Get Pumped!

Target Grade: Elementary/Middle
Author(s): Sophie Yu (Module 2 adapted from Lindsay Zhang's lesson)
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Brief Overview

In this lesson, mentees will be learning about the crossover between physics and biology in the cardiovascular system! In module 1, we will be using the **continuity equation** to discuss the relationship between vessel radius and velocity of blood flow and explore blood flow through the heart. In module 2, students will model the surgical procedure, balloon angioplasty, for widening a narrowed artery or vein.

Main Teaching Goals

- The **cross sectional area** of a vessel is inversely related to the **velocity** of blood.
- Blood circulates through the **atrium**, through a heart valve, into the **ventricle,** through another heart valve, before leaving the heart.
- What are the benefits and drawbacks of a **model**?
- Clogged arteries can result from the accumulation of fats known as **atherosclerosis**
    - A **balloon angioplasty** one method to surgically repair a blocked blood vessel using an inflatable balloon.
- **Engineering Design Process:** series of steps that engineers follow to come up with a solution to a problem.

Careers and Applications

The circulatory system is one of the central organ systems of the body. It is essential for the transport of nutrients, wastes, hormones and many other important compounds throughout the body.
In addition, heart disease is also the leading cause of death in America. Thus, healthcare workers from doctors to nurses to emergency medical technicians must be familiar with the basic functions and structure of the circulatory system in order to help their patients.

Agenda

- Introduction
- Module 1: Follow your heart (20 min)
    - Model 1A: Beating heart (5 minutes)
    - Model 1B: Heart circulation (10 minutes)

- Module 2: Is it all in vein? (40 min)
- Conclusion

Introduction

This lesson is a series of demos and modules leading up to the final project, unclogging a blocked blood vessel! For this entire lesson, challenge students to think about the cardiovascular system from an engineering/physics perspective. Based on last week's lesson, cater this lesson to your own site!

To start off the lesson, recap last week's lesson by asking what the students learned about heart valves and the cardiovascular system. Expand upon last week's concepts by asking them to feel for their radial (on the wrist closer to the thumb) or carotid pulses (side of the neck). They should feel a strong heartbeat as the heart contracts and relaxes, pushing blood through these major vessels.

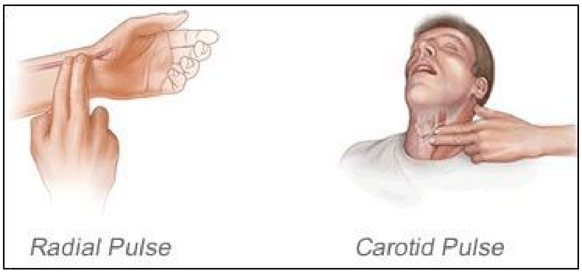

Figure 1: Radial and Carotid Pulse

The **circulatory system**, also known as the **cardiovascular system**, transports nutrients, oxygen, carbon dioxide, hormones, and blood cells around the body. Humans have a **closed** cardiovascular system, which means that the blood never leaves the system of vessels. The main vessels of the cardiovascular system include: **arteries,** arterioles, **capillaries,** venules, **veins.** We will mainly be focusing on the **arteries** which take blood away from the heart, the **capillaries** which are the smallest blood vessels of the body and the site of resource exchange, and finally the **veins** which return blood back to the heart.

Ask the students what aspects of the structure of the arteries, veins and capillaries enable them to do their own respective jobs. Arteries receive blood directly from the heart (extremely high pressure!). They have *thicker* walls which are less prone to damage while *elasticity* allows the arteries to expand with the sudden change of pressure and recoil, pushing the blood forward. The veins must often counteract gravity to push blood back up to the heart from the lower extremities. Blood in the veins in also generally at a low pressure. The veins have *one way valves*, kind of like the valves of the heart, which keeps the blood flowing in one direction. The capillaries are important for diffusion! The walls of the capillaries are often very thin, made of 1 layer of cells! In addition, capillaries are adjacent to almost every cell in the body, **creating an extremely large overall cross sectional area!**

