# Human Respiratory Mechanics Demonstration Model

Anderson, Janelle[1]; Goplen, Chris[1]; Murray, Lynn[1]; Seashore, Kristen[1]; Soundarrajan, Malini[1]; Lokuta, Andrew[2]; Strang, Kevin[2]; Chesler, Naomi[1]

[1]Department of Biomedical Engineering and [2]Department of Physiology,
University of Wisconsin-Madison

## ABSTRACT

Respiratory mechanics is a difficult topic for instructors and students alike. Existing respiratory mechanics models are limited in their abilities to demonstrate any effects of the rib cage movement on alveolar and intrapleural pressures. We have developed a model that can be used in both large and small classroom settings. The model contains digital pressure displays and computer integration for real-time demonstration of pressure changes that correspond to the different phases of breathing. Moving the simulated diaphragm and rib cage causes a volume change which results in pressure changes visible on the digital sensors and computer display. Device testing confirmed the model's ability to accurately demonstrate pressure changes in proportion to physiological values. Classroom testing in 369 surveyed students showed improved understanding of respiratory concepts ($p<0.05$). We conclude that our respiratory mechanics model is a valuable instructional tool and provide detailed instructions for those who wish to create their own.

Abbreviated title for the running head: **Respiratory Mechanics Model**

Address for correspondence:

Andrew J. Lokuta, Ph.D.
University of Wisconsin School of Medicine and Public Health
Department of Physiology
1300 University Ave
Madison, WI 53706
ajlokuta@physiology.wisc.edu

Accepted to **Advances in Physiology Education**

## INTRODUCTION

Our goal was to design and build a mechanical model that would improve student understanding of human respiratory mechanics. In particular, we sought to develop a model that demonstrates pressure changes in alveolar and intrapleural spaces with breathing as well as the three-dimensional expansion of the thoracic cavity by the rib cage and diaphragm. Though simple homemade models and basic commercial Plexiglas® lung models are available [Oregon Museum of Science and Industry, 2008; UCSB Physics, 2008], they have short life-spans and parts that are difficult to replace. Also, most models do not display pulmonary pressures, making it difficult for students to visualize the forces driving gas exchange between the lungs and the atmosphere [Chan *et al.,* 1996; McCulloch, 2004; Melo e Silva and Gaio dos Santos Ventura, 2006]. Other models do visualize the pressure changes using analog means, but the models are neither interfaced with a computer nor visually representative of human anatomy [Chinet, 1989; Kuebler *et al.,* 2007]. Furthermore, 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 may contribute between 5 and 42 percent of the lung's total volume change (Faithfull, 1979).

## DESIGN, FABRICATION, & COST

### *Design Considerations*

A model for teaching respiratory mechanics 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 13"x17" document camera. To maximize its usefulness, the device should be compatible with computer display software and be operable by a single user. The container housing the lungs should be transparent so 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 durable and easily replaced.

### *Mechanical Design*

The respiratory mechanics model we designed consists of a sealed transparent chamber in which diaphragm movement can be simulated using a piston, and rib cage movements can be simulated with 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 machining. The container was designed as a rectangular box (7.25"x7.25"x10") with a curved front panel. The box provides a flat back so that the model can be laid flat 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 to demonstrate a pneumothorax and subsequent atelectasis.

Volume changes are produced by two distinct methods: movement of a diaphragm piston and/or movements of rib membranes. These two different mechanisms were selected to clearly

differentiate between rib and diaphragm effects. Although variation in the tidal volume occurs with body position and in different physiological and pathological conditions, the diaphragm muscle provides approximately 58 % of the lung's volume change, with rib expansion contributing the rest (Faithfull, 1979). Similarly, our model's diaphragm piston motion provides a larger volume change than the motion of 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 wall 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 flanges which are screwed on to create a leak-proof seal while allowing easy replacement of the membrane material. The small holes in the container beneath the membrane side panels allow volume change when the rib membrane is stretched, but keep the rib membranes 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 are clamped onto a Y tube fitting, with the third port passing through the container top via a rubber stopper and exposing the balloons to atmospheric pressure.

Two digital pressure sensors are attached to the top of the model for simultaneous real-time measurement of 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 is 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 is needed to measure the negative and positive pressures created during simulated inspiratory and expiratory movements. Second, sensitive gauges are required to measure the small (~0.2 psi) pressure changes. Third, electronic sensors are necessary so the model can interface with computer 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.

*Electrical Design*

Two digital compound pressure sensors (PSA-C01, Autonics), set to range ±102 $cmH_2O$, were used to measure the pressure changes occurring within the alveolar and intrapleural spaces. Each sensor was interfaced with the BioPac® MP30 or MP35 analog-to-digital converter by a 9-pin female D-sub connector (Figure 2). For each transducer (alveolar and intrapleural), Pin 2 on the D-sub 9 was connected to the signal output of the transducer and pins 3 and 4 were connected to ground (Figure 3). Each pressure transducer was powered by a 15V power supply. As a consequence, a 12Ω resistor was soldered in parallel between pin 2 on the D-sub connector and ground to reduce the voltage input to the analog-to-digital converter, which was designed to handle a maximum 130 mV input. Pressure transducer digital outputs 1 and 2 were not used.

After soldering all connections, the D-sub housing units were secured; both connectors are shown connected to the MP30 in Figure 4.

To set-up the BioPac® data acquisition software, the sensors were plugged into channels 1 (alveolar pressure) and 2 (intrapleural pressure). 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 → wrench icon → Scaling) such that 59.3 mV = +102 $cmH_2O$ and 11.9 mV = -102 $cmH_2O$ according to calibration tests described below. Gain was set to 100 and the offset was changed as necessary to make sure a 0 $cmH_2O$ reading on the digital pressure sensor corresponded to a visual display of 0 $cmH_2O$ on the BioPac® system.

