Water Displacement Spirometer

BIOEN 327 E

Term Project Final Report

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Introduction

Clinical or Scientific Need
A spirometer is a medical device used by physicians, patients and researchers to observe lung functionality. Common measurements include inspiratory and expiratory volumes, ventilation patterns, and abnormal lung behavior. Table 1 describes how some of these measurements are defined. Physicians often study these measurements to analyze if patients have pulmonary abnormalities such as asthma, apnea, hypoventilation, hyperventilation, and dyspnea. Spirometry is a crucial, simple test that can diagnose lung diseases in their early stages. In addition, there are also incentive spirometers that help patients work on improving their respiration after surgery or lung illnesses such as pneumonia. They do so by motivating patients to take longer, deeper breaths. Some of these incentive spirometers do not take measurements.

Measurement	**Description**
Vital Capacity	Volume of air that is blown into a spirometer after maximum inhalation and expiration.
Tidal Volume	Volume of air expired or inspired when breathing normally
Inspiratory Reserve Volume	Volume of air able to be inspired after a tidal inspiration
Expiratory Reserve Volume	Volume of air able to be expired after a tidal expiration
Residual Volume	Volume of air remaining in the lungs after forced expiration
Functional Residual Capacity	Volume of air remaining in the lungs after a tidal expiration
Forced Expiratory Volume	Volume of air expelled in one second during rapid expiration

Table 1. Descriptions of common respiratory measurements recorded by spirometers

Existing Products
Current spirometers used in the clinics can range from $5 plastic incentive spirometers to $2500 digital, hand held spirometers[1]. Incentive spirometers usually contain a ball or piston that moves up the tubing when the user blows into the mouthpiece as shown in Figure 1. The user then tries to get the object to move higher than the previous expiration, which indicates more volume expired. Figure 2 is an example of a digital spirometer. Most digital spirometers contain a disposable tubing where the user blows into. Leaflets are often found inside the tubings which spin and take measurement as air flows in. The signal that is converted to digital signals and then amplified for display. The difference in pricing in digital spirometers is due to measurement capabilities, software functionalities, display and portability.

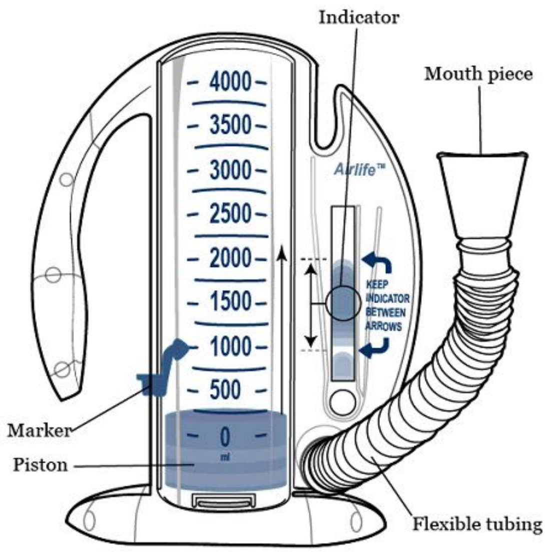


Figure 1. Diagram of an incentive spirometer[2]

Figure 2. Diagram of a digital spirometer[3]

Researchers and reviewers have found that digital spirometers used today are very reliable and accurate. Misdiagnosis of pulmonary diseases are rarely results of spirometry failure. Rather, they are caused by misinterpretation of spirometry data and underutilization of spirometers[4]. Our design is not commonly used as it is not portable and requires a large amount of fluid. However, compared to digital spirometers, our product is very cheap and easy to make, with data that is easily interpreted. This may be advantageous in global health settings as many areas do not have access to advanced technology or skilled physicians when pulmonary measurements need to be taken.

Design and Methods

Design Constraints

Limitations imposed on the purposed spirometer design included variables such as cost, portability, cleanliness, material, reusability, ease of use, safety, effective at all tests, and the testing environment. First and foremost the budget for this project was $100, which was to be spent on materials to build the device such as the bucket, trough, tube, gorilla glue and the pressure gauge. Other materials such as resistors, op amps and the breadboard were readily available in the lab already. Cleanliness is another important limitation imposed by both the FDA as well as ethical standards. To accomplish this the tube, which comes in contact with the mouth, is easily cleaned via disinfectant wipes or spray between the use of two separate individuals. The material used for both the tube, bucket, and trough must also be durable enough to withstand and not be deformed due to mild air or water pressure. Sturdy materials will allow for the spirometer to be both effective in one time use as well as reusable in the long term. In the testing of the spirometer it is also necessary to have a consistent environment with constant temperature and pressure in order to reduce confounding variables that may impact respiratory capabilities such as varying temperature.

