Cornell Institute for Biology Teachers

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Title:

The Physiology Behind How Blood Vessels Work

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Appropriate Level: Advanced Placement, Honors, or Regents

Abstract: This laboratory addresses the physical mechanisms by which our blood vessels function in allowing the circulatory system to do its job. Blood vessels are not simply rigid tubes that conduct blood to our tissues like copper pipes carrying water to our houses, nor are they infinitely extensible balloons that can accommodate any amount of blood pressure or volume. In fact, blood vessels have a complex material composition that allows them to do several different jobs and change their function depending on the situation. In essence, blood vessels are a dynamic tissue rather than a static one. Just as with other organs of the body, blood vessels are complex in nature because of the demand for their complex function. When a disease state changes these properties, it can have devastating and often fatal effects. In this exercise students will use models of blood vessels to determine the effects of normal blood vessel distensibility on the dynamics of blood flow, and investigate the nature of aneurysms.

Special Material: None. All equipment is available through the lending library. However, all demos can be put together in the classroom using basic laboratory equipment (e.g., flasks, hose clamps, latex tubing, etc.).

Time Requirement:

In class: The exercise can be carried out in one 45-minute period.

Before class: Teacher preparation includes putting together the Windkessel demo and distributing proper materials to each group of students. It may also be advisable to spend some time reviewing physiology behind atherosclerosis, and aneurysms.

Additional Teacher Information

Objectives:

After completion of this laboratory, the student should be able to:

- give reasons why it is important that blood vessels exhibit both elastic and inelastic properties;
- describe how the design of the arteries helps to convert a discontinuous pulse of blood coming directly from the heart into a more continuous flow in the bloodstream;
- describe what atherosclerosis is, how it alters blood flow, and why it often causes the problems it does (e.g., stroke);
- do the same for an aneurysm;
- describe how a blood vessel is able to change its response to different blood pressures.

Level of Course:

As written, this laboratory should be appropriate for Advanced Placement, Honors, or Regents students.

Information with which students must be familiar prior to exercise:

Students should be familiar with the general role of the blood vessels within the context of the circulatory system. They should also be able to understand how to read a plot and understand qualitative relationships between the two variables being compared.

Materials:

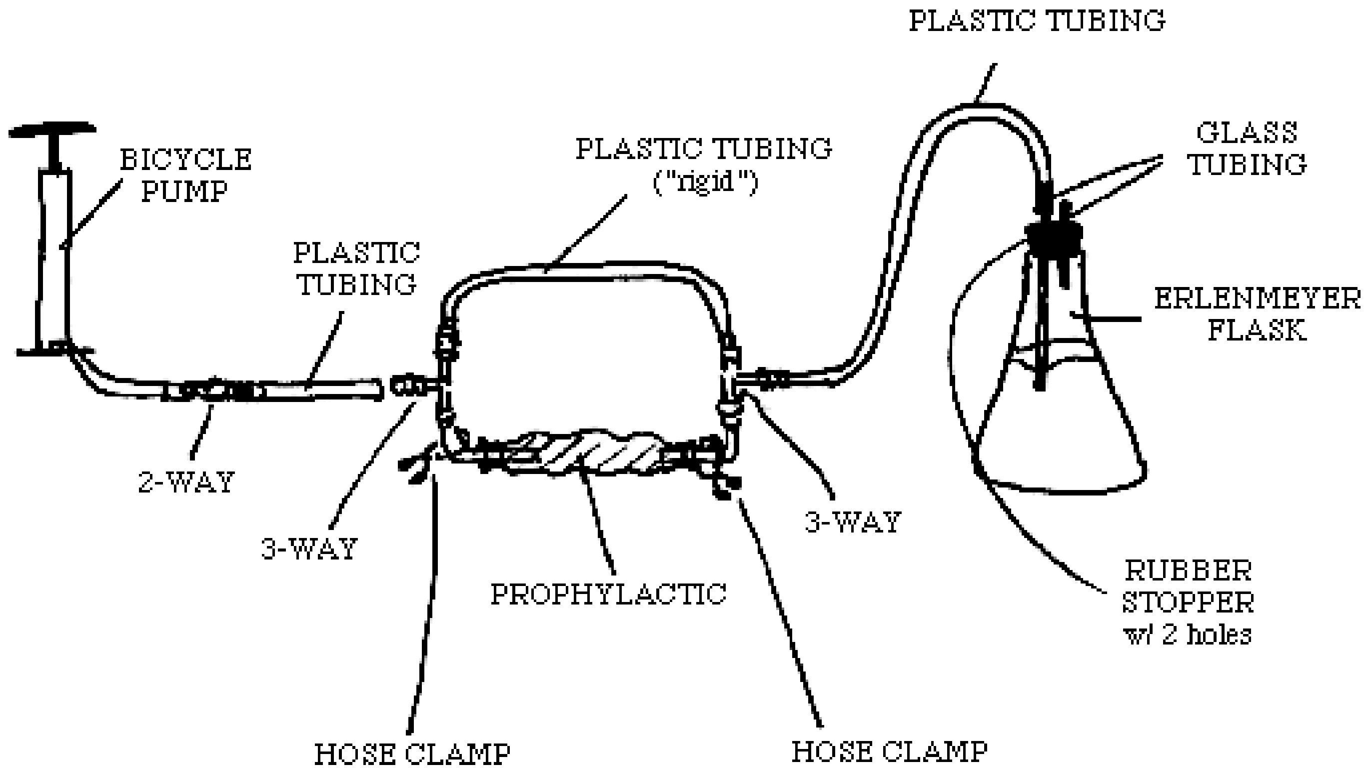
per team of students (2-4 students recommended per group)