### *Cost*

Project costs totaled $499.08 for two models: an initial prototype and final product. This includes the costs of some unused materials and does not include the cost of donated items. This price also includes initial prototype costs which would not be necessary in constructing a single respiratory model. The cost of a computer and the BioPac® hardware are not included in the total cost because they are not required to use the model.

The projected costs for constructing one model with no donated materials would be $430.41. The primary expenses are the pressure sensors and the acrylic and polycarbonate stock materials, which compromise 56% and 31% of the total price, respectively. Reducing material waste and utilizing bulk quantities would reduce costs somewhat further.

## TESTING

### *Physical Testing*

The most important aspect of ensuring the physical viability of our device was the strength of the seals around the cut polycarbonate pieces. We tested the efficacy of the seal in a variety of different ways. Submerging the prototype in 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.

While submersion 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 moved inwards to determine if and where the vapor was leaking out of the model. To examine the effectiveness of the seals on a still smaller scale, we rubbed soap along the seams and wet them slightly. When using the piston, bubbles appeared in areas where leakage occurred.

Finally, leak testing of our device was done by ensuring that the measured intrapleural pressure was always less than or equal to zero. If the calibrated signal for the intrapleural space rose above 0 $cmH_2O$, a leak existed somewhere in the device.

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 (MPX 399/2, Hugo Sachs Elektronik) 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 tested separately in triplicate. The pressures generated by the piston and rib membranes were also tested separately and together, again in triplicate.

*Educational Testing*

The most important aspect of this project was determining whether our model improved student understanding of respiratory mechanics concepts. In order to measure the instructional efficacy of the prototype, a method of surveying was developed for students in Human Physiology 335 at the University of Wisconsin-Madison. 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 in a classroom setting. 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 physical risk to the participants. Students participated voluntarily and anonymously with no incentive or risk to their grades and each student was provided with a written consent form. The class had 427 registered students but for each question on the surveys, we encountered a different number of respondents and that number was always less than 427. Additionally, some questions were randomly skipped by the participating students and fewer students overall chose to participate in the post surveys though there were equal losses from both the control group and the experimental group. Both the pre- and post- instructional surveys were developed in house after consultation with the SBS IRB, the University of Wisconsin Department of Physiology, and the University of Wisconsin Department of Biomedical Engineering.

The physiology students were randomly divided into control and experimental groups based on their laboratory sections All students were given a pre-survey during their regular laboratory period to test their knowledge of respiratory physiology concepts before the material had been covered in lecture or laboratory workshops. Then, two weeks after the pre-surveys, the students received post-surveys containing the same questions as the pre-survey. After giving the pre-survey, the lab instructor noted that answers b and c for question 2 are both valid for different points in the inspiration process. To compensate, b and c were both counted as correct answers and the wording of the question was changed in the post-survey to include all points of inspiration. All pre-lab introductory material was presented to both groups by the same lab instructor. 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 tested in the surveys was mentioned during the introduction. After the introduction, students in the control group 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 (i.e., a pneumothorax) was also demonstrated. All of the material that was tested in the surveys was either mentioned during the introduction or shown with our model or both. After the introduction and demonstration, students in the experimental group 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, would indicate thorough understanding of the material. One-way ANOVA was used to compare experimental to control survey scores and pre- and post-survey scores. A p-value less than 0.05 was considered significant.

## RESULTS

### *Physical*

After the final construction of the prototype, the device was tested using the high sensitivity pressure transducer noted above to determine the pressures generated by moving the rib membranes, the 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 (Figure 5). The device generated negative pressures, which accurately represents the required negative pressure in the intrapleural space. The pressure testing trials shown in Figures 5 and 6 were performed at a higher frequency than normal breathing to compensate for small leaks in the device and to maximize generated pressure.

The same procedure was followed for recording pressure through the alveolar sensor connection (Figure 6). The negative pressure generated by the piston alone and the combined rib membranes and piston movements together exceeded the minimum value allowed by the pressure transducer. Therefore, those recorded graphs do not go below -12.2 $cmH_2O$.

Measurements of pressure in the intrapleural and alveolar spaces were taken in separate trials. Note that each graph in both Figures 5 and 6 was generated by testing a single component of the device during separate trials using a single pressure port. The alveolar pressure was slightly more negative than the intrapleural pressure because the intrapleural space of the model has a greater volume than the alveolar space. This does not reflect pressure behavior when the diaphragm and ribs are operated concurrently, as in the human respiratory system. When operated concurrently, the intrapleural pressure generated by the piston will be more negative than the alveolar pressure to keep the lungs inflated. 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 7. 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 positions (demonstrating exhalation). The intrapleural space was always less than or equal to 0 $cmH_2O$, demonstrating that the final device was leak-free.

### *Educational*

Using the collected survey data, the average scores of the pre- and post-surveys for each lab were calculated, along with standard error for each average. The results were compared between the pre- and post-surveys for each lab, as well as between the control and experimental groups. The results of these calculations are shown in Table 1. Survey questions and responses can be found in the Appendix. For all labs, the average pre- and post-survey scores for both the experimental and control groups are shown in Figure 8.

