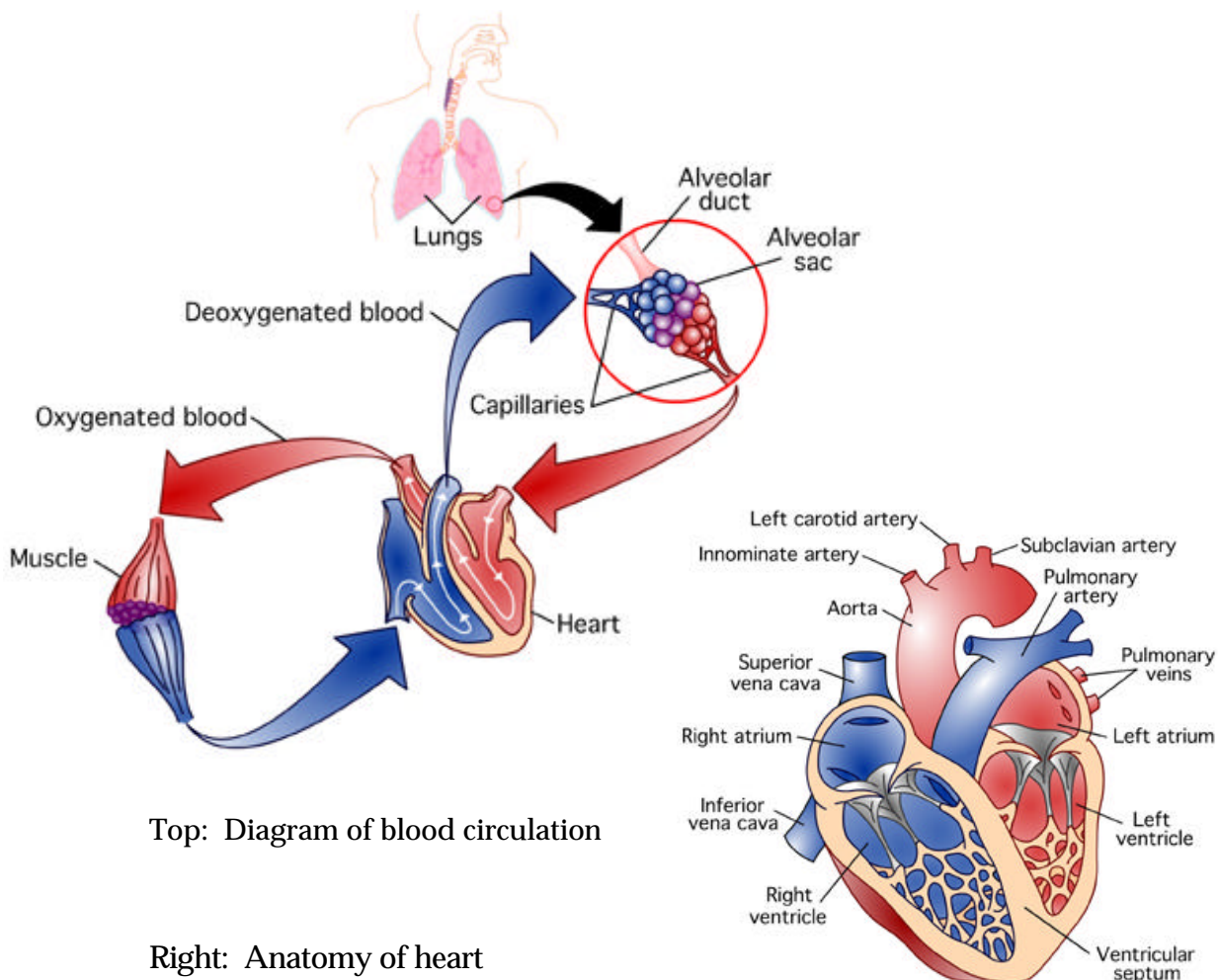


# Cardiovascular Physiology

The mammalian heart is a pump that pushes blood around the body and is made of four chambers: right and left atria and right and left ventricles. The two atria act as collecting reservoirs for blood returning to the heart while the two ventricles act as pumps to eject the blood to the body. As in any pumping system, the heart comes complete with valves to prevent the back flow of blood. Blood enters the heart at a low pressure and leaves at a higher pressure, and it is this high pressure that provides the force to propel the blood through the circulatory system. The figure below shows the organization of the human heart and the circulatory system.

