Teaching Model for Ventilation and Perfusion Mismatching

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Client: Dr. Chris Green UW-Health
Advisor: Prof. Chris Brace UW-Madison

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Abstract

Understanding the concept of Ventilation(V) and Perfusion(Q) in the Lungs and how the ratio between them affects the body is of great clinical significance, considering the fact that any mismatch in the ratio leads to a variety of problems such as hypoxia, hypoxia and hypercapnia. However, it is a difficult concept and there is virtually no representation of this concept available in the market and the medical faculty and students have to rely on a textbook diagram in 'Respiratory Physiology' by John West, which is not an effective way to learn for the students. This is why our Client, Dr. Christopher Green commissioned us to create an effective teaching model. While previous BME 2/300 students did work on the project, the design still needed significant improvements to be made to make it effective. After much deliberation on our three top design ideas, we decided to build upon the previous model and change it to include sliders and LED screens as well as change the housing of the components to fit the needs of the clients and make the model more effective. We are currently working on the fabrication of this improved model and will begin our testing process in the near future.

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I. Introduction

Chronic obstructive pulmonary disease, asthma, chronic bronchitis, pulmonary congestion, airway obstruction, pulmonary embolism, and many other common conditions lead to ventilation perfusion mismatching [1]. Ventilation perfusion mismatching is the main cause of hypoxemia; hypoxemia is a state of low oxygenated blood flow that leads to poorly oxygenated tissues. Although ventilation perfusion mismatching is very common, it is a very difficult concept for medical students to learn. The only demonstration of how ventilation perfusion mismatching occurs in the capillaries of the lungs is a textbook diagram by John West in his text Respiratory Physiology [2]. However, this textbook diagram is confusing and does not allow students the opportunity to physically observe different ventilation perfusion ratios and its effects on the oxygenation of the blood flow. It is necessary for medical students to have a physical, interactive model so they can unlock a deeper understanding of ventilation perfusion mismatching; according to the Harvard Gazette, active learning can subconsciously help students learn [3]. The main focus of this design process is to create a working prototype of an intuitive and interactive teaching model for medical students to learn the effects of ventilation perfusion mismatching.

II. Background

Lungs are a sponge-like organ housed within the rib cage in the human body and form a major part of the respiratory system. The lungs contain alveoli, which are the main site of gaseous exchange. An alveolus is a cluster of tiny air sacs that are surrounded by a mesh of tiny blood vessels called capillaries. The alveolus provides a moist site that helps in gaseous exchange. Gaseous exchange occurs mostly by diffusion[4].

When the air flows into the lungs and reaches the alveoli, Oxygen diffuses from the alveoli into the blood that flows into the pulmonary capillaries because there is a high concentration of oxygen in the lungs and a low concentration in the blood while the Carbon dioxide diffuses from the pulmonary capillaries to the alveoli due to the high concentration of Carbon dioxide in deoxygenated blood and the subsequent low concentration in the lungs [5].

This entire process of airflow into the lungs is known as Ventilation (V) and the flow of blood into the pulmonary capillaries is known as Perfusion (Q). Due to the increase in gravity as blood moves down towards the base of the lung, the weight of the fluid in the pleural cavity increases, thus increasing ventilation rates[6]. However, gravity also has a major effect on the perfusion rates. Since it pulls the blood towards the base, perfusion rates are much higher at the base than the apex. This leads to a lower V/Q ratio at the base.