Due to the IRB regulations the surveys were conducted anonymously and voluntarily with no risk or reward for participation. There was no assurance of equal participation between the pre- and post-instructional surveys because of the voluntary participation requirement. Only students who confirmed they voluntarily took the pre-instructional survey were given the post-

instructional survey, accounting for the differences in numbers for both survey groups. The losses of respondents were approximately equal in both groups. To preserve the anonymity of participating individuals, their corresponding surveys were not tracked. Therefore, individual results could not be determined, analyzed, or compared.

| | Average Pre-Quiz Score (Mean ± SD) | Average Post-Quiz Score (Mean ± SD) |
|---|---|---|
| **Control Groups** | | |
| **Lab 2** | 3.54 ± 1.37 | 3.59 ± 1.02 |
| **Lab 4** | 4.16 ± 1.11 | 3.54 ± 1.31 |
| **Lab 7** | 3.80 ± 1.10 | 3.52 ± 1.09 |
| | | |
| **Experimental Groups** | | |
| **Lab 1** | 3.53 ± 1.14 | 4.57 ± 1.05 |
| **Lab 3** | 3.86 ± 1.23 | 4.73 ± 1.00 |
| **Lab 5** | 3.80 ± 1.12 | 4.23 ± 1.03 |
| **Lab 6** | 3.93 ± 1.25 | 4.71 ± 1.16 |

**Table 1. Summary of pre- and post-survey scores.**

One-way ANOVA was used to compare experimental to control survey scores and pre- and post-survey scores. As expected, the pre-survey scores from the control group were not statistically different from the pre-survey scores from the experimental group. Furthermore, in the control group, no improvement in survey test scores was evident with instruction without the demonstration. In contrast, post-survey scores were significantly higher than pre-survey scores in the experimental group ($p<0.0001$) and post-survey scores were significantly higher in the experimental group than the control group ($p <0.0001$). These findings demonstrate that the model had a significant and positive impact on survey test performance.

## DISCUSSION

We constructed a device for representing human respiratory mechanics, with the option of using a computer to display the pressures. While the estimated cost of manufacture of this device may be high, it offers improved and expanded functionality over other available models. Most 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 [Chan *et al.,* 1996; McCulloch, 2004; Melo e Silva and Gaio dos Santos Ventura, 2006]. Other models do visualize the pressure changes using analog means, but the models are neither interfaced with a computer nor visually representative of human anatomy [Chinet, 1989; Kuebler *et al.,* 2007]. Furthermore, no currently available physical models illustrate the expansion of the rib cage. Our model demonstrates the effects of the rib cage and/or diaphragm on internal pressures, the biphasic nature of alveolar pressure changes, and the physiological effects of pneumothorax. All of these can be visualized in real time, further enhancing a student's ability to understand the functional interaction of the components of the human respiratory system.

It should be noted that no model is perfect, and ours suffers from some of the same shortcomings as others. For example the pleural space is, in reality, a virtual space filled with a

small volume of fluid and not an air-filled cavity. Since gases readily compress and expand (following Boyle's Law), the presence of an air-filled pleural space in our model blunts the effect of diaphragm and rib movements on lung (balloon) volume. Also, our model cannot represent the full range of flexibility of the actual thoracic cavity, or how it interacts mechanically with the diaphragm. Contraction of the diaphragm in the context of relaxed intercostals muscles can actually pull the ribcage inward, as in the "retractions" that occur in babies with respiratory distress syndrome. Shortcomings such as these need to be explicitly addressed with students whenever a mechanical model is used for teaching such complex topics.

Analysis of survey data indicated that the students exposed to the model scored 1.0 point higher on a six point scale than students given a lecture only. Furthermore, students exposed to the model demonstrated greater improvement in understanding than those only exposed to a lecture via analysis of the pre- and post-surveys. Thus, these data support 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, the data may not capture whether the device helps improve long-term retention of the key concepts tested. In the future administering post-demonstration surveys after a longer duration might 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 beforehand. As previously mentioned, there are numerous concepts that can be demonstrated with this device, so pre-lesson experimentation with the device and lesson planning are recommended. We welcome questions and inquiries to be directed to us at jjanderson1@wisc.edu.

## ACKNOWLEDGMENTS

Special thanks to Karen Seashore, Donna Jahnke, Lillian Larson, Wendy Crone, Kristyn Masters, Kynan Shook, Petro Extrusion Technologies, Kraton, and Autonics for their support, advice, and donations of time and materials that helped make this model possible.

## REFERENCES

Chan, V. *et al.* 1996. Model demonstrating respiratory mechanics for high school students. *Advan Physiol Educ.*, 270: 1-18.

Chinet, A. 1989. Chest-lung statics: a realistic analog for student laboratory. *Amer Physiol Soc*, 1043-4046/89.

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.

Kuebler, W. *et al.* 2007. A two-component simulation model to teach respiratory mechanics. *Adv Physiol Educ.*, 31:218-222.

McCulloch P. 2004. A simple model illustrating the balancing forces of lung and chest wall recoil.. *Advan Physiol Educ.*, 28: 125-127.

Melo e Silva and Gaio dos Santos Ventura, 2006. A simple model illustrating the respiratory system's time constant concept. *Advan Physiol Educ.*, 30: 129-130.

Oregon Museum of Science and Industry: The Lung. (21 July 2008) http://www.omsi.edu/visit/life/obp/u2_l1_body.html

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

UCSB Physics Lecture Demonstrations: Lung Model. (21 July 2008) http://www.physics.ucsb.edu/~lecturedemonstrations/New demos/Lung Model.htm

## FIGURE LEGENDS

**Figure 1.** Three-dimensional representations of the respiratory model. Main features include a flat back for laying the unit under a document camera, digital pressure sensors, side rib membranes, diaphragm piston, and intrapleural pressure plug.

**Figure 2.** BioPac® D-Sub pin connections (biopac.com).

**Figure 3.** Electrical connections schematic.

**Figure 4.** Respiratory model connected to BioPac® system.

**Figure 5.** Pressure generated by the rib membrane (top panel), piston (center panel) and rib membrane and piston movement (bottom panel) versus time as recorded by the intrapleural sensor.

**Figure 6.** Pressure generated by the rib membrane (top panel), piston (center panel) and rib membrane and piston movement (bottom panel) versus time as recorded by the alveolar sensor.

**Figure 7.** 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.

**Figure 8.** Mean pre and post-survey scores for control and experimental groups. Bars indicate standard deviation. *$p<0.0001$.

## APPENDIX – Pre-Survey and Responses

Note: Correct answers are in bold. Question 1 was not used in the statistical analysis of results.

