

PHYSIOEX 3.0 EXERCISE 33B: CARDIOVASCULAR DYNAMICS

Objectives

1. To define the following: blood flow; viscosity; peripheral resistance; systole; diastole; end diastolic volume; end systolic volume; stroke volume; cardiac output.
 2. To explore cardiovascular dynamics using an experimental setup to simulate a human body function.
 3. To understand that heart and blood vessel functions are highly coordinated.
 4. To comprehend that pressure differences provide the driving force that moves blood through the blood vessels.
 5. To recognize that body tissues may differ in their blood demands at a given time.
 6. To identify the most important factors in control of blood flow.
 7. To comprehend that changing blood vessel diameter can alter the pumping ability of the heart.
 8. To examine the effect of stroke volume on blood flow.
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The physiology of human blood circulation can be divided into two distinct but remarkably harmonized processes: (1) the pumping of blood by the heart, and (2) the transport of blood to all body tissues via the vasculature, or blood vessels. Blood supplies all body tissues with the substances needed for survival, so it is vital that blood delivery is ample for tissue demands.

The Mechanics of Circulation

To understand how blood is transported throughout the body, let's examine three important factors influencing how blood circulates through the cardiovascular system: blood flow, blood pressure, and peripheral resistance.

Blood flow is the amount of blood moving through a body area or the entire cardiovascular system in a given amount of time. While total blood flow is determined by cardiac output (the amount of blood the heart is able to pump per minute), blood flow to specific body areas can vary dramatically in a given time period. Organs differ in their requirements from moment to moment, and blood vessels constrict or dilate to regulate local blood flow to various areas in response to the tissue's immediate needs. Consequently, blood flow can increase to some regions and decrease to other areas at the same time.

Blood pressure is the force blood exerts against the wall of a blood vessel. Owing to cardiac activity, pressure is highest at the heart end of any artery. Because of the effect of peripheral resistance, which will be discussed shortly, pressure within the arteries (or any blood vessel) drops as the distance (vessel length) from the heart increases. This pressure gradient causes blood to move

from and then back to the heart, always moving from high- to low-pressure areas.

Peripheral resistance is the opposition to blood flow resulting from the friction developed as blood streams through blood vessels. Three factors affect vessel resistance: blood viscosity, vessel radius, and vessel length.

Blood viscosity is a measure of the “thickness” of the blood, and is caused by the presence of proteins and formed elements in the plasma (the fluid part of the blood). As the viscosity of a fluid increases, its flow rate through a tube decreases. Blood viscosity in healthy persons normally does not change, but certain conditions such as too many or too few blood cells may modify it.

Controlling blood vessel radius (one-half of the diameter) is the principal method of blood flow control. This is accomplished by contracting or relaxing the smooth muscle within the blood vessel walls. To see why radius has such a pronounced effect on blood flow, we need to explore the physical relationship between blood and the vessel wall. Blood in direct contact with the vessel wall flows relatively slowly because of the friction, or drag, between the blood and the lining of the vessel. In contrast, fluid in the center of the vessel flows more freely because it is not “rubbing” against the vessel wall. When we contrast large- and small-radius vessels, we see that proportionately more blood is in contact with the wall of small vessels, hence blood flow is notably impeded in small-radius vessels.

Although vessel length does not ordinarily change in a healthy person, any increase in vessel length causes a corresponding flow decrease. This effect is principally caused by friction between blood and the vessel wall. Consequently, given two blood vessels of the same diameter, the longer vessel will have more resistance, and thus a reduced blood flow.