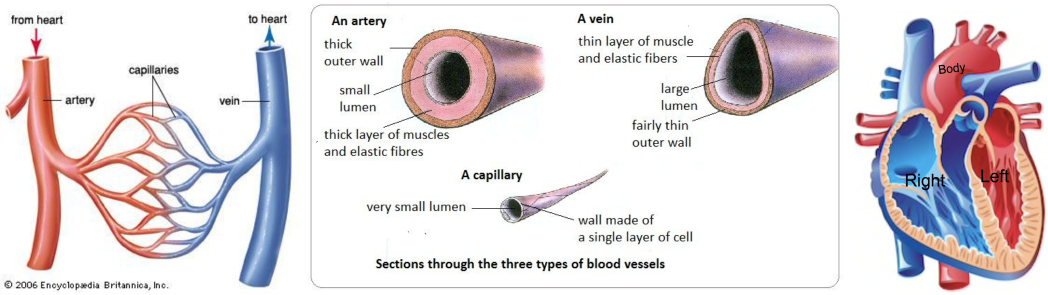

Figure 2: Vessels of the Cardiovascular System and the heart

The cardiovascular system is powered by the **heart**. The human heart is a four chambered organ. The upper quadrants are known as the **right and left atrium** respectively. The bottom quadrants are known as the **right and left ventricles**. The left and right side are separated by a muscled wall. The right side of the heart receives blood from the body and pumps it to the lungs to exchange CO2 for O2. The blood returns from the lungs to the left side of the heart where it is pumped to the rest of the body. The muscles of the **left ventricle** of the heart are much thicker than the right side to enable the heart to contract and pump the blood throughout the body. But how does contraction generate blood flow and pressure? The contraction of the muscles of the left side of the heart acts like a pump pushing the blood out of the aorta. A helpful analogy to explain this concept to the students could be relating the pumping of the heart to a bicycle pump.

Module 1: Follow your Heart

Introduction

In this module, mentors will focus on teaching the inverse relationship between cross sectional diameter and fluid velocity. In addition, mentors will also be modeling how the heart contracts, pushing blood throughout the body. These concepts are illustrated through the use of a mason jar and different diameters of straws to simulate the vessels. For this module, make sure that mentors know how to build the models to save time!

Teaching Goals

- The heart contracts, increasing blood pressure, and pushing blood into the arteries
- A larger vessel/straw diameter results in more flow while a smaller diameter results in more flow according to the **continuity equation.** More flow means water is moving at a faster velocity.
  - Capillary beds slow down the flow of blood, allowing nutrients/wastes enough time to move in and out of the cells.
- Blood circulation through the heart involves passing through 1) **atrium** 2) heart valve 3) **ventricle** 4) heart valve before exiting the heart.

Background for Mentors

Once the blood leaves the heart, it travels throughout the arteries, veins, and capillaries. When dealing with an **incompressible fluid** (fluid with constant density), the **continuity equation** applies. This equation states that the **cross sectional area** of a vessel multiplied by the fluid's **velocity** must stay constant. As a result, if the cross sectional area of a vessel increases, the velocity decreases.

Continuity equation: $A_1v_1 = A_2v_2$

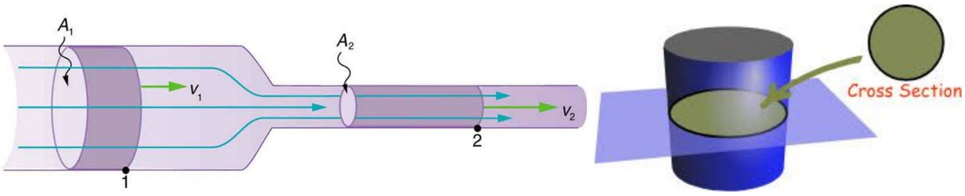

Figure 3: Continuity Equation

In the above image, v1 is smaller than v2 because A1 is larger than A2. To explain this to the students, use an example of a water hose. If a person turns on the water in a hose, the water will flow at a certain rate. However, if the person blocks off the hose opening a bit with a finger, the water will flow out much faster.

Important Note:

Therefore, theoretically, in larger vessels, blood flows at a slower rate. In narrower vessels, blood flows at a faster rate. We would expect that in the capillaries, which are the thinnest, blood should flow really quickly, but in **reality, the blood actually flows very slowly. This is because there are many, many, many capillaries throughout the body.** ***So the overall cross sectional area of all the capillaries combined is very large!***

In the second model, mentors will be focusing on blood flow through one side of the heart (right atrium, heart valve, right ventricle, and into the pulmonary circuit). Explain to students that the heart pumps blood from the atrium through a one way valve to the ventricle which then pumps the blood into an artery. Specifically, point out to students that the water in the jar on the left is and jar in the middle are equilibrating as small amounts of water are drawn from left to right.