Constraints including portability, ease of use, and effectiveness at all respiratory tests are all also very important to this project however are not completely fulfilled by the proposed design. While in theory the design is portable as it is all contained in a trough that is 42.5 cm by 35.5 cm by 11.25 cm, when filled with the water above the release hole and the bucket filled completely, the design contains over 12 liters of water which increases the weight of the apparatus and makes it difficult to transport easily. Ease of use is also impacted due to the water displacement from the bucket to the trough after each use, because depending on the volume of the displaced water, the water may have to be drained before another measurement can take place. However there is ease of use in the design in the sense that once the water is displaced, the change in pressure observed by the multimeter can be inputted to the Java program to complete a series of calculations and output the volume of air blown into the tube. Finally, the apparatus is not effective for inspiratory tests, as inhalation through the tube may lead to inhalation of water which violates safety standards.

Timelines for Our Work

<u>Proposed Timeline</u>

- 10/30 : 3D Printing Training
- 11/1 : Finalize goals, constraints and specifications
- 11/2-11/5 : Finalize model for spirometer including dimensions and acquire materials
- 11/6: Assemble spirometer
- 11/6-11/12 : Finalize equipment through user testing
- 11/13 : Finalize the oral presentation and written report
- 11/20 : Project Presentation / Project Paper due

<u>Actual Timeline</u>

- 10/30 : 3D Printing training
- 11/1-11/5: Finalized design and assembled sound-based spirometer
- 11/6: Tested viability of sound-based spirometer
- 11/7: Redesigned the entire project
- 11/8-11/15: Finalized design, acquired materials and assembled water displacement spirometer
- 11/16-11/20: Incorporated pressure gauge into system, worked on circuitry
- 11/21-11/26: Completed written report and oral presentation preparation
- 11/27: Project presentation/project paper due

Prototype Description

The prototype description is split into three sections: description of the final spirometer design, description of the final circuit design and description of the accompanying Java computer program.

- *Spirometer* -

The prototype works by assembling it as shown in the diagram below with the rubber stopper plugging the hole close to the rim of the bucket without the tube in it. Unscrew the water bottle top and place the funnel in the water bottle opening. Use the pitcher to pour water through the funnel and into the bucket. Fill to the Max Fill line. At which point firmly screw on the water bottle lid and fill the trough to the black line right above the top of stopper plugged hole. Release the stopper and connect the thin, long tube adhered to the bottom of the trough to the pressure gauge. At this point the prototype is ready for use. By blowing into the tube, practicing any expiratory test, water will be displaced from the bucket to the trough, increasing the pressure at the pressure gauge. This change in pressure can be read by recording the pressure before and after blowing through the tube, and can be read on the digital multimeter and inputted into the java program.

If for some reason the pressure gauge is not effective, the volume of the water displaced, equivalent to the volume of the air expired can be calculated by recording the new height of the water level in the bucket. If the water was originally at the max fill line, the change in height is equivalent to numerical value on the tape measure at the water level. This change in height multiplied by the cross sectional area of the base (pi*r^2 where r = 11.5 cm) will give an accurate value for air volume exhaled.

