

Teaching Model for Ventilation-Perfusion Mismatching

Brittany Glaeser, Kaitlin Lacy, Jenna Eizadi, and Zoe Schmanski

Department of Biomedical Engineering, University of Wisconsin-Madison, Madison, WI

Submitted 3 March 2021

Abstract: The abstract will be done after the journal paper is completed.

1. Introduction

Ventilation and perfusion (V/Q) mismatching is a difficult concept for medical students to visualize, specifically, how it can lead to dead space ventilation and hypoxemia. A model is needed to help the medical students conceptualize the different ventilation-perfusion ratios and their consequences.

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. As seen in Figure 1, in order for air to reach alveoli, it must enter through the oral or nasal cavities and flow through the structures of the respiratory system to reach the alveoli, which are tiny air sacs that contain thin walls with capillaries for gas exchange [1]. 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 [2].

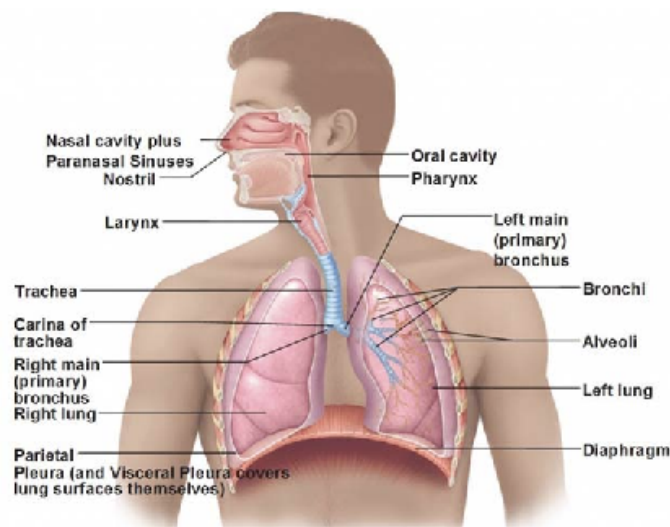


Figure 1. Anatomy of the respiratory system [3].

The V/Q ratio shows the matching of these two rates and may vary between individual alveoli. In extreme cases of high V/Q rates, dead space ventilation can occur in which there is air movement in the alveoli 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]. 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 ($P_A O_2$) where $P_I O_2$ 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].

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

$$P_A O_2 = P_I O_2 - (VO_2/V_A) * (P_B - 47 \text{ mmHG}) \quad (2)$$

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

2. Background

Medical students oftentimes have difficulty understanding that a high V/Q ratio leads to dead space or wasted ventilation and that a low V/Q can lead to hypoxemia. Students also struggle to visualize or understand that an increase in a V/Q ratio can be attributed to either an increase in ventilation or a decrease in perfusion. This holds significant clinical implications for physicians as it is important to understand the mechanisms included in V/Q mismatching in order to determine the correct treatment protocol. For example, hypoxemia from a shunt cannot be

corrected by supplemental oxygen and inadequate knowledge about the causes of hypoxemia can lead to incorrect care given to a patient [6].

Creating a reliable way to model the impact of changing ventilation and perfusion on V/Q ratios would help to improve medical education for future physicians. There are currently very limited options for educators to visually represent this concept, and this makes it a challenging concept both to teach and to learn. 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. 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 require extensive programming and mathematical manipulation that would be very challenging to develop for a classroom model. The creation of a physical model that could be easily manipulated by both instructors and students would be invaluable to education in this area.

A physical model was created that utilizes LED lights to represent ventilation of an alveolus and blood flow through a corresponding capillary. Coordinated blinking of the lights creates the illusion of flow, and the rates of ventilation and perfusion are able to be manipulated by the user in order to display different V/Q ratios.

3. Materials and Methods

Adafruit NeoPixel LEDs were utilized to represent both the air in the alveolus and the blood flowing through the capillary. A NeoPixel LED flex strip with silicone diffusive tubing was used to represent the capillary, with the colors blue and red depicting deoxygenated and oxygenated blood respectively. Three separate NeoPixel LED rings were nested concentrically to cover the alveolar area and depict the alveolus. The rates at which the alveolar LEDs illuminate, or blink, indicate minute ventilation. Additionally, the silicone LEDs mimic the direction of blood flow through the capillary and the rate of movement represents the speed of blood flow. Currently, the design also consists of four LED momentary contact buttons for the user to increase or decrease the rates of both ventilation and perfusion individually, which in turn

changes the V/Q ratio. The buttons are user-friendly as their size makes them easy to push, and the different colors allow for easy identification as to each of their functions. An Arduino Nano is used to control the input from the buttons and the output for the LED rates. An LCD display is incorporated into the design to display the values of ventilation, perfusion, and the overall V/Q ratio. The circuit schematic is shown in Figure 2. A 3D-printed PLA base design was used as housing for the LEDs as well as the housing for the circuitry and can be seen in Figure 3. Figure 4 shows the respective locations of the alveolus LEDs and the capillary LEDs in the base design.