Deoxygenated blood returns to the heart via the major veins (superior and inferior vena cava), enters the right side of the heart and from there is ejected to the pulmonary artery on the way to the lungs to pick up oxygen and release carbon dioxide. This oxygenated blood returns from the lungs to the left side of the heart via the pulmonary veins and is ejected to the aorta back to the body, where oxygen is released and carbon dioxide is collected. Even though both sides of the heart work at the same time, the complete division of the heart insures that there is no mixing of deoxygenated blood with oxygenated blood.



Top: Diagram of blood circulation

Right: Anatomy of heart

The mammalian heart is autorhythmic, since it will continue to beat if removed from the body (and kept in an appropriate solution). Although the CNS can influence the rate and strength of contractions, the rhythm comes from within the heart itself. The heart is composed almost entirely of large, strong muscle fibers, which are responsible for the pumping action of the heart. Other cardiac muscle cells are weakly contractile and produce the rhythm for, and conduct it to the rest of the heart. A group of these weak muscle cells is located in the sinoatrial (SA) node and acts as the pacemaker for the heart. These cells rhythmically produce action potentials, which spread via gap junctions to fibers of both atria. The resulting contraction pushes blood into the ventricles. While adjacent atrial fibers are connected by gap junctions, the only electrical connection between the atria and the ventricles is via the atrioventricular (AV) node, as shown in the picture below. The action potential spreads slowly through the AV node and then rapidly through the Bundle of His and Purkinje fibers to excite both ventricles.

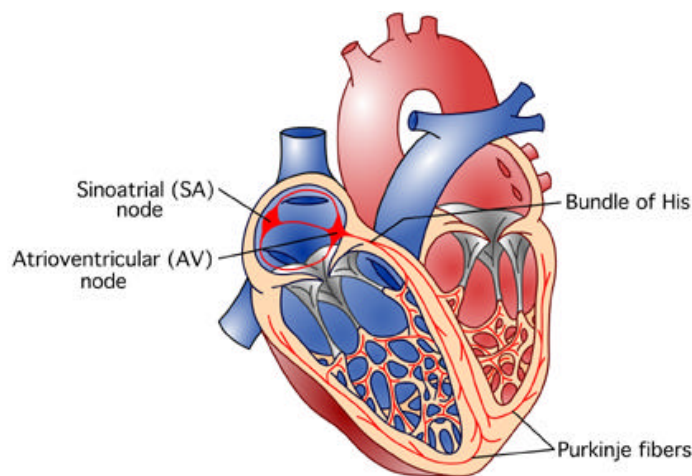


Diagram of human heart with SA and AV nodes

The semilunar valves are located between the ventricle and the artery on each side of the heart. In the relaxed heart, the high arterial pressure shuts the semilunar valves and prevents blood flow from the artery into the ventricle. Ventricular contraction increases the pressure of the blood in the ventricle. When the ventricular pressure is greater than the arterial pressure, the semilunar valves open and blood flows into the artery. The myocardium then relaxes, the ventricular pressure declines and the semilunar valves close.

## Electrocardiogram and Heart Sounds

The cardiac cycle involves a sequential contraction of the atria and the ventricles. The combined electrical activity of the different myocardial cells produces electrical currents that spread through the body fluids. These currents are large and can be detected by recording electrodes placed on the skin. In this lab you will attach three electrodes to a student subject. These electrodes will be connected to the iWorx unit and the signal will be displayed on the computer screen. The regular pattern of electrical activity produced by each heart beat cycle is called the electrocardiogram or ECG.