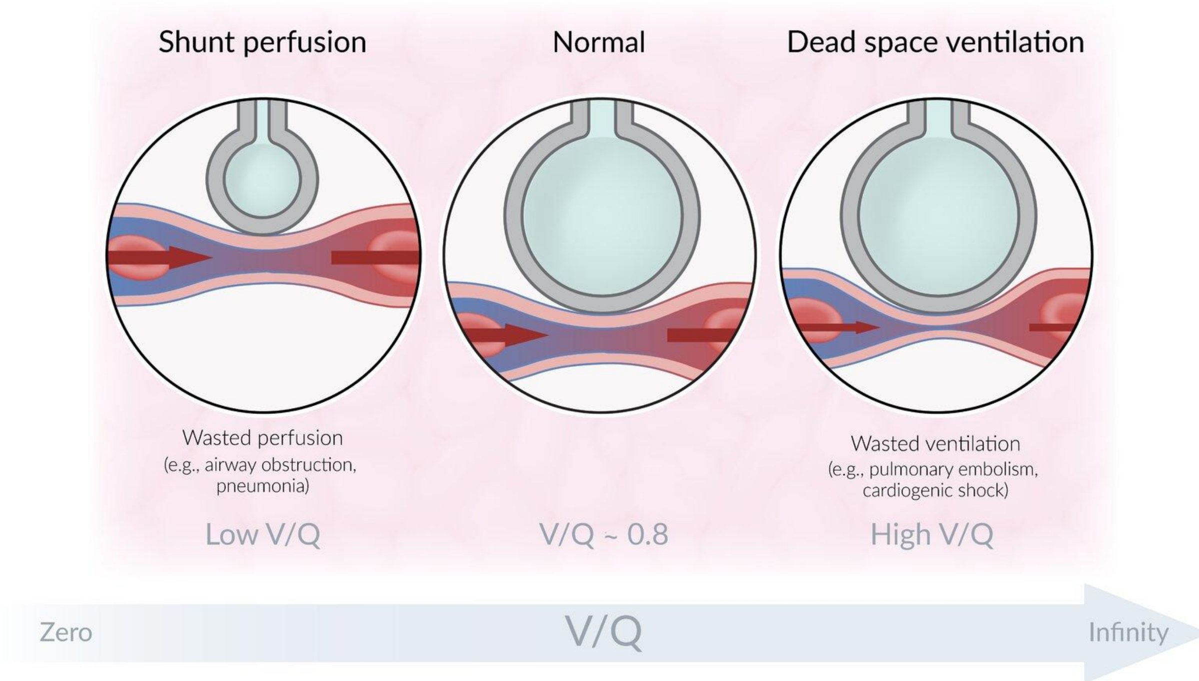


Figure1. Depictions and defining factors of different V/Q ratios[6]

It is known that in a healthy individual, the V/Q ratio is around 1 in the middle of the lung and varies between 0.3 and 2.1 across the lung while the average value lies around 0.8 [6]. Any mismatch in this ratio would be detrimental to the human body. A too-high ratio would be the result of decreased perfusion, and the most common cause of this are pulmonary embolisms (blood clot that travels to a lung artery). This leads to hypoxemia, which is low levels of oxygen in the blood.

A high ratio can also be associated with dead-space ventilation, which involves more ventilation than necessary. A too-low ratio refers to a decreased ventilation, which is typically the result of COPD, asthma, or an airway obstruction. It can lead to Hypoxia, which is the condition wherein less oxygen is available to the bodily tissues and in some cases can lead to hypercapnia, wherein there are high levels of Carbon Dioxide in the blood[6].