1. How well do you understand respiratory pressure changes: (N= 370)

| | 1. Poor | 2. Fair | 3. Good | 4. Very Good | 5. Excellent |
|---|---|---|---|---|---|
| **N** | 149 | 169 | 46 | 5 | 1 |
| **%** | 40.3 | 45.7 | 12.4 | 1.3 | 0.3 |

2. During inspiration, the alveolar pressure is: (N= 366)

| | 1. Positive | **2. Negative** | **3. Zero** |
|---|---|---|---|
| **N** | 163 | 187 | 16 |
| **%** | 44.5 | 51.1 | 4.4 |

3. During inspiration, the intrapleural pressure is: (N= 363)

| | **N** | **%** |
|---|---|---|
| **1. More negative than the intrapleural pressure at rest** | 167 | 46.0 |
| 2. Less negative than the intrapleural pressure at rest | 171 | 47.1 |
| 3. The same as the intrapleural pressure at rest | 25 | 6.9 |

4. When the diaphragm relaxes, which of the following are true: (N= 362)

| | **N** | **%** |
|---|---|---|
| **1. Intrapleural pressure increases** | 136 | 37.6 |
| 2. Intrapleural pressure decreases | 166 | 45.9 |
| 3. Intrapleural pressure returns to atmospheric pressure | 60 | 16.5 |

5. Which contributes most to lung expansion: (N= 368)

| | 1. Ribs | **2. Diaphragm** | 3. Esophageal dilation |
|---|---|---|---|
| **N** | 24 | 338 | 6 |
| **%** | 6.5 | 91.9 | 1.6 |

6. At the end of expiration, the lungs are: (N= 369)

| | **1. At functional residual capacity** | 2. At vital capacity | 3. Fully deflated |
|---|---|---|---|
| **N** | 272 | 56 | 41 |
| **%** | 73.7 | 15.2 | 11.1 |

7. When the chest wall is punctured, which of the following occurs: (N= 374)

| | **1. The lungs collapse** | 2. The lungs inflate | 3. The lungs return to functional residual capacity. |
|---|---|---|---|
| **N** | 304 | 38 | 32 |
| **%** | 81.3 | 10.2 | 8.5 |

## Post-Survey and Responses

Note: Correct answers are in bold. Question 1 was not used in the statistical analysis of results.

1. How well do you understand respiratory pressure changes: (N= 325)

| | 1. Poor | 2. Fair | 3. Good | 4. Very Good | 5. Excellent |
|---|---|---|---|---|---|
| **N** | 27 | 149 | 117 | 27 | 5 |
| **%** | 8.3 | 45.9 | 36 | 8.3 | 1.5 |

2. During inspiration, the alveolar pressure is: (N= 325)

| | 1. Positive & negative | 2. Positive & zero | **3. Negative & zero** | 4. Only negative | 5. Only positive |
|---|---|---|---|---|---|
| **N** | 14 | 40 | 135 | 87 | 49 |
| **%** | 4.3 | 12.3 | 41.5 | 26.8 | 15.1 |

3. When the chest wall is punctured, which of the following occurs? (N= 332)

| | **N** | **%** |
|---|---|---|
| **1. The lungs collapse** | 288 | 86.7 |
| 2. The lungs inflate | 42 | 12.7 |
| 3. The lungs return to functional residual capacity | 2 | 0.6 |

4. When the diaphragm relaxes, which of the following are true? (N= 327)

| | **N** | **%** |
|---|---|---|
| **1. Intrapleural pressure increases** | 161 | 49.3 |
| 2. Intrapleural pressure decreases | 109 | 33.3 |
| 3. Intrapleural pressure returns to atmospheric pressure | 57 | 17.4 |

5. During inspiration, the intrapleural pressure is: (N= 325)-

| | **N** | **%** |
|---|---|---|
| 1. **More negative than the intrapleural pressure at rest** | 186 | 57.2 |
| 2. Less negative than the intrapleural pressure at rest | 122 | 37.5 |
| 3. The same as the intrapleural pressure at rest | 17 | 5.3 |

6. At the end of expiration, the lungs are: (N= 325)

| | **1. At functional residual capacity** | 2. At vital capacity | 3. Fully deflated |
|---|---|---|---|
| **N** | 283 | 35 | 7 |
| **%** | 87.1 | 10.8 | 2.1 |

7. Which contributes most to lung expansion: (N= 321)

| | 1. Ribs | **2. Diaphragm** | 3. Esophageal dilation |
|---|---|---|---|
| **N** | 18 | 300 | 3 |
| **%** | 5.6 | 93.5 | 0.9 |