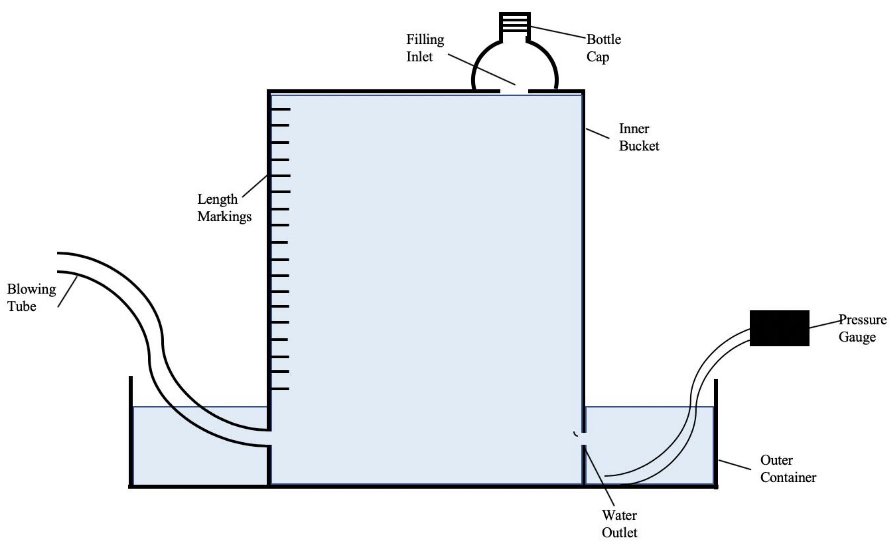


Figure 3. 2D sketch of final prototype with labels of each component

- *Circuit* -

The circuit used with the pressure gauge is a non-inverting amplifier using an op-amp. The pressure gauge has 4 prongs for connections to ground, positive output voltage, supply voltage, and negative output voltage. The positive output voltage is connected to the non-inverting amplifier to amplify the signal, increasing the sensitivity of the pressure gauge. The non-inverting amplifier uses two resistors, Rf = 47 Ω and Ri = 10 Ω. The outputted voltages are read using a multimeter, comparing the output to ground. A third resistor of resistance 1100 Ω is used to decrease the power supply voltage from 10V to around 2.38V, the needed voltage for the pressure gauge in order to supply it with 6 mA of current.

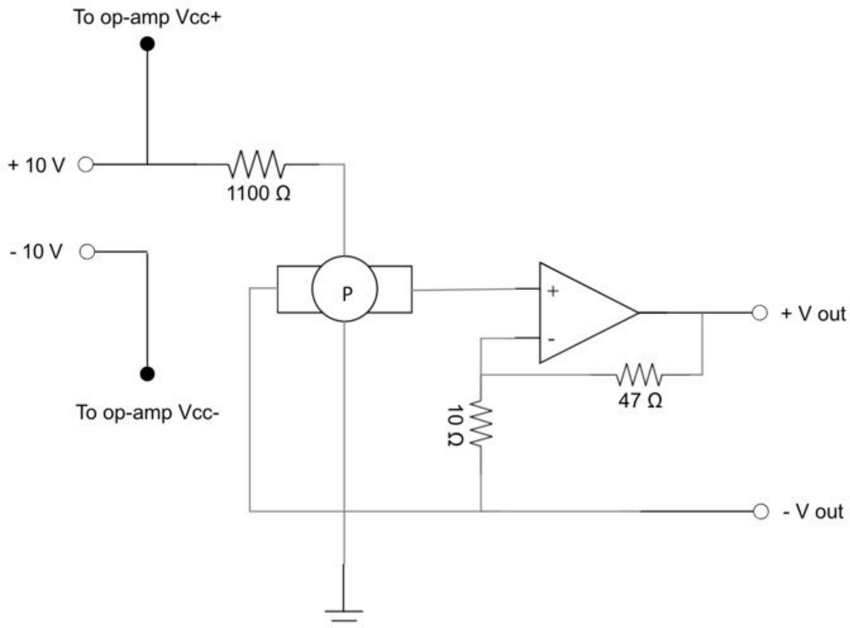


Figure 4. Circuit Diagram of Pressure Gauge and Amplifier

- *Java Program* -

A java program was created to expedite the calculations done after the measurements have been done. The initial and final voltages are first inputted. The program then uses a linear relationship between voltage and height to calculate the change in height of the bucket given the change in voltage of the pressure gauge circuit. This value is then multiplied by cross-sectional area of the bucket (0.0415 m^2) to get the volume of exhalation, and adjusted to ensure that the volume of exhalation is the volume at atmospheric pressure.

Specifications and Test Methods

The spirometer should perform in a fairly simple manner. The device should be able to measure total exhalation volume based on the voltage outputted from the circuit involving the pressure gauge. The spirometer design is relatively simple, as it can only measure total exhalation volume, compared to existing spirometers than can measure other important factors in respiratory function involving inhalation.

The spirometer was calibrated based on the change in height of the bucket. Initially, a relationship between the change in voltage reading and the change in height of the trough was going to be used in order to multiply the height by the cross-sectional area of the trough. However, the cross-sectional area of the trough is complex, so it was difficult to calibrate based on the change in height of the bucket. To find the relationship between the voltage and the height of the water within the bucket, ten measurements of voltage were taken by changing the height of water within the bucket. The voltage was used as the independent variable, and height as the dependent. From the graph, a linear formula was found, relating the voltage of the circuit and the height of the water within the bucket:

