Teaching Model for Ventilation and Perfusion Mismatching

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BME 200/300: Fall 2021
12.15.2021

Abstract

The concept of ventilation (V, air flow) and perfusion (Q, blood flow) in the lungs and the effect of ventilation and perfusion mismatch on the body is of great clinical significance. The typical V/Q ratio is around 0.8, and any mismatching of the ratio can lead to a variety of problems such as hypoxemia or dead space ventilation, which can lead to respiratory failure [1]. There is currently no effective teaching model for learning this concept available outside of textbook diagrams such as those in *Respiratory Physiology* by John West. The models found in literature lack helpful visual aids and interactive aspects. This is why the client, Dr. Christopher Green, has commissioned BME Design students to create an effective and interactive teaching model for ventilation and perfusion mismatching. Previous BME Design students began this project, but alterations to the design were necessary in order to create a more effective, intuitive, and visually helpful teaching model. This semester, the group has created a prototype which uses a 3D printed board designed in the image of an alveolus and capillary in the lungs, with LED lights to demonstrate movement of air and blood at different V/Q ratios. Knobs allow the users to visualize a wide range of V/Q ratios, and a digital display shows the V/Q ratio and partial pressure of oxygen.

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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 and perfusion mismatching is the main cause of hypoxemia. Hypoxemia is a state of low oxygenated blood flow that leads to poorly oxygenated tissues, which can ultimately lead to respiratory failure. Although ventilation perfusion mismatching is very common, it is a very difficult concept for medical students to learn. The only demonstration of ventilation and perfusion mismatching in the capillaries of the lungs are found in literature, such as *Respiratory Physiology*, a commonly used textbook by John West [2]. The diagrams found in literature are very confusing and do not allow the students to physically observe different V/Q ratios and their effects on blood and air flow in the lungs. It is necessary for medical students to have a physical, interactive model so they can unlock a deeper understanding of ventilation and perfusion mismatching. According to the Harvard Gazette, active learning assists students with their understanding, and it is imperative that medical professionals have a good grasp on this concept [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 and perfusion mismatching.

II. Background

The 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 the tiny air sac in the lungs that is surrounded by a mesh of 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.

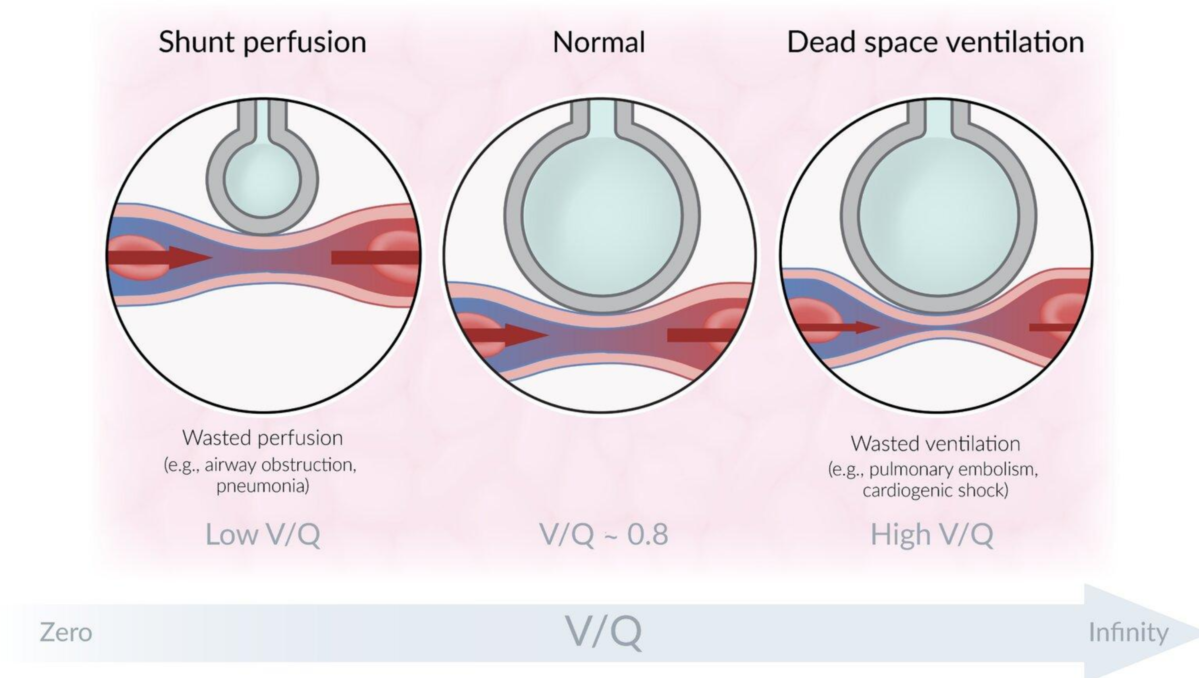


Figure 1. Depictions and defining factors of different V/Q ratios [6]

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].