ECG trace, P, QRS, and T waves are labeled

The action potentials recorded from atrial and ventricle fibers are different from those of nerves and skeletal muscle. The cardiac action potential is composed of three phases, a rapid depolarization, a plateau depolarization (which is pronounced in ventricular fibers) and a repolarization back to resting membrane potential. The components of the ECG can be correlated with the electrical activity of the atrial and ventricle fibers such that:

- the P-wave is produced by atrial depolarization
- the QRS complex is produced by atrial repolarization and ventricle depolarization
- the T-wave is produced by ventricle repolarization

In this lab you will record the ECG from a subject and listen to the characteristic "lub-dup" heart sounds. The "lub" sound occurs during the early phase of ventricle contraction and is produced by closing of the atrioventricular valves, which prevents blood flow into the atria. When the ventricles relax, the blood pressure drops below that in the artery and the semilunar valves close, producing the "dup" sound.

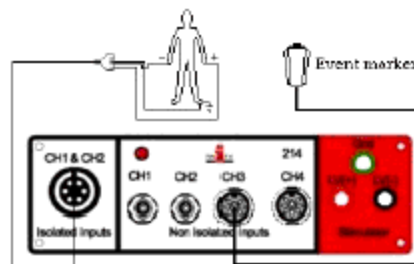
### *Equipment Required*

AMI cable and three ECG leads  
Alcohol swabs

Stethoscope  
Event marker

### *Equipment Setup*

1. The subject should remove all jewelry from their wrists and ankles.
2. Use the figure below to guide the placement of your electrodes. You want one on the inside of each wrist and one on the inside of your left ankle.
3. Clean your chosen sites with an alcohol swab, and apply the electrodes as follows...
  - the "2 -" lead to the right wrist
  - the "2 +" lead to the left wrist
  - the ground or reference lead to the left leg
4. Select the 0.3-35Hz filter setting on channel 2.
5. Use the DIN plug to connect the event marker to channel three.
6. The subject should sit quietly with their hands in their lap.



Equipment to measure ECG

Open LabScribe and load the "Heart #1" settings file.

### *ECG in a Resting Subject*

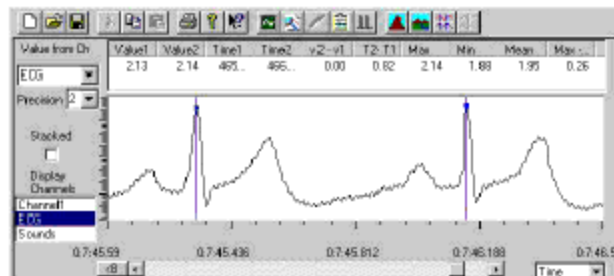
Aim: To measure the ECG in resting individuals.

#### Procedure

1. Start recording. If the ECG trace is upside down (QRS goes down) stop the recording and switch the positive and negative electrodes, or right click and invert the trace.
2. Have the subject open and close their fists, or move their arms across their chest. Notice that the trace moves around the screen and the ECG is distorted. This is a demonstration of why you need to keep still and relaxed when recording the ECG.
3. When you have a suitable trace, label your trace and record several minutes of data.
4. Stop recording and save the file.

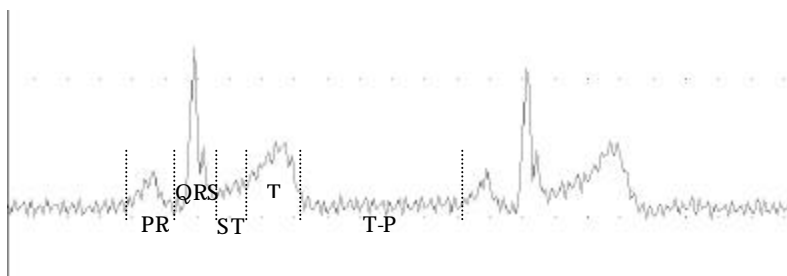
## Data Analysis

1. Move twelve heart beat cycles to the Analysis window.
2. Display only the ECG trace.
3. Measure the following and put them in your Journal:
  - the amplitude (v2-v1 or max-min) of ten QRS waves
  - the amplitude (v2-v1) of ten P waves
  - the amplitude (v2-v1) of ten T waves
4. Measure the instantaneous heart rate by measuring the time interval (T2-T1) between eleven adjacent QRS waves (shown below). Remember the display time can be expanded, which will help obtain a more accurate time measurement.
  - Store your values in Excel
  - Calculate the Mean Heart Rate (AVERAGE)
  - Calculate the Standard Deviation of the Mean Heart Rate (STDEV)