For a fun demo, students can feel the straw connecting the left most and middle jar, the straw should feel cold to the touch because it is filled with water! To connect this module with last weeks, mention that the balloons tied to the ends of the straws simulate one way valves, keeping blood flow going in only one direction!

Note: This model also applies for the left side of the heart if so the designations of the jars are in brackets.

From left to right:
Mason jar 1: right atrium [left atrium]
Mason jar 2: right ventricle [left ventricle]
Mason jar 3: artery and into the pulmonary circuit [aorta and into the body]

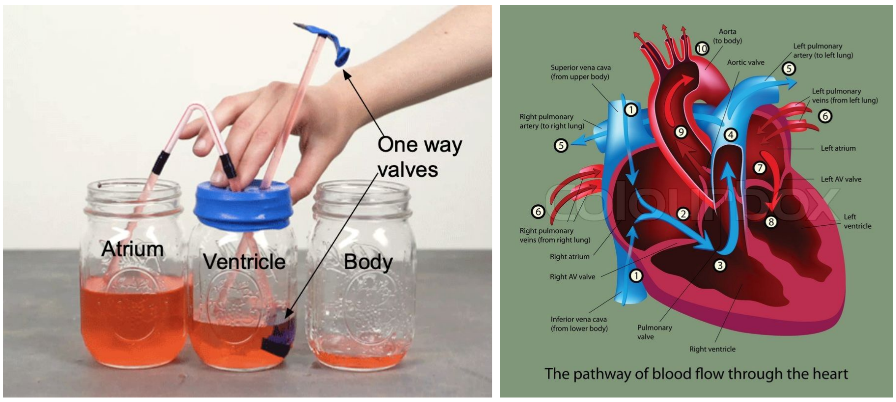

Figure 4: Model 2 of circulation through the heart and heart circulation

To reinforce the concepts of the second model, mentors can help mentees trace blood flow through the heart on a labeled heart diagram. Make sure to emphasize that the blood always returns back to the heart.

Both parts of this module involve models. What exactly is a model? A **model** is a representation using general concepts. Despite the fact that they are useful for illustrating some key points about the circulatory system, our model is not perfect. Models are built based on general concepts which doesn't necessarily mean that it will incorporate all of the intricacies of reality. It is important to discuss some of the pros and cons of a model with the mentees after the demo (sample pros and cons listed in the procedure section).

Materials

Note: some materials overlap between models 1 and 2

- Both models 1 and 2:
    - Mason jars: 3 per site (labeled atrium, ventricle, body)
    - Scissors: 2 pairs per site
    - Tape: 1 roll per 15 students
    - Paper towels: 1 roll per 10 students
    - Red food coloring: 1 per site
    - Site box
    - Water
- Model 1:
    - Rubber bands: 3
    - Red balloon: 4 (1 extra)
    - Straws: 3 (1 extra)
    - Plastic pipettes: 3 (1 extra)
    - Plastic boba straw: 3 (1 extra)
    - Wooden skewer: 2 per 10 students
- Model 2:
    - Red balloon: 2
    - Straws: 3

Procedure

For both sections, emphasize the pros and cons of a model:

1) What are the **pros** of this system?
    a) Model 1 simulates the pressure change needed to pump blood
    b) Model 2 illustrates how blood travels only in one direction
2) What are the **cons** of the system?
    a) Model 1 doesn't have one way valves
    b) Model 2 doesn't have blood that recirculates
3) These are just some examples! I'm sure your mentees can think of more :)
4) Despite the fact that there are pros and cons, by using more than one model, we can get a better idea of the overall system!

Beating Heart Model

1. Use the scissors to cut the bulb off of the pipette, discard bulb. (Figure 6g)
2. Take the balloon and cut off the stem area. (Figure 5e)
3. Fill the mason jar ¾ of the way with water, add 2 drops of red food coloring
4. Stretch the balloon over the edge of the mason jar so that it is taut. (Figure 5a)
    a. Wrap a rubber band around the edge if it helps keep the balloon in place (Figure 5b)
5. Use the wooden skewer and poke two small holes in the balloons. Keep the holes as small as possible while still allowing a straw to go through.
6. Set aside one jar for each type of “vessel.” (boba straw, normal straw model, pipette)
    a. *For the pipette and smaller straws use small mason jars.*
7. Thread each designated “vessel” through the holes of the balloon make sure the ends of the “vessels” are in the water. (Figure 5d)
    a. For the thin straw, thread the side without the bend into the balloon.
    b. For the boba straw, thread sharp side in.
    c. For the pipette stem, thread the wider side in,
8. Place models in the site box to catch the water. (Figure 5e)
9. Push down on each of the models and water will flow out of the straws. (Figure 5f) In which model is water flowing fastest? Why?
    a. Should be the pipette because of small cross sectional area,
    b. The boba straw should have the slowest moving water. In fact, it may be so slow that the water can’t even come out of the artery!
    c. These differences are visible because we are using the same pressure!