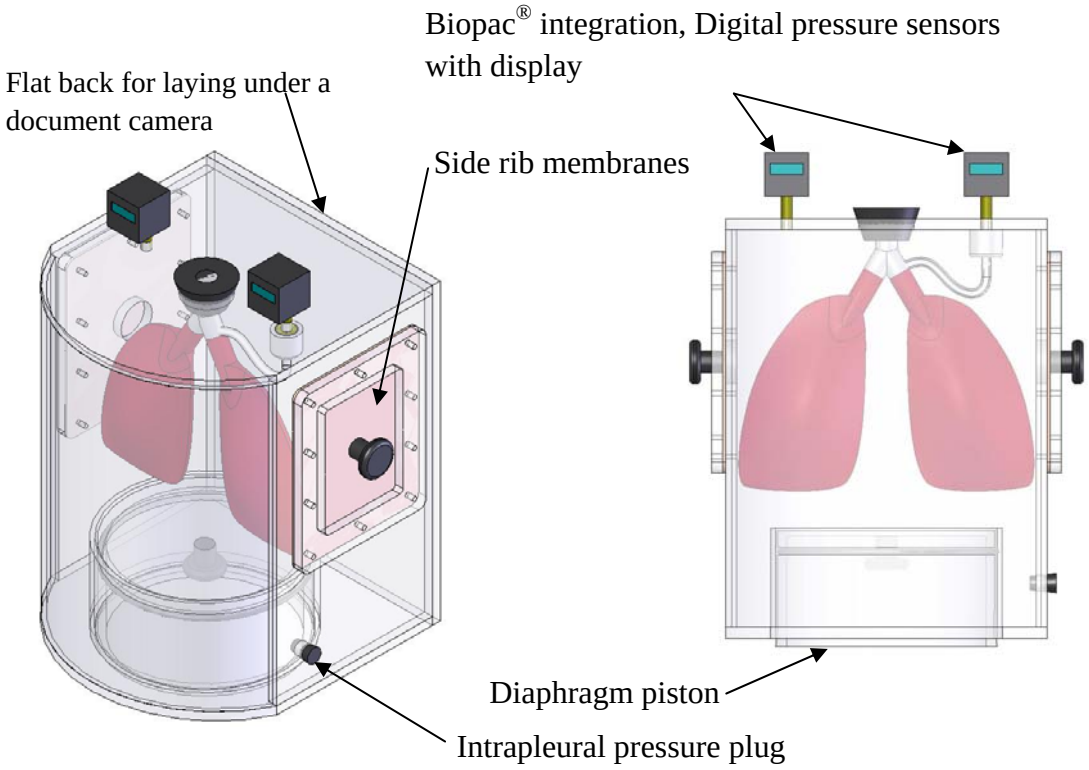
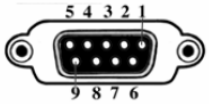



Figure 1. Three-dimensional representations of the respiratory model. Main features include a flat back for laying the unit under a document camera, digital pressure sensors, side rib membranes, diaphragm piston, and intrapleural pressure plug.

**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 2. BioPac® D-Sub pin connections (biopac.com).

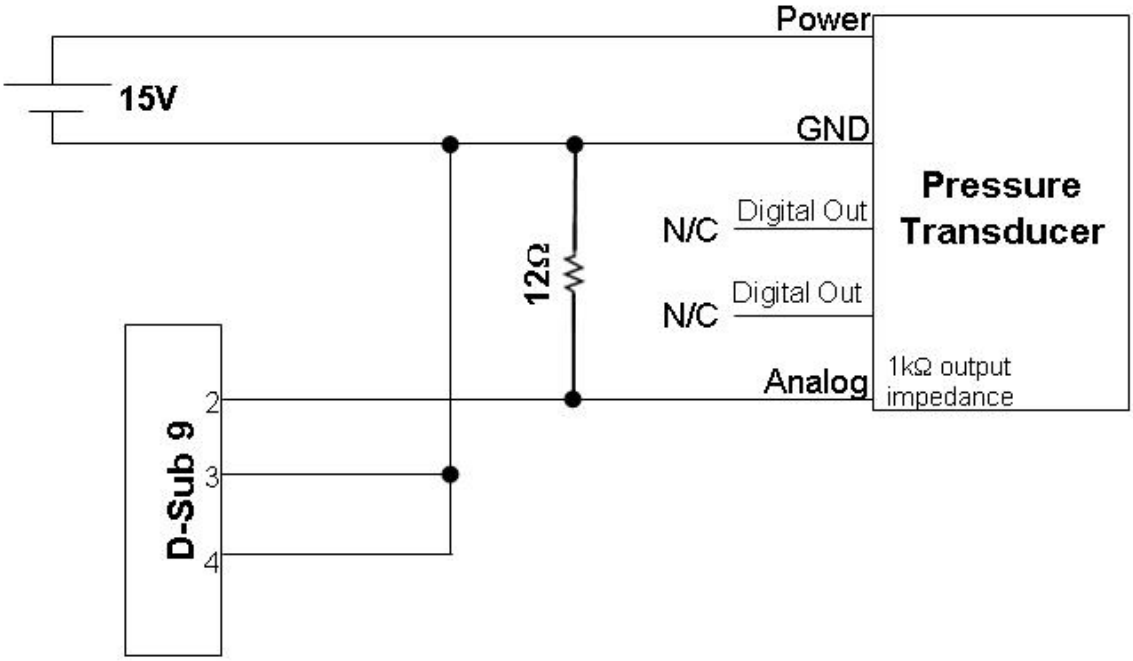



Figure 3. Electrical connections schematic.

