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Physical Models for the Role of Pressure in Biology and Medicine

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PHYSICAL MODELS FOR THE ROLE OF PRESSURE IN BIOLOGY AND MEDICINE

BY

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The members of the Defense Committee approve the thesis of Amanda Gorgy defended on April 13th, 2017.

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ABSTRACT

While the effectiveness of using demonstrations to facilitate learning in science courses remains controversial, it is generally recognized that the "hands-on" building of physical models leads to a better understanding of the underlying scientific concepts. A recent study published in Nature Communications flips the relationship between learning and building, suggesting that teaching and language evolved to allow the skills of using tools to be passed to children, providing an important survival advantage for early hominoids.

Work in our laboratory is aimed at encouraging collaborative interactions between science teachers and technical arts teachers in Florida's secondary school system. We design, build, and test equipment that can be used to illustrate important scientific concepts, with the objective of using these projects as examples of what students could build for their schools. In addition to providing low-cost demonstrations and laboratory equipment to science teachers, and hopefully slowing the disappearance of "shop" from the secondary school curriculum, we believe that the construction of physical models will provide a tangible analogy for the construction of scientific models that we use to understand natural phenomena.

Demonstrations are commonly used in chemistry and physics courses; however, the use of in-class demos in biology courses appears to be much less common. We present here several examples of simple apparatuses that illustrate scientific concepts important in biology and medicine with a focus on pressure systems.

ACKNOWLEDGEMENTS

I would like to thank Florida State University for giving me the opportunity to participate in this rewarding program and to meet so many influential individuals along the way. Four years ago, I would have never believed that I would one day become the individual I am today. It was with the help and guidance of individuals at FSU that I was able to remain resilient, no matter the number of times I failed. I would also like to thank the Honors Program at FSU and Dr. Stephanie Dillon for accepting my application into the CHM1051L course. If not for that course, I would not be writing this Honors Thesis today.

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It goes without saying (but I'm going to say it anyway) that I could not have done any of this without the help and guidance of my Thesis Director, Dr. Ken Goldsby. He has been the single most influential person during my entire duration at FSU. I would not be the person I am today if it was not for his dedication and compassion. His long jokes and boyish charm have made me truly enjoy coming into lab to work. He has shown me the power and difference a teacher and mentor can make in another's life. He has taught me to question everything and to accept nothing. He has showed me that a life of science means a life full of learning and collaborating with others. His guidance and mentorship has changed the way I lead, learn and act. Words truly cannot describe the positive influence that he has had over me these past three years. He has been the voice of reason (sometimes mania) and has always been there to give me advice when I sorely needed it. I have learned and grown so much under him and I am just now realizing how much I am going to miss him. He has become my dad away from home and the love and respect I have for him is unmatched. His willingness to help students, our school and our community goes far beyond what I had ever thought could be possible. It has been an honor working with him and I am envious of all the future students that will get to work with him in the future.

TABLE OF CONTENTS

List of Abbreviations and Symbols

In addition to the abbreviations listed below, standard SI units and abbreviations are used throughout this thesis.

a	area
atm	atmospheres
d	diameter
f	force
-g	gauge pressure
h	height
in	inch
lb	pound
m	mass
mmHg	millimeters of Mercury
p	pressure
pa	pascals
psi	pounds per square inch
PVC	polyvinyl chloride
r	radius

INTRODUCTION

While generally considered to lie in the domain of chemistry or physics, pressure is a prevalent and important topic in both medicine and biology. Examples include pressure and volume relationships in heart contraction (Kirkman, 2009), dialysis and osmotic pressure (Raimann, Tzamaloukas, Levin, & Ing, 2016), volume and pressure effects on renal function (Hebert, Stuart, & Stemper, 1975), and pulmonology. This list is by no means complete. It is difficult to appreciate the role of pressure in biology and physiology without an in-depth understanding of pressure itself.

We begin our understanding of pressure with the simple example of a pump attached to a round bottom flask. As the number of pumps increases, the pressure increases proportionally. We know this from the ideal gas law, $PV = nRT$, and can rearrange that to $P = (RT/V)\,n$ to show this relationship between pressure and number of pumps. When making the seemingly simple change of attaching a balloon to a pump the pressure vs. number of pumps relationship no longer holds the same correlation as it did in the round bottom flask example. The complications that arise with the inclusion of another factor, in this case elasticity, becomes even more prevalent when looking at physiological pressure systems.

Consider the circulatory system. The textbook blood pressure of a healthy individual is 120 over 80, which connotes a fraction or ratio to anyone not schooled in the science of blood pressure. If it is a ratio, then the units do not matter if the units are the same, and if it is a fraction, then a healthy blood pressure simplifies to 1.5. The units for blood pressure are mmHg, also known as torr, and 120 mmHg is a very different pressure than 120 atm or 120 Pa. Furthermore, blood pressures are “gauge” pressures, meaning that these pressures relative to a zero pressure defined as atmospheric pressure. So, the systolic pressure, 120 mmHg, converts to around 2.3 psi-g (pounds per square inch, gauge pressure). The investigations described in this thesis began as an investigation of pressure in the circulatory system, with the goal of modeling blood pressure in a way that provides some insight in this complex biological hydraulic system.

Investigating pressure in the circulatory system, led to considering other areas of biology and physiology that involve pressures, including osmotic pressure. Osmotic pressure plays a role in kidney function, pressure differentials in other organs, and blood pressure, where accumulate of fluid around the capillaries can cause swelling, referred to as edema. The involvement of osmotic pressure in other physiological pressure systems provided us with a context for development of an osmotic pressure demonstration.

Recent news surrounding the long-term effects of concussions led to the desire to understand the physics behind concussions. All of these projects were carried out with the Science and Technical Arts Collaborative Teaching (STACT) Project in mind. This initiative aims to provide examples of equipment that can be built by students and used to carry out scientific demonstrations. The science teachers will be provided with new (and affordable) tools for teaching basic scientific principles, but the real beneficiaries of this program are the students involved in designing and building these physical models for scientific concepts and principles. Demonstrations are commonly used in chemistry and physics; however, they seem to be far less common in biology and physiology. Beyond filling this void demonstrations that illustrate fundamental biological concepts, we hope that possibility of introducing demonstrations will provide an incentive for teachers to involve their students construction and experimentation in a "non-virtual" environment that better reflects the actual practice of experimental science.

BACKGROUND SCIENCE

Three projects are described in this thesis: the ***Water Manometer***, the ***Osmotic Pressure Demonstration***, and a simple accelerometer repurposed as what we are fondly calling the ***Brain-in-a-Box Demo***. The background science is presented separately for these projects

WATER MANOMETER. The importance of monitoring blood pressure, including the causes and consequences of high blood pressure, is a readily discussed medical topic as it affects almost everyone. In fact, when typing "pressure in medicine" into Google, the first thing that comes up is a link to high blood pressure medications and treatments. However, when we started to investigate the circulatory system and its pressure components, we quickly discovered that this system is more complicated than originally anticipated.