Figure 5 a-f: Building the Model

Figure 6 g-i: Making a Model Heart

Blood Circulation Model:

1) Using the model built with the normal straw vessels, extract the straw on the left side. Be careful not to damage the balloon,
2) Use a new straw and take the end that isn't bent and cut off the segment until the bend. (Figure 7b)
3) Next, use scissors to cut a very small incision in one side of this straw segment
4) Take the straw you extracted from the model and insert the end closer to the bend into the straw segment from step 3. (Figure 7c)
5) Tape the part where the straws meet. (Figure 7c)
6) Next, insert this straw back into the balloon. Remove the balloon from the mason jar. (Figure 7e)
7) On the end of the straw from step 5 that has been threaded through the ballon tape the neck of a balloon to simulate a heart valve, (Figure 7a)
8) On the end of the other straw, attach another balloon neck.
9) Set up the model like in figure 5 with the atrium on the left, then the heart, then the ventricle on the right.
10) Add water into the middle jar to about ¾ level. Fill the jar connected with the straw. Add food coloring. (Figure 7h)
11) Push down slowly on the balloon. Initially, the water level will drop in the middle jar and move toward the empty jar. However, have student observe that water will also be pulled from the jar on the other side to make up for the water lost from the middle jar. *Give enough time for water levels to equilibrate otherwise the effect won't be noticeable!*
    a) If mentees don't believe that the water is actually being pulled to the middle jar, have them feel the straw connecting left most and middle jar. It should feel cold to the touch due to the water filling the straw

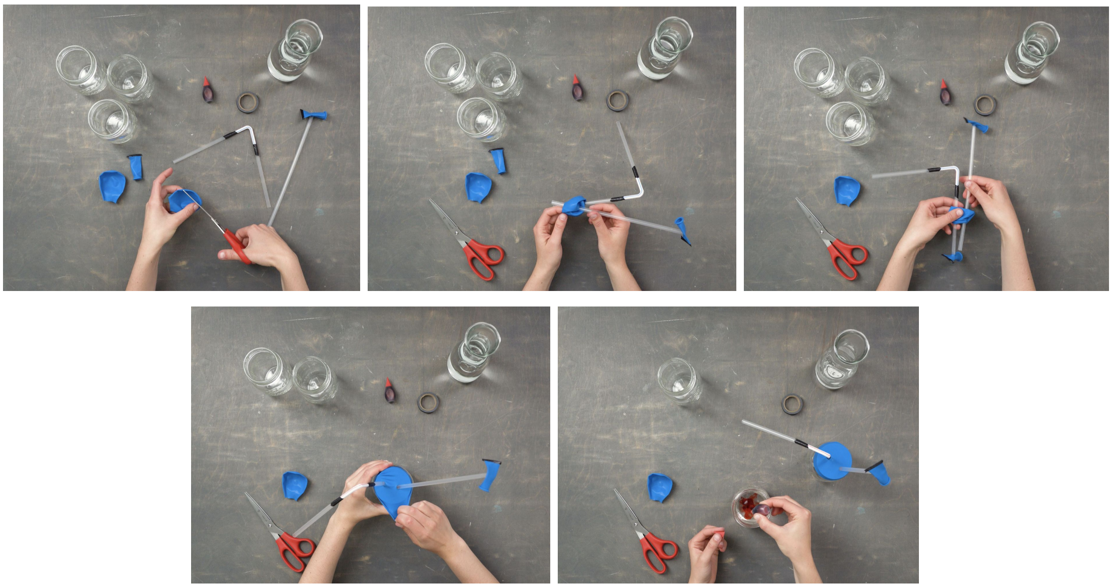

Figure 7 a-h: Model 2

Additional Notes for Mentors

If your kids don't do as well with models, mentors can have the kids participate in the building process (like sticking the straws into the balloon or pushing down on the balloon cover).
Model 1: Use the bigger jar for the boba straw demo and the smaller jars for the pipette and smaller straw demos. Specifically for the pipette demo, they are short, so make sure that the pipette is in the water. Make sure to keep the balloon secured and taut but not too tight. Water may need to be refilled occasionally. Also, make sure the holes aren't too big otherwise the system won't be air tight. When sticking in the straws consider folding the ends to make them smaller to more easily fit into the holes. In addition, make sure to emphasize that what is important is the *overall* cross sectional area of certain type of vessel that determine the velocity of blood flow. In the capillaries, blood flow is the slowest!
Model 2: Make sure to push slowly and give enough time for the water levels to equilibrate!

