DEPARTMENT OF
Biomedical Engineering
UNIVERSITY OF WISCONSIN–MADISON

Teaching Model for Ventilation-Perfusion Mismatching

BME 400 Final Report

December 9th, 2020

Client:
Dr. Chris Green

Advisor:
Dr. Amit Nimunkar

Team Members:
Team Leader/BSAC: Brittany Glaeser
Communicator: Kaitlin Lacy
BPAG: Jenna Eizadi
BWIG: Zoe Schmanski

Table of Contents

I. Abstract

Ventilation-perfusion (V/Q) mismatching explains the ratio between the air that reaches the alveoli in the respiratory system and the oxygen exchanged to the bloodstream. This concept taught during medical school is often challenging for medical students to grasp. The goal of this project is to develop and fabricate a physical teaching model for medical school professors to use to represent this complex subject. Currently, there are no competing physical models for V/Q mismatching on the market. Rather, the only current models include online simulations and textbook diagrams. The use of silicone diffused LEDs and a LED ring was chosen to depict V/Q ratios on a 3D printed base model of a single alveolus and single capillary. Testing was completed by determining the intensity of the LEDs through an overhead display to determine the optimal brightness to represent a variety of V/Q ratios. Future work includes incorporating buttons to separately increase and decrease ventilation and perfusion in order to represent a larger range of ratios, as well as incorporating a display to show the V/Q ratios.

II. Introduction

2.1 Background

Maintaining normally oxygenated blood depends on the gas exchange between the air in the alveoli of the lungs and the blood of the pulmonary capillaries. The alveoli open and close through the action of smooth muscle projections called alveolar cusps, and this allows inhaled oxygen to enter and diffuse across the alveolar walls into the bloodstream [1]. In order for air to reach alveoli, it must enter through the oral or nasal cavities, flow through the pharynx, the larynx, and into the trachea. The trachea branches into the two bronchi of the lungs at the carina and air then flows into the bronchioles before finally reaching the alveoli [2]. Adjacent alveoli are separated by alveolar septa which consist of thin walls with capillaries for gas exchange. This exchange of gas requires proper ventilation of the lungs as well as proper perfusion of the capillaries and is often evaluated by medical professionals through a metric known as the ventilation-perfusion (V/Q) ratio [1].

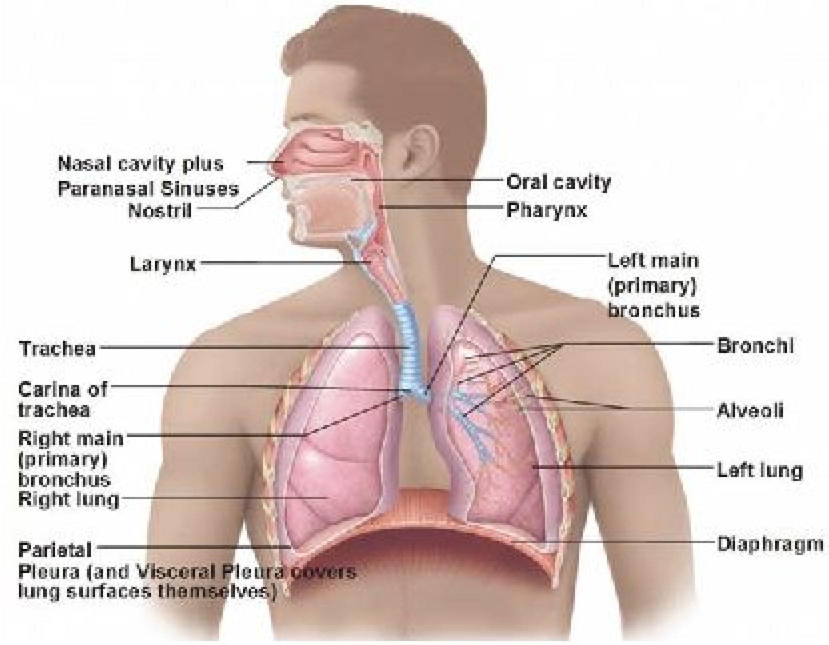

Figure 1. Anatomy of the respiratory system [3].

The V/Q ratio shows the matching of these two rates and may vary depending on the part of the lung. In extreme cases of high V/Q rates, dead space ventilation can occur in which there is air movement with ventilation that is unable to participate in gas exchange. Dead space can increase when there is a loss of alveolar function, decreased cardiac output, hypotension, pulmonary embolism, and vasoconstriction [4]. Anatomic dead space is the air volume in the nose, trachea, and bronchi that normally is not involved with gas exchange while physiological, or total dead space, is the sum of anatomic and alveolar dead space [4]. Inversely, a shunt occurs when there is perfusion, but no ventilation of the corresponding alveoli and can be seen in Figure 2. Therefore, there is no contribution to blood oxygenation from this area, and hypoxemia can result, which is a condition where there are low oxygen concentrations in the blood [5]. The alveolar ventilation, the amount of air that reaches the alveoli for gas exchange, can be calculated using Equation 1, where tidal volume is defined as the amount of air that moves into or out of the lungs. In a normal healthy adult, normal tidal volume is about 500 ml and dead space is about 150 ml [4]. Equation 2 can be used to calculate the partial pressure of oxygen in the alveolus (P_AO_2) where P_IO_2 is the partial pressure of inspired oxygen, VO_2 is O_2 consumption, V_A is ventilation, and P_B is barometric pressure [4]. Finally, the shunt fraction can be calculated with Equation 3, where Q_s is the blood flow through the shunt, Q_t is the blood flow through the lung, Cc_{O_2} is the pulmonary end-capillary O_2 content, Ca_{O_2} is the arterial O_2 content, and Cv_{O_2} is the mixed venous O_2 content [4].

$$\text{Alveolar Ventilation} = \text{Respiratory Rate x (Tidal Volume - Dead Space)} \tag{1}$$

$$P_AO_2 \ = \ P_IO_2 \ - \ (VO_2/V_A) * (P_B - 47\ mmHG) \tag{2}$$

$$Q_s/Q_t \ = \ (Cc_{O_2} - Ca_{O_2})/(Cc_{O_2} - Cv_{O_2}) \tag{3}$$

It has been observed that students oftentimes have difficulty understanding that a high V/Q ratio leads to dead space ventilation or wasted ventilation and that a low V/Q can lead to hypoxemia. It is also hard for students to visualize or understand that an increase in a V/Q ratio can be due to either an increase in the ventilation or a decrease in perfusion and thus is important for determining the correct treatment. It is important for physicians to understand the mechanisms included in V/Q mismatching to allow for the correct treatment protocol to be chosen. It is difficult for medical students to understand that, for example, hypoxemia from a shunt cannot be corrected by supplemental oxygen. This inadequate knowledge about the causes of hypoxemia can thus lead to incorrect care given to a patient [6].

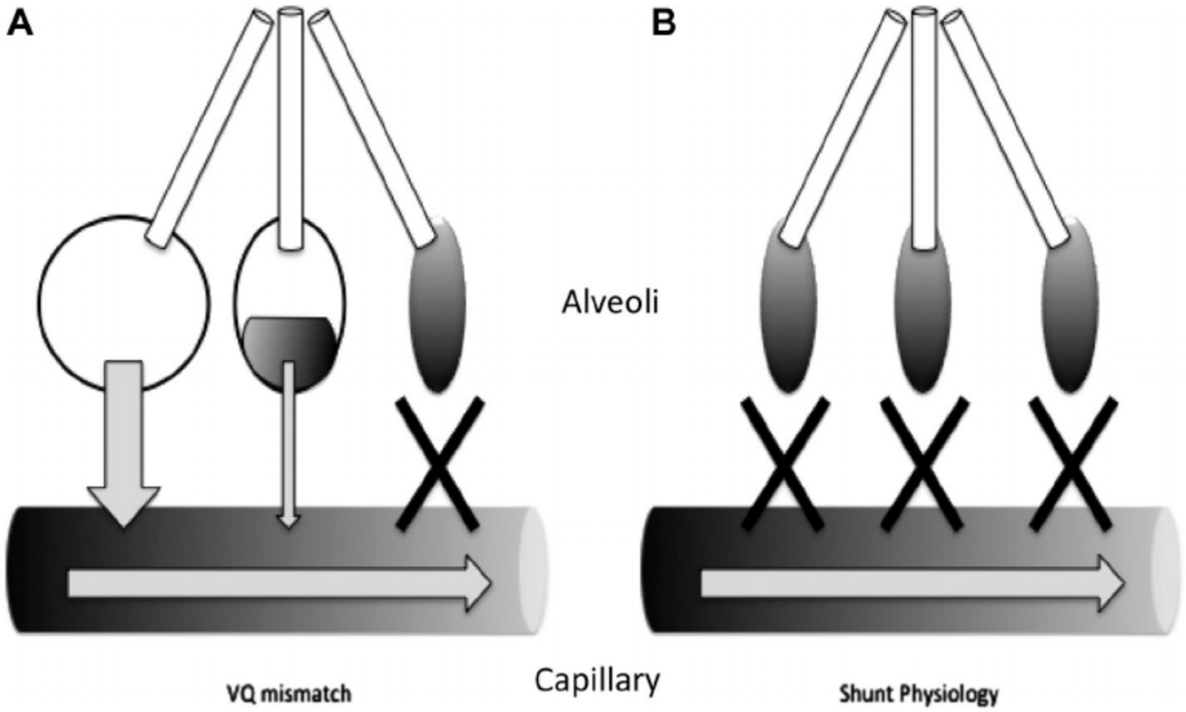

Figure 2. Comparison of VQ Mismatch and a shunt [7]

