HOW WE TEACH | Classroom and Laboratory Research Projects

A plumber’s guide to the cardiovascular system

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Washburn SE, Stewart RH. A plumber’s guide to the cardiovascular system. Adv Physiol Educ 44: 163–168, 2020; doi:10.1152/advan.00104.2019.—Blood flow through the cardiovascular system is governed by the same physical rules that govern the flow of water through domestic plumbing. Using this analogy in a teaching laboratory, a model of the cardiovascular system constructed of pumps and pipes was used to demonstrate the basic interactions of pressure, flow, and resistance in a regulated system, with student volunteers providing the operational actions and regulatory components. The model was used to validate predictions and explore solutions prompted by student discussion. This interactive teaching laboratory provides an engaging experiential exercise that demonstrates regulation of flow and pressure in an intact cardiovascular system with adaptive changes in heart rate and resistance. In addition, the system provides strong clinical correlates and illustrates how this regulated system responds to challenges such as heart failure, inappropriate vasodilation, and hemorrhage. The results demonstrate that, with limited practice, the instructor can effectively guide the students to reliably reproduce physiologically appropriate results.

INTRODUCTION

The goal for the development of this hands-on learning project was to construct an activity to actively engage students and model the complex interactions between cardiac function, vascular function, and the baroreceptor reflex. There is strong evidence that “active learning” is a powerful pedagogical approach for teaching physiology (5, 6, 8). Exercises with a strong participation component allow students to “learn by doing” and help them understand relationships and integrate information, both of which are critical for learning physiology. Active involvement in the learning process has been successfully applied in the physiology laboratory with an associated improvement in performance on exams, creative thinking, problem-solving skills and interpretation (2, 10). In addition, conducting a laboratory exercise with a guided-inquiry-based teaching approach further facilitates student learning (1).

Students often struggle with concepts underlying the function of the cardiovascular system. The results of previous research indicate that some of this difficulty arises because mastery of physiology requires causal reasoning; students believe that memorizing and learning are equivalent, and they encounter difficulties integrating material (7). Another contribution to the difficulty in learning these concepts arises because of the disconnect between the dynamic events that occur during the typical cardiac cycle and the static images used to depict these processes. As a result, students fail to create the rich mental models needed to master this information (3). Furthermore, students learn more when they are actively engaged than they do in a passive lecture environment, and extensive research supports this observation, especially in college-level science courses (4).

Using the analogy of plumbing, we constructed a model of the cardiovascular system using pumps and pipes, had the students operate it, and used it to demonstrate the basic interactions of pressure, flow, and resistance in a regulated system.

MATERIALS AND METHODS

The exercise was conducted during a regularly scheduled 2-h laboratory in the Physiology I course for first-year Doctor of Veterinary Medicine (DVM) professional students in the Texas A&M College of Veterinary Medicine & Biomedical Sciences DVM program. One model was used for the laboratory, which has ~75 students. While the activity was directed and led by the instructor, the activity was designed to actively engage students in problem solving and critical thinking. The activity was not designed as a demonstration, but rather an experiment in which the model was used to validate predictions and explore solutions prompted by student discussion. We have successfully employed this exercise at least twice a year for 21 yr.

The learning objectives for this exercise were that, at the conclusion of the exercise, students would be able to 1) explain the relationship between flow, pressure gradient, and resistance and know the appropriate units for each; 2) explain the effects of a pump rate and resistance on flow and pressure within a fluid circuit; and 3) explain how this system is regulated and, by extension, how the system responds to interventions such as decreases in pump activity (representing heart failure), resistance (peripheral vasodilation), and volume (hypovolemia).

List of Materials

The following are the materials used in this experiment (see Fig. 1):

- Jorvet 400-mL nylon dose syringe (Patterson Veterinary, item no. 078022232), quantity: 2
- 2,000-mL plastic graduated cylinder (VWR, item no. 470121–906), quantity: 2
- Flexible plastic tubing, 3/8 × 9/16 in. (VWR, item no. 89068–556), quantity: ~70 ft
- Keck tubing clamp, 14 mm (Cole-Parmer, item no. EW-06835–10), quantity: 3
- 1-Liter plastic bottle with lid (empty soda or water bottle), quantity: 2
- Block of wood (~16 × 12 in. and ~1 in. thick), quantity: 7