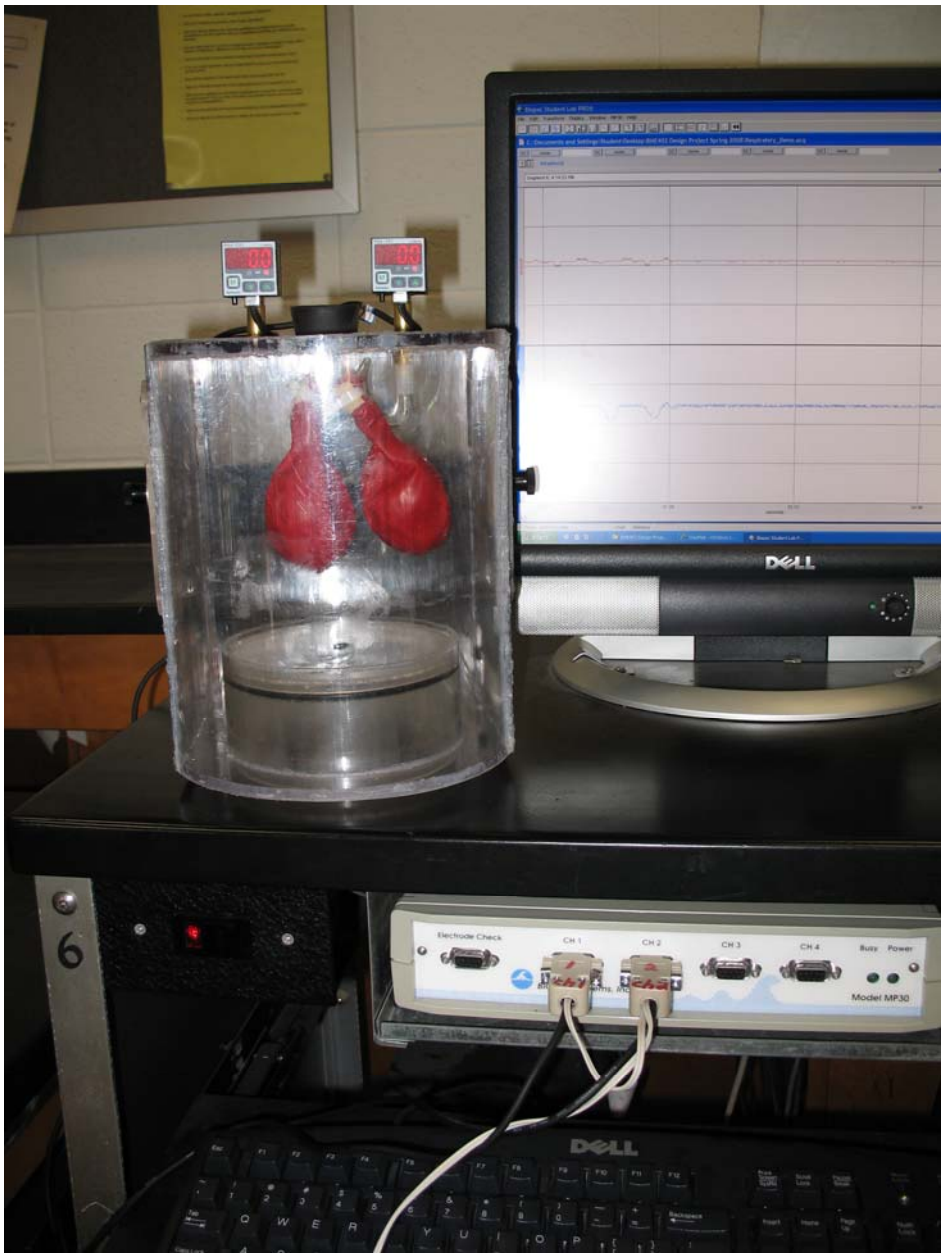



Figure 4. Respiratory model connected to BioPac® system.

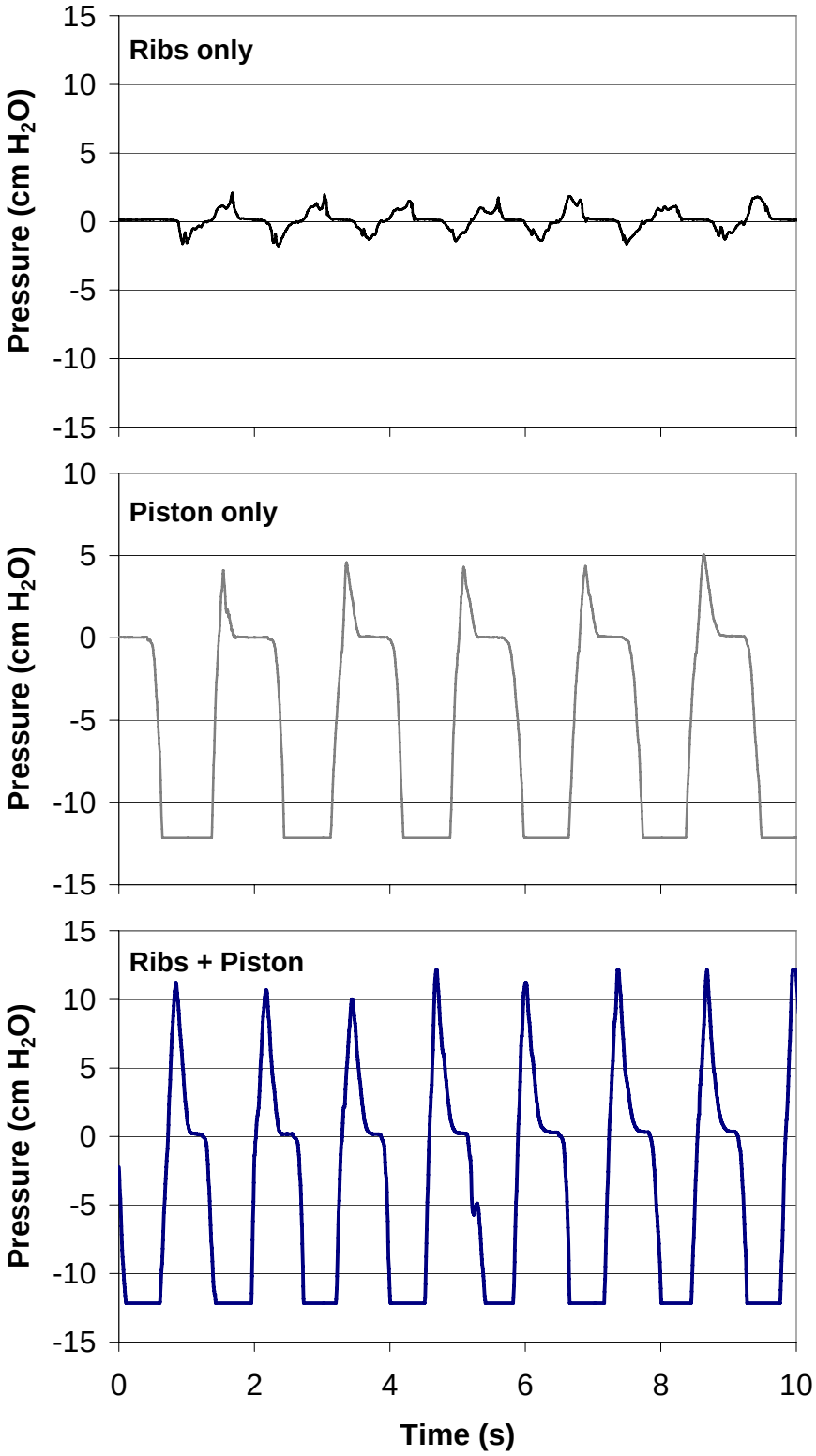



Figure 5. Pressure generated by the rib membrane (top panel), piston (center panel) and rib membrane and piston movement (bottom panel) versus time as recorded by the intrapleural sensor.