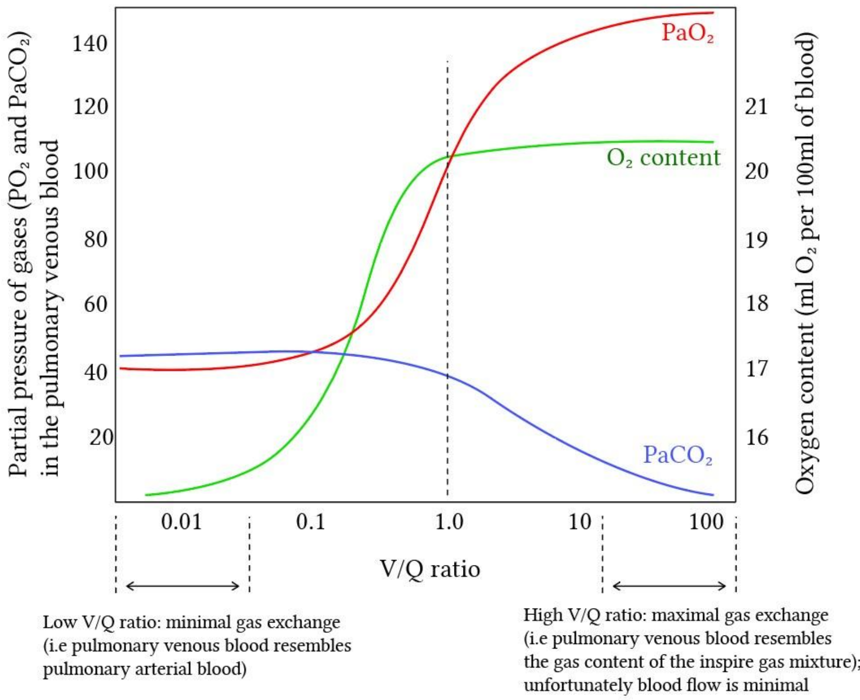


Figure 2. Relationship between V/Q ratio and partial pressure of oxygen and carbon dioxide [7]

The 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 the prototype, much 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: Sliders with LEDs and Screen

The slider with LEDs and screen model uses a 3D printed case that houses differently colored LEDs, potentiometer knobs for adjusting the V and Q values, and a digital display that shows the V/Q ratio and partial pressure of oxygen value according to the V/Q ratio. White LEDs represent the air flowing into the alveolus, and the blue-purple-red gradient LEDs represent the blood flowing through the capillaries. Along with that, the speed at which the lights flash assist in demonstrating the changes in air and blood flows that occur at different V/Q ratios.

