EMG signal from skeletal muscle that is recorded from the surface of the skin has a frequency range of 2-500 Hz and the amplitude can range from 50μV to 5mV. Since the maximum sampling frequency of the BioRadio is 960 Hz, it is possible that some of the high-end frequency content of the EMG signal may not be recorded with this instrumentation. There are many different techniques for processing a raw EMG signal. In the introduction, it was mentioned that EMG could be used as a control source. The EMG signal is usually high pass filtered to remove any types of movement artifact. Another simple method for processing the EMG signal is rectification. Rectification simply computes the absolute value of a signal. Electronically, rectification is typically done with a set of diodes, but in a computer, it is quite simple to take the absolute value of all the samples (Figure 5.3). After rectifying, one can find the average value of the EMG waveform.

![Raw and Rectified EMG Signal](image.png)

**Figure 5.3:** Raw and Rectified EMG signal. Note the different Y-axis values.
Another way to process the EMG signal is to find the average power. In order to quantify the average power in the EMG signal, a type of processing known as RMS power is performed. RMS power stands for root mean square. The RMS power of a periodic waveform is defined as:

\[ P_{\text{rms}} = \sqrt{\frac{1}{T_0} \sum_{n=0}^{T_0} [f(n)]^2} \]

This means that the waveform is first squared (a different way of rectifying the signal) and then the average value of the squared waveform is calculated. Finally, the square root of that number is calculated yielding the RMS (root mean square). For a waveform, the RMS value provides a descriptor of the average power in a signal. The equation above uses a summation instead of the more traditional integral since the data being acquired is discrete. For continuous signals, replace the summation with an integral.

Bin integration can also be performed after rectification (Figure 5.4). Bin integration is another way to quantify the EMG signal. Bin integration works by taking a small window over the EMG recording, say 5 points, and integrating the area in that window. Then the window is slid to the next 5 points, and integration is performed again. The result of bin integration is a time varying waveform that describes the muscle contraction from the EMG recording.

Figure 5.4: Raw and bin integrated EMG signal. Note the different Y –axis values.
High and low pass filtering is also commonly used to process EMG for use as a control signal. In order to remove high frequency noise, a low-pass filter can be applied to the EMG data. This will effectively smooth the EMG signal. On the other hand, a high-pass filter can be applied to remove low frequency noise such as motion artifact. A high pass filter will provide a faster response time. There are many tradeoffs between using a high pass and low pass filters in signal processing. The example below (Figure 5.5) shows a raw EMG signal and then the same signal low pass filtered at 25 Hz and high pass filtered at 25 Hz. Notice how low pass filtering the EMG signal removes much of the information content of the signal. Notice how the high pass filter removes the low frequency noise from the signal.

Figure 5.5: Low and high pass filtering of the EMG signal. Note the different Y-axis values.
Experimental Methods

Experimental Setup

You will be using 2 channels for the EMG laboratory. Use the BioRadio Configuration Wizard to set Channel 1 and Channel 2 for low level recording. Name channel 1 “Biceps” and channel 2 “Triceps”. Select high input resolution and record the sampling rate you use. Save this configuration as “Lab5 EMG”. You will need six snap electrodes from the BioRadio kit for this laboratory. Identify the bicep muscles on the arm of someone in the lab group. The biceps is the large, superficial muscle located on the anterior side of the proximal arm (Figure 5.6). The biceps is responsible for flexing the arm at the elbow joint. Identify the triceps muscle on the same arm. The triceps is the large superficial muscle located on the posterior side of the proximal arm (figure 5.6). The triceps is responsible for extending the arm at the elbow joint. It is important to properly prepare and clean the electrode site before attaching the snap electrodes. Place two snap electrodes on the surface of the skin above the biceps, separated by about 2 inches. Then place two more snap electrodes on the surface of the skin above the triceps of the same arm, again about 2 inches apart. It is responsible for extending the elbow joint. Finally, place two electrodes on the bony surface of the subject’s elbow.

Connect snap leads to all of the electrodes. Connect one of the snap leads from the biceps to the positive input of channel 1 on the universal harness. Connect the other snap lead from the biceps to the negative input of channel 1 on the universal harness. Connect one of the snap leads from the triceps to the positive input of channel 2 on the universal harness. Connect the other snap lead from the triceps to the negative input of channel 2 on the universal harness. Connect one of the snap leads from the subjects elbow to the input on the universal harness labeled “ground”. Connect the other snap lead from the subject’s elbow to one of the inputs on the universal harness labeled “Ref”. Connect the universal harness to the transmitter and turn the transmitter on. Connect the receiver to the data collection computer as per the User Guide.

Figure 5.6: Locations of the biceps and triceps.
Procedure and Data Collection


2. Instruct the subject to sit and relax with his/her test arm hanging to the side of their body. Start capture mode. EMG data should begin scrolling across the screen.

3. Begin saving data and name the file “weights.bd”. The subject should hold their arm at a 90-degree angle with their palm facing up. The subject will hold three weights for five seconds each. Approximate values of weights to use are 2.5, 5.0, and 10.0 lbs. After recording 5 seconds of relaxed arm muscle activity, have another lab group member gently place the lightest of the calibrated weights into the hand of the subject’s test arm. The subject should maintain the arm position with the weight for five seconds. Repeat with the middle value weight and then with the heaviest weight. Then stop saving data.

4. Stop the Capture mode and use View mode to open the file you just saved. Check to make sure that you have obtained an EMG signal. Export the entire file to an ASCII file. Save it as “weights.dat”.

5. Request the subject to relax their arm like before. Start Capture and begin saving data. Name the file “control.bd”. Request the subject to maximally flex their biceps for 5 seconds. Immediately relax the biceps for 5 seconds. Repeat this flexing/relaxing cycle to obtain a total of 3 cycles. Stop saving data.

6. Stop the Capture mode and use View mode to open the file you just saved. Check to make sure that you have obtained an EMG signal. Export the entire file to an ASCII file. Save it as “control.dat”.

7. Begin saving data again and name the file “cocontract.bd”. Start with the subject relaxed, with their test arms at rest. Then after a few seconds, instruct the subject to push their palms together and push as hard as they can for a few seconds. Then have them relax again for a few seconds.

8. Stop the Capture mode and use View mode to open the file you just saved. Check to make sure that you have obtained an EMG signal. Export the entire file to an ASCII file. Save it as “cocontract.dat”.


Data Analysis

Calibrated Weights

Using Excel, open the file “weights.dat”. Plot Biceps EMG over time and print this plot.

Rectify the signal by taking the absolute value of it, and store the result in a column. Plot this column versus time. For each weightlifting segment of the rectified signal (a total of three), calculate the average value of the rectified EMG signal. You should have three data points. Make a plot of Average Rectified EMG vs. weight using those 3 data points.

EMG Control

Using the BioRadio DSP Toolbox type in the file “control.dat”. Process the raw data and show the 3 ~ 4 muscle contractions. Print this plot.

Set the DSP method for channel 1 to RMS value and bin size to 5, zoom in on a transition area of this data, and print this plot.

Set the DSP method for channel 1 to RMS then LPF. Set the bin size to 5 and the low pass cutoff to 10 Hz. Zoom in on the same transition area as above.

Set the DSP method for channel 1 to RMS then HPF. Set the bin size to 5 and the high pass cutoff to 50 Hz. Zoom in on the same transition area as above.

Co-contraction

Using the BioRadio Capture program. Open the file named “cocontract.bd”. Zoom into a section that shows a few seconds before and a few seconds after the subject pushes their palms together. Turn off all filters and print this plot. Now turn on the high pass filter for both channels and set them to a cutoff of around 10 Hz. Print this plot.

Discussion Questions

1. Which type of muscle fibers is recruited for tasks that need fine control over a long period of time? Which type of muscle fiber is recruited for a task that needs a short quick burst of energy?

2. Sometimes when carrying a heavy box for an extended amount of time, and then removing the box from your arms, your limbs seem to keep on lifting, even though the weight is no longer on your arms. Why do you suppose this happens?
3. Why can’t the average or bin integral be performed without first rectifying the EMG waveform?

4. Using the plot from the calibrated weights experiment, what did you find the relationship between EMG and force was? Did this appear to be a linear relationship?

5. What are the two mechanisms that the nervous system has to increase the force that a muscle is generating?

6. Many special signal-processing techniques can be applied to extract or enhance certain properties of the EMG. Explain why one would use the RMS value rather than the average value of an EMG signal, and what signal property it enhances.

7. In terms of control, what advantages does the high pass filtered signal have over the low pass filter? What disadvantages are there? Use the plots that you made with the BioRadio DSP Toolbox illustrating RMS value, RMS and low-pass filtered, and RMS and high-pass filtered data from the “control.dat” file.

8. For the “cocontract” data what does EMG from the biceps and triceps do as the subject exerts force against the other palm. Explain why this happens. Hint: Think about the angle of the elbow during the task and the antagonist muscles that are being measured. In what other tasks might contraction occur and why is it important?

9. Why might someone want to high pass filter the EMG data? Use the plots you made from the cocontraction data to explain this. Think about the frequency range of the EMG signal and sources of artifact in the signal.

10. Explain why the “size principle” is an efficient process for the body to use.

**NOTE: Graduate Students Should Continue and Complete the Following Sections.**

**Graduate Analysis and Discussion**

1. Using MATLAB, create a band pass filter with a cutoff frequency of 15Hz and 50Hz. Rectify the signal from Channel 1 of the “Calibrated Weights” data file, and apply the filter you just made. Verify the filter is working correctly by looking at the resulting signal’s power spectrum. Find the standard deviation of the noise when the weights are being lifted.

2. From the analysis that you have completed on the EMG signals, what would you expected the limiting factors on the number of discrete levels of EMG that could be used as a control source.
3. Spinal cord injury subjects at the C5/6 level lose the ability to open and close their hand. By electrically stimulating muscles in a coordinated fashion, hand grasp could be restored. One control source for this system may be to use the EMG from a voluntary muscle to proportionally control the strength of the stimulation. Outline the characteristics of a system that could be used to control this. What tools that we have (or haven’t) discussed would you need, and how would they be used?

4. How would muscle fatigue affect the output of the system outlined above? Describe ways to avoid or work around fatigue related output differences.

5. Earlier, the innervation ratio was defined as the number of muscle fibers innervated by a single neuron. Explain why it is easier to grade the force produced by a muscle with a lower innervation ratio.

6. Botulism bacteria produce toxins that are lethal if a sufficient amount is ingested. However, some cosmetic physicians have found it useful in removing wrinkles, since it causes permanent muscle relaxation when applied to small areas of wrinkles. Knowing that acetylcholine is necessary for muscle contraction, how do you suppose small amounts of botulism toxin works to remove these wrinkles?
References


Lab 6

The Electro-oculogram
Introduction

Sight is probably the most important of the five senses to many human beings. Our visual system continuously provides feedback on objects and interactions with our environment in almost everything that we do. The eyes help us to zone in on objects that are right in front of us such as a book we are reading, they allow us to track a plane shooting across the sky at an air show, and they allow us to focus on an object that is far off in the distance. Several muscles are responsible for moving the eyes around to complete these different types of tasks. Each of these distinct tasks performed by the eyes requires specific types of controlled movements. These movements each have their own name and will be explained in this laboratory. Researchers have performed experiments to understand how the eye functions, and the electro-oculogram (EOG) is one of the observed phenomena that can give us insight.

Several theories exist on the exact mechanism responsible for generating the EOG potential. However, regardless of its exact mechanism, the EOG is an important biopotential that can provide us with information about the visual system. One important example where the EOG is used is during overnight sleep studies (you will actually be completing an overnight sleep study in a future lab). Sleep studies often include the EOG as one of many biopotentials that are recorded. During certain portions of a sleep cycle, the eye movements become very erratic and relatively large in magnitude. Monitoring and recording the EOG signal can help to detect these stages of sleep. In addition, completing eye tracking exercises and monitoring the resulting EOG can allow diagnosis of certain eye diseases. For example, an ophthalmologist can use the EOG to diagnose retinal disorders that can lead to blurred vision.

In this lab, students will monitor and record the EOG signal from both the left and right eyes of a subject. Various eye movement experiments, such as target tracking exercises, will be performed. The data will be processed and analyzed to identify characteristics of and problems with interpreting the EOG signal.

Equipment required:

- BioRadio 110
- Snap Electrodes
- Microsoft Excel
- Measuring Tape
- MATLAB (Graduate Students)

Figure 6.1: The human eye is integral in supplying feedback to the nervous system about the environment.
The human eyes contain several anatomical structures that function much like a camera and allow us to focus on and track objects in the visual field (Figure 6.2). The cornea and the lens are two important structures that help the eyes to focus on objects. The lens is responsible for focusing the visual image on the back of the eye. The lens changes shape and coordinates with the cornea to change the direction of the rays of light entering the eyes, hence, focusing the light on the retina. The retina contains the photoreceptors (rods and cones) that are responsible for transducing the light into an electrical signal for the brain. The fovea is the part of the retina that is the most sensitive. In the fovea photoreceptive cells are abundant. The rest of the retina has photoreceptive cells as well, but they are not as densely populated as in the fovea, and thus provide a lower resolution image. The lower resolution region allows for detection of a new object for targeting, such as when you may first recognize an object in your peripheral vision. The extraocular muscles rotate the eyeball to focus the point of interest on the fovea. The pupil opens and closes in response to light intensity. The iris is the colored part of the eye.