Our first attempt to model pressure changes along the circulatory system involved connecting three different diameters of PVC pipe (2-in, 1-in, and 1/2-in) with water pressure gauges (0-80 psi-g) at each junction. The large-diameter side was connected to a water faucet in the lab, and the small-diameter

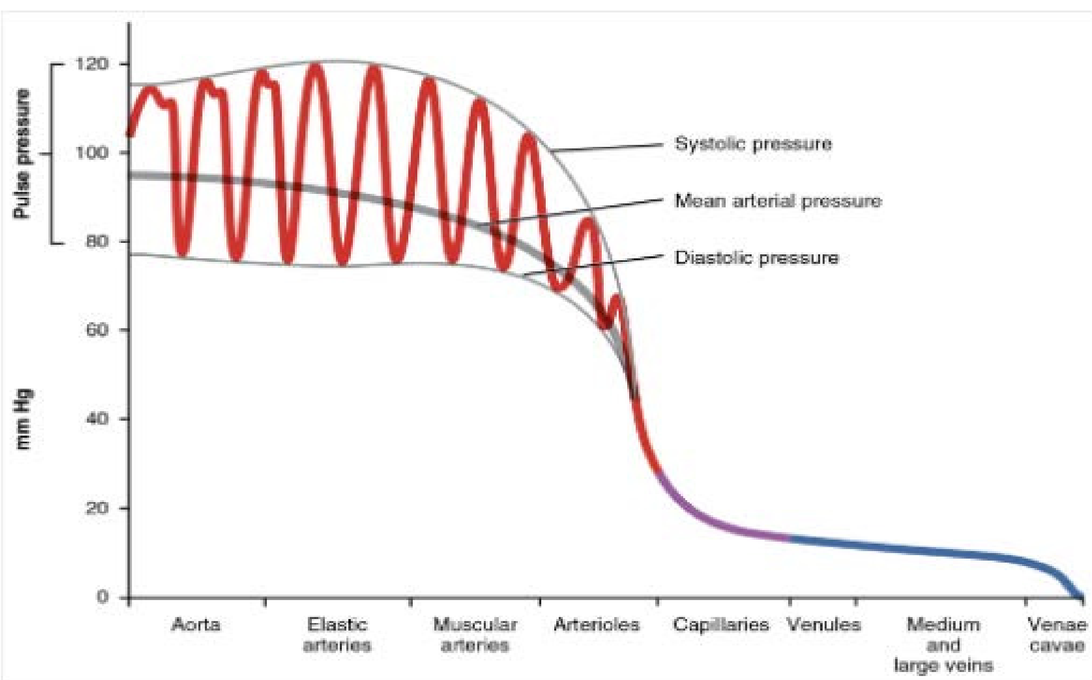


Figure 1. This graph shows gauge pressure in mmHg along the circulatory system (OpenStax, 2016).

size was connected to a hose that drained into a chase between the laboratory benches. The objective was to show the pressure drops at the junctions, analogous to the pressure drops that occur along the circulatory system, as shown in **Figure 1**.

This simple flow system did not show pressure drops where the flow was restricted at the junctures between the PVC pipes, possibly because the lab water pressure is too high (60 psi-g) to observe the small drops in pressure, but more likely because hydraulic pressure dynamics can be complicated. This complexity is not limited to plumbing; it is equally, if not more complicated, for the circulatory system. The heart is essentially a pump, and all pumps have a high-pressure side and a low-pressure side. The heart is pumping blood at a relatively high pressure and the highest pressure occurs in the aorta, which has the largest diameter of the blood vessels in the circulatory system; however, the aorta is also the blood vessel closest to the high-pressure side of the heart. Even during diastole when the heart is not actively pumping blood, the pressure in the aorta (80 mmHg) is still much higher than at any other point along the circulatory system (arterioles, capillaries, venules, etc.). In addition to diameter, the pressure in the various regions of the circulatory system depends on cross sectional area and velocity of blood flow, as shown in **Figure 2**. For example, the very low blood pressure in the capillaries is due to their large total cross-sectional area.

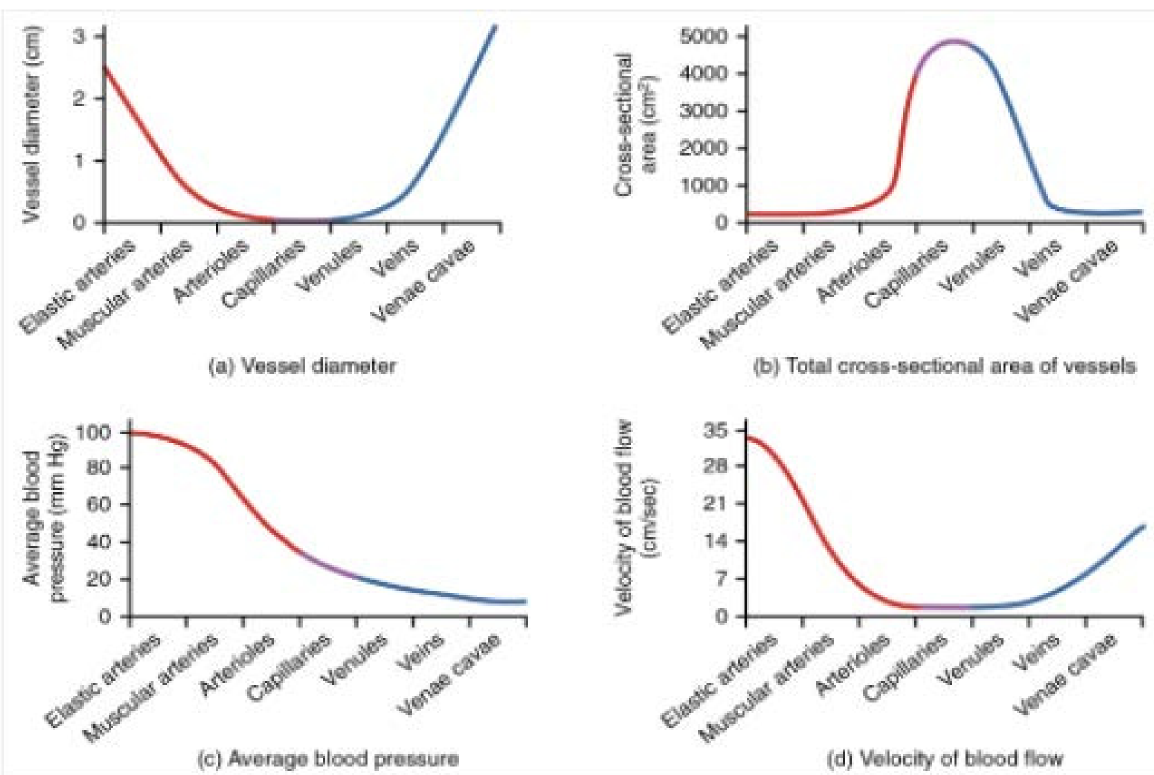


Figure 2. Graphs showing the diameter, pressure, area, and velocity of blood flow along the circulatory system. (OpenStax, 2016)