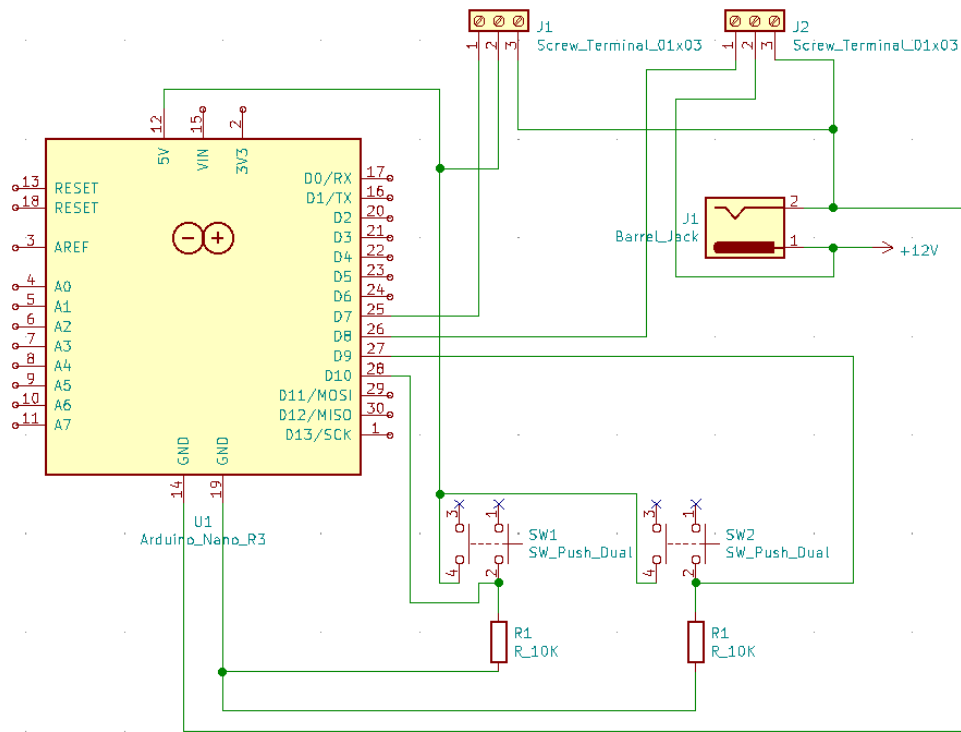


Figure 2. LED circuit with 12V power supply, Arduino Nano, Barrel Jack Connector, and 2 Tactile Push Buttons