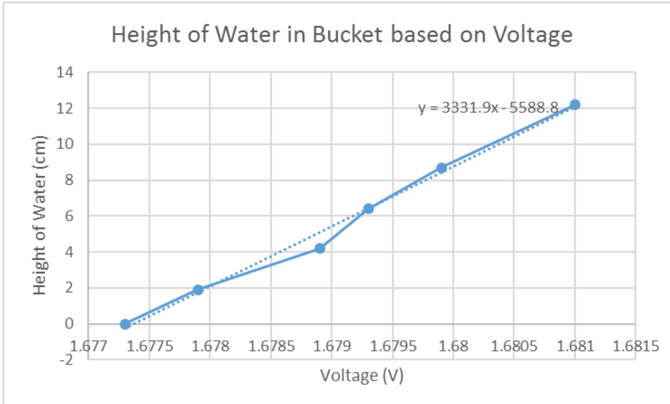


Figure 5. This graph displays the relationship found between the change in voltage from the pressure gauge to the change in height of the water

Thus the change in height could be found using the change in voltage by simply differentiating the linear relationship.

$h = height,\ v = voltage,\ dh = change\ in\ height,\ dv = change\ in\ voltage = |initial - final\ voltage|$

$$h = 3331.9v - 5588.8$$

$$\frac{dh}{dv} = 3331.9$$

$$dh = 3331.9dv$$

From there, volume could be calculated by multiplying the calculated change in height by the cross-sectional area of the bucket.

The volume at which the person breathes into the tube is at atmospheric pressure however the pressure of the air trapped in the bucket above the max fill line is at vapor pressure, this difference in pressure is the reason for the system not equilibrating when the plug is removed from the bucket with the water level in the trough above the hole. This difference in pressure will result in a small difference in the volume calculated by the pressure gauge as that calculates change in volume at vapor pressure. To account for this, the equation $P_1 V_1 = P_2 V_2$ is used to solve for volume at atmospheric pressure, where P_1 is atmospheric pressure, V_1 is the air volume at atmospheric pressure (desired value), P_2 is pressure at top of bucket calculated by $P_{atm} + \rho g h$ (where h = 0.17 m, g = gravity, and ρ = water density), V_2 is the air volume at the pressure at the top of the bucket.

To test the accuracy of the design, the calculated volume based on the reading of the pressure gauge and the volume calculated with the change in height of the water within the bucket are compared to values taken by a digital spirometer for the Vital Capacity volume. The volume obtained by the digital spirometer acts as a theoretical value for the volume measurement, while the experimental values of volume come from the calculation based on the output of the pressure gauge and the volume calculated via change in height . To determine whether the design is successful, the percent error can be calculated based on the theoretical and experimental values of volume mentioned previously. If the percent error calculated is less than 10% for the values averaged over multiple trials, then it can be determined that the design is successful.

Fabrication Procedure
The fabrication procedure is split into two sections: fabrication of the spirometer, and fabrication of the circuit involving the pressure gauge.

- *Spirometer* -
Fabrication of this device began with gathering all the components including a 12 liter bucket with a 11.25 cm radius, a 42.5 cm by 35.5 cm by 11.25 cm trough, a 0.8 cm diameter tube, a thin 1 meter long tube for the pressure gauge, plastic water bottle, gorilla glue, rubber stopper, funnel, water pitcher, sharpie and measuring tape. Before assembling any pieces two 0.45 cm diameter holes were drilled 3.5 cm from the top of the bucket on opposite sides. One hole will be used to insert the tube into the bucket and the other will allow for water to be released from the bucket once air enters. Another hole was drilled into the bottom of the bucket, in order for water to be added to bucket once it is glued to the trough. Gorilla glue was then applied to the top rim of the bucket and the bucket was glued down into the center of the trough. Gorilla glue was then added in between the rim and the base of the trough to ensure an air-tight seal. The plastic water bottle was cut 5.5 cm for the cap and glued around the hole on the bottom of the bucket that is now facing upward. The long thin tube, for the pressure gauge, was then glued down to the base of the trough around the bucket. The long thin tube is 1 m long and 30 cm of which were glued down and the other end was connected to the pressure gauge in the circuit. The gorilla glue was allowed to dry for 24 hours before any testing occurred. Finally the measuring tape was glued long the length of the bucket and a sharpie was used to create a max fill line for the bucket at the top of the measuring tape and a max fill line for the trough 1 cm above the unplugged hole 3.5 cm from the top of the bucket.

