

Respiratory System Mechanics



Objectives

1. To explain how the respiratory and circulatory systems work together to enable gas exchange among the lungs, blood, and body tissues
2. To define **respiration**, **ventilation**, **alveoli**, **diaphragm**, **inspiration**, **expiration**, and **partial pressure**
3. To explain the differences between **tidal volume**, **inspiratory reserve volume**, **expiratory reserve volume**, **vital capacity**, **residual volume**, **total lung capacity**, **forced vital capacity**, **forced expiratory volume**, and **minute respiratory volume**
4. To list various factors that affect respiration
5. To explain how **surfactant** works in the lungs to promote respiration
6. To explain what happens in **pneumothorax**
7. To explain how **hyperventilation**, **rebreathing**, and **breathholding** affect respiratory volumes

The physiological functions of respiration and circulation are essential to life. If problems develop in other physiological systems, we can still survive for some time without addressing them. But if a persistent problem develops within the respiratory or circulatory systems, death can ensue within minutes.

The primary role of the respiratory system is to distribute oxygen to, and remove carbon dioxide from, the cells of the body. The respiratory system works hand in hand with the circulatory system to achieve this. The term **respiration** includes *breathing*—the movement of air in and out of the lungs, also known as **ventilation**—as well as the transport (via blood) of oxygen and carbon dioxide between the lungs and body tissues. The heart pumps deoxygenated blood to pulmonary capillaries, where gas exchange occurs between blood and **alveoli** (air sacs in the lungs), oxygenating the blood. The heart then pumps the oxygenated blood to body tissues, where oxygen is used for cell metabolism. At the same time, carbon dioxide (a waste product of metabolism) from body tissues diffuses into the blood. The deoxygenated blood then returns to the heart, completing the circuit.

Ventilation is the result of muscle contraction. The **diaphragm**—a dome-shaped muscle that divides the thoracic and abdominal cavities—contracts, making the thoracic cavity larger. This reduces the pressure within the thoracic

cavity, allowing atmospheric gas to enter the lungs (a process called **inspiration**). When the diaphragm relaxes, the pressure within the thoracic cavity increases, forcing air out of the lungs (a process called **expiration**). Inspiration is considered an “active” process because muscle contraction requires the use of ATP, whereas expiration is usually considered a “passive” process. When a person is running, however, the *external intercostal muscles* contract and make the thoracic cavity even larger than with diaphragm contraction alone, and expiration is the result of the *internal intercostal muscles* contracting. In this case, both inspiration and expiration are considered “active” processes, since muscle contraction is needed for both. Intercostal muscle contraction works in conjunction with diaphragm muscle contraction.

Respiratory Volumes

Ventilation is measured as the frequency of breathing multiplied by the volume of each breath, called the **tidal volume**. Ventilation is needed to maintain oxygen in arterial blood and carbon dioxide in venous blood at their normal levels—that is, at their normal **partial pressures**. [The term *partial pressure* refers to the proportion of pressure that a single gas exerts within a mixture. For example, in the atmosphere at sea level, the pressure is 760 mm Hg. Oxygen makes up about 20% of the total atmosphere and therefore has a partial pressure (P_{O_2}) of $760 \text{ mm Hg} \times 20\%$, close to 160 mm Hg.]

Oxygen diffuses down its partial pressure gradient to flow from the alveoli of the lungs into the blood, where the oxygen attaches to hemoglobin (meanwhile, carbon dioxide diffuses from the blood to the alveoli). The oxygenated blood is then transported to body tissues, where oxygen again diffuses down its partial pressure gradient to leave the blood and enter the tissues. Carbon dioxide (produced by the metabolic reactions of the tissues) diffuses down its partial pressure gradient to flow from the tissues into the blood for transport back to the lungs. Once in the lungs, the carbon dioxide follows its partial pressure gradient to leave the blood and enter the air in the alveoli for export from the body.