The total cross-sectional area has a dramatic difference in the velocity of the blood flowing through the capillaries. The relationship between blood flow rates and cross-sectional area is explained by Poiseuille's equation (OpenStax, 2016)

$$Q = \frac{\pi \, \Delta P \, r^4}{8 \, \mu \, L}$$

where Q is the flow rate, r is the radius of the tube, ΔP is the change in fluid pressure, μ is the viscosity of the fluid, and L is the length of the tube. This equation can be rewritten as

$$\Delta P = Q\left(\frac{8 \, \mu \, L}{\pi \, r^4}\right)$$

and by analogy with Ohm's law, $E = IR$, the term $8\mu L/\pi r^4$ is recognized as the resistance to flow. The change in pressure is directly proportional to resistance, which is inversely proportional to radius to the 4th power (r^4); therefore, an increase in the total cross-sectional area of the capillaries decreases the blood pressure. A third factor is that the elasticity of the aorta is very different than that of the capillaries. The aorta maintains its high blood pressure due to an "expansion and recoiling effect" (OpenStax, 2016), allowing for a higher pressure in the larger diameter blood vessels than found in the smaller diameter veins. Of course other factors such as the leg muscles acting as a "second pump" also contribute to the difficulties modeling the circulatory system.

Upon considering the difficulties in measuring differences in pressure in the ranges common for physiological processes, it became apparent that a simple manometer would allow measurements in the desired pressure range. Furthermore, coupling a water manometer with a classic physics demonstration known as the "Two-Balloon Experiment" (**Figure 3**) would make it possible to show the effects of elasticity on pressure.

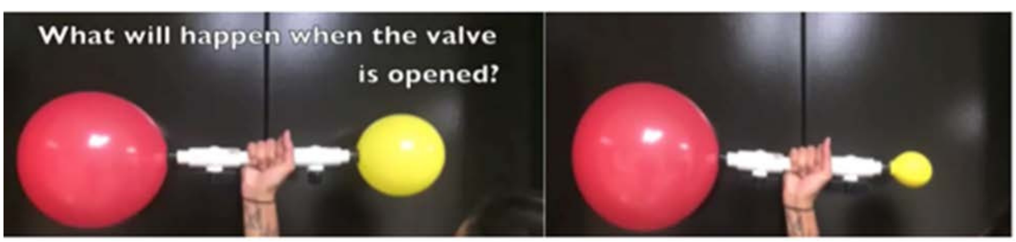


Figure 3. The two-balloon experiment, showing the relationship between pressure and elasticity in a rubber balloon.

In this demonstration, two similar balloons are inflated to different volumes and connected by a tube containing a valve in the closed position (we used 1/2-in PVC pipe and fittings). When students are asked to predict what will happen when the valve is opened, most students predict that air will move from the large balloon to the small balloon until they are the same size; however, as shown above, the opposite result is observed. If you then ask the students to recall which part of blowing up a balloon is the hardest, or better yet, give them a balloon to blow up, they will note that it is hardest at the beginning. Therefore, the pressure (force/area) is greatest at the beginning and decreases as the rubber balloon is stretched, that is until limits in the elasticity of the balloon are reached. It is then seen that pressure should be thought of in terms of elasticity rather than area. For example, imagine two vessels, one spherical and one cubic, with the same moles of gas, the same volume and the same temperature. The pressure, according to the ideal gas law, must be the same as well but the areas of the vessels are different. The two-balloon demonstration, a fun demonstration, but for some students the relationship between pressure and the volume of the balloon is difficult to grasp. We thought it would be helpful to measure the pressure of the balloon as it was being inflated.

Historically pressure was measured a manometer, an easily constructed apparatus that measured pressure as the height of a liquid displaced in column. **Figure 4** shows both a closed (a) and open (b) mercury manometer. A closed manometer gives the absolute pressure of the gas from the height of the mercury column whereas the open manometer gives the "gauge" pressure, the pressure above atmospheric. Using the density of the liquid, the height of displacement can be converted to weight per area, giving physically meaningful units consistent with pressure = force/area. Most manometers use mercury, including sphygmomanometers, which originally measured blood pressure using a mercury manometer, because the high density of the liquid (13.6 g/cm^3) allows a wide range of pressures to be measured using a relatively small column (1 atm = 760 mm of mercury). It has become increasingly difficult to use mercury in classrooms and teaching labs because of the cost of mercury and concerns about the toxicity of a volatile heavy metal.

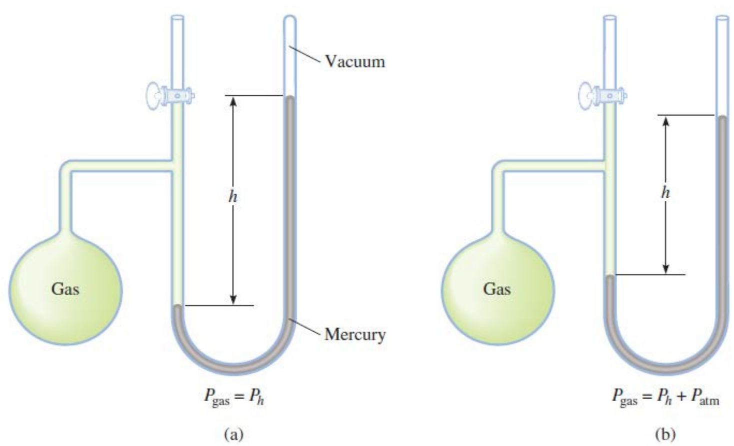


Figure 4. Typical examples of (a) closed and (b) open mercury manometers as illustrated in most general chemistry textbooks. (Raymond & Goldsby, 2016)

Given our goal was to measure pressure in the range of physiological processes, a water manometer seemed to be a viable option. Even a very high blood pressure will not exceed 200 mmHg, corresponding to just under 4 psi. Considering the two-balloon experiment, our initial goal was to construct a manometer that could be used to measure lung pressure. It surprises most people to learn that average maximum lung pressure is a mere 2 psi-g. The pressure range of most gauges sold in hardware stores is 0-15 psi-g or higher. (Low-pressure gauges can be ordered online, but generally at a significantly higher cost and inconvenience.)

The density of water is 1 g/cm^3, so two pounds of water would occupy a volume of

$$2\ \text{lb/in}^2 \times 456.3\ \text{g/lb} \times 1\ \text{cm}^3\text{/g} \times (1\ \text{in}/2.54\ \text{cm})^3 = 56\ \text{in}\ (2\ \text{sig figs})$$

corresponding to a column of water roughly 4-5 ft × in^2. The low density of water compared to mercury allows for much smaller pressure differences to be measured. A manometer of that height is large, but manageable, and it would have the bonus of being seen from the back of even a large lecture hall. By blowing on one end of the tube, lung pressure can be measured as the difference in the water levels, and inches of water to any other desired pressure units. Custom attachments allow for a number of measurements to be carried out with this simple manometer. Water manometers have been built before and tutorials can be found online (Deardorff, 2017) (Institute of Physics, 2007). These water manometers are crudely made from plastic tubing and are taped to a door or board of some kind with measuring tape in the middle. We improved on these designs by building a water manometer with attachments that can demonstrate different pressure relationships.