- *Circuit* -
A pressure gauge was obtained from Dr. Neils, and the data sheet for the pressure gauge was found. The pressure gauge requires a current of around 6 mA, and has an input resistance of about 475 Ω[5]. The voltage required for the pressure gauge was determined using Ohm's Law (V = IR). Using the actual input impedance of the pressure gauge (395 Ω), the optimal voltage supplied to the pressure gauge should be around 2.38 V. The pressure gauge has a sensitivity of 3.5 mV / kPa, and a maximum pressure reading of 1.5 psi. This maximum pressure reading was determined to not be an issue, because the pressure gauge would be under a maximum depth of water of around 24 cm. The pressure due to this water could be calculated by multiplying the height by density and gravity. The pressure value we calculated was 2347.33 Pa, or 0.34 psi, much lower than the maximum value the pressure gauge could read. Therefore the pressure gauge would satisfy the device's need. A circuit was designed to incorporate the output from the pressure gauge, amplifying it to receive a stronger signal, therefore a stronger sensitivity. When designing the circuit, the resistor values were difficult to find in order to get a strong signal without saturating the op-amp. Resistor values were determined based on estimating the gain needed, finding resistors that match the gain, and repeating with different resistor values until a strong signal with high sensitivity was obtained. After the amplification signal was obtained, a subtractor using an op-amp and a second power supply was attempted. The subtractor's purpose would be to subtract the initial voltage reading from the final voltage reading, so the final voltage reading would represent the voltage difference due to the change in height rather than the final voltage due to pressure of the water at the final height. Thus, the subtractor would serve as a tool

to ‘zero’ the signal from the pressure gauge. However, this subtractor design was determined to be too difficult and time-intensive to complete given it’s non-essential function. A simple Java program was coded to expedite the process of calculating the volume from the voltage. The two voltages (initial and final) are first inputted into the program. The program then calculates the change in height based on the linear relationship found and the change in voltage, and then multiplies by the cross-sectional area of the bucket (0.0415 m^2) to find the volume exhaled.

Results and Discussion

Test results and evaluation/discussion

The original spirometer prototype which was envisioned for this project was a device similar to a kazoo, in which a pvc pipe, with a small hole in it, was covered with a plastic film. The idea behind this design was that the volume could be calculated using the equation Q = v*A where we calculated the flow volume from the cross sectional area and velocity. To achieve this, it was hypothesized that the velocity could be calculated from a model reliant on a microphone picking up different frequencies and amplitudes of the sound as air hits the film. However this iteration of the project was unsuccessful because changing the velocity of air going through the tube was evidently not related to the frequency of the sound picked up by the microphone.

In the second iteration the spirometer based upon water displacement was created, which is described in the pages above. The Vital capacity of Subject 1 was taken for three trials using the digital spirometer as well as the water displacement spirometer prototype, on the same day with constant temperature and pressure. When using the prototype the volume was calculated using both the pressure gauge and java program as well as the change in height multiplied by the cross sectional area of the bucket. Both of these values were adjusted to represent the volume of the air at atmospheric pressure. The data for the digital spirometer is recorded in Table 2 and the measurements regarding the change in pressure and height from the water displacement spirometer is recorded in Table 3, which are then computed to volumes which are recorded in Table 4. Table 5 then represents the average volume, from the three trials, for each condition.

Vital Capacity (Exhale)	Trial #1	Trial #2	Trial #3
Digital Spirometer	2.63 L	2.60 L	2.65 L

Table 2: Vital Capacity volumes taken by the digital spirometer for subject 1.

	Trial #1	Trial #2	Trial #3
Change in height (cm)	5.8	6.0	6.0
Initial Pressure (mV)	1.7970	1.7977	1.8001

Final Pressure (mV)	1.7987	1.7994	1.8018

Table 3. Includes the physical measurements recorded from the three trials testing the spirometer prototype.

Vital Capacity (Exhale)	Trial #1	Trial #2	Trial #3
Volume calculated by height measurements	2.44	2.53	2.53
Volume calculated by pressure measurements	2.43	2.49	2.46

Table 4: Vital Capacity volumes calculated using the pressure gauge and java program versus the volume calculated for the same exhale using the change in height measured directly.

	Digital spirometer	Pressure gauge	Height measurements
Average Volume Exhaled	2.63	2.46	2.5

Table 5: Averaged volumes for the three trials are represented here for each Vital Capacity measurement type.