- 1 Windkessel set-up
- 10-12 inches of surgical tubing
- 2-3 inches of reinforced tubing which can easily fit over the surgical tubing, (and/or, 2 feet of cloth string)
- 1 adjustable hose-clamp
- 1 two-way hose connector (to fit between pump and surgical tubing)

materials needed to construct the Windkessel:

- 1 bicycle pump
- 1 two-way hose connectors
- 2 three-way hose connectors
- 3 feet of plastic or rubber tubing (Tygon tubing works well)
- 1 prophylactic (preferably non-lubricated!)
- 2 hose clamps
- 1 foot of thin glass tubing
- 1 rubber stopper w/ 2 holes large enough to fit glass tubing
- 1 Erlenmeyer flask (1000 ml)

The above-listed items should be connected to allow the bike pump to pump air through the tubing and eventually into the flask, as shown in the diagram. The tubing should be fitted together to allow the path of air to the prophylactic to be cut off when the hose clamps are in place.



Note: Replace prophylactic if it is visibly punctured or torn.

Tips for the Teacher:

It has been our experience that many instructors of biology (from junior high school all the way up to the college level) have a "natural" aversion to physics. We, the authors, believe it is especially important that the teachers implementing this exercise should try not to let this attitude (should one exist) carry over into the classroom. Since it is probably here that the students will first learn how to approach the sciences (including physics), it is important to remember that the students (usually) do not have any preconceived notions about physics except what they perceive from their teachers. Hopefully, any physical principles presented here are biologically relevant enough and interpretable enough so that both teacher and student will profit from them. The concepts introduced here should be understandable to any interested student even though the detailed analyses of these phenomena are challenging to the most sophisticated scientists.

Section I

Although this section deals with many seemingly "non-biological" issues (i.e., viscosity, elasticity and viscoelasticity), they are material properties that are ever present in biological organisms. Since physiology can be characterized as the study of the physical processes of organisms, one must understand some of the physics behind the physical processes in order to apply them to a biological context.