OSMOTIC PRESSURE DEMONSTRATION. Of the four colligative properties covered in general chemistry, osmotic pressure is arguably the most important given the vital role it plays in biological and physiological processes. Osmosis is the spontaneous flow of a solvent from a solution of low solute concentration to high concentration when the solutions are separated by a selectively permeable membrane. Osmotic pressure is the name given to the pressure that would be required to oppose that process.

The most common method for demonstrating osmosis is to use an egg and observe changes in egg size (expanding and shriveling) as a result of osmosis. Unfortunately it takes hours to observe these changes; moreover, this demonstration relates poorly to the illustration shown in the majority of science textbooks. A few videos of demonstrations using an apparatus similar to the classic depiction can be found online; however, the time must be compressed from a few days to a few minutes in order to see a significant shift in volume in a reasonable amount of time, compromising the effectiveness of the demonstration. This demonstration also fails to relate to the U-tube figure that is seen in most Biology and Chemistry textbooks to model osmosis. Another demonstration can be found on YouTube, which can be seen in **Figure 5**. This demonstration has its advantages; one being that it resembles the U-tube figure seen in textbooks and that it only takes 30 seconds to see via video. However, the video is a time lapse. The actual demonstration takes 72 hours to show a difference comparable to the figure in science textbooks.

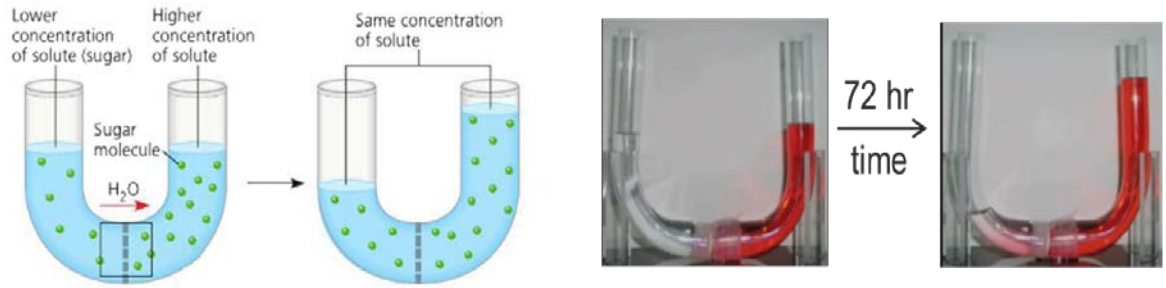


Figure 5. The figure on the left is a typical representation of osmosis as illustrated in most general chemistry textbooks. The figure on the right is an actual demonstration of osmosis requiring 72 hours to observe a change in volume comparable to that shown in textbook illustrations.

A demonstration of osmosis in an apparatus similar to the one shown in textbooks would allow students to see the movement of solvent from one side of the membrane to the other in real time and enhance their understanding of this important colligative property. We reasoned that by decreasing the diameter of the tube showing the water levels while maintaining the surface area of the membrane, it should be possible to increase the rate at which the level of the solution increases on the high-concentration side of the membrane allowing the demonstration to be done in a 15-minute period.

Brain-in-a-Box Demonstration. The brain-in-a-box demonstration is a simple and cost effective model that shows the happenings of the brain when under a concussion. The purpose of the demonstration is to be able to clearly distinguish between the coup and the contrecoup injuries. Many educational websites quickly explain a concussion and do not provide this distinction. With the recent media covering the long-term effects of concussions it is more than appropriate to assume that the order of impact matters medically. A previous demonstration similar to this one was found but lacked key elements that we value in our demonstrations (Drew & Drew, 2004). The demonstration in **Figure 6** retained the correct relative densities of the brain and CSF fluid as well as the size of the brain in comparison to the skull. This accuracy caused the demonstration to be unclear. It cannot be seen which side the brain is colliding with in any of the pictures shown in **Figure 6**. Improvements sought to be made to enhance the educational quality of this demonstration of concussions.

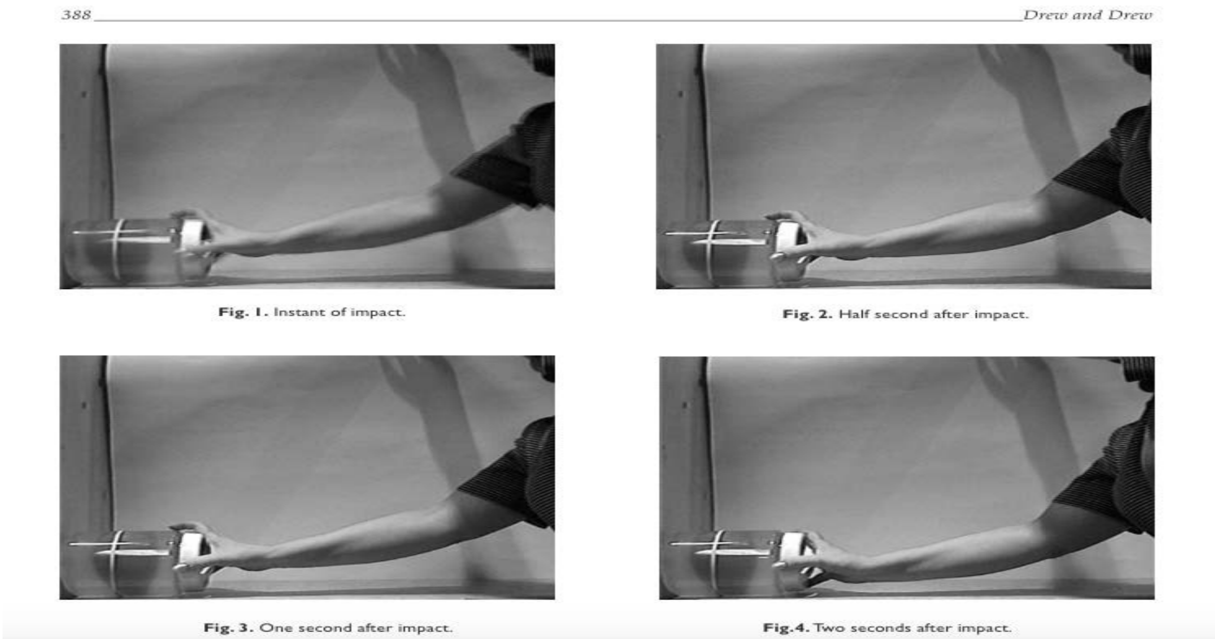


Figure 6. This figure taken from (Drew & Drew, 2004) attempts to show what happens to the brain during impact trauma to the head that results in a concussion.

The brain-in-a-box demonstration constructed as a part of this thesis improves upon previous demonstrations and also incorporates the use of an accelerometer allowing the force and therefore pressure of the racquetball to be calculated. Using the angle of the string attached to the racquetball the deceleration and consequent acceleration can be found.