There are three pairs of extraocular muscles that control eye movements (Figure 6.3). The medial and lateral rectus muscles control movement of the eyes in the horizontal plane. The superior and inferior rectus muscles control vertical movement of the eyes. The superior and inferior oblique muscles function to rotate the eye. This torsional movement supplied by the oblique muscles helps to keep the visual fields in the upright position for small lateral rolls of the head.
These muscle pairs are reciprocally innervated. In other words, they are antagonists, when one muscle in the pair contracts the other relaxes. The reciprocal mechanisms allow the eyes to stay aligned on an object so that the same image appears on both retinas. The extraocular muscles in the eyes allow for depth perception. Double vision occurs when this mechanism does not function properly and the two retinas have different focal points. Cranial nerves III, IV, and VI are responsible for innervating the muscles described above that control eye movements.

The three pairs of muscles that control eye movements are capable of creating many different types of movements. *Fast* saccadic eye movements are used to quickly fixate a target. *Smooth pursuit* eye movements are used for tracking a target. *Vestibular ocular* eye movements keep the eyes focused on a target even while the head is moving. An example of this would be someone running to catch a ball. Their head moves while they run, yet they are able to stay focused on the ball. *Vergence* movements let the eye track near and far targets. The vergence movements are unique from the other types because they are the only ones that allow the eyes to move in opposite directions. *Optokinetic* movements occur when moving through a target filled environment.

Using the extraocular muscles to generate these kinds of movement, we attempt to place the target image on the fovea. The eye can then “jump” to focus on the new target, and this jumping is called a saccade. Saccades can be observed in individuals as they are reading, or looking out the window while riding in a car. When scanning a visual scene, we make about 3 saccades/second, integrating each of these visual “snapshots” into a high-resolution “mind’s eye” view of the scene. Go ahead and watch someone’s eyes as they read this lab. You will see several saccades per line of text they read.

**Figure 6.3:** The are three pairs of extraocular muscles that are responsible for moving the eye up, down, left, right, and torsionally.
So what is the exact physical mechanism responsible for generating the EOG signal we measure? We are not measuring the EMG from the extraocular muscles. Instead, scientists believe that there are other signals specific to the eye or eye region that give rise to these EOG. Though the exact origin of the EOG has not been conclusively determined, there are several theories that have been proposed as the mechanism behind it. The first is the cornea-retinal dipole theory. It states that an electric dipole is formed through the eye because the cornea is positively charged, while the retina is negatively charged. As you may remember from physics, a dipole creates an electric field that can be measured. This is the potential that is being measured by the EOG. As the eye changes direction, so does the dipole, and thus, the detected signal (Figure 6.4). The second school of thought is similar to the one described above, but instead of the dipole being created by the cornea and the retina, the dipole is believed to be the potential difference across the retina itself. The third theory states that it is the eyelid movement that creates a sliding potential source, which is responsible for the potential recording. The cornea-retinal theory is most widely accepted, and will be used for illustrative purposes in this lab.

Figure 6.4: A) The cornea is positively charges while the retina is negatively charged. B) This creates a dipole with an electric field that can be measured.

The EOG is an important signal to be aware of when recording EMG from facial muscles or EEG. Typical EOG signals have amplitudes in the millivolt range with frequencies of DC - 100Hz. In Lab 4 we learned that EEG signals are on the order of microvolts and in Lab 5 that EMG is in the millivolt range. Since the eyes are located close to the brain and facial muscles, the different signals may create artifact in one another. EOG can be severely contaminated by the EMG signal, and to a lesser degree, by the EEG signal as well. The reciprocal is also true. EOG can contaminate EEG and EMG recorded around the head and face regions. In some cases, such as slow eye movements, the EOG can create a DC offset in the EEG signal. These concepts will be more fully explained in a future laboratory. For the purposes of this laboratory we will be
concerned with measuring the DC component of the EOG signal. The DC component of the EOG signal can be used to measure eye movement +/- 30 degrees.

As mentioned in the introduction, the EOG is one of the standard biopotentials measured during a sleep study. This is because a type of sleep of particular interest is called rapid-eye-movement (REM) sleep. REM involves, as the name implies, very quick and random eye movements. In a normal night of sleep, REM sleep occurs about every 90 minutes, lasting about 5 to 30 minutes at a time. This is the time that is usually associated with active dreaming, reduced muscle tone, reduced cardiac and respiratory rates, and increases in brain activity. Because the increased brain activity during REM resembles that of a conscious person, REM sleep is also called paradoxical sleep.

Experimental Methods

Experimental Setup

Using the BioRadio Configuration Wizard, select three channels for recording. All three channels should be set for HIGH LEVEL recording. Choose the high resolution and note the sampling frequency. Name channel 1 “VEOG-R”, channel 2 “VEOG-L”, and Channel 3 “HEOG”. Save this configuration as “Lab 6 EOG”.

You will need seven snap electrodes for this laboratory. **NOTE: For this laboratory, you may want to attach all of the snap leads to the snap electrodes before you place the snap electrodes on the subject. It may be uncomfortable for the subject if you apply pressure to these electrode positions afterwards.** Properly prepare and clean the surface of the skin before applying any snap electrodes (Figure 6.5). Place one snap electrode above the right eye and one above the left eye just above the eyebrows. These electrodes will be used as references. Similarly, place one snap electrode below the right eye and one below the left eye. These electrodes will be used to measure vertical displacement of the eye. Place one snap electrode to the left of the left eye on the left temple and one to the right of the right eye on the right temple. These electrodes will be used to measure horizontal displacement of the eyes. Finally, place the last electrode between the two eyes, just above the bridge of the nose. This electrode will be used as a reference.

If you have not already, attach snap leads to all of the electrodes. Attach the snap lead from electrode between the eyes, just above the bridge of the nose to an input on the universal harness labeled “REF”. Connect the snap lead from the electrode above the right eye to the positive input connector of channel 1. Connect the snap electrode from the electrode below the right eye to the negative input connector of channel 1. Connect the snap lead from the electrode above the left eye to the positive input connector of channel 2. Connect the snap electrode from the electrode below the left eye to the negative input connector of channel 2.
snap lead from the electrode on the temple next to the right eye to the positive input connector of channel 3 on the universal harness. Connect the snap lead from the electrode on the temple next to the left eye to the negative input connector of channel 3 on the universal harness. Take all lead wires and run them behind the ear so the subject has an unobstructed field of vision.

Connect the universal harness to the BioRadio transmitter. Turn the transmitter on.

**Procedure and Data Collection**

For each of these experiments, it is very important that the subject keeps their head still while tracking objects. Only the subject’s eyes should move to track the object.

1. Run the BioRadio Capture software.

2. In a quiet room, have the subject sit relaxed in a chair, with their eyes closed. Start capture mode. Data should begin scrolling across the four channels. Begin saving the data. Name the file “eyesclosed.bd”.

3. With their eyes still closed, request the subject to look straight ahead. Then request them to slowly begin moving their eyes all the way to the left, hold it for five seconds, then all the way to the right, hold it for five seconds, and then back to center. Stop saving data.

4. Start the capture program again and begin saving data. Name the file “eyesopen.bd”. With their eyes open, request the subject to look straight ahead. Then request them to slowly begin moving their eyes all the way to the left, hold it for five seconds, then all the way to the right, hold it for five seconds, and then back to center. Stop saving data.

5. Using a tape measure mark off five increments that are 1 foot apart. You should have 4 total feet. Hold the tape measure at eye level in front of the subject at a distance of 3 feet away. The center of the tape measure or yardstick should be aligned with the subject’s nose. Begin saving data to a file. Name the file “htrack.bd”. Instruct the subject to look at the point 2 feet to the left of center, hold it for five seconds, then 1 foot left of center, hold it for five seconds, continue in this fashion fixing on all five points until they reach the point two feet to the right of center and have held it for five seconds. Stop saving data.

6. Stop the Capture mode and use View mode to open the file you just saved. Check to make sure that you have obtained EOG signals. Export the entire file to an ASCII file. Save it as “htrack.dat”.

7. Repeat step 7 for the vertical direction (saving it “vtrack.bd”). Hold the tape measure vertically this time. Instruct the subject to start at the top point and work their way down, fixing on each of the five locations for 5 seconds each.

8. Stop the Capture mode and use View mode to open the file you just saved. Check to make sure that you have obtained EOG signals. Export the entire file to an ASCII file. Save it as “vtrack.dat”.

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9. Start BioRadio capture. Begin saving data. Name the file “blinks.bd”. Request the subject to stare at an object off the eye’s center axis. Request the subject to blink a few times. After a few blinks have been recorded, stop saving data.

10. Stop the Capture mode and use View mode to open the file you just saved. Check to make sure that you have obtained EOG signals. Export the entire file to an ASCII file. Save it as “blinks.dat”.

11. Start BioRadio capture. Begin saving the data and call the file “crossed.bd”. Request the subject to look straight ahead for 5 seconds, and then cross their eyes for 5 seconds. Stop saving data.

12. Stop the Capture mode and use View mode to open the file you just saved. Check to make sure that you have obtained EOG signals. Export the entire file to an ASCII file. Save it as “crossed.dat”.

Data Analysis

Analysis Eyes Closed and Open Data

Using the BioRadio software, print out the recordings for both the eyes open and eyes closed plots. Is there a difference between the two recordings? If so, what is the source of this difference? How might you create a filter to make the two recordings appear the same?

Analysis of Horizontal Eye Tracking

Using Excel, open the data file named “htrack.dat”. Plot HEOG over time and print this plot. Calculate the average voltage over each of the five positions. Then calculate the angle of the eye at each of the locations. You should be able to do this since you know the distances. Assume that the eye looking straight ahead is zero degrees and moving to the right is a positive angle.

Now plot these angles versus the average voltage at each angle.

Analysis of Vertical Tracking

Repeat the same analysis for vertical tracking.

Analysis of Blinking

Print out plots of the sections containing blinks from the BioRadio software.
Analysis of Eyes Crossed

Use the BioRadio software to print the recording in which the eyes were crossed.

Discussion Questions

1. During the experiment where the subject crossed their eyes, what happened to the EOG potential? Explain why this occurs. Feel free to draw a diagram to assist the explanation.

2. What muscles are responsible for moving the eye so quickly in the horizontal direction? In the vertical direction?

3. Look at the plot of blinking on the EOG signal. Which channels does blinking affect and why?

4. Blink artifacts do contaminate the EOG signal, but why is this not so much of a concern clinically? How do blinks introduce artifact into the EOG recording? What channels do blinks appear on? How could these affect EOG measurements on that channel?

5. In the second experiment, what kinds of eye movement can be seen on the plots of the horizontal and vertical tracking exercises?

6. Imagine you are a baseball player standing in the outfield. Suddenly a fly ball is hit to your right and you begin running after it. You run a short distance, plant yourself where the ball is headed, wait a few seconds, and then catch the ball. Explain all of the different eye movements that would have occurred during that sequence of events.

7. A new hypothetical company called VisionSoft wants to create a new operating system that does not require the use of the mouse. How can the EOG be used as a new way to interact with the computer? What are some problems the designers may encounter?

NOTE: Graduate Students Should Continue and Complete the Following Sections.

Graduate Analysis and Discussion

1. You should be able to develop an equation to determine horizontal angle of the eye from the voltage output on HEOG. Use the plot you made in Excel above. What is this equation?
2. Using this equation you can now determine the angle of the eye at each point in time. You know now eye angle at many discrete points in time. Plot the angle of the eye over time. Plot the velocity of the eye over time.

3. Do the peaks in the velocity plot occur where you would expect?

4. Using MATLAB, create a filter that should aid in reducing the blinking artifact in the data file that contained blinking artifact.
References


Laboratory 7

Signal Processing and Artifact Removal
Introduction

As you now understand, electrical signals originating from physiological processes of the body can be measured using electronic equipment. Each of these biopotentials has different amplitude and frequency characteristics that make them distinct from other measurements. For example, the ECG signal appears very different from the EEG, EOG, or EMG signals. However, sometimes recordings are done where one physiological signal may contaminate the other due to the proximity of the recording electrodes.

In order to extract the desired signal from a contaminated signal processing must be performed. Digital signal processing (DSP) can be used to extract meaningful information from recorded physiological signals. Digital signal processing methods are simply digital models of analog signal processing methods. As compared to analog signal processing, digital signal processing provides a person with the flexibility to easily change the parameters of the filter. If this type of processing were done with analog electronics, one would have to rebuild or replace parts in a circuit each time a parameter change was desired. Digital signal processing allows the computer to change the filter parameters and provide instant results!

This laboratory will cover some techniques and background on how signal processing can be applied to separate out physiological signals that might be interfering with each other. This will require understanding of Fourier analysis, some basic filters such as highpass and low pass, and how these basic analog filters can be converted into their digital equivalents.

Equipment required:
- BioRadio 110
- Laboratories 3 (EEG), 4 (EMG), and 5 (EOG) for reference
- Chewing Gum
- Microsoft Excel and BioRadio DSP Toolbox
- MATLAB (graduate students)
Background

**Frequency Domain Analysis**

Up to this point, we have been analyzing recorded biopotentials in the time domain. The BioRadio software plots signals in the time domain. In other words, it shows the amplitude of the electrical potential across time. Time domain processing is somewhat limiting if we wish to process these signals to eliminate artifacts. The more practical method is to do frequency domain analysis. There is a bi-directional relationship between the time domain and frequency domain. Suppose a sound generator is used to generate a 60 Hz tone. If you looked at the electrical signal output of the tone generator on an oscilloscope, you would see a continuous periodic signal that has a frequency of 60 Hz. This means that only a single frequency is in that signal, 60 Hz. Plotting the same signal in the frequency domain would reveal a peak at 60 Hz, and zero elsewhere (Figure 7.1). This transformation is reversible. Given a plot of the frequency of a signal, it can be converted into a time-domain signal.