The Effect of Blood Pressure and Vessel Resistance on Blood Flow

Poiseuille’s equation describes the relationship between pressure, vessel radius, viscosity, and vessel length on blood flow:

$$\text{Blood Flow} = \frac{\Delta P \pi r^4}{8 \eta l}$$

In the equation, ΔP is the pressure difference between the two ends of the vessel and represents the driving force behind blood flow. Viscosity (η) and blood vessel length (l) are not commonly altered in a healthy adult. We can also see from the equation that blood flow is directly proportional to the fourth power of vessel radius (r^4), which means that small variations in vessel radius translate into large changes in blood flow. In the human body, changing blood vessel radius provides an extremely effective and sensitive method of blood flow control. Peripheral resistance is the most important factor in blood flow control, because circulation to individual organs can be independently regulated even though systemic pressure may be changing.

Vessel Resistance

Imagine for a moment that you are one of the first cardiovascular researchers interested in the physics of blood flow. Your first task as the principal investigator for this project is to plan an effective experimental design simulating a simple fluid pumping system that can be related to the mechanics of the cardiovascular system. The initial phenomenon you study is how fluids, including blood, flow through tubes or blood vessels. Questions you might ask include:

1. What role does pressure play in the flow of fluid?
2. How does peripheral resistance affect fluid flow?

The equipment required to solve these and other questions has already been designed for you in the form of a computerized simulation, which frees you to focus on the logic of the experiment. The first part of the computer simulation indirectly investigates the effects of pressure, vessel radius, viscosity, and vessel length on fluid flow. The second part of the experiment will explore the effects of several variables on the output of a single-chamber pump. Follow the specific guidelines in the exercise for collecting data. As you do so, also try to imagine alternate methods of achieving the same experimental goal.

The primary features on the screen when the program starts are a pair of glass beakers perched atop a simulated electronic device called the equipment control unit, which is used to set experiment parameters and to operate the equipment. When the **Start** button (beneath the left beaker) is clicked, the simulated blood flows from the left beaker (source) to the right beaker (destination) through the connecting tube. Clicking the **Refill** button refills the source beaker after an experimental trial. Experimental parameters can be adjusted by clicking the plus (1) or minus (2) buttons to the right of each display window.

The equipment in the lower part of the screen is called the data collection unit. This equipment records and displays data you accumulate during the experiments. The data set for the first experiment (Radius) is highlighted in the **Data Sets** window. You can add or delete a data set by clicking the appropriate button to the right of the **Data Sets** window. The **Record Data** button at the lower right part of the screen activates automatically after an experimental trial. Clicking the **Delete Line** or **Clear Data Set** buttons erases any data you want to delete.

You will record the data you accumulate in the experimental values grid in the lower middle part of the screen.

Activity: Studying the Effect of Flow Tube Radius on Fluid Flow

Our initial study will examine the effect of flow tube radius on fluid flow.

1. Conduct the initial equipment setup.
 - The **Radius** line in the data collection unit should be highlighted in bright blue. If it is not, choose it by clicking the **Radius** line. The data collection unit will now record flow variations due to changing flow tube radius.

- If the data grid is not empty, click **Clear Data Set** to discard all previous values.
 - If the left beaker is not full, click **Refill**.
2. Adjust the flow tube radius to 1.5 mm and the viscosity to 1.0 by clicking the appropriate plus or minus button. During the course of this part of the experiment, maintain the other experiment conditions at:
 100 mm Hg driving pressure (top left)
 50 mm flow tube length (middle right)
3. Click **Start** and watch the fluid move into the right beaker. (Fluid moves slowly under some conditions—be patient!) Pressure (currently set to 100 mm Hg) propels fluid from the left beaker to the right beaker through the flow tube. The flow rate is displayed in the Flow window when the left beaker has finished draining. Now click **Record Data** to display the flow rate and experiment parameters in the experimental values grid (and retain the data in the computer's memory for printing and saving). Click **Refill** to replenish the left beaker.
4. Increase the radius in 0.5 mm increments and repeat step 3 until the maximum radius (6.0 mm) is achieved. Be sure to click **Record Data** after each fluid transfer. If you make an error and want to delete a data value, click the data line in the experimental values grid and then click **Delete Line**.

What happened to fluid flow as the radius of the flow tube was increased?