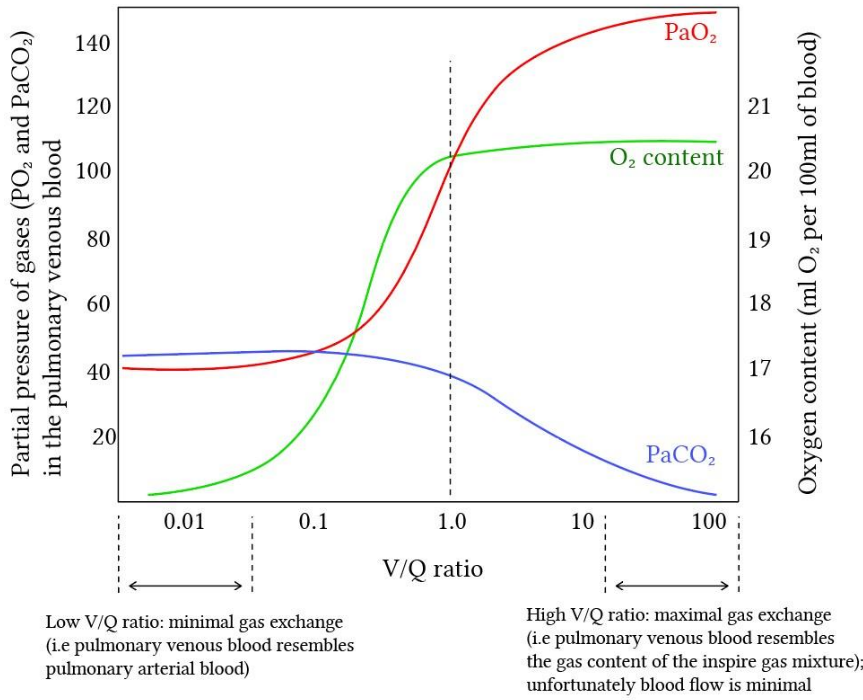


Figure2. Relationship between V/Q ratio and partial pressure of gases[7]

Our client, Dr. Chris Green, a medical educator and a pediatric pulmonologist with UW-Health. observed that this is a concept that students often struggle with which inspired him to create a teaching model for ventilation and perfusion mismatching to help students understand the concept better.

To design and build our prototype, lots of foundational research must be done to understand what is happening in each alveoli. Having a complete understanding of the ventilation and perfusion process is absolutely essential so that the teaching model can be adequate enough to teach it to another person. Understanding the causes and consequences of the V/Q mismatch is also essential, as the end goal of the teaching model is to understand the concept and be able to apply it into practice as a medical professional. Researching previous work done on teaching models and analyzing the benefits and drawbacks also shapes the prototype, as being able to improve from what is already out there is key to designing a product. Given the technical nature of this project, knowledge and experience working with the mechanical pieces, such as LEDs, Arduino products, and wires makes the manufacturing process easier, and also allows for more advanced features on the prototype. Dr. Green has offered his assistance in the mathematical process of computing the ratio, but a baseline understanding at minimum of how the equation works is required in order to effectively teach the concept.

One of the most important design specifications is that Dr. Green is looking for sliders that can adjust the V/Q ratio to represent different levels of mismatching. Along with this, a digital display that shows output of the partial pressure of oxygen and the partial pressure of carbon dioxide is very important. The client needs to be able to show the device in a lecture hall, under a document camera for example, so the model must be less than about 10 in or 25 cm on any side. Another specification given by the client is that the model does not necessarily need to be realistic, but must be a good representation and visualization of what happens in the body at different V/Q levels leading to hypoxemia

III. Preliminary Designs

Design 1: Slider with LEDs and Screen

The slider with LEDs and screen model uses a 3D printed case that houses differently colored LEDs, slides for adjusting the V/Q ratio, and a digital display where the values the client would like to teach his students about can be displayed. The different colored LEDs represent different things, flowing in and out of the alveoli. Along with that, the speed at which the lights flashed could assist in demonstrating the changes that occur at higher or lower V/Q ratios.