Normal tidal volume in humans is about 500 milliliters. If one were to breathe in a volume of air equal to the tidal volume and then continue to breathe in as much air as possible, that amount of air (above and beyond the tidal volume) would equal about 3100 milliliters. This amount of air is called the **inspiratory reserve volume**. If one were to breathe *out* as much air as possible beyond the normal tidal volume, that amount of air (above and beyond the tidal volume) would equal about 1200 milliliters. This amount of air is called the **expiratory reserve volume**. Tidal volume, inspiratory reserve volume, and expiratory reserve volume together consti-

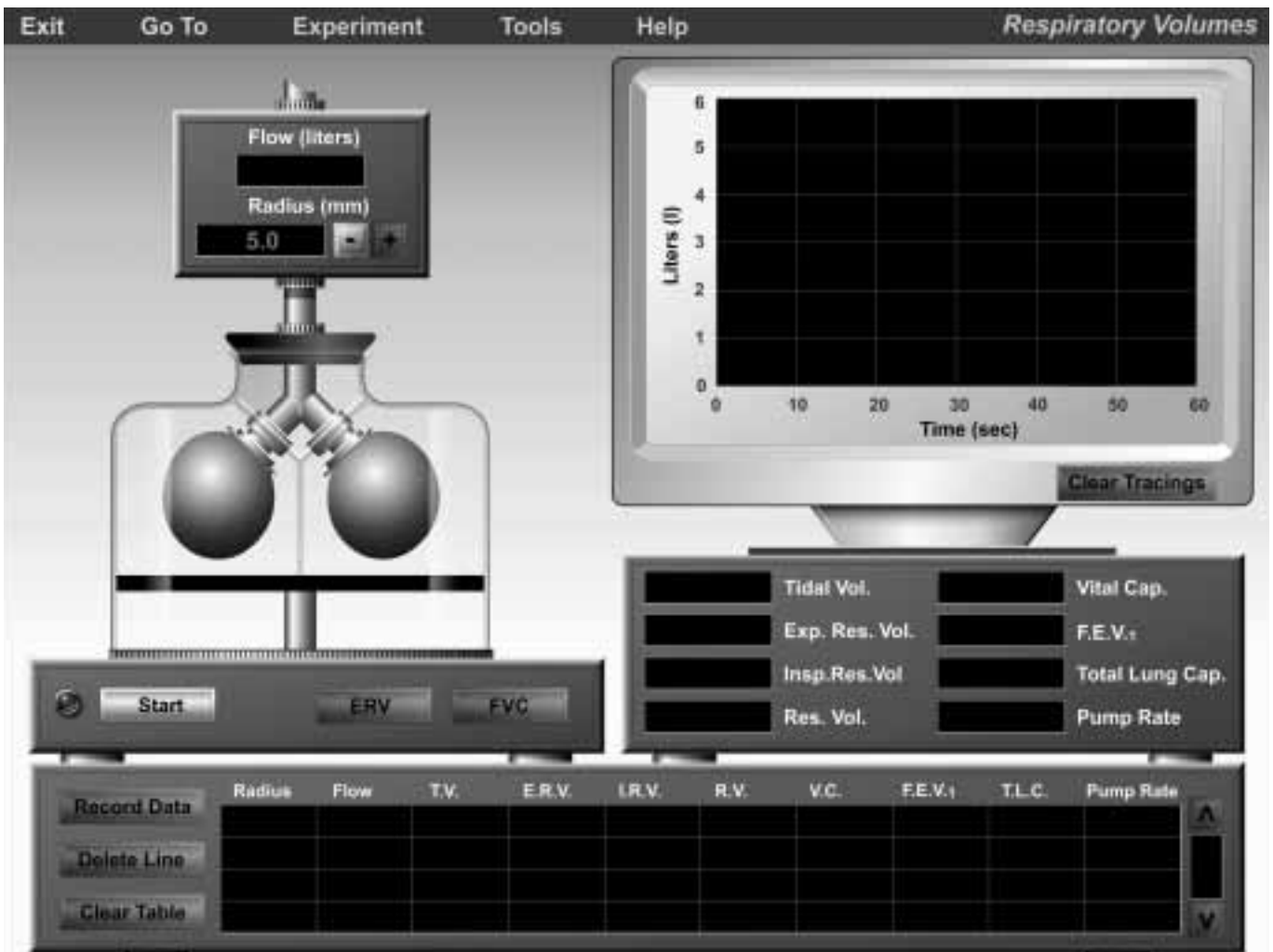


Figure 7.1 Opening screen of the Respiratory Volumes experiment.