![Figure 7.1: Example of Fourier transforms of two signals. Notice that there are peaks at both positive and negative frequencies. This negative frequency is the same as the positive frequency due to a trigonometric relationship. So, there really are not two frequencies, they are one and the same.](image)

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The basis behind these frequency transformations is the Fourier transform. The Fourier transform is an extremely powerful mathematical tool that allows scientists and engineers to analyze the frequency components of signals. Many of the signal processing techniques that are covered in this laboratory will employ frequency-based tools. The mathematical basis of the Fourier transform is the following:

\[
F(\omega) = \int_{-\infty}^{\infty} f(t)e^{-j\omega t} \, dt
\]

\(F(\omega)\) denotes the frequency domain signal, where \(\omega\) is the frequency in radians. Now, to convert back from the frequency domain to the time domain, the inverse Fourier transform is used.

\[
f(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} F(\omega)e^{j\omega t} \, d\omega
\]

When signals are represented in the frequency domain, the function is typically capitalized, thus the \(F(\omega)\) and \(f(t)\).

The Fourier transform only exists for signals that satisfy the following three properties:

1. Absolutely integrable
2. Has a finite number of discontinuities
3. Finite number of minimum and maximum points.

Simply stated, the above three properties mean that the signal must be bounded and contain a finite number of discontinuities.

Frequency analysis is particularly useful in the design of filters. Filters are used to emphasize frequency bands that are important and de-emphasize frequency bands that are not a part of the desired signal. As you have learned, 60 Hz noise is evident in almost all physiological recordings due to the interference from surrounding electrical systems. Without frequency domain analysis, there are no tools that can be used to eliminate this noise. However, if a filter can be designed to block out this 60 Hz noise quality of the physiological recording will be improved. Since this noise may obscure the signal being recorded, a 60 Hz notch filter is used to eliminate this artifact. A notch filter is an extremely narrow band filter that does not allow a band of signals to pass through. For example a 60 Hz notch filter is frequently used to block out 60 Hz noise.

**Filters**

As mentioned earlier, DSP techniques implemented on the computer are actually based on mathematical models of analog hardware filters. There are four main types of filters of which you should be aware. These include lowpass filters, which allow low frequencies to pass through, highpass filters, which allow high frequencies to pass through, bandpass filters, which allow signals within a certain frequency band to pass through by combining a high and low pass filter, and bandstop filters, which prevent certain frequency bands from passing through.
Figure 7.2: Diagram of four basic filter types. Ideal filters would have the steep cutoffs as seen in the diagram, however, real-world filters do not have perfect frequency cutoffs.

Understanding how to analyze hardware filters requires knowledge of the concept of complex impedance. As you know, resistors have certain impedance. Ideally, the impedance of a resistor is independent of the frequency of the signal passing through it. Capacitors and inductors also have impedances associated with them. The only difference here is that capacitors and inductors have complex impedances. In other words, their impedance is dependant on the frequency of the signal passing through them. Understanding complex impedance is a power tool for characterizing hardware filter circuits.

Recall the fundamental equations for a capacitor and inductor:

\[ i = C \frac{dV}{dt} \]; The current through a capacitor

\[ V = L \frac{dI}{dt} \]; The voltage across an inductor

Where C and L are the capacitance or inductance values.
Now, suppose an operator $s$ exists, which acts like $\frac{d}{dt}$. Substituting $s$ in the equations above yields: $i = CsV$, $V = LsI$. Ohm's Law states that $R = V/I$. The complex impedance $Z_C$ of a capacitor is then $Z_C = \frac{1}{Cs}$, and the complex impedance $Z_L$ of an inductor is $Z_L = Ls$.

You may be wondering what $s$ means. One can substitute $j\omega$ for $s$, and now you have a relationship between frequency and impedance. So, when replacing $j\omega$ in the equations above, as frequency $\omega$ increases to infinity, the complex impedance of a capacitor goes towards zero, and the complex impedance of an inductor goes towards infinity. And as an additional note, $Z$ is used to denote complex impedance instead of $R$, to avoid confusion.

So now, we can treat inductors and capacitors as resistors with complex impedance. The first circuits to analyze with this approach are the first order lowpass and highpass filters (Figure 7.3 and 7.4). These circuits contain both an $R$ and a $C$ element. The low pass filter is measured across the capacitor while the highpass filter is measured across the resistor.

First we will analyze the lowpass filter (Figure 7.3). When presented with this circuit, we first solve for the transfer function of this circuit. The transfer function, $V_{\text{out}}/V_{\text{in}}$, of this circuit is $\frac{Z_C}{Z_C + R_1}$. Substituting values, this becomes $\frac{1}{RCj\omega + 1}$. It is obvious that for low frequency values, this transfer function approaches one, and for high frequency values, this transfer function becomes zero, thus making it a low pass filter, since low frequency values will pass, but high frequencies are attenuated. Solving for the transfer function of the highpass filter is left as an exercise for the student.

Now, how do we determine when the filter begins to attenuate high frequency signals? This requires the computation of the cutoff frequency. Looking at the transfer function, this is when the
value of $\omega$ is equal to $\frac{1}{RC}$. This is because when $\omega$ is equal to $RC$ in the transfer function, the value of $V_{out}/V_{in}$ becomes $\frac{1}{2}$.

Ideally, we would want filters to pass or block signal components at the exact specified cutoff frequencies. However, we do not live in an ideal world, nor do we have access to ideal filter components. Realizable filters attenuate over a range of frequencies rather than dropping off to 0 at a specific frequency.

To characterize how fast the filter is able to attenuate signals at the cutoff frequency, we perform a measurement called a Bode plot. The Bode plot illustrates frequency on the x-axis and the attenuation of the signal on the y-axis. On the y-axis 1 refers to no attenuation while 0 refers to no amplitude at that frequency. Bode plots are extremely useful in visualizing the frequency response of a filter. Experimentally, this can be performed by measuring the output of a circuit at different frequencies, then plotting these values on a semilog scale.

![Figure 7.5: Low pass Bode Plot for the RC circuit above. The cursor shows the 3dB point to be at 161 Hz, even though the cutoff frequency was designed for 100 Hz. See that low frequencies are passed up to about 100 Hz, and then attenuated for frequencies above that.](image)
Decibels, or dB, relate the output power of a circuit to the input power. Decibels are a logarithmic scale, so that high values of gain or attenuation don’t require very large numbers. Computing between voltage and decibels is done through the following equation:

\[ dB = 20 \log \left( \frac{V_{out}}{V_{in}} \right) \]

Some may observe that \( V^2/R \) is a measurement of power. Now, performing some math, the R term drops out since it is present in both the numerator and denominator. Furthermore, using the exponent property of logarithms, this equation becomes

\[ dB = 10 \log \left( \frac{V_{out}^2}{V_{in}^2} \right) \]

So, using this equation, when the amplitude of a signal is \( \frac{1}{\sqrt{2}} V_0 \), the dB value is –3dB.

At this 3dB attenuation point, the power is reduced by \( \frac{1}{2} \) and is sometimes referred to as the half-power point.

These filters that have been mentioned up to this point are considered first-order filters. They are relatively simple to construct and analyze. However, they are not always the best filter for the application. First order filters have a slow cutoff, and there may be some applications where filter with a steeper frequency cutoff is desired. In those instances, higher order filters requiring several R, C and L components can be designed, and are more complex to design and analyze. Higher order filters will have steeper rolloffs. This means that the frequency associated with the 3 dB
point will be much closer to the cutoff frequency used to design the circuit. These higher order filters do a better job of approximating the ideal filter, since they will only emphasize a tighter frequency band with a steeper rolloff.

**Table 1:** List of commonly used higher order filters.

<table>
<thead>
<tr>
<th>Name</th>
<th>Advantage</th>
<th>Disadvantage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Butterworth</td>
<td>Maximally flat in the passband (passband ripple is zero)</td>
<td>Roll off is not very steep compared to other filters</td>
</tr>
<tr>
<td>Chebychev</td>
<td>Monotonic roll-off, steeper than the Butterworth</td>
<td>Some passband ripple.</td>
</tr>
<tr>
<td>Elliptical</td>
<td>Steeper rolloff than Chebychev filter.</td>
<td>Non-monotonic roll off, ripple in both the passband and stopband.</td>
</tr>
<tr>
<td>Bessel</td>
<td>Designed for linear phase</td>
<td>Slow rolloff compared to other filters above.</td>
</tr>
</tbody>
</table>

These filters also have phase effects as well. Recall from circuits that phase relates to how a certain signal is delayed. For example, the sine wave is an example of a cosine wave that has a phase delay of 90 degrees or $\pi/2$. The phase of a filter is determined by looking at the denominator of the transfer function. Now, note that there are two terms in the denominator, a real term and an imaginary term ($j\omega$). The analysis of the phase angle is done in the imaginary plane, where the x-axis represents real values, and the y-axis represents the imaginary values. Recall the generic form of the lowpass filter transfer function was $\frac{K}{\alpha + j\omega}$. The phase $\theta(\omega)$ is determined by taking the angle of $K$ – arctan($\omega/\alpha$). Since K is always real, the angle of K is 0 when K is positive, or ±180 when K is negative. So, the phase for the low pass filter illustrated above is as follows. When $\omega$ is small, the phase is 90 degrees. When $\omega$ is equal to the filter cutoff, then the phase is 45 degrees, and for large $\omega$, the phase becomes 0 degrees.
Digital Filtering

Digital signal processing is a very powerful tool for signal analysis. The analog filters described above are actual hardware circuits. Therefore, if changes in the cutoff frequency or filter order are desired, parts must be replaced. Digital signal processing allows filters to be based on the mathematical rules of these filters. This allows the implementation of these filters in software, thus giving instant flexibility in filter design. In the BioRadio software, there are some filter settings that are based on a higher order digital filter known as a Chebychev filter. In order to design these filters for the computer, we create an array with filter coefficients to mimic the frequency response of the hardware filter. These filter coefficients are then convolved with the digitally sampled signal. The result is an array containing values of the filtered signal.

There are two main types of digital filters: FIR and IIR filters. FIR, or finite impulse response filters, are designed without using feedback from the output, i.e., the output of the filter has no impact on the next sample that is filtered. These FIR filters have linear phase and variable steepness, depending on the filter order. IIR, or infinite impulse response filters use feedback so that the filtered output has an effect on the next value. IIR filters do not have linear phase, but the advantage to using them is that fewer filter coefficients are used for an equivalent performing FIR filter. IIR filters are commonly used to approximate higher order analog filters such as the Chebychev, Bessel, or Butterworth filters.
**Biopotentials to be measured**

In this laboratory several different biopotentials located in close proximity will be measured at the same time. Digital filtering tools will then be used to attempt to remove the undesired biopotential from the desired one. Other signals contained within the signal one is attempting to measure are known as artifact. First, we will briefly review the EEG, EOG and EMG biopotentials. Recall that the electroencephalogram (EEG) is a measurement of the activity of the brain. More specifically, the signal that is measured on the scalp originates from the post-synaptic potentials of the neurons in the brain. When these neurons fire synchronously, the EEG appears as a signal with a certain frequency. Brain waves can be used to determine when a person is sleeping, awake, or having a seizure. The electro-oculargram (EOG) is a measurement of the electric field generated by the eye. The EOG is used in sleep studies to help characterize when a person is in REM sleep. The EOG can also be used to determine the direction of a person’s gaze. Finally, the electromyogram (EMG) measures the number of muscle fibers depolarizing and can be used as an indicator of muscle force. EMG can often be higher amplitude than the other biopotentials in the body.

<table>
<thead>
<tr>
<th>Signal</th>
<th>Typical Frequencies (Hz)</th>
<th>Typical Amplitude (μV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EEG</td>
<td>8 - 13 (α)</td>
<td>20-100</td>
</tr>
<tr>
<td></td>
<td>13 - 22 (β)</td>
<td>5-10</td>
</tr>
<tr>
<td></td>
<td>0.5 - 4 (Δ)</td>
<td>20-100</td>
</tr>
<tr>
<td></td>
<td>4 - 8 (θ)</td>
<td>10</td>
</tr>
<tr>
<td>EOG</td>
<td>DC-100</td>
<td>10 – 5000</td>
</tr>
<tr>
<td>EMG</td>
<td>2-500</td>
<td>50 – 5000</td>
</tr>
</tbody>
</table>

*Table 2.* Typical amplitudes and frequencies for the signals we will be measuring in this laboratory are shown above.

Instead of measuring the EMG from the arms as we did in the EMG laboratory we will be measuring facial EMG. Muscles in the face and neck are used for chewing, talking, and maintaining the posture of the head. EMG often times creates large artifact in the EOG and EEG signals. For example, a patient may be in an epilepsy monitoring unit, with scalp EEG electrodes placed on the head. If a seizure starts occurring while they are eating lunch, there is going to be a large amount of EMG artifact polluting the EEG signal. This is obviously undesired, so the engineer must understand what frequencies the EMG contains, and filter those frequencies out while minimally affecting the EEG data.

