Cardiovascular Dynamics

OBJECTIVES

1. To understand the relationships among blood flow, pressure gradient, and resistance
2. To define resistance and describe the main factors affecting resistance
3. To describe Poiseuille's equation and how it relates to cardiovascular dynamics
4. To define diastole, systole, end systolic volume, end diastolic volume, stroke volume, isovolumetric contraction, and ventricular ejection
5. To describe Starling's Law and its application to cardiovascular dynamics
6. To design your own experiments using the lab simulation for pump mechanics
7. To understand what is meant by the term compensation

The cardiovascular system is composed of a pump—the heart—and blood vessels that distribute blood containing oxygen and nutrients to every cell of the body. The principles governing blood flow are the same physical laws that apply to the flow of liquid through a system of pipes. For example, one very elementary law in fluid mechanics is that the flow rate of a liquid through a pipe is directly proportional to the difference between the pressures at the two ends of the pipe (the **pressure gradient**) and inversely proportional to the pipe's **resistance** (a measure of the degree to which the pipe hinders or resists the flow of the liquid):

$$\text{Flow} = \text{pressure gradient/resistance} = \Delta P/R$$

This basic law applies to blood flow as well. The "liquid" is blood, and the "pipes" are blood vessels. The pressure gradient is the difference between the pressure in arteries and that in veins that results when blood is pumped into arteries. Blood flow rate is directly proportional to the pressure gradient, and inversely proportional to resistance.

Recall that resistance is a measure of the degree to which the blood vessel hinders or resists the flow of blood. The main factors governing resistance are 1) blood vessel *radius,* 2) blood vessel *length,* and 3) blood *viscosity.*

Radius. The smaller the blood vessel radius, the greater the resistance, due to frictional drag between the blood and the vessel walls. Contraction, or *vasoconstriction,* of the blood vessel results in a decrease in the blood vessel radius. Lipid deposits can cause the radius of an artery to decrease, preventing blood from reaching the coronary tissue and result in a heart attack. Alternately, relaxation, or *vasodilation,* of the blood vessel causes an increase in the blood vessel radius. As we will see, blood vessel radius is the single most important factor in determining blood flow resistance.

Length. The longer the vessel length, the greater the resistance—again, due to friction between the blood and vessel walls. The length of a person's blood vessels change only as a person grows; otherwise, length generally remains constant.

Viscosity. Viscosity is blood "thickness," determined primarily by *hematocrit*—the fractional contribution of red blood cells to total blood volume. The higher the

hematocrit, the greater the viscosity. Under most physiological conditions, hematocrit does not vary by much, and blood viscosity remains more or less constant.

A fourth factor in resistance is the manner of blood flow. In *laminar* flow, blood flows calmly and smoothly along the length of the vessel. In *turbulent* flow, blood flows quickly and roughly. Most blood flow in the body is laminar, and the experiments we will conduct in this lab focus on laminar flow.

Poiseuille's equation expresses the relationships among blood pressure, vessel radius, vessel length, and blood viscosity on laminar blood flow:

$$\text{Blood flow } (\Delta Q) = \pi \Delta P r^4 / 8 \eta l$$

or

$$\text{Blood flow } (\Delta Q) = \frac{\pi \Delta P r^4}{8 \eta l}$$

where

ΔP = pressure difference between the two ends of the vessel
r = radius of the blood vessel
η = viscosity
l = vessel length

This equation states that changes in pressure, blood vessel radius, viscosity, and vessel length all have an effect on blood flow. Note that the effect of radius (r) on blood flow is especially strong (fluid flow varies with radius to the fourth degree).

The main method of controlling blood flow is via contraction or relaxation of the smooth muscle found in the tunica media of an artery. When contracted, the radius of the artery becomes much smaller, resulting in more resistance to blood flow within the artery. The smaller arteries and arterioles that regulate blood flow throughout the body are referred to as *resistance vessels* and are very important to maintaining arterial blood pressure. If all blood vessels were to completely relax, blood pressure would fall to very dangerous levels. It is also known that the lining of arteries, the *endothelium,* releases nitric oxide in response to rapid flow in the vessel. The nitric oxide causes a dilation of the artery that reduces the shear stress.

