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Curriculum Units by Fellows of the National Initiative
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There is Math in Your Heart

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1. Introduction

Many of us have grown up with the idea that the heart is symmetric, completely red and perfectly shaped as it is seen in Valentine's cards. Furthermore, some biology books show diagrams and models with a multicolored picture where the deoxygenated blood is blue. However, these approaches are for didactic purposes only. When we take a closer look at a real human heart, we can see that it is not symmetric, but it has a tendency to be symmetric; it does not have the "Valentine's" shape; it is not completely red, and it does not have the blue colored sections as cartoons on the books show.

In this unit, I present a mathematical analysis of some aspects of heart function. These concepts can be combined with the use of colored diagrams as well as hands-on activities, in order to provide a more complete level of learning. Using only abstract concepts or only hands-on activities may create a situation where "one leg grows larger than the other one."

This curriculum unit will be taught in Algebra-1 and Algebra-2 classes. Students review concepts of word problems, ratio, proportions, percent and equations. One aspect of the unit will include conversion of units and the comparison between the metric and the English systems to understand concepts of flow, pressure and speed within the cardiovascular system. Changing from one type of unit to another one is an excellent skill to have that will be used in science as well as in math. In addition, geometric concepts will be explored, such as the calculation of the surface area of a heart and graphing of a cardioid. Graph reading skills will also be studied, using the data obtained from heart diseases.

I believe that illustrating the physiology of a heart in a set of math lessons is a good way to enhance understanding of the function of our organs. It is important as well to analyze the function of the components of the cardiovascular system such as the ventricles, atriums, valves, veins, arteries, blood and its composition/function.

2. Facts about the heart

The heart is a hollow organ located in the thorax and between the lungs; it is above the diaphragm. Its shape is similar to a blunt cone. It is suspended by the great vessels, on the broader end, also called the base, which enables this portion of the heart to be directed upward, backward and to the right. The pointed end is called the apex and points downward, forward and to the left. In other words, the human heart is placed in the body in an oblique position, with the right side almost in front of the left.

The heart is an involuntary organ, which means that its action is not under our conscious control. Some individuals can voluntarily relax, causing the heart rhythm to slow. It is also possible to increase the heart rate when exercising, but the level of control is limited. We cannot stop it and cannot re-initiate it.

The heart wall is composed of three layers: the epicardium, the myocardium and the endocardium. The prefix "myo" means muscle. The prefix "endo" means "inside." The prefix "epi –" means "on, upon, at, by, near, over, on top of, toward, against, among." In this particular case, the closest meaning is "on top of."

The heart is composed of cardiac muscles, which are interconnected by junctional complexes called gap junctions. Each set of neighboring cardiac muscle cells may be connected by a large number of gap junctions, which physically lock the cells together and allow the transfer of electrical signals from cell to cell. The gap junctions among the whole heart ensure that all the cells in the heart will participate of the beating action.

A cardiac muscle excites itself and can generate an electrical impulse and contraction independent of the nervous system. Nerves that come to the heart are directly related to rate and strength of contraction, but the heart will beat in their absence. These nerves do not initiate the heartbeat. In contrast, skeletal muscles contract only when they receive a nerve impulse.

The Cavities of the Heart

The heart is divided into two halves by a muscular partition called the ventricular septum. This partition allows the heart to be divided into left and right sides, which after birth, do not communicate with each other. Both sides of the heart contract and relax almost simultaneously. The right side contains venous blood. The left side contains arterial blood. Each side is subdivided into two cavities of unequal size; the smaller, called the atrium, is on top, and the larger, called ventricle, is on the bottom.

The ventricle located on the left side propels blood at a higher pressure than the right ventricle, which does not really requires as much pressure, due to the fact that its action will be only applied on the shorter pulmonary circulation. The amount of blood pumped into the circulatory system will be analyzed in the section called "Math of the Heart."

Valves of the Heart

There are four valves in the heart, but the most famous are the tricuspid and the bicuspid valves, which are located between the atria and ventricles. The right atrio-ventricular valve is the tricuspid valve, which is formed by three flaps. The left atrio-ventricular valve is the bicuspid valve, which is formed by two flaps. The bicuspid valve is also called the mitral valve. In order to remember the position of these valves, we can imagine the number 32 written on our chest, meaning that the tricuspid valve is located on the right and the bicuspid valve is on the left.

3. Facts about the Cardiovascular System

The perfect arrangement of arteries, veins and capillaries along the entire body ensures the proper distribution of the blood.

Arteries receive blood from the heart and carry it to the capillaries; the veins return that blood back to the heart. Arteries divide into branches through the body, becoming smaller at each division. Arteries are characterized by their elasticity.