tute the **vital capacity**, about 4800 milliliters. It is important to note that the histological structure of the respiratory tree (where air is found in the lungs) will not allow *all* air to be breathed out of the lungs. The air remaining in the lungs after a complete exhalation is called the **residual volume**, normally about 1200 milliliters. Therefore, the **total lung capacity** (the vital capacity volume plus the residual volume) is approximately 6000 milliliters.

All of these volumes can be easily measured using a *spirometer*. Basically, a spirometer is composed of an inverted bell in a water tank. A breathing tube is connected to the bell's interior. On the exterior of the inverted bell is attached a pen device that records respiratory volumes on paper. When one exhales into the breathing tube, the bell goes up and down with exhalation. Everything is calibrated so that respiratory volumes can be read directly from the paper record. The paper moves at a pre-set speed past the recording pen so that volumes per unit time can be easily calculated. In addition to measuring the respiratory volumes introduced so far, the spirometer can also be used to perform pulmonary function tests. One such test is the **forced vital capacity**

(**FVC**), or the amount of air that can be expelled completely and as rapidly as possible after taking in the deepest possible breath. Another test is the **forced expiratory volume (FEV₁)**, which is the percentage of vital capacity that is exhaled during a 1-sec period of the FVC test. This value is generally 75% to 85% of the vital capacity.

In the following experiments you will be simulating spirometry and measuring each of these respiratory volumes using a pair of mechanical lungs. Follow the instructions in the "Getting Started" section at the front of this lab manual to start up PhysioEx. From the Main Menu, select **Respiratory System Mechanics**. You will see the opening screen for the "Respiratory Volumes" experiment (Figure 7.1). At the left is a large vessel (simulating the thoracic cavity) containing an *air flow tube*. This tube looks like an upside-down "Y." At the ends of the "Y" are two spherical containers, simulating the lungs, into which air will flow. On top of the vessel are controls for adjusting the radius of the tube feeding the "lungs." This tube simulates the trachea and other air passageways into the lungs. Beneath the "lungs" is a black platform simulating the diaphragm. The "diaphragm" will move down, sim-

ulating contraction and increasing the volume of the “thoracic cavity” to bring air into the “lungs”; it will then move up, simulating relaxation and decreasing the volume of the “thoracic cavity” to expel air out. At the bottom of the vessel are three buttons: a **Start** button, an **ERV** (expiratory reserve volume) button, and an **FVC** (forced vital capacity) button. Clicking **Start** will start the simulated lungs breathing at normal tidal volume; clicking **ERV** will cause the lungs to exhale as much air as possible beyond the tidal volume; and clicking **FVC** will cause the lungs to expel the most air possible after taking the deepest possible inhalation.

At the top right is an oscilloscope monitor, which will graphically display the respiratory volumes. Note that the *Y*-axis displays liters instead of milliliters. The *X*-axis displays elapsed time, with the length of the full monitor displaying 60 seconds. Below the monitor is a series of data displays. A data recording box runs along the bottom length of the screen. Clicking **Record Data** after an experimental run will record your data for that run on the screen.

Activity 1: Trial Run

Let’s conduct a trial run to get familiarized with the equipment.