Time interval between adjacent QRS waves (T2-T1) = 0.82s

5. The next step will be to look at the time it takes for each component of a complete heart rate cycle. Measure the time interval (T2-T1) of each of the following as in the figure below. Make these measurements in ms.
  - (T2-T1) of ten PR intervals
  - (T2-T1) of ten QRS waves
  - (T2-T1) of ten S-T segments
  - (T2-T1) of ten T waves
  - (T2-T1) of ten T-P segments



Components of the heart rate cycle

6. Calculate the following:
  - the average amplitude of the P wave, the QRS wave, and the T wave.
  - the average time interval (in seconds) between adjacent QRS waves and the calculated average heart rate.
  - the average intervals of each of the components of the heart rate cycle.

### Questions

1. Is the amplitude of the different waves the same in different cardiac cycles?
2. Which wave has the largest amplitude?
3. What is the heart rate?
4. What component of the heart rate cycle do you expect to change the most when the heart rate changes?

### *ECG Recordings from Other Students*

Aim: To measure heart rate from all students.

### Procedure

Record the ECG of all the students.

### Data Analysis

Make measurements as in the previous experiment, and compile the data on the board.

### Questions

1. Is the amplitude of the different waves the same in different individuals? Why?
2. For each individual, which wave has the largest amplitude? Is this result the same for all individuals?
3. Is the average heart rate the same for each individual?
4. Is the standard deviation of the heart rate the same for each individual?
5. What variation is there within the class?
6. Is there any obvious correlation between heart rate and sex, apparent fitness, or diet?

## *ECG and Heart Sounds*

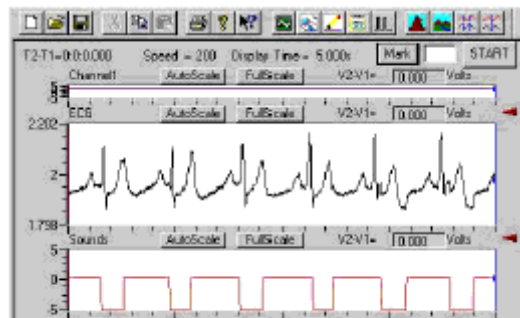
Aim: To measure the ECG in resting individuals.

### Procedure

1. Place the head of the stethoscope on the left side of the subject's chest and listen for the heart sounds. Move the stethoscope head to different positions until clear heart sounds are heard.
2. Start and press the event marker on "lub" and release on "dup."
3. After collecting at least 10 accurate samples, stop recording and save the file.

### Data Analysis

1. Move the heart beat cycles to the Analysis window.
2. Measure the time delay (T2-T1) for ten of the following, store them in the Journal and compute the averages:
  - the peak of the QRS wave and the lub sound
  - the peak of the T wave and the dup sound