The aorta—the major vessel that is connected to the left ventricle—has a diameter of approximately 1 inch, which is equal to 2.54 cm or 0.0254m.

Capillaries are tiny vessels about 8M in diameter that connect arterioles with venules. Venules are small veins.

Pulmonary Circulation

The system of vessels that carries blood coming out of the right side of the heart, starting with the pulmonary artery and extending through the lungs, is called the pulmonary circulation. As blood flow through the lungs, it will pick up oxygen at the lung before it returns to the heart. The term pulmonary comes from the Latin root "pulmon," which means lung. There is a separate circulation called "bronchial circulation," which supplies blood to the lungs.

Systemic Circulation

The system of vessels that carries oxygenated blood from the heart, through the arteries and through the body, returning deoxygenated blood back to the heart through the veins is called systemic circulation. While blood circulates through the body, oxygen diffuses from capillaries into adjacent cells. In exchange, CO_2 diffuses into the blood for removal from the tissue.

4. Math of the Heart & the Cardiovascular System

It is said that the heart is similar in size to a fist; in other words, a closed hand, making a fist, represents the size of our heart. It weighs a bit less than one pound.

During its contraction, the impact is felt on the wall of the chest, between ribs five and six. To be more precise, this impact is felt most strongly below the left nipple and approximately 8 cm (about 3 inches) to the left of the symmetric axis. The symmetric axis is the vertical line that divides the human body in two equal parts.

The function of the heart is to supply the proper amount of blood for each part of our body. Some organs will receive more blood than others, depending on the actual function of the organ. It depends as well on the activity performed in a given period of time. For instance, if a person is running or practicing sports, muscles are consuming large amounts of energy and they must receive more blood flow than they do when the person is at rest. During a period of exercise, blood flow will be diverted to muscles from other organs, such as the digestive system. Definitely, the human body is a smart system that can adjust and adapt to different situations.

Cardiac Cycle

There are two phases in a cardiac cycle; a contraction period called systole, and a relaxation period called diastole.

The contraction and relaxation of the heart represents one heartbeat. One heart beat is one cardiac cycle.

Ventricles are relaxed during diastole. This is the moment when ventricular filling happens.

Ventricles contract during systole, propelling blood into the pulmonary and systemic circuits. An average normal cardiac cycle occurs around 70 to 72 times per minute. This number represents the heart rate. Given a pulse rate of 70 to 72, the time for a cardiac cycle is 0.8 second.

The cardiac cycle varies in inverse proportion to the size of a person. This statement is extended as well to all warm-blooded animals. It makes sense that the circulation on a small body will be completed in a small period of time and, therefore, determining more "mini-cycles" per a given period of time than a larger body. The heart of an elephant for example, beats around 25 times per minute. The heart of a mouse beats around 700 times per minute. In general, if the body is small, the consumption of oxygen by the tissues of the animal will be faster in comparison to a larger animal.

Heartbeat Rate Variations

Heartbeat is a bit faster in women than in men. Comparing fetuses, the heart rate of a female fetus is approximately 140 to 145, while for a male fetus is 130 to 135. Heart rate is also influenced by age. At birth the rate is approximately 140 beats per minute. When the individual is three years old, the rate is 100 beats per minute. Youngsters have a rate of 90 beats per minute; adults have it at about 75 beats per minute, while elderly people have it at 70 to 80 beats per minute.

The heartbeat rate is influenced by the posture of our body. Standing up the heartbeat rate is 80; sitting is 70 and when lying down the heartbeat rate is 66. Therefore, some patients are told to lie down when physicians want to slow down the heartbeat rate.

A chemical reaction is always influenced by the variation of temperature. Normally, the chemical reactions tend to be faster when temperature increases. The heartbeat is a function of several chemical reactions and, therefore, it will depend on the temperature of the body. In any chemical reaction the rate is doubled when the temperature increases by 10 $^{\circ}$ C, but it is reduced by half if the temperature decreases 10 $^{\circ}$ C. Therefore when a person has a fever, the temperature increases and all chemical processes in our body will occur a bit faster without increasing the physical activity. This will induce our heart to speed up the ejection of blood and therefore, to have a higher heartbeat rate.

It has been demonstrated experimentally that if an animal heart is filled with a hot liquid, the heartbeat rate increases proportionally with the temperature, but up to a maximum point of about 44 $^{\circ}$ C (111.2 $^{\circ}$ F). If this point is reached, the heart will stop beating. On the other extreme, if an animal heart is filled with cold liquid, the heartbeat rate decreases and the heart stops beating at about 17 $^{\circ}$ C (62.6 $^{\circ}$ F). In order to be able to practice cardiac surgery, the heart is slowed down by surgeons, by an induced hypothermia, which is accomplished by cooling the blood. Hypothermia slows cellular metabolism decreasing the need of oxygen.