Module 2: Is it all in vein?

(adapted from Lindsay Zhang's lesson, Fall 2016)

Introduction

As we have established through the circulatory system model, the vessels are essential for carrying blood around the body. What happens when one of these vessels is clogged? In this module, we will be using PVC pipe and playdough to demonstrate a surgical procedure known as a **balloon angioplasty**. What sort of engineering design choices could the students make to unclog a vessel?

Teaching Goals

- Fixing a clogged demo artery
    - Engineering Design Process!
        - What engineering choices can your mentees make to unclog an artery as quickly as possible?

- One example of a common real life fix that students can adopt as part of their designs is a **balloon angioplasty**: the surgical repair of a blood vessel using an inflatable balloon.

Background for Mentors

Coronary heart disease is the second leading cause of death for people 15-59 years old. The major established contributors to coronary heart disease include tobacco use, alcohol use, high blood pressure, high cholesterol, physical inactivity, poor nutrition, and obesity.

A common illness of the circulatory system is **arteriosclerosis**, the accumulation of fatty deposits, causes arteries to be blocked. These deposits stiffen/thicken the walls of arteries. This slows down or stops the flow of blood which can lead to high blood pressure, blood clots, heart attacks, and strokes. Treatment involves rest, exercise, diet changes, and various medications. In some cases, surgeons may remove clots or replace blood vessels with an angioplasty!

There are three main ways of dealing with arteriosclerosis, two different kinds of coronary angioplasty and coronary bypass surgery. **Angioplasty** is the surgical repair of a blood vessel using an inflatable balloon. A catheter, which is a hollow, flexible tube, is used in angioplasties. In the case of the balloon catheter, a catheter with an inflatable tip is used to expand a partly closed artery. In the second case, a stent is placed on top of the balloon catheter, which is then inflated in the artery. The stent expands and keeps the artery open. A Coronary artery bypass surgery uses a piece of a vein from the leg or artery from the chest or wrist. The piece of artery/vein is attached to the coronary artery above and below the blockage so the blockage can be bypassed.

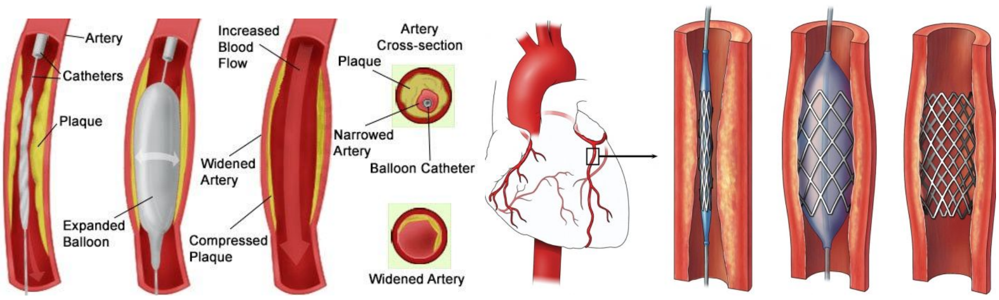

Figure 8: Stent Balloon Angioplasty versus Balloon Angioplasty

In this module, the students will be designing their own balloon catheters. How can they use their limited resources to maximize the efficiency of their tool?