Because fluid flow is proportional to the fourth power of the radius, _____ changes in tube radius cause _____ changes in fluid flow.

Is the relationship between fluid flow and flow tube radius linear or exponential?

In this experiment, a simulated motor changes the diameter of the flow tube. Explain how our blood vessels alter blood flow.

After a heavy meal when we are relatively inactive, we might expect blood vessels in the skeletal muscles to be somewhat _____, whereas blood vessels in the digestive organs are probably _____.

Activity: Studying the Effect of Viscosity on Fluid Flow

With a viscosity of 3 to 4, blood is much more viscous than water (1.0 viscosity). Although viscosity is altered by factors such as dehydration and altered blood cell numbers, a body in homeostatic balance has a relatively stable blood

consistency. Nonetheless it is useful to examine the effects of viscosity changes on fluid flow, because we can then predict what might transpire in the human cardiovascular system under certain homeostatic imbalances.

1. Set the starting conditions as follows:
 - 100 mm Hg driving pressure
 - 5.0 mm flow tube radius
 - 1.0 viscosity
 - 50 mm flow tube length
2. Click the **Viscosity** data set in the data collection unit. (This action prepares the experimental values grid to record the viscosity data.)
3. **Refill** the left beaker if you have not already done so.
4. Click **Start** to begin the experiment. After all the fluid has drained into the right beaker, click **Record Data** to record this data point, and then click **Refill** to replenish the left beaker.
5. In 1.0 unit increments, increase the fluid viscosity and repeat step 4 until the maximum viscosity (10.0) is reached.

How does fluid flow change as viscosity is modified?

Is fluid flow versus viscosity an inverse or direct relationship?

How does the effect of viscosity compare with the effect of radius on fluid flow?

Predict the effect of anemia (e.g., fewer red blood cells than normal) on blood flow.

What might happen to blood flow if we increased the number of blood cells?

Explain why changing blood viscosity would or would not be a reasonable method for the body to control blood flow.

Blood viscosity would _____ in conditions of dehydration, resulting in _____ blood flow.

Activity: Studying the Effect of Flow Tube Length on Fluid Flow

With the exception of the normal growth that occurs until the body reaches full maturity, blood vessel length does not significantly change. By conducting this part of the exercise, we will be able to understand the physical relationship between vessel length and blood movement by observing how blood flow changes in flow tubes (vessels) of constant radius, but of different lengths.

1. Set the starting conditions as follows:
 - 100 mm Hg driving pressure
 - 5.0 mm flow tube radius
 - 3.5 viscosity
 - 10 mm flow tube length
2. Click the **Length** data set in the data collection unit. (This action prepares the experimental values grid to display the length data.)
3. **Refill** the left beaker if you have not already done so.
4. Click **Start** to begin the experiment. After all the fluid has drained into the right beaker, click **Record Data** to record this data point, and then click **Refill** to refill the left beaker.
5. In 5 mm increments, increase the flow tube length by clicking the plus button next to the length window and repeat step 4 until the maximum length (50 mm) has been reached.

How does flow tube length affect fluid flow?

Explain why altering blood vessel length would or would not be a good method of controlling blood flow in the body.

Activity: Studying the Effect of Pressure on Fluid Flow

The pressure difference between the two ends of a blood vessel is the driving force behind blood flow. In comparison, our experimental setup pressurizes the left beaker, thereby providing the driving force that propels fluid through the flow tube to the right beaker. You will examine the effect of pressure on fluid flow in this part of the experiment.

1. Set the starting conditions as follows:
 - 25 mm Hg driving pressure
 - 5.0 mm flow tube radius
 - 3.5 viscosity
 - 50 mm flow tube length
2. Click the **Pressure** data set in the data collection unit. (This action prepares the experimental values grid for the pressure data.)
3. **Refill** the left beaker if you have not already done so.
4. Click **Start** to begin the experiment. After all the fluid has moved into the right beaker, click **Record Data** to record this data point. Click **Refill** to refill the left beaker.
5. In 25 mm Hg increments, increase the driving pressure by clicking the plus button next to the pressure window and repeat step 4 until the maximum pressure (225 mm Hg) has been reached.