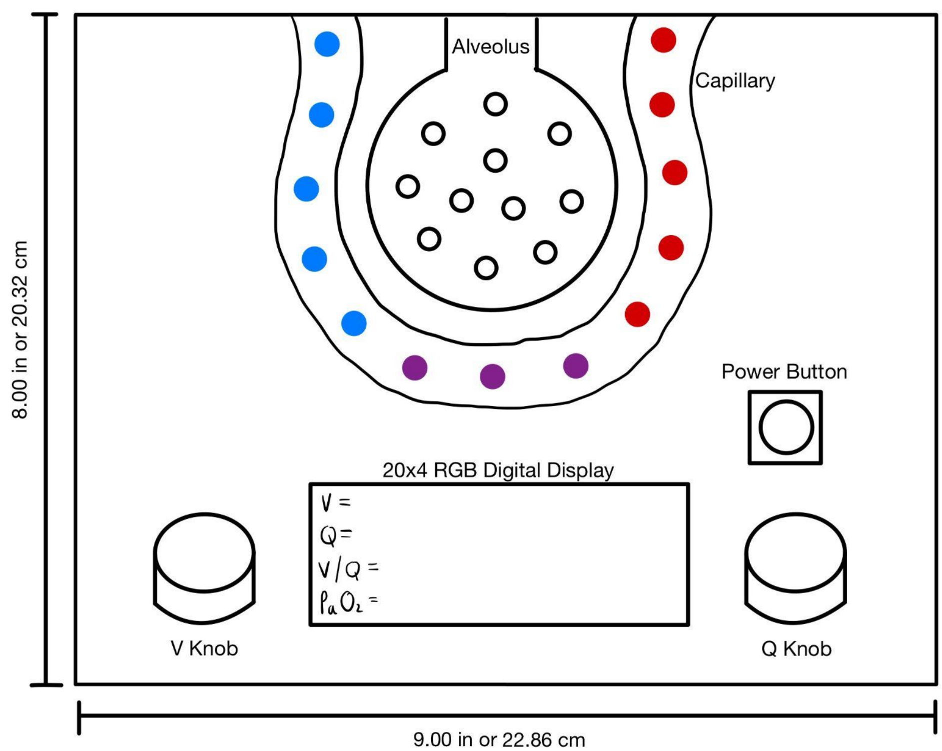


Figure 3. Design drawing for slider with LEDs and screen design

Design 2: Computer Animation

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

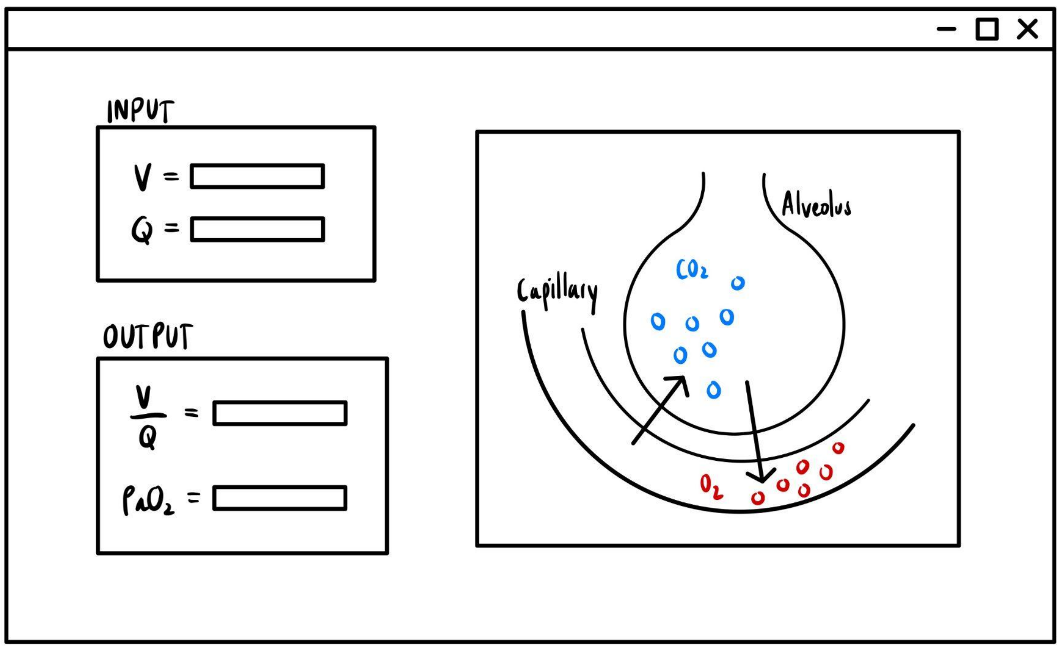


Figure 4. Design drawing for computer animation design

Design 3: Water/Dye Concentrations

The water and dye model uses a flexible tube that can expand and relax to show different blood flow levels. A colorful dye can be used to represent oxygenation of the blood. The water would run through the tube at different rates and depending on the ventilation value, a certain amount of dye would be excreted into the tube to show a colorful oxygenated blood flow. The amount of dye excreted and speed of water would be controlled by a computer program. The program could display the qualitative data on the computer such as V/Q ratio and partial pressure of oxygen in the blood.

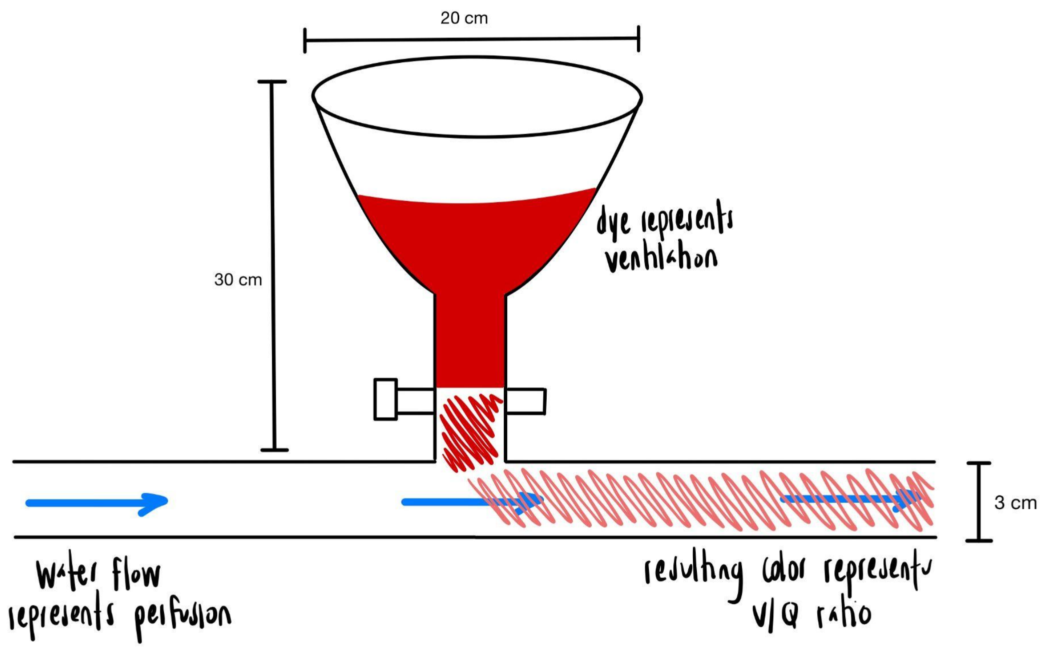


Figure 5. Design drawing for water/dye concentration design

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.

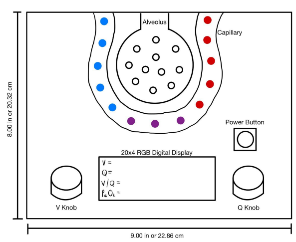
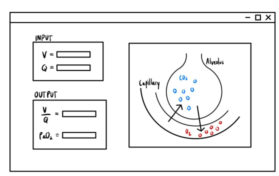
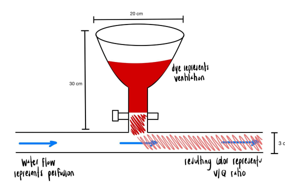
Criteria (Weight)	**Sliders with LEDs and Screen** 		**Computer Animation** 		**Water/Dye Concentrations** 	
Intuitive use (30%)	5/5	30%	4/5	24%	2/5	12%
Learning Outcomes (30%)	4/5	24%	2/5	12%	4/5	24%
Adjustability (20%)	4/5	16%	5/5	20%	4/5	16%
Ease of fabrication (10%)	3/5	6%	2/5	4%	1/5	2%
Cost (5%)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

Figure 6. Design matrix for the three final designs, showing the benefits of the Sliders with LEDs and Screen design.