In our first experiment, we will take a closer look at how pressure, vessel radius, blood viscosity, and vessel length affect blood flow.

Vessel Resistance

Follow the instructions in the Getting Started section at the front of this manual for starting PhysioEx 7.0. From the main menu, select the fifth lab, **Cardiovascular Dynamics.** The opening screen for the "Vessel Resistance" activity will appear (see Figure 5.1).

Notice the two glass beakers and the tube connecting them. Imagine that the left beaker is your heart, the tube is an artery, and the right beaker is a destination in your body, such as another organ. Clicking the **Start** button underneath the left beaker will cause blood to begin flowing from the left beaker to the right beaker. You may adjust the radius of the tube, the viscosity of the blood, or the length of the tube by adjusting the (+) and (−) buttons next to the corresponding displays.

You may also adjust the pressure by clicking the (+) and (−) buttons for pressure on top of the left beaker. Clicking **Refill** will empty the right beaker and refill the left beaker.

At the bottom of the screen is a data recording box. Clicking **Record Data** after an experimental run will record that run's data in the box.

The Effect of Pressure on Blood Flow

$$\text{Blood flow } (\Delta Q) = \frac{\pi \Delta P r^4}{8 \eta l}$$

Recall that ΔP in Poiseuille's equation stands for the difference in pressure between the two ends of a vessel, or the pressure gradient. In order to study the pressure gradient, you will observe how blood flows at a given pressure, then change the pressure to observe the effects of the change on the blood flow.

1. Set the **Pressure** to 25 mm Hg by clicking the (−) button on top of the left beaker.

2. Set the **Radius** of the tube to 6.0 mm.

3. Set the blood **Viscosity** to 3.5.

4. Set the vessel **Length** to 50 mm.

5. Highlight the **Pressure** data set by clicking the word Pressure in the box at the bottom left of your screen.

6. Make sure the left beaker is filled with blood. If not, click **Refill.**

7. Click **Start.**

8. When the right beaker is full, click **Record Data.** Your data will appear in the data recording box.

9. Click **Refill.**

10. Increase the **Pressure** by 25 mm Hg (that is, set it to 50 mm Hg.) Leave the radius, viscosity, and length settings the same. Click **Start** again, and click **Record Data** once the right beaker is full. Click **Refill.**

11. Continue repeating the experiment, increasing the **Pressure** by 25 mm Hg each time, until you have reached 225 mm Hg. Remember to click **Record Data** after each run.

12. Now click **Tools** at the top of the screen. A drop-down menu will appear. Highlight **Plot Data** and click it. You will see your data appear in a data plot. Note that there are two slide bars: one for the X-axis and one for the Y-axis. Set the slide bar for the X-axis to "Pressure" and the slide bar for the Y-axis to "Flow." You may wish to print the data plot by clicking **Print Plot** at the top left of the plot data window. Click the "X" at the top right of the plot data screen to close the window.