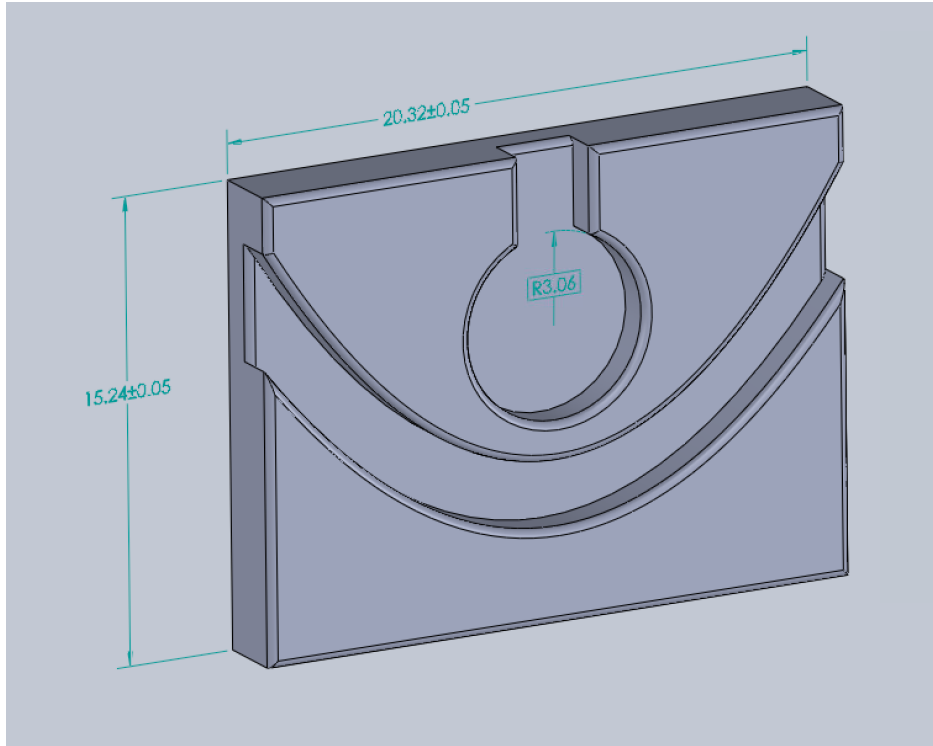


Figure 3. CAD drawing of the base design with dimensions in centimeters.

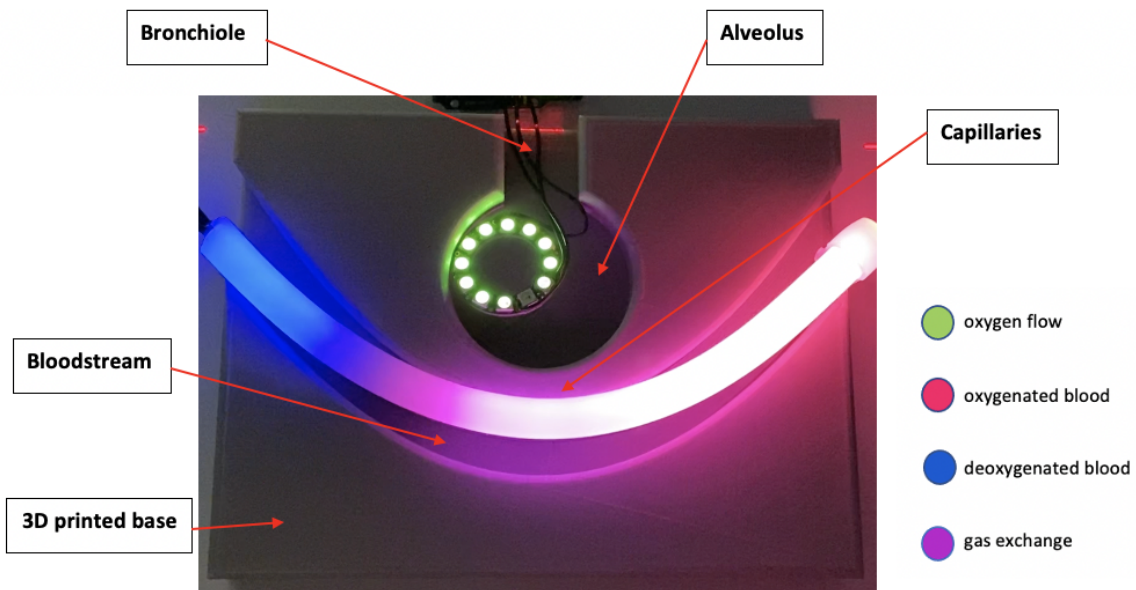


Figure 4. 3D printed base modeling the alveoli and bloodstream along with the ring and silicon strip LEDs to show the oxygen gradient for the V/Q ratios.

4. Results and Discussion

Button Verification Analyses

In this section, we will demonstrate that the buttons are capable of increasing and decreasing a set value by the number of times pressed, without introducing bouncing of the button or other input errors. We will press the button a predetermined amount of times and compare this to the number of presses recorded by a microcontroller. For the analysis, we will apply a Linear Regression T-Test to determine if the number of times a button is pressed correlates to how many times the microcontroller it records being pressed.

Insert Figure: Scatterplot visualization of linear regression t-test

Results from this section will verify that the selected buttons can increase and decrease a set value equivalent to the number of times pressed.

Flow and Blinking Rate Testing

In this section, we will show the results from a test to determine if a notable difference can be observed by the user of the model when the rate of flow in the capillary or blinking in the alveolus changes. The test will consist of a video showing the same or changing rates of flow or blinking on the model, and a human subject will determine if they observe a noticeable change in the rates. To analyze the data, we will perform a One-Sample T-Test of Proportions to compare the difference in means of questions answered correctly for the observed group to 0.5, or the probability of answering questions correctly at random.