2.2 Existing Devices and Current Methods

West (2016) presents a ventilation and perfusion model that utilizes water pumps to simulate the movement of air into the lungs and blood flow [8]. A dye is placed into the water to show the gas exchange between the lungs and the bloodstream as well as the resulting oxygenation of the blood. This model is not a physical model and the textbook uses this model as an analogy to describe V/Q ratios. A physical model of this design is described in detail in Preliminary Designs 3.1.C. Another model is a multi-scale computational model relying on the use of a series of ordinary and partial differential equations. It models the vascular network of the entire lung generated by a space-filling algorithm and tested by comparing it to existing literature [9]. A model like this [9] would most likely be beyond the programming abilities of the team.

2.3 Problem Statement

During medical school, students are taught about the importance of ventilation/perfusion mismatching and the effects it has on the body. Oftentimes, the students have difficulty understanding that a high V/Q ratio leads to dead space ventilation or wasted ventilation and that a low V/Q can lead to hypoxemia, which is a condition where there is a low oxygen concentration in the blood. A physical model representing the mechanisms underlying ventilation/perfusion mismatching would help students understand this concept.

2.4 Client Information

Dr. Chris Green is a retired pediatric pulmonologist and continues to teach lectures at UW-Madison School of Medicine. During his lectures, he discusses ventilation and perfusion mismatching and understands that the concept is difficult for some students to comprehend. Therefore, he has requested a physical model to use in his classroom to help teach the students the concept of ventilation and perfusion mismatching.

2.5 Design Specifications

This design must portray ventilation and perfusion at the micro-scale level (alveolar level) to accurately show the gas exchange between the alveoli and capillaries. The model should also include an interactive component for the user to change the V/Q ratio with a minimum of five ratio settings. Since this device will be used during lectures at the UW-Madison School of Medicine, the device should be able to be used multiple times in a given lecture and require little to no setup or clean up. Also, since the device will likely be used in a lecture hall containing about 180 students, the device must be large enough for students to see with the use of a projector, and while not being used during the lecture, the model must be able to withstand storage for long periods of time. While there may be some students with visual impairments, it is assumed that the students can see the screen in the lecture hall as they would already need to for class, or they have existing accommodations in place that provide them opportunities to learn that are tailored to their unique circumstances. Color blindness affects about 8% of males and less than 1% of females because it is an X-linked recessive trait and has different consequences, most commonly red-green color blindness. For many physicians, this can cause implications when examining a patient’s rash, pallor, or blood, but it doesn't mean they cannot become a physician. One study had shown that the prevalence among those in a medical profession is roughly 8% of males and less than 1% of females, similar to that of the overall population [10]. To account for these individuals, altering the brightness and the rate of flow on the LEDs will make it accessible for any students that may be colorblind. For easy portability between classroom and storage, the design should ideally weigh less than 6.8 kg (15 lbs). For detailed design specifications, see Appendix A.

III. Preliminary Designs

3.1 Flow Mechanism Design Models

3.1.a LED Flow Model

The LED Flow Model consists of an alveolar duct leading into a single alveolus surrounded by a capillary tube. LEDs would line both the capillary tube and the alveolar duct to represent blood flow and gas flow respectively. Ideally, as the blood flows through the capillary tube from left to right (represented by the red arrow in Figure 3), the LEDs would change color to show that the blood has been oxygenated. The gas exchange would also be modeled using LEDs, where carbon dioxide would be modeled using one color flowing out of the duct and oxygen would be modeled by another color flowing into the duct and then into the bloodstream oxygenating the blood.

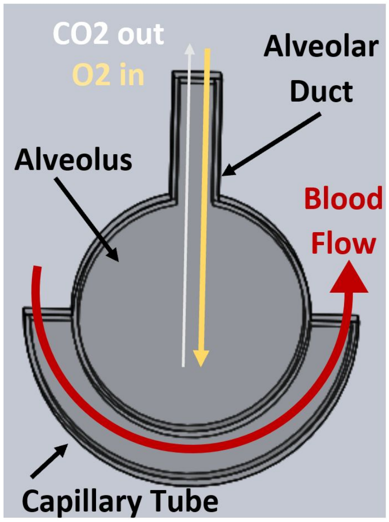

Figure 3. LED flow model with arrows to represent LED placement

3.1.b Bead Flow Model

The Bead Flow Model consists of a tube representing a bronchiole that is connected to two alveoli that are surrounded by a single capillary tube which can be seen in Figure 4. This design would model flow using beads suspended in water. Pumps in the back of the design would control the amount of water and beads flowing through the system. The number of beads that are released into the alveoli represents the amount of ventilation, while the number of beads that mix with the water would represent the amount of perfusion. The release of the beads would be regulated through a pinched tube, with a smaller diameter corresponding to fewer beads flowing through the system. A complication with this design would be finding a way to separate the beads from the water with little effort from the user.

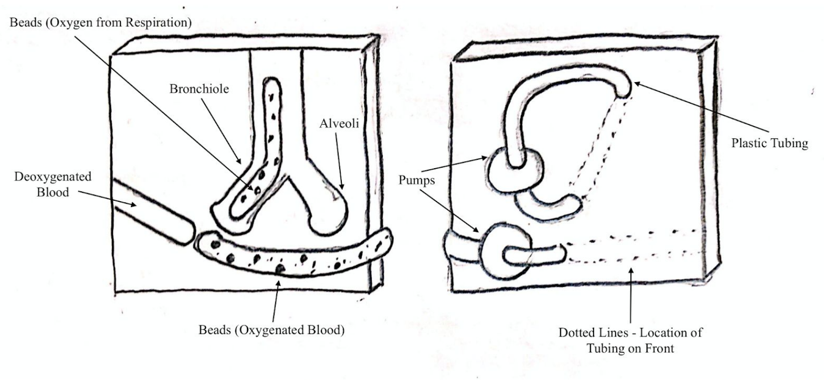

Figure 4. Bead Flow Model with black dots representing beads.

3.1.c Water Flow Model

The Water Flow Model is based on the idea from John West's (2016) model presented in his textbook [8], this model is seen in Figure 6. This model would include a closed water system and a water pump to move the water from a reservoir through the design's capillary tubes. An example of a closed water system can be seen in Figure 5.

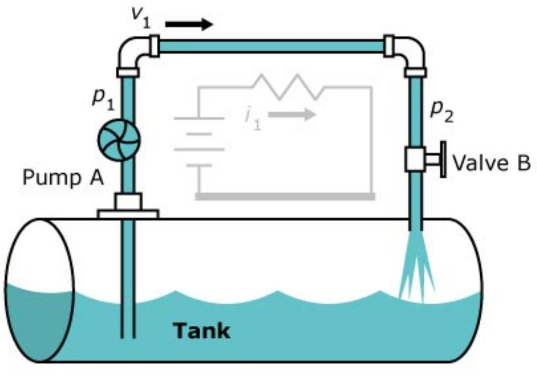

Figure 5. Closed water system with pump and reservoir [11]

Dye would be inserted through the alveolar duct portion of the design and then flow into the capillary tube where the water flows through. The amount of dye used represents the amount of ventilation and the concentration of the water and the dye would represent the V/Q ratios. The water flow model would require a water reservoir and a waste reservoir. The reservoir with clean water would allow clean and clear water to flow through the capillaries and the waste reservoir would hold the water that has already been mixed with the dye. This design can get messy involving the dye and can become heavy depending on the size of the reservoirs.

