Human Respiratory Mechanics Demonstration Model

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ABSTRACT

Currently existing human respiratory mechanics models are limited in their abilities to demonstrate effects of the rib cage movement on alveolar and intrapleural pressures and do not display any pressures. We have developed a model that can be used in both large and small classroom settings. The model also contains digital pressure displays and computer integration for real-time pressure data to visually demonstrate pressure changes that correspond to the different phases of breathing. Moving the diaphragm and rib cage causes a volume change which results in pressure changes visible on the digital sensors and computer display. Device testing affirmed the model's ability to accurately demonstrate pressure changes in proportion to physiological values. Classroom testing showed improved understanding of respiratory concepts in 369 surveyed students.

INTRODUCTION

Our goal was to design and build an adequate mechanical model of human respiratory physiology for class instruction. The model demonstrates pressure differences between alveolar and intrapleural spaces. It also demonstrates the expansion of the thoracic cavity by the rib cage and diaphragm, displaying a three dimensional expansion. The device is small enough to use with a document camera or demonstrate close-up with smaller class sections.

Though simple homemade models and basic commercial Plexiglas® lung models are available, they have short life-spans and parts that are difficult to replace. Currently available models do not display pulmonary pressures, making it difficult for students to visualize the forces driving gas exchange between the lungs and the atmosphere. No currently available physical models illustrate the expansion of the rib cage. Though most of the lung's volume change is due to the diaphragm's contractions, the rib cage movement contributes between 5 and 42 percent of the lung's total volume change (Faithfull, 1979).

To determine the efficacy of our model, a research plan outlining a series of surveying and analysis procedures was conducted after receiving approval from the Social and Behavioral Sciences Institutional Review Board (SBS IRB). Additionally, a series of physical tests were done to ensure the pressures generated could effectively demonstrate the actual mechanics of the respiratory system. The device is compatible with BioPac®, a commonly used physiology software package which we customized to graph alveolar and intrapleural pressures in real-time. When a BioPac® system is unavailable, the model's digital pressure sensors will still display the instantaneous pressures generated.

DESIGN, FABRICATION, & COST

Requirements

The device should contain both intrapleural and alveolar pressure displays to demonstrate pressure relationships during inspiration and expiration. To accommodate different classroom settings, the model should be functional in a small classroom as well as a large lecture hall. Because document cameras are frequently used in lecture halls to present information to students, the device must fit under a typical 13x17" document camera. The device should be compatible with BioPac® software and operable by a single user. The container housing the lungs should be transparent such that the inner components of the model are visible. To allow for transport, the device should weigh no more than twenty pounds. One of the major concerns with previous models is the difficulty of replacing components. Therefore, components under frequent stress should be made more durable and easily replaceable.

Mechanical Design

The respiratory demonstration model consists of a sealed transparent chamber in which pressures can be changed using the piston and elastic membranes to inflate and deflate balloons representing the lungs (Figure 1). The container, which corresponds to the thoracic cavity, was constructed of transparent polycarbonate to allow a clear view of the lungs. Polycarbonate was chosen over acrylic and other transparent materials for ease of construction. The container was designed as a rectangular box (7.25"x7.25"x10") with a curved front panel. The box provides a flat back such that the model can be used on a document camera or overhead projector while the curved front panel allows a wider viewing angle. In order to mimic the intrapleural space, a constant negative pressure must be maintained within the container. A plug in one side panel of the model can be removed to apply a residual negative pressure to reflect functional residual capacity in vivo. In addition, the plug can be removed after lung inflation to demonstrate pneumothorax.

Volume changes are produced by two distinct methods: a diaphragm piston and rib membranes. These two different mechanisms were selected to clearly differentiate between rib and diaphragm effects. In the body, the diaphragm muscle provides at least 58 % of the lung's volume change, with rib expansion contributing the rest. Similarly, our model's diaphragm piston provides a larger volume change than the rib membranes. The 5" diameter diaphragm piston is located on the bottom of the model and mimics the function and location of the diaphragm muscle in the human body. By pulling out the piston, the volume in the container increases, causing the pressure inside to decrease and the lungs to expand. The piston can be removed to provide access to the interior of the container for part replacement when needed. The rib membranes represent chest expansion and are located on both side panels of the model. Sections of gum rubber, selected for its durability and elasticity, are stretched over holes in the side panels that increase the internal volume when pulled outwards. The gum rubber is attached to the panels by a flange which was screwed on to create a leak proof seal while allowing easy replacement of the membrane material. The small hole in the container beneath the membrane side panel allows air flow when the rib membrane is stretched, but keeps it from collapsing inward when negative pressure is created inside the container. Handles are attached to both the piston and rib membranes for easy manipulation by the user.

Elastic lungs are located within the model chamber and inflate or deflate according to the internal volume and pressure changes. Standard latex balloons were selected for the lungs because they are easy to replace, readily available, and have minimal leakage due to their seamless design. Two balloons were clamped onto a Y tube fitting whose third port passes through the container top via a rubber stopper and exposes the balloons to atmospheric pressure.

Two digital pressure sensors were attached to the top of the model and measure both intrapleural and alveolar pressures. The intrapleural pressure sensor is exposed to the internal space of the container by threading it directly into the top panel. The alveolar pressure sensor threads through the top panel, as well, and was attached to a tube that passes through the Y-fitting and into one of the balloons. Although expensive, electronic compound pressure gauges with displays were selected for several reasons. First, a compound gauge was needed to measure the negative and positive pressures created in the model. Second, sensitive gauges were required to measure the small (~0.2 psi) pressure changes. Third, electronic sensors were necessary so the model could interface with Biopac® software to provide real-time graphs. Finally, digital displays are required so that the model can stand alone and function without the computer interface. The sensors are powered independently by a power adaptor that can be plugged into any 110-120 volt wall outlet.