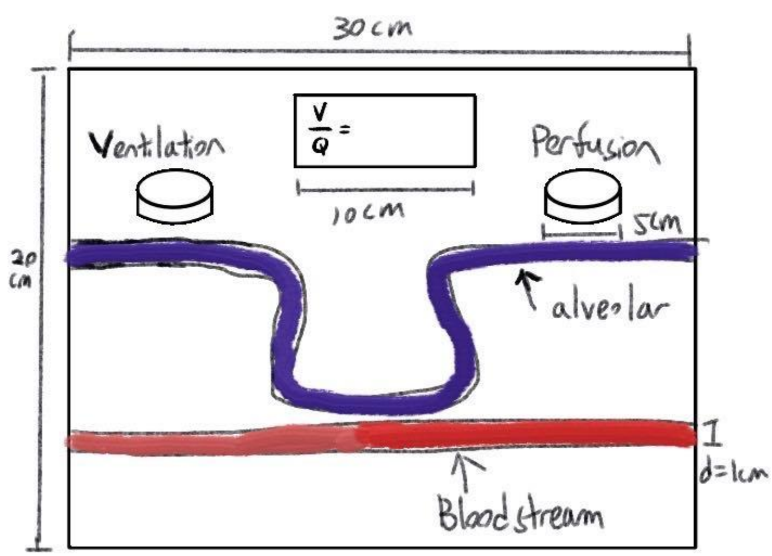


Figure3. Design drawing for slider with LEDs and screen design

Design 2: Computer Animation

The software animation model refers to use of a programming language to create a software where V and Q values could be input and the V/Q ratio, partial pressure of oxygen, and any other levels the client would like to calculate would be output. Along with these values, the program would provide an animation of one or multiple alveoli with flow rates depicted through use of arrows, number of molecules, and speed at which the molecules flow through the animation.

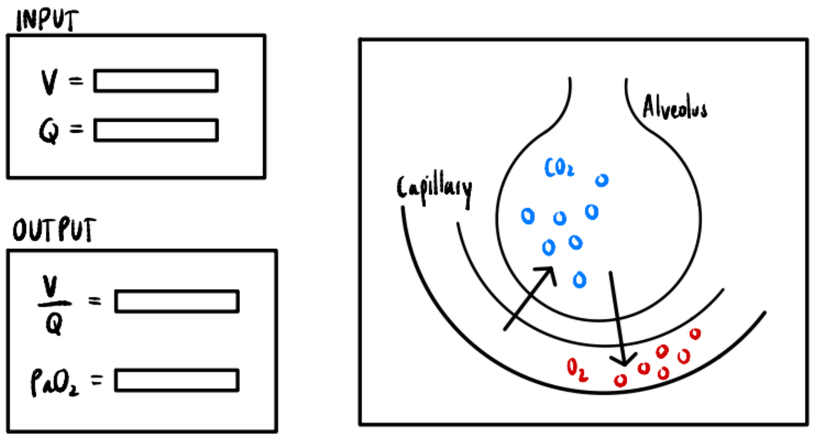


Figure4. Design drawing for computer animation design

Design 3: Water/Dye Concentrations

The water and dye model uses a flexible tube that can expand and relax to show different blood flow volume measurements and a colorful dye that can be used to represent oxygenation of the blood. The water would run through the tube at different rates and depending on the avelious represented some amount of dye would be excreted into the tube to show a colorful oxygenated blood flow. The amount of dye excreted and velocity of water would be controlled by a computer program so that qualitative data can be displayed on a computer to show the V/Q ratios and oxygen levels of the portrayed blood flow.

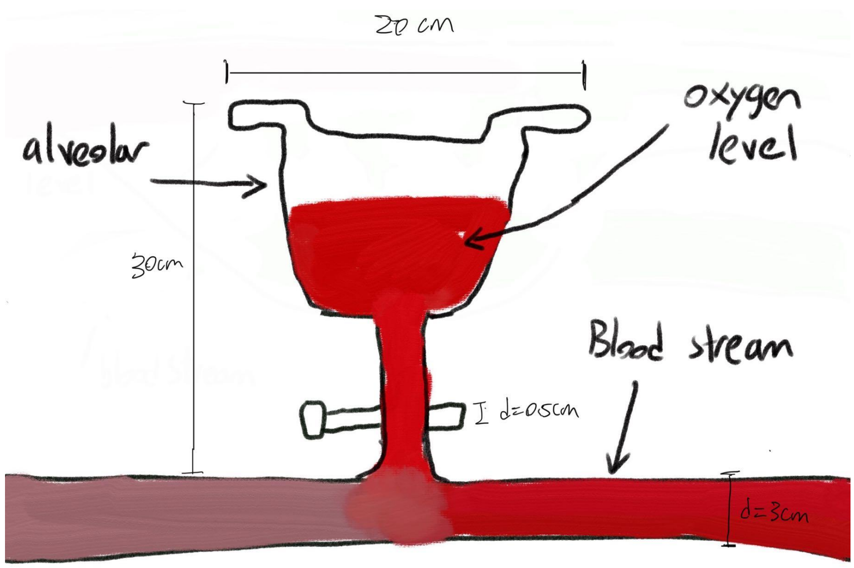


Figure5. Design drawing for water/dye concentration design

IV. Preliminary Design Evaluation

Design Matrix

To determine necessary criteria for the design matrix, the primary purpose of this device was prioritized. Scores were given largely based on effectiveness of the potential designs as teaching models.