1. Click the **Start** button (notice that it immediately turns into a **Stop** button). Watch the trace on the oscilloscope monitor, which currently displays normal tidal volume. Watch the simulated diaphragm rise and fall, and notice the “lungs” growing larger during inhalation and smaller during exhalation. The **Flow** display on top of the vessel tells you the amount of air (in liters) being moved in and out of the lungs with each breath.
2. When the trace reaches the right side of the oscilloscope monitor, click the **Stop** button and then click **Record Data**. Your data will appear in the data recording box along the bottom of the screen. This line of data tells you a wealth of information about respiratory mechanics. Reading the data from left to right, the first data field should be that of the *Radius* of the air flow tube (5.00 mm). The next data field, *Flow*, displays the total flow volume for this experimental run. *T.V.* stands for “Tidal Volume”; *E.R.V.* for “Expiratory Reserve Volume”; *I.R.V.* for “Inspiratory Reserve Volume”; *R.V.* for “Residual Volume”; *V.C.* for “Vital Capacity”; *FEV₁* for “Forced Expiratory Volume”; *T.L.C.* for “Total Lung Capacity”; and finally, *Pump Rate* for the number of breaths per minute.
3. You may print your data at any time by clicking **Tools** at the top of the screen and then **Print Data**. You may also print the trace on the oscilloscope monitor by clicking **Tools** and then **Print Graph**.
4. Highlight the line of data you just recorded by clicking it and then click **Delete Line**.

5. Click **Clear Tracings** at the bottom right of the oscilloscope monitor. You are now ready to begin the first experiment. ■

Activity 2: Measuring Normal Respiratory Volumes

1. Make sure that the radius of the air flow tube is at 5.00 mm. To adjust the radius, click the (+) or (–) buttons next to the radius display.
2. Click the **Start** button. Watch the oscilloscope monitor. When the trace reaches the 10-second mark on the monitor, click the **ERV** button to obtain the expiratory reserve volume.
3. When the trace reaches the 30-second mark on the monitor, click the **FVC** to obtain the forced vital capacity.
4. Once the trace reaches the end of the screen, click the **Stop** button, then click **Record Data**.
5. Remember, you may print your trace or your recorded data by clicking **Tools** at the top of the screen and selecting either **Print Graph** or **Print Data**.

From your recorded data, you can calculate the **minute respiratory volume**: the amount of air that passes in and out of the lungs in 1 minute. The formula for calculating minute respiratory volume is:

$$\text{Minute respiratory volume} = \text{tidal volume} \times \text{bpm (breaths per minute)}$$

Click **Tools** and then **Calculator**. Calculate and enter the minute respiratory volume: _____

Judging from the trace you generated, inspiration took place over how many seconds? _____

Expiration took place over how many seconds? _____

Does the duration of inspiration or expiration vary during ERV or FVC? _____

6. Click **Clear Tracings** before proceeding to the next activity. Do *not* delete your recorded data—you will need it for the next activity. ■

Activity 3: Effect of Restricted Air Flow on Respiratory Volumes

1. Adjust the radius of the air flow tube to 4.00 mm by clicking the (-) button next to the radius display. Repeat steps 2–5 from the previous activity, making sure to click **Record Data**.

How does this set of data compare to the data you recorded for Activity 2?

Is the respiratory system functioning better or worse than it did in the previous activity? Explain why.

2. Click **Clear Tracings**.
3. Reduce the radius of the air flow tube by another 0.50 mm to 3.50 mm.
4. Repeat steps 2–6 from Activity 2.
5. Reduce the radius of the air flow tube by another 0.50 mm to 3.00 mm.
6. Repeat steps 2–6 from Activity 2.

What was the effect of reducing the radius of the air flow tube on respiratory volumes?

What does the air flow tube simulate in the human body?

What could be some possible causes of reduction in air flow to the lungs?

7. Click **Tools** → **Print Data** to print your data.

Express your FEV₁ data as a percentage of vital capacity by filling out the following chart. (That is, take the FEV₁ value and divide it into the vital capacity value for each line of data.)