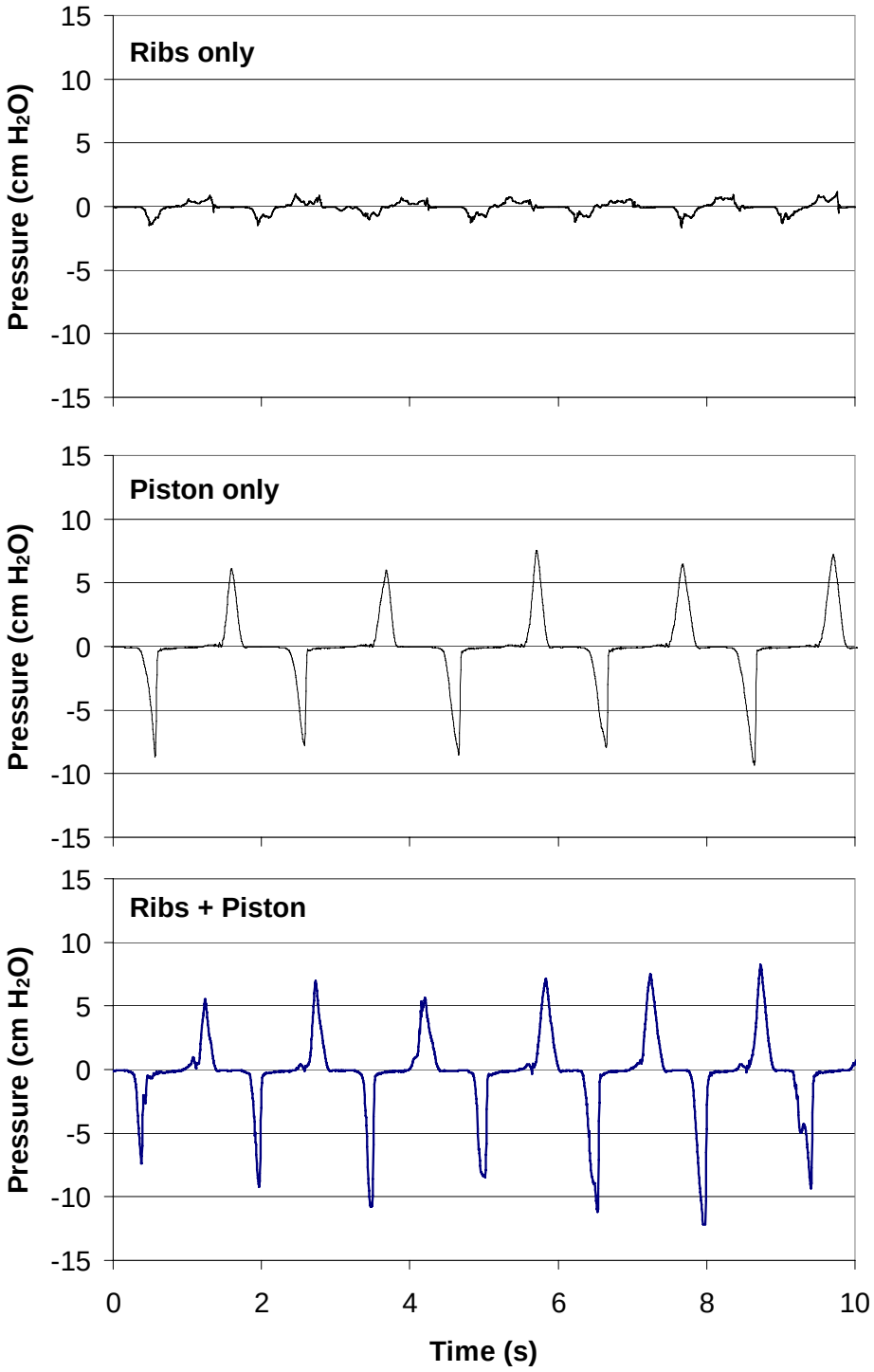



Figure 6. Pressure generated by the rib membrane (top panel), piston (center panel) and rib membrane and piston movement (bottom panel) versus time as recorded by the alveolar sensor.