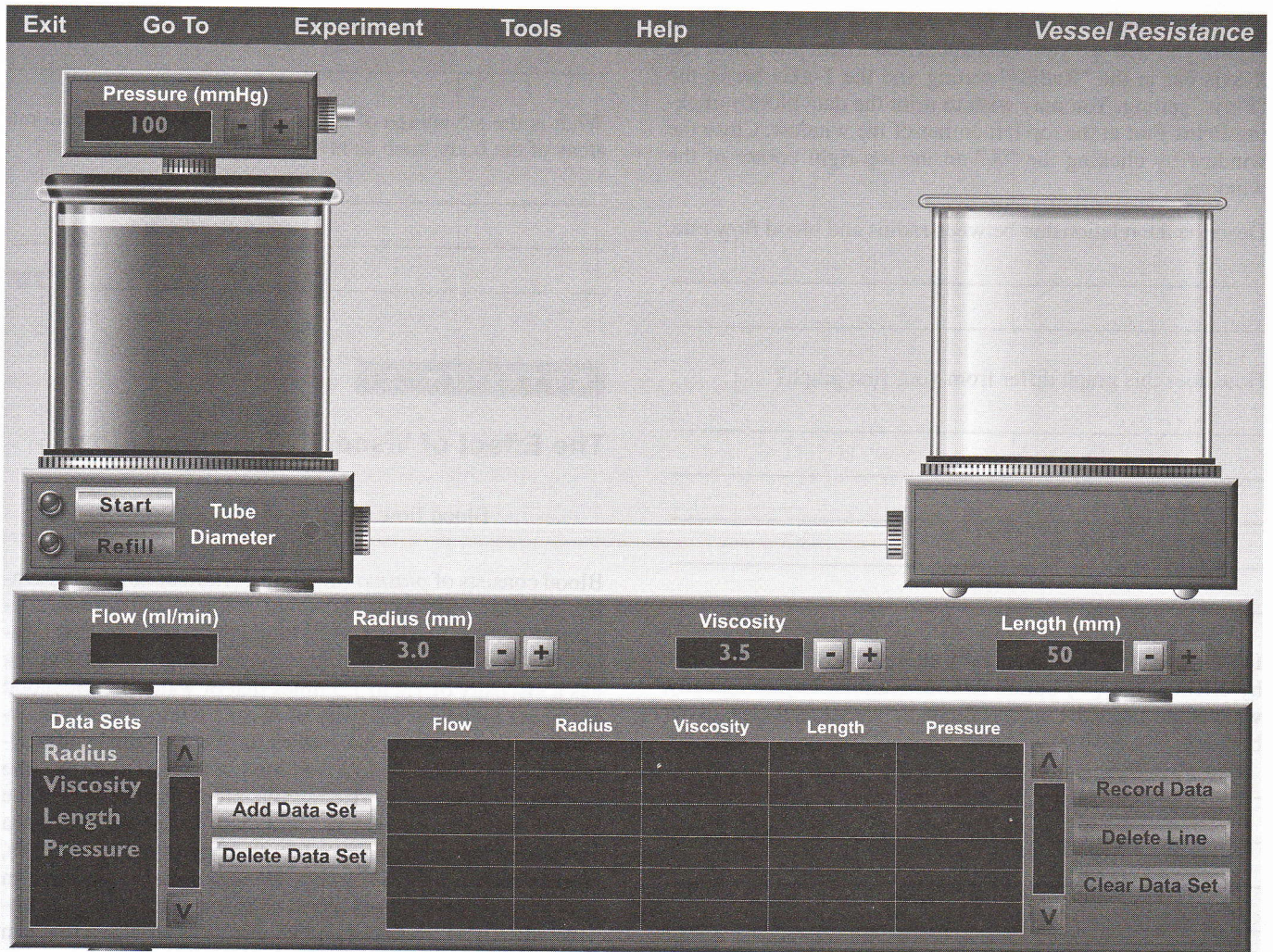Describe the relationship between pressure and blood flow.

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FIGURE 5.1   Opening screen of the Vessel Resistance experiment.

What kind of change in the cardiovascular system would result in a pressure change?

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Why would such a change cause problems?

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The Effect of Vessel Radius on Blood Flow

$$\text{Blood flow } (\Delta Q) = \frac{\pi \Delta P r^4}{8\eta l}$$

The next parameter of Poiseuille's equation we examine is vessel radius. In the equation, this parameter is taken to the fourth power (r^4). This means that a small change in vessel radius can result in a large alteration in blood flow.

1.   At the lower left corner of the screen, under "Data Sets," click **Radius.**

2.   Be sure that the left beaker is full. If not, click **Refill.**

3.   Set the **Pressure** to 100 mm Hg.

4.   Set the vessel **Length** to 50 mm.

5.   Set the blood **Viscosity** to 1.0.

6.   Set the **Radius** of the tube to 1.5 mm.

7.   Click **Start** and allow the blood to travel from the left beaker to the right beaker. When the blood has completely transferred to the right beaker, click **Record Data.**

8.   Increase the radius of the tube by 1.0 mm (set it to 2.5 mm) and repeat the experiment. Leave all the other settings the same. Continue repeating the experiment until you reach the maximum radius setting of 6.0 mm. Be sure to click **Refill** and **Record Data** after each run.