Cardiac Output

It is estimated that in a person at rest, the volume of blood ejected in each systole is around 70 to 80 ml. This amount of blood moves from the left ventricle to the aorta. It is called the stroke volume. Similarly, the same amount is forced from the right ventricle to the pulmonary artery. Therefore, the total cardiac output is around 140 to 160 ml. Given a pulse rate of 70 and a stroke volume of 80 ml, the amount of blood that leaves the left ventricle is 70 x 80 ml = 5.6 liters per minute. This is called the cardiac output.

Properly written and considering the transformation of units, we will have the following expression:

$$70\,\frac{beat}{min} \times 80\,\frac{ml}{beat} = 5600\,\frac{ml}{min} \times \frac{liter}{1000\ ml}$$

$$= 5.6\,\frac{liter}{minute}$$

$$\boxed{\text{CARDIAC OUTPUT}} = \boxed{\text{HEART RATE}} \times \boxed{\text{STROKE VOLUME}}$$

While exercising, the cardiac output may be doubled.

The heart has the ability to regulate the cardiac output depending on de activity of an individual. If the demand for oxygen increases, the oxygen supply must also increase. Cardiac output is determined by heart rate, preload, afterload and contractility.

Preload

A way to easily understand the meaning of preload, is to pay attention to the prefix "pre," which means "prior to" or "before." Therefore, preload refers to the amount of blood prior to the load (contraction). While researching for the term "preload," I found several descriptions such as that preload is the end volumetric pressure that stretches the ventricle to its greatest dimension depending on the needed demand. When a person is running, the demand will make the heart beat faster to supply the greater amount of oxygen that is needed.

The volume of the blood is directly proportional to the force used by the ventricle to contract. However, if the volume exceeds the accepted limit, the effectiveness of the contraction will decrease. This is called Starling's Law of the Heart.

Afterload

Afterload is a term that indicates what happens after a chamber of the heart has been loaded with blood. Specifically, the afterload is roughly the pressure that the heart has to push against. For the left ventricle, this is the pressure in the aorta.

Contractility

Contractility is the natural characteristic of the heart to contract during systole. This is due to the fact that the cardiac muscle fibers shorten during systole.

Contractility is important for the circulation of the blood in the system. Poor contractility decreases the ejection of blood with the immediate consequence of reducing stroke volume. In a chain reaction, the cardiac output is reduced, and the rest of the organs will not receive the proper amount of blood needed to function normally.

Rate of Flow

It is common that individuals admitted into the ER room with life-threatening situations are given intravenous fluids. After physicians have taken all the precautions and in order to keep their patients within the normal range of vital signs, they order an infusion of some volume of fluid within a stated amount of time. For example, they might order to administer 1000 ml of saline solution in 8 hours, which is equivalent to 125 ml per hour. These are units of flow. To illustrate the change of units, I will write the following expression:

1000ml/8hours = 125 ml/hour = 3000 ml/24 hours

To calculate the flow rate, it is needed the information about the volume of the fluid to be infused, the calibration of the tubing (also called the drop factor) and the time ordered for the infusion that normally is applied in drops. Drops are units of volume and are represented by *gtt*. The unit *gtt* is an abbreviation of the Latin "gutta." In the metric system, 1 drop is equivalent to 0.05 mL or 20 drops per each milliliter. Some old home-cooking-recipes, show 24 drop equals ¼ teaspoon, which according to US definitions, it makes the drop equals to 0.051 milliliters. This number is very close to the metric equivalence.

$$\frac{Volume\ (ml) x\ Calibration\ (\frac{drops}{ml})}{Time\ (minutes)} = \text{Flow Rate (drops / min)}$$