Insert Figure: Boxplots of one-sample t-test of proportions for each question

Results from this section will determine if the rate of change in flow and blinking rate generates a noticeable difference for the human eye.

Teaching Model Validation

In this section, we will show an analysis of the model's capability to improve upon a human subject's understanding of ventilation or perfusion ratios by graphically displaying what occurs when the rates are modulated. We will distribute a Google Form with two

parts: one administered before viewing the model, and one following. The questions will be multiple choice and similar in nature meant to gauge understanding prior to viewing the model and to assess whether the model increased understanding. For analysis, we will use a Difference of Means Hypothesis Test to compare the initial test score to the final test score for each subject.

Insert table: Mean score from the initial and final test as well as statistics and conclusions from a hypothesis test

The results from this testing will verify that our model achieves the goal of being able to help medical students understand ventilation and perfusion mismatching.

Discussion

Analysis of results from each of the three tests will be discussed.

5. Conclusion

Conclusions will be drawn after prototyping and testing.

6. 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] J. B. West, "Chapter 5: Ventilation-Perfusion Relationships," in *Respiratory physiology: the essentials*, Baltimore: Williams & Wilkins, 1974, pp. 70–71. [Accessed: Sept. 2020.]
- [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_BAtWqtINIEIRcmDRC9M11EaAqR0EALw_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].

7. Appendix

Design Process

A. Preliminary Designs

Flow Mechanism Design Models

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 4), 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.

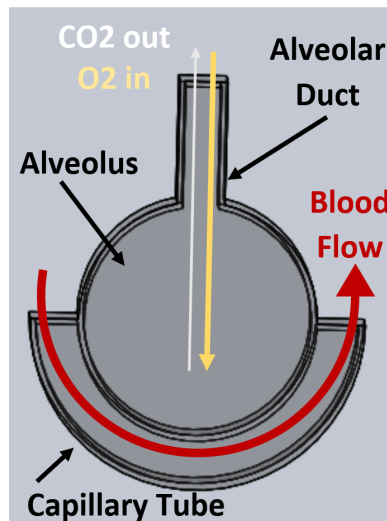


Figure 4. LED flow model with arrows to represent LED placement

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 [7]. 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.

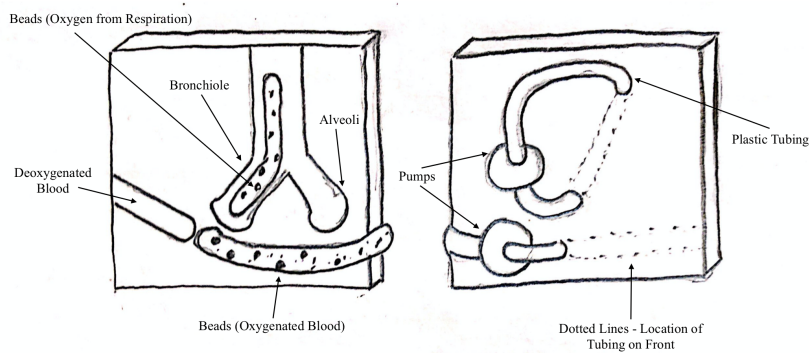


Figure 5. Bead Flow Model with black dots representing beads.

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 5. 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 6.

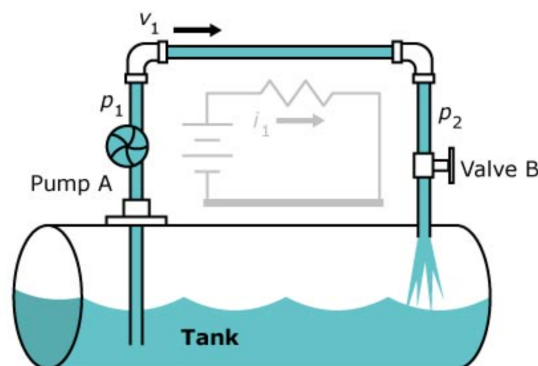


Figure 6. Closed water system with pump and reservoir [11]

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.

