MODEL DEMONSTRATING RESPIRATORY MECHANICS
FOR HIGH SCHOOL STUDENTS

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We wanted to develop educational materials appropriate for the high school student which would present physiological concepts in an innovative way. The impetus was in response to the lack of physiology educational materials appropriate for the high school level. To this end, we developed an exercise that presents the physiological basis for respiratory mechanics. The materials were designed to engage students in interactive learning and to stimulate interest for future science study. The emphasis of the exercise was the construction of a model that could be built by high school students to demonstrate respiratory mechanics. The use of models to present complex materials has been shown to be an effective medium for science learning. Our exercise contains directions for an inexpensive, easy-to-build model, as well as many supplemental teaching tools. Questions are interspersed throughout the text and at the end of the laboratory experience to facilitate the learning process. Answers are provided to the questions. Students and teachers alike are challenged to build, manipulate, and discuss their experience during the investigation of respiratory mechanics.


Key words: lung model; education; teaching; inspiration; expiration

The teaching of physiology is often overlooked in high school curricula. Some of this is due, in part, to the lack of appropriate educational materials for high school students. Many physiology texts and laboratory experiments are written for the college level. Most of today’s physiological experiments require expensive laboratory equipment, are too complex, and are generally not appropriate for the high school student. Because of these factors, presentation of basic physiological concepts is often omitted. These limitations challenge physiologists to develop appropriate educational materials that present physiology in an innovative and effective way.

Our goal was to develop a physiologically sound, inexpensive model that demonstrates the basic concepts of pulmonary mechanics (8). Although existing models can be purchased at high cost, our model was constructed with economical materials readily available through scientific catalogs.

Our rationale for using a model was because “evidence suggests that with the use of activity-based science programs, teachers can expect substantially-improved performances in science processes” (3). In the scientific world, models are frequently used to explain complex ideas. Models have been shown to change the focus and organization of scientific thinking (6). As a departure from the traditional data-proven hypothesis testing, models encourage logic,
reasoning, and creativity (7). Concrete models also relate the unknown with the familiar and provide a new perspective on information gathering.

When faced with the unknown, the tendency is to revert to the most basic stage of thinking: Piaget’s sensorimotor stage. The use of concrete models allows a see-touch interaction to supplement new information processing. Having a model that students can actively manipulate ensures thinking on the most basic sensorimotor level. Such sensory stimulation in learning is an integral part of information processing (5). Further information can then be integrated with higher levels of Piaget’s stages of meaningful learning.

Active participation with models reaches all types of learners in the visual, auditory, kinesthetic, and tactile scheme of learners. Building and manipulation of the models satisfy the kinesthetic and tactile learners. Teacher presentation and discussion during the laboratory exercise reach the auditory learners, whereas the supplied text and instructions enhance visual learning experiences. Once the information has been gathered by these different types of learners, all types converge during the questioning and reflecting period of learning.

The use of models is also supported by constructivism, as defined by Tobin (9). Although models are an invaluable tool of education, models are not the sole magical solution to material presentation. “We would be also misled if we said that constructivism advocates the so called ‘hands-on-science.’ The important part is not that students manipulate things physically but that they do it for a purpose and engage in discussion about it” (9).

Our exercise not only provides an easy-to-build model demonstrating respiratory mechanics (8), it also comes with supplemental teaching tools. In addition to the construction of the model, the supportive text contains discussion questions, photographs of the model under construction, organizational maps, and instructive background information on the physiology related to the respiratory system.

Within the text are questions for the students to answer to mentally focus the thinking process. Questions are designed in a set, so that the first few questions in the set review comprehension of the previous paragraphs. The last question in a set provokes thought on the subsequent passages. At the end of the exercise, there are questions for discussion and integration of the entire learning experience.

LABORATORY EXERCISE

Questions are inserted within the text to help focus thinking and test comprehension of the material. Questions marked with arrows are comprehension questions that are used to review previous passages. Questions marked with asterisks provoke thinking on subsequent passages.

Figure 1 presents a concept map that organizes the basic concepts of the text material.

Background

Although breathing is only one component of the respiratory system, it is what first comes to mind when we talk about respiration. Breathing involves exchanging the air in our lungs with air in the environment. This is necessary for our bodies to maintain the appropriate levels of oxygen (O₂) and carbon dioxide (CO₂) needed for life.