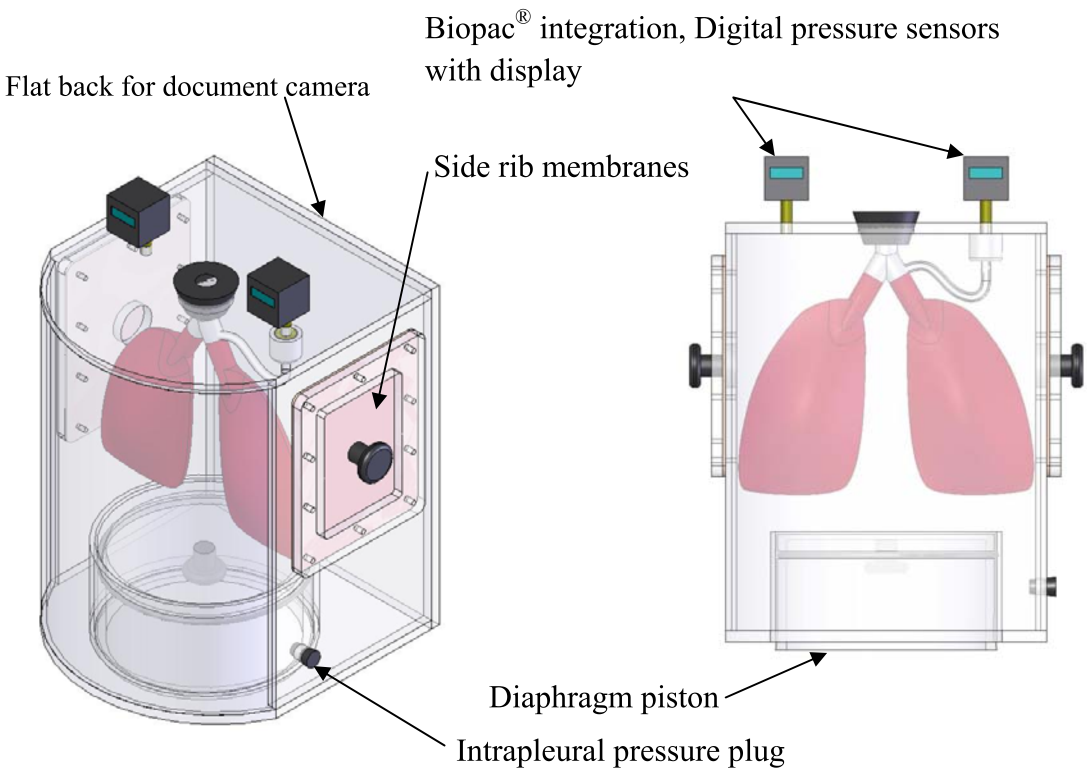


Figure 1. A SolidWorks 3D representation of the respiratory model. Main features include a flat back for a document camera, digital pressure sensors, side rib membranes, diaphragm piston, and intrapleural pressure plug.

Electrical Design

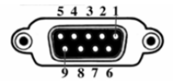
Two digital compound pressure sensors (PSA-C01, Autonics), set to range from ±10kPa, were used to measure the pressure changes occurring within the alveolar and intrapleural spaces. Both sensors interface with the BioPac® MP30 or MP35 analog-to-digital converter by a 9-pin female D-sub connector (Figure 2, 3). Pin 2 was soldered to the orange analog positive voltage wire on the pressure sensor, and pins 3 and 4 were soldered to the sensor's blue ground wire and to the power supply's ground wire (Figure 4).

Figure 2. BioPac® MP30 analog-to-digital converter.

MP Input — *Front Panel*

CH 1, CH 2, CH 3, CH 4

9 PIN FEMALE DSUB (1 of 4)



Pin	MP35	MP30
1	Shield drive	Shield drive
2	Vin+	Vin+
3	GND	GND
4	Vin−	Vin−
5	Shield drive	Shield drive
6	+5 V (100 mA max aggregate)	+5 V (50 mA max)
7	ID resistor lead 1; I^2C SCL	ID resistor lead 1 (+5 V)
8	ID resistor lead 2; I^2C SDA	ID resistor lead 2
9	−5 V (100 mA max aggregate)	−5 V (50 mA max)

Figure 3. BioPac® D-Sub pin connections (biopac.com).

Additionally, a 12Ω resistor was soldered in parallel between pin 2 on the D-sub connector and the GND wire on the pressure sensor to reduce the voltage input to the MP30, which was designed to handle a maximum of 130 mV input. The brown wire on the pressure sensor was soldered to the 15V power supply. After connecting all of the wires, D-sub housing units were placed around the connectors to enclose the wires (figure 5).