It is not important to know in depth about viscoelasticity, only that blood vessels are viscoelastic and not totally elastic. However, if a student asks for more information the teacher can provide the example of silly putty as a viscoelastic material. If it is pulled apart rapidly, it snaps like a very stiff (non-fluid) material. If it is pulled apart very slowly, one can see it flow apart like a fluid. Another example of elasticity is to roll the putty into a ball and bounce it. Another example of the putty's viscous nature is to let it sit in its container -- over time it will flow into a puddle like water (only much slower!). The bottom line is that silly putty will exhibit a time-dependence to its material properties (i.e., the physical behavior of this material depends upon the time-frame over which it is loaded). This is also what blood vessels do. Besides the benefits of elastic vessels, the high-end of the strain (deformation, or stretching) energy due to high blood pressures is absorbed by the vessel. This not only helps to moderate peak blood pressures, it also keeps the pulses of blood flow from "echoing" back and forth along blood vessels as one might expect with a perfectly elastic tubing.

Section II

The Windkessel is a model that shows the capacitative property of arteries (i.e., it "stores up" blood pressure and allows blood flow to occur when the heart is between contractions. It will only be of use if the connections are airtight and if the hose clamps create an airtight closure when applied.

Also, be sure the bicycle pump is not the type that will pump air on both the up-stroke and the down-stroke. You only want the kind that pumps on the down-stroke (to simulate heart contraction) and fills on the up-stroke (to simulate the heart filling).

Ask students why less-elastic arteries (as with hardening of the arteries/atherosclerosis) pose a problem. Answer: it results in increased blood pressure, as seen with the solid vessel in the model.

Section III

Smooth muscle is also a major constituent of the artery walls, but it is not considered in this exercise. Although the involuntary smooth muscle contraction does affect blood flow, we are concentrating only on the affects of the material properties of the blood vessels.

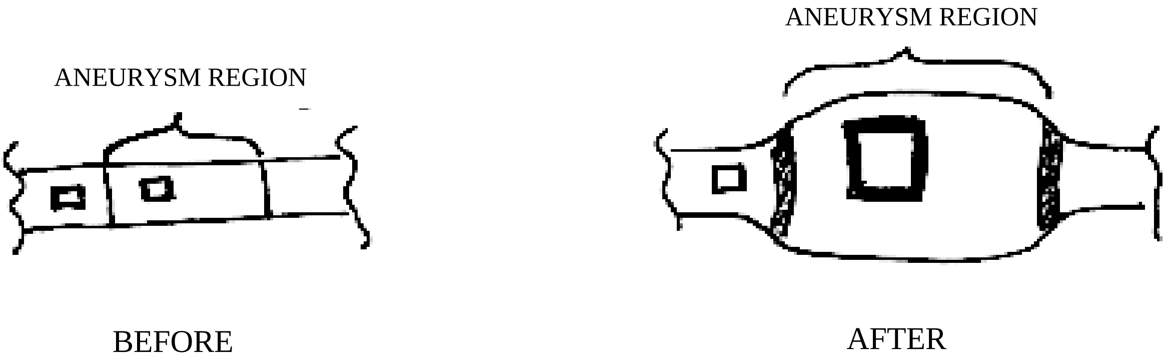
Stiffness is simply a measure of the rigidity of a material (or, the lack of extendibility). As we stretch a rubber band for example, the material actually undergoes a molecular change that alters its properties (i.e., stiffness). Therefore, a rubber band will stretch easily until it becomes a crystal (at which point it usually breaks). If you have access to a polarized light source, you can demonstrate these molecular changes occurring by stretching thin latex (e.g., a surgical glove or a dentist's rubber dam) between a polarized light source and an analyzer, and then observing through a microscope (you will see dramatic changes in colors as the polymer chains in the latex re-orient themselves).

When doing this section of the lab, it is important that the student pumping do so very cautiously--not only for safety reasons and so the others can make thorough observations, butalso so that the "aneurysm" does not become too large. An aneurysm too long for the reinforced tubing that is supposed to cover it will result in a predictable location for the second aneurysm.

The aneurysm should not burst until the length of the tubing has expanded. However, the danger is within the connections made for this portion of the experiment. The connectors and the bicycle pump attachment may come undone if not secured or if the pressure in the tube is allowed to get to dangerous levels. This can be avoided by following the directions listed.