Moving air into and out of our lungs changes the volume of our lungs in three dimensions. When we inhale or breathe in, our lungs increase in volume. When we exhale or breathe out, our lungs decrease in volume until they reach their resting or equilibrium position. Such volume changes are caused by changes in pressures. Inhalation is also known as inspiration, and exhalation is also known as expiration.

1) What happens to lung volume when you inhale? When you exhale?
2) How does air move, and what pressures of the body are involved?

Units of measurement for pressure are millimeters of mercury (mmHg) and centimeters of water (cmH₂O), where 1 cmH₂O = 1.3 mmHg. Some of the pressures involved in breathing are presented in Table 1.
Resting pressures are pressures before any breathing occurs. Because atmospheric and alveolar pressures are equal at rest, we can set them both at 0 cmH₂O. So, any subsequent changes in pressure will be described relative to atmospheric pressure, 760 mmHg, as 0 cmH₂O.

### TABLE 1

<table>
<thead>
<tr>
<th>Pressures</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atmospheric</td>
<td>Pressure of the air in the environment</td>
<td>At sea level, it is 760 mmHg</td>
</tr>
<tr>
<td>Alveolar</td>
<td>Pressure inside lung</td>
<td>Resting = 760 mmHg</td>
</tr>
<tr>
<td>Pleural</td>
<td>Measure of pressure in the thoracic cavity that is determined by measuring pressure between 2 pleural membranes</td>
<td>Resting = 755 mmHg</td>
</tr>
</tbody>
</table>

The actual movement of air from the environment into our respiratory systems follows a pressure gradient. Air is made of 21% O₂, 0.03% CO₂, 79% nitrogen, water vapor (H₂O), and other gases. The gases in airflow from regions of high pressures to areas of low pressures.

3) Describe the three pressures involved in breathing.

4) How does air get into the lungs?

**Basic Concepts of the Respiratory System**

The structures of the respiratory system are in direct contact with the environment through the nose and mouth. At rest, the pressure in the lungs (alveolar pressure) is equal to the atmospheric pressure (760 mmHg or 0 cmH₂O). Because air moves from areas of high pressures to areas of low pressures, air flows...
into the lungs when the atmospheric pressure is higher than the alveolar pressure. When the alveolar pressure is less than atmospheric pressure, it is called subatmospheric.

Encasing and protecting the lungs is the rib cage. The rib cage is part of the chest wall. The chest wall has a natural tendency to expand. If no other muscles or bones were connected to the chest wall, it would tend to get larger in volume.

Between the chest wall and the lungs is a fluid-filled pleural space. It is a completely sealed sac surrounding the lungs. Although this fluid-filled pleural space is a very thin space, it is very important for breathing. At resting or equilibrium position, pleural pressure (the pressure within the pleural space) is \(-6.5\) cm\(H_2O\). Pleural pressure is a measure of the pressure within the thoracic cavity. The thoracic cavity is the space in which the lungs and heart are located.

Lungs contain structures called alveoli. Gas exchange occurs in the alveoli. The lungs themselves are soft organs with elasticity, much like a balloon. They expand during inhalation. The balloon expands when air enters it, too. A balloon has a tendency to collapse. This tendency for collapse in the lung is called elastic recoil. Because of elastic recoil, the lung tends to collapse. Elastic recoil makes exhalation a passive process.

The chest wall wants to expand. The lungs want to collapse. This tug-of-war between the chest wall and the lungs creates a negative pressure in the pleural space. This is why the pleural pressure, at rest, is \(-6.5\) cm\(H_2O\). The tug-of-war reaches its balancing point at \(-6.5\) cm\(H_2O\). Reaching the balancing point of the tug-of-war prevents the chest wall from expanding any further and prevents the lungs from collapsing any further.

Also important for breathing are the muscles of respiration. The most important muscle of respiration is the diaphragm. It moves down to enlarge the thoracic cavity during inspiration. It does the opposite during expiration. The diaphragm moves back up during expiration. There also are accessory muscles of respiration. These muscles are attached to the ribs and the clavicle (collarbone). These muscles move the chest wall. All of the muscles of respiration assist in increasing lung volume and generating a subatmospheric pressure in the alveoli within the lungs, which allows air to move in during inspiration.

An illustration showing the anatomic structures of the respiratory system is presented in Fig. 2. To correlate the body's respiratory structures with the model we are presenting, see Fig. 3.

5) Which way does the diaphragm move during inhalation? During exhalation?

6) What is elastic recoil of the lung?