There are some cases where measuring facial EMG is desired. EMG from the face can be used during biofeedback to help a person relax their facial muscles. Biofeedback works by sending an error signal (usually some sort of tone) that quantifies the person’s state of relaxation. The subject then seeks to minimize or maximize the signal that helps them relax. Biofeedback is sometimes used by people who are stressed out or by sports athletes who try to put themselves in a relaxed state of mind before playing their game. Another use for facial EMG is the diagnosis of tempomandibular joint pain. Some people, either through stress or other environmental factors have a disorder in which they tighten their jaw muscles constantly, but unconsciously. As a result, they feel this pain in their jaws. Monitoring facial EMG could diagnose this.
Facial EMG is also useful to determine when a patient has entered REM sleep. When REM sleep occurs, the pons in the brain creates an inhibitory effect on the motor neurons to help prevent people from acting out their dreams. So, this inhibitory effect then causes decreased muscle tone throughout the body. Measuring facial EMG can give an indicator of the muscle tone during sleep. Also, EMG can be used in the diagnosis of amyotrophic lateral sclerosis, also known as Lou Gerhig’s disease. This is a degenerative wasting disease where a person eventually loses all control of their muscles in their body due to muscle atrophy and motor neuron damage. The facial EMG is used to help diagnose ALS since this loss of muscle tone first begins in the head and neck muscles.

So in this laboratory, we will be measuring several different biopotentials simultaneously, and use digital signal processing techniques to help separate out each of the signals.

**Experimental Methods**

*Experimental Setup*

Using the BioRadio Configuration Wizard, select all eight channels for recording, and set them all for low-level input signals. Choose the medium input resolution, and note the sampling rate. Name channel 1 “EEG-FP1”, channel 2 “EEG-FP2”, channel 3 “EEG-O1”, channel 4 “EEG-O2”, channel 5 “EOG-L”, channel 6 “EOG-R”, channel 7 “EMG-L”, and channel 8 “EMG-R”. Save this configuration as “Laboratory 7 DSP”. Program the BioRadio transmitter and receiver to this configuration as per the User Manual.

This laboratory assumes that you have a basic knowledge of recording EEG, EOG, and EMG signals from the previous laboratories in this book. It is advisable to review the laboratories associated with these biopotentials prior to completing this one.

For the purposes of this laboratory we will be recording 4 channels of EEG, 2 channels of EOG, and EMG. The EMG we will be recording for this laboratory will be from the masseter muscles (Figure 7.7). The masseter muscles are used to clench the jaw and are involved with mastication (chewing). In order to locate them, feel the sides of your face as you clench your teeth together. The slight bulging of the region towards the back of the jaw is the masseter muscle contracting. Properly clean the surface of the skin above the masseter muscle. Attach two snap electrodes over the left masseter muscle separated by about an inch. Connect snap leads to the electrodes. Attach one of the snap leads to the positive input of channel 7 on the universal harness and the other to the negative input of channel 7 on the universal harness. Repeat for the right masseter muscle attaching the snap leads to channel 8 on the universal harness.
Two channels of EOG will be recorded. Properly prepare the surface of the skin before attaching the surface electrodes for EOG. Attach a snap electrode just left of the subject’s left eye, and slightly above the midline of the eyes on the left temple. Connect a snap lead to the electrode and connect the other end of the snap lead to the positive input of channel 5 on the universal harness. Attach another electrode just right of the right eye, but slightly below the midline of the eyes on the right temple. Connect a snap lead to the electrode and attach the other end of the snap lead to the positive input of channel 6 on the universal harness.

Two snap electrodes will be placed on the left mastoid about one inch apart and one snap electrode will be placed on the right mastoid. The mastoids are the bony processes at the base of the skull behind the ears. Properly prepare and clean the electrode sites before placing the electrode on the skin. Place snap electrodes on these three locations. Connect snap leads to these three electrodes. Connect the snap lead from the electrode on the right mastoid to one of the inputs on the universal harness labeled “REF”. Connect the snap lead from one of the electrodes on the left mastoid to the other input on the universal harness labeled “REF”. Connect the other snap lead from the left mastoid to the input on the universal harness labeled “ground”.

Connect the negative input of channel 5 on the universal harness to one of the stackable connectors on the universal harness labeled “REF”. One of the snap leads from a reference electrode should already be attached to that input. However, these are stackable connectors. Therefore, more than one input connector can be connected to a single snap lead. Connect the negative input of channel 6 of the universal connector to the other input connector on the universal harness labeled “REF”. This connector should already have the other reference snap lead from the mastoid connected to it.

Place gold cup electrodes filled with Elefix gel onto locations FP1, FP2, O1, and O2 (Figure 7.8). Cover with cotton and tape in place. You may want to use gauze to wrap a headband around the electrodes on the head to ensure they stay in place throughout the test. Connect the lead from the gold cup electrode at location FP1 to the positive input of channel 1 on the universal harness. Connect the lead from the gold cup electrode at location FP2 to the positive input of channel 2 on the universal harness. Connect the lead from the gold cup electrode at location O1 to the positive input of channel 3 on the universal harness. Connect the lead from the gold cup electrode at location O2 to the positive input of channel 4 on the universal harness. The negative inputs for
channels 1 and 2 on the universal harness should be connected to one of the reference connectors on the universal harness. The negative inputs for channels 3 and 4 on the universal harness should be connected to the other reference connector on the universal harness. You should now have a total of four stackable connectors from the universal harness connected to the snap lead from each reference electrode.

You should prepare five or six mental math problems that can be easily solved in the head prior to the start of testing. Do not let the subject know what these problems are before testing is started.

Connect the universal harness to the BioRadio transmitter. Turn the transmitter on.

![Figure 7.8: Typical EEG electrode placement map. For this laboratory, use FP1, FP2, O1, and O2.](image)

**Procedure and Data Acquisition**

Before separating combined signals, we will identify biopotentials that have minimal noise and artifacts to give us a baseline. Start the BioRadio Capture software, and make sure that the student remains very still during the recording of the potentials.

1. Have the subject sit down and relax with their eyes closed. Wait for a few minutes until the subject is relaxed.

2. Start Capture mode in the BioRadio software and begin saving data. Name the file “baseline.bd”. Allow the subject to remain sitting still with their eyes closed and record for about 10 seconds of data. When the subject is finished have them relax again for a minute. Then instruct them to clench their teeth together, flexing their masseter muscles for about 5 seconds. Finally, have the subject relax their jaw, and instruct them to move their eyes all the way to the left, and then all the way to the right, without moving their head. Have them move their eyes in the same fashion two more times. Then stop saving data.
3. Stop the Capture mode and use View mode to open the file you just saved. Check to make sure that you have obtained EEG, EMG, and EOG signals on the appropriate channels and times. Export the entire file to an ASCII file. Save it as “baseline.dat”.

Now we can analyze combined signals...

4. With the subject still seated and relaxed with their eyes closed, give the subject a piece of chewing gum and request them to start chewing it. After a few moments of them relaxing and chewing, start Capture mode and begin saving data. Name the file “EEG-Chew bd”. For 10 seconds, record biopotentials from the subject as they chew with their eyes closed and relaxed. When they are finished stop saving data.

5. Stop the Capture mode and use View mode to open the file you just saved. Export the entire file to an ASCII file. Save it as “EEG-Chew.dat”.

6. Request the subject to throw away the gum they have been chewing. Request the subject to sit still with their eyes closed and relax for a few minutes. Then start Capture mode and begin saving data. Name the file “EEG-Talk.bd”. Record 10 seconds of this relaxed data. Then request the subject to begin talking. They can recite anything they want to as long as they continue talking for 5 seconds (i.e. the alphabet, words to a song). After five seconds of reciting, request them to open their eyes. Stop saving data.

7. Stop the Capture mode and use View mode to open the file you just saved. Export the entire file to an ASCII file. Save it as “EEG-Talk.dat”.

8. The subject should remain seated, however this time they may open their eyes. Give the subject another piece of gum to chew. Start Capture mode and begin saving data. Name the file “EOG-Chew.bd”. Instruct the subject to look all the way to the left, then straight ahead, and then all the way to the right while chewing on a piece of gum. Be sure to keep the head still and move only the eyes when shifting gaze. The subject should complete several cycles of slowly moving their eyes back and forth while chewing the gum. Stop saving data.

9. Stop the Capture mode and use View mode to open the file you just saved. Export the entire file to an ASCII file. Save it as “EOG-Chew.dat”.

10. This task will be the same as the EEG-Talk, however, instead of EEG we will record EOG. Start capture mode and begin saving data. Name the file “EOG-Talk.bd”. Instruct the subject to look all the way to the left, back to center, and then all the way to the right, while talking. They can be reciting the same thing they did during the EEG-Talk experiment. The subject should complete several cycles of slowly moving their eyes back and forth while talking. Stop saving data.
11. Stop the Capture mode and use View mode to open the file you just saved. Export the entire file to an ASCII file. Save it as “EOG-Talk.dat”.

12. Start capture mode and begin saving data. Name the file “EEG-EOG.bd”. Request the subject to look around at random objects in the room while keeping their eyes still. They should focus on each object for a few seconds and then move to a new object. These locations should be high, low, left, and right of their location. After looking at about 6 locations instruct the subject to blink several times in a row.

13. Stop the Capture mode and use View mode to open the file you just saved. Export the entire file to an ASCII file. Save it as “EEG-EOG.dat”.

Data Analysis

1. Use the BioRadio Toolbox software. Open and plot the baseline data for all for channels of EEG, EOG, and EMG data. For the EEG and EOG data, low pass filter the signal at 25 Hz. For the EMG data, high pass filter the data at 5 Hz. Also perform a spectral analysis of all the baseline data.

2. Open the “EEG-Chew” file. Display the entire time duration of the recording. You should see portions of the EEG signal in channels 1~4 contaminated with noise, corresponding to the EMG signals in channels 7 and 8. Turn on only channels 1 and 2 (EEG-FP’s), and apply an appropriate filter to get rid of this EMG noise. Print out the filtered signals. What other signal (besides the ones from masseter muscles) are we filtering out as well?

3. Display the raw signal in channels 1 and 2 again. Apply a band pass filter to see alpha waves and change the time interval to display only that segment. Can you still see EMG artifacts? Why or why not? Redisplay the raw signal in channels 1 and 2. Apply a band pass filter to show the beta waves. Can you still see the EMG component of the recorded signal? Display channels 3 and 4, and print it.

4. Open the “EEG-Talk” file. Display channels 1 and 2, and print it. Apply a high pass filter with a cutoff frequency of 30 Hz, and print out the filtered signal.

5. Open the “EOG-Chew” file. Display channels 1 and 2, and apply a band pass filter to obtain just the EOG. Plot this filtered signal.

6. Open the “EOG-Talk” file. Display channels 1 and 2, and print it. Apply the same band pass filter used in the “EOG-Chew” experiment. Plot this filtered signal.

7. Open the “EEG-EOG” file. Display channels 1 and 2, and apply an appropriate filter to show a relatively uncontaminated EEG signal. Plot the filtered signal.

Discussion Questions
1. From the “Baseline” experiment, comment on the relative amplitudes of the EMG compared to the EOG and EEG signals.

2. Explain why complete elimination of artifacts is nearly impossible using only the DSP techniques discussed in this laboratory.

3. Can you see EEG artifact in the EMG plot (channels 7 and 8) from the “EEG-Chew” experiment?

4. If you did not know what the frequency ranges for the EEG and EMG signals were do you think it would be more difficult to filter out the EMG due to talking or EMG due to chewing? Why? List some of the differences in the usage of the masseter when chewing compared to talking to further explain your answer.

5. Would it be more difficult to filter EMG due to talking or EMG due to chewing, when analyzing an EOG signal? Use the plots from the “EOG-Chew” and “EOG-Talk” to explain this, and compare to the results of the previous Discussion Question.

6. In the “EEG-EOG” experiment, what is different about channels 1 and 2 versus channels 3 and 4 that change the amount of EMG noise included?

7. In the “EEG-EOG” experiment, what kind of filter did you propose to use? Indicate the cutoff frequencies for the filter.

8. Explain how a bandpass or bandstop filter can be constructed by combining a lowpass and highpass filter together. If a bandpass filter for 10-25 Hz is desired, what cutoffs are necessary for the HP and LP filters? And for a bandstop filter of 50-60 Hz?

9. In the Background, walk through each of the steps and show why the transfer function for the lowpass filter is the one listed there. What is the cutoff frequency of this filter?

10. Thinking back to your physics classes, why is it that the capacitor has zero resistance for infinite frequency, and why the inductor has infinite resistance for infinite frequency?

11. Solve the transfer function for the first order highpass filter and show that it indeed does pass high frequencies and attenuates low ones.

**NOTE: Graduate Students Should Continue and Complete the Following Sections.**
Graduate Analysis and Discussion

1. Plot the phase for a first order highpass filter with a cutoff frequency of 50 Hz. What are the R and C values required here for this desired cutoff frequency?

2. In this laboratory, you learned that digital filtering is a useful tool to filter digitally acquired data. What are some drawbacks to using digital filtering? In which instances would it be better to have an analog filter instead of a digital filter?

3. Why would a filter with linear phase be more ideal for DSP filtering than one that is not? What is the tradeoff between using a linear phase filter vs. a filter with non-linear phase?

4. Design and draw a simple, first order low pass filter with realistic filter component (resistor, capacitor) values, given a voltage source of 5V, with a cutoff frequency of $\omega_c = 30\text{Hz}$. Design and draw a simple, first order high pass filter with the same restrictions, but $\omega_c = 13\text{Hz}$. Recall that simple filters can be cascaded to make specialized filters to meet the need of a specific application. If you were to cascade the two simple filters you just made, what application (pertaining to this laboratory) would you apply it to?
References

1. Bronzino, Handbook of Biomedical Engineering.


Lab 8

Polysomnography
Introduction

Sleep is a very important part of human life, equally important as water, air, and food. During sleep the body works to strengthen neuronal connections, rebuild cells, and remove byproducts of cell metabolism. A person deprived of sufficient amounts of sleep may develop serious illnesses.