Intuitive use is the ability of the client to understand and use the product immediately after receiving it. The weight of this criteria is 30%, as the product will be used as a teaching model, and both the client and students must be able to use the model easily. The LEDs and screen design received full points as the interactive component of the sliders is easy to understand.

The learning outcomes criteria refers to the design's effectiveness in leading students to understand the concept of ventilation and perfusion mismatching. Since the major purpose of the design is teaching, the weight of this criteria is given 30%. The LEDs and screen design allows students to understand the concept without confusion because oxygen levels at different V/Q ratios can be seen by adjusting the V/Q sliders.

The adjustability criteria refers to the ability to adjust V/Q input in order to be more precise and variable. The weight of adjustability is 20% because high adjustability will allow the client to better explain the concept of V/Q mismatching to different students. The adjustability of the LEDs and screen design is considered high because the slider in the design allows the client to adjust the ratio of V/Q in order to show the effects that different ratios have on flow rates.

Ease of fabrication was given a weight of 10% as there are many great resources available to us through the engineering department that will make the fabrication process much easier, especially for 3D printing.

The cost criteria was given a weight of 5% as the budget given by the client should be more than enough for the materials involved.

The safety criteria was given a weight of 5% as there are little to no safety risks involved.

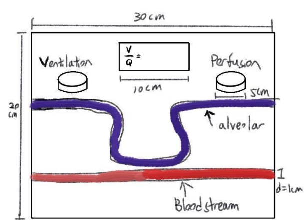
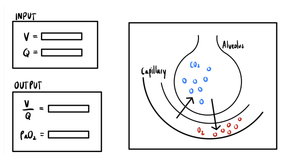
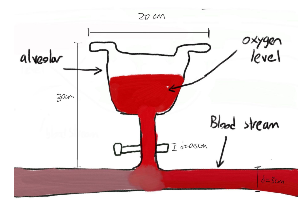
Criteria (Weight)	**Slider with LEDs and Screen*** 		**Computer Animation*** 		**Water/Dye Concentrations** 	
Intuitive use (30%)	5/5	30%	4/5	24%	2/5	12%
Learning Outcomes (30%)	4/5	24%	2/5	12%	4/5	24%
Adjustability (20%)	4/5	16%	5/5	20%	4/5	16%
Ease of fabrication (10%)	3/5	6%	2/5	4%	1/5	2%
Cost (5%)	2/5	2%	5/5	5%	2/5	2%
Safety (5%)	4/5	4%	5/5	5%	5/5	5%
Total		**82%**		**70%**		**61%**

Figure6. Preliminary design matrix

Proposed Final Design

After much discussion as a team with both the client and advisor, the proposed final design is the slider with LEDs and screen design. This design would offer the best learning outcomes for medical students, allow for hands-on teaching and learning experiences, and be an intuitive tool for the classroom.

V. Fabrication/Development Process

Materials

Although fabrication has not yet begun, the team plans to create the device with sliders, a digital display, LEDs of different colors, Arduino Uno for programming, and 3D printed housing for all electrical components.