ECG trace with heart sounds

### Questions

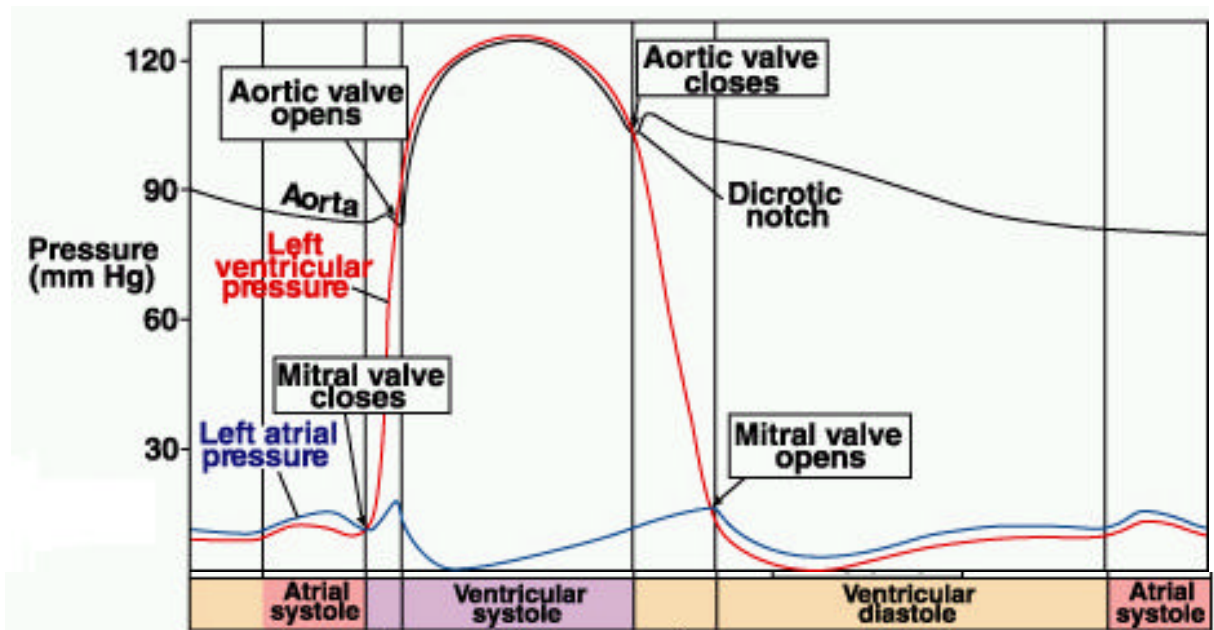
1. Why is the lub sound recorded around the peak of the QRS wave?
2. Is the time delay between the QRS wave and the lub sound always the same?
3. Should it be? Explain your results.
4. Why is the dup sound recorded around the peak of the T wave?
5. Is the time delay between the T wave and the dup sound always the same?
6. Should it be? Explain your results.

## ELECTROCARDIOGRAM AND PERIPHERAL CIRCULATION

The arterial system functions as a pressure reservoir. Blood leaves the arterial system continuously through the capillaries, but enters intermittently from the heart. Between contractions the heart is relaxed (diastole) and the chambers fill with blood from the veins.

During this time the heart does not pump blood into the arterial system but blood flows out through the capillaries; as a result the arterial pressure slowly declines.

When the ventricles contract, (systole) the pressure of the blood inside the ventricles increases to close the atrioventricular valves. Further contraction increases the ventricular pressure until it exceeds the arterial pressure. At this point, the arterial pressure is at its lowest point during the cardiac cycle, the semilunar valves are forced open, and blood flows into the artery. Blood entering the arterial system inflates the arteries a little and increases blood pressure to a maximum systolic pressure.



Wiggers diagram showing the relationship between pressure and volume changes in the left heart and aorta. Adapted from Silverthorn Fig. 14-27.

While the variation in arterial blood pressure during the cardiac cycle is smoothed out by the inherent elasticity of the major arteries, blood still exhibits pulsatile flow through the arteries and arterioles. In this lab you will measure the pulsatile flow of blood through the finger of a subject and correlate it with the ECG. In addition you will examine the effects of temperature on peripheral circulation.



### Equipment Required

AMI cable and three ECG leads  
Alcohol swabs

Plethysmograph  
Ice, cold and hot water, plastic bags

### Equipment Setup

1. Apply the ECG electrodes on the wrists and ankle as in the previous experiment.
2. Plug the plethysmograph into channel three and place the plethysmograph on the volar surface of the distal segment of a middle finger with the Velcro.
3. The subject should sit quietly.