Sleep has mystified scientists trying to understand how a person can be asleep, but at the same time have vivid dreams as if he or she were awake. It was originally believed that during sleep the functions of the body slowed down. We now know that the opposite is true. The brain, for example, is indeed very active during sleep. At times, when measured by biomedical instrumentation, the brain appears to be awake, even though the person is soundly asleep.

One tool physicians use to study sleep is polysomnography (PSG). In this procedure, patients with sleep disorders go into a clinic and sleep there overnight while specialized monitoring equipment measures specific physiological signals. You should be familiar with some of these signals already. The ECG, EEG, EMG, and EOG are all measured during a standard PSG study (Figure 8.1). In addition to these signals respiratory monitoring is also critical during a sleep study.

The recorded biopotentials are used to measure and quantify different stages of sleep. As people sleep during the night different stages of sleep occur. These stages vary from light sleep to very deep sleep. These stages repeat over and over throughout the night and each stage plays an important role. Standard software packages exist today capable of scoring an entire night worth of sleep data to determine the different amounts of time spent in each stage.

These polysomnographs, or sleep studies, are extremely important to doctors who treat patients with sleep disorders. There are many types of sleep disorders, ranging from mild problems like insomnia and snoring, to sleep apneas and hypopneas that may be fatal. Thus, it is very important to use this specialized equipment to study the sleep patterns of these afflicted people.

Materials

- BioRadio
- A laptop computer (recommended, but if not a desktop computer in the same room where the subject will be sleeping)
- Universal Differential Harness
- Medical Tape
- Nasal Cannula Thermistor
- Respiratory Effort Belt
- Microsoft Excel
- MATLAB (Graduate Students)
Background

Purpose of sleep

The exact purpose of sleep is still not entirely known by scientists. As mentioned previously, scientists once theorized that the brain shut down during sleep. However, we now know that is not true. There is some research that believes the sleeping process is very important for strengthening neuronal connections. For example, during one experiment researchers taught subjects a new concept. These subjects were then divided into two groups. The researchers deprived one group of REM sleep and left the other group to sleep naturally. It was found that the group deprived of REM sleep could not remember the concept as well as those who had REM sleep. This illustrates that sleep may be important in helping the brain establish connections between neurons and as a result, help to re-enforce learned material. Additionally, sleep is a time where cells can regenerate and repair themselves. In an experiment with rats deprived of REM sleep, it was found that their lifetime was shortened to five weeks from the normal two years. Rats deprived of all forms of sleep showed signs of immune system dysfunction, low body temperature, and body sores after three weeks. Students in college may have noticed this effect also when spending many late nights studying, and finding themselves with a cold in the weeks.

Figure 8.1: The BioRadio can be used to perform an overnight PSG study. The signals displayed from top to bottom include two channels of EEG, two channels of EOG, chin EMG, ECG, breath rate from a oral/nasal thermistor, and respiratory effort indicated by a piezoelectric belt. The time scale shown is 10 seconds.
afterwards. Therefore, sleep plays an important role in cell regeneration and immunity. In fact, when people are ill, the body forms very powerful sleep-inducing chemicals. During an immune response to infection, the immune system creates cytokines. These cytokines induce sleep, helping the body to conserve energy to combat the infection.

An active inhibitory process induces sleep. This was discovered by stimulation of certain portions of the brain. Stimulating these areas prevented sleep from occurring. Using this knowledge, scientists were able to disprove the passive theory of sleep. In the passive theory it was believed that a certain portion of the brain became fatigued after a certain number of wakeful hours. In this active inhibitory theory, scientists found that the raphe nuclei, located in the lower pons and medulla portions of the brain, send out inhibitory signals to the thalamus, neocortex, hypothalamus and limbic system. These signals actively induce sleep.

Chemicals in the blood have also been found to cause drowsiness. Agents that block serotonin have been found to cause insomnia. Therefore it is believed that serotonin may play a role in sleepiness. When a person has been awake for a long period of time the body begins producing certain peptides. It is believed that these peptides in the blood stream cause sleepiness. The body also receives cues from the natural environment about when to sleep. These are guided by the circadian rhythm of the body, also known as the biological clock. One important signal used by the biological clock is the amount of light seen by a person. The amount of light seen by a person controls the production of melatonin hormone that causes sleepiness. During periods of darkness, more melatonin is produced.

**Types of sleep cycles**

When a person sleeps, they pass through two types of sleep, non-REM and REM sleep. The non-REM sleep can be divided into four stages. In all, a person cycles between a total of 5 different cycles of sleep during the night. The different stages of sleep can be determined by monitoring an EEG of the person while they sleep.

A person begins in stage 1 sleep, and then goes to stage 2, 3, and then 4. This process then reverses, and after stage 1 sleep, the person goes into REM sleep. The process is then repeated. Each sleep cycle (stages 1-4 and REM sleep) lasts from 90-100 minutes, and is repeated approximately 4-5 times during the night. Initially when the person is first asleep, more time is spent in deep sleep, stages 3-4. However, as the night goes on, the sleep cycle begins to shorten. Less time is spent in deep sleep, while more time is spent in REM sleep. Normally, about 45% of total sleep time is spent in stage 2 sleep, and 25% in REM sleep. The remaining 30% occurs in the other stages. As people age the number of hours they sleep per night typically decreases and the percentage of time spent in stage 4 and REM also decreases.

Stage 1 sleep is characterized as the light sleep one experiences when just starting to fall asleep. The EEG recording shows alpha wave activity associated with quiet wakefulness. During stage 1 sleep, a person is easily woken, and may remember strange fragmented images and thoughts. The eyes move slowly and muscle activity slows. Also quite commonly noticed is hypnic myoclonia, the sudden muscle contractions that occur when the body feels that it is starting to fall or slip.
Stage 2 sleep occurs after stage 1, and at this time, eye movement stops and the measured EEG shows slower brain activity in the theta band. This activity may be interrupted by brief bursts of waves in the alpha frequency called sleep spindles. Stage 3 sleep also shows theta wave activity, but fewer sleep spindle complexes.

In stage 4 sleep, the EEG slows even further to delta waves, a very low frequency signal. Stages 3 and 4 are considered deep sleep, and it is extremely difficult to wake a person in this stage of sleep. No eye movement or muscle activity is noted, and people who are awakened at this time of sleep will feel disoriented and confused. In deep sleep, the blood pressure and pulse decrease, blood vessels dilate, muscles become relaxed, and the body goes into a relaxed restful state.

REM sleep is one of the most interesting of the sleep stages. REM sleep is characterized by fast, rapid eye movements, giving this stage its name. These rapid eye movements are measured by the EOG during sleep. The person’s breathing also becomes faster and shallower and the heart rate and blood pressure increases. Also, very importantly, muscle movement is inhibited during REM sleep by activating the pons in the brain, causing excitation of the medullary inhibitory area. The purposes of this are to inhibit motor neurons and paralyze muscle movement. The lateral motor strip also helps to inhibit muscle movement in the spinal column by active inhibition by the pons. REM sleep is the time that most people have dreams. Many of these dreams are strange and nonsensical images. Researchers believe that during REM sleep, the brain attempts to categorize and assimilate the information processed during that day, and a result of this attempt to organize random information are dreams. People typically spend two hours each night dreaming, however, they may not remember any of these dreams by the time they wake.

During REM sleep, not only are the eyes active, but the brain is active as well. The brain shows beta wave activity, very much like the beta wave activity that is recorded when a person is alert and awake. In fact, by looking at the EEG itself, one cannot distinguish between awake and alert activity from REM sleep. Thus, this process is called paradoxical sleep, since the EEG shows wakeful brain activity, even though the person is clearly asleep. People in REM sleep are more difficult to wake than people in stage 3-4 sleep, however, when people wake up in the mornings, they most likely wake up after a REM sleep stage. People who have been sleep deprived or extremely tired may not go into a REM sleep stage. Instead, more time is spent in deep sleep, such as stages 3-4 than in REM. Another indicator of REM sleep is the chin EMG measurements. As mentioned before, as a person enters REM sleep, the brain sends a signal to inactivate motor neurons during sleep, disabling muscle movement. Another consequence of this motor inactivation is decreased muscle tone. The chin EMG is used to detect this. As a person enters REM sleep, the chin EMG measurement will show muscle tone to be less than other stages of sleep. Hyperpolarizing motoneurons prevent most skeletal muscle activity during this stage.

As mentioned in the introduction, many tools that we have previously covered are used to determine when the body is in REM sleep. The EEG is used to find beta wave activity, the EOG is used to measure rapid eye movement, the ECG measures heart rate, EMG is used to measure decreased muscle tone, and respiratory effort and rate is determined by a respiratory belt and nasal cannula.

Sleeping Disorders
Sleeping disorders are the main reason why sleep studies are conducted. At least 40 million Americans suffer from different sleep disorders. These disorders can cause problems at work, social life, and may even endanger the person’s life if left untreated. The most common types of sleep disorders are sleep apnea, insomnia, and narcolepsy. Narcolepsy and sleep apnea are the most life threatening.

Sleep apnea occurs when a person suddenly stops breathing during sleep. Frequently, people who snore loudly or are overweight are at risk for sleep apnea. However, not all people who snore are at risk for sleep apneas. People with sleep apnea suddenly stop breathing because the upper airway (Figure 8.2) collapses during the person’s efforts to inhale air. While the person’s brain becomes oxygen deprived, the brain responds by causing the person to gasp for air. As a result the person awakens and the sleep cycle is disrupted. Sleep apneas result in tiredness and irritable in the morning and can cause headaches due to several periods of oxygen deprivation. For some high-risk people, obstructive sleep apnea may cause death due to respiratory arrest during deep sleep. A sleep study can diagnose obstructive sleep apnea. An airflow sensor is used to monitor breathing during sleep. A clinician can diagnose apneas by reviewing the saved data from the sleep study.

These pauses in breathing during sleep can be classified into apneas and hypopneas. An apnea is defined as an 80% decrease or greater in breathing that last for more than ten seconds. Hypopneas refer to a pause in breathing that lasts more than ten seconds combined with a partial awakening or decrease in blood oxygen. Losing weight and changing ones sleeping habits by sleeping on the side or back can help to treat sleep apneas. Other methods include using a continuous positive air pressure (CPAP) machine. A CPAP supplied constant air pressure to the airway to keep it open during the night through a mask worn by the patient. However, CPAP machines are cumbersome to use and may cause irritation and dryness in the airways due to constantly moving air. In more extreme cases, patients may elect to undergo surgery to correct apneas.
Insomnia is experienced by nearly all people at some point in life, however, some people have extreme cases of insomnia that require medical attention. Normally, mild insomnia is caused by stress, diet, jet lag and other factors, but serious insomnia may be an indication of a deeper medical problem. It is very important to have these serious cases of insomnia diagnosed, since prolonged insomnia leads to immune system weakness, and may eventually cause death indirectly. The most common treatment for insomnia is sleeping pills, however, long-term use of these pills may actually cause addiction and cause serious problems with good natural sleep.

Another common sleep disorder is narcolepsy. Narcolepsy is when a person feels the urge to suddenly take naps during the day, even when they have had a normal amount of sleep the night prior. These narcoleptic attacks can last between several seconds to 30 minutes, and while in a narcoleptic attack, these people experience hallucinations and may be in a catatonic state, suggesting that REM sleep is occurring at these points. The cause of narcolepsy is often found to be neurological disease or injury to the brain. Drugs can control narcolepsy. Narcolepsy is extremely dangerous, since a person may have a narcoleptic attack during a crucial time like driving a car or operating heavy machinery.

Equipment used for Sleep Studies

Tools such as the EEG, ECG, EOG, and EMG have been covered in previous labs. You should be comfortable with setting up and monitoring these signals during the sleep lab. In addition to the EEG, ECG, EOG, and EMG measurements, sleep studies use a thermistor to measure airflow and a piezoelectric or resistive belt to monitor respiratory effort.

Pulse oximeters are also used for sleep studies. Pulse oximeters measure the percent saturation of oxygen in the blood stream. If a person has an apnea during sleep, the oxygen saturation in the blood will drop since the person is not breathing. A pulse oximeter is not used in this laboratory. A thermistor is used in this lab because it responds to the breath exiting a person’s mouth or nose. If an apnea were to occur one would notice a flat line on the thermistor graph even though the respiratory effort belt indicates the person attempting to breathe.

A thermistor is an electronic component similar to a resistor. Unlike a resistor, a thermistor is built using a semiconductor process that makes it extremely sensitive to changes in temperature. Under constant current, a thermistor will change its resistance as a function of the temperature. Normally, manufacturers of resistors attempt to make their components less sensitive to variations in temperature, since a circuit that is designed with a resistor should have the same resistance regardless of the surrounding temperature. On the other hand, thermistor manufacturers need to make their devices extremely sensitive to temperature, so that small changes in temperature can be transduced into voltages. The relationship of the resistance of a thermistor to temperature is given by the following equation:

\[ R = Ke^{\beta / T} \]

K represents the intrinsic resistance of the device since \( R=K \) when \( T=0 \), \( \beta \) is a sensitivity constant that characterizes each different type of thermistor, and \( T \) is the temperature in Kelvin.
As you notice from the equation above, the relationship between the temperature and resistance is a non-linear equation. In fact, it is exponential. As a result, if measuring a larger temperature range is desired, some linearization will need to be performed. By linearizing the relationship between temperature and resistance, the thermistor is made useful over a broader range of temperatures. A first order linearization is accomplished by connecting a series resistance with the thermistor, creating a current limiting resistance. The equation for this is given by:

\[ R_L = R_m \frac{(\beta - 2T_m)}{\beta + 2T_m} \]

\( R_L \) is the value of the resistance desired for linearization, \( R_m \) is the resistance of the thermistor at the midpoint of the temperature range desired, and \( \beta \) is a sensitivity constant that characterizes each different type of thermistor.