The purpose of calculating the pressure that the “brain” undergoes in a frontal impact is reasonable when thinking about the long-term effects of concussions. It is reasonable to speculate that the deceleration of the racquetball could be greater than the acceleration. This would then make the pressure on the back of the brain greater in a frontal impact then the pressure on the front of the brain. The function of the occipital lobe is very different from the frontal lobe. Understanding the differing effects the brain encounters on both the front and occipital lobes is integral to understanding the long-term effects of concussions. It is also important in creating the proper gear to preventing, as much as possible, those long-term issues from ensuing.

THE STACT PROJECT

All of the demonstrations described in this thesis were developed in support of the STACT (Science and Technical Arts Collaborative Teaching) Project, an initiative to encourage the use of shop classrooms for scientific purposes. We provide science teachers with demonstrations and shop teachers with projects for their students. We believe these collaborations will provide students with the opportunity to engage in critical-thinking aspects that are present in an actual research laboratory. We have worked with shop teachers at public schools in north Florida and developed projects to demonstrate how this collaboration could be of use. At the start of this project, most demonstrations fell under the physical sciences. However, we have been working to implement other fields of science including biology and medicine. This thesis falls under that category and works heavily to incorporate both medicine and biology to understand pressure and its components. One aspect of this project that should not be overlooked is the small budget that teachers would be able to spend on these types of demonstrations. When considering potential STACT projects, we focus on obtaining materials that can be easily afforded by teachers in middle or high schools. Students should be provided the appropriate tools and materials that a typical 6-12 school with technical arts program that includes building and construction in its curriculum would have.

Experimental

In addition to the initial goal of developing pressure demonstrations for biology and medical applications, the aim of the STACT Project is to generate scientific demonstrations that can be used and made by students in middle and high school classrooms. Therefore, we purchased materials (components of the apparatuses) and supplies (consumables used to assemble the materials) from local stores whenever possible. When it became necessary to order materials, we used the same vendors that a secondary school teacher might use; for example, Home Science Tools (www.homesciencetools.com). Vendors and part numbers for specialty items are included in the materials list. The tools used to cut materials and assemble the apparatuses are standard for any industrial arts program with a construction course (e.g. woodworking) in its curriculum. Materials were selected with sensitivity to the limited budgets of secondary school teachers.   Bearing in mind the resourcefulness of secondary school teachers, especially the shop and art teachers who are always finding treasures in trash of others, supplies like wood and PVC pipe may be available for repurposing, bring down the cost significantly.

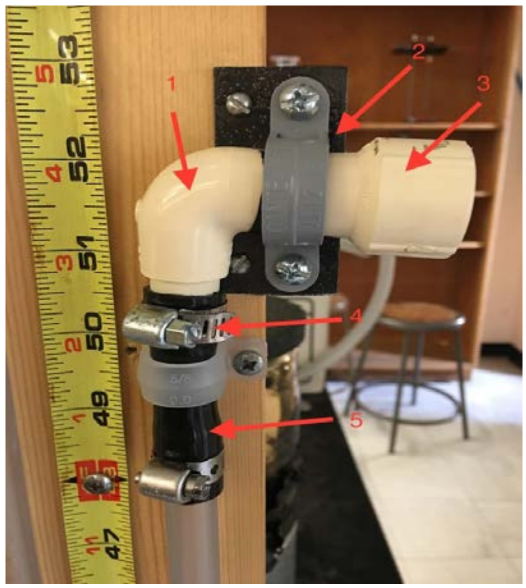
Construction of the Water Manometer

Base. The base was constructed using a 8-foot tall board which was first sanded using a Hand Sander to prepare for the staining of the board. The wood was then stained, according to instructions. One of the 8-foot Clear PVC Unthreaded Pipe was cut into 7-foot and 1-foot segments and the other was cut in half into 4-foot segments. [See Osmotic Pressure Demonstration construction for further use of one of the 4-foot segment.] The 7-foot tall Clear PVC Pipe was then attached to one of the ¼” 90-degree Clear PVC Elbows and was sealed using PVC glue. The leftover 1’ tall Clear PVC Pipe was then attached to the same 90-degree Clear PVC elbow as the 7’ tall PVC pipe. This portion was also sealed using the same sealant as before. The other ¼” 90-degree Clear PVC Elbow was then attached to the other side of the 1’

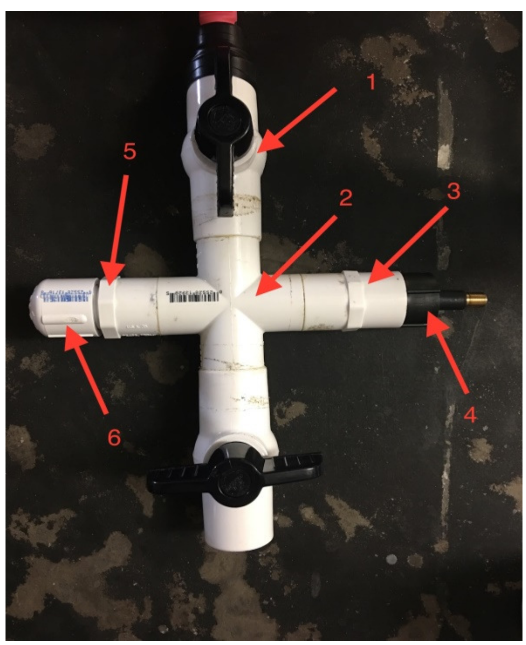
Clear PVC Pipe segment and sealed. The 4' tall Clear PVC pipe was then attached to the other end of the ¼" 90-degree Clear PVC Elbow and was sealed. In order to attach the ¼-inch Clear PVC to the ½-inch PVC Drip Irrigation Female Adaptor a piece of hosing was used to ensure a watertight connection between the ¼-inch Clear PVC Pipe and a ½-inch PVC Pipe which was then attached to the ½-inch PVC Drip Irrigation Female Adaptor. Two metal hose clamps were used over the hose-PVC connections to reinforce watertight connections. Cable clamps were used to attach the whole manometer to the board. The tape from the tape measure was then cut and placed in between the manometer tubes to measure the water levels to convert to pressure measurements.

Water Manometer Attachment. The water manometer was then attached to Part 5 on Figure 1 pictured to the left. This was a plastic hose which was then attached to a ½" PVC pipe. That pipe was then inserted into a ½" 90-degree elbow PVC joint which was attached to Part 3. Part 2 was made using a metal plate (?) to hold the weight of the attachments onto the water manometer. A conduit clamp was then attached to the metal plate to go over Part 3 and hold it up. Metal hose clamps (Part 4) were placed on both sides of the plastic hose (Part 5). Another clamp was used around the plastic hose and ½" PVC pipe attachment to serve as a holder for the apparatus.

