INTRODUCTION

Pressures within the pulmonary system can be tough for students to understand. Many physiology textbooks start the respiratory section with a review of anatomy and then review the gas laws. These gas laws often seem abstract. The presentation of these ideas often starts with equations and arithmetic. Unfortunately, some students turn off when they see equations, and some students get so wrapped up in the equations that they lose sight of the concepts.

We have developed an activity that provides a review of, or introduction to, the gas laws as they pertain to respiratory function. Another problem that often arises in teaching this section is the diversity of student interests. Some students are motivated by crime scene approaches (e.g., Refs. 1, 2). Others have a strong interest in conservation biology and ecology and are more interested in animals and comparative physiology (3). This activity can be tailored to either audience using either a crime scene based on the “Fixing the Pool” comedy routine by Jon Reep (http://www.cc.com/video-clips/6qpcrd/comedy-central-presents-fixing-the-pool), or discovering how elephants manage to snorkel at greater depths than humans (4, 5).

In this activity, we have scenarios involving snorkels to motivate a hands-on activity that allows students to work out, without doing any math, an understanding of the overall principles of the effect of volume on pressure (and vice versa) and their implications for snorkeling. The depth at which one can snorkel is limited by the water pressure; for a horizontal snorkel (or one with an extra-large mask), dead space can be a limitation, but dead space is not the focus of this exercise.

Description of Model

To mimic snorkeling at depth, we used a flimsy disposable water bottles to represent the lungs and a length of ½-in.-diameter PVC pipe at least 12 in. long to represent the snorkel. We have found that the container for the water is a bit tricky. The container must be at least 12.5 in. deep and be water tight. We have conducted this experiment using plastic wastebaskets that are opaque. The most inexpensive transparent plastic container of small volume that we have found is the Takeya Freshlok Airtight Dry Food Pasta container, 2.7-liter size.

We securely taped the bottle to the PVC pipe, making sure that the pipe did not touch the bottom of the bottle. We find it best to have the pipe only inserted as far as the narrow mouth opening; this facilitates getting water out, if water should get into the bottle, see Fig. 1. We found that duct tape works well, but Silicone Rescue Tape works even better.

We filled the container with water as full as possible, but allowed room for the bottle and pipe to be inserted to the bottom of the container. If the container is placed inside a sink or other larger container, this is something the students could work out.

If an opaque container, such as a plastic waste basket is used, then one needs a quiet room so that the students can hear the bottle crunch, or they can peer into the waste basket, or they can put their hands into the water-filled waste basket and water and feel the bottle change shape.

The total cost for one setup was less than $15.

Audiences and Settings and Scalability

This activity is part of our undergraduate pre-health professionals’ physiology laboratory with up to 100 students at one time. In addition, we have also done it as outreach activities for high school students as part of their summer camp activities as well as with a minority enrichment group activity for 5th to 12th graders.

Crime Scene Activity

Particularly for health professional undergraduate students, we used the crime scene scenario given in Fig. 2. We provide the scenario at the beginning of the laboratory. Then we have the students put the bottle connected to the PVC pipe into the water-filled container, and they observe that the bottle collapses. One can then ask a series of questions, such as:

“Why does the bottle collapse?”

“How is what happens to the bottle different from what happens when you dive into the deep end of the pool?”

“How can you change the bottle apparatus to mimic what happens when you dive into the pool? Try it. Does it work?”

“Can you explain what must be different about the bottle in the two cases, since it is the same bottle?”

“Can you test your explanation?”

Here is one example of a sequence we have used and some options for how to guide the students, if they get stumped.

We put the PVC/bottle combination into the water container and submerge it until a crunch sound is heard, or until someone observes that the bottle has changed shape (see Fig. 3). If the bottle does not collapse initially, take it out, crush it, and then blow air into it to restore it to its initial shape. In our experience, the bottle will always collapse after that.

We ask the students to say what happened and explain why it happened. A surprising number are unwilling to attempt to explain what happened, and so we ask some leading questions.
We take a different water bottle and squeeze it. “Why did the bottle collapse?” Eventually they can work out that the water pressure outside the bottle is so much greater than the air (atmospheric) pressure inside the bottle that the plastic cannot withstand the pressure difference, and the bottle collapses.