The sliders were chosen because they offer the user the ability to easily adjust the V and Q values. Two will be used so that the V/Q ratio can be manipulated by changing V, Q, or both. The digital display was selected so that the user can see the V/Q ratio as well as partial pressure of oxygen and carbon dioxide results from the V and Q values inputted. LEDs of different colors will allow the user to visualize the flow of oxygen and blood through the alveolus. The Arduino Uno will conduct the calculations as well as allow for the programming of the LEDs, potentially to flash at different speeds for different V/Q ratios levels. 3D printed housing for all of these components was chosen as it is not expensive to create, readily available at the UW-Madison Makerspace

Methods

The exact methods for creating the prototype are still to be determined. However, the fabrication plan includes 3D printing the housing for the LEDs, purchasing the digital display, sliders, and other electrical components, and assembling and printing using the tools at the UW-Madison Makerspace. Printing will be achieved by using SolidWorks to create a computer generated image of the electrical housing with its exact dimensions and precise shape. Along with this, assembling the circuitry will be a large component of the creation of the device.

Final Prototype

Final prototype has not yet been fabricated.

Testing

Testing has not yet been conducted. However, testing with the client and potentially the client's students would allow for better understanding of the effectiveness of the teaching model, whether or not it is intuitive, and how well the LED configuration can represent the flow rates.

VI. Results

Data and results will be collected after testing is conducted.

VII. Discussion

Discussion will be completed after fabrication and testing.

VIII. Conclusions

The team has been tasked with creating a teaching model for ventilation and perfusion mismatching. This issue is the most common cause of hypoxemia, however students have a difficult time grasping the complex topic. The client, Dr. Chris Green, is seeking an effective teaching model that offers a good visualization of the V/Q ratio in an alveolus of the lung. Findings and additional conclusions will be explained as fabrication and testing occurs.

For future work, the team plans to finalize the slider with LEDs and screen design. After the configuration and other specifics of the LEDs, such as color and flashing speed, are decided, fabrication can begin. Fabrication will include creating housing for the electrical components, purchasing the desired LEDs and a digital display, and assembling the circuitry. After fabrication is completed, testing will begin. This will consist of inputting different V and Q values and ensuring that the output oxygen and carbon dioxide levels are correct based on calculations that the client has provided. Along with this, the LEDs will be tested by inputting different V and Q values and ensuring that the correct colors and flashing speeds are observed. Moreover, the design will be tested by the client and potentially by students, to determine whether or not it is intuitive and helpful.

IX. References

[1] Adrienne Santos-Longhurst. (2018, October 26). What you need to know about V/Q mismatching. [Peer reviewed publication]. Available: https://www.healthline.com/health/v-q-mismatch#causes.

[2] West, J. B., & Luks, A. (2021). *West's respiratory physiology: The essentials*. Wolters Kluwer.

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[5] Deborah Leader, R. N. (n.d.). What people with copd should know about v/q mismatch. *Verywell Health*. Retrieved September 24, 2021, from https://www.verywellhealth.com/what-is-vq-mismatch-in-the-lungs-914928.

[6] Respiratory physiology - Knowledge @ AMBOSS. Amboss.com. Published 2021. Accessed October 15, 2021. https://www.amboss.com/us/knowledge/Respiratory_physiology/

[7] A. Yartsev, "Effects of ventilation-perfusion mismatch on gas exchange: Deranged physiology," *Effects of ventilation-perfusion mismatch on gas exchange | Deranged Physiology*, 07-Dec-2019. [Online]. Available: https://derangedphysiology.com/main/cicm-primary-exam/required-reading/respiratory-system/Chapter%200732/effects-ventilation-perfusion-mismatch-gas-exchange. [Accessed: 20-Oct-2021].

X. Appendix

Product Design Specification

Teaching Model for Ventilation and Perfusion Mismatching
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09/24/2021

Function:

Ventilation and perfusion mismatching is the most predominant cause of hypoxemia. However, medical students often have a very difficult time understanding this concept. Other than a textbook diagram by John West in his text *Respiratory Physiology* [1], there are no relevant representations of ventilation/perfusion mismatching. Our goal is to improve a prototype completed by previous UW Madison students to create an effective teaching model of ventilation/ perfusion mismatching to be studied by medical students for a deeper understanding of hypoxemia.