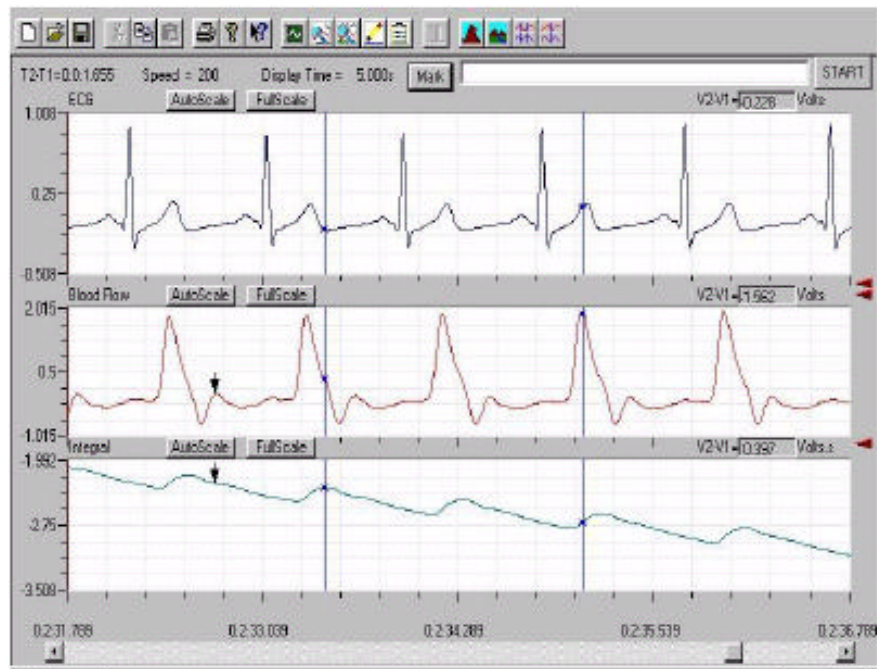
Open the "Heart #2" settings file.

### ECG and Volume Pulse in a Resting Subject

Aim: To measure and correlate the ECG and volume pulse in a resting individual.

#### Procedure

1. Record about one minute of data of ECG and finger pulse. Your data should look similar to the figure below.
2. Save the file.



ECG trace with blood flow, and its integral (volume).  
The arrows on the two lower channels point to the diastolic notch.

### Data Analysis

1. Move about five heart beat cycles to the Analysis window.
2. Click to de-select channels one and three (Blood Flow) to display the ECG and the integrated finger pulse traces.
3. Move the first cursor to the peak of the QRS wave and the second cursor to the peak of the next finger pulse signal in channel four (Integral).
4. Enter the time (T2-T1) difference into the Journal.

### Questions

1. What produces the QRS wave in the ECG?
2. What does the peak of the blood flow trace represent?
3. What processes, therefore, take place between these two events?
4. What, therefore, does this time value represent?
5. Does the falling phase of the volume pulse have a small, transient plateau or upward deflection, as shown in the figure above (arrow)? This is called the dicrotic notch.
6. What property of the aorta and arteries can cause this transient increase in blood pressure after the blood has left the ventricles?

### *The Volume Pulse*

Aim: To measure the volume pulse in other individuals.

### Procedure

1. Make plethysmograph recordings of all the students in the class.
2. Save the files.

### Questions

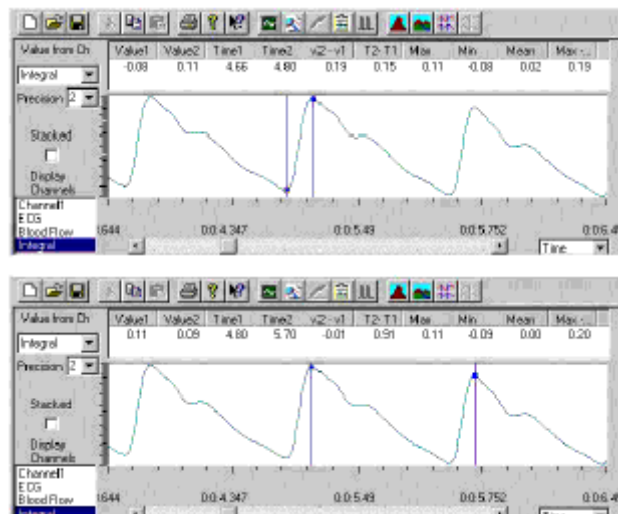
1. Do all student traces have a dicrotic notch in the integrated signal displayed on channel four?
2. Is the size of the dicrotic notch correlated with age, smoking, or fitness? Does it correlate with the tightness of the plethysmograph strap?