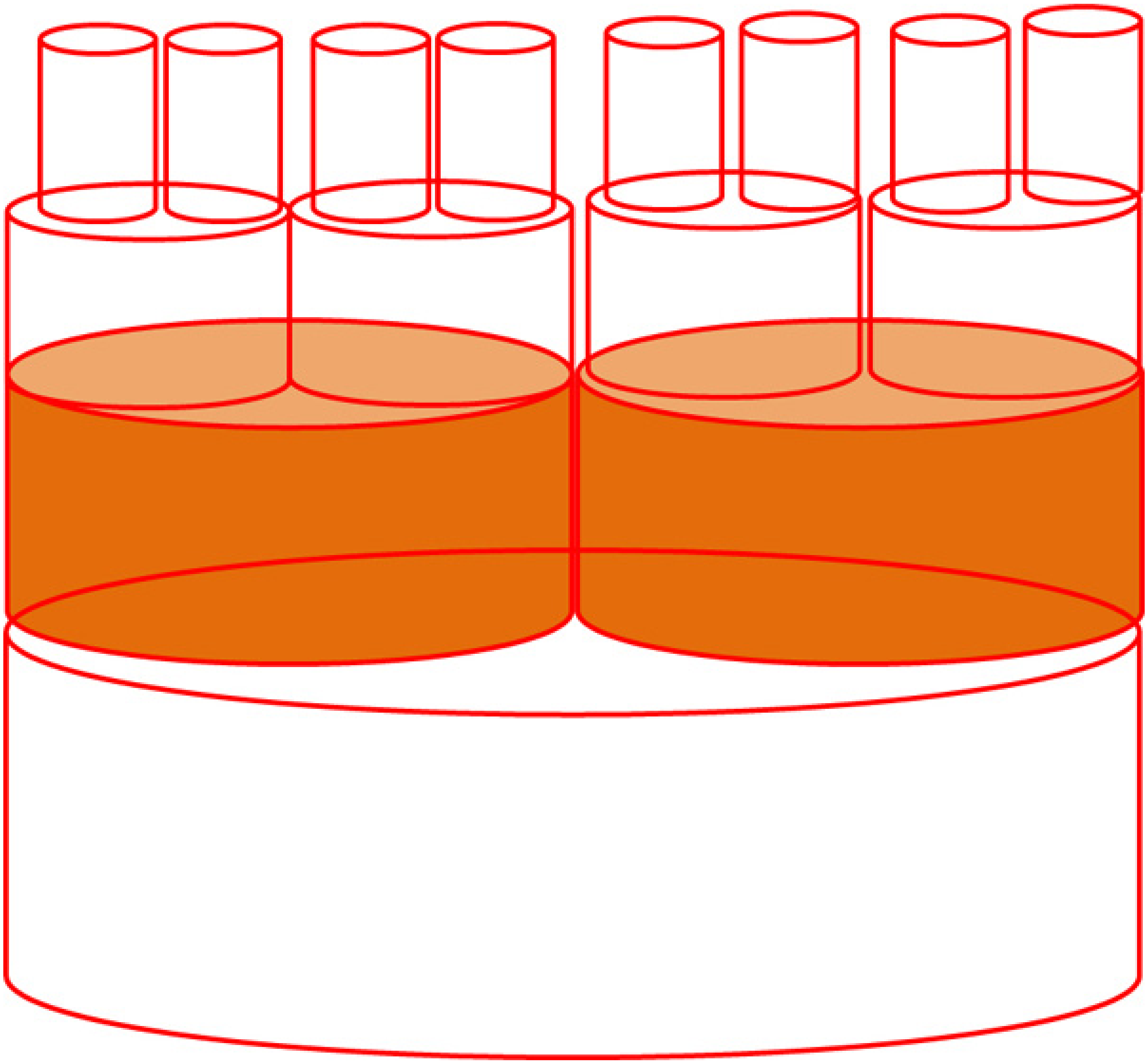
Blood Flow

The circulation of blood in the arteries is controlled by a balance of blood flow, blood pressure and peripheral vascular resistance. Blood flow (which is measured as a volumetric flow rate) is calculated by multiplying the speed of the blood times the cross-sectional area. Blood flow represents how fast the volume of blood passes through the cross section. The units of blood flow are calculated in milliliters per minute.