Balloon Attachment. The balloon attachment was made by assembling the parts in the



1. Genova 1/2-in dia 90-degree elbow CPVC fitting
2. CARLON 1/2-in PVC clamp
3. Genova 1/2-in dia adapter CPVC fitting
4. 1/2-in hose clamp
5. Smartpond water garden ½-in vinyl tubing



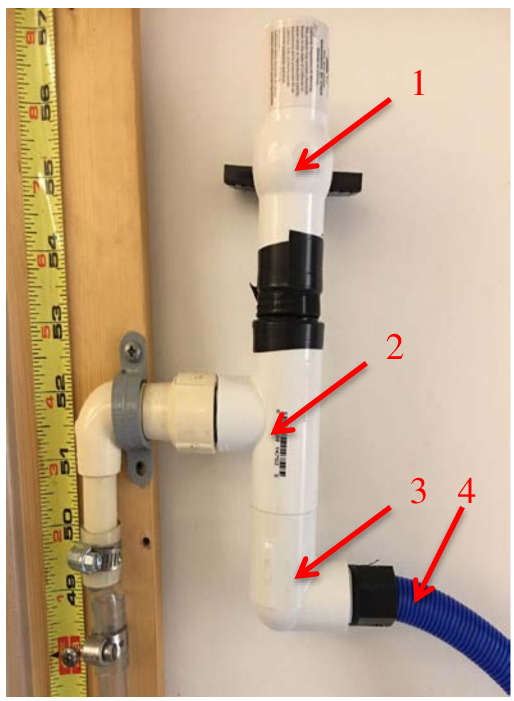
1. 1/2-in PVC sch 40 female in-line ball valve
2. 1/2-in dia 90-degree PVC sch 40 cross tee
3. LASCO 1/2-in dia PVC sch 40 Adapter
4. replacement valve stem
5. 1/2-in dia PVC sch 40 adapter
6. 1/2-in dia PVC sch 40 cap

figure to the right. Each of the parts were sealed using PVC cement. The balloon pump is attached to part 4 and the manometer is attached to part 5. Part 6 is a cap used during testing of potential leaks in the balloon attachment.

Methods. The balloon attachment is first screwed onto the water manometer. A balloon is then attached to the bottom valve (Part 1 but on bottom) and sealed using electrician's tape. By pumping air into the balloon attachment the pressure of the balloon as it inflates can be read on the water manometer. This can be done by measuring the inches risen on the left side and the inches decreased on the right side and adding them up then converting to psi (pounds per sq. inch) as that is the pressure unit used when discussing physiological pressures. It can be seen from this demonstration that the more air is pumped into the balloon the lower the pressure gets as the radius of the balloon expands.

Check Valve Attachment. The check valve attachment was obtained from an instructables website titled "Easiest Check Valve". It was made by modifying the picture to the left obtained from the instructables website. Our model is depicted below with the parts list to the right.

Methods. The check valve attachment is first screwed onto the water manometer. The flexible riser can then be attached to a mouthpiece and blown into allowing for a reading of the pressure exerted from a maximum lung expulsion using the water manometer.



1. 1/2-in PVC sch 40 female in-line ball valve
2. 3/4-in Dia x 3/4-in dia x 1/2-in dia (thread) 90-degree PVC sch 40 tee
3. 3/4-in dia (slip) x 1/2-in dia (thread) 90-degree PVC sch 40 elbow
4. Orbit 18-in flexible riser

Construction of the Osmotic Pressure Apparatus

The Osmotic Pressure Apparatus was constructed by first inserting the 2-in Dia Coupling into one of the 2-in Dia 90-degree Bushings and sealed using PVC glue. The 2-in Dia PVC coupling was cut so that it would be unseen when in between the two 90-degree Bushings. This was done to decrease leaking. The end of the coupling that was not sealed into the 90-degree Bushing was sanded to minimize the risk of tearing the semi-permeable membrane upon assembly of the apparatus. Each of the 2-in Dia x ¾-inch

Dia PVC Bushings were sealed into the 2-in Dia 90-degree PVC Bushings. A hole was drilled into each of the ¾-in Dia PVC Plugs to fit the ¼-inch clear PVC pipe. Refer to the Construction of the Water Manometer for information regarding the initial use of the clear PVC piping. The ¾-in Dia PVC Plugs with attached the ¼-inch Dia Clear PVC pipe were then screwed into these Bushings and sealed. Glass tubing about 14" in height was then attached to a 12" ruler using Nylon Cable Ties and Rubber hosing to keep the glass tubes from moving around. Each of the glass tubes were then wrapped with shrink tubing on the bottom end of the rulers. These tubes are then inserted into the ¼-in Dia Clear PVC pipes when assembling the apparatus.

Methods. The semi-permeable membrane is opened according to package instructions, and cut into 2" sections to be placed over the elongated 2-in Dia PVC Bushing and Coupling. The two 90-degree Bushings are then pushed together to the point where the Coupling should no longer be seen. The side with the extended length due to the attachment of the PVC coupling is the side where the Karo Syrup is placed to "speed-up" the osmotic process. The other side is filled with DI water. The purpose of the clear PVC insertion into the ¾-in Dia PVC Plug is to provide visibility for when the Karo Syrup and the DI water are poured into the Bushings. After the apparatus is filled on both sides with the Karo Syrup and DI water the glass tubing with the shrink wrap is carefully inserted into the ¾-inch Dia Clear PVC pipe. The level of the Karo syrup should significantly rise over a 50-minute class period due osmosis acting on the relative concentrations of the Karo syrup and DI water.

Construction of the Brain-in-a-Box Demo

Container. The construction of the Brain-in-a-Box apparatus began by using a plastic plate and tying the fishing line into it. Approximately a fishing line length of 10 cm was used. The optimal length was chosen to be able to keep the fishing line string straight and the ball in the middle of the animal cracker container when inverted. This was then glued to the middle of the inside of the animal cracker container lid. The racquetball was then punctured, using a drill, and filled with a plastic anchor. This is where the other end of the fishing line was attached. The plastic anchor was glued into the racquetball using a silicone sealant. The container was then filled with water and the lid was then sealed onto the container using a silicone sealant. The container can then be inverted so that the ball is strung in the middle of the animal container jar using the clear fishing line.

Base. A circle was cut out of the wood board (dimensions) according to the circumference of the animal cracker container lid. The wood board was then sanded and stained using Miniwax Wood Finish. The container portion can then be placed into the base and used to push the apparatus along a flat surface for the demonstration.

Methods. The demonstration is used to model the brain "floating" in the Cerebrospinal Fluid (CSF). The relative densities are not exact due to it inhibiting the clarity of the demonstration. A cubic animal cracker container was needed to make sure that a flat surface would hit the wall upon impact. Moving the apparatus at a constant velocity until it hits the wall would then show, upon impact, which regions of the skull the brain is colliding with to model a concussion.

RESULTS

WATER MANOMETER. The first edition of the water manometer showed a jump in pressure in the first pump followed by a decrease in pressure in pumps 2-20. In **Figure 7** it can be seen that in the first pump the pressure is at about 22 psi-g. It then decreases to about 18 psi-g after the second pump. The water manometer shows that the first pump of air yields about a fifth higher pressure than the pressure of the balloon after the second pump. The second edition of the pump showed a slower increase in pressure, (2-3 pumps) followed by a decrease in pressure.