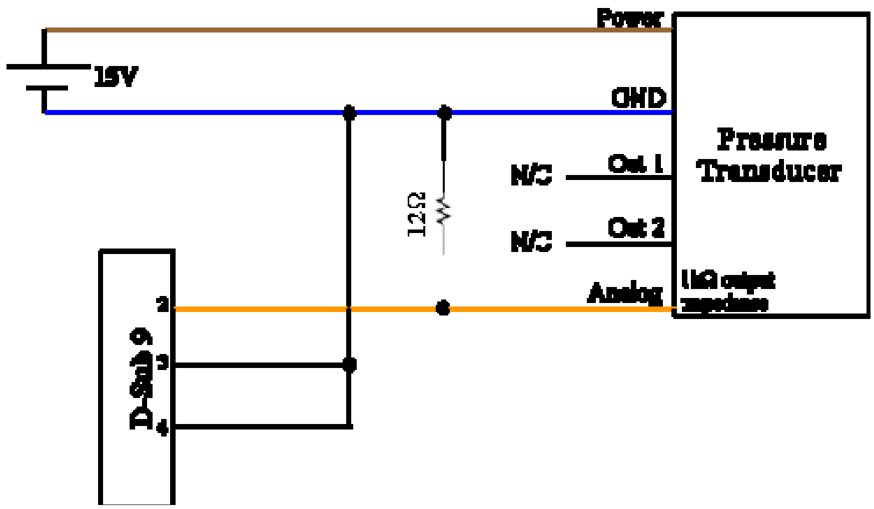


Figure 4. Electrical connections schematic.

To set-up the BioPac® data acquisition software, the two sensors were plugged into channels 1 (alveolar) and 2 (intrapleural). The data acquisition time (under MP30 → Set Data Acquisition Time) was set to 5 minutes to ensure a long enough period of time for demonstration purposes. Both channels were scaled (under MP30 → Set Up Channels → click the wrench icon to the right of each channel → Scaling) so 59.3 mV = +10 kPa and 11.9 mV = -10 kPa. Gain was set to x100 and the offset was changed as necessary to make sure a 0 kPa reading on the digital pressure sensor corresponded to a visual display of 0 kPa on the BioPac® plot. Plot displays were changed under the Display menu to display the alveolar and intrapleural graphs separately.

Figure 5. Respiratory model connected to BioPac® system.

Cost

Project costs totaled $499.08 for two models: an initial prototype and final product. This includes several overestimates, due to packaged quantities and unused materials, as well as several underestimates due to donated items. This price also includes initial prototype costs which would not be necessary in constructing a single respiratory model.
The projected costs for constructing one model would be $430.41. A bill of materials with the estimated costs is found in Appendix A. Primary expenses are the pressure sensors and the acrylic and polycarbonate stock materials, which compromise 56% and 31%, respectively, of the total price. Reducing material waste and utilizing bulk quantities would reduce costs.

TESTING

Physical

The most important aspect to ensuring the physical viability of our device is ensuring the strength of the seals around the cut polycarbonate pieces. We tested the efficacy of the seal in a variety of different ways. Dunking the prototype into a sink filled with tap water allowed us to assess the overall effectiveness of the seals. Water leaking into the prototype indicated a problem area. Small amounts of water were poured into the prototype and the device was rotated to run the water along the sealed edges. Holes in the seals were indicated by water leaking out through them.

While the dunk testing was efficient for large scale leak testing, we also tested the seals using dry ice. A weigh boat containing dry ice was placed within the model and sprayed with water to produce a cloudy vapor. The piston was then replaced and thrust inwards to determine if and where the vapor was leaking out of the model. To examine the effectiveness of the seals on a much smaller scale, we rubbed soap along the seams and wet them slightly. When using the piston, soaped areas bubbled at areas where leaks occurred.

Periodically throughout construction we tested the alveolar and intrapleural pressures generated by the piston and rib membranes separately. The device was connected to a high sensitivity pressure transducer through the pressure sensor attachments at the top of the device. The measured pressures were recorded and graphed using LabView software. The alveolar and intrapleural pressures were input separately and three tests were run for each. The pressures due to the piston and rib membranes were assessed separately as well as together, resulting in the three separate tests for each pressure output.

Software

Leak testing of our device was done by examining the signal displayed using BioPac®. If the device was perfectly sealed, the intrapleural pressure would always be less than or equal to zero as the pressure in this space should never be positive. If the calibrated signal for the intrapleural space rose above 0 kPa, this would mean a leak existed somewhere in the device.

Educational

The most important aspect of our design was verifying that our model improved student understanding of respiratory physiology. In order to measure the instructional efficacy of the prototype, a method of surveying Physiology 335 students at the University of Wisconsin-Madison was developed. Because students in undergraduate physiology classes will be the primary beneficiaries of the finished device, it was important to determine if their learning improved with use of the prototype. Prior to surveying any students, a protocol was submitted to the Social and Behavioral Sciences Institutional Review Board (SBS IRB). This protocol was approved for SBS IRB exemption because the proposed study only involved surveying college students and posed no risk to the participants. Each student was provided with a written consent form, which allowed them to choose to participate in the study. A survey of 369 Physiology lab students was conducted.

The study we developed took place in two parts: pre-surveys and post-surveys. The physiology lab students were divided into control and experimental groups based on their lab sections. There were 151 students in the control group and 218 students in the experimental group. All students were given a pre-survey in their lab, during regular class time, to test their knowledge of respiratory physiology concepts before the material had been covered in lecture or lab experiments.

Two weeks after the pre-surveys, the students received post-surveys containing the same questions as the pre-survey. In the control group, the lab instructor gave a short introduction to the respiratory lab explaining basic respiratory pressures and volumes. All of the material present on the post-surveys was mentioned during the introduction and on the pre-survey. After the introduction, students were given the post-survey on respiratory physiology concepts. In the experimental group, the lab instructor gave the same lab introduction, but added a breathing demonstration using our model. The pressure changes in the intrapleural and alveolar spaces due to the diaphragm and rib membranes were graphed in real-time using BioPac® software and displayed on a projector. The response of the lungs after a puncture wound to the thoracic cavity (known as pneumothorax) was also demonstrated using our model. All of the material that was present on the surveys was either mentioned during the introduction or shown with our model. After the introduction and demonstration, students were given the same post-survey as the control group, with additional questions specific to our prototype. The results of the pre- and post-surveys were tabulated and compared. A perfect survey score, 6/6 points, would indicate thorough understanding of the material.