How does driving pressure affect fluid flow?

How does this plot differ from the others?

Although changing pressure could be used as a means of blood flow control, explain why this approach would not be as effective as altering blood vessel radius.

Pump Mechanics

In the human body, the heart beats approximately 70 strokes each minute. Each heart beat consists of a filling interval during which blood moves into the chambers of the heart, and an ejection period when blood is actively pumped into the great arteries. The pumping activity of the heart can be described in terms of the phases of the cardiac cycle. Heart chambers fill during **diastole** (relaxation of the heart) and pump blood out during **systole** (contraction of the heart). As you can imagine, the length of time the heart is relaxed is one factor that determines the amount of blood within the heart at the end of the filling interval. Up to a point, increasing ventricular filling time results in a corresponding increase in ventricular volume. The volume in the ventricles at the end of diastole, just before cardiac contraction, is called the **end diastolic volume**, or **EDV**.

Blood moves from the heart into the arterial system when systolic pressure increases above the residual pressure (from the previous systole) in the great arteries leaving the heart. Although ventricular contraction causes blood ejection, the heart does not empty completely. As a result, a small quantity of blood (**end systolic volume**, or **ESV**) remains in the ventricles at the end of systole.

Because the oxygen requirements of body tissue change depending on activity levels, we would expect the **cardiac output** (amount of blood pumped by each ventricle per minute) to vary correspondingly. We can calculate the stroke volume (amount of blood pumped per contraction of each ventricle) by subtracting the end systolic volume from the end diastolic volume ($SV = EDV - ESV$). It is possible to then compute cardiac output by multiplying the stroke volume by heart rate.

The human heart is a complex four-chambered organ, consisting of two individual pumps (the right and left sides) connected together in series. The right heart pumps blood through the lungs into the left heart, which in turn delivers blood to the systems of the body. Blood then returns to the right heart to complete the circuit.

Using the **Pump Mechanics** part of the program you will explore the operation of a simple one-chambered pump, and apply the physical concepts gained in the simulation to the operation of either of the two pumps comprising the human heart.

In this experiment you can vary the starting and ending volumes of the pump (analogous to EDV and ESV, respectively), driving and resistance pressures, and the diameters of the flow tubes leading to and from the pump chamber. As you proceed through the exercise, try to apply the ideas of ESV, EDV, cardiac output, stroke volume, and blood flow to the on-screen simulated pump system. For example, imagine that the flow tube leading to the pump from the left represents the pulmonary veins, while the flow tube exiting the pump to the right represents the aorta. The pump would then represent the left side of the heart.

Select **Pump Mechanics** from the Experiment menu. The equipment for the Pump Mechanics part of the experiment will become visible within a moment.

As you discovered in the previous experiment, there are two simulated electronic control units on the computer's screen. The upper apparatus is the *equipment control unit*, which is used to adjust experiment parameters and to operate the equipment. The lower apparatus is the *data collection unit*, in which you will record the data you accumulate during the course of the experiment.

This equipment is slightly different than that used in the Vessel Resistance experiment. There are two beakers: the *source* beaker on the left and the *destination* beaker on the right. The pressure in each beaker is individually controlled by the small pressure units on top of the beakers. Between the two beakers is a simple pump, which can be thought of as one side of the heart, or even as a single ventricle (e.g., left ventricle). The left beaker and flow tube are analogous to the venous side of human blood flow, while arterial circulation is simulated by the right flow tube and beaker. One-way valves in the flow tubes supplying the pump ensure fluid movement in one direction—from the left beaker into the pump, and then into the right beaker. If you imagine that the pump represents the left ventricle, then think of the valve to the left of the pump as the bicuspid valve and the valve to the right of the pump as the aortic semilunar valve. The pump is driven by a pressure unit mounted on its cap. An important distinction between the pump's pressure unit and the pressure units atop the beakers is that the pump only delivers pressure during its downward stroke. Upward pump strokes are driven by pressure from the left beaker (the pump does not exert any resistance to flow from the left beaker during pump filling). In contrast, pressure in the right beaker works against the pump pressure, which means that the net pressure driving the fluid into the right beaker is calculated (automatically) by subtracting the right beaker pressure from the pump pressure. The resulting pressure difference between the pump and the right beaker is displayed in the experimental values grid in the data collection unit as **Pres.Dif.R.**