7) What is the tendency of the chest wall movement?

8) How are pressure and volume related?

Respiratory Mechanics

So far, changes in lung volume and pressure during breathing have been presented. For air to enter the respiratory system, alveolar pressure must be subatmospheric (\(<760\) mm\(Hg\)). Inspiration is an active process that requires the muscles of respiration. The most important muscle of respiration is the diaphragm. In contrast to inspiration, exhalation is a passive process. Exhalation involves elastic recoil of the lung, or the lung's desire to return to its equilibrium position, like a balloon.

A scientific law important to pressure-volume changes is Boyle's Law. Boyle's Law states that, when the volume of a gas changes, its pressure also changes (if temperature is constant). The relationship between pressure and volume is an inverse one. This means that, if volume goes up, pressure goes down. If volume goes down, pressure goes up. Boyle's Law is represented as \(P_1V_1 = P_2V_2\).

In Boyle's Law, \(P_1\) represents the pressure in one situation, and \(V_1\) represents the volume in that same situation. \(P_2\) represents the changed pressure in the second situation, and \(V_2\) represents the changed volume in the second situation.

9) Which part of breathing is an active process? Does it require the muscles of respiration?
atmospheric pressure
at 760 mm Hg

FIG. 2.
Structures of respiratory system including trachea, bronchi, lungs, pleural space, and chest wall. Also labeled are 3 pressures involved with breathing.

FIG. 3.
Schematic of constructed labeled model with correlative anatomic structures of the respiratory system.
10) Describe Boyle's Law.

11) *How does alveolar pressure become subatmospheric?*

**Inhalation.** Inhalation is an active process. The accessory muscles of respiration move the chest wall. During inspiration, the chest wall moves upward and outward. The diaphragm moves downward. These movements increase the volume of the thoracic cavity. As the thoracic volume expands, the lungs also expand through a hydraulic coupling of the lungs and chest wall. Expansion of the lungs results in a subatmospheric pressure in the lung, driving air from the atmosphere into the lungs. At the new expanded volume, the lungs have a greater elastic recoil (greater tendency to collapse), which decreases intrapleural pressure by the “tug of war” between the lung’s tendency to collapse and the thoracic cavity (chest) expanding. The pleural pressure decreases three (3) units of pressure from its resting pleural pressure of $-6.5 \text{ cmH}_2\text{O}$ to become $-9.5 \text{ cmH}_2\text{O}$. Recall that pleural pressure is a measure of the pressure inside the thoracic cavity.

Again, as the thoracic cavity expands, the lungs expand because the lungs and thoracic cavity are hydraulically linked. According to Boyle’s Law, pressure decreases as volume increases. Therefore, when the lungs increase in volume, their alveolar pressures decrease. Alveolar pressures decrease ~1–2 units of pressure to become subatmospheric. This process creates a difference between the atmospheric and alveolar pressures. The pressure difference allows air to flow into the lungs until alveolar pressure becomes equal to atmospheric pressure. (Lung volume has a limit to expansion or else the lungs would burst.)

A schematic illustration detailing the process of inhalation is presented in Fig. 4.

**Exhalation.** Unlike inhalation, exhalation is a passive process. Air has moved into and filled the alveoli during inhalation so that the alveolar pressures are

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**FIG. 4.**

Schematic representation of changes in the chest wall, diaphragm, thoracic cavity, lungs, and pressures during inhalation.
once again equal to atmospheric pressure (0 cmH₂O or 760 mmHg). Now the elastic recoil of the lungs begins to take effect. The elastic recoil compresses lung space. Compression of the lung space causes its volume to decrease. Again, Boyle’s Law works. When the lung volume decreases, the alveolar pressure increases.

Because air flows from a region of higher pressure to an area of lower pressure, the air moves out of the alveoli. It is then returned to the environment. Air is expelled from the lung until the lung reaches its resting or equilibrium position. At equilibrium position, the alveolar pressures and atmospheric pressure are once again equal.

As the lungs return to their resting position, the chest wall moves inward and downward; the diaphragm rises. Pleural and alveolar pressures are returned to their resting values.

A schematic illustration of the process of exhalation is presented in Fig. 5.