RESULTS

Physical

After the final construction of the prototype, the device was tested by using a high sensitivity pressure transducer to determine the pressures generated by the rib membranes, piston, or both. The pressure sensors were removed from the prototype for the testing. The transducer was connected in place of the intrapleural sensor connection at the top of the prototype, and the pressures from the movement of the piston, rib membranes, and both were recorded (Figures 7, 8, 9). Production of negative pressure changes was most important because the human respiratory system maintains negative pressures in both the alveolar and intrapleural spaces.

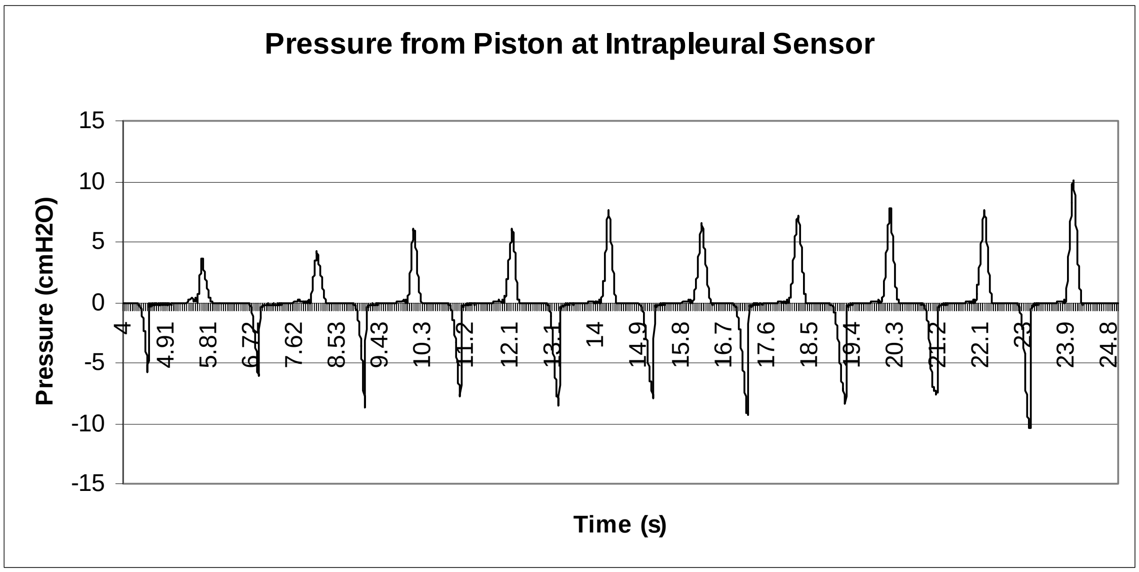


Figure 7. Graph of pressure generated by piston movement as recorded by the intrapleural sensor.

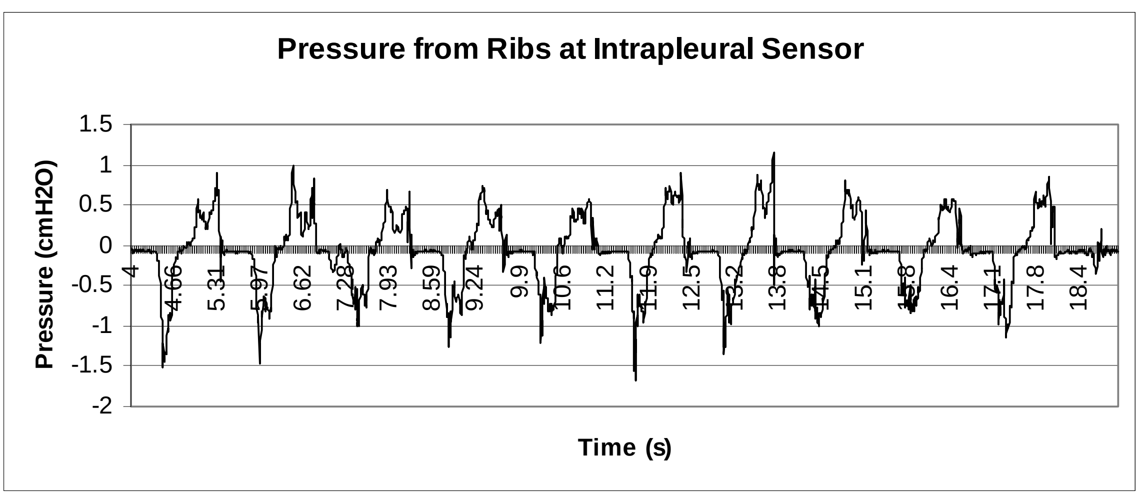


Figure 8. Graph of pressure generated by rib membrane movement as recorded by the intrapleural sensor.