It can be seen from the data that the volumes measured by the digital spirometer were very similar to that of the water displacement spirometer. The volume from the water displacement spirometer calculated using the observed change in pressure had a 6.46% error when compared to the theoretical value given by the digital spirometer where as the volume calculated from the height measurements had a 4.94% error. This error could be coming from a few different avenues such as non constant radius, leakage due to imperfectly sealed gorilla glue, and the linear equation to calculate pressure. In calculating the volume for the digital spirometer the height, measured directly or through the found relationship between height and pressure, is multiplied by the cross-sectional area of the bucket. However, the bucket radius is not completely constant as the base of the bucket is 11.5 cm however the top is 13.5 cm. As both calculations make use of the height multiplied by the cross-sectional area this error therefore impacts both the pressure gauge calculated volume as well as the volume calculated by direct height measurements. This change is not accounted for in the equation and as a result may underestimate the volume expired. Unfortunately, from use it was found that the seal between the water bottle and bucket was not completely airtight and as a result air would leak into the bucket at the seal resulting in very slow equilibration of the water between the bucket and the trough. This leakage allowed for increased volumes of water to be released when taking measurements, however due to the slow rate at which the water was equilibrating it is unlikely that this significantly impacted the data. In order to calculate change in height based upon change in pressure, a linear relationship between the two is used. While this linear fits the data well there are outliers that show that the circuit as well as the linear fit isn't completely accurate with an $R^2 = 0.9905$, therefore resulting in a small difference in the calculated volume. This source of error only contributes to error in the volume calculated by the pressure gauge which may contribute to the larger percent error for this volume in comparison to that taken directly by height measurements.

COMSOL model

COMSOL was used to predict the behavior of the water inside the bucket if someone were to breathe 5 L of air into the spirometer over 5 seconds. Specifically, COMSOL was used to model the pressure of water in the bucket over time.

A 2D axi-symmetrical cylinder was created to represent the water in the bucket at the start, with a radius of 11.5 cm and a height of 23.5 cm. A very short cylinder was created on top of the water to create the air pocket at the top of the bucket at the beginning of the experiment, with a radius of 11.5 cm and a height of 1 cm.

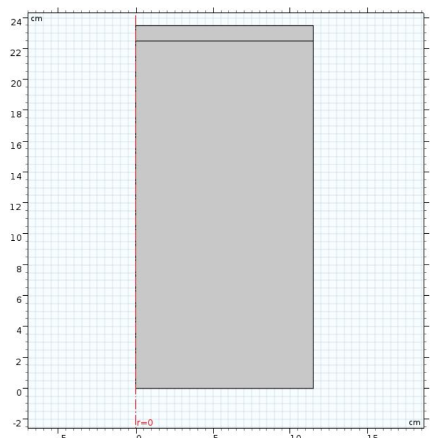
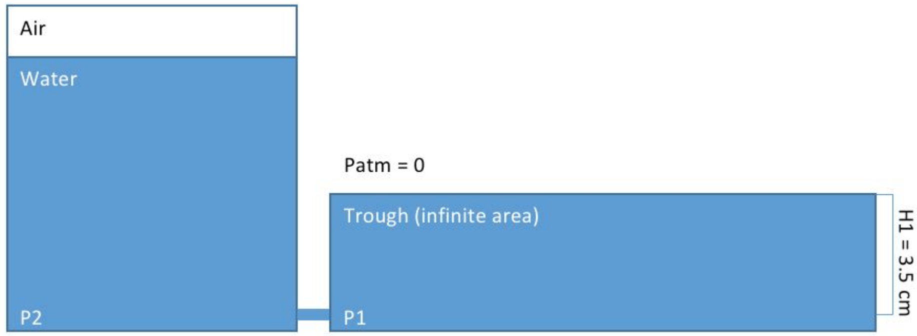


Figure 6. Geometry of Modeled Spirometer (2D Axi-Symmetrical Cylinder)

The Deforming Geometry physics model was used on the interface between the air and water in order to increase the volume of air over time and simultaneously decrease the volume of water over time. The velocity of deformation was set at - 0.02407 m/s in the z-direction (cylindrical coordinates). This was calculated by dividing the Q (flow rate of air in) by the cross-sectional area of the bucket. Q is defined as Volume per Time. In this case, 5 L of air is entering over 5 seconds, so 1 L/s, or 0.001 m^3/s.

The Laminar Flow physics model was used to simulate the water flow within the bucket. The inlet had a velocity of 0.02407 m/s, because this is how fast the height of water will change. Although no actual water is being inputted into the spirometer during exhalation, water needs to be simulated as entering at 0.02407 m/s because the laminar flow physics model is separate from the deformed geometry physics model, and the initial water should move down with the interface between the air and water. The outlet was defined as having a pressure of 342.32 Pa (relative pressure). This was calculated based on the pressure of the outlet hole of the bucket (as can be seen in the diagram). The height of the trough was assumed to be 3.5 cm above the hole, and the cross-sectional area of the trough is infinite, so the height does not change. This can be assumed because the movement of water in the bucket should not depend on a slight increase in height of the trough, and it is not of interest in this experiment.