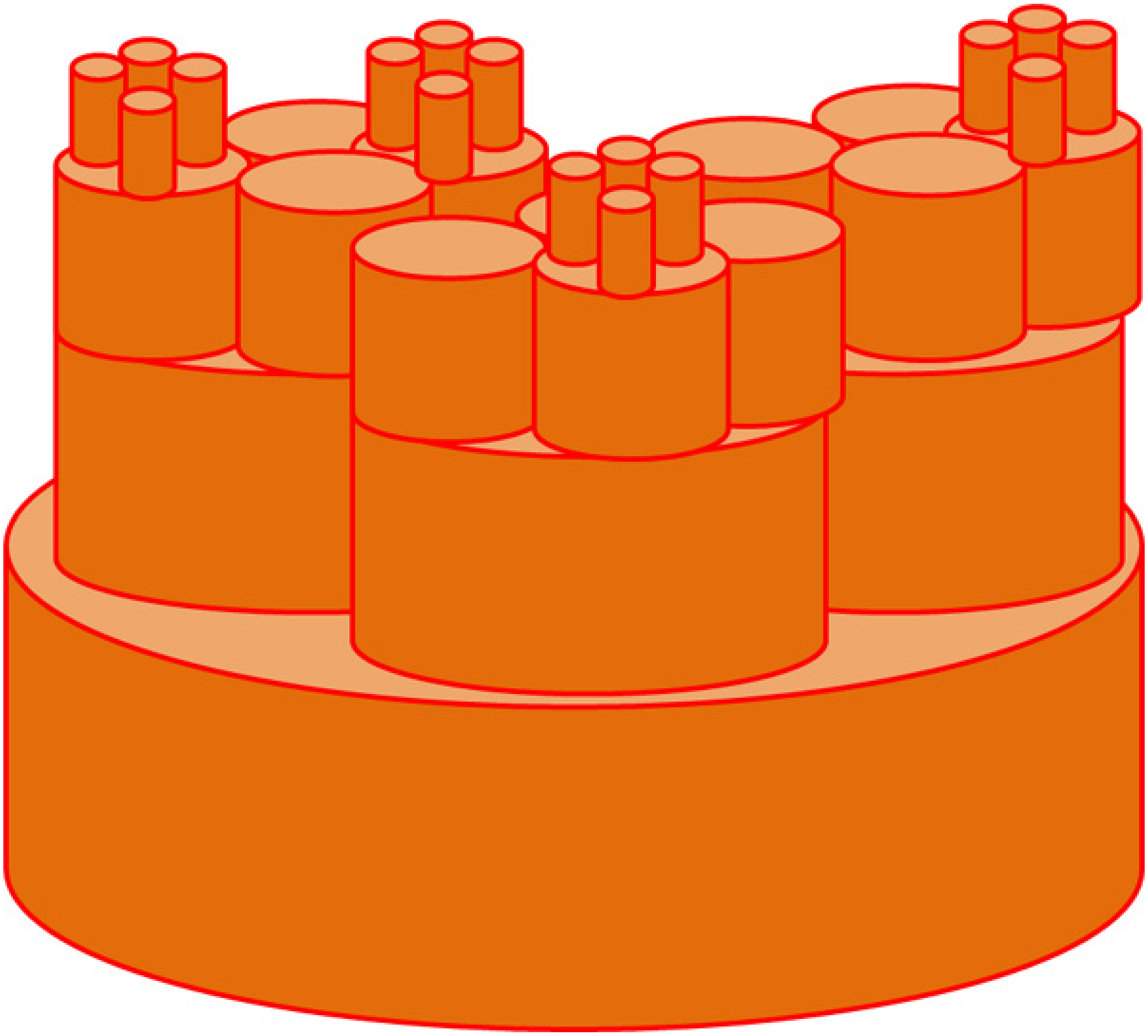
Blood Flow = (blood velocity) x (cross-sectional area)

Cross-sectional Area of Vascular Tree

A vascular tree is a set of vessels distributed in an anatomic structure of branches obtained by a continuous division of the vessels. It works as a blood distribution network very similar to the branches on a tree. In the picture below, a simple idea of a division of vessels is presented, although this model does not really represent how the vessels divide.



In this other picture, the model represents a closer idea of the division of vessels, although is not yet the perfect model.



The total cross-sectional area of the vascular tree is a maximum value in the capillaries. This can be demonstrated using a mathematical model of geometric series. The summation of the entire cross sectional areas of the vascular tree will be greater than the initial cross section area of the aorta. The division of the vessels starts right there with the aorta increasing the number of cross sections; and as the division continues, the flow of the blood keeps its circulation towards the tissue. Exactly the reverse occurs starting from capillaries to venules to veins and back to the heart.

Hematocrit

Hematocrit is the volume percent of red cells in the blood. To find the hematocrit of an individual, a blood sample is centrifuged in a tube. Red cells will accumulate at the bottom of the tube; the hematocrit is defined as the height of the red cell column divided by the total height and is usually expressed as a percentage.