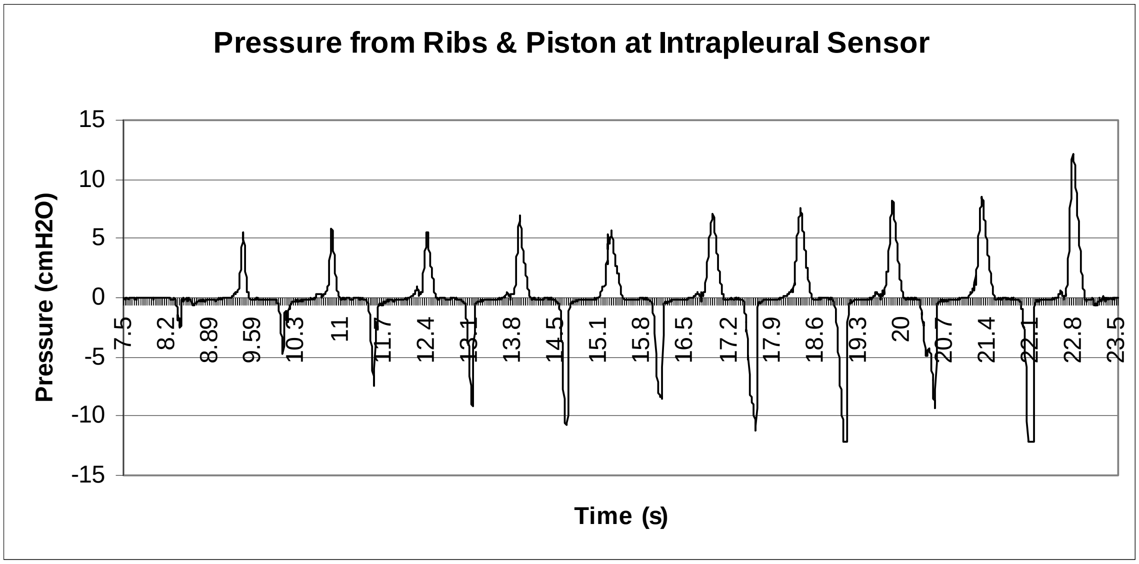


Figure 9. Graph of pressure generated by rib membrane and piston movement as recorded by the intrapleural sensor.

The same procedure was followed for recording pressure through the alveolar sensor connection (Figures 10, 11, 12). The negative pressure generated by the piston alone and both the rib membranes and piston together exceeded the minimum value allowed by the pressure transducer. Therefore, those recorded graphs do not go below -12.16 cmH_2O.

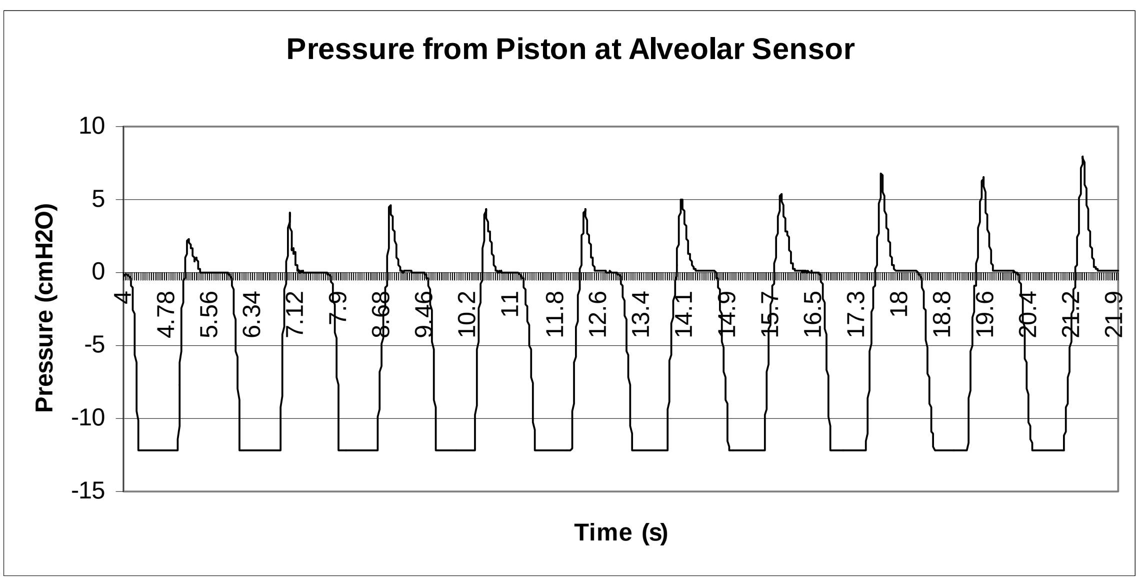


Figure 10. Graph of pressure generated by piston movement as recorded by the alveolar sensor.

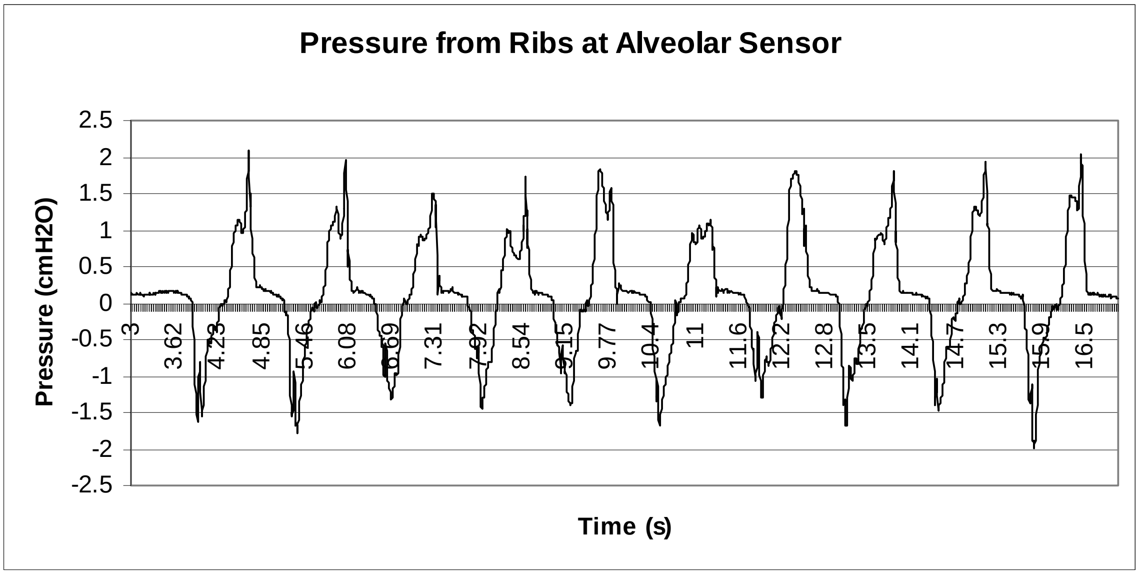


Figure 11. Graph of pressure generated by rib membrane movement as recorded by the alveolar sensor.