It may be worthwhile to reinforce the point learned from the Windkessel (section II) when a steady, continuous flow of air can be heard from the surgical tubing model; also, if you have access to a portable ultrasound (used in many clinical settings to hear heart contractions, etc.) you can let the class hear the sounds of blood flowing through your arteries for comparison.

When the students mark the tubing it should like this:



Using the reinforced tubing should give better results than wrapping the string around the aneurysm. That is to say, we have seen that the string may often unravel or slide down the tubing so that the aneurysm region is no longer reinforced and you do not get the aneurysm occurring in a different spot. However, if you can get it to work, the string as a reinforcing fiber provides a better illustration of what the collagen fibers are doing than simply putting a rigid sleeve over the latex tubing.

Additional tips:

- For both instances when a bicycle pump is used, it is advised that enough extra tubing be used to allow the student to pump comfortably without disturbing the set-up.

- You may want to spend some class time before the lab introducing atherosclerosis and aneurysms to provide more detailed medical relevance to this laboratory and the functioning of blood vessels.

- Although not covered in this exercise, you may want to discuss how the information covered relates to hemorrhaging or strokes.

Answers to Questions

Section II-Continuous Vs. Pulsating Flow (The Windkessel)

2. With the hose clamps closing off the flow to the elastic vessel, begin pumping the bicycle pump with short brisk strokes. By observing the bubbles in the flask, describe the fluid flow of air through the rigid tubing with each up-stroke and down-stroke of the pump (take note of how violently the bubbles come out of the tube and into the water).
   The air is flowing in pulses with each down-stroke of the bicycle pump. Nothing is happening with each upstroke (there may be some water drawn back through the tubing--this is inconsequential and only an artifact of the pump).

   The bubbles produced in the flask are very violent with each down-stroke; one can demonstrate this by marking the maximum height of water that is "bubbled" up.

What's happening to the elastic vessel? Why?
Nothing. Because the hose clamps are closing it off from the rest of the circuit.

What does a down-stroke represent? *A heart contraction.*

3. With the hose clamps removed, start pumping again and observe the fluid flow of air into the flask. How is it different from the previous case?
The air flow is now continuous with no "bursts" of flow as in the previous case. The bubbles are not as violent as in the previous case. Maximum height of bubbling should be lower than the previous case.

What is the elastic vessel doing with each upstroke and down-stroke of the pump?
The elastic vessel expands with each down-stroke and recoils with each upstroke. This is because the pressure is raised with each down-stroke and stretches the latex. As pressure from the pump is relieved, the latex recoils back into place and pushes the air through the circuit until the next down-stroke re-inflates the latex tube.

Is the peak pressure of air flow higher or lower now that the elastic element is in the circuit? *Lower*. How can you tell?
The peak pressure is lower in the circuit with the elastic element. You can see this by comparing the relative bubbling action within the flask. One should be able to qualitatively see that the elastic element causes the height of the bubbling to be drastically reduced.

4. The Windkessel demonstration is a model of the elasticity of the vessel walls of the circulatory system. In this model, what components represent the:
   heart? *Bicycle pump*
   a healthy artery? *elastic element*
   the blood? *Air (NOT Water!)*

5. What was the purpose of the flask filled with water?
Simply for observational purposes. It would be difficult to observe the flow of air without the flask and water.

6. From Section I and what you have just observed in this demonstration, how does the elasticity of the blood vessel allow it to keep blood flowing continuously when the heart can only contract in pulses?
The elastic elements of the blood vessel can be stretched via pressures exerted by blood flow (during heart contraction). When this blood flow pressure is released (in between heart contractions) the elastic elements return to their original lengths. This elastic recoil causes a continuous flow of blood between heart contractions where without it there would only be discontinuous spurts of blood flow.

Section III - Physics Behind Aneurysms

2. Describe what you saw and heard as you closed off the hose clamp and the tubing expanded.
As the flow becomes more restricted, you should hear a higher pitched "swooshing" sound. As this aperture becomes small enough for the air flow to become continuous, as evidenced by the continuous "swooshing" sound (as in the Windkessel), this model becomes appropriate for a healthy

artery. You should also note the cyclical swelling of the tubing with each down-stroke of the bicycle pump. As the tubing expands, the wall of the artery becomes noticeably thinner.