9.   Click **Tools** on top of the screen and select **Plot Data.** Again, you will see your data appear on a data plot. Slide the X-axis bar to the "Radius" setting and the Y-axis bar to the "Flow" setting. You may wish to print the data plot by clicking **Print Plot** at the top left corner of the window. Close the window by clicking the "X" on the top right corner of the window.

Describe the relationship between radius and blood flow rate.

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How does this graph differ from your first graph?

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In this activity, we mechanically altered the radius of the tube by clicking the (+) button next to **Radius.** Physiologically, what could cause the radius of a blood vessel to change in our bodies?

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In a clogged artery, what has happened to the radius of the artery? How has this affected blood flow? What could be done to fix this condition?

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When a blood vessel bifurcates (splits) into two smaller vessels, the radii of the two smaller vessels add up to a larger cumulative radius than the radius of the original vessel. However, blood flow is slower in the two vessels than in the original. Why?

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What is the advantage of having slower blood flow in some areas of the body, such as in the capillaries of our fingers?

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The Effect of Viscosity on Blood Flow

$$\text{Blood flow } (\Delta Q) = \frac{\pi \Delta P r^4}{8 \eta l}$$

Blood consists of *plasma* (the fluid portion of blood, containing proteins, nutrients, and other solutes) and *formed elements* (including red and white blood cells and platelets). Viscosity is a measurement of the "thickness" of blood. Plasma has a viscosity of 1.2 to 1.3 times that of water. Whole blood has about twice the viscosity of plasma alone. Blood viscosity depends mainly on *hematocrit*, or the fractional contribution of red blood cells to total blood volume. The higher the hematocrit, the more viscous the blood is; the lower the hematocrit, the less viscous the blood. In severe *anemia*, a condition characterized by a low number of red blood cells, blood viscosity is low. In *polycythemia vera*, a condition in which the number of red blood cells increases, there are abnormally high hematocrit counts, resulting in blood that can be twice as viscous as normal.

1.   Set the **Pressure** to 100 mg Hg.

2.   Set the vessel **Radius** to 6.00 mm.

3.   Set the vessel **Length** to 50 mm.

4.   Set the blood **Viscosity** to 1.0.

5.   Highight **Viscosity** under "Data Sets" at the bottom left corner of the screen.

6.   Make sure that the left beaker is filled with blood. If not, click **Refill.**

7.   Click **Start.** After the blood has completely transferred to the right beaker, click **Record Data** and then **Refill.**

8.   Increase the **Viscosity** value by 1.0 and repeat the experiment. Leave all the other settings the same. Continue repeating the experiment until you have reached the maximum viscosity value of 10.0. Remember to click **Record Data** after each run and **Refill.**

9.   Click **Tools** at the top of your screen, and select **Plot Data.**

10. Move the X-axis slide bar to the "Viscosity" setting, and the Y-axis slide bar to the "Flow" setting. You may wish to print your graph by clicking **Print Plot** at the top left corner of the window. Click the "X" at the top right corner to close the window.

Describe the relationship between viscosity and blood flow.

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How does this graph compare to the previous graphs for 1) blood flow and pressure, and 2) blood flow and radius?

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Predict the effect of polycythemia vera on blood flow rate.

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How would blood viscosity alter with dehydration of the body?

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What would happen to blood flow if the body were dehydrated?

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ACTIVITY 4

The Effect of Vessel Length on Blood Flow

$$\text{Blood flow }(\Delta Q) = \frac{\pi \Delta P r^4}{8 \eta l}$$

In this activity we will examine how vessel length (l) affects blood flow. Recall that longer vessels have greater resistance than shorter vessels. Shear forces between the laminar layers increase resistance and lessen flow. In humans, blood vessels change length when the body grows, but otherwise length stays constant.

1. Set the **Pressure** to 100 mm Hg.

2. Set the vessel **Radius** to 6.0.

3. Set the blood **Viscosity** to 3.5.

4. Set the vessel **Length** to 10 mm.

5. Highlight the **Length** data set at the bottom left. Be sure the left beaker is filled with blood; if not, click **Refill**.