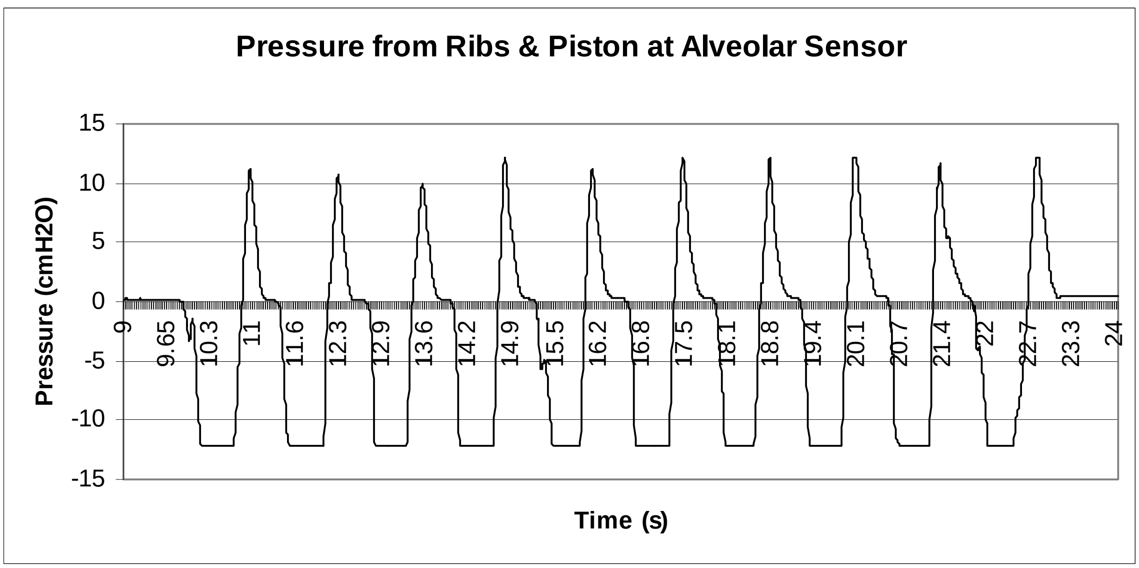


Figure 13. Graph of pressure generated by rib membrane and piston movement as recorded by the alveolar sensor.

The average negative pressure generated by the piston was -8.05 cmH_2O at the intrapleural sensor and -12.16 cmH_2O at the alveolar sensor (the minimum pressure allowed by the pressure transducer). The average negative pressure generated by the rib membranes was -1.23 cmH_2O at the intrapleural sensor and -1.57 cmH_2O at the alveolar sensor. This value is much smaller than the pressure generated by the piston, which accurately represents the difference in contribution of the ribs and diaphragm to breathing in the human body. The overall average negative pressure was -8.79 cmH_2O at the intrapleural sensor and -12.16 cmH_2O at the alveolar sensor. These generated pressures are large enough for the prototype to show the differences between pressures in the intrapleural and alveolar spaces, as well as the differences between the contributions of the ribs and diaphragm.

Software

Graphs of the intrapleural and alveolar pressures generated by the model, as displayed when interfaced with BioPac®, are shown in Figure 14. Alveolar pressure correctly demonstrated a decrease in pressure and a return to atmospheric pressure when the piston or rib membranes were pulled outwards (demonstrating inhalation) and an increase in pressure and again returning to atmospheric as the piston or rib membranes were pushed back to their initial starting states (demonstrating exhalation). The intrapleural space was always less than or equal to 0 kPa, demonstrating that the device was leak-proof.