Give an example of what the closing of the hose clamp simulated?
Chronic clogging of the blood vessels as in atherosclerosis. A high resistance in the circuit is created which creates back pressure.

Did the aneurysm occur suddenly or gradually? *Suddenly*

3. Reclose the clamp all the way and try to make another aneurysm appear. Where does it occur? *In the same spot*. Why?
This was originally the weakest point along the tube which is why it first occurred here. On the second try, it has become even weaker and will always occur at the same spot under similar conditions.

4. Look at the squares you drew. How do their **areas** compare now?
The square inside the expanded region is much larger in surface area.

Gently squeeze the aneurysm with your fingers and compare to adjacent, unexpanded tubing. Explain why they feel different?

Hint 1: Since this is a closed system, the pressure within the tubing must be constant everywhere within the tubing; so the air pressure within the tubing is the same everywhere.

Hint 2: Which is stiffer, an unstretched rubber band or one that is stretched to its limit?

Although the internal pressure is the same at each point, the portion of tubing that has expanded has undergone a fundamental change in its polymer composition (i.e., it has experienced molecular rearrangement becoming more crystal-like). Therefore, as the intermolecular bonds of the expanded rubber are stretching, the rubber is becoming more ordered (or crystalline) and becoming increasingly rigid. Thus, when we "feel" that the tubing seems stiffer, it is not because there is any more air pressure within the tubing; it is because the material itself has changed to become stiffer.

This explanation may not seem to offer much reassurance. For example. why then do arteries need collagen if the elastin will eventually reach a crystalline state? However, in reality the collagen allows the artery to reach this high level of stiffness before extreme, uncontrolled expansion takes place as it would with only elastin. Thus, less unnecessary stretching occurs within the artery walls and there is less chance of an aneurysm.

5. Again, close the hose clamp and begin pumping. Does an aneurysm appear in the same place? *No*
Discuss why or why not.
Since the rigid tubing, or the string, acts as the collagen fibers in blood vessels do to reinforce the more extendible elastin; they are essentially reinforcers for the latex. Here, the latex tubing begins to expand in the same place as in the other two trials. However, at a certain point of stretching, it reaches a maximum point where the "reinforcers" join in and protect the tubing from ballooning up. Thus the rest of the non-reinforced latex tubing is free to balloon at the next weakest spot--which is what happens.

6. What did the surgical tubing alone represent? *Elastin only*
   the rigid tubing, or string? *Collagen fibers only*

7. Discuss why it is so important for blood vessels to be made up of this composite of elastic and relatively inelastic elements (elastin and collagen).
   Without this composite make-up of blood vessels, they would either be too pliant or too rigid to accomplish the goal of carrying the life-giving blood to its many destinations. A vessel too pliant would keep expanding with peak blood pressures until it experienced an aneurysm that would likely lead to rupture of the vessel and internal bleeding. If a vessel were too rigid, it would not be able to absorb the high peak pressures and again and there would be danger of aneurysms and rupture. Also, there would be no continual flow of blood that could lead to several medical complications. This is why maintenance of blood pressure and healthy blood vessels is so important, especially in the brain and in capillaries that are particularly vulnerable to high blood pressures.

The Physiology of Blood Vessels

CIBT
Student Laboratory Exercise

Section I - Understanding Material Properties

As we observe the world around us, we see that objects exhibit certain characteristics depending upon the material from which they are made. For instance, we know from experience that a liquid like water will easily pour out of a pitcher because it is a fluid. Likewise, we know that cold molasses will not pour as easily out of the same pitcher although it is also a fluid. The measure of a liquid's "fluidity" is described by its **viscosity**. The more viscous a fluid is, the less tendency it has to flow. For example, cold molasses is a much more viscous fluid than water. Thus, a fluid does not have to flow like water to be called a fluid. Did you know that glass which appears extremely brittle under the influence of a quick load is actually a fluid? You can check this by looking at a window in a very old house and comparing the thickness of the glass at the top and at the bottom. Over many years, the glass will tend to flow towards the ground and the bottom of the window will become thicker than the top!