Radius	FEV ₁	Vital Capacity	FEV ₁ (%)
5.00			
4.00			
3.50			
3.00			

Factors Affecting Respiration

Many factors affect respiration. *Compliance*, or the ability of the chest wall or lung to distend, is one. If the chest wall or lungs cannot distend, respiratory ability will be compromised. **Surfactant**, a lipid material secreted into the alveolar fluid, is another. Surfactant acts to decrease the surface tension of water in the fluid that lines the walls of the alveoli. Without surfactant, the surface tension of water would cause alveoli to collapse after each breath. A third factor affecting respiration is any injury to the thoracic wall that results in the wall being punctured. Such a puncture would effectively raise the intrathoracic pressure to that of atmospheric pressure, preventing diaphragm contraction from decreasing intrathoracic pressure and, consequently, preventing air from being drawn into the lungs. (Recall that airflow is achieved by the generation of a pressure difference between atmospheric pressure on the outside of the thoracic cavity and intrathoracic pressure on the inside.)

We will be investigating the effect of surfactant in the next activity. Click **Experiment** at the top of the screen and then select **Factors Affecting Respiration**. The opening screen will look like Figure 7.2. Notice the changes to the equipment above the air flow tube. Clicking the **Surfactant** button will add a pre-set amount of surfactant to the “lungs.” Clicking **Flush** will clear the lungs of surfactant. Also notice that valves have been added to the sides of each simulated lung. Opening the valves will allow atmospheric pressure into the vessel (the “thoracic cavity”). Finally, notice the changes to the display windows below the oscilloscope screen. **Flow Left** and **Pressure Left** refer to the flow of air and pressure in the left “lung”; **Flow Right** and **Pressure Right** refer to the flow of air and pressure in the right “lung.” **Total Flow** is the sum of Flow Left and Flow Right.