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• Wooden dowel rod (~1 in. diameter, at least 100 cm in height), quantity: 7
• ¾-in. Brady foot valve with spring (Grainger, item no. SFV-75), quantity: 2
• ¾-in. Brady line check valve (BubbleMac, Check Valve Brady ¾ in.; available from Amazon), quantity: 2
• Plastic zip ties, quantity as needed to secure tubing
• Plastic T-port connector, 10 mm (VWR, item no. 46600–060), quantity: 13
• Red food coloring
• Water, quantity: ~4 Liters
• Waterproof silicone glue (to glue T-connector into soda bottle cap)
• Mop and bucket (to comically illustrate the lymphatic system)
• Disposable paper hats/gowns for student role assignment with the following labels:
  - Right ventricle
  - Left ventricle
  - Sinoatrial node
  - Systemic vascular resistance
  - Baroreceptor reflex

**Assembly Instructions**

Drill a hole into the center of each wooden block (using 1-in. drill bit) and insert the dowel rod (1 in.) to make stanchions. Use wood glue if needed for additional support. Mark off 90 cm at 10-cm intervals from the table surface on each stanchion. Drill a hole in the center of each soda bottle cap and insert the stem of the T-port connector and glue the connector in place with waterproof silicone glue. Place the cap back on the bottle; do not glue the cap to bottle. Invert the bottle and secure it to a stanchion, such that the tubing can be attached to each end of the connector inserted into the cap. For the remaining five stanchions, attach a length of tubing ~100 cm, such that the fluid level that will appear in the tubing can be read using the dowel rod measurements (Fig. 2). Taping the tubing, rather than gluing, facilitates removal when draining and disassembling the model. Attach the remaining tubing and valves to the system (Fig. 1). Note that each of the foot valves connect to the end of a tubing segment and is then placed at the bottom of each of the plastic graduated cylinders (Fig. 1). Approximate lengths of tubing segments are shown in Fig. 3. These can be adjusted according to the size of the table used to hold the model.

**Description of Intact Apparatus**

The graduate cylinders (Fig. 1, see B) represent the central venous and pulmonary venous reservoirs from which the “ventricles” draw water. To create a ventricle to be manned by a student volunteer, a dose syringe (A) of a type used in veterinary large-animal medicine is connected to the system between two one-way valves: a foot valve (H) and a check valve (I). The foot valve is connected to the end of the tubing and positioned at the bottom of the graduate cylinder, allowing the dose syringe to draw water into the tubing. The check valve is...
positioned in the tubing line downstream from the dose syringe. The internal diameter of the tubing accommodates the barb fitting of the valve. Zip ties can be applied around the tubing for extra security. The plastic soda bottles (E) are positioned immediately downstream from each of the two check valves. The upright tubing segments are attached to the stanchions with masking tape for easy removal. The tip of the “venous” end of the tubing should be positioned beside the foot valve at the bottom of the graduated cylinders. This positioning should be monitored and maintained throughout the exercise. When assembled, the apparatus represents anatomic components of the cardiovascular system, as well as the related physical properties (Fig. 4). These include handheld pumps (cardiac chambers) that can change volume and contain unidirectional valves, the windkessel behavior of the soda bottle (arterial system), water column height (blood pressure), and flow through the tubing (blood vessels). See supplemental figures for pictures (all supplemental figures are available at https://doi.org/10.6084/m9.figshare.11619834).

Experimental Procedures

Preparation of the model and students before laboratory exercise. Once the model is assembled on a table, each of the two graduated
The protocol is as follows.

1. **THE PHYSICS OF FLOW.** The learning objective is to explain the relationship between flow, pressure gradient, and resistance and to know the appropriate units for each.

   The laboratory begins with a discussion of three concepts: 1) application of Ohm’s law to blood flow the vasculature; 2) a comparison of resistors in series and resistors in parallel; and 3) the relationship between pressure at the base of a column of water and column height. The principles of Ohm’s law are provided in the following equation:

\[
\text{Flow} = \frac{\text{Inlet pressure} - \text{Outlet pressure}}{\text{Resistance}}
\]

   The students are reminded that there must be a pressure difference for flow to occur. Ohm’s law is then applied to the systemic circulation, giving the following equation:

\[
\text{CO} = \frac{\text{MAP} - \text{CVP}}{\text{SVR}}
\]

   where CO is cardiac output, MAP is mean arterial pressure, CVP is central venous pressure, and SVR is systemic vascular resistance.