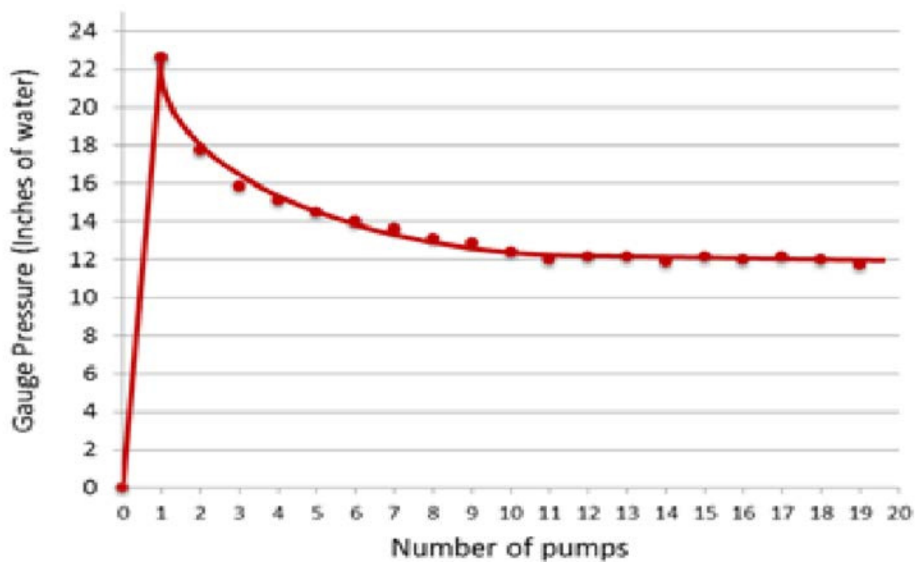


Figure 7. Graph showing the relationship between pressure and volume of air being pumped into the balloon.

OSMOTIC PRESSURE DEMONSTRATION

The osmotic pressure demonstration can show in a time vs. height graph osmotic pressure in a 15-minute period, well under the time a science teacher would take to show a demonstration in the middle of a lecture. No full day of experimentation needed to be done or for an elapsed (real-time 72 hours)

YouTube video to be shown. The demonstration was done previously and had modifications done to it that will be discussed in the following section.

Figure 8. The change in height due to osmotic pressure over time.

Column Height versus Time for a Typical Osmotic Pressure Run

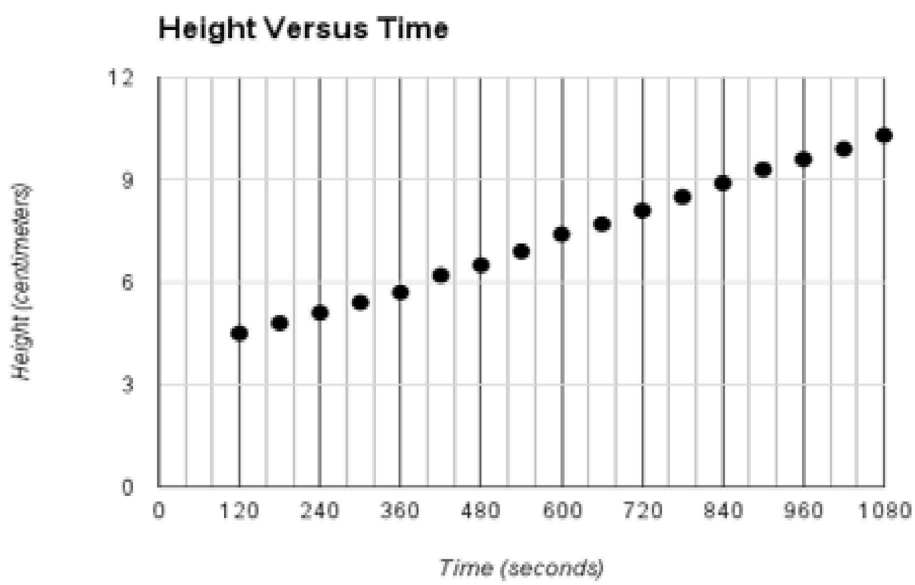


Figure 9. Graph of height in the osmotic pressure demonstration versus time

The graph in **Figure 9** gives an initial rate of osmosis of 9 cm^3/hr, which is reasonable compared to the <u>average</u> rate for the full-size osmosis apparatus estimated at 2 cm^3/hr, because the initial rate is expected to be faster than the average rate. Corn syrup is roughly 1:1 fructose:glucose. One tablespoon is 15 mL. Mono-saccharides like fructose and glucose are $C_6H_{12}O_6$. Assuming 4 Cal/g for sugars,

$$(60\ \text{Cal/Tbsp})(1\ \text{Tbsp}/15\ \text{mL})(1\ \text{g}/4\ \text{Cal})(1\ \text{mol}/180\ \text{g}) = 0.0056\ \text{mol/mL} = 5.6\ \text{mol/L}$$

The osmotic pressure demonstration will run at an average rate of 2 cm^3 per hour. This allows for more than enough time to set up and run the demonstration in a class period.

BRAIN-IN-A-BOX DEMONSTRATION.

The brain-in-a-box demonstration uses a racquetball tethered to a fishing line suspended in water as a model of the brain in the skull. The brain being the racquetball and the skull being the animal cracker jar. The apparatus is essentially an accelerometer. This allows the apparatus to be pushed at a constant velocity (indicated by the racquet ball staying straight up). Once the apparatus hits the wall the racquetball decelerates (coup injury) and then accelerates (contrecoup injury). As this thesis focuses on pressure systems in physiological ranges, this demonstration shows the pressure that the brain encounters under an impact. Pressure is defined as the Force over the Area. Using this equation, we can see that the pressure the brain encounters is the force of the impact over the area of the brain being impacted. Force is equal to mass * acceleration. Therefore, the deceleration and acceleration multiplied by the mass of the racquetball over the area of the racquetball would be the pressure of the brain in a concussion. A simplification of this equation is shown below:

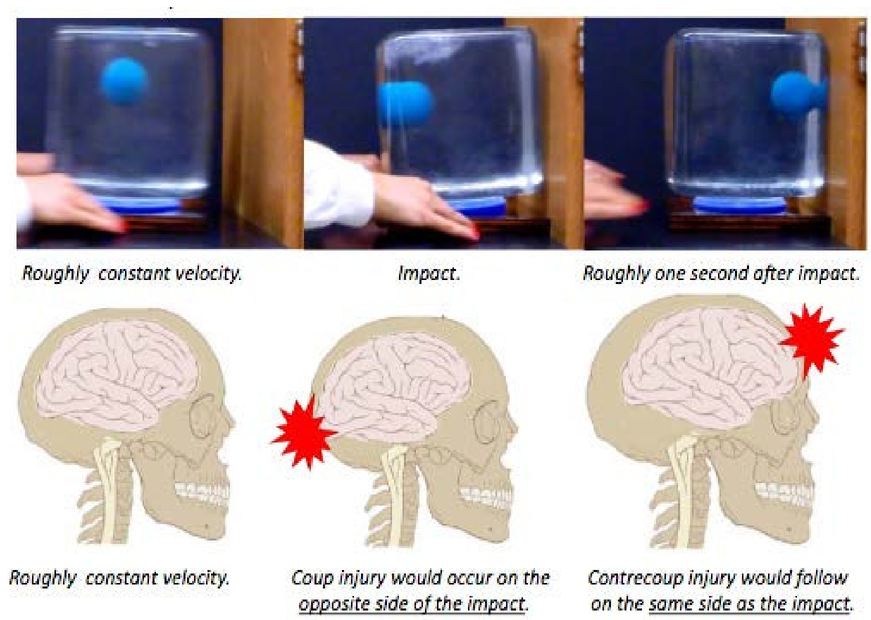


Figure 10. A comparison of a schematic of a concussion and the brain-in-a-box accelerometer

DISCUSSION

WATER MANOMETER.