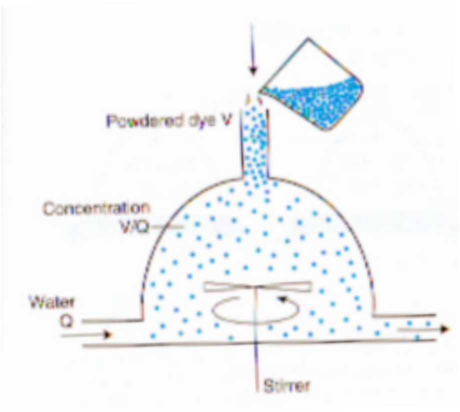

Figure 6. Water flow model using dye [8]

3.2 LED Mechanism Design Models

3.2.a Original LED Model

The Original LED Model consists of the LED Flow Model lined with singular LEDs of different colors. This design would feature each individual LED linked together into a system by some component that could alter the colors of the system as needed. While this design is simple, it does not allow for a gradient of colors to represent the difference in flow rates between each of the V/Q ratios.

Figure 7. Individual LEDs that would line the LED Flow Model [12]

3.2.b Diffused LED Model

The Diffused LED Model features an LED strip lining the LED Flow Model. The LED strip has functionality that would allow for each color gradient to be achieved, while also permitting different colors to be present on the same strip. This design is promising as it easily incorporates different color gradients in a synchronous fashion and could be modulated to model a large variety of different V/Q ratios. In addition, the diffused component of this model would greatly increase the light diffraction to intensify the colors from the LEDs.

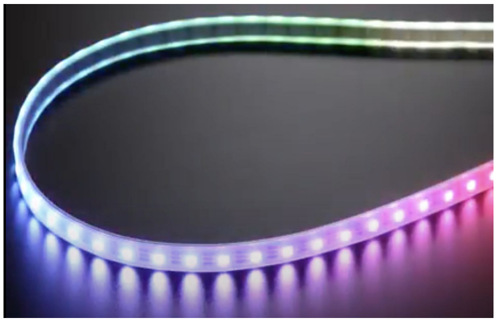

Figure 8. LED strip in diffused tubing representing a variety of color gradients [13]

3.2.c Water-Submerged LED Model

The Water-Submerged LED Model contains an LED strip lining the LED Flow Model. This design features similar benefits proposed in the above Diffused LED Model but attempts to increase the light intensity from the LEDs through light diffraction in water. The main drawback of this design is that it could potentially pose a challenge to incorporate water with an electronic system.

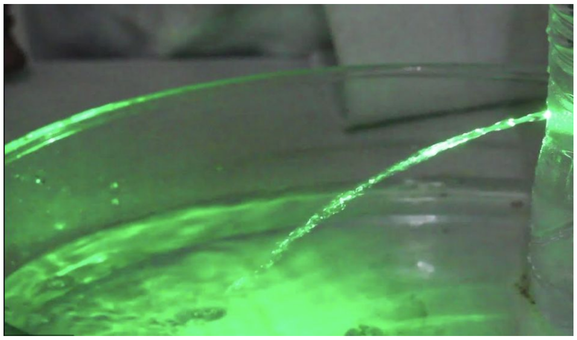

Figure 9. LED light diffraction in a stream of water [14]

IV. Preliminary Design Evaluation

4.1 Flow Mechanism Design Matrix

Table 1. *The design matrix with categories on the left, their weights in parentheses, and each design labeled on the first row. The dark green cells represent the designs that won each category as well as the design that won overall.*

Designs **Categories**	LEDS		BEADS		DYE	
Effectiveness (35) (Competency)	5/5	**35**	3/5	**21**	2/5	**14**
Ease of Use (30)	5/5	**30**	4/5	**24**	1/5	**6**
Ease of Fabrication (15)	4/5	**12**	3/5	**9**	2/5	**6**
Viability (10)	4/5	**8**	4/5	**8**	2/5	**4**
Safety (5)	3/5	**3**	4/5	**4**	4/5	**4**
Cost (5)	4/5	**4**	3/5	**3**	2/5	**2**
Total (100)	92		69		36	

4.2 Flow Mechanism Design Evaluation

Effectiveness: Effectiveness was determined by the accuracy of the device to portray ventilation/perfusion mismatching. The design was considered more effective if it had a larger quantity of V/Q ratios it was able to present and if those ratios were represented in a precise way that would be observable to those using it. Effectiveness also took into consideration how well the device would appear in front of a lecture full of students. The LEDs scored perfectly in the effectiveness category as this design allows for a gradient of V/Q ratios, rather than set values in both the beads and dye design which lead to their lower scores in this category.

Ease of Use: Ease of use was considered as to how intuitive the device would be to operate for someone who may not have a technical background. This would include how easy it would be for the user to adjust the V/Q ratios as well as any action on their part to reset components of the device between different modeling sessions. It also considers the effort it would take to set up and store the device. As the users are professors or possibly students at the medical school, this device needs to be something that they can incorporate into the teaching of V/Q mismatch with very little effort as they have very busy schedules with lots of curriculum to go through. The LED design scored high in this category as it would be easily adjustable versus both of the other two designs that would require more effort to modify. The dye design scored the lowest in this category due to the complicated setup and reset of this model.

Ease of Fabrication: Ease of fabrication considers the ability of the team to produce the model. The fabrication process is a vital aspect of the design process, as it is important to be able to fabricate the device easily and effectively. Ease of fabrication takes into consideration the need for 3D printing, electronics, and outsourcing materials. The LED model was considered the simplest to fabricate due to the easy integration into an electronic system while both the beads and dye designs would need an intermediate component and would lead to a more complicated process.

Viability: Viability is characterized by the ability of the device to model ventilation/perfusion mismatching over a long period of time with little to no decrease in accuracy and precision. The time period will be determined by the client's needs but is anticipated to be at least 5 years. In addition, the device will be used multiple times throughout the year. The dye model was ranked lower than the other two designs because of the complications in storing and resetting the system.

Safety: Safety is an important criterion to consider for any product. Safety was ranked with low importance as the model does not have eminent safety concerns. Safety considered electrical concerns and other outstanding hazardous components. Both the beads and dye designs were scored higher than the LEDs in the safety category because they did not pose any serious electrical risks.

Cost: Cost is ranked as one of the least important criteria for the design matrix determined by the flexible budget of $1000 provided by the client for designing and fabricating the device. An important aspect of the design will be in minimizing the cost of resetting the model after every use. LED design scored the highest in the cost category primarily due to the minimal cost of resetting the device compared to the other two models.

4.3 LED Mechanism Design Matrix

Table 2. *The design matrix with categories on the left, their weights in parentheses, and each design labeled on the first row. The dark green cells represent the designs that won each category as well as the design that won overall.*

LED Designs **Categories**	Diffused LEDs		LEDs + Water		Original LEDs	
Effectiveness (50) (Competency)	5/5	**50**	5/5	**50**	3/5	**30**
Ease of Fabrication (35)	4/5	**28**	3/5	**21**	5/5	**35**
Safety (10)	5/5	**10**	4/5	**8**	4/5	**8**
Cost (5)	4/5	**4**	3/5	**3**	5/5	**5**
Total (100)	92		82		78	

4.4 LED Mechanism Design Matrix Evaluation

Effectiveness: The effectiveness of LEDs was determined by how clearly they would demonstrate ventilation/perfusion ratios and whether those ratios would be clearly observable by a lecture of students. For this category, it was thought that the diffused LEDs and the water LEDs would clearly show the V/Q ratios while also demonstrating the flow of capillary blood and oxygen, whereas the original LEDs would be able to accurately show V/Q ratios, but would not clearly show the flow of movement.

Ease of Fabrication: Ease of fabrication considered how easy it would be to incorporate the LEDs into the design and how much fabrication easy design would require. The original LEDs would be the easiest to incorporate as they can simply be added into the design with simple circuitry, whereas the diffused and water LEDs would require additional components. The water LEDs would require the most fabrication to be able to house the water and waterproof the LEDs.

Safety: Safety is important to consider when dealing with any electrical components. The water LEDs and the Original LEDs were ranked the lowest. The water LEDs could cause issues with the water involved because it could cause issues if any open wires were exposed to the water. The original LEDs were also ranked lower because of their open wires and circuits compared to the diffused LEDs.

Cost: Cost was considered the lowest ranking category as this is likely not an issue with any of the LED designs chosen. It was determined that the original LEDs would be the most cost-efficient design as they would not require extra components to diffuse/refract the light.

4.5 Proposed Final Design

Based on the high score of the “Diffused LEDs” from the design matrix, the team chose this method of modeling for the final design. It scored highest in the two criteria of the highest importance, signifying that the design will effectively cover the client’s requirements for the model. The design will include the base model representing the alveoli and bloodstream where ventilation-perfusion takes place, along with the visual oxygen flow representation using the diffused LEDs. In addition, a dial will be incorporated onto the base to choose between five different ventilation-perfusion ratios to be shown by the model.