Viscosity

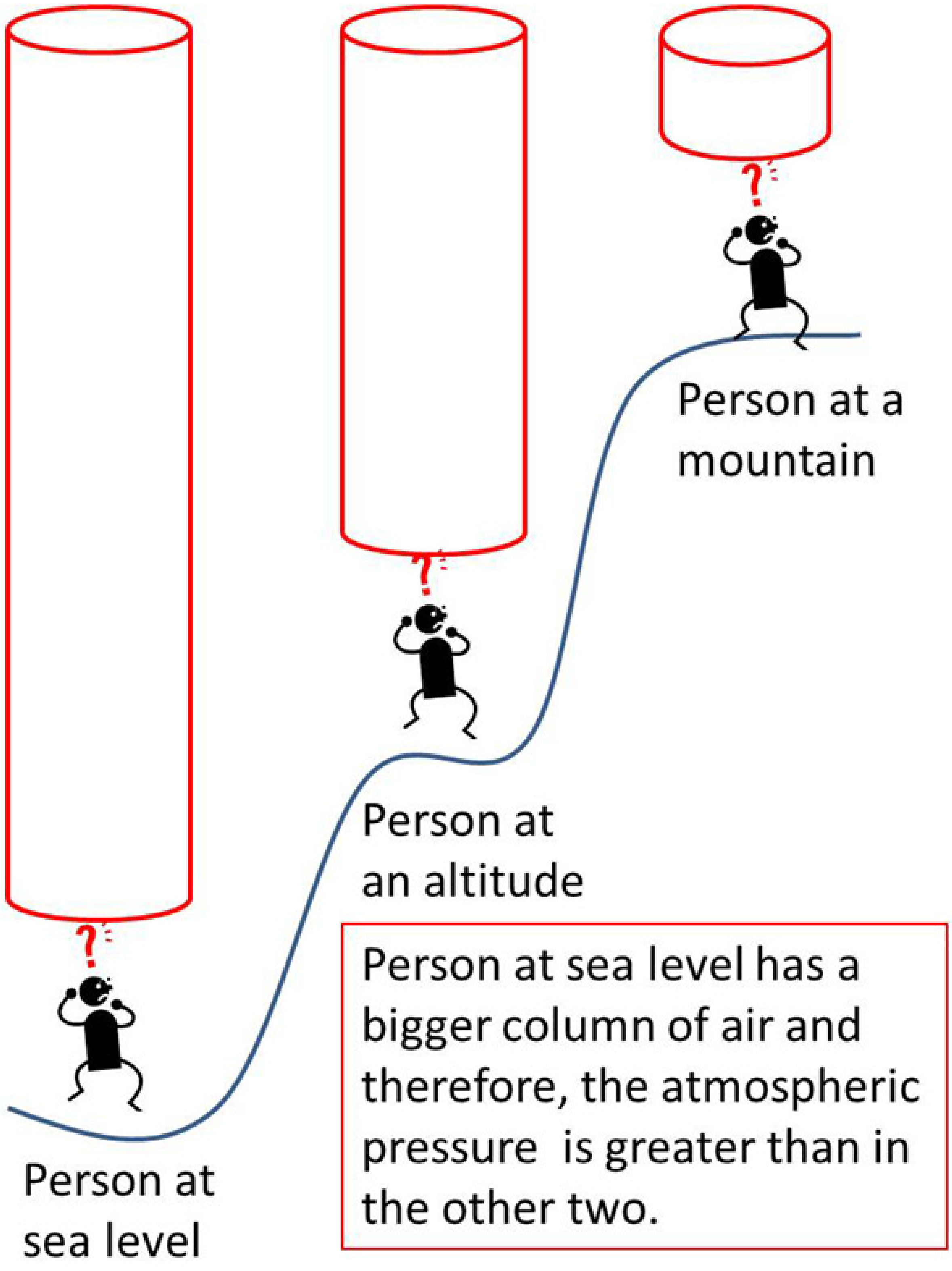
Viscosity is a measure of resistance of the fluid to flow. It is also considered "an internal friction." The viscosity of liquids decreases rapidly when the temperature increases. Blood is a liquid composed of plasma and particles such as red cells; its viscosity depends on the viscosity of the plasma and on the hematocrit. Viscosity is studied using ideal liquids, called Newtonian fluids. Although the plasma is considered a Newtonian fluid, the blood is not due to the presence of red cells, which create a non-ideal fluid.

Peripheral Vascular Resistance

The force opposing blood flow is called the Peripheral Vascular Resistance (PVR). The PVR is directly proportional to blood viscosity and to the length of the vessels, but inversely proportional to the diameter of the vessel. With more viscous blood, there is more resistance to flow. With longer vessels, there is more resistance of the blood to flow. With smaller vessels, there is more friction and therefore, more resistance of the blood to move.

Pressure

Pressure is the result of applying a force perpendicularly over a surface area of an object. Mathematically, pressure is defined as the force divided by an area. A force applied on a small area will result in a bigger pressure. A force applied on a larger surface and equally spread on the surface will produce a minimum pressure. If the given area is 1 m^2 and the given force is 1 Newton the pressure will be 1 Newton per square meter, which is a unit called "Pascal." To start with some examples, atmospheric pressure is the pressure that we feel on our head, ears, and the rest of our body. Our body gets used to atmospheric pressure, so that when we go to a place that it is at a different altitude with respect to sea level, our body will feel the difference. There are several units used to measure pressure. We will have the opportunity to explore some of these units, including some conversion factors, before we enter in detail the study of blood pressure.