Clicking the **Auto Pump** button will cycle the pump through the number of strokes indicated in the Max. strokes window. Clicking the **Single** button cycles the pump through one stroke. During the experiment, the pump and flow rates are automatically displayed when the number of pump strokes is 5 or greater. The radius of each flow tube is individually controlled by clicking the appropriate button. Click the plus button to increase flow tube radius or the minus button to decrease flow tube radius.

The pump's stroke volume (the amount of fluid ejected in one stroke) is automatically computed by subtracting its ending volume from the starting volume. You can adjust starting and ending volumes, and thereby stroke volume, by clicking the appropriate plus or minus button in the equipment control unit.

The data collection unit records and displays data you accumulate during the experiments. The data set for the first experiment (**Rad.R.**, which represents right flow tube radius) is highlighted in the **Data Sets** window. You can add or delete a data set by clicking the appropriate button to the right of the **Data Sets** window. Clicking **Delete Data Set** will erase the data set itself, including all the data it contained. The **Record Data** button at the right edge of the screen activates automatically after an experimental trial. When clicked, the **Record**

Data button displays the flow rate data in the experimental values grid and saves it in the computer's memory. Clicking the **Delete Line** or **Clear Data Set** button erases any data you want to delete.

You will record the data you accumulate in the experimental values grid in the lower middle part of the screen.

Activity: Studying the Effects of Radius on Pump Activity

Although you will only be manipulating the radius of the right flow tube in this part of the exercise, try to predict the consequence of altering the left flow tube radius as you collect the experimental data. (Remember that the left flow tube simulates the pulmonary veins and the right flow tube simulates the aorta.)

1. Conduct the initial equipment setup.
 - Click the **Rad.R.** data set to activate it. The data collection unit is now ready to record flow variations due to changing flow tube radius.
 - If the experimental values grid is not empty, click **Clear Data Set** to discard all previous values.
 - If the left beaker is not full, click **Refill**.

2. Adjust the **right** flow tube radius to 2.5 mm, and the **left** flow tube radius to 3.0 mm by clicking and holding the appropriate button. During the entire part of the radius experiment, maintain the other experiment conditions at:

- 40 mm Hg left beaker pressure (this pressure drives fluid into the pump, which offers no resistance to filling)
- 120 mm Hg pump pressure (pump pressure is the driving force that propels fluid into the right beaker)
- 80 mm Hg right beaker pressure (this pressure is the resistance to the pump's pressure)
- 120 ml starting volume (analogous to EDV)
- 50 ml ending volume (analogous to ESV)
- 10 strokes in the Max. strokes window

Notice that the displayed 70 ml stroke volume is automatically calculated. Before starting, click the **Single** button one or two times and watch the pump action.

To be sure you understand how this simple mechanical pump can be thought of as a simulation of the human heart, complete the following statements by circling the correct term within the parentheses:

- a. When the piston is at the bottom of its travel, the volume remaining in the pump is analogous to (EDV, ESV) of the heart.
- b. The amount of fluid ejected into the right beaker by a single pump cycle is analogous to (stroke volume, cardiac output) of the heart.
- c. The volume of blood in the heart just before systole is called (EDV, ESV), and is analogous to the volume of fluid present in the simulated pump when it is at the (top, bottom) of its stroke.