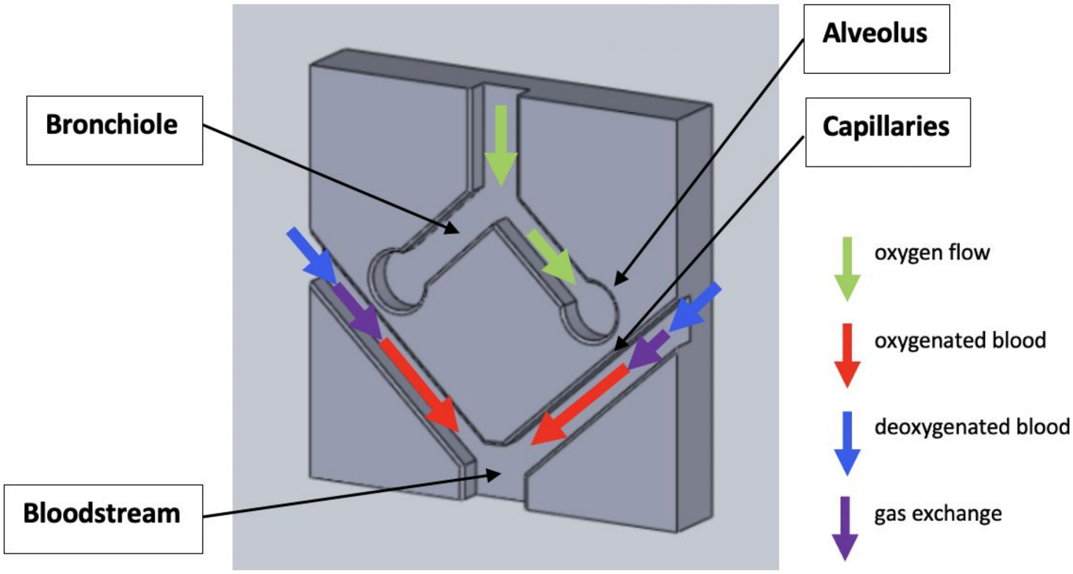

Figure 10. CAD drawing of the base modeling the alveoli and bloodstream along with arrows to show the oxygen gradient to be represented using diffused LEDs.

V. Fabrication & Development Process

5.1 Materials

The base model is 3D printed from polylactic acid (PLA), a plastic material with high-temperature resistance and hardness [15]. Adafruit Neopixel Ring with 16 LEDs and Adafruit LED flex strip with silicone tube was used for the final design due to its programming capabilities, light-diffusing effects, and easy integration into the 3D printed base. A complete materials list can be found in Appendix B.

5.2 Selection of LEDs

To model the alveolar portion of gas exchange within the model, it was elected to use a NeoPixel Ring with 12 Circular RGB LEDs [16]. The design of this product features a circular base that has 12 LEDs implanted along the circle and allows for the control of individual LEDs within the model. For the capillary portion of the model, an LED strip encased in a silicon diffusive tubing was selected [17]. This product features 60 LEDs along a one-meter strip, but in groups of 3-LEDs-per-pixel. For the prototype, the LED strip was able to be cut to a favorable length for the model. Both LED selections are easily programmed with a microcontroller to represent varying brightnesses and colors.

5.3 Fabrication

The base of the design is 3D printed in PLA as shown in Figure 11 (See Appendix C for dimensions). The silicone LEDs are cut to length and placed into the capillary portion of the base and then wired to the Arduino Uno Microcontroller and an external 12V power supply using a 12V DC 2 amp wall plug which is connected to a DC power barrel jack mounted on a breadboard. The circular LEDs are placed into the alveolus of the base and are powered by 5V supplied by the Arduino Uno. The schematic for the circuit set up as seen in Figure 12. The script for the Arduino can be found in Appendix D.

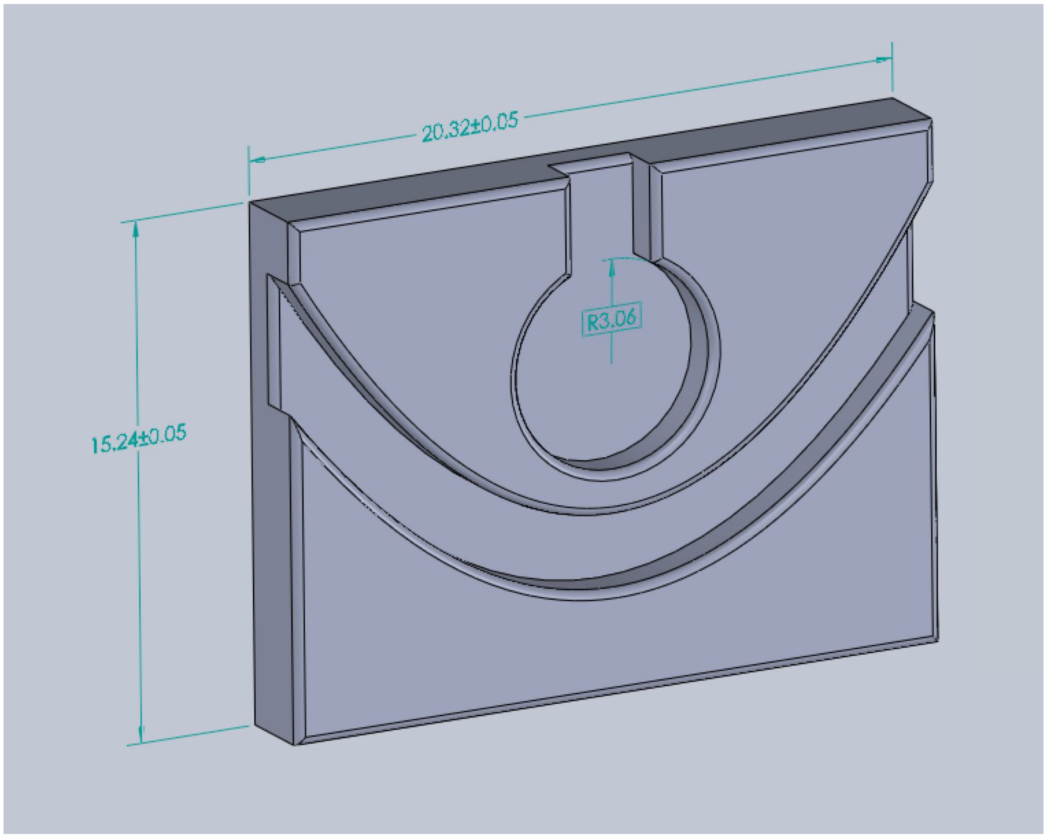

Figure 11. CAD drawing of the base design with dimensions in centimeters. For a more complete set of dimensions, see the drawing in Appendix C.

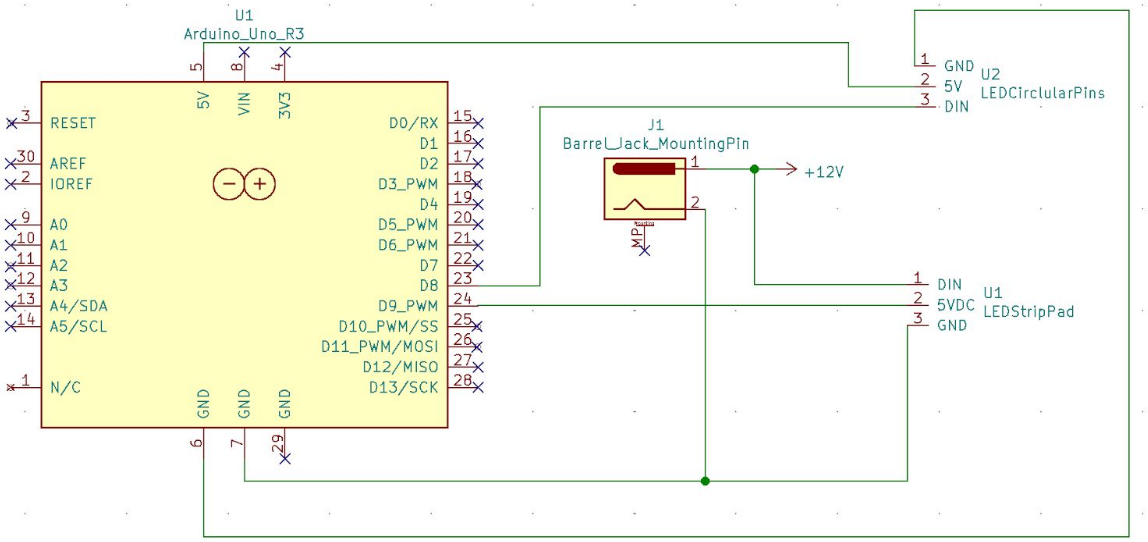

Figure 12. LED circuit with 12V power supply, Arduino Uno, and Barrel Jack Connector

