DEPARTMENT OF
Biomedical Engineering
UNIVERSITY OF WISCONSIN–MADISON

Teaching Model for Ventilation-Perfusion Mismatching

BME 400 Preliminary Report

October 7th, 2020

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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. Three preliminary designs were created that fit the client's requirements, but ultimately the use of LEDs was chosen to depict V/Q ratios on a 3D printed base model of the alveoli and bloodstream. Further, three different types of LED representations were considered and diffused LEDs were chosen to best depict oxygen concentration gradients. As stated previously, the base of the model will be 3D printed using plastic from the UW-Madison Makerspace. The diffused LEDs will be incorporated and controlled by a dial that will be programmed to show at least five critical V/Q ratios. Alterations to the model will be made as different modes of modeling are tested throughout the fabrication process.

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 consists 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].

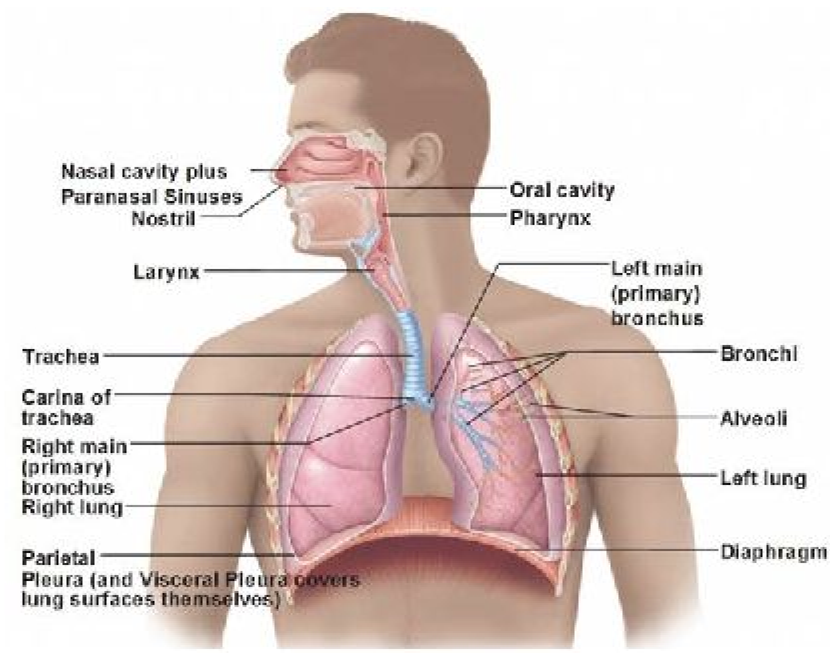


Figure 1. Anatomy of the respiratory system [3]

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. 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 [5].