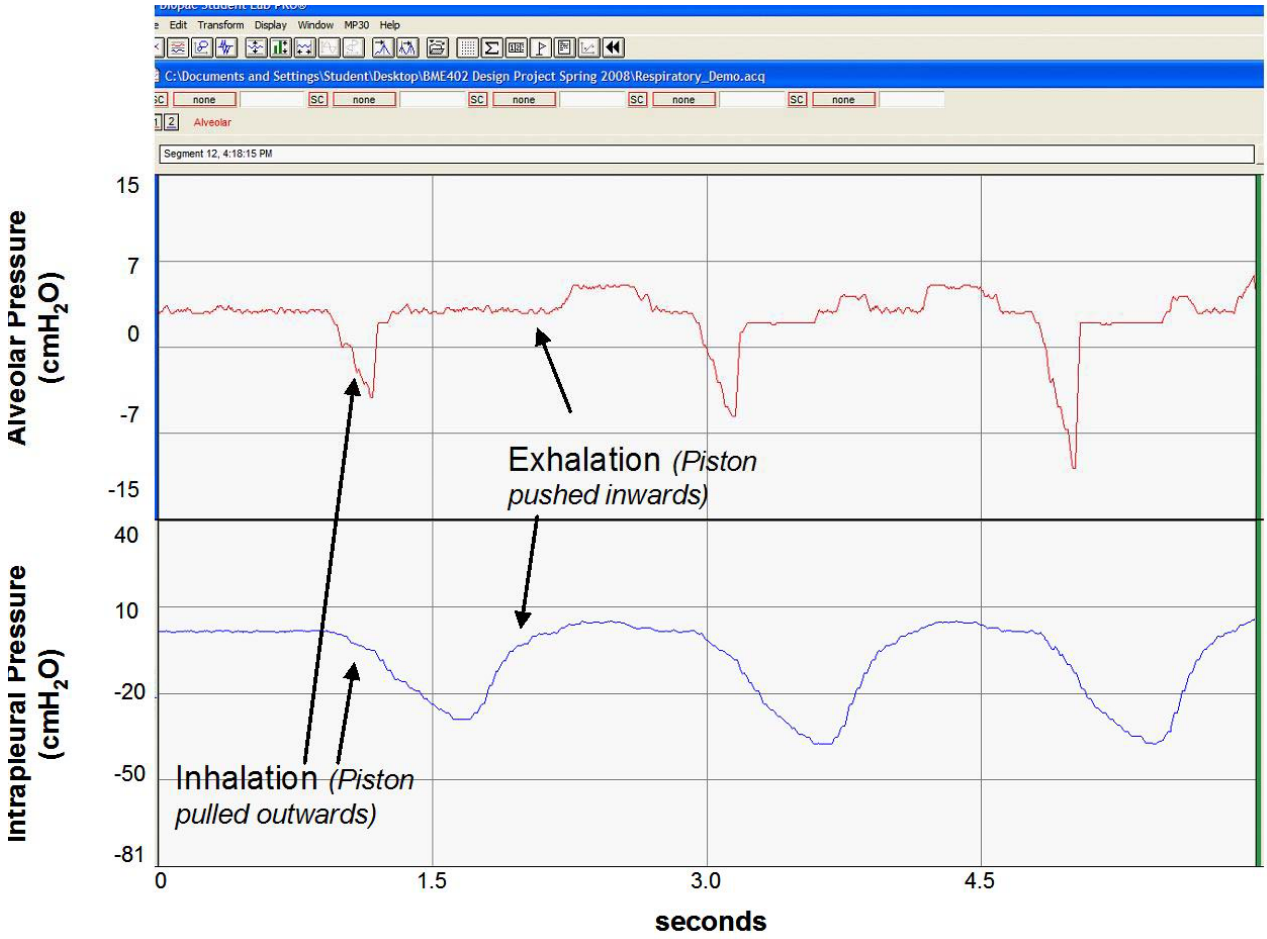



Figure 7. Intrapleural and alveolar pressures generated by the model interfaced with BioPac®. The top graph shows alveolar pressure changes; the bottom graph shows intrapleural pressure changes.

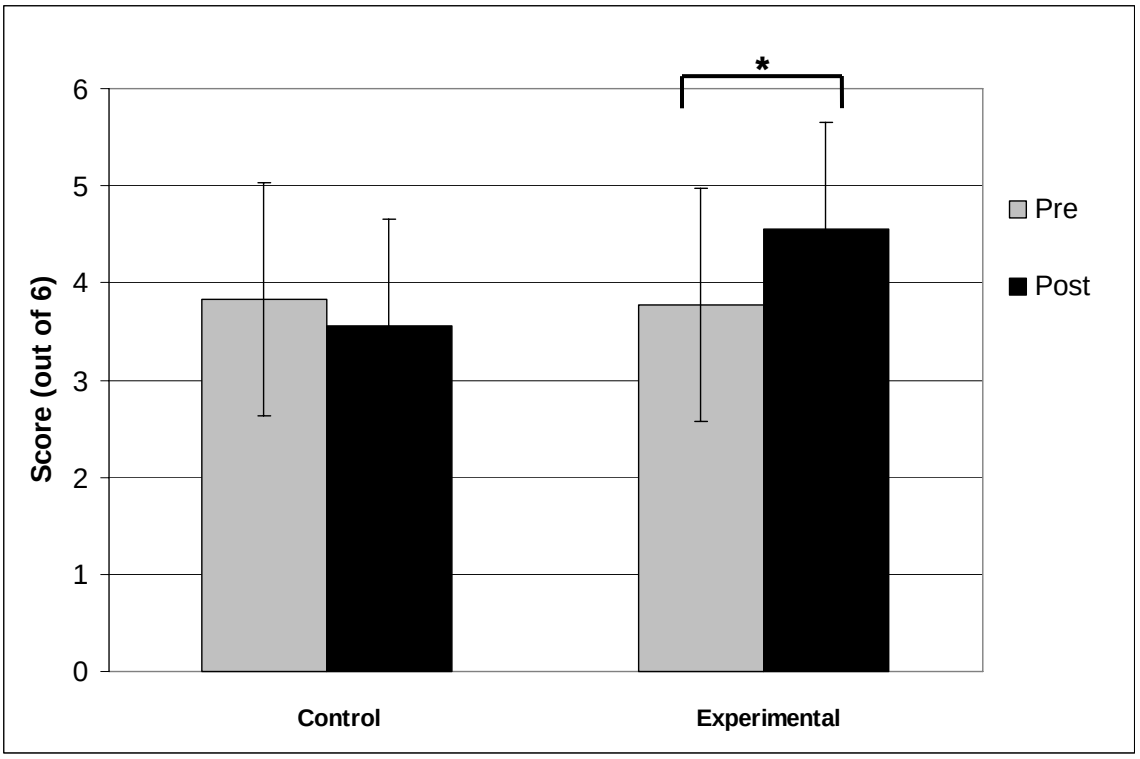



Figure 8. Mean pre and post-survey scores for control and experimental groups. Bars indicate standard deviation.
* $p < 0.0001$