So this would seem to suggest that Jon’s dad was lucky the garden hose collapsed. Surprisingly few students ask the question, “Why don’t my lungs collapse when I dive into the deep end of the pool?” So we have to ask that question. “How is a person diving into the deep end of the pool different from our demonstration?” They realize of course that they are holding their breath. “How can we mimic that with this setup?” Most realize they can put their thumb on the top to mimic holding their breath. “If you now insert the bottle into the water container, there is no crunch sound and no obvious change in the bottle shape. Why not?”

At this point we emphasize an understanding of pressure and volume.

If the bottle did not collapse, then the pressure gradient across the bottle must not be high enough. The pressure gradient in the open case was the water pressure outside the bottle and atmospheric pressure because the tube was open. “What has changed when the tube is closed?” Clearly the water pressure is the same. So it must be that the pressure inside the bottle is higher than atmospheric. “How can that be?” If they cannot answer that (and most cannot), we perform one of three options.

Option 1. We drop a hint by asking, “What would happen if we squeeze the bottle with the pipe closed?” See Fig. 4. That is usually enough to make the students realize that squeezing the bottle a bit will decrease its volume, and, if the pipe is closed, that would raise the pressure. We ask, “How can we test this?” Often we have to suggest putting a balloon on the top of the pipe (when the pipe and bottle are out of the water

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**Fig. 1.** Bottle taped to PVC pipe.

**Fig. 2.** Crime scene scenario.

**Fig. 3.** Bottle collapsed.

**Fig. 4.** When one squeezes the bottle, the bottle’s volume (V) decreases from the solid to the dashed lines. This decrease in volume increases the pressure (P) inside the bottle, if the snorkel is closed. When the bottle is squeezed (from solid lines to dashed line), the volume decreases, so the pressure increases.
container!). We do that, and, before putting the bottle under water, ask for predictions. Then we put the bottle in, and the balloon partly inflates.

Option 2. We put a balloon on the top of the pipe (when the pipe and bottle are out of the water container!) We do that, and, before putting the bottle under water, ask for predictions. Then we put the bottle in, and the balloon partly inflates. We then ask the students to explain why the balloon inflates. Air must be moving from bottle to balloon; therefore, the bottle volume is getting a bit smaller and air pressure inside the bottle is getting a bit greater. See Fig. 5.

Option 3. We use a bottle/balloon model of the diaphragm and the lung. See Fig. 6. We ask, “By contracting the diaphragm (pulling down on the balloon), what happens to the intact balloon?” It inflates. “Why?” Well it must be that the pressure inside the balloon is less than air pressure. “Why would that be?” Because the intact balloon expanded. “Why would the intact balloon expand?” Because the pressure between the two balloons inside the bottle has gone down. “Why?” What has happened to the volume between the two balloons inside the bottle? That volume increases. Therefore, the larger the volume, the lower the pressure. Then we return to the snorkel and see if the students can apply that principle to the snorkel. Of course, in the snorkel case, the volume decreased, and the pressure increased.

Elephant Activity

In this activity, we use the fact that elephants can snorkel at a depth of 2 m, to initially engage the students and then provide them with the supplies to make the apparatus and explore what happens when snorkeling. Some leading questions to ask are:

“How can you make a setup to mimic snorkeling?”

“How is this snorkeling setup different from when you dive into the deep end?”

“How do you think the pleural space is different in the elephants compared with us?”

As an example, here is a sequence we have used. We start by telling the students that a key limitation to how deep one can snorkel is the water pressure that the pleural space can withstand. For humans, that is ~40 cm. However, elephants can use their trunk to snorkel, and that is ~2 m. Elephants are the only known animal that has a pleural space that is very fibrous and tough. We ask, “Could this be related to why they can snorkel so much deeper than humans (and other animals)? We want you to explore the effect of water pressure on structures under different conditions.”

We then provide the students with the materials and some general instructions, such as the following.

You have two different types of plastic bottles to mimic the human and elephant lung. In addition, there are PVC pipes,
tape, and a deep bucket of water. Determine which bottle collapses when connected to the PVC snorkel and placed into the water.

“How can you mimic holding your breath and diving deeply with this system?”