5.4 Final Design

The final design consists of silicone covered LEDs representing a capillary surrounding a single alveolus. A gradient of blue to red represents the flow of oxygen into the bloodstream with blue representing deoxygenated blood and red representing oxygenated blood. To show various ventilation and perfusion ratios, the color of the capillary will change with an increase in red in the gradient to portray an increase in oxygen meaning higher rates of perfusion therefore a lower ratio and an increase in blue will portray less perfusion and therefore a higher overall ratio. A circular LED ring is placed in the Alveoli and is used to model rates of perfusion. Lights here sequentially turn on and then off to show oxygen flowing into the alveolus and excess oxygen flowing back out of the alveolus, also known as dead space ventilation. When the circular LED is brighter and a faster rate of turning on and off, this is to show an increase in ventilation and a higher V/Q ratio whereas dimmer and slower LEDs show a decrease in ventilation and a lower V/Q ratio. If the circular LEDs appear off, this is to represent a shunt where oxygen is unable to reach the site of gas exchange but blood flow begins as normal. Currently, changing the rate of ventilation or perfusion is done by typing values 0-4 into the serial monitor to alter the capillary rate and A-D to alter the alveolus rates. An input value of ‘0’ indicates that there is no blood flow and an input of ‘5’ indicates high rates of perfusion. Similarly, an input of ‘A’ indicates a shunt, or no ventilation, and an input of ‘D’ indicates high rates of ventilation, or dead space ventilation. The use of a ring LED and silicone LED strip inside the compartments of the base design is shown in Figure 13.

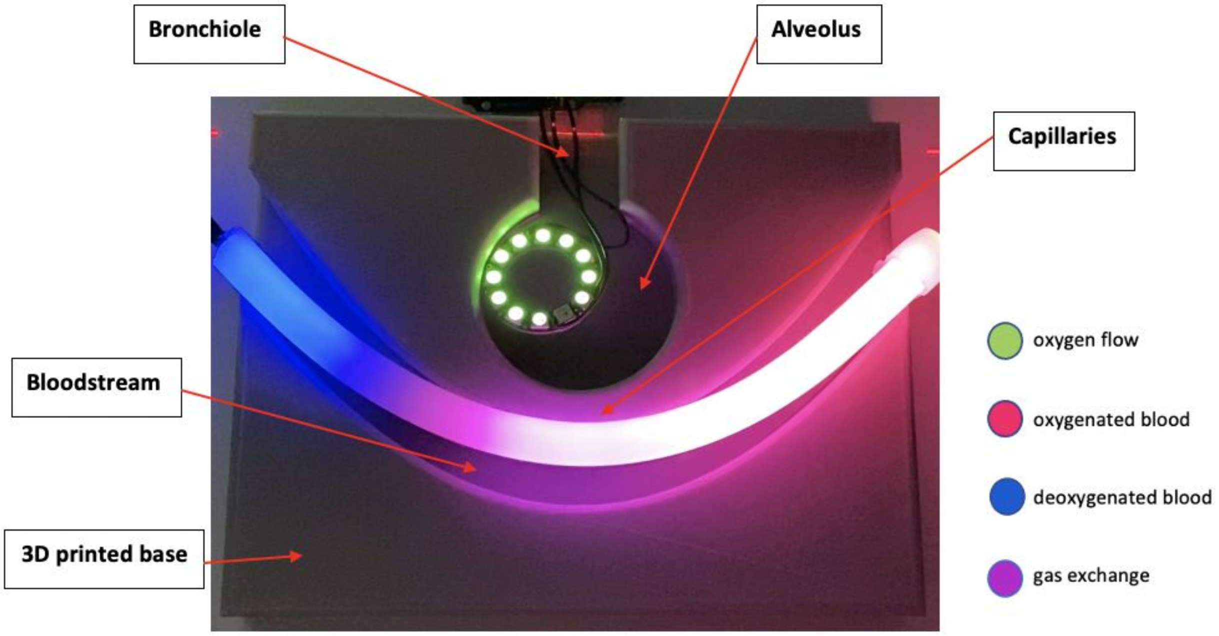

Figure 13. 3D printed base modeling the alveoli and bloodstream along with the ring and silicon strip LEDs to show the oxygen gradient for the V/Q ratios.

VI. Testing

6.1 Procedure

Testing focused on the ability of the model to produce a distinguishable difference in LED intensity under a document camera given varying levels of LED brightness. The levels of brightness tested include: 10, 25, 50, 100, 150, 200, and 255, and were altered in the Arduino code (see Appendix D). Images were taken with a smartphone of both the model and the projection of the model through the document camera at each level of brightness. As a post-processing step, the images were uploaded to ImageJ and analyzed for the average intensity using the following procedure. For the alveolus, the same circular area was highlighted in each image using the boundaries of the circular hollowed-out portion of the 3D printed base as a guide. ImageJ was then able to provide the average intensity of the light in this region. Similarly, the boundaries of the capillary channel in which the silicone LEDs rest was highlighted, and ImageJ analyzed this area to provide the average intensity of the light.

A Linear Regression T-Test was performed on both the alveolus and capillary brightnesses. This test indicates whether any two variables are linearly correlated. In each test, the Arduino value indicating the LED brightness was the independent variable, and the intensity of the LEDs measured with ImageJ was the dependent variable. The null hypothesis was defined as there is no linear relationship between the brightness and intensity of the LEDs, and the alternative hypothesis was that a linear relationship exists.

6.2 Analysis

For the images of the alveolus, it was found that the test yielded statistically significant results at a p-value of 0.01, meaning that the brightness level and intensity of the LEDs are linearly correlated. This suggests that for the circular LED, there is a significant increase in the intensity with an increase in brightness. The linear relationship is further demonstrated in the plot in Figure 14, with the trendline determined from the Linear Regression T-Test included. The coefficient of determination (R^2) is defined as 0.908 and, from this value, the correlation coefficient (R) is 0.95, indicating a strong, positive linear correlation. However, for the capillary images, the results concluded that it cannot be assumed that there is a linear relationship between the brightness and intensity of the silicon strip LED at a p-value of 0.01, meaning that there was no significant evidence to prove that there is a difference in each brightness level. The plot of the collected data is shown in Figure 15, along with a linear trendline, where the coefficient of determination (R^2) is 0.675 indicating an R-value of 0.82.

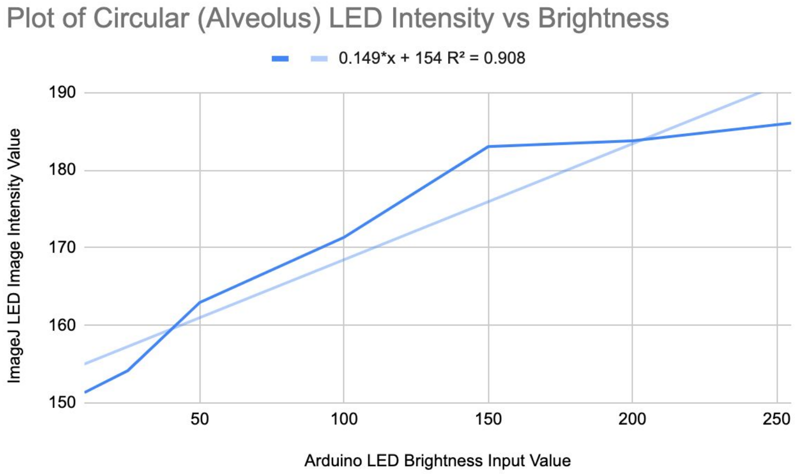

Figure 14. Image J testing results for circular LED with a linear trendline.