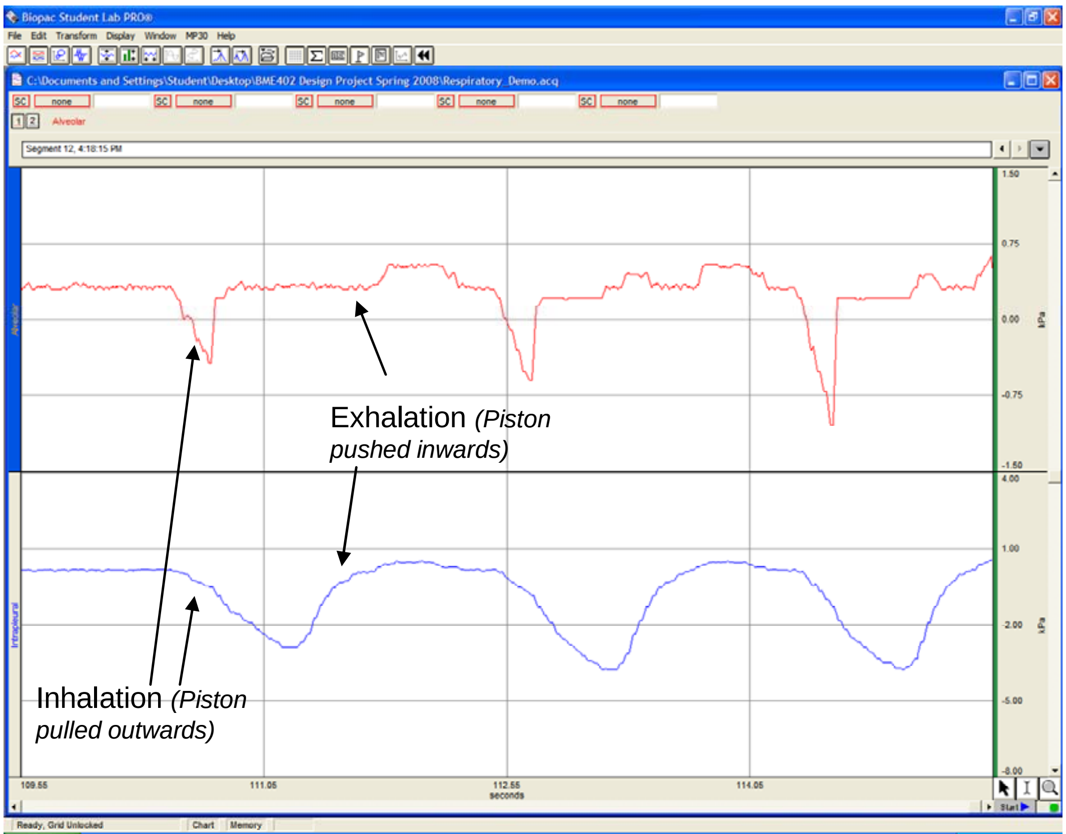


Figure 14. Graphs of intrapleural and alveolar pressures generated by the model interfaced with BioPac®. The top graph shows alveolar pressure changes; the bottom graph shows intrapleural pressure changes.

Educational

Based on data collected, ANOVA tests, at the 0.05 significance level, were conducted to determine statistically significant differences between the experimental and control group's post-survey scores. Pooling the control and experimental groups from each day, ANOVA analysis revealed a statistically significant difference in post-survey scores between the two groups (p-value <0.0001). Similarly, analysis for each of the three lab days individually also indicated significant difference in post-survey scores between the control and experimental groups (Table 1).

Table 1. P-values from ANOVA for post-lecture surveys according to lab day, where H_0: $\mu_{control} = \mu_{experimental}$ and $\alpha = 0.05$.

The overall difference in post-survey scores between the control and experimental groups, at a 95% confidence level, was calculated to be 1.0 ± 0.2 points. Likewise, the difference in score between the control and experimental groups was tabulated for each lab day and is reported in Table 2. All lab days showed an increased score when compared to the control groups on the same day.

[redacted]

Table 2. Average post-lecture score increase in experimental group compared to control group.

As expected, ANOVA tests comparing the pre-surveys from the control to the experimental groups revealed no statistical difference between them.

Next, the mean difference between the pre- and post-scores for the experimental group, at a 95% confidence level, was calculated to be 0.8 ± 0.2 and –0.2 ± 0.3 for the control group. In essence, the groups that were shown the model improved their score in the post-survey compared to the pre-survey. On the other hand, because zero is within the confidence interval, there is no significant difference in the pre- and post- survey scores for the control groups. The mean differences between the pre- and post-surveys were also calculated for each lab day (Table 3).

[redacted]

Table 3. Average difference in pre-and post-lecture survey scores for control and experimental groups by each lab day.

DISCUSSION

We have constructed a device capable of accurately representing human respiratory mechanics with the option of using BioPac®. While the estimated cost of production for this device may be high, we believe the investment is worth it due to this device's superiority over other available models. Our model demonstrates correctly sized anatomical features, the effects of the rib cage and/or diaphragm on internal pressures, the biphasic nature of the alveolar pressure, and the physiological effects of pneumothorax. All of these visualizations can be done in real time, further enhancing a student's ability to understand the functional interaction of the components of the human respiratory system.

Analysis of survey data indicates that the post-survey of the experimental group was higher by 1.0 ± 0.2 points compared to that of the control group. Furthermore, the experimental group also had a greater increase between the pre- and post-survey compared to the control group. Thus, the data supports our conclusion that the instructor's use of the model improves student understanding of respiratory physiology.

Because the post-surveys were administered immediately after explaining the concepts and demonstrating the model, data may not be capturing whether the device helps improve learning retention. Thus, administering post-lecture surveys after a longer duration would better capture long-term improvements in learning.

When using this model in a classroom setting, we recommend familiarizing oneself with the functionality of the device and practicing the demonstration alone before using the device with students. As previously mentioned, there are numerous concepts that can be demonstrated with this device, and it is best to learn how they all work and decide which concepts to demonstrate in class. We welcome questions and inquiries to be directed to us at jjanderson1@wisc.edu.

ACKNOWLEDGMENTS

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Faithfull, D. *et al*. 1979. Measurement of the relative contributions of rib cage and abdomen/diaphragm to tidal breathing in man. *Br J Anaesth.*, 51(5): 391-8.

Samuels, M.L. and Witmer, J.A. 2003. *Statistics for the Life Sciences.* Upper Saddle River NJ: Prentice Hall.