## *The Effect of Cold on Volume Pulse*

Aim: To measure the effects of cold on volume pulse and heart rate.

### Procedure

1. Make sure to label your trace appropriately.
2. Calibrate the plethysmograph integral by recording several seconds of no data.
3. Put the plethysmograph on the subject and make a control recording for about three minutes.
4. Place a bag of ice and cold water on the left forearm and begin recording again for about three minutes.
5. Enter "remove" and simultaneously remove the ice and record for three minutes.
6. Stop recording and save the file.



Integral of pulse (volume); top window-measuring amplitude of signal (v2-v1), bottom window-measuring time interval (T2-T1)

### Data Analysis

1. Measure the following for the blood flow (integral of pulse) and create a graph of your results:
  1. the amplitude of five peaks; calculate the mean value.
  2. the time interval between the five peaks; calculate the heart rate.
  3. Repeat these measurements every 20 seconds through your trace to see the effects of cooling and subsequent recovery on peripheral circulation and heart rate. Note when ice was applied and removed in your graph.

### Questions

1. What is the effect of cooling on peripheral circulation?
2. What factors change peripheral circulation?
3. What is the effect of cooling on heart rate? Explain your observations.

### *The Effect of Heat on Volume Pulse*

Aim: To measure the effects of heat on volume pulse and heart rate.

#### Procedure

1. Move the plethysmograph to the middle finger of the right hand.
2. Repeat the above experiment, but this time place a bag of hot water on the right forearm.

#### Questions

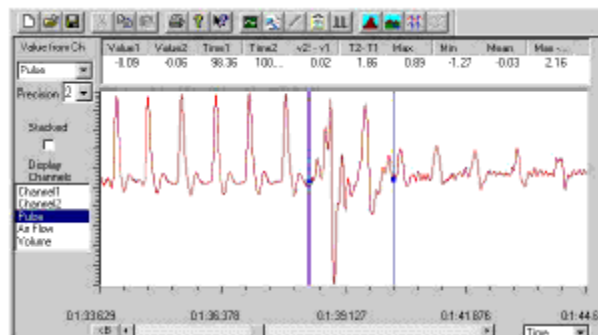
1. What is the effect of heat on peripheral circulation and heart rate? Explain your results.

### *The Effects of Gravity on Peripheral Circulation*

Aim: To study the effects of gravity on blood circulation in the finger.

#### Procedure

1. Record and label the resting finger pulse.
2. Enter "hands on head" as the subject places both hands on their head.
3. Enter "hands high" as the subject reaches with both hands as high as possible (be careful of the cable).
4. Stop recording and save the file, your data may look like the figure below.



Plethysmograph data recorded with a change in the subject's hand elevation.

#### Data Analysis

1. Move data from at least 10 pulses collected during rest into the Analysis window.

2. Record the peak blood flow as the voltage difference ( $v_2 - v_1$ ) for at least 5 beats, and calculate the average.
3. Calculate the heart rate between each beat for 10 beats and calculate the average.
4. Repeat with data obtained in the other two hand positions.

#### Questions

1. What happens to the size of the finger pulse when the hands are raised?
2. If the size of the finger pulse signal indicates blood pressure, what do you think happens to blood pressure in the fingers when the hands are raised over the head?