Likewise, we know from experience that a rubber band will stretch when we pull on it and snap back when we let it go. We know that it does because we know it is **elastic**. Elasticity is the measure of a materials ability to return to its original length when stretched or compressed. Did you know that steel is also an elastic material! In fact, steel is very elastic, but only over a very small range of stretching (probably too small for you to see with the naked eye). Designers have taken full advantage of metal's natural elasticity to produce metal springs for everything from shock absorbers to toys.

Biomedical researchers can use this knowledge of material properties to study the way our body functions. Scientists have characterized blood vessels as an elastic material that can be stretched and recoiled by the pressure of the blood flowing through it. However, researchers have also identified a viscous nature in the vessels as well. Blood vessels use this fluid nature (although the viscosity of a blood vessel is probably closer to molasses than water) to absorb some of the high peak pressures due to blood flow. Therefore, blood vessels are classified as both viscous and elastic, or **viscoelastic**. A good example of a viscoelastic material we are probably all familiar with is silly putty. Silly putty can be bounced like an elastic ball, but it can also flow like a fluid when allowed enough time to do so. Although we will be concentrating on the elastic properties of blood vessels, it is important to keep in mind that blood vessels also exhibit some fluid-like properties and are not purely elastic.

Section II-Continuous Vs. Pulsating Flow (The Windkessel)

Fluid flow of blood within a circulatory system is driven by a pumping heart. With each rhythmic contraction, the heart pumps out a certain volume of blood into its arteries. These arteries carry the life-sustaining blood to tissues through smaller capillaries. Blood eventually returns to the heart through the veins. Although the heart produces discontinuous pulses of blood flow, the body's tissues require a steady flow of blood to maintain optimum function. In addition, the dramatic changes in pressure due to a discontinuous flow of blood would damage the thin-walled capillaries (where nutrient and gas exchange between the blood and tissues take place).

Blood vessels (especially arteries) are able to convert high-pressure pulses of blood into a continuous flow by stretching with each heart contraction. As the heart is filling with blood, the blood vessel recoils to its normal size and keeps the blood flowing continuously even when the heart is between contractions. The arteries take the bulk of this responsibility because only they experience the high pressures due to the contracting of the heart. The aorta (the major artery leading out of the heart) must be able to withstand tremendous fluctuations in pressure and convert them into a continuous blood flow. Similarly, the smaller arterioles also maintain a continuous flow of blood within themselves.

Materials needed (work in teams of 2-4)

- 1 Windkessel set-up

Note: Before proceeding, make sure that the Erlenmeyer flask is filled with enough water so that the longer glass tube (attached to stopper) reaches the water but the shorter one does not.

1. Look at the Windkessel set-up before you. Diagram the set-up below being sure to label the following: **pump, rigid vessel, elastic vessel, hose clamps, flask**.

2. With the hose clamps closing off the flow to the elastic vessel, begin pumping the bicycle pump with short brisk strokes. By observing the bubbles in the flask, describe the fluid flow of air through the rigid tubing with each up-stroke of the pump and also with each down-stroke of the pump. Take note of how violently the bubbles come out of the tube and into the water.

   What's happening to the elastic vessel? Why?

   What does a down-stroke represent?

3. With the hose clamps removed, start pumping again and observe the fluid flow of air into the flask. How is it different from the previous case?

   What is the elastic vessel doing with each upstroke and down-stroke of the pump?

Is the peak pressure of air flow higher or lower now that the elastic element is in the circuit? ____

How can you tell?

4. The Windkessel demonstration is a model of the elasticity of the vessel walls of the circulatory system. In this model, what components represent:

   the heart? ______________________________________

   an healthy artery? ________________________________

   the blood? ______________________________________

   a diseased artery? ________________________________

   Add these labels (heart, healthy artery, blood) to the diagram made in question 1.