   If we assume that central venous pressure is zero, i.e., equal to atmospheric pressure, the equation can be rearranged to the following:

\[
\text{MAP} = \text{CO} \times \text{SVR}
\]

   This provides the rationale for regulation of mean arterial pressure by altering cardiac output and/or systemic vascular resistance. Factors affecting vascular resistance are discussed, with particular focus on the effect of radius. The difference between resistors in series and resistors in parallel are discussed using anatomic examples.

   A general discussion on hydrostatic columns follows, including the idea that pressure at the top of a water column is referred to as zero because it is normalized to atmospheric pressure. This concept of hydrostatic columns is developed by asking questions such as, “If the water column is 10 cm tall, what is the pressure at the bottom of the water column if measured in cm of water?” Answer: 10 cm of water. This discussion helps the students to interpret the meaning of the water column if measured in cm of water?" Answer: 10 cm of water.

   Experience will guide this choice. Materials should be available to identify the five student volunteers according to their roles: right ventricle, left ventricle, sinoatrial node, arteriolar resistance, and baroreceptor reflex. Our laboratory uses labeled disposable isolation caps and gowns for this purpose. We have been using this exercise for 21 yr and have had it fall both before and after the lecture material is delivered. It is our experience that is can be used effectively to either introduce or reinforce the concepts. The questions and verbal prompts throughout the exercise are posed to the audience as a whole. Students call out their answers, or individual students can be called on to answer.

2. **APPARATUS DESCRIPTION.** The students are provided a description of the apparatus detailing what each component of the model represents and how it works. This description stresses how the apparatus represents anatomic components of the cardiovascular system, as well as the related physical properties (Fig. 4). These include handheld pumps (cardiac chambers) that can change volume and contain unidirectional valves, the windkessel behavior of the soda bottle (arterial system), water column height (blood pressure), and flow through the tubing (blood vessels). At this point, the red food coloring has not been added to the water in the apparatus. Note that the windkessel behavior of the soda bottles not only provides a discussion point for the behavior of large arteries, but is also essential to the proper function of the apparatus. In the absence of the bottles, water shoots from the upright tubing segments during systole.

3. **GENERATING FLOW.** The learning objective is to explain the effects of a pump rate and resistance on flow and pressure within a fluid circuit.

   The instructor points out that there is currently no flow through the apparatus and asks for suggestions. The students will suggest that the ventricles need to pump, prompting the instructor to ask for two volunteers. The volunteers are outfitted with the disposable caps and gowns marked “left ventricle” and “right ventricle.” They are issued two operational rules: 1) when pumping, the handheld pump should not be completely filled or emptied; and 2) the “ventricles” cannot look at each other. The first rule ensures that stroke volume is adjustable, whereas the second prevents direct coordination between the “ventricles” to match heart rate or stroke volume.

   The instructor asks the “ventricles” to begin pumping. The food coloring is then added to one of the graduated cylinders, allowing the audience to appreciate the direction of flow as the dye moves through the apparatus. If leaks are observed, the instructor can note that the apparatus includes a lymphatic system and demonstrates this by use of a mop.

   Usually, after 1 or 2 min, the volumes in the two graduated cylinders are clearly different. At that point, the instructor stops the action and asks the audience why this is so. When someone proposes that the ventricles should pump at the same time, a third volunteer is requested and asked to don a cap and gown and play the role of the “sinoatrial node.” The “ventricles” are informed that they should initiate the downstroke of each beat when the “sinoatrial node” says, “Pump.” The “sinoatrial node” is asked to establish a steady cadence and allow 2–3 s for each beat.

   The “sinoatrial node” is instructed to start. Often, after a few minutes, the difference in volumes in the graduated cylinders reoccurs. The action is stopped, and the audience is asked for suggestions. When someone suggests that the stroke volumes need to be the same, we ask how that is to be accomplished in a system where the “ventricles” have no direct coordination. The instructor guides the discussion to the recognition that each “ventricle” can make the appropriate adjustments by monitoring the volume in the graduated cylinder from which they are pumping. When the volume increases, the stroke volume should be increased, and, when the volume decreases, the stroke volume should be decreased. We extend the analogy to the Frank-Starling mechanism, explaining that an increase in end-diastolic volume (preload) leads to an increase in stroke volume. The “sinoatrial node” is restarted with this additional rule in place, and pumping is continued long enough to observe that the system behavior is now quite stable. The hand pumps used to create flow in the described apparatus are unaffected by changes in preload, which is an advantage in a teaching laboratory, as it requires the student volunteer “ventricles” to make the adjustment consciously. This requirement promotes a discussion with the class concerning the specifics of that adjustment and how the Frank-Starling mechanism in true ventricles produces an analogous adjustment.