APPENDIX A – Production Cost Estimate

Description	Vendor	Part Number	Qty	Price (Each)	Price (Tot)
8" outer diameter acrylic tube (thickness= 3/16")	McMaster-Carr	8486K837	1	$ 41.40	$ 41.40
5" outer diameter acrylic tube (t= ¼")	McMaster-Carr	8486K583	1	$ 25.65	$ 25.65
5" inner diameter acrylic tube (t= 1/8")	McMaster-Carr	8486K582	1	$ 21.35	$ 21.35
Silicone Adhesive (3.0 oz)	McMaster-Carr	7587A37	1	$ 3.37	$ 3.37
Tube-to-tube Y fitting (3/8")	McMaster-Carr	53415K241	1	$ 2.86	$ 2.86
Rubber stopper with through hole (13/64"), size 7	McMaster-Carr	9545K33	1	$ 2.21	$ 2.21
Polyurethane tubing: inner diameter 3/8" (t=1/16")	McMaster-Carr	5108K56	2	$ 0.92	$ 1.84
Button head socket cap screws #6-32	McMaster-Carr	92949A146	1	$ 6.53	$ 6.53
Metal knob (1/4" -28 threads)	McMaster-Carr	6079K32	1	$ 4.54	$ 4.54
Piston O-ring (inner diameter = 4.125")	McMaster-Carr	9452K193	1	$ 0.38	$ 0.38
12"x12" acrylic sheet (t= .177")	McMaster-Carr	8560K211	1	$ 5.05	$ 5.05
1/32" pure gum rubber sheet	Small Parts, Inc	PGRS-0031-F	1	$ 8.55	$ 8.55
15"x55" polycarbonate sheet (t= .25")	Midland Plastics	n/a	1	$ 42.20	$ 42.20
Polycarbonate Cement	Midland Plastics	n/a	1	$ 8.02	$ 8.02
Small #8 knobs	Dorn True Value	n/a	2	$ 2.46	$ 5.19
#8 nylon washers	Dorn True Value	n/a	4	$ 0.07	$ 0.30
#8 nylon wing nuts	Dorn True Value	n/a	2	$ 0.65	$ 1.37
Nylon hose clamps	Dorn True Value	n/a	2	$ 0.50	$ 1.06
Rubber stopper	Dorn True Value	n/a	1	$ 0.13	$ 0.14
9 pin D-sub male	Radioshack	2761427	2	$ 1.99	$ 4.20
9 pin D-sub hood	Radioshack	2761539	2	$ 1.99	$ 4.20
Compound pressure gauge	Autonics, Inc.	PSA-C01	2	$ 120.00	$ 240.00
Total					***$ 430.41***

APPENDIX B- Product Design Specifications

Product Design Specifications
Respiratory Demonstration Device

Janelle Anderson, Malini Soundarrajan, Chris Goplen, Lynn Murray, Kristen Seashore
May 6th, 2008

PURPOSE & DEVICE FUNCTION:

Currently, a basic balloon and latex membrane model is being used to represent the lungs, and diaphragm, respectively for classroom instructional purposes. While they demonstrate respiratory mechanics, the models have a short lifespan and do not display alveolar and intrapleural pressure changes.

Our goal is to design and build an adequate mechanical respiratory model for class instruction purposes. This model should demonstrate pressure differences between alveolar and intrapleural spaces. It must further demonstrate the expansion of the thoracic cavity from the rib cage as well as the diaphragm, thereby displaying a 3-D expansion. The device should be compatible with BioPac® software to graphically display intrapleural and alveolar pressure changes. The device must also be portable and small enough to use with a document camera.

CLIENT REQUIREMENTS:

Long-lasting, easily replaceable parts
Portable
Displays alveolar and intrapleural pressures
Operable by one user
Compatible with BioPac® software

DESIGN REQUIREMENTS:

1. Physical and Operational Characteristics
    a. Performance Requirements
        i. Reusable. The unit will be used about four weeks per year, so the pieces should be durable.
        ii. Easily replaceable lungs and diaphragm.
        iii. Operable by a single user.
    b. Safety
        i. Non-toxic and non-absorbing materials.
        ii. Durable. The device should withstand regular usage.
        iii. No sharp edges. Edges should be rounded to prevent any cuts or scrapes from being incurred by the demonstrator or students.
    c. Shelf Life
        i. Approximately 30 years.
    d. Operating Environment
        i. Lecture hall and laboratory instructional settings.
        ii. Between room temperature and temperature of document camera (25°C-30°C).
    e. Size

i. Must fit on or near a document camera for lecture demonstrations (13” x 17”).
ii. Portable such that a professor or lab instructor can lift the device and accessories to transfer it easily to and from classrooms.
iii. Device should be small enough to fit in a standard cabinet or storage closet for easy storage.

f. Weight
i. The device should weigh less than 15 pounds so that it can be transported, without inducing excessive stress on the lab instructor’s arm and back muscles.

g. Pressure Measurement
i. Must display alveolar and intrapleural pressures relative to each other.
ii. Digital gauges to integrate with BioPac®.
iii. Pressure measurements should be easily readable using lecture document camera.
iv. Pressure measurements should also be plotted on BioPac® software for use in a laboratory setting.

h. Aesthetics
i. Transparent container to better visualize lung mechanics. Membrane material does not need to be transparent.
ii. Red colored lungs to enhance physiological representation.
iii. Cylindrically shaped container to model the thoracic cavity.

2. Production Characteristics
a. Quantity: 1 unit
b. Target Product Cost: under $500

3. Miscellaneous
a. Competition:
i. Acrylic model with latex diaphragm and balloon lungs


[2]

b. Ethics:

i. Model could replace use of animals in teaching students.

References:

[1] http://www.lib.mcg.edu/edu/eshuphysio/program/section4/4ch2/asidpg28.htm. Thoracic Cavity Volume.

[2] http://www.xecu.net/kiirenza/anatomy/resp_models.htm. *Picture of current model.*