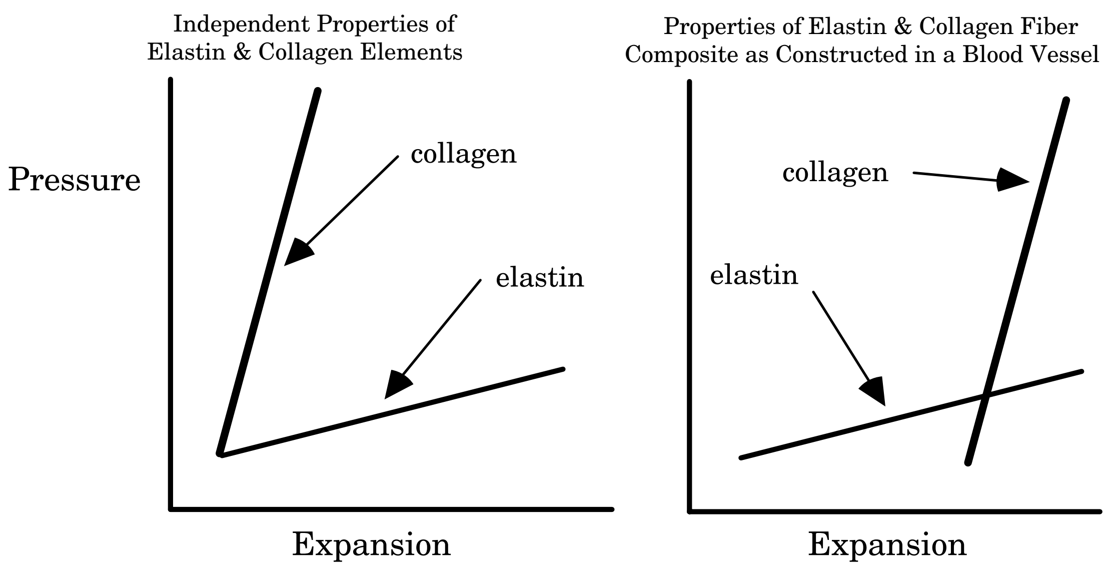
5. What was the purpose of the flask filled with water?

6. From Section I and what you have just observed in this demonstration, how does the elasticity of the blood vessel allow it to keep blood flowing continuously when the heart can only contract in pulses?

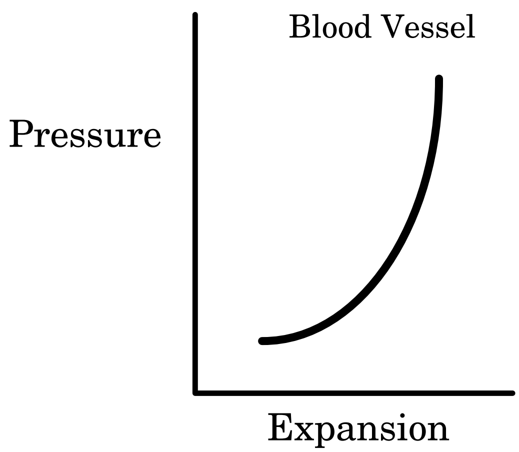
Section III - Physics Behind Aneurysms

As we saw in Section II, it is important to have elastic vessels that can withstand some of the high pressures caused by a pulsing flow of blood. The vessel's elasticity allows it to stretch and convert a pulsating flow of blood into a continuous flow. However, there are situations when high blood pressures are unavoidable and overly pliant vessels are undesirable. These can be due to environmental factors (e.g., heavy athletic activity) or pathological conditions (e.g., **atherosclerosis**--a condition caused by clogging and hardening of the arteries). During these situations, the vessel must be strong or stiff enough to prevent the appearance of an **aneurysm**. An aneurysm is simply an abnormal "ballooning" of the blood vessel that will often lead to rupture. This can be a very serious situation if the vessel in question normally supplies blood to an important organ such as the brain (a cerebral aneurysm, which leads to a stroke). An aortic aneurysm can cause massive bleeding and death.