Summary
Breathing is the cyclic process of inspiration and expiration. Breathing involves changes in lung volume from their equilibrium or resting position. To move air into the lungs, a subatmospheric pressure is created. The muscles of respiration, of which the diaphragm is the most important, increase the thoracic cavity volume during inspiration. An increase in the volume of the thoracic cavity, likewise, increases lung volume. This creates a lower pressure in the alveolar spaces so that air flows into the lungs. At the end of inspiration, alveolar pressure equals atmospheric pressure. Then, expiration occurs. The elastic recoil of the lungs pushes the lungs to a smaller volume. The higher pressure created in the alveoli forces the air back into the environment. The cycle begins again to continue breathing.

Answers to Text Questions

1) Lung volume increases upon inhalation. Lung volume does the opposite during exhalation, so lung volume decreases during expiration.

2) Air moves in a direction from areas of high pressure to areas of low pressure. In the body, the only way air can move into the lungs is when the lung (alveolar) pressure becomes subatmospheric (or <760 mmHg). Therefore, the three pressures involved in breathing are alveolar pressure, pleural pressure as a measure of the pressure inside the thoracic cavity, and atmospheric pressure.

FIG. 5.
Schematic representation of changes of the lungs, chest wall, diaphragm, thoracic cavity, and pressure during exhalation.
3) Atmospheric pressure is the pressure of the air in the environment. Although it changes at different altitudes, atmospheric pressure is regarded as a constant at sea level (760 mmHg). By convention, we have set atmospheric pressure equal to alveolar pressure when the lung is at rest. We also designate atmospheric pressure as 0 cmH₂O. Subsequent changes in pressure are described relative to atmospheric pressure.

Alveolar pressure is the pressure within the alveoli of the lung. The alveoli are the areas of gas exchange in the lung, or specifically, the O₂-CO₂ exchange. Before any breathing occurs (while the lungs are at rest), alveolar pressure is equal to atmospheric pressure, since the respiratory passages are in contact with the environment. Therefore, at rest, alveolar pressure is also 760 mmHg or 0 cmH₂O. Note that alveolar pressure is subject to change.

Pleural pressure is a measure of the pressure in the thoracic cavity outside the lung. The thoracic cavity is the cavity in the body in which the lungs and heart are located. The thoracic cavity pressure is not directly measurable, so pleural pressure is used. Pleural pressure is the pressure between two pleural membranes. The pleural membranes are located as the outside covering of the lungs and the inner lining of the chest wall. The very tiny space between the chest wall and the lungs is called the pleural space or cavity. This pleural space is fluid filled. The pressure in this space is known to be 755 mmHg, so we have designated its pressure as -5 mmHg or -6.5 cmH₂O (1.3 mmHg = 1.0 cmH₂O).

4) Air enters the lungs through the nose and mouth. Then it follows the respiratory passages on its journey to the alveoli. In order, the respiratory passages include the nasal and oral cavities, the pharynx, the larynx, the trachea, the bronchi, and bronchioles. After passing through the bronchioles, air finally reaches the alveoli.

Because air moves from regions of high pressure to regions of lower pressure, alveolar pressure must be less than atmospheric pressure for air to flow into the lungs.

5) The diaphragm moves down upon inhalation. The diaphragm moves up during exhalation.

6) Elastic recoil of the lungs is the tendency for the lung (and alveoli) to collapse. Elastic recoil is a natural property of the lung.

7) The tendency of the chest wall is to move out. Note that this tendency of the chest wall to move out and the elastic recoil of the lung to move in (collapse) results in a tug-of-war effect. The tug-of-war is balanced at the resting position of the lung and chest wall. The tug-of-war also creates a negative pressure inside the pleural space. This is what makes the pleural space pressure 755 mmHg or -6.5 cmH₂O.

8) Pressure and volume are inversely related, as stated by Boyle’s Law. When volume increases, pressure decreases. When volume goes down, pressure goes up.

9) Inhalation is the part of breathing that is active. Inhalation requires the muscles of respiration. (Recall that exhalation is a passive process.)

10) Boyle’s Law describes an inverse pressure-volume relationship. Boyle’s Law is written as \( P_1V_1 = P_2V_2 \). \( P_1 \) and \( V_1 \) represent the pressure and volume in an original situation. \( P_2 \) and \( V_2 \) represent the pressure and volume in the changed situation.