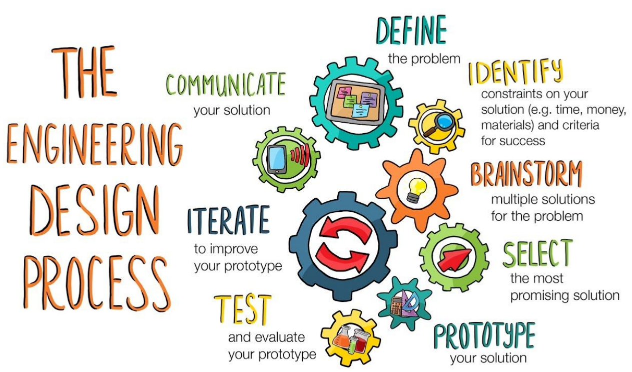

Figure 9: Engineering Design Process

The **engineering design process** is a cyclic process requiring multiple steps in order to solve a problem. For students, it is important to emphasize the iterative nature of this process, because almost no experiments/designs in real life succeed the first time around! Mentors can work with mentees to design a unique tool, put it to the test, and refine the model.

Materials

Each group needs:

- Model "blocked arteries": 1 per 4 students
    - Playdough: 1 can per 2 models
- Clown balloons (long and thin): 2 per 4 students
- Air pump, for clown balloons: 2 per site
- Boba Straws: 2 per 4 students
- Regular Straws: 2 per 4 students
- Paper clips: 2 per 4 students
- Thin wire: 2 per 4 students
- Pipe cleaner: 1 per 4 students
- Rubber bands: 4 per 4 students
- Aluminum foil (approx 1 foot x 1 foot piece): 1 per 4 students

For the entire class to share:

- Water source
- Site boxes: 1 per site
- Phone timer: 1 per 8 students
- Mason jar: 1 per 8 students
- Tape: 1 roll per 10 students
- Paper towels: 1 roll per 10 students

Procedure

- Creating a clogged artery:
    - Stuff a handful of clay into the PVC pipe, ensure that there is a hole about 1 cm in diameter through the clay. Make sure that the clay isn't stuffed right at the end which would be easy for the students to just pull out and will also make it harder to test.
    - *Tip:* First clog the tube and then use a straw to poke a hole through the center. Make sure this is one of the straws you don't need!
    - Clog all the arteries except for 1. Leave that one clean for a control measurement. Then clog it as well.

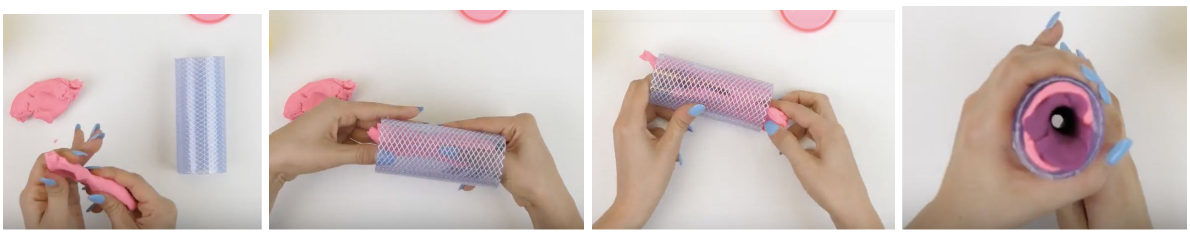

Figure 10: Making the clogged artery

- **Controls:** In front of the class, hold the "artery" at a *60 degree angle* and pour 1 mason jar of water through the clean PVC pipe and time it. Pour 1 mason jar of water into the clogged PVC pipe at the same angle and time it (make sure water doesn't spill over the sides. (5 minutes)
- **Brainstorm:** Split students into groups of 4 to think of ideas on paper. (10 minutes)
- **Purchase materials [for advanced sites]**: Allow groups to come up one at a time to "purchase" materials. (5 minutes)
    - Keep track of how many points they spend based on the attached materials list and point values.
- **Build:** Groups build their artery declogger and test on their own test artery, allow students to "purchase" more materials as necessary. (20 minutes)
    - **If students are stuck**, try the following steps to lead them through the most simple balloon catheter design.
        - Ask students what their goal for their tool is:
            - Their goal should be to create an opening through the playdough.
        - Next, ask them what sort of tool they think could be used to enlarge the hole:
            - Possibilities include:
                - The **thin wire** could be used to scrape away the excess clay
                - Maybe the **balloon** could be expanded to push the clay aside
        - Encourage the students to make their own modifications to make their tool more unique
    - Examples:

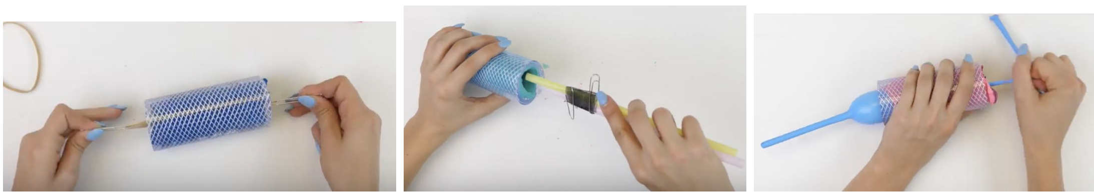

Figure 11: Sample artery "decloggers"