## **The Effects of Exercise on ECG and Peripheral Circulation**

At rest, the distribution of blood to a particular organ may be very different from that seen during exercise. For example, the blood flow to the gut decreases during exercise, while blood flow to the skeletal muscles increases dramatically. Furthermore, the amount of blood flowing around the circulatory system may be increased several times. In this laboratory you will record the electrocardiogram and the finger pulse from a (healthy) subject. These parameters will be recorded when the subject is at rest and immediately after exercise.

- ☛ This experiment involves exercise and an elevation of heart rate. It should not be performed by anyone who is not healthy or has a personal or family history of cardiovascular or respiratory problems.

### *Equipment Setup*

1. Make sure the ECG is connected to the subject and channel 2.
2. Place the plethysmograph on the volar surface of the subject's middle finger, and plug it into channel 3.
3. The subject should sit quietly.

Load the "Heart #3" settings file.

### *ECG and Volume Pulse in a Resting Subject*

Aim: To measure and correlate the ECG and volume pulse in a resting individual. This recording will be used as a control for the post-exercise data.

#### Procedure

1. Record a resting ECG and pulse for 5 minutes.
2. Save the file.

### *ECG and Volume Pulse After Exercise*

Aim: To measure and correlate the ECG and volume pulse immediately after exercise.

#### Procedure

1. Leave the student connected to the electrodes, but disconnect the ECG leads from the student. Keep the plethysmograph attached to the student and disconnect it from the iWorx unit.
2. Make sure the cord is not tangled, and that they don't get pulled or crushed.

3. Remember that plethysmograph is still attached to the student, so the subject should exercise carefully, but rigorously enough to elevate heart rate. Try running up and down the stairs for 5 minutes.
4. Immediately after exercise, reconnect the subject to the iWorx unit while the subject sits down.
5. Record for three minutes every 5 minutes for the next 30 minutes. Make sure you label your data appropriately.
6. Stop recording and save the file.

### Data Analysis

1. You should have traces for the resting individual and immediately after exercise. For each condition, analyze the data as you did for the original resting subject.
2. Use the cursors to measure the amplitude of the integrated signal (or blood flow) every 10 seconds for the entire record, or until the signal has returned to a resting level for 30 seconds, (i.e. three or four measurements that are reasonably constant).

### Questions

1. Create a plot for each subject that shows the effect of exercise on the average heart rate and the standard deviation of the heart rate before and at each data point after exercise (please give your plots to the TAs).
2. Find which components of the complete heart rate cycle change the most from the resting to the exercise condition. Be sure to look at the amplitude of the waves and the length of the intervals. Can you give a good physiological explanation for why certain aspects of the cycle are affected more than others?
3. What is the effect of exercise on the rate of blood flow through the fingers?
4. Is this what you would expect and why? What do you expect to find if the rate of blood flow was measured before and after exercise to the calf? The gut? Why?
5. When comparing the rest condition to immediately after exercise, what do you expect to happen to heart rate? To the stroke volume? To the total cardiac output? To the total peripheral resistance?

### *Finger Pulse After Hand Exercise*

Aim: To measure and correlate the ECG and volume pulse immediately after exercise.

#### Procedure

1. Disconnect the ECG leads from the volunteer.
2. Note: the dynamometer is not plugged into the hardware at this time.
3. Rhythmically squeeze the dynamometer bulb for a few minutes or until the forearm muscles fatigue.
4. Start recording and stop exercising. Record for three minutes or until the amplitude of the finger pulse signal has attained a reasonably constant level for one minute; during this time mark your file "Finger Pulse—Recovery from Arm Exercise."
5. Stop recording and save the file.

#### Data Analysis

1. Examine blood flow (integral of finger pulse), recorded immediately after exercise.
2. Measure the amplitude of a signal every 10 seconds for the entire record, or until the signal has returned to a resting level for 30 seconds, during which four or five cycles are reasonably constant.
3. Enter your data into the Journal.

#### Questions

1. What is the effect of hand exercise on the rate of blood flow through the fingers?
2. Compare the effects of hand exercise and leg exercise on blood flow by comparing the data from the first exercise to this one. Are they the same or different? Explain your data.