Client requirements:

- Sliding knobs for changing the V/Q ratio to represent different levels of mismatching
- Output that shows oxygenation (client will help with calculations)
- A digital display of some sort for the values (or displayed on computer screen)
- Able to be showed in lecture hall under document camera
- Not necessarily realistic, but good representation of what happens in the body at different V/Q levels leading to hypoxemia

Design requirements:

1. **Physical and Operational Characteristics**
    a. Performance requirements:
        i. A physical model to represent the concept of ventilation/perfusion mismatching and how it leads to hypoxemia
        ii. Used in a classroom setting
        iii. Ability to change ventilation/perfusion ratio

    b. Safety:
        i. No danger of electrocution (no loose wires)

ii. Shell has no sharp corners

c. Accuracy and Reliability:
   i. All coding should be free of error and reproducible/stored where it can be retrieved easily
   ii. This will be further analyzed after our testing phase

d. Life in Service:
   i. Arduino Uno may need to be replaced after approximately one year depending on the conditions under which it is stored
   ii. Under good conditions for electrical components, expected life in service should be at least 5 years
   iii. As a teaching model, device should last throughout lectures and hands on learning

e. Shelf Life:
   i. The product should be able to withstand storage for long periods of time. (At least five years under good condition of electronic components)
   ii. The product needs to be reusable and could be set up easily
   iii. The product will be placed in a sealed container in order to maintain a low moisture level
   iv. Ideal storage temperature is in the range of 10-27℃ [2] (50-80 ℉)

f. Operating Environment:
   i. Classroom setting, not exposed to harsh elements
   ii. Slight risk of damage due to mishandling between transition from classroom to storage

g. Ergonomics:
   i. Very light and portable
   ii. Be able to be displayed in a lecture hall using a document camera, or seen in a small-group setting (within 3 meters of the device)

h. Size:
   i. Roughly 1 ft x 1 ft

i. Weight:
   i. Easily movable and carryable, no more than 15 lbs

j. Materials:

i. 3D printed base because it is lightweight and cost effective
ii. LED lights to represent V/Q ratios because they are energy efficient

k. Aesthetics, Appearance, and Finish:
   i. No specific color
   ii. Dinner-plate sized
   iii. No loose wires or sharp corners
   iv. Digital display of some kind for relevant values
   v. Computer program for inputting different V/Q ratios and visualizing effects on the human body if possible

2. Production Characteristics

a. Quantity: number of units needed
   i. 4 units
      1. 3D printed base to hold all components together
      2. LED lights connected to create a string of illumination
      3. Arduino to connect the LEDs and program the model
      4. Sliders/ buttons to change the ventilation/perfusion mismatching ratios

b. Target Product Cost:
   i. To be determined once production phase begins
   ii. Similar cost to previous semster's prototype (about $140)

3. Miscellaneous

a. Standards and Specifications:
   i. No applicable at this time

b. Customer:
   i. Medical students and educators would be the customers
   ii. Should be an effective teaching model, with interactive learning aspects for medical students to understand the complex topic

c. Patient-related concerns:
   i. Device will need to be carefully stored in order to prevent deterioration of electrical components

d. Competition:
   i. Currently, there are no effective teaching models on the market

Citations

[1] West, J. B., & Luks, A. (2021). *West's respiratory physiology: The essentials*. Wolters Kluwer.

[2] *Storing electronics in a storage unit: Storing electronics in heat + cold*. EZ Storage. (2019, October 22). Retrieved September 24, 2021, from https://www.ezstoragenow.com/blog/delicate-balance-properly-storing-electronics-heat-cold/#:~:text=The%20trick%20to%20properly%20storing,between%2050%20and%2080%20degrees.

Preliminary Materials and Costs Table

Item	**Manufacturer**	**Quantity**	**Cost/Unit**	**Link**
Digital Display	Adafruit	1	$9.95	https://www.adafruit.com/product/181
Slider Option 1	Adafruit	2	$0.75	https://www.adafruit.com/product/5093
Slider Option 2	Adafruit	2	$0.95	https://www.adafruit.com/product/2058