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 and Methods

The model runs through an Arduino Mega 2560, which was chosen because of the large number of digital ports. The capillary is represented by a NeoPixel LED flex strip, which contains 15 pixels that are individually controlled in the code. The gradient from blue to red represents the deoxygenated (blue) and oxygenated (red) blood moving through the capillary. Gas exchange would actually happen anywhere in this capillary if this was completely anatomically correct, but this was the best way it could be represented with a simple LED strip [7]. The speed of the LEDs turning on and off represents the perfusion rate, and at max speed, the perfusion value is 100. There is also a condition in the code testing if the perfusion value is less than 2, and if it passes, the capillary goes off, representing virtually no perfusion. An example of this code can be seen in Figure 7. To represent the ventilation in the alveolus, 10 individual LED bulbs were used. When all 10 of them are on the ventilation value is between 90 and 100, and when they are all off the ventilation rate is between 0 and 10. Ten holes with 3.175 mm diameter were drilled in the alveolus to be able to fit the terminals of the LED bulbs so the wires could be plugged into the Arduino. Another hole with 9.525 mm diameter was drilled at the inner surface of the LED strip channel which allows the terminal of the LED strip to be able to get through and connect to the breadboard. Controlling this ventilation and perfusion rate is facilitated through 2 potentiometers, which are attached to black knobs that are very easy to turn and adjust. Two 22.9 mm diameter holes were designed into the housing so the potentiometers could fit smoothly. They are calibrated so when fully turned, the value is 100, and when fully turned the other way, the value is 0. To visualize values (along with V/Q ratio and P_aO_2), a 20x4 LCD screen is utilized which allows for 4 lines of text, which is plenty of room for everything that needs to be displayed.

To house all of the components, A 3D-printed PLA box was created that has all the holes and divots needed to be able to fit all the potentiometers, lights, and LCD screens in it (see Figure 9). This PLA material was chosen because it has a 50 MPA tensile strength and 80 MPA flexural strength [10]. High strength of the outer shell secures enough mechanical strength of the model for daily storage and accidental impact due to fall down or hit by other objects. The model is 8.89cm tall, allowing for enough room to fit the Arduino Mega, 3 small breadboards, and a large amount of wires connecting all the components. A bottom for this model was also printed out of PLA, measuring slightly bigger (23.368 cm) than the top of the model to ensure a snug fit (see Figure 10). A hole cut in the side leaves enough room to connect the USB cord from the Arduino Mega to power through a computer. All the electronic components are glued inside the box with EPOXY glue and electronic tape in order to fit the components tightly in the box. Black plastic allows for the lights to stand out for clear viewing, and the 22.86 cm by 21.59 cm size allows for it to fit underneath a document camera without any difficulty.

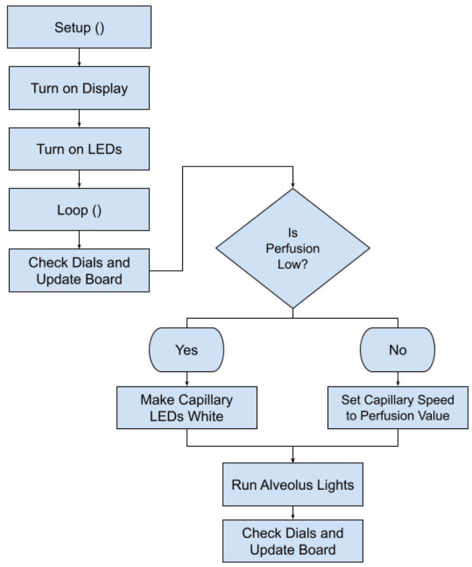


Figure 7: Code diagram

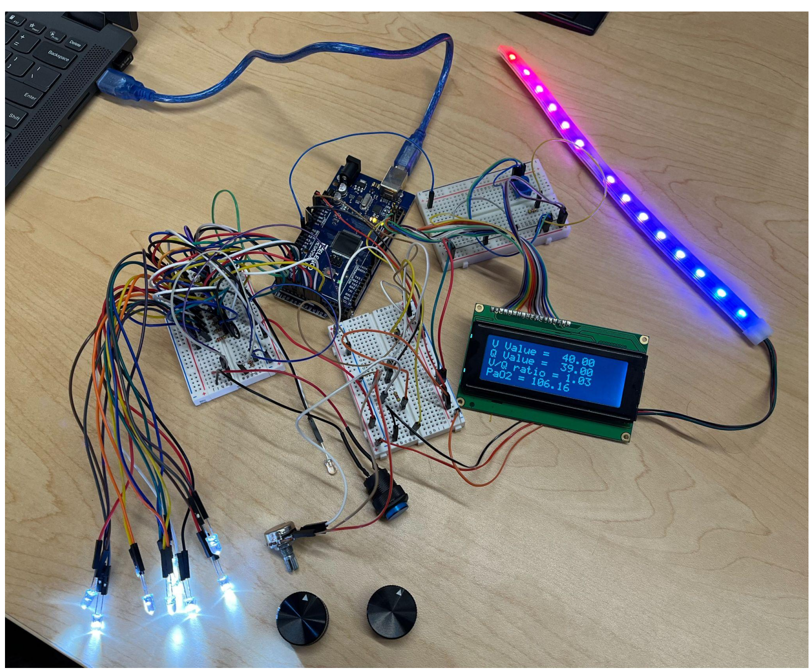


Figure 8: Internals of the model, including NeoPixel LED strip, 20x4 LCD Screen, 5mm LED bulbs, potentiometer/knobs, and Arduino Mega 2560.