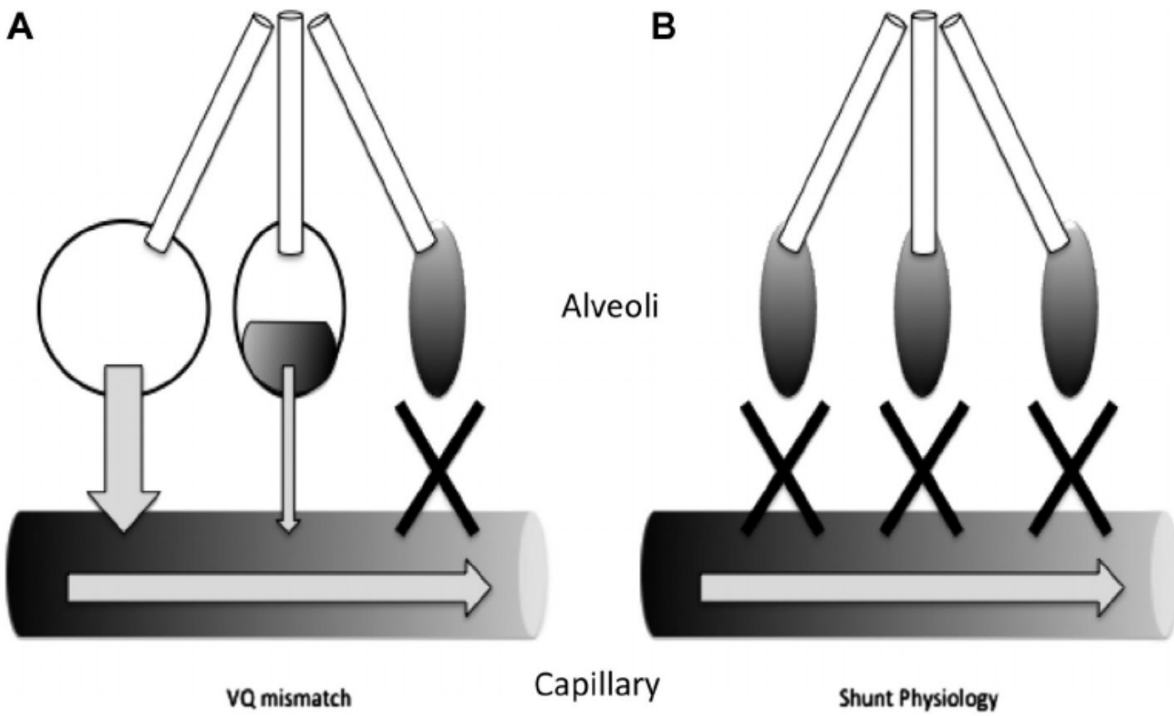


Figure 2. Comparison of VQ Mismatch and a shunt [6]

2.2 Existing Devices and Current Methods

One existing model for ventilation and perfusion mismatch is John West's model presented in his textbook *Respiratory Physiology.* Here, he describes a model that utilizes water pumps to simulate the movement of air into the lungs and blood flow. 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 [7]. A model like this 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. 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.

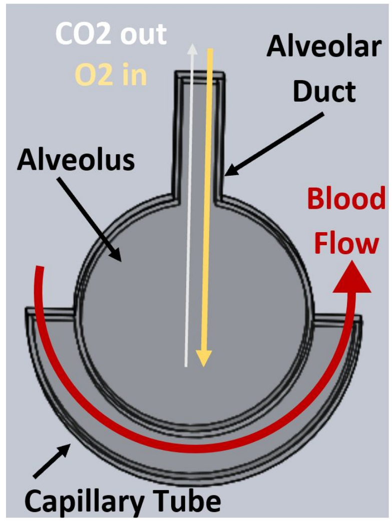


Figure 3. LED flow model with arrows to represent LED placement

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 of the user.

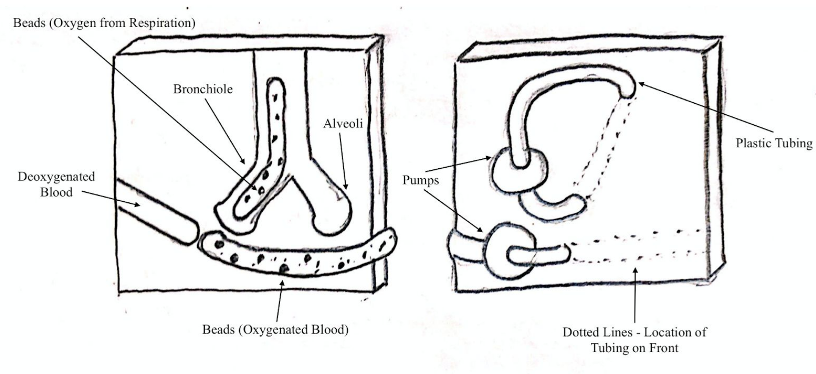


Figure 4. Bead Flow Model with black dots representing beads.

3.1.c Water Flow Model

The Water Flow Model is based on the idea from John West's model presented in his textbook *Respiratory Physiology*, 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.

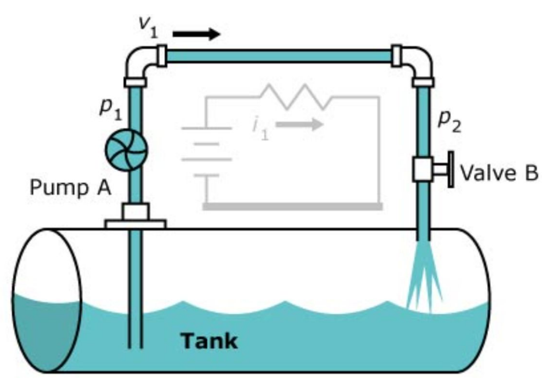


Figure 5. Closed water system with pump and reservoir

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.