6. Click **Start** and allow the fluid to completely transfer from the left beaker to the right beaker. When finished, click on **Record Data.** Then click **Refill.**

7. Increase the vessel **Length** by 10 mm (to 20 mm) and repeat the experiment. Continue to repeat the experiment until you have reached the maximum vessel length of 50 mm. Remember to click **Record Data** and **Refill** after each run.

8. Click **Tools** on top of the screen, then select **Plot Data.** Move the X-axis slide bar to "Length" and the Y-axis slide bar to "Flow." If you wish, click **Print Plot** on the top left of the window to print your graph. Click "X" at the top right of the window to close the window.

Describe the relationship between vessel length and blood flow.

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Why is vessel radius a more important factor in controlling blood flow resistance than vessel length?

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To print the data from the data recording box, click **Tools** on top of the screen and then select **Print Data.** ▮▮▮

Pump Mechanics

The heart is an intermittent pump. The right side of the heart pumps blood to the lungs so that blood can take up oxygen. This blood is then returned to the heart, pumped by the left side of the heart to the rest of the body, and then returned to the right side of the heart again. This *cardiac cycle* happens in one heartbeat, and involves both contraction and relaxation. Blood moves into the right atrium of the heart from the vena cavae (*superior vena cava* from the head and *inferior vena cava* from the rest of the body). On the left side of the heart, blood is returned to the heart by the pulmonary veins coming from the lungs. During **diastole** (when the ventricles are relaxed), the blood entering the atria flow through the atrioventricular valves into the ventricles. The blood volume in the ventricles at the end of diastole is referred to as the **end diastolic volume** (EDV). When the atria begin to contract, the ventricles begin to contract, or enter **systole.**

At the start of systole, the pressure within the ventricles rises, due to the force of the myocardial (*myocardium* is cardiac muscle mass) walls on the enclosed blood. This rise in pressure closes the atrioventricular valves, yet is not enough
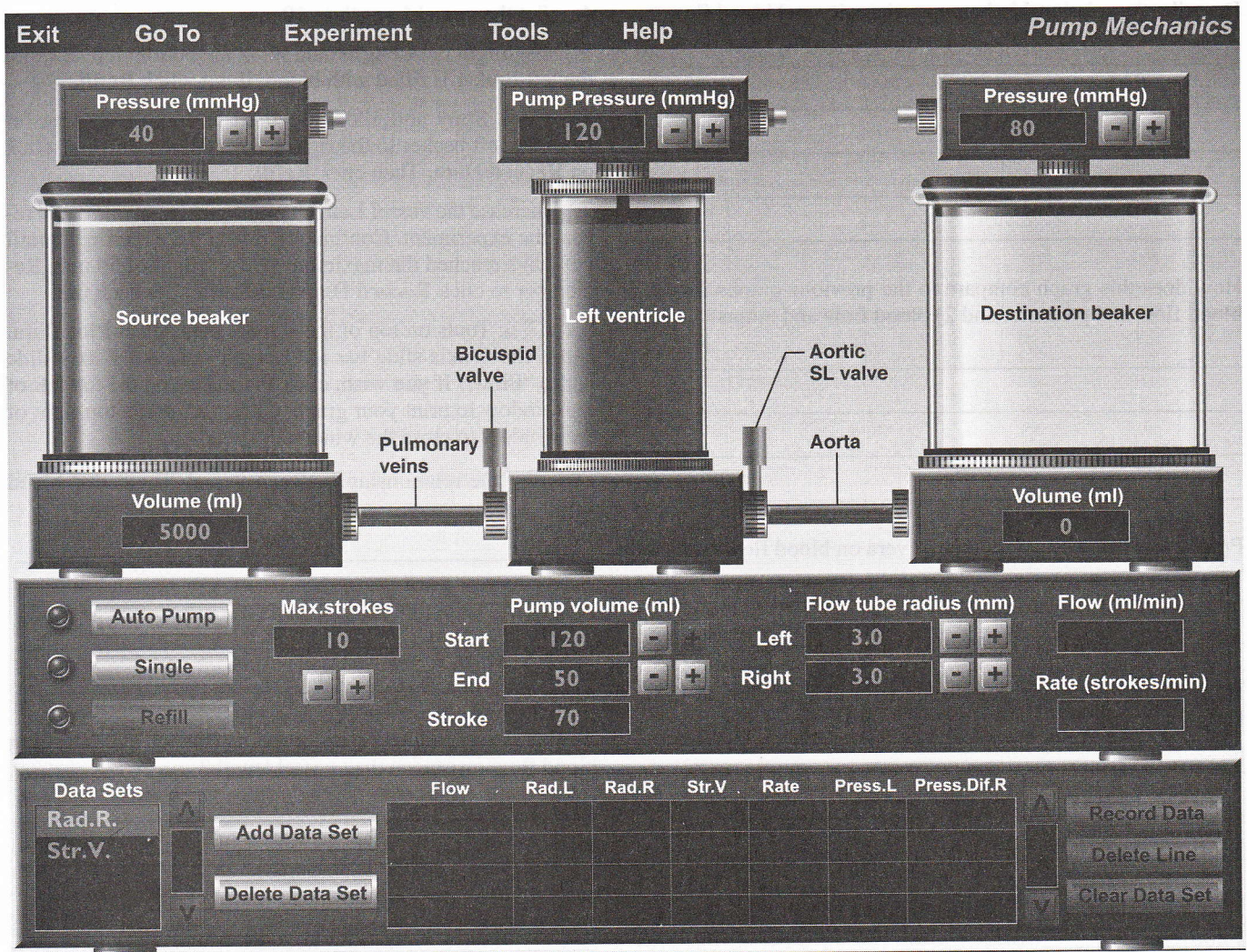
FIGURE 5.2 Opening screen of the Pump Mechanics experiment with labels added.