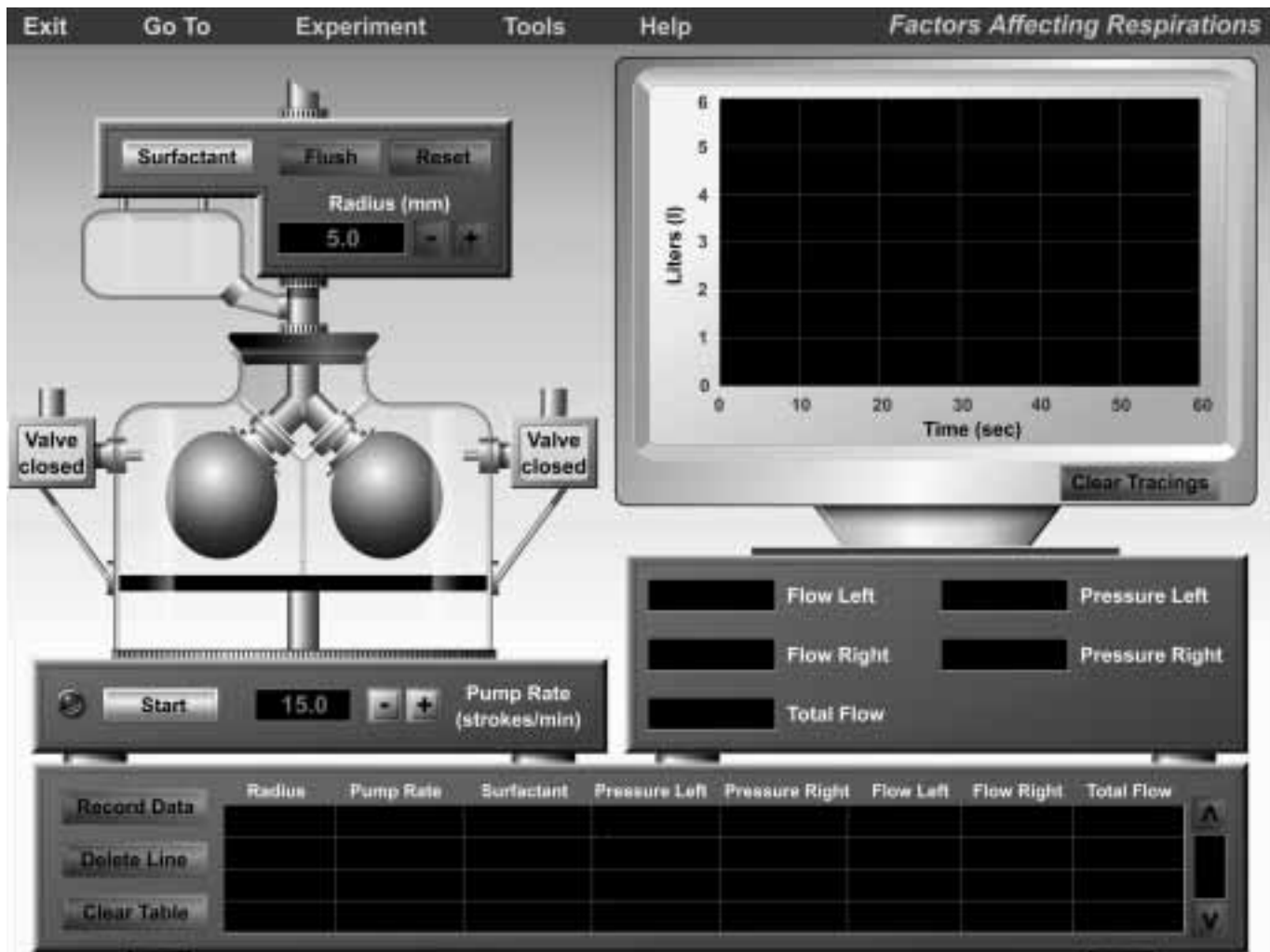


Figure 7.2 Opening screen of the Factors Affecting Respiration experiment.

Activity 4: Effect of Surfactant on Respiratory Volumes

1. The data recording box at the bottom of the screen should be clear of data. If not, click **Clear Table**.
2. The radius of the air flow tube should be set at 5.0 mm, and the Pump Rate should be set at 15 strokes/minute.
3. Click **Start** and allow the trace to sweep across the full length of the oscilloscope monitor. Then click **Record Data**. This will serve as the baseline, or control, for your experimental runs. You may wish to click **Tools** and then **Print Graph** for a printout of your trace.
4. Click **Surfactant** twice to add surfactant to the system. Repeat step 3.

When surfactant is added, what happens to the tidal volume?

As a result of the tidal volume change, what happens to the flow into each lung and total air flow?

Why does this happen?

Remember, you may click **Tools** and then either **Print Data** or **Print Graphs** to print your results. ■

Activity 5: Effect of Thoracic Cavity Puncture

Recall that if the wall of the thoracic cavity is punctured, the intrathoracic pressure will equalize with atmospheric pressure so that the lung cannot be inflated. This condition is known as **pneumothorax**, which we will investigate in this next activity.

1. Do *not* delete your data from the previous activity.
2. If there are any tracings on the oscilloscope monitor, click **Clear Tracings**.
3. Click **Flush** to remove the surfactant from the previous activity.
4. Be sure that the air flow radius is set at 5.0 mm, and that Pump Rate is set at 15 strokes/minute.
5. Click on **Start** and allow the trace to sweep the length of the oscilloscope monitor. Notice the pressure displays, and how they alternate between positive and negative values.
6. Click **Record Data**. Again, this is your baseline data.
7. Now click the valve for the left lung, which currently reads “Valve closed.”
8. Click **Start** and allow the trace to sweep the length of the oscilloscope monitor.
9. Click **Record Data**.

What happened to the left lung when you clicked on the valve button? Why?

What has happened to the “Total Flow” rate?

What is the pressure in the left lung? _____

Has the pressure in the right lung been affected? _____

If there was nothing separating the left lung from the right lung, what would have happened when you opened the valve for the left lung? Why?

Now click the valve for the left lung again, closing it. What happens? Why?

Click **Reset** (next to the **Flush** button at the top of the air flow tube). What happened?

Describe the relationship required between intrathoracic pressure and atmospheric pressure in order to draw air into the lungs.

Design your own experiment for testing the effect of opening the valve of the right lung. Was there any difference from the effect of opening the valve of the left lung?