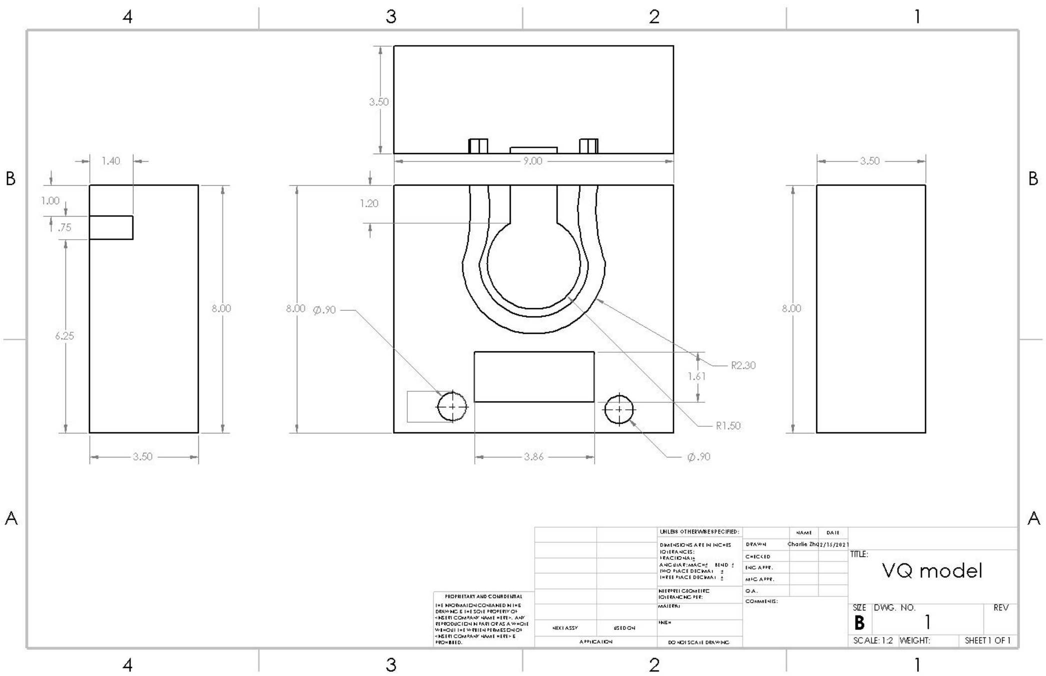


Figure 9: Top CAD model of print

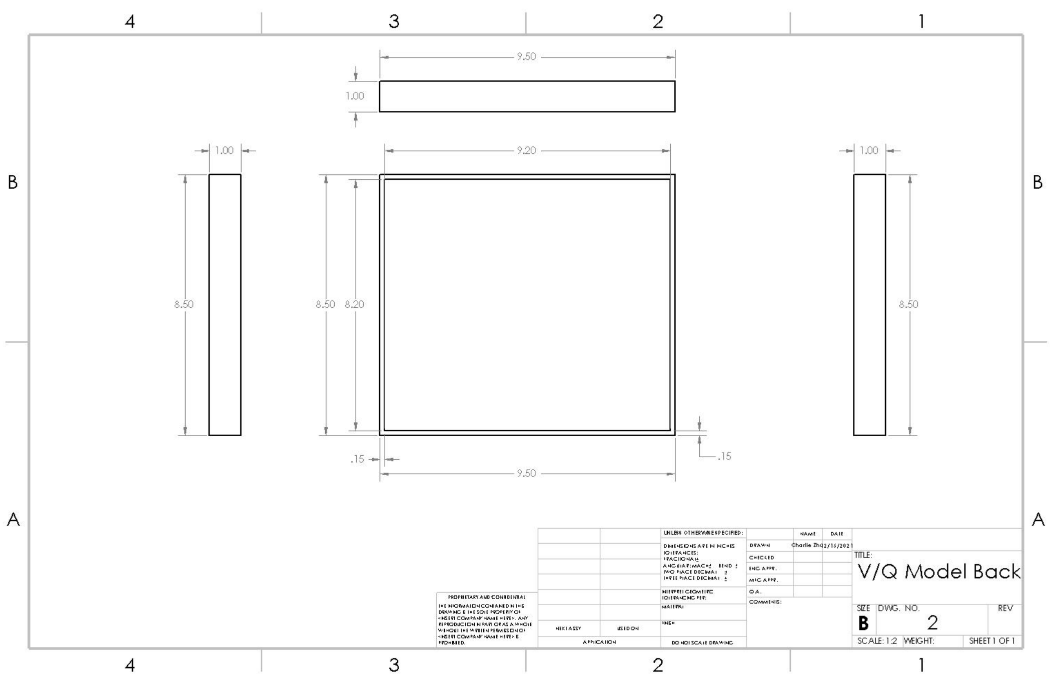


Figure 10: Bottom CAD model of print

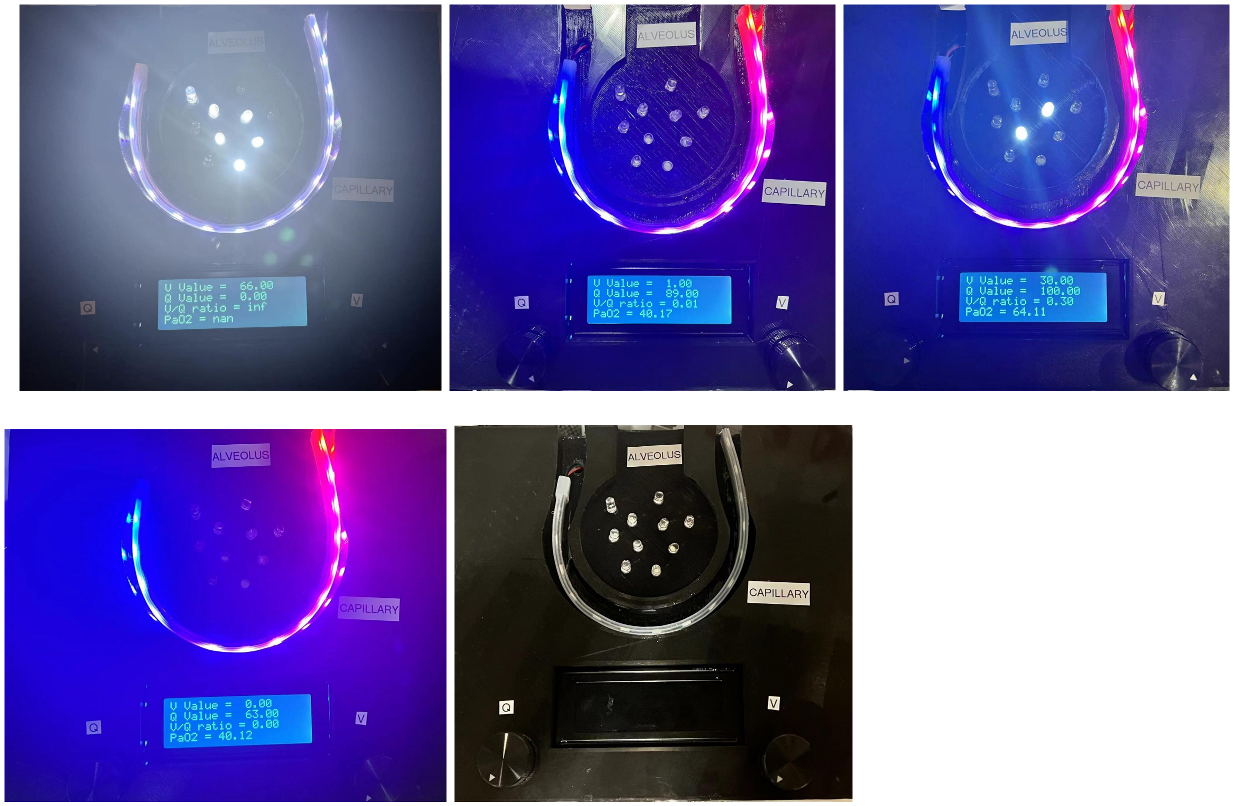


Figure 11: Model display when Q=0, V≠0 (Line 1 left), when V=1,Q≠0 (Line 1 middle), when Q≠0,V≠0 (Line 1 right),when Q≠0,V=0 (Line 2 Left), and when turned off (Line 2 middle)

Testing

The first test that was completed on the model was an initial qualitative test under a lecture hall document camera. Two team members visited a lecture hall in the health science learning center where the client, Chris Green, teaches. There, the original prototype from spring 2021 was tested underneath the document camera and on the projector. The test was completed on the original prototype to confirm the design specifications the new model was going to represent. To test visibility, intuitiveness, and potential improvements the prototype was placed on the document camera stage and then the image projected was evaluated from the back of the classroom. This test was designed to point out the visual flaws and failures of the existing model. The expected outcomes will describe aesthetic characteristics that can be improved in the next model.

Similarly to the initial qualitative test, the final prototype was tested under a document camera in a lecture hall. A document camera in a lecture hall, similar to the clients, was used. During the test, the same aspects as before (visibility, intuitiveness, and potential improvements) were evaluated. The expected results were improvements in component dimensions, projection visibility, and intuitiveness/ understanding of the model. However, the test still allowed for growth by evaluating and defining areas of physical improvements.

The last test was a repeatability/ quantitative test. This test was used to determine the durability of the electrical components and accuracy of the code. The test consists of changing the perfusion value and the ventilation value by turning the Q and V knobs respectively. Then based on the Q and V values, the V/Q ratio and partial pressure of oxygen were calculated by hand and compared to the displayed values from the code. This process was repeated five times to ensure the results were reliable. The test results will evaluate the ability of electrical components to work in harmony with each other and produce accurate displayed values every time. Additionally, the code is evaluated based on its accuracy and speed. The results will conclude if there are errors or variances in the displayed values when compared to the hand calculated values. The expected outcomes are the displayed values match the calculated values and the program runs smoothly and similarly every time.