In this laboratory, the thermistor is located in the oral/nasal cannula. This cannula has three prongs and is taped underneath the subject’s nose (Figure 8.3). Two of the prongs point up and into the person’s nostrils and the third is bent around so that it is located in front of the person’s mouth. As a person breathes, their air warms up the thermistor, causing a change in voltage, which can be related to breathing rate.

Another tool that is typically used for overnight sleep studies is the respiratory effort belt. This belt is firmly worn around the person’s chest or abdomen. It is used to measure the “depth” of a person’s breathing during the study. There are two types of respiratory effort belts, the piezoelectric belt and the resistive belt.

The piezoelectric belt works on the principle of piezoelectric materials. Piezoelectric materials, like quartz, exhibit qualities that make them ideal for transducing force into voltage. These materials, when compressed, will show a change in voltage proportional to the change in compression. Similarly, when an electric potential is applied, the piezoelectric material will compress or expand, depending on the polarity of the potential.

The equation governing the voltage generated by a piezoelectric belt is given by:

\[ \Delta V = \frac{D \Delta F}{\varepsilon (A/X)} \]

Figure 8.3: The respiratory effort belt and nasal/oral thermistor are used to detect respiration signals.
ΔV is the change in voltage, D is the amount of charge generated per unit force applied, F is the force applied, ε is the dielectric constant of the material, A is the area of the crystal perpendicular to the force applied, and X is the thickness of the crystal.

Purely resistive belts are also used to measure respiratory effort. These belts rely on the equation that governs the resistance of a material. When the belt stretches, the resistance increases, causing an increased voltage for constant current. When the belt returns to its normal shape, the resistance decreases causing a lower voltage.

The equation that governs the resistance measured on this type of belt is:

\[ R = \frac{\rho L}{A} \]

R is the resistance of the belt, \( \rho \) is the resistance per unit length depending on the material, L is the length of the resistive material, and A is the area of the resistive material. As the belt stretches, L increases slightly, increasing resistance.

![Wheatstone Bridge](image)

**Figure 8.4:** Wheatstone Bridge. \( R_{\text{out}} \) models the strain gauge resistance.

This resistive belt can be modeled as a strain gauge since the resistance changes as more strain is applied to the device. However, we need a method to create a relationship between the changes in resistance into a change in voltage that can be measured. This time, in order to linearize the effects of the strain gauge, we use the Wheatstone bridge, which converts changes in resistance into changes in voltage.

So, when the length of the strain gauge changes, \( R_{\text{out}} \) also changes, this \( V_{\text{out}} \) measured here changes as well, except it is linearly related to \( R_{\text{out}} \). The output voltage can be derived as

\[
V_{\text{out}} = \left( \frac{R_2}{R_1 + R_2} - \frac{R_4}{R_3 + R_4} \right) V_{\text{batt}}
\]
Experimental Methods

Experimental Setup

Using the BioRadio Configuration Wizard, select all eight channels for recording. All channels should be set for low-level signal recordings. However, select the largest input range for channel 8 (60.768mV). All other input ranges can remain as the defaults. Choose the medium input resolution, and note the sampling rate. Name channel 1 “EEG-O1”, channel 2 “EEG-O2”, channel 3 “REOG”, channel 4 “LEOG”, channel 5 “Chin EMG”, channel 6 “ECG”, channel 7 “Airflow”, and channel 8 “Resp”. Save this configuration as “Lab 7 Sleep”. Program the BioRadio transmitter and receiver to this configuration as per the User Guide.

As you may have noticed, the sleep experiment will involve many concepts and techniques that have been discussed in previous labs. In fact, you may want to review these laboratories (3, 4, 5, and 6) as it may help setup run smoother. Proper electrode and sensor setup is a very important part in a sleep lab. If any of the electrodes fall off during the course of the night, the experiment may need to be repeated. **NOTE: This laboratory requires that the data collection computer have approximately 100MB of free disk space to save the data.** Unlike previous labs, you will be recording biopotentials from all eight channels for approximately eight hours. Therefore, you will be handling significantly larger amounts of data. In addition, you **MUST** install a new set of AAA batteries into the BioRadio transmitter before the start of this study.

During the polysomnograph you will measure two channels of EEG, two channels of EOG, EMG from the chin, the ECG, respiratory effort, and oral/nasal airflow. It is very important that you properly prepare the electrodes sites before applying the electrodes. We will start by placing the reference and ground electrodes on the subject. One snap electrode will be placed on one of the mastoids of the subject. Connect a snap lead to this electrode and connect it to the input on the universal harness labeled “GND”. One gold cup electrode should be placed on the subject’s left mastoid and one on the right mastoid. Connect one of these to an input on the universal harness labeled “REF”. Connect the gold cup electrode from the other mastoid to the other input on the universal harness labeled “REF”.

We will now attach the gold cup electrodes to the back of the subject’s head to monitor EEG. EEG will be recorded from sites O1 and O2. It is very important that you properly prepare these electrode sites before applying the gold cup electrodes. Fill one gold cup electrode with the provided Elefix gel and then place on location O1. Cover with cotton and then tape in place with medical tape. Fill another gold cup electrode with the provided Elefix gel and then place on location O2. Cover with cotton and then tape in place with medical tape. Connect the lead from the gold cup electrode at location O1 to the input labeled the positive lead of channel 1 on the universal harness. Connect the lead from the gold cup electrode at location O2 to the input labeled positive lead of channel 2 on the universal harness. The negative inputs for channels 1 and 2 on the universal harness should be connected to one of the inputs on the universal harness labeled “REF”.

You should take care to wrap the head with gauze after these electrodes are in place (Figure 8.5). It is very important that these electrodes stay attached throughout the course of the night. The
subject will be rolling their head around on a pillow throughout the course of the night and if the head is not wrapped this may pull the electrodes off of the head. The gauze can be used to wrap a headband around the head. The headband should wrap around the front of the head in order to cover the reference and ground electrodes and then around the back of the head in order to cover the two EEG electrodes. The headband wrap should be taught to hold the electrodes in place, but not so tight that it is uncomfortable for the subject. It should be wrapped in such a way that it holds the electrodes against the head, but does not pull them toward the top of the head.

Next we will place the EOG electrodes on the subject. We will use snap electrodes to measure EOG. Two channels of EOG will be recorded. Properly prepare the surface of the skin before attaching the surface electrodes for EOG. Attach a snap electrode just left of the subject’s left eye, and slightly above the midline of the eyes on the left temple. Attach another electrode just right of the right eye, but slightly below the midline of the eyes on the right temple. Connect the snap electrode near the subject’s right eye to the positive input of channel 3 on the universal harness. Connect the snap electrode near the subject’s left eye to the positive input of channel 4 on the universal harness. The negative inputs for channels 3 and 4 on the universal harness should be connected to one of the inputs on the universal harness labeled “REF”.

Chin EMG will also be recorded for this polysomnograph study. Two snap electrodes will be placed on the chin approximately one inch apart. It is important that you properly prepare the electrode sites before placing the electrodes on the chin. Place the two snap electrodes on the chin. Connect one of the snap electrodes to the positive input of channel 5 on the universal harness. Connect the other snap electrode to the negative input of channel 5 on the universal harness.

Snap electrodes will also be used to measure ECG. It is important that you properly prepare the electrode sites before applying the snap electrodes. One snap electrode should be placed on the skin above the right clavicle and one should be placed on the skin above the left clavicle. Connect the electrode above the left clavicle to the positive input of channel 6 on the universal harness. Connect the electrode above the right clavicle to the positive input of channel 6 on the universal harness.

The oral/nasal thermistor will be used to monitor airflow from the subject. The thermistor should be mounted between the nostrils and upper lip of the subject (Figure 8.3 and 8.5). There are three prongs on the thermistor. The side with two prongs should point up, one prong slightly into each nostril. The prong on the bottom of the thermistor should be bent around so that the tip is positioned directly in front of, but not in, the subject’s mouth. The thermistor can be taped in place and the wires can be run over the ears and over the back of the head. Two other pieces of medical tape can be placed over the wires on the face further hold the thermistor in place and keep the leads from dangling around on the face. The leads from the thermistor should be connected to airflow inputs of the resistor pod. The airflow outputs of the resistor pod should then be connected to the input for channel 7 on the universal harness.

Finally, the provided piezoelectric respiratory effort belt should be placed around the torso of the subject. Securely fasten the respiratory effort belt around the subject just above the stomach and below the rib cage. In this position both diaphragm and chest breathing should be captured. The
resistor pod needs to be connected inline between the leads of channel of on the universal harness and the leads of the respiratory effort belt. Connect the leads of the respiratory effort belt to the resp inputs of the resistor pod. Then connect the resp outputs of the resistor pod to the inputs of channel 8 on the universal harness. Also, make sure that the blue, ground output of the resistor pod is connected to the blue, ground input of the universal harness.

To avoid tangling and discomfort for the subject the lead wires from the thermistor, the ground and reference electrodes, chin EMG, and ECG electrodes should be run around the back of the head. It is also a good idea to place a piece of medical tape over the EOG, EMG, and ECG snap electrodes to ensure they stay attached throughout the night. The BioRadio transmitter can be worn on the included armband during the night. Connect the universal harness to the BioRadio transmitter. Turn the transmitter on.

You should now check that you have properly hooked up the system using the BioRadio software. You may need to adjust the amplitude and time scales. Verify both channels of EEG by instructing the subject to close their eyes and relax. Verify the ECG signal is correct. Verify the EOG is working by having the subject move their eyes to the left and right. Verify that the chin EMG is working by having the subject scrunch their chin. Verify the thermistor is working by having the subject breathe out of their nose once and then out of their mouth once. Verify that the respiratory effort belt is working properly by having the subject breathe normally. You may need to adjust the tightness of the respiratory effort belt.

Procedure and Data Collection

1. Using the BioRadio software begin capture mode and start saving data. Name the file “sleep.bd”. The subject can now go to sleep.

2. In the morning when the subject wakes up stop saving data and turn the BioRadio transmitter off.

Data Analysis

1. Take a deep breath. There is a lot of data here, but you will first break them down into smaller chunks for analysis. Using View mode in the BioRadio software, open the data file “sleep.bd” that you created. Export the entire file. Name the file “sleep.dat”.

2. Using either the BioRadio Capture software or the BioRadio DSP Toolbox, try to find different stages of sleep according to what you know about sleep stages and signal
processing. For each stage, zoom in and plot a segment of a channel (or channels), and mark the identifying characteristics directly on the plot. Can you see the sleep cycle repeating?

3. For each stage in the first cycle, calculate the average breathing rate (channel 8), how hard the subject was breathing (channel 7), and the heart rate (channel 5). On the same graph, plot these average values against the different sleep stages. What do you see happening in the different stages? Does this make sense? Explain.

Discussion Questions

1. Overnight sleep studies can be used to determine if a person has an obstructive sleep apnea. Think about the signals were recorded. Which would be important in diagnosing an obstructive sleep apnea? Sketch a plot of these signals to illustrate normal sleep and an apnea.

2. There is a sleep disorder called REM sleep behavior disorder in which the individual’s body moves according to what he/she is dreaming. For instance, when a person suffering from REM sleep behavior disorder dreams of throwing a Frisbee, they may find that their arm hurts in the morning because they have slammed it into the wall while asleep. Explain what mechanisms are (or are not) involved in this individual, and suggest what may help to reduce the severity of the disorder.

3. Why is it important to be aware the file size for sleep studies? What can be done to keep the file size as small as possible but without sacrificing quality? And what quality is being sacrificed in order to keep the file size small?

4. When using the thermistor or respiratory effort belt, why is linearization required, even though there is a proportional change in resistance to a change in either temperature or strain? More clearly, in a circuit, why isn’t there a linear relationship between change in resistance and the voltage measured across that resistance? What is done to correct for this?

5. Why is the EEG during REM sleep considered paradoxical beta? What mechanisms ensure that it is paradoxical?

6. Show how the equation for the Wheatstone bridge is linear. Would it still be linear if \( R_2 \) were defined as the input variable and \( V_{\text{out}} \) as the circuit output? Why?

**NOTE:** Graduate Students Should Continue and Complete the Following Sections.

Graduate Analysis and Discussion

1. Use the Wheatstone Bridge in Figure 8.4. Assume that \( R_1=R_2=R_4=10 \text{ Ohms} \). Assume that the battery voltage is 5 Volts. Plot the output voltage if the value of \( R_3 \) varied from 1 – 20 Ohms.
2. Use the Wheatstone Bridge in Figure 8.4. Assume that $R_1=R_2=R_3=10 \text{ Ohms}$. Assume that the battery voltage is 5 Volts. Plot the output voltage if the value of $R_4$ varied from 1 – 20 Ohms.

3. Suggest how an automated program that could be developed to automatically score sleep studies.
References


3. www.library.thinkquest.org/25553/English/basics/brain/index.shtml
Lab 9

Sports and Exercise Lab
Introduction

Some individuals are capable of hitting homeruns in the major leagues while others cannot even make contact with the bat on the ball. In addition, some people are able to set new track records with the speeds they can run while others cannot run fast at all. Some nights a pitcher throws the ball extremely well while on other nights he “doesn’t have it”. All humans are given the same basic set up muscles and nervous system to control them. So what are the mechanisms responsible for the variations among people and the day-to-day variations among the same athlete?