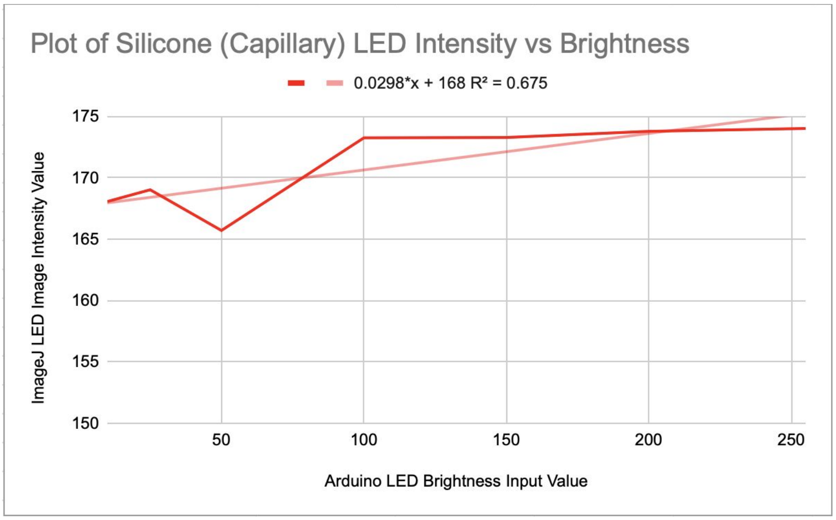

Figure 15. Image J testing results for silicone LED with a linear trendline.

VII. Conclusion

7.1 Discussion

Ventilation and perfusion mismatching is a common disorder that results from improper alignment of ventilation, or airflow, and perfusion, or blood flow through the pulmonary capillaries. Mismatching can potentially be corrected, but it is important to understand how and where the mismatching is occurring. Currently, there are no physical models to help teach this concept to medical students, so a teaching model used in a classroom setting will help to improve the knowledge of medical students. The ventilation and perfusion model is used for teaching purposes in a classroom rather than as a medical device, therefore, there are no standards applicable to the design.

This semester, the team was able to fabricate the first prototype of the teaching model for ventilation-perfusion mismatching. While the model is successfully able to demonstrate multiple ventilation-perfusion ratios with the use of different colors and flow rates, further adjustments will be made in the next semester to create a final prototype that is the most effective in representing V/Q ratios.

Challenges arose during testing of the design as there was limited time in the BME teaching labs to retrieve photos for evaluations. Due to this, there were fewer trials than what was preferred that could have altered the results. While the circular LED demonstrated a linear relationship between the brightness and intensity, the testing results for the capillary LEDs did not display a statistically significant linear relationship, meaning it was unable to be determined if the colors and brightnesses portrayed would be adequate in showing V/Q ratios. Therefore, further testing and alterations to the program may need to be done in order to achieve the desired outcomes. Also, because of time limitations from delayed shipments and materials that disassembled either during transportation or poor solder connections, survey testing was unable to be conducted this semester.

7.2 Future Work

The team has completed a list of future work to be completed next semester. First, the model will need further testing to determine proficient brightnesses and color ratios that will be understood by the mass majority of users. This will be done by further testing in the BME lab and analyzing data via ImageJ as well as surveying participants on their comprehension before and after using the design as well as ease of use. The team will also work on incorporating an interactive component into the model in the form of buttons or a dial. This will allow for the user to increase or decrease one or both of the two measurements (ventilation or perfusion) and see the outcome on the model. This addition will lead to an infinite number of V/Q ratios able to be represented and ideally would be displayed on the digital display. The addition of buttons or a dial will result in the modification of the Arduino code to fit these components. The single compartment base will also be edited and reprinted with space to integrate the microcontroller and circuitry into the backside of the model. It will also need to include holes for the wires to pass through the piece to the back as well as add another silicone LED strip in the capillary for a more aesthetically pleasing final product. Finally, a material will be selected to cover the alveolus and diffuse the light similar to the diffusion occurring in the capillary tube.

VIII. References

[1] K. A. Powers and A. S. Dhamoon, “Physiology, Pulmonary, Ventilation and Perfusion.” Jan-2020 [online] Available: https://pubmed.ncbi.nlm.nih.gov/30969729/ [Accessed: Oct. 2020.]

[2] D. C. Tidy, “The respiratory system: Lung Function and Chest Anatomy,” *Patient.info*, 31-May-2018. [online]. Available: https://patient.info/news-and-features/the-respiratory-system . [Accessed: 07-Oct-2020].

[3] A. Sanpanich, W. Sroykham, C. Phairoh, W. Angkhananuwat, K. Petsarb, and Y. Kajornpredanon, *Human Respiratory System*. 2016. [online] Available: https://ieeexplore.ieee.org/author/37085502032 [Accessed: Sept. 2020]

[4] S. Intagliata, W. G. Gossman, and A. Rizzo, “Physiology, Lung Dead Space.” 15-May-2019.[online] Available: https://pubmed.ncbi.nlm.nih.gov/29494107/ [Accessed: Sept. 2020].

[5] R. Desai, J. Ling, T. Marshall, E. Debevec-McKenney, and A. Greico, “Pulmonary Shunts,” *Osmosis*, 2020. [online]. Available: https://www.osmosis.org/learn/Pulmonary_shunts . [Accessed: 2020].

[6] C. Green, M.D., private communication, Dec. 2020.

[7] J. Mosler, C. Hypes, and S. P. Whitmore, 2015.

[8] West's Pulmonary Physiology, Tenth Edition, John B. West and Andrew Luks, Wolters Kluwer, 2016, pp 70-71.

[9] Marquis, A., Beard, D., and Pinsky, D., 2019. Towards a Multi-Scale Model of Ventilation-Perfusion Matching. *FASEB Journal.* [online]. Available: https://faseb.onlinelibrary.wiley.com/doi/full/10.1096/fasebj.2019.33.1_supplement.lb455 [Accessed: Oct. 2020].

[10] J. Anthony and B. Spalding, “Colour vision deficiency in the medical profession,” British Journal of General Practice, June-1999. [online]. Available: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC1313448/pdf/10562750.pdf [Accessed: 05-Dec-2020].

[11] Johnson, H., 2010. Water Analogy. [online] Available: http://www.sigcon.com/Pubs/edn/WaterAnalogy.htm [Accessed: Oct. 2020].

[12] Amazon.com. 2020. 5mm LED Light Diodes Circuit Assorted Kit. [online] Available: https://www.amazon.com/MCIGICM-Circuit-Assorted-Science-Experiment/dp/B07PG84V17 [Accessed: Oct. 2020].

[13] Industries, A., 2020. Adafruit Neopixel Digital RGBW LED Strip - White PCB 60 LED/M. [online] Available: https://www.adafruit.com/product/2842?gclid=Cj0KCQiA5bz-BRD-ARIsABjT4nhM98AqggdvEfywGOP5sjd9akE-uPtn_BAtWqtINlElRcmDRC9M11EaAqR0EALw_wcBlength=1 [Accessed: Oct. 2020].

[14]YouTube. 2013. Bending of Light. Laser Beam demonstration. [online]. Available: https://www.youtube.com/watch?v=ifbCsha7Syc. [Accessed: Oct: 2020].

[15] Curbell Plastics. 2020. *LED Lighting and Diffusion Solutions.* [online]. Available: https://www.curbellplastics.com/Research-Solutions/Industry-Solutions/Markets/Lighting. [Accessed: 23-Oct-2020].

[16] A. Industries, “NeoPixel Ring - 12 x 5050 RGB LED with Integrated Drivers,” adafruit industries. [Online]. Available: https://www.adafruit.com/product/1643. [Accessed: 15-Oct-2020].

[17] A. Industries, “NeoPixel RGB Neon-like LED Flex Strip with Silicone Tube,” adafruit. [Online]. Available: https://www.adafruit.com/product/3869?gclid. [Accessed: 15-Oct-2020].

[18] J. B. West, “Chapter 5: Ventilation-Perfusion Relationships,” in *Respiratory physiology: the essentials*, Baltimore: Williams & Wilkins, 1974, pp. 70–71. [Accessed: Sept. 2020.]

[19] Warriner Dr, Bayley M, Shi Y, Lawford PV, Narracott A, Fenner J (2017) Computer model for the cardiovascular system: development of an e-learning tool for teaching of medical students. BMC Med Educ 17: 017-1058. [Accessed: Sept. 2020.]

[20] W.Dassen et al., "The application of complex research simulation models in education; A generic approach," 2011 Computing in Cardiology, Hangzhou, pp.465-468. [Accessed on: Sept. 2020.]

X. Appendix

A. Product Design Specification (PDS)

Teaching Model for Ventilation and Perfusion Mismatching Product Design Specification

Clients: Dr. Chris Green

Advisors: Amit Nimunkar

Team: Jenna Eizadi; eizadi@wisc.edu;
Zoe Schmanski; zschmanski@wisc.edu;
Brittany Glaeser; bmglaeser@wisc.edu;
Kaitlin Lacy; klacy2@wisc.edu;

Date: 2020/09/17

Problem Statement:

During medical school, students are taught about the importance of ventilation/perfusion mismatching and the effects it has on the body. Oftentimes, the students have a difficulty understanding that a high Ventilation/Perfusion (V/Q) ratio leads to dead space ventilation, or wasted ventilation, and that a low V/Q can lead to hypoxemia, which is a condition where there is low oxygen concentrations in the blood. A model representing the mechanisms underlying ventilation/perfusion mismatching would help students understand this concept.