VI. Results

The initial qualitative test on the original model yielded results that are congruent with design specifications that the fabrication plans will pursue. For example, the V and Q values were constrained to numbers 1-5 but the model would benefit from a wider range to represent different respiration cases. Additionally, the green colored LEDs representing the alveolus were a strange representation of oxygen in the lungs and confused the viewer. The full results of the initial quantitative test are listed in the appendix.

The final qualitative test on the final model yielded positive results aligning with the end goal of the project. The results varied significantly from the initial qualitative test, sometimes even being the exact opposite description. For example, the V and Q knobs yielded a range from 0.00-100.00, whereas the original model only had a scale from 1-5. Additionally, the originally green colored LEDs in the alveolus were replaced with white LEDs. The White LEDs were more visible on the projected screen and they represented oxygen in the alveolus better. The full results of the final quantitative test are listed in the appendix.

The repeatability test yielded very accurate results. The displayed values all matched with the relevant calculated values; however the discrepancy in significant figures makes the displayed values not exact values. For example during the first data collection, The V value was set at 90.00L/min and the Q value at 100.00L/min, the hand calculated P_aO_2 value was 101.8412mmHg but the displayed P_aO_2 was 101.84mmHg. The attendant uncertainty of the displayed values due to significant figures is ±0.01. The full results from the repeatability test are displayed in the appendix.

VII. Discussion

The implications of results from the initial qualitative test with the original model compared to the final qualitative test with the newest prototype confirms the newest model has properties of an improved teaching model. Specifically, the new model is much easier to view and understand in front of a lecture hall; thus, more students are able to engage and interact with the model in class. According to an article written by Anjana Verma et. al., forms of interaction in a medical classroom setting will positively impact the students' learning [9]. Therefore, the changes made to produce the new teaching model will increase interactiveness and overall understanding of perfusion and ventilation mismatching.

The results from the repeatability test ensure the newest prototype is electronically working properly and displays accurate V/Q ratios and P_aO_2. The model must display accurate calculations for medical students to understand how V/Q mismatching impacts oxygenation in the capillaries.