11) The process of lowering alveolar pressure to subatmospheric pressure is what happens during inhalation. First, the accessory muscles of respiration move the chest wall up and out, and the diaphragm moves down. This creates an expansion of the thoracic cavity. The expansion of the thoracic cavity causes an expansion of the lungs because the lungs and thoracic cavity are hydraulically linked. Follow-

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### TABLE 2

List of supplies required for construction of the lung apparatus

<table>
<thead>
<tr>
<th>Supplies (local craft stores or department stores)</th>
<th>No. and letter designations in parentheses correspond to directions in text.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Balloon (4 X 2.5 cm; 2A)</td>
<td></td>
</tr>
<tr>
<td>Epoxy or silicon base glue (2B)</td>
<td></td>
</tr>
<tr>
<td>Carpet thread (2C)</td>
<td></td>
</tr>
<tr>
<td>Stiff wire (5 cm; 2D)</td>
<td></td>
</tr>
<tr>
<td>Science supplies (VWR Scientific)</td>
<td></td>
</tr>
<tr>
<td>20 cm 0.047 X 0.067 (IDXOD) polyethylene tubing (2E)</td>
<td></td>
</tr>
<tr>
<td>18-gauge 1-in. needle or Luer adaptor (2F)</td>
<td></td>
</tr>
<tr>
<td>60 ml syringe (2G)</td>
<td></td>
</tr>
</tbody>
</table>

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TABLE 3
List of supplies required for construction of the manometer

<table>
<thead>
<tr>
<th>Supplies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scrap wood or tongue depressor that is approximate size of ruler (3A)</td>
</tr>
<tr>
<td>Clear plastic tape</td>
</tr>
<tr>
<td>Science supplies</td>
</tr>
<tr>
<td>6-in. (15-cm) plastic ruler (3B)</td>
</tr>
<tr>
<td>2 15-cm, 5/32×7/32×1/32 (ID×OD×wall, in.) glass tubing (3C and 3D)</td>
</tr>
<tr>
<td>3/16×5/16×1/16 (ID×OD×wall, in.) flexible plastic tubing 7 cm length (3E)</td>
</tr>
<tr>
<td>15 cm length (3F)</td>
</tr>
<tr>
<td>Ring stand (3G)</td>
</tr>
<tr>
<td>2 Extension round jaw clamps (3H)</td>
</tr>
<tr>
<td>2 Straight clamp holders (3I)</td>
</tr>
<tr>
<td>30-ml syringe (optional) (3J)</td>
</tr>
<tr>
<td>3-Way valve (3K)</td>
</tr>
</tbody>
</table>

All science supplies can be found in the VWR Scientific Catalog. A listing of addresses for other supply companies is provided in Table 4.

ing Boyle’s Law, when the volume of the lungs increases, the pressure in the lungs (alveolar pressure) decreases. Now the alveolar pressure drops 1-2 units from its atmospheric pressure of 760 mmHg/0 cmH₂O to become subatmospheric.

CONSTRUCTION OF THE MODEL

Purpose

Through the construction and manipulation of the model, students will develop an understanding of the mechanism of breathing.

Objectives

At the completion of this laboratory, you should be able to: build a working model that illustrates the mecha-

FIG. 6.
The first 2 steps involved in constructing the lung apparatus. Polyethylene tubing is inserted into balloon. Thread is wrapped around the base of the balloon to secure the balloon to the tubing. 2A, balloon; 2C, thread; 2E, polyethylene tubing.
nism of breathing; use the model to explain the mechanism of breathing; explain how the lung is able to remain inflated even after exhalation; discuss the relationship between lung expansion and intrapleural pressure.

**Procedure**

Students will manipulate a fluid-filled syringe that represents the pleural space. Inside the syringe is a balloon that represents the lungs. The balloon stays in direct contact with the environment through a piece of small tubing that represents the respiratory passages. Finally, there is a device connected to the pleural cavity called a manometer. The manometer allows the student to observe pressure changes within the pleural space. Recall that the pressure in the fluid-filled pleural space is a measure of the pressure in the thoracic cavity.

To make the directions for assembling the model as clear as possible, each item has been assigned a number and letter (in parentheses) identification. The number before the letter indicates in which table the item is listed. The number/letter identification will be used as a reference in the directions. Table 2 presents a list of supplies required for the construction of the lung apparatus. Table 3 presents a list of supplies required for the construction of the manometer. Table 4 contains a list of science supply companies and their addresses, phone numbers, and fax numbers.

Figures 6–9 show the steps necessary to assemble the lung apparatus of the model. Figures 10 and 11 depict most of the steps involved in constructing the manometer. Figures 12 and 13 correspond to the steps involved in attaching the lung apparatus to the manometer. Figure 14 is the completed model, with the lung apparatus connected to the manometer.