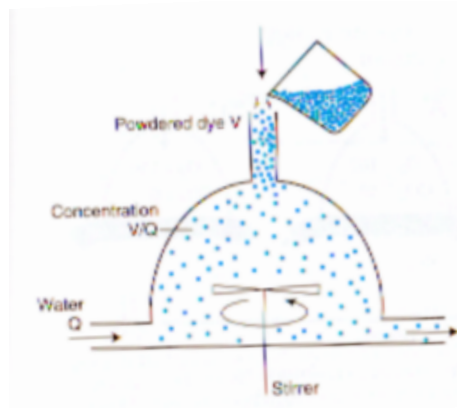


Figure 7. Water flow model using dye [8]

LED Mechanism Design Models

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

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.

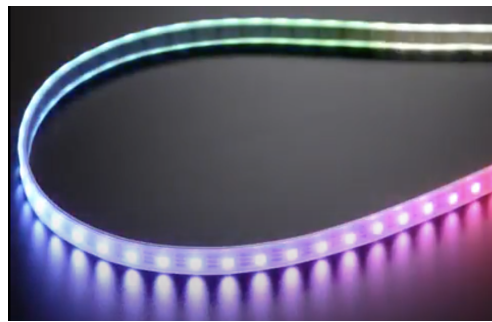


Figure 9. LED strip in diffused tubing representing a variety of color gradients [13]

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.

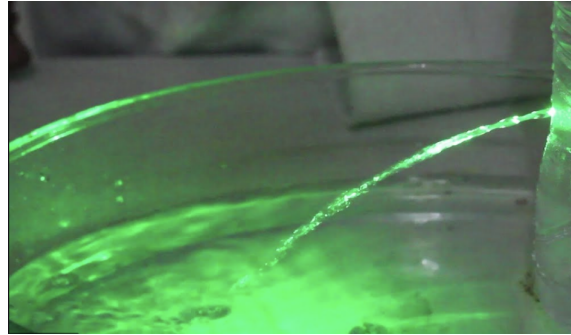


Figure 10. LED light diffraction in a stream of water [14]

B. Design Matrices

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	LEDS		BEADS		DYE	
	Design 1	Design 2	Design 1	Design 2	Design 1	Design 2
Categories						
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	

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.

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	Diffused LEDs		LEDs + Water		Original LEDs	
Categories						
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

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.

First Prototype

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.

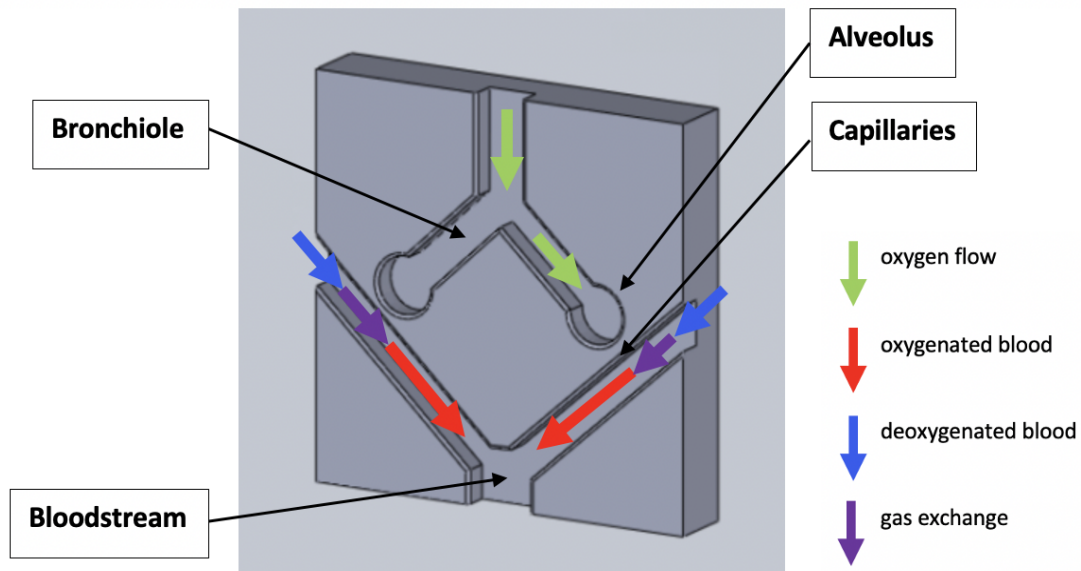


Figure 11. CAD drawing of the base modeling the alveoli and bloodstream along with arrows to show the oxygen gradient to be represented using diffused LEDs.