to force the semilunar valves (going to the pulmonary trunk and aorta) to open. Because the blood is contained within the ventricles and the volume of blood remains constant, this is termed **isovolumetric contraction.** This ends as the pressure within the ventricles rises, so that the semilunar valves are forced open to allow the blood to leave. During the remainder of systole, the blood is forced into the pulmonary trunk and aorta, and ventricular volume falls. This ejection of blood is termed **ventricular ejection,** during which ventricular pressure rises and then begins to decline. When ventricular pressure falls below aortic pressure, the semilunar valves close, ending systole. At the end of ejection, a volume of blood approximately equal to that ejected during systole remains. This volume is referred to as the **end systolic volume** (ESV). This residual volume is fairly constant unless heart rate has increased or vessel resistance has fallen.

Cardiac output is the amount of blood each ventricle pumps per minute. During exercise, tissues need more oxygen and send neural signals to the heart to increase the heart rate. During this same exercise, respiration increases so that there is plenty of oxygen to oxygenate the blood. The changes in the thoracic cavity caused by increased respiration (especially inspiration) cause an increase in the blood returned to the heart.

Starling's Law states that when the rate at which blood returns to the heart changes, the heart will adjust its output to match the change in inflow. As more blood is returned to the heart, the amount of blood pumped to the body per contraction per ventricle (**stroke volume**) increases. Thus, exercise leads to an increase in the stroke volume of the heart. By definition, cardiac output is the stroke volume times the number of heart beats per minute. A "normal" stroke volume is 70 ml and, with a heart rate of 75 beats per minute, the cardiac output is a little over 5 liters per minute. This is the approximate volume of blood in the body. The heart pumps this entire volume of blood in the body each minute of life.

Select **Pump Mechanics** from the **Experiment** menu at the top of the screen. Figure 5.2 shows the opening screen with labels added. There are now three beakers on screen. Imagine that the left-most beaker represents blood coming from the lungs; the middle beaker represents the left side of your heart (simplified here as a single pump); and the right-most beaker represents the rest of your body, to where blood must be delivered. In between the first two beakers is a flow tube (or vessel), analogous to a vein. In between the second and third beakers is another flow tube (or vessel), analogous to an artery. One-way valves in the flow tubes ensure that