Remember, you may click **Tools** and then either **Print Data** or **Print Graphs** to print your results. ■

Variations in Breathing

Normally, alveolar ventilation keeps pace with the needs of body tissues. The adequacy of alveolar ventilation is measured in terms of the partial pressure of carbon dioxide (P_{CO_2}). Carbon dioxide is the major component for regulating breathing rate. Ventilation (the frequency of breathing multiplied by the tidal volume) maintains the normal partial pressures of oxygen and carbon dioxide both in the lungs and blood. *Perfusion*, the pulmonary blood flow, is matched to ventilation. The breathing patterns of an individual are tightly regulated by the breathing centers of the brain so that the respiratory and circulatory systems can work together effectively.

In the next activity you will examine the effects of rapid breathing, rebreathing, and breathholding on the levels of carbon dioxide in the blood. Rapid breathing increases breathing rate and alveolar ventilation becomes excessive for tissue needs. It results in a decrease in the ratio of carbon dioxide production to alveolar ventilation. Basically, alveolar ventilation becomes too great for the amount of carbon dioxide being produced. In rebreathing, air is taken in that was just expired, so the P_{CO_2} (the partial pressure of carbon dioxide) in the alveolus (and subsequently in the blood) is elevated. In breathholding, there is no ventilation and no gas exchange between the alveolus and the blood.