**Assembling the Lung Apparatus**

**Part 1: connecting the balloon to the small tubing.**

A. Insert the polyethylene tubing (Fig. 6, 2E) inside the balloon (Fig. 6, 2A) just short of the full length of the balloon.
To thread tubing connected to the balloon through the syringe, step shown in this figure must be completed first. Stiff wire must be threaded through polyethylene tubing. Figure corresponds with instructions in Part 3: attachment of balloon apparatus to syringe apparatus. 2D, wire.

**Part 2: making the connection for the manometer.**

A. Remove the plunger from the syringe (Fig. 7, 2G).

B. Drill a hole in the top of the syringe, just to the right of center (see TIPS FOR TEACHERS).

C. If the connector is going to be a shortened needle, then follow these instructions for shortening it. Score the needle with a small triangle file, and break it (see TIPS FOR TEACHERS).

D. Insert the Luer adapter/needle (Fig. 7, 2F) into the hole on the top of the syringe (Fig. 7, 2G).

E. Glue (Fig. 7, 2B) the connector to the syringe. Use glue to be certain there is a complete seal. Allow the glue to dry overnight.

**Part 3: attachment of balloon apparatus to syringe apparatus.**

A. Because the tubing attached to the balloon is very flexible, you will need to thread a piece of stiff wire (Fig. 8, 2D) into the open end of the tubing. Take care not to puncture the balloon with the wire. From the bottom of the syringe chamber, insert the tubing/wire complex through to the top of the syringe (Fig. 9).

B. Once a few centimeters of tubing are through the top of the syringe, remove the wire. To ensure that the balloon maintains a snug fit against the inside top of the syringe chamber, place a small amount of glue on the open rim of the balloon (Fig. 9). Pull the rest of the tubing up through the syringe opening until the balloon is snug against the top of the syringe.

C. Add additional glue around the tubing to maintain a snug contact between the tubing and the inside of the syringe. This should seal the center opening of the syringe. If the model is placed horizontally, the glue will drip. To prevent this, tape the tubing to the edge.
Figure illustrates that tubing (and wire) should be threaded through the top of the syringe, i.e., from the wide open end at the bottom of the syringe to the narrow tip at the top. Once a few centimeters of tubing are through the top of the syringe, place glue around the rim of the balloon (indicated by a small arrow), such that, when tubing is pulled completely through the top of the syringe, the balloon will adhere to the underside of the syringe. Additional glue should be applied around the top of the tubing to seal the center opening.

Assembling the Manometer

Part 1: connecting the flexible tubing to the glass tubing. 
A. Connect one end of the 7-cm flexible tubing (Fig. 10, 3E) to the bottom end of one piece of glass tubing (Fig. 10, 3C or 3D).

B. Attach the free end of the 7-cm flexible tubing (Fig. 10, 3E) to the bottom end of the other glass tubing (Fig. 10, 3C or 3D).

Part 2: constructing the main body of the manometer.
A. Tape the ruler (Fig. 10, 3B) to the broad side of your scrap wood or tongue depressor (Fig. 10, 3A).

B. Tape one piece of glass tubing (Fig. 10, 3C and 3D) on each side of the wood or tongue depressor. The flexible tubing should resemble the letter "U."

c. Connect the three-way valve (Fig. 11, 3K) to the free end of the 15-cm flexible tubing (Fig. 11, 3F).

d. Connect the 15-cm piece of flexible tubing (Fig. 11, 3F) to the top end of the glass tubing on the right side of the ruler as shown in Fig. 11. The tapered end of the three-way valve should be projecting out but should be in line with the flexible tubing. The off/on lever of the three-way valve should be in the same plane as the face of the ruler.

Attaching the Manometer to the Lung Model

Part 1: assembling the ring stand.
A. Connect an extension round jaw clamp (Fig. 12, 3H) to a clamp holder (Fig. 12, 3I). This will form a complete ring stand clamp that can be attached to the stand. Do this for both clamps and holders. If your extension clamp already has a means for attaching it to the ring stand,
To complete the manometer, tape the ruler to the broad side of the scrap wood. Connect the 7-cm flexible tubing to each of the glass tubings. Tape 1 piece of glass tubing on each side of the ruler. The 7-cm flexible tubing will resemble the letter "U." 3A, wood; 3B, ruler; 3C and 3D, glass tubes; 3E, 7-cm flexible tubing.