4. **SYSTEM REGULATION.** The learning objective is to explain how this system is regulated.

   At this stage, the instructor can discuss alternative regulatory mechanisms capable of providing appropriate blood flow to various tissues in light of changing metabolic needs. That discussion highlights the need to maintain a sufficient upstream (mean arterial) pressure and, subsequently, the role of mechanisms necessary to monitor and manipulate that pressure. The last of the student volunteers, the fourth and fifth, are sought. One plays the role of the “arterioles” and the other acts as the “baroreceptor reflex.” The
“arterioles” will manipulate the tubing clamps to adjust resistance by “clamping down” or “opening up.” The “baroreceptor reflex” will attempt to maintain a target mean arterial pressure by altering heart rate via the “sinoatrial node” and resistance via the “arterioles.” The water column height varies between systole and diastole. It is important to point out that the mean pressure is best approximated as the midpoint in this cycle.

We then provide our final instructions to the volunteers. We direct the “sinoatrial node” and “arterioles” to respond to the demands of the “baroreceptor reflex.” We direct the “baroreceptor reflex” to monitor mean arterial pressure (the average water column height in the systemic arterial pressure stanchion) to provide appropriate instructions to “sinoatrial node” and “arterioles.” That guidance indicates that the “baroreceptor reflex” should call for the “sinoatrial node” to “speed up” and the “arterioles” to “clamp down” when the arterial pressure column is too low and, conversely, call out to “slow down” and “open up” when the column is too high.

An audience member can be recruited to monitor “heart rate.” This information can be utilized by the audience to appreciate changes in system behavior. However, the most important feedback mechanism for the audience comes about by listening to the “baroreceptor reflex” and the “sinoatrial node.” The “sinoatrial node” is calling out, “Pump... pump... pump...” and the “baroreceptor reflex” is calling out, “Speed up... clamp down... slow down.” The audience can easily identify changes in the instructions and the pump cadence in response to the interventions described. Therefore, the “baroreceptor reflex” and “sinoatrial node” are encouraged to speak out clearly, and the audience is instructed to listen carefully.

In the authors’ laboratory, the target arterial pressure is set as an average water column height of 65 cm. This value will depend on the apparatus constructed and the experience of the instructor. Once the volunteers are clear in their duties, the “sinoatrial node” is asked to restart the pump. Once equilibrium is achieved, the prevailing conditions are noted as being the baseline against which the results of three subsequent interventions are to be evaluated. Those interventions are heart failure (left or right), inappropriate arteriolar vasodilation, and hypovolemia.

5. INTERVENTIONS. The learning objective is to explain how the system responds to interventions such as decreases in pump activity (representing heart failure), resistance (peripheral vasodilation), and volume (hypovolemia).

The following three interventions are then demonstrated so that the students can see and, importantly, hear how the model responds. For each of these, the intervention can be instituted after pumping has begun. This makes it easier for the audience to appreciate the changes in regulatory activity. Each of these scenarios needs to run only 1 or 2 min for the audience to appreciate the effects.

Left (or right) heart failure: If one of the students acting as a ventricle begins to tire, it can provide a humorous opening for the demonstration of heart failure. If not, the instructor can actively interfere with one “ventricle’s” ability to pump by grasping the stem of the dose syringe with a gloved hand. If the left ventricle is targeted, the following effects will be observed. Due to a fall in cardiac output and mean arterial pressure (i.e., water column height), the “baroreceptor reflex” will call out, “Speed up... clamp down... speed up... faster... clamp down more.” The cadence of the “sinoatrial node” will increase accordingly. In addition, the cylinder out of which the left ventricle is pumping will begin to overflow, and the water column height in the pulmonary capillary stanchion will increase.

Based on the observed responses in the model, the audience is asked to predict the expected clinical findings in a case of left-sided heart failure. Those findings should include an elevated heart rate, cold limbs caused by peripheral vasoconstriction, and pulmonary edema. They are then asked how right-sided failure might present differently. The concept of shock with its causes and manifestations can be introduced at this point. In addition, the stage is set for discussion of the impact of elevated venous pressure on capillary pressure and edema formation. It is pointed out that left-sided heart failure often leads to pulmonary edema, whereas right-sided failure leads to peripheral edema.