The goal of the water manometer was to be able to have a physical demonstration that could measure pressure at physiological ranges. Looking at the results from the balloon attachment, it can be seen that there is an obvious relationship between pressure and elasticity. As the balloon size increases, the pressure decreases. This is due to the elasticity of the balloon being tighter in a smaller balloon. This causes the balloon to push on the air inside of it. However, as more air is pumped into the balloon, the balloon stretches and its elasticity increases. The increased elasticity allows the air inside of the balloon to be subjected to less of a force from the balloon. This relationship shows that pressure cannot simply be thought of as inversely related to area. A more accurate way of thinking would be in terms of elasticity.

Figure 7 shows the relationship between pressure and pumps of air taken from data that we collected using the first edition of the water manometer. Modifications were made to this design (details can be found in the experimental section) due to a leak allowing air to flow out of the water manometer when the PVC valves were closed. It is important to note that although air was leaking out of the apparatus, the water manometer was still able to demonstrate the relationship between pressure and area. The modifications made to the apparatus still modeled the relationship between pressure and elasticity. There is no major difference between the modified water manometer and the original, besides from the sizes of the pumps used. The pump in **Figure 7** had a much larger volume of air compared to the second pump used. The smaller volume pump allows for more precise data points modeling the same curve seen in **Figure 7**. It is also important to note that the higher pressure of the air inside the balloon is due to the elasticity of the balloon. At a smaller area, the balloon is not as elastic and is *pushing on* the air inside of it more than when compared to a larger volume balloon. The increased elasticity of the balloon as more air is being pumped inside of it is what allows the pressure to decrease. This distinction is important because it explains why just focusing on the relationship of area to pressure does not explain why the pressures are the way they are in the circulatory system.

The balloon attachment, as previously discussed, shows the relationship between the elasticity of the balloon and pressure. Another attachment is the check valve attachment. The purpose behind building this particular attachment arose from blowing into the water manometer to measure lung pressure. However, when doing this it feels as though the maximum lung pressure that could be achieved is limited by the amount of air available in the lungs. It seemed as though maximum lung capacity was being measured rather than lung pressure.

We sought to make a one-way valve that would only allow air to be blown into the water manometer and not sucked out. This was done by using a small ball and an O-ring and putting it inside of a PVC fitting. When air is being blown into the manometer, the ball raises allowing air to flow through. When air is being sucked out the ball presses down on the O-ring sealing the air inside of the water manometer. This allowed for a measurement of lung pressure not lung capacity. After using the one-way check valve attachment it can be seen that the height of the water in the manometer cannot be raised much more after the first try. The maximum lung pressure can be easily seen with this one-way check valve because it holds the air long enough to take an accurate measurement.

Problems with the one-way check valve design stemmed from the design of the homemade attachment. Due to the nature of the ball on the O-ring, if blowing into the mouthpiece using a small force causes the ball to release air rather than trap it in the water manometer. Only during high pressures can the check valve function the way it was intended. Overall, the water manometer still accomplishes everything that it was made to do. It demonstrates maximum lung pressure and explains pressure in terms of elasticity rather than area in a physical form, not via a textbook.

OSMOTIC PRESSURE DEMONSTRATION.

The osmotic pressure apparatus built as a part of this thesis is both similar to the figure in science textbooks and takes under 15 minutes to be seen. The demonstration also had its issues with leaking which were fixed by shaving the PVC to minimize membrane tearing and using extra grease to make the stoppers fit tightly into the clear PVC extension. The old model also did not allow for the levels of Karo Syrup and DI water to be seen. Issues therefore arose when there was no increase in height on the Karo Syrup side due to membrane tearing, etc. With these modifications, the osmotic pressure demonstration allows for a watertight and time effective model to show osmosis in real time.

BRAIN-IN-A-BOX DEMONSTRATION.

The brain-in-a-box demonstration constructed as a part of this thesis improves upon previous demonstrations and also incorporates the use of an accelerometer allowing the force and therefore pressure of the racquetball to be calculated. Improvements on this model include attaching the accelerometer to wheels with very low friction. This would allow the apparatus to be pushed along a table for long enough to achieve zero acceleration. The purpose of this being that the deceleration of the apparatus colliding with the wall can be measured. If the ball is accelerating prior to its collision with the wall then an accurate measure of the deceleration would not be possible.

The benefits of building these cost and time-effective demonstrations is exemplified when bringing these apparatuses to middle and high schools. At a local event, STEAM Day, at FSU High

School the water manometer and brain-in-a-box demonstration were brought. The school includes students from grades K-12 making the age of our audience much younger than anticipated. When showing and explaining the brain-in-a-box demonstration to one elementary school student he proceeded to explain the demonstration to another student that came up. The effectiveness of having students experience visual and kinesthetic demonstrations of scientific principles is irrefutable. A young child quickly grasped the concept of a concussion in less than five minutes, to the point where he could explain it all to another individual. These types of demonstrations are vital to increasing the learning of students in middle and high schools. All of the demonstrations done as a part of this thesis aim to help and advocate for the STACT (Science and Technical Arts Collaborative Teaching) Project.

SUMMARY

The answer we have found through the development of these projects is that pressure is a complicated mechanism especially in physiological systems. The ability to understand and relate pressure to biological and physiological systems is in fact possible. This conclusion is supported by data that was obtained as part of this thesis. Throughout the development and implementation of each of these projects many issues arose, providing a realistic context for us to learn more deeply about pressure systems from both a shop teacher's and a science teacher's perspective. Each of the demonstrations discussed in the body of this thesis provide teachers with the materials to construct, modify and make use of the apparatuses to show scientific concepts focusing on pressure. These pressure demonstrations have been optimized for teaching making the next step to be the implementation of these demonstrations in actual science classrooms. Due to the relatively quick nature of the majority of these demonstrations, there does not need to be a lesson plan made for these demonstrations. Rather, the use of the demonstrations can be easily incorporated into an already existing lesson plan making the use of these project much more feasible. Further research might include student and teacher feedback on the effectiveness of the demonstrations as well as a comparison of student achievement with and without the incorporation of the demonstrations.

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