Units of Pressure

There are many alternate units used to express pressure. I will refer only to those that are related to blood pressure or that are needed to understand this curriculum unit.

One atmosphere is equivalent to the pressure obtained by a column of 760 mm of mercury. Therefore, it is said that one atmosphere equals 760 mmHg (Hg is the chemical symbol for mercury). Since pressure is quantified as force divided by area, the force of the mercury is in reality its own weight. When calculating the pressure, the area of the base where the weight of the mercury is applied gets simplified and disappears from the calculations. The calculations includes the density of the fluid, which is mass divided by volume; the volume of the fluid is calculated as the product of area "A" times the height "h" of the mercury. The mass of mercury is calculated as the product of density "ρ" times volume. Substituting, we find that pressure equals the product of density "ρ" times the height "h" of the given liquid.

$$\text{Volume} = \text{Area x height} \qquad V = A \cdot h$$

$$\text{Mass} = \text{Density x Volume} \qquad M = \rho \cdot V$$

$$\text{Force} = \text{Weight} \approx \text{Mass x Acceleration of gravity}$$

$$\text{Pressure} = \frac{Weight}{Area} \qquad P = \frac{\rho \cdot V}{A} \cdot g$$

$$V = A \cdot h$$

$$P = \frac{\rho \cdot A \cdot h}{A} \cdot g$$

$$P = \rho \cdot h \cdot g$$

This formula illustrates that pressure depends on the height of a liquid, independently from the area, since the area disappears from the calculations as it is shown above.

Pounds per square inch (or PSI) have been for a long time a common way to measure pressure; although recently the International system has switched to Pascal as the unit for pressure. Another unit is the Torr and one Torr is equal to one mmHg.

Blood Pressure

Blood pressure, which is created by the pumping action of the heart, is the force that blood exerts against the walls of the circulatory system. Blood pressure is usually measured in mmHg. Blood pressure measurement typically consists of two readings. One is called the systolic pressure, which reflects the pressure of the heart during systole. The other reading is called diastolic pressure and occurs when the heart is at rest between beats.

Inequalities and Blood Pressure

A normal systolic blood pressure is considered to be no more than 120 mmHg, which it can be written as the inequality: Normal SBP ≤ 120 mmHg

A normal diastolic pressure is considered to be no more than 80 mmHg, or written as an inequality: Normal DBP ≤ 80

The category of pre-hypertension is given when the systolic blood pressure is between 120 and 139 mmHg or the diastolic pressure is between 80 to 89 mmHg. Using inequalities we can express these numbers as:

120 SBP 139 mmHg

80 DBP 89 mmHg

Individuals in pre-hypertension category re treatable, but some steps need to be taken to not reach the next category.

High blood pressure (or hypertension) is the next category after pre-hypertension. It has two stages; stage 1 is defined as a systolic reading between 140 and 159 mmHg and diastolic reading between 90 and 99 mmHg. Using inequalities:

Systolic High Blood Pressure reading 140 ≤ SHBP ≤ 159 mmHg

Diastolic High Blood Pressure reading 90 ≤ DHBP ≤ 99 mmHg

Stage -2 hypertension is defined as a systolic reading of 160 mmHg or higher and a diastolic reading of 100 mmHg or higher. Using inequalities:

Systolic High Blood Pressure reading SHBP ≥ 160 mmHg

Diastolic High Blood Pressure reading DHBP ≥ 100 mmHg

All readings above 120/80 indicate a health risk; the risk increases if the readings increase. Sometimes, the systolic and diastolic readings are not in the same category; in that case, physicians assume that an individual is in the most dangerous of the categories. For example, let's assume that your systolic reading is 160 and your diastolic reading is 80. Because of your systolic reading of 160, you would be in stage-2 hypertension and, because of your diastolic reading of 80 you would be in the normal group. However, when both readings are put together and analyzed, the result will be that you are in the hypertension stage-2, because the most severe one prevails.

5. Lesson Plans

Lesson-1: Introduction to the unit "There is math in your heart." Time: 50 minutes. (Suggested for Algebra-1 and Algebra-2)

Facts of the cardiovascular system from the quantitative point of view (10 minutes)

In this portion of the lesson, teacher presents facts of the cardiovascular system, which are directly related to conversion of units and scientific notation, such as diameter of vessels, flow of circulation, and pressure. Other important facts to mention are that the heart works as a pump to supply oxygen to the entire body and that the vessels divide creating more section areas, for which the pressure getting far away from the heart is each time lesser.

Class discussion about the numerical and functional facts presented (15 minutes)

Allocating a few minutes for the "why's" and "how's," and approaching the answers using students' prior knowledge, will enable the class to participate.