Client Requirements:

- The device needs to accurately model ventilation and perfusion mismatching
- The device should include an interactive component that will allow the user to change the ratios of ventilation and perfusion
- The device should be large enough to be seen in a classroom full of 180 people with the use of a projector or camera, yet small enough for easy storage
- The device is able to be used multiple times per lecture
- The budget for the project is $1000

Design Requirements:

1. **Physical and Operational Characteristics**
    a. **Performance Requirements:**
        - The device will likely be used in a classroom setting
        - Must model a range of ventilation/perfusion ratios

        1. Minimum of five settings: dead space ventilation, high V/Q ratio, 1:1 ratio, low V/Q, and shunt

b. **Safety:**
    - No open wires that could be harmful to the user
    - No sharp edges or corners that could be dangerous during transport of the device

c. **Accuracy and Reliability:**
    - Students in the lecture hall need to be able to easily differentiate between the different settings
        1. When asked, users can correctly identify that the oxygenation of the blood has increased or decreased 19 out of 20 times when viewed on a screen as in a lecture

d. **Life in Service:**
    - At least five years

e. **Shelf Life:**
    - Electrical components must be of good quality so they will not degrade and need to be replaced

f. **Operating Environment:**
    - Will be used in a classroom setting
        1. Likely with use of document camera or projector
    - Portability of the device could mean there is a chance of damage between storage and classroom
    - Damage could occur if misused

g. **Ergonomics:**
    - People should be able to view the device on a screen from 14 meters away
    - People with visual impairments, such as color blindness, should be able to learn from the design

h. **Size:**
    - No more than 0.61 x 0.61 m (2ft x 2ft)
    - Maximum dimensions of 0.22 x 0.27 m (8.5 x 11 in)
        1. Must fit on a tabletop
        2. Must fit under a document camera

i. **Weight:**
    - Less than 6.8kg (15lbs)

j. **Materials:**
    - No Material Restrictions

k. **Aesthetics, Appearance, and Finish:**
    - No unfinished points, edges, or open wires

2. **Production Characteristics**

a. **Quantity:**
    - Only one Ventilation/Perfusion Model will be needed for client's classroom

b. **Target Product Cost:**
    - The product should remain under a total budget of $1,000

3. **Miscellaneous**

a. **Standards and Specifications:**
    - Not applicable at this time

b. **Customer:**
    - Easy to use for professors in medical school with no technical background
        1. Controller with different settings
    - Minimal set-up and reset time
        1. Maximum set-up time of two minutes
        2. Maximum reset time of one minute
    - Differentiation in color, brightness, or speed between blood coming to and leaving the lungs
    - Differentiation in color, brightness, or speed between air exerting and leaving the alveolus
    - Visible flow of blood

c. **Competition:**
    - West's model for V/Q matching [18]
        1. Uses pumps and dye to show the effect of V/Q ratios on blood oxygenation
    - E-learning Computer Model for Cardiovascular System [19]
        1. Incorporated a Lumped Parameter Model (LPM) into an e-learning environment to create a tool to help students, undergraduate medical students, in particular, understand cardiovascular physiology, map disease progression, and classify the severity of a disease.
    - Circ-Adapt [20]
        1. A computational model of the pulmonary and respiratory systems that is used to investigate clinical aspects by incorporating mechanical and hemodynamic interactions.
        2. Contains flexible parameters to mimic various physiological states.

B. Materials and Expenses

Table 3. Expenses. Summary of expenses for the model

Item	**Part Number**	**Link**	**Description**	**Vendor**	**Cost**	**Quantity**	**Subtotal**
Neopixel Flex Strip with Silicone Tube	3869	https://www.adafruit.com/product/3869?gclid=CiwKCAiw5p_8BRBUEiwAPpJO6-iskV-hGOTETEw9-UiGUYAAeoXBLnH974c0ATku9Am6wkZcOHl-LRoC3n8QAvD_BwE	LED Strip with silicone diffuser cover that is 1m long	Adafruit	$34.95	1	$34.95
Neopixel Ring with 16 LEDs	1463	https://www.adafruit.com/product/1463	Circular LED ring powered by 5V	Adafruit	$9.95	1	$9.95
12V DC Wall plug adapter	12V2A0823	https://www.amazon.com/Adapter-100-240V-Transformers-Switching-Adaptor/dp/B07GRZB5Y9/ref=sr_1_1?dchild=1&keywords=12V+DC+2A+power+supply+adapter+with+2.1+mm&qid=1603983837&sr=8-1	12V wall plug for silicone LEDs with 2 amps	Amazon	$9.99	1	$9.99
Breadboard Friendly Female DC Power Barrel Jack	B074LK7G86	https://www.amazon.com/DIKAVS-Breadboard-friendly-2-1mm-Barrel-Jack/dp/B074LK7G86/ref=sr_1_1?dchild=1&keywords=barrell+jack+adapter+for+breadboard&qid=1603983934&sr=8-1	Barrel Jack for 12V power supply to be integrated to circuit for silicone LEDs	Amazon	$9.99	1	$9.99
Arduino Uno Microcontroller	A000066	https://www.amazon.com/Arduino-A000066-ARDUINO-UNO-R3/dp/B008GRTSV6/ref=sr_1_3?crid=26WY4EDJSCJMI&dchild=1&keywords=arduino+uno+microcontroller&qid=1607324751&sprefix=arduino+Uno+micr%2Caps%2C227&sr=8-3	Microcontroller to power and control LEDs	Amazon	$23.00	1	$23.00