P1 = Patm + pgH1 = pgH1

P2 = P1 = pgH1 = (997 kg/m^3)(9.81 m/s)(3.5 cm) = 342.32 Pa

Figure 7. Calculation of Pressure at Bottom of Bucket

This was simulated as a time-dependent study, looking at how the pressure of the bucket changes over time. According to how the spirometer is expected to act, there should be no excess pressure in the bucket after 5 seconds, as the air pushes down, and the water flows out of the bucket into the trough. Results are shown below.

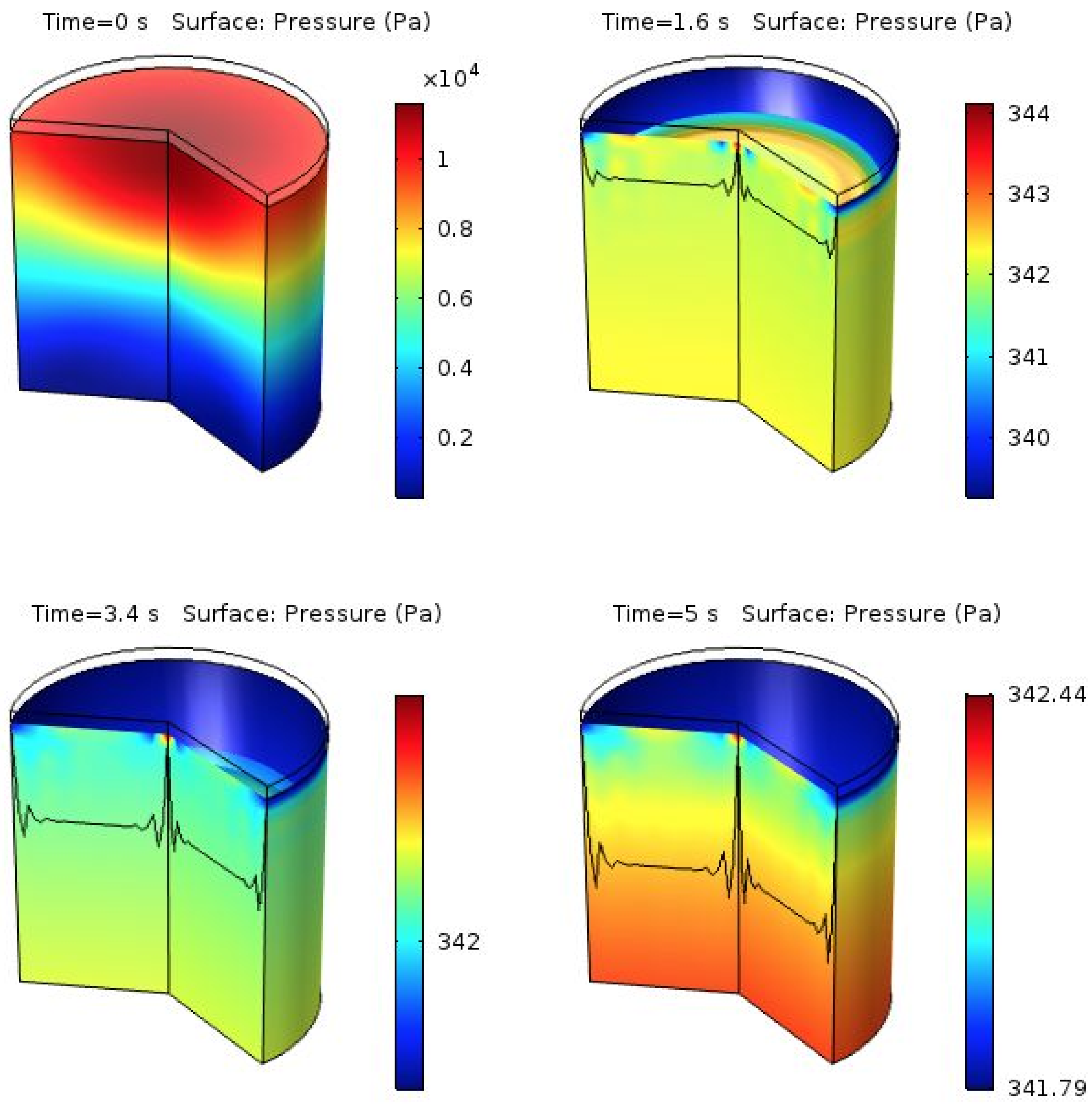


Figure 8. Results of COMSOL Simulation of Water Displacement

As one can see, at time t=0, there is a large pressure gradient due to the height of the water. This is to be expected, as pressure is proportional to depth. As the study begins, and the air-water interface moves down, the pressure of the water equilibrates as water is moving out of the bucket. By the end of the 5 seconds, the water is equal in pressure (within reasonable margin). This is the result expected, and confirms the spirometer design works as expected. As the air-water interface moves down, pressure of the water increases and pushes the water out into the trough. Because of this water movement, when air flow stops, the pressure of the water remaining in the bucket should be relatively the same, as there is no pressure pushing the water out into the trough. This can be seen in figure 7, time t=5 s. The pressure is relatively the same (around 342.32 Pa) within the section of water below the air-water interface (shown as the black line). Therefore the COMSOL allowed us to correctly simulate the water flow as 5 L of air enters over 5 seconds.

Recommendations for future work

Due to the limited time, scope, budget and resources of this project, there are many additional features and improvements that can be added to the current product. A functional addition is an automated water refilling system that fills up the center bucket with water after each measurement. This feature will limit the set up time for each use. This can be implemented with an additional tube that connects from a faucet to the inlet with a stopper system that opens up between measurements. Another possible addition to the design is a mechanism that disposes some water in the outside container between measurements so it does not overflow. This can be done with an addition of a tubing and stopper inserted into the container. Finally, some user studies can be performed in low-resource settings to gauge the improvements that can be done to the device as this low cost product is most likely to be used in that environment. The device can be further improved after learning shortcomings such as measurement types, accuracy and portability that the physicians need in those settings.

Acknowledgements