Throughout the course of this laboratory book you have learned how biopotentials yield information about how the body is functioning. This information includes how muscles coordinate their levels of activation to perform a task, the level of concentration of the brain, and how sympathetic tone may be increasing to prepare the body for action.

Many individuals exercise or play sports. Whether it is done professionally, for stress relief, for competition, or to just have fun, exercise is an integral part of being a healthy human being. Several systems have been designed in order to supply athletes with information about how their body is functioning in order to optimize their performance on the playing field. In addition, many exercise machines currently include feedback to users in order to optimize their work out.

During sports and exercise the body must perform basic functions that can be analyzed using the BioRadio. These include hand-eye coordination, muscle coordination, and sympathetic tone. This laboratory will experiment with a few of these specific functions that the body commonly accomplishes while participating in sports and exercise.

Equipment required:
- BioRadio 110
- Snap electrodes
- Gold cup electrodes
- A ball that can be caught with one hand
- A hat with a visor
- Microsoft Excel and BioRadio DSP Toolbox
- MATLAB or LabView (Graduate Students)
Background

As stated earlier, there are currently many systems available that provide feedback to individuals who are exercising. One popular example is treadmills that come equipped with a heart rate monitor. The treadmill provides a digital display to indicate the heart rate of the person performing a cardiovascular workout. Using this feedback allows an individual to maintain a target heart rate throughout their workout. Other systems are available that measure galvanic skin resistance (GSR) to determine sympathetic tone by measuring the electrodermal response. GSR systems output a small current along the skin, usually between small electrodes on two fingers of the hand. The unit then measures the voltage between the two points. As a person’s sympathetic tone increases they will begin to sweat and the conduction of the skin will increase, i.e. the voltage measured will decrease. Often times these systems supply auditory feedback to individuals for use as a relaxation device. You may have heard of the “fight or flight” response. This occurs in the body when preparing for threatening situations. The responses of the body include increased heart rate, increased blood pressure, increased respiration rate and effort, and sweating. Athletes may experience this before a big game. Therefore, they may use this type of device to calm themselves before a big event.

Other systems are currently designed to measure the biomechanics of an athlete. Some systems use LEDs (light emitting diodes) located all along a subject’s torso and limbs to track the position of their body throughout a motion. For example, a pitcher may be able to use this system to analyze the throwing motion of his arm. They may be able to then determine why on some days he pitches well and on other days he does not pitch well. This system could also be used to effectively analyze a golfer’s swing so that it becomes more repeatable. Interestingly, it is currently being shown that recording EMG from muscles can yield the same information about limb orientation as LED markers. Current research has focused on using artificial neural networks (ANN) with several EMGs as the inputs to determine the orientation of the arm in space. Finally several companies spend a lot of time researching biomechanics of the human body in order to make their devices ergonomic such as keyboards, telephones, and chairs. Sampling the EMG from people during tasks may provide insight into how to make these devices more ergonomic.

Motion Artifact

As you have learned throughout the course of this lab book, there are many sources of noise that you may encounter when recording a biopotential. For most of the experiments that we have done up to this point, the site of recording has been kept fairly stable. Therefore, much motion artifact has been avoided. However, one of the most problematic sources of noise for measurements during sports activities is motion artifact. An example of motion artifact would be a person wildly moving their arm around when EMG was being recorded from the forearm. Motion artifacts are disruptions in the signal that arise from movement at the electrode-electrolyte interface. The skin stretching during recording is a major reason for motion artifact. The wires can move around and cause artifact. Slight movement of a lead or lead connection will also cause disruption in the signal.
Motion artifact will not affect EMG nearly as much as it will effect the EOG, EEG, or ECG. This is due to the fact motion artifact has a low frequency spectrum and EMG has a high frequency spectrum compared to the other signals. Therefore, high pass filtering could be used to remove motion artifact from the EMG signal.

Several methods for limiting motion artifact include… electrodes and lead wires should be securely fastened. You could use tape to secure the electrode

**Experimental Methods**

A total of three different tasks will be complete for this laboratory. Each task represents a subset of an activity performed during a sports activity. A different BioRadio configuration will be used for each task. Use the BioRadio Configuration Wizard to setup these channel configurations.

**NOTE:** As described above, in each of these exercises motion artifact can be a problem. In each of these configurations, be sure to run the wires so that they do not impede the movement of the subject. Additionally, you may find the need to use medical tape to ensure that the electrodes stay in place during the experiments. Also, for the experiments below you may want the same person to be the subject for each of the three tasks. If this is the case be sure to read the setups for each of the tasks before starting. This will prevent you from removing electrodes that would be needed for subsequent tasks and then reapplying them.

**Walking and Squatting**

**Experimental Setup**

Using the BioRadio Configuration Wizard, configure channels 1-4 for EMG recordings. All four channels should be set for low-level recording. Choose a high or medium sampling rate, and note the sampling frequency that you choose. Name channel 1 “EMG-R-thigh”, channel 2 “EMG-L-thigh”, channel 3 “EMG-R-calf”, and channel 4 “EMG-L-calf”. Save this configuration as “Sports -Walking”.

You will need to use ten snap electrodes for this task. It is important that you properly prepare each of the electrode sites before applying the snap electrodes. The rectus femoris is the large muscle in the anterior thigh that acts to extend the lower shank (Figure 9.1). This is a large superficial muscle that we will be recording EMG from. The rectus femoris acts to extend the lower shank. Place two snap electrodes on the skin above the rectus femoris of the right leg and two snap electrodes on the skin above the rectus femoris of the left leg. The large superficial muscle on the posterior side of the shank that makes up the calf is the gastrocnemius. The gastrocnemius is responsible for extending the foot. Place two electrodes over the right gastrocnemius and two electrodes over the left gastrocnemius. Finally place one electrode on the left kneecap and one on the right kneecap for the ground and the reference electrodes.

Connect snap leads to all of the electrodes. Connect one snap lead from the electrodes above the rectus femoris of the right leg to the positive side of channel 1 on the universal harness and the
other to the negative side. Connect one snap lead from the electrodes above the rectus femoris of the left leg to the positive side of channel 2 on the universal harness and the other to the negative side. Connect one snap lead from the electrodes above the gastronemius of the right leg to the positive side of channel 3 on the universal harness and the other to the negative side. Connect one snap lead from the electrodes above the gastronemius of the left leg to the positive side of channel 4 on the universal harness and the other to the negative side. Finally, connect the snap lead from one of the knees to the reference input on the universal harness and from the other knee to the ground input on the universal harness.

**Figure 9.1:** The rectus femoris is a large superficial muscle in the anterior side of the thigh that is responsible for extending the lower leg.

**Procedure and Data Collection**

1. Start the BioRadio program, begin capture mode, and turn the transmitter on. Start saving the data to a file. Save this file as “walking.bd”. Request the subject to walk around the room at a normal pace for about 30 seconds. Stop saving data when finished. Export this file to a file named “walking.dat”.

2. Now begin saving data again. Save this file as “squat.bd”. Request the subject to slowly squat up and down five times in a row. When the subject is finished stop saving data.

3. Start saving another data file named “toes.bd”. Have the subject stand normally, and then instruct them to elevate themselves onto their toes for 2 seconds. Have them lower, and repeat this 2 more times. Stop saving data.

**Concentration**

**Figure 9.2:** Squatting should generate larger EMGs in the leg muscles.
Experimental Setup

Using the BioRadio Configuration Wizard, configure channel 1 to record ECG, channel 2 to record EEG, channel 3 forearm EMG. All three channels should be set for low-level recordings. Choose a high or medium sampling rate, and note the sampling frequency that you choose. Name channel 1 “ECG”, channel 2 “EEG”, and channel 3 “EMG”. Save this configuration as “Sports – Concentration”.

You will need to use six snap electrodes and one gold cup electrode. It is important that you properly prepare each of the electrode sites before applying the snap electrodes. Place one snap electrode on the surface of the skin above the left clavicle and one above the right clavicle to measure ECG. Place one snap electrode to the right of the midline of the forehead, as close as possible to the hairline. Place two snap electrodes above the palmaris longus muscle of the forearm. Use the left forearm if the subject is left-handed and the right if the subject is right-handed. This is a superficial muscle that acts to flex the wrist (Figure 9.4). Place a snap electrode on the elbow of the same arm of the subject for a ground electrode. Fill the gold cup electrode with Elefix gel and place on location O2 of the subject and cover with tape.

Connect snap leads to all of the snap electrodes. Connect the snap lead from the left clavicle to the positive input of channel 1 on the universal harness and the lead from the right clavicle to the negative input of channel 1. Connect the EEG electrode on the back of the head to the positive input of channel 2 on the universal harness. Connect the negative input of channel 2 on the universal harness to one of the reference inputs on the universal harness. Connect the snap lead from the reference electrode on the subject’s forehead to the same input reference. Connect one of the subject’s snap leads from the skin above the palmaris longus muscle of the forearm to the positive input of channel 3 and the other to the negative input of channel 3. Finally, connect one of the snap leads from the elbow of the subject to the ground input on the universal harness.

![Palmaris Longus](image)

**Figure 9.4.** The palmaris longus is a superficial muscle of the forearm that is responsible for flexing the fingers.
Procedure and Data Collection

Have the subject stand ready with a golf ball, golf putter, and a cup placed away from the subject. Use the BioRadio software to start saving the file in capture mode, naming it “concentration.bd”. Have the subject stand and prepare to putt the golf ball into the cup. They should concentrate and visualize putting the ball into the cup a few times just before they putt. When the subject is ready, have them put the ball into the cup. Stop capture when this is finished. You may want to try other tasks that require concentration and have an EMG component to be measured. When you are finished, export the data file to a file named “concentration.dat”.

Hand-eye coordination

Experimental Setup

Using the BioRadio Configuration Wizard, configure channel 1 to record EOG, channel 2 to record EEG, channel 3 forearm EMG. All three channels should be set for low-level recordings. Choose a high or medium sampling rate, and note the sampling frequency that you choose. Name channel 1 “EOG”, channel 2 “EEG”, and channel 3 “EMG”. Save this configuration as “Sports – Hand Eye coordination”.

You will need to use six snap electrodes and one gold cup electrode. It is important that you properly prepare each of the electrode sites before applying the snap electrodes. Place one snap electrode above the right eye and another below the right eye to measure EOG. Place one snap electrode to the right of the midline of the forehead, as close as possible to the hairline. Ask the subject which hand they would rather use to catch a ball. Place two snap electrodes above the palmaris longus muscle of this forearm. This is a superficial muscle that acts to move the fingers. Place one snap electrode on the elbow of the same arm of the subject for the ground. Fill the gold cup electrode with Elefix gel and place on location O2 of the subject and cover with tape.

Connect snap leads to all of the snap electrodes. Connect the snap lead from the electrode above the right eye to the positive input of channel 1 on the universal harness and the lead below the eye to the negative input of channel 1. Connect the EEG electrode on the back of the head to the positive input of channel 2 on the universal harness. Connect the lead from the electrode on the subject’s forehead to one of the reference inputs on the universal harness. Connect the negative input of channel 2 on the universal harness to the same reference connector on the universal harness. Connect one of the subject’s snap leads from the skin above the palmaris longus muscle of the forearm to the positive input of channel 3 and the other to the negative input of channel 3. Finally, connect the snap lead from the elbow of the subject to the ground input on the universal harness.
Procedure and Data Collection

The subject should wear a cap with a visor so that the visor blocks their peripheral vision in the upward direction. In the BioRadio software, begin capture by saving the file, calling it “handeye1.bd”. The person operating the computer should then stand behind the subject, holding a small ball out of the subject’s vision range, so that the ball cannot be seen. Then, without prior warning, have the partner drop the ball in front of the subject. The subject should attempt to catch the ball without moving their head. Stop saving data. Repeat this three more times. Name the files “handeye2, 3, and 4”.

Data Analysis

Walking and Squatting

Put the BioRadio capture program into view mode. Open the file named “walking.bd”. Turn on the high pass filter and set it to a cut off around 10 Hz in order to filter movement artifact from the data. Print out a few cycles of walking from the BioRadio capture program.

Using the BioRadio DSP Toolbox, type in the filename “walking.dat”. Set the DSP mode for channels 1 – 4 to bin integration and set the bin size to 10. Process and print the data.

Put the BioRadio capture program into view mode. Open the file named “squat.bd”. Turn on the high pass filter and set it to a cut off around 10 Hz in order to filter movement artifact from the data. Print out a few cycles of walking from the BioRadio capture program.

Put the BioRadio capture program into view mode. Open the file named “toes.bd”. Turn on the high pass filter and set it to a cut off around 10 Hz in order to filter movement artifact from the data. Print out a few cycles of walking from the BioRadio capture program.

Concentration

Using the BioRadio Capture software, open the data file named “concentration.bd”. Print out a section of data that shows the physiological signals changing as a function of the subject attempting to putt a golf ball.

Using the BioRadio DSP Toolbox manipulate the EEG data in the file “concentration.dat”. Low pass filter the EEG channel at 25 Hz and perform a spectral analysis before and during the putt. Notice any differences.
Hand-Eye Coordination

Using the BioRadio Capture software, open the data file “handeye.bd”. Export the data to ASCII format. Determine the reaction time of the subject from the time when the eye first moved to when the muscle moved to catch the ball, or vice versa. Use the DSP Toolbox software package for this analysis. Complete this on all four trials.

Discussion Questions

1. Consider each of the three tasks that you completed in this laboratory. How are they related to sports activities or exercise and why would it be important to monitor these aspects of the activity?