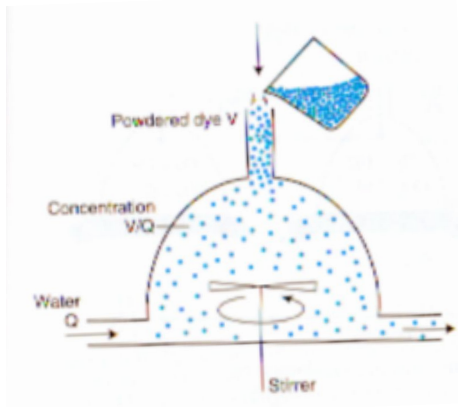


Figure 6. Water flow model using dye

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

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.

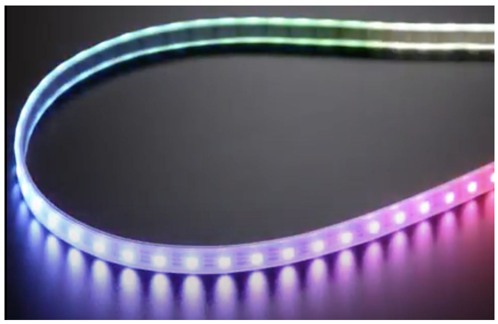


Figure 8. LED strip in diffused tubing representing a variety of color gradients.

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.

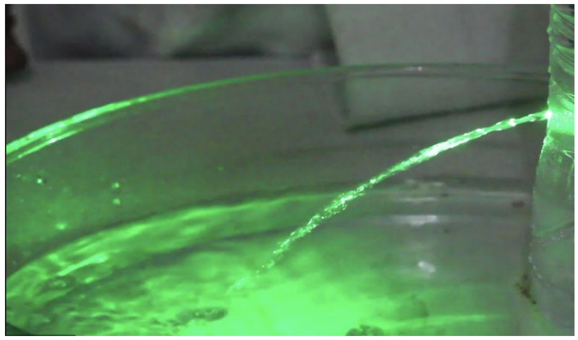


Figure 9. LED light diffraction in a stream of water.

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.

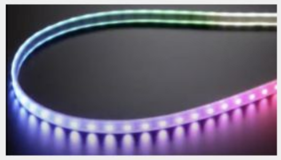
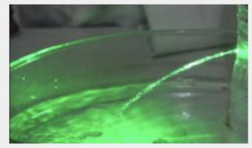
Viability: Viability is characterized by the ability of the device to model ventilation/perfusion mismatching over a long period of time with little to no decrease in accuracy and precision. The time period will be determined by the client's needs but is anticipated to be at least 5 years. In addition, 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 our 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 our 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. We 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.