Total Cost: $87.88

C. CAD Drawing

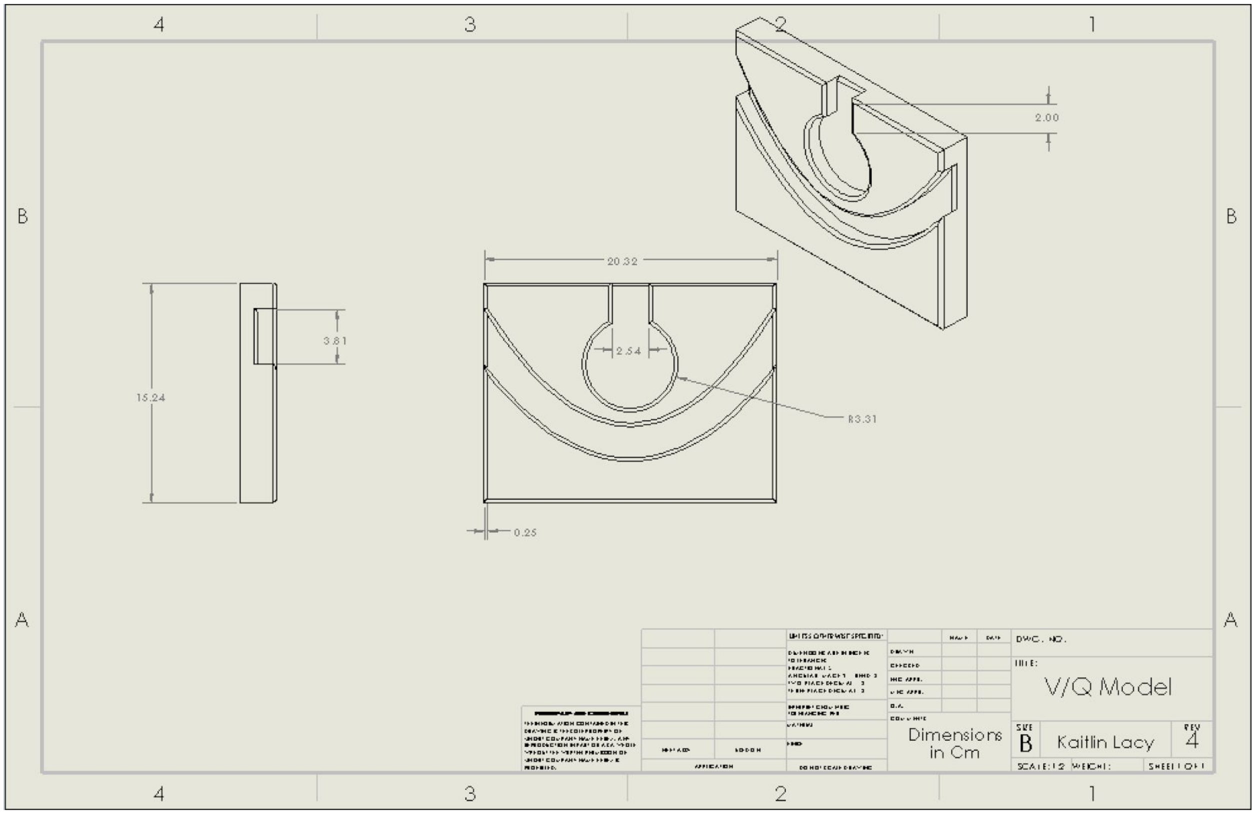

Figure 16. CAD drawing of base design with dimensions in centimeters

D. LED Code for Arduino Uno

```
//This code currently has two settings (highQ to run lights and off)
//Ideally will have 5 different settings and will include the alveolus LEDs


#include <Adafruit_NeoPixel.h>
#include <elapsedMillis.h>

//Initializes variables used in Capillary code
  elapsedMillis capillaryTime = 100;
  int CAP_LED_NUMBER = 5;
  int blue = 0;
  int red = CAP_LED_NUMBER;
  int pixelNumber = 0;

  //Initializes variables used in Alveolus Code
  int ALV_LED_NUMBER = 16;
  elapsedMillis alvWaitTime;
  elapsedMillis delayTime;
  int position = 0;
  int green = ALV_LED_NUMBER;
  int yellow = 0;
  int endposition = ALV_LED_NUMBER;
  int endpositionoff = ALV_LED_NUMBER/2;
  int brightness = 255;
  int dim = 100;
  int i = 0;
  int j = ALV_LED_NUMBER/2;
  int alvLightsDelay = 200;
  bool fillAlveolus = true;
  bool diffusedAlveolus = true;

  //high,mid,low Q refers to the amount of perfusion
  bool highQ = true;
  bool midQ = false;
  bool lowQ = false;
  bool off = false;
  String readCommand;

  //high, mid, low P refers to amount of Ventilation
  bool highV = true;
  bool midV = false;
  bool lowV = false;
  bool alvOff = false;

  Adafruit_NeoPixel capillaryLED(CAP_LED_NUMBER, 9, NEO_GRB + NEO_KHZ800);
  Adafruit_NeoPixel alveolusLED(ALV_LED_NUMBER, 8, NEO_GRB + NEO_KHZ800);


//Sets up serial monitor and LED strip
void setup() {
  Serial.begin(9600);
  capillaryLED.begin();
  alveolusLED.begin();
}



void loop(){
  //When a command is recognized in serial monitor, it will read it and update booleans
  while(Serial.available()){

    //Variable containing serial input
    readCommand = Serial.read();
 //strcmp compares characters, when they charaters are equal it will return 0
 //Character = 1 will run capillary LEDs
 //Character = 0 will turn off capillary LEDs
  if(readCommand == "1" ){
    highQ = true;
    off = false;
    midQ = false;
        Serial.println("highQ");
  }
  else if(readCommand == "2"){
    highQ = false;
```

```
    off = false;
    midQ = true;
    Serial.println("midQ");
  }
  else if(readCommand == "3"){
    highQ = false;
    off = false;
    midQ = false;
    lowQ = true;
    Serial.println("lowQ");
  }
  else if(readCommand == "0"){
    off = true;
    highQ = false;
    midQ = false;
    lowQ = false;
  }

//  //Letter values will change the ratios for the Alveolus LEDs
  if(readCommand == 'A'){
    highV = true;
    midV = false;
    lowV = false;
    alvOff = false;
    brightness = 255;
    alvWaitTime = 200;
  }  else if(readCommand == 'B'){
    highV = false;
    midV = true;
    lowV = false;
    alvOff = false;
    brightness = 150;
    alvWaitTime = 300;
  }else  if(readCommand == 'C'){
    highV = false;
    midV = false;
    lowV = true;
    alvOff = false;
    brightness = 50;
    alvWaitTime = 400;
  }  else if(readCommand == 'D'){
    highV = false;
    midV = false;
    lowV = false;
    alvOff = true;
    brightness = 0;
  }

  }
  ////////////////////////////////////////////////////////////////////////////////////////////////////////////////////
  ///////////////////////////////////////////////////////////////////////////////////////////////////////////////////
  //////////////////////////////////////////////////////////////////////////////////////////////////////////////////
  //Runs capillary LED code
  if(highQ){
       if (capillaryTime > 250){
         red = CAP_LED_NUMBER * 4;
     if(pixelNumber < CAP_LED_NUMBER){
       for(int i = 0; i < CAP_LED_NUMBER; i++){
          capillaryLED.setPixelColor(i, red, 0, blue);
          capillaryLED.show();
          red = red - 4;;
          blue++;
        }
     capillaryLED.setPixelColor(pixelNumber, 0, 0, 0);
    capillaryLED.show();
     pixelNumber++;
     capillaryTime = 0;
     red = CAP_LED_NUMBER * 4;
     blue = 0;
     }
     else{
      pixelNumber = 0;
     }
       }
  }
  if(midQ){
           if (capillaryTime > 350){
             red = CAP_LED_NUMBER *2;
     if(pixelNumber < CAP_LED_NUMBER){
       for(int i = 0; i < CAP_LED_NUMBER; i++){
```

```
          capillaryLED.setPixelColor(i, red, 0, blue);
          capillaryLED.show();
          red = red - 2;
          blue++;
         }
     capillaryLED.setPixelColor(pixelNumber, 0, 0, 0);
    capillaryLED.show();
     pixelNumber++;
     capillaryTime = 0;
     red = CAP_LED_NUMBER *2;
     blue = 0;
     }
     else{
      pixelNumber = 0;
     }
        }
  }
    if(lowQ){
            if (capillaryTime > 450){
     if(pixelNumber < CAP_LED_NUMBER){
        for(int i = 0; i < CAP_LED_NUMBER; i++){
          capillaryLED.setPixelColor(i, red, 0, blue);
          capillaryLED.show();
          red--;
          blue++;
         }
     capillaryLED.setPixelColor(pixelNumber, 0, 0, 0);
    capillaryLED.show();
     pixelNumber++;
     capillaryTime = 0;
     red = CAP_LED_NUMBER;
     blue = 0;
     }
     else{
      pixelNumber = 0;
     }
        }
  }

  //Turns off LEDs
  if(off){
    capillaryLED.clear();
    capillaryLED.show();
  }
  ////////////////////////////////////////////////////////////////////////////////////////////////////////
  ////////////////////////////////////////////////////////////////////////////////////////////////////////
  ////////////////////////////////////////////////////////////////////////////////////////////////////////
 if(fillAlveolus){
     // Turns LEDs on
       //while ( i <= (ALV_LED_NUMBER/2)){
        if(i <= (ALV_LED_NUMBER/2)){
          //Sets each side of the Circular LED
          alveolusLED.setPixelColor(i,0,green=brightness,0);
          alveolusLED.setPixelColor(endposition, 0, green=brightness, 0);
          //Turns on the LEDs
          if (alvWaitTime > alvLightsDelay){
            alveolusLED.show();
            i++;
            endposition--;
            alvWaitTime=0;
          if (i == (ALV_LED_NUMBER/2)+1){ //The +1 allows the bottom light to turn on otherwise it entered this if statement too early

              fillAlveolus = false;
              i++;  // for some reason its entering this loop twice so I'm trying this to stop that
          }
          }
            }


  }
  if(!fillAlveolus){

   //Turns Alveolus yellow
   if(diffusedAlveolus){
// dimming all of the lights to show that oxygen has diffused out of the alveolus and slightly changing the color
   for (int x=0; x<=ALV_LED_NUMBER; x++){
      alveolusLED.setPixelColor(x,yellow=dim,green=dim+2,0);
      alveolusLED.show();
   }
   diffusedAlveolus = false;
```

```
  delayTime = 0;
  }
    // Turns LEDs off
     //delayTime pauses at yellow for a second
     if ( j >= 1 && delayTime > 1000){
         alveolusLED.setPixelColor(j,0,0,0);
         alveolusLED.setPixelColor(endpositionoff, 0, 0, 0);
         if (alvWaitTime > alvLightsDelay){
           alveolusLED.show();
           j--;
           endpositionoff++;
           alvWaitTime=0;

          if (j==0){
             fillAlveolus = true;
                // Resets variables
      i=0;
      j = ALV_LED_NUMBER/2;
      endpositionoff = ALV_LED_NUMBER/2;
      endposition = ALV_LED_NUMBER;
      diffusedAlveolus = true;
    }
  }
 }

 }
if(alvOff){
  for(int i = 0; i < ALV_LED_NUMBER; i++){
    alveolusLED.setPixelColor(i, 0, 0, 0);
    alveolusLED.show();
 }
 }
}
```