2. What determines how quickly the person’s heart rate will start to level off? Relate your answer to how the heart develops during physical exercise. Would a physically fit person have a slower or faster heart rate than a non-fit person?

3. Does the EEG change for the concentration exercise before and during the putt? Would you expect it to? Why or why not?

4. How could biofeedback help to increase athletic performance?

5. Examine the plots that you made with the hand eye coordination data. How many times did the hand react first? How many times did the eyes react first? What accounts for the differences in the four trials?

6. Explain how the EMG can be used to help an athlete re-train after a muscle injury.

NOTE: Graduate Students Should Continue and Complete the Following Sections.

Graduate Analysis and Discussion

1. Suppose that you could electrically stimulate the legs of a paralyzed individual to control the muscles. The level of force produced by the muscle is dependent upon the level of stimulation. There is a positive, linear relationship between the two. Explain how you could use the EMG signals from the walking data to determine how to stimulate the leg muscles to enable a paralyzed individual to walk again.

2. Using MATLAB, create a filter that will eliminate all but the alpha and beta frequency range in the EEG signal during the concentration task. Compare the unfiltered and filtered signals.
References


Lab 10

Student Designed Laboratory
Introduction

Throughout the course of this lab book you have learned how to monitor and record various physiological signals. You should now feel comfortable using the BioRadio to monitor and record ECG, EEG, EMG, and EOG. Some of the other sensors you have gained experience with include piezoelectric sensors and thermistors. In addition, you have learned how to remove artifact and digitally process these signals in order to extract useful information. In this laboratory you will use the knowledge that you have acquired and relate it to a real world biomedical engineering problem of your own design. You should design your own application for the BioRadio, form a hypothesis, and prove or disprove it using the tools you have developed throughout this course. It is possible that you could monitor one or more of the signals that you have learned about already and apply it to a new application, or you may want to try and monitor a signal not discussed in this laboratory book. The BioRadio can be used to monitor and record any signal within the specifications of the device, not only those covered in the laboratories in this book.

Here are some things to keep in mind when formulating your hypothesis:

1. The BioRadio is not a tethered device. Therefore, you could do an experiment in many locations not usually capable with standard tethered equipment. Loading the BioRadio software onto a laptop computer makes this a portable device. Some examples for laboratories that you might want to attempt include improving sports performance: place kicking a football, punting football, swinging bat in baseball, kicking soccer ball, running out of the blocks, jumping to a basket, basketball free throws, etc.

2. You may want to use the BioRadio to monitor a signal already covered and then go above and beyond the digital signal processing discussed in this laboratory book to analyze the data. For instance, you may want to write automated routines for analyzing data such as FFT analysis that would allow you to set thresholds to determine peaks.

3. For the purposes of the laboratories in this book, the only mechanical sensors we used were the piezoelectric effort belt and the thermistor. However, any external sensor could be used with the BioRadio as long as the sensors have an output no greater that +/- 1.25 Volts. There may be some other signal you wish to monitor that you are capable of scaling the output to this level. An example is an accelerometer for motion analysis.
Equipment required:
- BioRadio 110
- BioRadio Lab Kit
- BioRadio User’s Guide
- Any other items defined by the students

Background

As a part of the lab project you are completing you should perform a literature review on the topic that you are investigating. You should provide information on any previous work that has been done in this area relevant to your hypothesis. You should determine the incidence and significance of the topic you are covering.

Experimental Methods

Experimental Setup

The experimental setup that you use should be well documented. Another researcher should be able to read the experimental setup section of your lab report and repeat your experiment using the BioRadio. As part of your experimental setup you should be sure to include all of the methods you undertook to prevent sources of noise from causing artifact in your data. Careful note should be taken of the BioRadio channels that were used, the configuration of those channels, and the sampling rate and resolution used for the experiment.

Procedure and Data Collection

Your lab report should include a detailed methods section that outlines the steps taken once the device was setup on the subject. Any tasks performed by the subject should be outlined in detail.

Data Analysis

You have learned how each of the signals in this laboratory can be processed to obtain useful information. You may want to use the filtering available in the BioRadio Capture software or DSP Toolbox to process and print your data. Several plots of your data should be made to illustrate your findings. You may want to use other programs such as MATLAB or LabView to analyze the data.

Discussion Questions

The discussion should include the results of all your testing. You should be able to prove or disprove the hypothesis you made from your results. In addition, the discussion should include any problems that you encountered or “strange” data and possible explanations.
Graduate Analysis and Discussion

The graduate student should be able to take advantage of programs such as MATLAB or LabView to digitally process the signals collected. You should go above and beyond the processing techniques covered in this lab book and design your own filters. An example would be to design an adaptive filter or process the data with a fast Fourier transform and analyze the signal in the frequency domain.
Appendix A

Exporting BioRadio Capture Files
I. Exporting data from the BioRadio Capture software to an ASCII file

Use the following steps to export saved BioRadio data into ASCII format. Once in ASCII format, other programs such as MATLAB and Excel can import the data.

1. If the desired file to export is not already open in the BioRadio software, open it.
2. Click on the File menu, and select “Export data file”.

3. After clicking on Export data file, a dialog box will appear with options on how to save the data.

   To select the time option, click on the tab labeled “Time”. The choices are to export the whole recording, the time interval that is currently displayed, or a user specified duration. The other option allows a choice of channels to be exported. This can be selected by clicking on the “Channel” tab. Place a checkmark next to the channels to export.

4. Once finished choosing export options, click on the “Export...” button. A file dialog box will appear. From this dialog box you can choose the directory and filename the data will be saved under. The file will be given a default extension of “.dat”.
II. Importing ASCII data into Microsoft Excel

1. Start Microsoft Excel

2. Go to the File menu, and click on “Open…”

3. A file dialog box will appear. Change the “Files of type” drop down list to “All Files (*.*)

4. At this point, all files in the chosen directory will appear. Navigate to the directory of the exported BioRadio file. Select the desired file (which will have a .dat extension), and click on the “Open” button.
5. After clicking on the Open button, the Text Import Wizard dialog box will appear. The data is stored in tab-delimited format, so each column represents a channel. The first column, however, is a time index. The columns after the time index represent channel 1, channel 2, etc. Since the default setting for the Text Import Wizard is tab-delimited files, click on the “Finish” button to continue the importing process. The data will then be imported into the Excel worksheet.

6. In the Excel worksheet, you may notice that some of the cells do not contain numbers, but “####” instead. This is because there is insufficient space in the cell to show all the digits of that value. There are two ways to correct this problem.

One method is to highlight the columns with the cells containing “####”. Then go to the Format menu and click on “Cells…”

At this point, a Format Cells dialog box will appear. Select the “Number” category, and you may decrease the decimal precision if desired. Click the OK button when finished. The cells will then show the correct value.
The other method is to increase the width of the columns. This can be accomplished by selected all the columns with the “#####”, and then moving the mouse to the right edge of the selected column header, and clicking and dragging the selection outwards.

7. In the Excel worksheet you will notice that column A contains data, column B is empty, and then there are subsequent columns that contain data. Column C starts that channels of data that you collected. This is data from channel 1, column D is data from channel 2, …etc.

8. The information in column A is not applicable to anything you will be doing in these labs. You should delete column A by right clicking on the letter A and selecting “Delete”. All columns should then shift one place to the left. Your new column A should be blank.
9. In order to make a time column you should type the following into cell A1, “0”. Then in cell A2 you should type, “=A1+(1/SR)” and click enter. However in place of SR type the sampling rate that your data was sampled at. The cell should now equal 0 + (1/SR).

10. Single click on the cell A2 again so that it is highlighted in black. Then double-click on the bottom right corner of the cell (A tiny black square should be there to click on). This will fill in the rest of column A. You now have a time column to plot your data against.
III. Plotting data in Microsoft Excel

1. To plot data in Excel you first will need to create a time column (See Above). You will need to know that rate at which your data was sampled to make this time column.

2. The chart wizard dialog box will appear. Select a chart type and subtype then Finish. A chart will appear in the worksheet.
IV. Importing ASCII Data into Matlab

1. Start Matlab. At the command prompt, change to the directory where the .DAT file is located by using the ‘cd’ command. For example, if your data file is in the directory c:\mydata type “cd c:\mydata”.

2. To import the data file, type
   
   ```matlab
   data = load('filename.dat'); (where filename.dat is the name of your file)
   ```

3. The data will be imported into Matlab and saved as a variable called “data”. The row value is sample number and the column value is channel. As mentioned earlier, remember that the first column is the time index.

   a. So, to plot channel 1, type

   ```matlab
   plot(data(:,2));
   ```
Appendix B

BioRadio Laboratory Kit
Digital Signal Processing Toolbox
The BioRadio Digital Signal Processing Toolbox

The BioRadio Digital Signal Processing Tool Box allows you to process data files that have been exported to an ASCII file using the BioRadio software. If you do not yet know how to export a BioRadio data file to an ASCII file, please refer to Appendix A. Only small file sizes (less than three minutes) should be used. Therefore, only when using the BioRadio software to create ASCII files, limit the files to less than 3 minutes. Signals can be analyzed in both the time and frequency domains. The high and low pass filters utilize a Butterworth filter.

To Process and View Data in the Time Domain:

1. In the box labeled “Name of the Exported BioRadio File:”, type in the file path of the ASCII file to process. Be sure to include the .dat extension as part of the filename. You may also browse files by clicking on the open file icon next to the filename box. Files need to have the .dat extension that is associated with an exported BioRadio file.

2. Next, you must enter the sampling rate at which the data was sampled in the box labeled “Sampling Rate”. Enter this value in Hz.
3. You will now need to set the DSP configuration for each channel of data you wish to view. Click on the green button labeled “Set DSP”. A pop up menu will appear that will allow you to set the DSP configuration for each channel.

**DSP Methods**

**None (Raw Data)** – The raw data exported from the BioRadio data file will be plotted.

**Low Pass Filter** – The data will be low pass filtered using a digital FIR filter. You will need to specify the low pass cutoff frequency.

**High Pass Filter** - The data will be high pass filtered using a digital FIR filter. You will need to specify the high pass cutoff frequency.

**Bandpass Filter** - The data will be band pass filtered using a digital FIR filter. You will need to specify the low pass cutoff frequency and the high pass cutoff frequency. When you specify the high and low cutoffs for the bandpass filter set the low pass cutoff to be the low frequency of the bandpass and the high pass cutoff to be the high frequency of the bandpass.

**Bin Integration** – The absolute value of the data points will first be calculated. Then the data will be summed into bins of a user-defined length. For data point \( x(n) \), data points \( x(n-s) \) to \( x(n+s) \) will be added together where \( n \) is the current data point and \( s \) is equal to one half the bin size defined by the user. For data points that do not exist a zero is assumed.

**RMS** – The RMS value of the data will be found for specific bins of data. The value for data point \( x(n) \), will be the RMS value of data points \( x(n-s) \) to \( x(n+s) \) where \( n \) is the current data point and \( s \) is equal to one half the bin size defined by the user. For data points that do not exist a zero is assumed.

**Rectify** – The absolute value of each data point will be calculated.

Also available are: Bin Integration with low, high, or band pass filters applied afterwards, RMS with low, high, or band pass filters applied afterwards, and Rectification with low, high, or band pass filters applied afterwards.
4. Select the DSP method you wish to use for each channel from the “DSP Method” drop down menu located next to each label. Depending upon the method that you choose, parameters will appear for each channel. These parameters include a low pass filter cutoff, a high pass filter cutoff, and a bin size. Set each of these to a desired level for those that apply.

5. When each channel is set up to the desired specifications, click on the green button at the bottom of the screen labeled “Configure and Exit”. This will save your parameters and close the window. You can change these parameters at anytime by clicking on the “Set DSP” button again.

6. In order to view the processed channels of data you will first need to turn on the channels you wish to view. Located to the right of the plot labeled “Physiological Data” are eight View switches. Turn the switches on that correspond to the channels that you wish to view.

7. When finished, click on the green button located at the bottom of the screen labeled “Process Data”. The processed data in the time domain should now appear in the plot labeled “Physiological Data”. The plot will automatically scale itself to the largest signal. Shown on the x-axis is time in seconds. Shown on the y-axis is voltage in millivolts.
8. Once plotted you can zoom in on sections of the plot by double-clicking on the first and/or last numbers located on the time and voltage scales and typing in new values.
To Process and View Data in the Frequency Domain:

A spectral analysis of the data will be performed on the processed data. Therefore, any filter parameters or DSP methods that you have setup in the “Set DSP” pop up menu will be included in the spectral analysis. To perform a spectral analysis of just the raw data, the DSP method in the pop up menu should be set to raw data for that channel.

1. First you will need to select the channel you wish to perform a spectral analysis on. Select this channel from the drop down menu of channels located next to the plot labeled “Spectral Analysis”. IT IS IMPORTANT THAT THE VIEW SWITCH FOR THIS CHANNEL HAS ALSO BEEN TURNED ON.

2. Next you will need to select the time interval over which you want the analysis to be performed. You must select a start time and a stop time. The times correspond to those times in the time domain plot “Physiological Data”.

3. Select the display unit you wish to view from the control labeled “Display Unit”.

4. Select the type of plot you wish to view from the control labeled “Log/Linear”.

5. Select the type of window you wish to use for the analysis from the control labeled “Window”.

6. Finally, select the filter order that you would like to use.

7. Once you have all of these parameters set up, click on the button labeled “Spectrum Analysis” at the bottom of the screen.
Printing Data

1. You can print the plot at anytime by clicking on the button labeled “Print” underneath the plot. Your default printer will be used to print the plot.

Exiting the Program

1. To exit the program, click on the button labeled “Exit” underneath the plot.