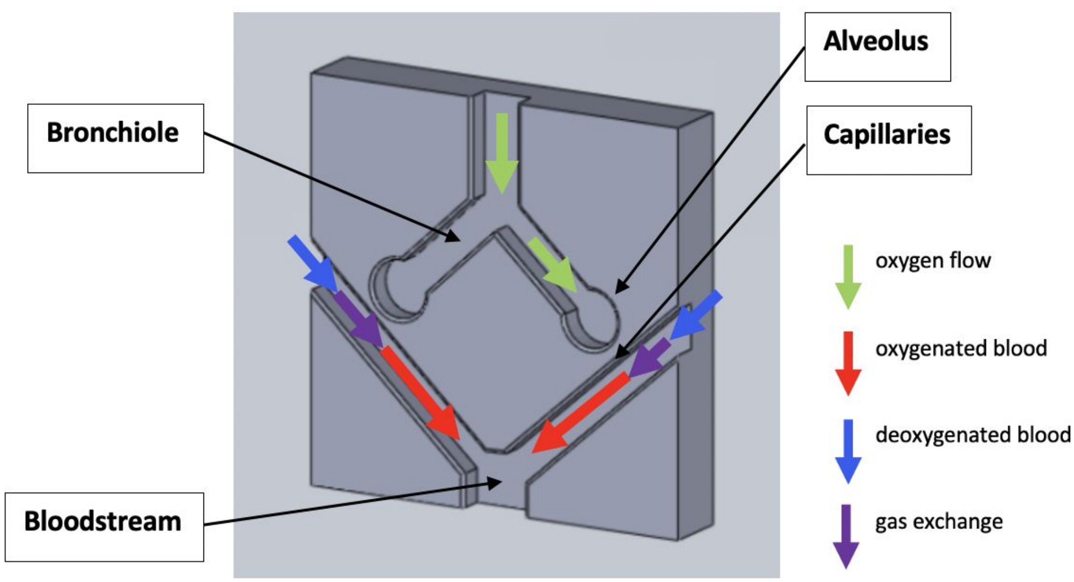


Figure 10. CAD drawing of the base modeling the alveoli and bloodstream along with arrows to show the oxygen gradient to be represented using diffused LEDs.

V. Fabrication & Development Process

5.1 Materials

The base model will be made up of a plastic material that can be 3D printed. Polycarbonate (PC) and polylactic acid (PLA) are two plastics being considered for the base material. Both plastics have high temperature resistance and hardness. However, PC is slightly stronger than PLA and has a higher toughness [8]. Both plastics also have light diffusing capabilities for the potential of embedding the LEDs within the base material. PLA is a cheaper material for 3D printing but both are within the budget of this project.

Uniform LEDs with multiple color capabilities will be utilized for this design. A dial or switch will be used to manipulate the LEDs to represent the five different ventilation-perfusion ratios. A microcontroller will be needed to program the dial/switch mechanism with the specific LED gradients for each ratio. The team will use their experience with Arduino microcontrollers for the first prototype of the design with the possibility of upgrading later in the design process.

5.2 Prototype Plan

The chosen final design will be constructed using 3D printing of the base and LED electronics to model the five intended ventilation-perfusion mismatching ratios. A CAD drawing will be used to 3D print the base in the UW Makerspace. The team will insert LEDs and diffuser casings along the alveoli and bloodstream cut-outs of the base model to model the oxygen gradient. A code will be written to program the LEDs using a dial to allow the model to represent five different ratios.

Testing will include creating the prototype and working with the electronics to correctly model the ratios. The team will try different methods of adding the LEDs into the model to see which works best in creating a clear and easy to interpret color gradient. Testing will also be done with the code to get the correct coloring to model the chosen scenario. Ideally, the LEDs would be tested by creating a survey for other individuals to determine whether or not five significant V/Q ratios are distinct from one another.

VI. Conclusion

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.

With a determined preliminary design, the team will begin the fabrication of the teaching model for ventilation-perfusion mismatching. An initial materials list, including the LEDs and a microcontroller, will be created for the first round of orders to begin fabrication. A diffuser for the LEDs would then be chosen. The diffuser will likely be a type of thin plastic covering that lines the LEDs. The team will use the CAD drawing to 3D print the base model out of the chosen plastic before being able to add the LEDs. Simultaneously, an Arduino code will be written to control the LEDs to model different ventilation-perfusion ratios using an equation for equal distribution of light for the given ratios. Adjustments will continue to be made as the team discovers the best methods to create an effective model.

VII. References

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VIII. Appendix

A. Product Design Specification (PDS)

<u>Teaching Model for Ventilation and Perfusion Mismatching Product Design Specification</u>

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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**

j.

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
- Portability of the device could mean there is a chance of damage between storage and classroom
- Damage could occur if misused

g. Ergonomics:

- People with heights from () should be able to comfortably use the device

h. Size:

- No more than 2ft x 2ft
- Maximum dimensions of 6ft x 8ft
    1. Must fit on a tabletop

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 or brightness between blood coming to and leaving the lungs
      - Air can be visualized entering the lungs
      - Visible flow of blood

   c. **Competition:**
      - West's model for V/Q matching [9]
         1. Uses pumps and dye to show the effect of V/Q ratios on blood oxygenation
      - E-learning Computer Model for Cardiovascular System [10]
         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 [11]
         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.