- UW Department of Bioengineering
  - Dr. Neils
  - BioEn 327 TA's: Max, Nick, Jack, Renae
- The MILL makerspace

References (information that may not be found in undergraduate textbooks)

1. Developments in Handheld Spirometry | RT. (2017, November 1). Retrieved November 23, 2018, from RT Magazine - For Decision Makers in Respiratory Care
2. How to Use Your Incentive Spirometer. (2017, April 18). Retrieved November 23, 2018, from Memorial Sloan Kettering Cancer Center
3. Digital Spirometer | Respiratory Spirometer | MIR Spirobank. (n.d.). Retrieved November 23, 2018, from QuickMedical - Medical Equipment and Supplies
4. Hegewald, M. J., Gallo, H. M., & Wilson, E. L. (2016). Accuracy and Quality of Spirometry in Primary Care Offices. *Annals of the American Thoracic Society, 13*(12), 2119-2124. doi:10.1513/annalsats.201605-418oc
5. 10 kPa Uncompensated Silicon Pressure Sensors | MPX10 Series. (2008, Oct.). Retrieved November 23, 2018, from NXP Semiconductors N.V.

Self-evaluation

Our group did not collaborate with another group. Within our group, the group members worked well together. We distributed the work evenly and communicated well. The group members used resources all around campus to complete the project. Members were able to work on the parts of the project that they had expertise or were interested in.

Report Distribution

Eric: Clinical/scientific need, existing products, timeline, prototype description (figure 3), future work, acknowledgements, references, self-evaluation

Anna: Design Constraints, Prototype Description (spirometer), Fabrication Procedure (spirometer), Test results and evaluation/discussion, references, self-evaluation

Tom: Prototype description (circuit, java program), Specifications and Test Methods, Fabrication Procedure (circuit), *COMSOL* model, references, self-evaluation, appendix

Appendix

```
import java.util.*;

public class Spirometer {

   public static final double SLOPE = 3331.9; //change in height per change in volume
   public static final double RADIUS = 11.5; //radius of bucket to calculate area

   public static void main(String[] args){
      Scanner console = new Scanner(System.in);
      System.out.print("Initial Voltage: ");
      double v1 = console.nextDouble();
      System.out.print("Final Voltage: ");
      double v2 = console.nextDouble();
      System.out.println("Volume of Exhale: "+ calculateVolume(calculateHeight(v1, v2))/1000 + " L");
   }

   //calculates the volume of exhalation based on height
   public static double calculateVolume(double height){
      return Math.PI * height * RADIUS * RADIUS;
   }

   //calculates the change of height based on the inputted voltage values
   public static double calculateHeight(double v1, double v2){
      return 3331.9 * Math.abs(v1 - v2);
   }
}
```