FIG. 10.

you can ignore the above directions. Refer to Fig. 12 for a picture of both clamps.

b. Attach both extension clamps to the ring stand so that they follow the configuration shown in Fig. 13.

Part 2: preparing the lung apparatus to connect to the ring stand. a. Fill the syringe (lung apparatus) one-half full with water by the method described. 1) Block the needle adapter at the top of the lung apparatus/syringe with your finger or by some other means. 2) Turn the syringe so that the open end is facing up. Pour ~30 ml water into the opening. 3) Replace the plunger making sure that the open end of the syringe remains on top. 4) Once you have the plunger in far enough so that you can turn the lung apparatus upside down without water loss, turn it to that position. 5) Remove your finger from the needle adapter and carefully push the plunger up until water starts to come through the adapter.

to test the lung apparatus, attach a three-way valve to the needle adapter, and close it to the environment. When you pull on the plunger, the balloon should expand. Set this apparatus aside for now.

c. To fill the manometer with water, open the three-way valve to the environment and attach a 10- or 30-ml water-filled syringe (3J) to the closed end of the three-way valve. Open the three-way valve to the water syringe, and close it to the environment. Refer to Fig. 14 for proper positioning of the syringe. Practice with the three-way valve until you become familiar with how it works. Fill the manometer tubing carefully. Add only enough water to partially fill the tubing.

Part 3: attaching the lung apparatus and the manometer to the ring stand. a. Attach the lung apparatus to the extension clamp making sure that the plunger is positioned below the balloon (Fig. 14). If the lung apparatus is in the proper position, pushing the
Supplies needed to complete the manometer are shown. Connect the 3-way valve to the free end of the flexible tubing. Connect the 15-cm flexible tubing to 1 of the glass tubings. Tapered end of the 3-way valve should be in the position shown. 3F, 15-cm tubing; 3K, 3-way valve.

R. Place the other extension clamp to the right of the lung model. Attach the manometer to this clamp (Fig. 14).

c. To join the lung apparatus to the manometer, connect the tapered end of the three-way valve to the needle/luer adapter (Fig. 14).

d. The lung model is complete!

DEMONSTRATION OF RESPIRATORY MECHANICS

Inspiration

1) Before you begin, note the pleural space/thoracic cavity pressure by observing the level of the water inside the manometer. Record the pressure as measured by the ruler reading so that you have a beginning or reference point.

2) Pull the plunger of the syringe down. This is analogous to the movement of the diaphragm during inspiration. Observe what happens. Note what happens to the balloon. At the same time, note the changes in the pleural/thoracic cavity pressure from the manometer reading. Continue observations until the balloon and the manometer readings have stopped fluctuating.

3) Note the new pressure as recorded by the manometer. Recall that the manometer is measuring the pressure within the fluid-filled “pleural space” that is an indication of the pressure inside the thoracic cavity. Also note what has happened to the balloon inside the syringe.

4) Before you continue to the exhalation portion of the exercise, be sure you are comfortable with the
Manometer and the lung apparatus will be supported on a ring stand with extension clamps. Figure shows 2 options (a. or b.) for supporting the model, depending on which type of clamps are available. Extension round jaw clamps and clamp holders are shown in a. If these are going to be used, connect a jaw clamp to a clamp holder. Two sets are needed. Jaw clamp and holder may be one unit, as shown in b. Again, 2 clamps are needed. 3H, extension round jaw clamps; 3l, straight clamp holders.

For discussion. Correlate the observed changes in the balloon and manometer to what happens when you exhale.

ANSWERS TO DISCUSSION

Inspiration
At the end of expiration but just before inspiration, the lung is said to be at rest. At rest, alveolar pressure inside the lungs is equal to atmospheric pressure (760 mmHg or 0 cmH₂O). Also at rest, the pressure of the pleural space (as a measure of the thoracic cavity pressure) is 755 mmHg or −6.5 cmH₂O. In the model, the resting pleural pressure is determined by noting the original level of water in the manometer that is next to the ruler. This number is used as a comparative value for pleural pressure during inspiration and expiration.
When you pull the plunger of the syringe down, this correlates to the downward movement of the diaphragm. Although not depicted in the model, the chest wall in the body has also risen upward and outward. These movements of the chest wall and diaphragm have created a larger thoracic cavity. Coupled with an expanded thoracic cavity, there is an increase in lung volume because the thoracic cavity and lungs are hydraulically linked. The pleural pressure decreases from its original value of $-6.5 \text{ cmH}_2\text{O}$ to its new value of $-9.5 \text{ cmH}_2\text{O}$. Because of this decrease in pressure, you should see the level of the manometer drop from its original reading to a new lower reading.