- **Testing:** One by one, groups test their declogger in front of everyone else, 1L of water is poured through and timed. The winning group has the fastest time for all the water to flow through with a reasonably low point expenditure (allow mentors to decide on this). In addition, mentors can also time how long students take to actually unclog the artery as a tiebreaker. [for advanced sites] (10 minutes)
- **Reflection:** Have the students consider how their designs could have been improved! Would this design be feasible for an actual operation? (5 minutes)
- **Repeat:** If there's extra time, encourage students to make more modifications to see if they get better results.

Material	"Cost"
Long, thin balloons	3 points per

Straws	1 point per
Wire	2 points per foot
Paper Clips	1 point per 2
Pipe Cleaners	2 points per
Rubber Bands	1 point per 2
Tape	2 points per foot
Foil	3 points per square

Conclusion

Through these two cardiovascular engineering lessons, students have been exposed some of the applications of engineering in a healthcare setting. Currently, biomedical engineering is more important than ever as America's aging population expands and there is an unprecedented demand for more sophisticated medical devices that can provide more efficient and effective care.

To recap this lesson, ask students what they have learned about engineering from the past two lessons. How were they able to apply the thought processes of an engineer to biological topic? Has their opinion of engineering changed?

References

- Lindsey's lesson: http://beam.berkeley.edu/lessons_archive/artery.pdf
- Carotid/radial pulses: https://www.pinterest.com/pin/365565694723888271/
- Artery, capillary, vein: https://s-media-cache-ak0.pinimg.com/
- Structure of arteries, capillaries, veins: https://www.pdhpe.net/the-body-in-motion/how-do-the-musculoskeletal-and-cardiorespiratory-systems-of-the-body-influence-and-respond-to-movement/circulatory-system/structure-and-function-of-the-heart-arteries-veins-capillaries/
- Continuity equation: https://physics.info/flow/
- Model heart: https://www.pinterest.com/r3antonich/
- Heart: https://www.shutterstock.com/search/valves+of+the+heart
- Cross sectional Area: https://www.mathsisfun.com/definitions/cross-section.html
- Continuity Equation: https://courses.lumenlearning.com/boundless-physics/chapter/fluids-in-motion/
- Beating Heart Module: https://www.kiwico.com/diy/Science-Projects-for-Kids/3/project/Pumping-Heart/2883

Summary Materials Table

Material	Amount per Group	Expected $$	Vendor (or online link)	Reusable?
Mason Jar	3 per site	$29.99 (pack of 30)	Amazon/Inventory	Yes
Rubber Band	3 per site	$5.99 (pack of 600)	Amazon	Yes
Red Balloon	4 per site		Inventory	No
Straws	3 per site		Inventory	No
Plastic Pipette	3 per site		Inventory	No
Red food coloring	2 per site		Inventory	Yes
Boba Straw	3 per site		Inventory	
Wooden skewer	2 per site		Inventory	Yes
Scissors	1 per 4 students		Inventory	Yes
Tape	2 rolls per site		Inventory	Yes
Paper towels	1 roll per site		Amazon	
Clown balloon	2 per 4 person small group		Inventory	Maybe
Clown balloon pumps	2 per site		Inventory	Yes
Paper clips	4 per 4 person small group		Inventory	No
Thin wire (2 foot each)	2 per 4 person small group	$3.82 (40 yards)	Amazon	Yes
Pipe cleaner	2 per 4 person small group	$6.99 (200 pipe cleaners)	Amazon/Inventory	No
Aluminum foil	2 feet per 4 person small group		Inventory	Maybe
Clay	~1 pound per site	$8.91 * 2	Inventory/Amazon	Yes

PVC pipe	4, 4 inch tubes per site	$19 (5 feet)	McMaster/Inventory Masterkleer PVC Clear Tubing, 1-1/4" ID, 1-5/8" OD	Yes
Points paper print out/heart print out	1 per group of 4 students			
Balloon pumps	2 per site	$3.79 for 5 * 2 = (12 pumps in total)	Amazon/Inventory (2 in inventory are functional)	