3. Click the **Auto Pump** button in the equipment control unit to start the pump. After the 10 stroke volumes have been delivered, the Flow and Rate

windows will automatically display the experiment results. Now click **Record Data** to display the figures you just collected in the experimental values grid. Click **Refill** to replenish the left beaker.

4. Increase the right flow tube radius in 0.5 mm increments and repeat step 3 above until the maximum radius (6.0 mm) is achieved. Be sure to click **Record Data** after each trial.

The total flow rates you just determined depend on the flow rate into the pump from the left and on the flow rate out of the pump toward the right. Consequently, the shape of the plot is different than what you might predict after viewing the vessel resistance radius graph.

Try to explain why this graph differs from the radius plot in the Vessel Resistance experiment. Remember that the flow rate into the pump did not change, whereas the flow rate out of the pump varied according to your radius manipulations. When you have finished, click the close box at the top of the plot window.

Complete the following statements by circling the correct term within the parentheses.

- a. As the right flow tube radius is increased, fluid flow rate (increases, decreases). This is analogous to (dilation, constriction) of blood vessels in the human body.
- b. Even though the pump pressure remains constant, the pump rate (increases, decreases) as the radius of the right flow tube is increased. This happens because the resistance to fluid flow is (increased, decreased).
Apply your observations of the simulated mechanical pump to complete the following statements about human heart function. If you are not sure how to formulate your response, use the simulation to arrive at an answer. Circle the correct term within the parentheses.
- c. The heart must contract (more, less) forcefully to maintain cardiac output if the resistance to blood flow in the vessels exiting the heart is increased.
- d. Increasing the resistance (e.g., a constriction) of the blood vessels entering the heart would (increase, decrease) the time needed to fill the heart chambers.

What do you think would happen to the flow rate and the pump rate if the left flow tube radius is changed (either increased or decreased)?

Activity: Studying the Effect of Stroke Volume on Pump Activity

Whereas the heart of a person at rest pumps about 60% of the blood in its chambers, 40% of the total amount of blood remains in the chambers after systole. The 60% of blood ejected by the heart is called the stroke volume, and is the difference between EDV and ESV. Even though our simple pump in this experiment does not work exactly like the human heart, you can apply the concepts to basic cardiac function. In this experiment, you will examine how the activity of the simple pump is affected by changing the pump's starting and ending volumes.

1. Click the **Str.V.** (stroke volume) data set to activate it. If the experimental values grid is not empty, click **Clear Data Set** to discard all previous values. If the left beaker is not full, click **Refill**.
2. Adjust the stroke volume to 10 ml by setting the Start volume (EDV) to 120 ml and the End volume (ESV) to 110 ml (stroke volume = start volume – end volume). During the entire stroke volume part of the experiment, keep the other experimental conditions at:
 - 40 mm Hg left beaker pressure
 - 120 mm Hg pump pressure
 - 80 mm Hg right beaker pressure
 - 3.0 mm left and right flow tube radius
 - 10 strokes in the Max. strokes window
3. Click the **Auto Pump** button to start the experiment. After 10 stroke volumes have been delivered, the Flow and Rate windows will display the experiment results given the current parameters. Click **Record Data** to display the figures you just collected in the experimental values grid. Click **Refill** to replenish the left beaker.
4. Increase the stroke volume in 10 ml increments (by decreasing the End volume) and repeat step 3 until the maximum stroke volume (120 ml) is achieved. Be sure to click the **Record Data** button after each trial. Watch the pump action during each stroke to see how you can apply the concepts of starting and ending pump volumes to EDV and ESV of the heart.

What happened to the pump's rate as its stroke volume was increased?

Using your simulation results as a basis for your answer, explain why an athlete's resting heart rate might be lower than that of the average person.

Applying the simulation outcomes to the human heart, predict the effect of increasing the stroke volume on cardiac output (at any given rate).

When heart rate is increased, the time of ventricular filling is (circle one: increased, decreased), which in turn (increases, decreases) the stroke volume.