In order to combat this situation, **blood vessels are made up of a composite of elastic material** (mostly elastin) **and inelastic material** (mostly collagen fibers). Elastin is a highly extensible rubber-like protein found in vertebrates. Collagen fibers are very stiff and relatively inextendible. The **stiffness** of collagen is 1000 times that of elastin! (stiffness is a measure of a material's resistance to stretch). This is like the difference between a cotton string and latex rubber. Therefore, it takes 1000 times more force to stretch collagen the same amount as elastin. Study the qualitative plots below showing pressure within the blood vessel vs. expansion of the vessel.



At low pressures, the elastin allows the vessel to expand and function normally. As in the Windkessel demo, the vessel is free to expand and accommodate the high-pressure flow of blood. At extremely high pressures, more and more of the collagen fibers reinforce the elastin and protect it from expanding uncontrollably. Therefore, blood vessels will exhibit a pressure-to-expansion relationship that allows the vessel to become increasingly stiff as pressure increases. The actual relationship for a blood vessel would look more like the following plot.



-At low pressures, it is advantageous for the blood vessel to be very extendable. But, at high pressures, the vessel needs to be able to become increasingly stiffer so as to avoid rupture! The result is a combination of the two lines shown on the previous page.

-The reason for the smooth curve is that collagen fibers are oriented differently so that as higher pressures are experienced by the vessel, more and more collagen fibers join in to reinforce the vessel.

Note: What would happen if the systemic pressures are chronically (habitually) above the normal levels? The Windkessel effects will become diminished.

What if you combine high blood pressure with hardening of the arteries (which is common among the elderly)? Both contribute to loss of the Windkessel effect and substantial damage to the arteries will result. This condition can lead to a situation where aneurysms are likely to occur.

Materials (work in groups of 2-4)

- 1 Bicycle pump (salvaged from the Windkessel)
- 1 piece of surgical, latex tubing about 10-12" long
- 1 adjustable hose clamp
- 1 pair of safety goggles per person.
- 1 permanent marker

1. Take a piece of surgical tubing (10-12 inches) and attach it to the bicycle pump via a connector (wet the tubing to secure it high up on the connector-about three notches should do). **Wear safety glasses and make sure these connections are very secure - high pressures will be experienced by the system!** Place an adjustable hose clamp on the other end without closing it. Begin pumping the bicycle pump at a slow, steady rate while a partner slowly tightens the hose clamp.

   You should begin to observe a steady flow of air (as in the Windkessel). This situation models the normal conditions of blood flow through a healthy artery.

As you continue to close the clamp, watch the tubing for an aneurysm! **When one appears, immediately close off the hose clamp completely and stop pumping.**

2. Describe what you saw and heard as you closed off the hose clamp and the tubing expanded.

   Give an example of what the closing of the hose clamp simulated?

   Did the aneurysm occur suddenly or gradually? _______________________

3. Mark both ends of the aneurysm with a permanent marker and deflate the tubing by opening the hose clamp.

   Now draw a small square (about 1 x 1mm) between the two marks and one more the same size on either side just outside the aneurysm region.

   Reclose the clamp all the way and pump slowly to make another aneurysm appear. Where does it occur? ____
   Why?

4. Look at the squares you drew. How do their **areas** compare now?

Gently squeeze the aneurysm with your fingers and compare to adjacent, unexpanded tubing. Explain why they feel different.

Hint 1: Since this is a closed system, the pressure within the tubing must be constant everywhere within the tubing; so the air pressure within the tubing is the same everywhere.

Hint 2: Which is stiffer, an unstretched rubber band or one that is stretched to its limit?

5. Deflate the tubing.

   Next, take some string or reinforced tubing and place it over the aneurysm region so that the marked off areas are well covered (if using the string, loosely wrap it many times over the area of the aneurysm you just marked off; it may help to have someone hold the other end of the tubing steady so that the string does not slip off).

   Again, close the hose clamp and begin pumping. Does an aneurysm appear in the same place? ________ Discuss why or why not.

6. What did the surgical tubing alone represent? ____________________
   the rigid tubing, or string? ____

7. Discuss why it is so important for blood vessels to be made up of the composite of elastic and relatively inelastic elements (elastin and collagen)