An ethical consideration for the use of the teaching model is understanding the model's purpose is only to improve medical students' understanding of V/Q mismatching. The model abstractly demonstrates what happens in the alveolus during V/Q mismatching; however, it is not an accurate depiction of what occurs automatically. Additionally, the teaching model should not be used as a diagnostic tool. Instead, the model is produced to help medical students understand what is happening in the human lungs but how to diagnose a patient with hypoxemia.

As a result of the initial qualitative test, the model was changed in the following ways: larger display board, larger baseboard, more accurate alveolus and capillary shape, white alveolus LED lights, black PLA, constant oxygenation gradient in the capillary, V and Q knobs for a wider range of values, and display of P_aO_2 value. The new model included all of the previously listed characteristics but could continue to be improved by building a slightly larger baseboard to comfortably enclose all electrical components. Lastly, the quantitative test confirmed proper calculation code but the display could be changed to show more significant figures for more accurate values.

A potential source of error in the two qualitative tests is missing information that could have better-constructed design specifications that could have been recorded in a more thorough examination of the prototype under the document camera. A potential source of error in the quantitative test is that the same equation was used in the code as it was used in the hand-calculated values. The equation was obtained directly from the client but if it was in any way flawed, the test would not have been able to determine the displayed values of V/Q ratio and P_aO_2 were correct.

VIII. Conclusions

The team was 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, was seeking an effective teaching model that offers a good visualization of the V/Q ratio in an alveolus of the lung. After much discussion and deliberation, the team finalized the sliders with the LEDs design. However, after preliminary testing and with the client's suggestion, it was decided that the display screen had to be made bigger. It was also necessary to make the model more anatomically accurate. The model was hence redesigned to reflect the new requirements. Further, the buttons that controlled V/Q ratio values were replaced with knobs to allow the model to represent a wider range of ratios.

The model was then tested under a document camera that was similar to the one in the health-sciences lecture hall to check for visibility, usability, and intuitiveness. The code was then tested multiple times to check its accuracy. Simultaneously, the durability of the electrical components were tested.

Necessary future work includes testing the model with the client and a small group of his medical students to receive feedback on criteria such as intuitive use and helpful visual representation. Furthermore, future work to improve the reach of this teaching model includes testing the prototype with a larger population of medical students to determine if the model could be helpful on a larger scale, outside of only Dr. Green's classroom. Along with these plans, continuing with the programming and circuitry to ensure the code runs smoothly is another necessary part of future work. As the code is complicated and many electrical elements are included in the circuit, the lights can occasionally respond slowly. Researching alternative ways to program the lights can improve the speed and responsiveness of the lights to the potentiometer knobs. Lastly, the addition of another alveolus to better mimic the lung would be a very helpful future step. There are many alveoli throughout the lungs, and the gas exchange occurring in each one does not stand alone. Visualizing how the different alveoli throughout the lung work together is important for furthering understanding of ventilation and perfusion mismatching.

Overall, the model is a well functioning prototype; however, improvements could be made. A model displaying multiple alveoli would be beneficial to understand how they interact, and since V/Q ratio can depend on the location in the lung, having an alveoli and capillary from the top of the lung and the bottom would be ideal [2]. The code could be improved to be more accurate and responsive. More advanced testing could be done on the model to be positive that it is durable enough to handle exterior damage, but it can be inferred that based on the properties of PLA, it will still work if accidentally dropped [10].

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X. Appendix

A. Updated Product Design Specification

Teaching Model for Ventilation and Perfusion Mismatching
Alex Houle, Charlie Zhu, Darshigaa Gurumoorthy, Kendra Besser, and Milica Lukic
12/15/2021

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. The teaching model will represent an alveolus and a capillary with individual lights; the lights will blink at different speeds to demonstrate different perfusion and ventilation rates. Lastly, the ventilation and perfusion rates will be converted to a ratio and partial pressure of oxygen values that will be displayed on the model.

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. An interactive model that has movable knobs that change V and Q values
        ii. V and Q values vary from 0-100 L/min
        iii. Used in a classroom setting under a document camera
        iv. Clearly visibility of LEDs and LED display board under a document camera

v. Displayed V/Q ratio and P_aO_2 value on LED display board
vi. Accurate coding calculations of V/Q ratio and P_aO_2 in mmHg based on set V and Q values
vii. Power obtained via USB cord to computer

b. Safety:
   i. No danger of electrocution (no loose wires)
   ii. Shell has no sharp corners

c. Accuracy and Reliability:
   i. Coding calculations of V/Q ratio and P_aO_2 should be accurate compared to manually calculations
   ii. Electrical components should be durable and sturdilly connected to a breadboard
   iii. Electrical work and coding should be able to produce accurate results for different V and Q values during at least 5 consecutive tests

d. Life in Service:
   i. Under a safe temperature range (10°C to 40°C), expected life in service should be at least 10 years
   ii. Electrical components should help conserve battery
   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 ten years under good condition of electronic components)
   ii. The product needs to be reusable and 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°C to 40°C. [2]

f. Operating Environment:
   i. Classroom setting, not exposed to harsh elements
   ii. Used under a document camera during lectures
   iii. Slight risk of damage due to mishandling between transition from classroom to storage

g. Ergonomics:

i. Less than 0.3m x 0.3m and made out of the lightest possible PLA in order to be easily 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. Maximum display size of 22.86cm x 22.86cm in order to fit under the document camera

i. Weight:
   i. Easily movable and carryable, no more than 6.8 kg.