Note that, in the body, the pleural space surrounding the lungs is very tiny. The pleural space has been greatly expanded in the model to explain the concept of inspiration.

Because lung volume increases, the alveolar pressure drops a few units of pressure to become subatmospheric. Recall that the lungs have elasticity much like the balloon. The balloon expands with air that is incoming from the environment through the small tubing (respiratory passages). The air flows inward to fill the expanding balloon. This occurs until atmospheric pressure is once again reached inside the balloon.
In both the lungs and the model, the lungs and the balloon have a limit to their elastic properties. They both can expand only so much before they burst.

Expiration
At the end of inspiration, air has filled the alveoli so that the alveolar pressures are once again equal to atmospheric pressure. The process of expiration returns the lungs and thoracic cavity to their original resting positions.

When you push the syringe plunger up, this is analogous to the movement of the diaphragm during expiration. Note that you are actively pushing the plunger. In the body, the movement of the diaphragm and the accessory muscles of respiration are a passive process during expiration.

Also in the body, the elastic recoil of the lung, or the lung's desire to collapse, takes effect. Elastic recoil compresses the lung volume. According to Boyle's Law, when the volume has decreased, the pressure should increase. As a result of this decrease in lung volume, an increase in alveolar pressure occurs, causing air to move from a region of higher pressure to region of lower pressure and out of the respiratory system into the environment. You should see the balloon deflate as a result of this process.
You should see the manometer level rise from its end-inspiratory value to its original value before inspiration. In the body, this is correlative to the return of pleural pressure from $-9.5\, \text{cmH}_2\text{O}$ to $-6.5\, \text{cmH}_2\text{O}$.

Note that there is a return to the equilibrium position and not a complete collapse of the balloon. In the model, this is because the water inside the syringe prevents the balloon’s collapse. Water molecules effectively distribute the surface tension of the balloon as it deflates to keep the balloon from collapsing all the way. If the balloon had been in air, the balloon would definitely collapse to a flattened structure.

In the body, the lungs also do not collapse. This is due to the tug-of-war effect between the desired outward movement of the chest wall and the inward elastic recoil movement of the lung. This tug-of-war is balanced at the resting or equilibrium position of the lung. The forces of the tug-of-war create a negative pressure in the pleural space. This is why the pleural pressure in the body is $755\, \text{mmHg}$ or $-6.5\, \text{cmH}_2\text{O}$.

**TIPS FOR TEACHERS**

**Options**

We have presented two options for classroom presentation of the laboratory exercise. These two options are only suggestions, and individual teachers may have other ideas for the presentation of this exercise.

**Student construction of model (two class periods).** Two students per model is the ideal learning situation. Two days of laboratory sessions may be required for completion of the exercise. Field testing has shown that it takes students $\sim 30\, \text{min}$ to actually build the model and $20\, \text{min}$ to read the background information. The subsequent day may be used to reinforce the previous day’s activities by completing the laboratory exercise.

**Interactive demonstration (one class period).** The models may be prebuilt by the teacher. After an introductory briefing, students will investigate respiratory mechanics by manipulating the model.

**Helpful Hints**

**Steps to be completed before class.**

1) For the small piece of wood used to make the ruler, cut the wood into desired sizes, or use tongue depressors.
2) Cut all tubing (glass and flexible plastic) to save time.
3) So that students will not be required to poke holes in the hard plastic with needles, drill a hole in the top of the syringe for the luer/neddle adaptor before class. If you are using the needle as the needle adaptor, shorten the needle so that $\sim 3\, \text{mm}$ remains. To do so, score the needle with a small triangle file and break it.

**Additional tips.**

1) Although the model only takes $20–40\, \text{min}$ to construct, it is suggested that the glue be allowed to dry overnight.
2) When filling the syringe and manometer with water, students may want to work over the sink until the water levels have stabilized.
3) If the flexible tubing for the manometer does not fit snugly around the glass tubes, clamp or tie the joint so that there is no water loss.
4) Shop around for supply distributors when ordering supplies.
5) Pull text questions out to use as discussion questions upon laboratory completion.

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