What do you think might happen to the pressure in the pump during filling if the valve in the right flow tube became leaky? (Remember that the pump offers no resistance to filling.)

Applying this concept to the human heart, what might occur in the left heart and pulmonary blood vessels if the aortic valve became leaky?

What might occur if the aortic valve became slightly constricted?

In your simulation, increasing the pressure in the right beaker is analogous to the aortic valve becoming (circle one: leaky, constricted).

Activity: Studying Combined Effects

In this section, you will set up your own experimental conditions to answer the following questions. Carefully examine each question and decide how to set experiment parameters to arrive at an answer. You should try to set up your own experimental conditions to formulate a response, but you can examine your previously collected data at any time if you need additional information. As a rule of thumb, record several data points for each question as evidence for your answer (unless the question calls for a single pump stroke).

Click the **Add Data Set** button in the data collection unit. Next, create a new data set called **Combined**. Your newly created data set will be displayed beneath Str.V. Now click the **Combined** line to activate the data set. As you collect the supporting data for the following questions, be sure to click **Record Data** each time you have a data point you wish to keep for your records.

How is the flow rate affected when the right flow tube radius is kept constant (at 3.0 mm) and the left flow tube radius is modified (either up or down)?

How does decreasing left flow tube radius affect pump chamber filling time? Does it affect pump chamber emptying?

You have already examined the effect of changing the pump's end volume as a way of manipulating stroke volume. What happens to flow and pump rate when you keep the end volume constant and alter the start volume to manipulate stroke volume?

Try manipulating the pressure delivered to the left beaker. How does changing the left beaker pressure affect flow rate? (This change would be similar to changing pulmonary vein pressure.)

If the left beaker pressure is decreased to 10 mm Hg, how is pump-filling time affected?

What happens to the pump rate if the filling time is shortened?

What happens to fluid flow when the right beaker pressure equals the pump pressure?

Studying Compensation

Click the **Add Data Set** button in the data collection unit. Next, create a new data set called **Comp**. Your newly created data set will be displayed beneath Combined. Now click the **Comp**. Line to activate the data set. As you collect the supporting data for the following questions, be sure to click **Record Data** each time you have a data point you wish to keep for your records.

Adjust the experimental conditions to the following:

- 40 mm Hg left beaker pressure
- 120 mm Hg pump pressure
- 80 mm Hg right beaker pressure
- 3.0 mm left and right flow tube radius
- 10 strokes in the Max. strokes window
- 120 ml Starting volume
- 50 ml Ending volume

Click **Auto Pump** and then record your flow rate data. Let's declare the value you just obtained to be the "normal" flow rate for the purpose of this exercise.

Now decrease the right flow tube radius to 2.5 mm, and run another trial. How does this flow rate compare with "normal"?

Leave the right flow tube radius at 2.5 mm radius and try to adjust one or more other conditions to return flow to "normal." Think logically about what condition(s) might compensate for a decrease in flow tube radius. How were you able to accomplish this? (Hint: There are several ways.)

Decreasing the right flow tube radius is similar to a partial (circle one: leakage, blockage) of the aortic valve or (increased, decreased) resistance in the arterial system.

Explain how the human heart might compensate for such a condition.

If we wanted to increase (or decrease) blood flow to a particular body system (e.g., digestive), would it be better to adjust heart rate or blood vessel diameter? Explain.

Complete the following statements by circling the correct response. (If necessary, use the pump simulation to help you with your answers.)

- a. If we decreased overall peripheral resistance in the human body (as in an athlete), the heart would need to generate (more, less) pressure to deliver an adequate amount of blood flow, and arterial pressure would be (higher, lower).
- b. If the diameter of the arteries of the body were partly filled with fatty deposits, the heart would need to generate (more, less) force to maintain blood flow, and pressure in the arterial system would be (higher, lower) than normal.

Activity: Printing Your Data

When you have finished with all experiments, you can print your recorded data sets and turn them in if your instructor requests them. Simply go to **Tools**, and select **Print Data**.