Learning about conversion factors and scientific notation (15 minutes)

To understand the size of the vessels, it is necessary to help students to compare the diameter of the vessels with the diameter of their wrist. After presenting examples on conversion of units and scientific notation, students solve exercises on the white board. Other options include individual small white boards or plane paper.

Closure and assigning homework (10 minutes)

A handout with exercises about scientific notation and conversion of units will be handled to the class. Examples for the homework are presented.

Lesson-2: Using formulas, Formula of area and formula of flow, what is flow? (Suggested for Algebra-1 and Algebra-2)

Presenting facts about flow, proportions and working with formulas (25 min)

To understand flow an empty bottle of soda of preferable 2 liter will be used. Students will fill up the bottles with water, and the will measure the time that it takes to empty it, through tubes of different diameters. The data will be recorded in a table and later used to analyze the results.

Keeping the volume constant (2 liter), the time to empty the bottle depends only on the sectional area of the tube; and the sectional area of the tube depends on the square of the radius. Radius is half of the diameter of the tube.

Comparison of recorded data (15 minutes)

Flow is calculated as volume over the sectional area; therefore, in each case, the only variable is the diameter of the tubes (or the radius of the tube), because the volume is the same. The expression obtained will look like: $Q = V/t$, where Q is flow, V is volume and t is the time that the bottle takes to empty.

Students will fill in the blank spaces on the attached table and will find out the relationship between flow and area.

Volume (Liters)	Time (seconds)	Diameter (cm)	Radius (cm)	Area	Flow (L/sec)
2L		0.5	0.25	0.625	
2L		0.75	0.375	0.5625	
2L		2	1	1	
2L		3	1.5	2.25	
2L		4	2		
2L		5	2.5		
2L		8	4		

Presentation of conclusions and class discussion (10 minutes)

Students will present their results per groups. Conclusions obtained will be written on the white board or on a large sticky paper to hang it on the wall.

Lesson-3: What is Pressure? (Suggested for Algebra-1 and Algebra-2)

Lecture about pressure (10 minutes)

Using the third picture from section 4 "The Math of the Heart," explanation about understanding atmospheric pressure will be presented. The next part is the explanation of the transformation from the general formula $P=F*g/A$, where P is pressure, F is the force applied on area $\boldsymbol{A}$; to the use of density and height of a fluid with the formula $P = \rho h g$.

Practicing Exercises about pressure (15 minutes)

The last part of the lesson is to describe what blood pressure is as well as difference of pressure. At this point, some conversion of units will be presented.

Sharing solutions and explaining before the class (10)

Students present their solutions before the class

Closure and assigning homework; checking for understanding (10 minutes)

Checking for understanding will include questions about difference of pressure and conversion of units.

Lesson-4: Using series (Suggested for Algebra-2)

Lecture about sum of all the terms of a series (15minutes)

The summation of all the terms of a sequence uses the example illustrated in section 4 "The Math of the Heart," and it is based on the wrong assumption that the cross sectional area of the new vessels is exactly half of the previous one. This assumption will conclude that the sum of all cross sectional areas is equal to the initial area. Off course this assumption is not right. Using the example illustrated on figure-2 of section-4, it is demonstrated that the sum of all sectional areas of all the vessels is greater than the cross sectional area of the initial vessel.

Exercises about sum of terms of a series (15 minutes)

Students' presentations (20 minutes)

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List of materials for classroom use

- Zip block bags

- Plastic tubes with different diameters and different lengths

- Shoe boxes

- Graph paper

- Three different colors of pen or pencils

- Ruler

- Empty bottles of soda, preferable 2 liter

- Water, soda, juice or other liquid

- Chronometer or a proper watch

- Calculator (Graphic calculator is not really necessary)

- Instrument to measure blood pressure (Only if available)

Appendix

District and California standards are embedded in all the lessons presented in this curriculum unit. Algebra-1 and Algebra-2 standards both include the study of scientific notation, graphing, interpreting data, and application of formulas. The information about the cardiovascular system and the heart include as well standards from Biology, Anatomy and Physiology.

The study of series and summation at Algebra-2 level is presented with the calculation of the sum of all sectional areas of the cardiovascular system, without counting the aorta. These concepts are standards for California and for our school district.

Understanding and using formulas to calculate area, volume, density, flow rate and pressure, are part of the algebra-1 standards where it is stated that students will learn how to manipulate variables and formulas.

Implementation of district standards will be done using direct instruction, cooperative learning and students' presentations. It is intended to include a presentation of completed work before the community at a parents' night. A mini contest among my classes where I have taught this curriculum unit may be as well possible.

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