You can also put balloons on the nonbottle end of the PVC tubing and then submerge them.

“Do you think human lungs and elephant lungs are able to withstand pressure differently? Can you use a different bottle to mimic the elephant case?”

After completing the bottle exercise, we then talk about the pressures. At 2 m of depth, the pressure of the water is ~150 mmHg. Therefore, the veins need to be at a higher pressure than this in order for the veins to be open, say 160 mmHg. We ask, “If blood flows from capillaries eventually to veins, would capillary pressure be greater or smaller than venous pressure?”

Of course, to flow, it must be that capillary pressure is greater than venous pressure, so the pressure inside the capillary must be greater than 155 mmHg, say 190 mmHg. Such a high absolute pressure does not cause a problem for nearly all parts of the body, because the pressure outside the capillary is 150 mmHg, and, therefore, the net pressure across the capillary is only 190 − 150 = 40 mmHg, similar to the situation on land.

However, the pressure on the lung side of the pleural capillaries is atmospheric, or 150 mmHg less than the pressure inside the capillary. So, in the pleural capillaries, the net pressure across the capillary is only 190 − 0 = 190 mmHg.

This high pressure would presumably either break the capillaries or cause the movement of fluid from capillary to interstitial space, and that would create great problems (5). The current theory is that an evolutionary ancestor of the elephant had a mutation so that the connective tissue in their pleural cavity was increased, which protects the capillaries from rupture. This mutation provided a selective advantage.

**Conclusions**

Many students were fascinated by the elephant. Most students were amused by the comedy routine. The campers and school students were excited to solve the problem, and several worked out interesting ways to put together the bottle and PVC pipe apparatus. One particularly insightful student, after plunging in the bottle and PVC pipe apparatus a few times and trying the balloon, had the great idea of using a PVC pipe to connect two setups, while one of the bottles was in the water and collapsed. When he pulled the bottle out, it stayed collapsed. He then rotated the setup 180° and put the uncollapsed bottle in the water. It promptly collapsed, inflating the top, previously collapsed bottle. The rest of the students immediately did the same thing, and seemed to never tire of putting in a bottle, taking it out, rotating it 180° and putting in the other bottle. The crime scene scenario engaged some students. In these ways, we captured the students’ attention when otherwise many might roll their eyes when hearing about pressure and volume changes. After the activity, many had a better grasp of the pressures and, more importantly, had improved their problem-solving skills and ability to think critically and apply it to a novel situation.

**DISCLOSURES**

No conflicts of interest, financial or otherwise, are declared by the authors.

**AUTHOR CONTRIBUTIONS**

A.E.P., M.U., S.N.W., and M.A.M. performed experiments; A.E.P., M.U., S.N.W., and M.A.M. analyzed data; A.E.P., M.U., S.N.W., and M.A.M. interpreted results of experiments; A.E.P. and M.A.M. prepared figures; A.E.P. and M.A.M. drafted manuscript; A.E.P. and M.A.M. edited and revised manuscript; A.E.P., M.U., S.N.W., and M.A.M. approved final version of manuscript; M.A.M. conceived and designed research.

**REFERENCES**

1. **Milanick M, Prewitt RL.** Fact or fiction? General chemistry helps students determine the legitimacy of television program situations. *J Chem Educ* 90: 904–906, 2013. doi:10.1021/ed300155p.

2. **Quinlan CL.** Use of crime scene investigations in anatomy and physiology: potential for going beyond knowing in NGSS dimensions. *Am Biol Teach* 80: 221–226, 2018. doi:10.1525/abt.2018.80.3.221.

3. **Robischon M.** Blue tigers, black tapirs, and the pied raven of the Faroe Islands: teaching genetic drift using real-life animal examples. *Am Biol Teach* 77: 108–112, 2015. doi:10.1525/abt.2015.77.2.5.

4. **West JB.** Snorkel breathing in the elephant explains the unique anatomy of its pleura. *Respir Physiol* 126: 1–8, 2001. doi:10.1016/S0034-5687(01)00203-1.

5. **West JB.** Why doesn’t the elephant have a pleural space? *News Physiol Sci* 17: 47–50, 2002. doi:10.1152/nips.01374.2001.