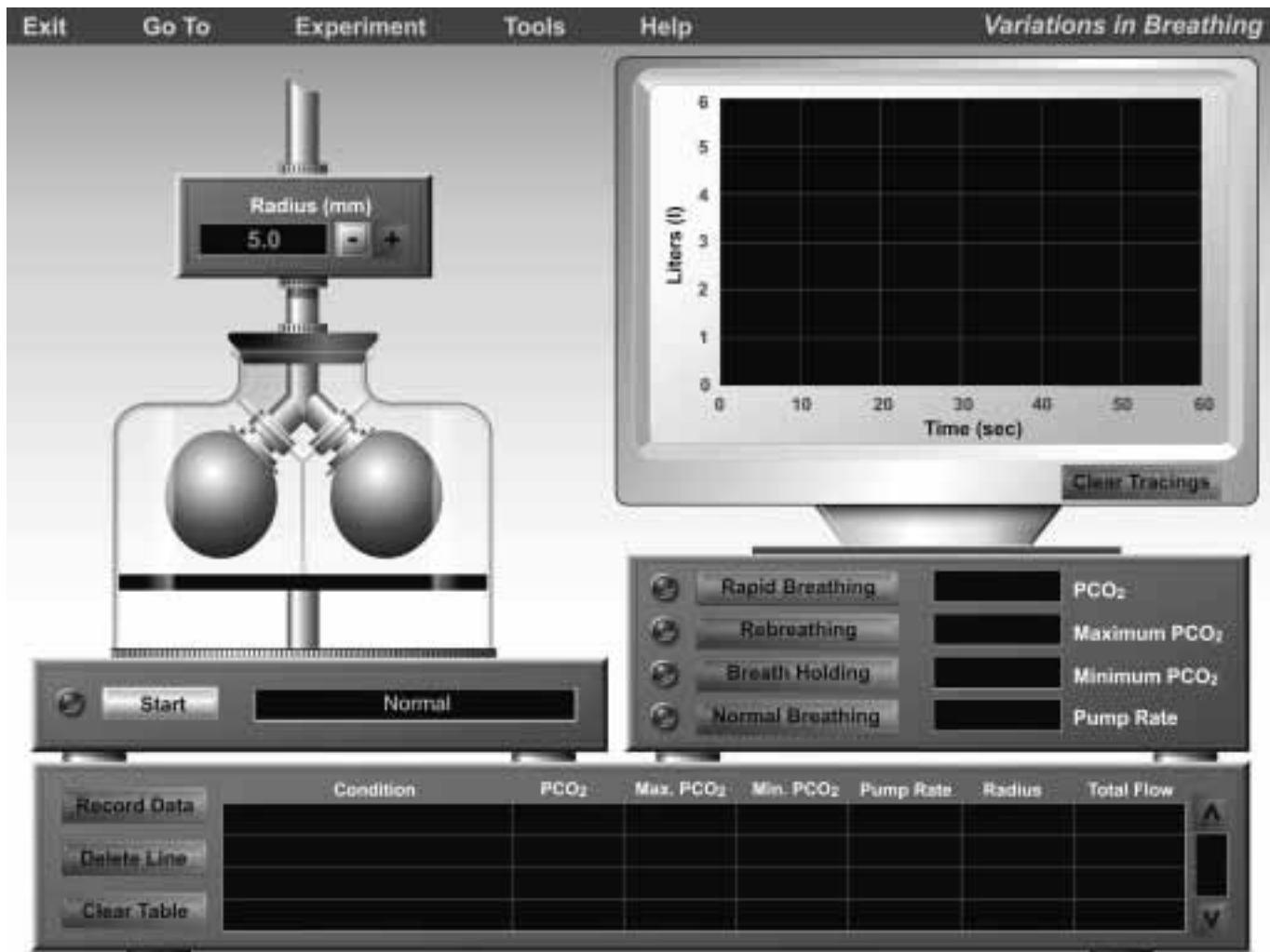


Figure 7.3 Opening screen of the Variations in Breathing experiment.

Click **Experiment** at the top of the screen and select **Variations in Breathing**. You will see the next screen, shown in Figure 7.3. This screen is very similar to the ones you have been working on. Notice the buttons for **Rapid Breathing**, **Rebreathing**, **Breath Holding**, and **Normal Breathing**—clicking each of these buttons will induce the given pattern of breathing. Also note the displays for **P_{CO_2}** , **Maximum P_{CO_2}** , **Minimum P_{CO_2}** , and **Pump Rate**. ■

Activity 6: Rapid Breathing

1. The oscilloscope monitor and the data recording box should both be empty and clear. If not, click **Clear Tracings** or **Clear Table**.
2. The air flow tube radius should be set to 5.0. If not, click the (+) or (–) buttons next to the radius display to adjust it.
3. Click **Start** and conduct a baseline run. Remember to click **Record Data** at the end of the run. Leave the baseline trace on the oscilloscope monitor.

4. Click **Start** again, but this time click the **Rapid Breathing** button when the trace reaches the 10-second mark on the oscilloscope monitor. Observe the P_{CO_2} levels in the display windows.

5. Allow the trace to finish, then click **Record Data**.

What happens to the P_{CO_2} level during rapid breathing?

Why?

Remember, you may click **Tools** and then either **Print Data** or **Print Graphs** to print your results.

Click **Clear Tracings** before continuing to the next activity. ■

Activity 7: Rebreathing

Repeat Activity 6, except this time click the **Rebreathing** button instead of the **Rapid Breathing** button.

What happens to the P_{CO_2} level during rebreathing?

Why?

Did the total flow change?

Why?

How does the rebreathing trace compare to your baseline trace? (Look carefully—differences may be subtle.)

Why?

Click **Clear Tracings** to clear the oscilloscope monitor. ■

Activity 8: Breath Holding

1. Click on **Start** and conduct a baseline run. Remember to click **Record Data** at the end of the run. Leave the baseline trace on the oscilloscope monitor.
2. Click **Start** again, but this time click the **Breath Holding** button when the trace reaches the 10-second mark on the oscilloscope monitor. Observe the P_{CO_2} levels in the display windows.
3. At the 20-second mark, click **Normal Breathing** and let the trace finish.
4. Click **Record Data**.

What happens to the P_{CO_2} level during rebreathing?

Why?

What change was seen when you returned to “Normal Breathing”?

Remember, you may print your data or graphs by clicking **Tools** at the top of the screen and then selecting either **Print Data** or **Print Graph**.

Histology Review Supplement

Turn to p. 157 for a review of respiratory tissue.