Inappropriate arteriolar vasodilation (septic shock, maldistribution shock): The “arterioles” are instructed to dilate maximally by removing the tubing clamps completely. The “baroreceptor reflex” is warned that the “arterioles” are no longer responsive to their demands, even though the target pressure is completely unchanged. The class will see that the model responds by markedly increasing heart rate with no corresponding ability to increased vascular resistance. The clinical correlate is a patient with a high heart rate and warm limbs.

Hypovolemia: The “arterioles” are reinstated to normal function. Fluid is removed from the system by detaching one of the standing tubes from its stanchion and lowering the tip sufficient to “hemorrhage” into a pitcher. Enough water is poured out to reduce the water level in the system by ~30% and the simulation is run again. If the instructor feels the effects are not large enough, more water can be removed, as long as caution is taken not to remove so much water that the foot valves are allowed to draw air. When pumping is restarted, the audience will hear the “baroreceptor reflex” urging the “sinoatrial node” to “speed up” and the “arterioles” to “clamp down.” The observed response of a high heart rate and peripheral vasoconstriction is then related to the patient with an elevated heart rate and cold limbs.

The following questions can provide useful prompts for discussion as the exercise is conducted.

• What is the effect on the systemic pressure gradient, i.e., the difference between mean arterial pressure (MAP) and central venous pressure (CVP), when the pumps are not active? What are the effects on MAP and CVP when the pumps are turned on? What are the effects on MAP and CVP of speeding up the pumps or slowing down the pumps?
• What is the effect on the systemic pressure gradient when the radius of the systemic arterioles is decreased? What change in systemic vascular resistance occurs when the radius of the systemic arterioles is decreased?
• What happens when right and left cardiac outputs are not matched?
• What would happen in the absence of a baroreceptor reflex?
• What is the effect on pulmonary capillary pressure when left ventricular pump function is impaired?
• How could the intestinal bed be protected from the increase in capillary pressure associated with increased MAP?
• What is the effect on MAP and heart rate (HR) when systemic arteriolar resistance is decreased, as seen in inappropriate vasodilation?
• What is the effect on MAP, HR, and systemic vascular resistance (SVR) when blood volume is decreased as seen in hypovolemia?

To ensure the success of this exercise, the instructor should attend closely to four important points regarding the student volunteers: 1) The “ventricles” should not look at each other so that they will not be tempted to coordinate rate and stroke volume; 2) the “sinoatrial node” should not watch the arterial pressure column and respond to it instead of to the “baroreceptor reflex”; 3) the “baroreceptor reflex” should understand that the mean pressure in the arterial column is best approximated by the column height as the midpoint between the systolic and diastolic extremes; and 4) the “baroreceptor reflex” should issue commands that are clear and loud so the audience can clearly appreciates calls to “speed up” and “clamp down.”

DISCUSSION

This teaching laboratory provides an engaging interactive exercise for students. The modeling provides an excellent visualization of the complex interactions between pressure, flow, and resistance in a regulated system, including an important clinical correlation in how the system responds to challenges such as heart failure, inappropriate vasodilation, and
hemorrhage. It provides an opportunity for students to engage in the process of building, testing, and refining mental models. Having an instructor present to prompt verbal predictions strengthens this learning (9). We have not attempted to measure specific changes in learning outcomes, but we have observed increased student engagement and active audience participation, based on the number of comments and questions from students. It is an easily affordable, valuable, and easily replicated exercise in cardiovascular physiology. With limited practice, the instructor can effectively guide the students to reliably reproduce physiologically appropriate results. For example, in 21 yr of conducting this exercise at least twice a year, every demonstration of hemorrhage, i.e., volume removal, resulted in increased heart rate and arteriolar constriction. One minor limitation is that the model does not allow changes in ventricular contractility. We also appreciate that, in the body, the ventricles are electrically connected, and this is not the case in the model. However, in the model, the instructions to the “ventricles” to “contract” are in response to the cue from the “sinoatrial node,” which ensures they are coordinated.

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DISCLOSURES

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

AUTHOR CONTRIBUTIONS

R.H.S. conceived and designed research; S.E.W. and R.H.S. performed experiments; S.E.W. and R.H.S. analyzed data; S.E.W. and R.H.S. interpreted results of experiments; S.E.W. and R.H.S. prepared figures; S.E.W. and R.H.S. drafted manuscript; S.E.W. and R.H.S. edited and revised manuscript; S.E.W. and R.H.S. approved final version of manuscript.

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