j. Materials:
   i. Baseboard material should be compatible with skin contact
   ii. All materials exposed from the outside should be able to withstand sanitation in between uses
   iii. Lights used to represent oxygen and blood flow should be within 80 lumens which is safe to human eyes [3]
   iv. Arduino Mega to allow for large amount of digital ports required

k. Aesthetics, Appearance, and Finish:
   i. Black baseboard
   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. 5 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. Knobs and potentiometers to change the ventilation/perfusion mismatching ratios
      5. Resistors, breadboards, and wires to connect electrical components to arduino
      6. LCD screen to display values

b. Target Product Cost:
    i. Similar cost to previous semster's prototype (about $140)
    ii. Maximum budget of $1000

3. Miscellaneous

a. Standards and Specifications:
    i. BS 9000 - Electronic Components Package (Assessed Quality System) [4]
    ii. IEEE 1118.1-1990 - IEEE Standard for Microcontroller System Serial Control Bus [5]
    iii. IEC/EN-62471Photobiological Safety of Lamps and Lamp Systems [6]

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. Petersson and Glenny's ventilation perfusion model [7]
    ii. Herrmann's ventilation perfusion system [8]

Citations

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B. Materials and Costs Information

Table 1. Cost and materials chart in order of purchase with the most recent at bottom.

Item	**Manufacturer**	**Quantity**	**Cost/Unit**	**Link**
Digital Display	Adafruit	1	$24.95	https://www.adafruit.com/product/498#technical-details
Panel Mount 10K potentiometer	Adafruit	2	$1.90	https://www.adafruit.com/product/562
Panel Mount Right Angle 10K Linear Potentiometer	Adafruit	2	$3.00	https://www.adafruit.com/product/3395
Solid Machines Metal Knob	Adafruit	2	$7.90	https://www.adafruit.com/product/2056#description
3D printing prototype (1) fabrication cost	Ultimaker	1	$25.92	https://making.engr.wisc.edu/mini-mart/
3D printing prototype_board (2) fabrication cost	Ultimaker	1	$23.28	https://making.engr.wisc.edu/mini-mart/
3D printing prototype_lid (2) fabrication cost	Ultimaker	1	$22.96	https://making.engr.wisc.edu/mini-mart/
3D printing prototype_board (3) fabrication cost	Ultimaker	1	$37.92	https://making.engr.wisc.edu/mini-mart/
3D printing prototype_lid (3) fabrication cost	Ultimaker	1	$16.00	https://making.engr.wisc.edu/mini-mart/
3D printing prototype_lid (4) fabrication cost	Ultimaker	1	$18.32	https://making.engr.wisc.edu/mini-mart/

Super Glue	Pacer	1	$1.15	https://making.engr.wisc.edu/mini-mart/
Arduino Mega	Elegoo	1	$22.00	https://making.engr.wisc.edu/mini-mart/
Large Breadboard	Adafruit	1	$3.00	https://making.engr.wisc.edu/mini-mart/
Led bulbs	Adafruit	16	$4.00	https://making.engr.wisc.edu/mini-mart/
Female to male Arduino wires	Adafruit	40	$2.00	https://making.engr.wisc.edu/mini-mart/
Heat Shrink	Eventronic	9	$0.90	https://making.engr.wisc.edu/mini-mart/
Epoxy	Hardman	5	$7.50	https://making.engr.wisc.edu/mini-mart/
LED Strip	Adafruit	2	$25.00	https://www.adafruit.com/product/3919?gclid=CjwKCAjww5r8BRB6EiwArcckCzEIg95MquQekbTMIV_LZ4VwndfflJ-GjxrnGvsVQTvlRloZGAF2jxoCVIoQAvD_BwE
Bright White 5mm LED (25 pack)	Adafruit	1	$6.95	https://www.adafruit.com/product/754
Total	$254.65			

C. Testing/Experimental Data:

Table 2. Comparing the initial qualitative test results to the final qualitative test results, each row evaluates the same topic.

Initial Test	Final Test
Model has to be connected to personal laptop through USB to obtain power	Model has to be connected to personal laptop through USB to obtain power
Grey PLA produces a shine that distracts the viewers eyes from the LED lights, Black PLA would increase visibility of the LEDs	Black PLA contrasted well with the LEDs and made the front face of the model easier to see on the projected screen
Electronic display needs to be roughly 4 times larger than the previous model because display was very hard to read on the projected screen	Display screen was large enough to produce clear and easy to read values
Red and dark colored text was difficult to view on a black display screen	The text on the display was very visible and easy to read against the contrasting background
Green LEDs do not display well under the document camera and make the alveoli difficult to understand	LED lights and LED flex strip are easy to see on the projection
Scratches on the PLA baseboard are very apparent under the document camera	Baseboard has a clean finish and is not distracting to the viewer
Previous model alveolus is too complex and difficult to understand	Labels made the alveolus and capillary representation intuitive and easy to understand
Overall prototype dimensions (17.24cm x 17.24cm) are too small to have model well spaced out	Overall prototype dimensions (22.86cm x 21.59cm) fit well on the projection screen
The V and Q buttons only had values 1-5	The V and Q knobs ranged from values 0.00-100.00

Table 3. Comparing displayed values of V/Q ratio and P_aO_2 (calculated by code) to values calculated manually.

V Value (L/min)	Q Value (L/min)	V/Q Ratio Displayed	P_aO_2 Displayed (mmHg)	V/Q Ratio Calculated	P_aO_2 Calculated (mmHg)
90.00	100.00	0.90	101.84	0.9000	101.8412
6.00	37.00	0.16	50.42	0.1622	50.4199
29.00	56.00	0.52	82.14	0.5179	82.1384
59.00	100.00	0.59	86.86	0.5900	86.8567
6.00	74.00	0.08	43.33	0.0811	43.3342