LAB 3: RESPIRATORY MECHANICS

Pressures throughout the cardiovascular system are important for the health of the body and of the system itself. Today we explore pulmonary pressures and volumes.

Throughout these experiments, record in your notebook the purpose of the experiments, the methods you used, and the results. Include the measurement uncertainties and state their main sources. Feel free to include commentary or ideas that you develop along the way. You will then convert these records into a formal, typed report, which will also include a brief analysis of your results, suggestions for future experiments, and answers to the related questions provided for each section.

Part 1: Inspiratory and expiratory pressures

Procedure

Make the following predictions and measurements, entering the values in your notebook using the format tabulated below.

1. Predict the pressure that you can achieve by exhaling through a tube into a manometer or pressure gauge. Express the pressure as Pascals, psi, meters of water, and mm of mercury.

2. Predict the negative pressure (vacuum) that you can achieve by inhaling against a closed volume. Express the pressure as Pascals, psi, m of water, and mm of mercury.

3. Use an electromechanical pressure gauge and/or manometer to determine your maximum inspiratory pressure. If you use the GPS-BTA gas pressure sensor with the LabPro hardware and Logger Pro, do not exceed 200 kPa of applied pressure. Verify the pressure gauge operation using a syringe, expanding and compressing the air by a factor of 2. Note any hysteresis in the gauge. Use alcohol wipes to disinfect any connections that will come in contact with your mouth.

4. Use a water-column manometer to determine your maximum expiratory pressure. Repeat with an air pressure gauge as outlined above for inspiration.

Related questions

1. Design an experiment to determine the extent to which your maximum inspiratory pressure is determined by the volume of your lungs, versus the strength of your diaphragm and chest. You do not have to perform the experiment.

2. Estimate the frontal area of your lungs. Use this value and the maximum inspiratory pressure to estimate the differential force acting on your thorax.

3. Compare the pressures observed above to typical systolic and diastolic blood pressures.
Part 2: Measurement of Lung Volumes and Lung Capacities

Introduction

The purpose of this part of this experiment is to determine the statistical distribution of various respiratory volumes and capacities among the members of your class.

The respiratory volumes, which do not overlap, may be defined as follows:

A. Tidal Volume (TV) — the amount of air inspired or expired.
B. Inspiratory Reserve Volume (IRV) — the amount of air that can be inspired above what is taken in during a tidal inspiration.
C. Expiratory Reserve Volume (ERV) — the amount of air that can be forcibly expired at the end of a tidal expiration.
D. Residual Volume (RV) — the amount of gas remaining in the lungs at the end of a maximal forced expiration.

In addition to these volumes, there are four capacities, which are combinations of these volumes:

E. Total lung capacity (TLC) — the sum of the four lung volumes.
F. Vital capacity (VC) — the maximal amount of air that can be forcibly expired after a maximal inspiration.
G. Functional residual capacity (FRC) — the amount of air remaining in the lungs after a tidal expiration.
H. Inspiratory capacity (IC) — the maximal amount of air that can be inspired after a normal expiration.

![Figure 1. Idealized spirometer record, with lung volumes and capacities.](image)

Finally, there are two rate-dependent volumes.

I. **Respiratory Minute Volume**, which is the total amount of air that can be moved into the system per minute.

\[
RMV = \text{tidal volume (TV)} \times \text{rate of breathing/min}
\]
Not all of this air is available for gaseous exchange because of the anatomical dead space in the trachea and bronchi (on average 150-200 cc). The actual volume of air exposed to the alveolar surfaces per minute is \( (TV - \text{dead space volume}) \times \text{respiratory rate} \), which we will abbreviate RR.

J. **Forced Expiratory Volume (FEV\textsubscript{1})**, which is the volume expelled in one second during a rapid exhalation. The maximal capacity of the lungs to ventilate depends essentially upon two factors:

1) The vital capacity. This is the total volume of gas that can be displaced by a single maximal respiratory effort.

2) The speed at which this volume can be exhaled. This depends on lung compliance and on the resistance of the airways.

Normal persons should exhale at least 75% of their total vital capacity during the first second.

**Table 2.1 Typical Lung Volumes and Capacities:**

<table>
<thead>
<tr>
<th>Compartment</th>
<th>20-30 yr. Male</th>
<th>50-60 yr. male</th>
<th>20-30 yr. female</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Surface Area</strong></td>
<td>(1.7 M(^2))</td>
<td>(1.7 M(^2))</td>
<td>(1.6 M(^2))</td>
</tr>
<tr>
<td><strong>IC</strong></td>
<td>3600</td>
<td>2600</td>
<td>2400</td>
</tr>
<tr>
<td><strong>ERC</strong></td>
<td>1200</td>
<td>1000</td>
<td>800</td>
</tr>
<tr>
<td><strong>VC</strong></td>
<td>4800</td>
<td>3600</td>
<td>3200</td>
</tr>
<tr>
<td><strong>RV</strong></td>
<td>1200</td>
<td>2400</td>
<td>1000</td>
</tr>
<tr>
<td><strong>FRC</strong></td>
<td>2400</td>
<td>3400</td>
<td>1800</td>
</tr>
<tr>
<td><strong>TLC</strong></td>
<td>6000</td>
<td>6000</td>
<td>4200</td>
</tr>
<tr>
<td><strong>RV/TLC \times 100 (%)</strong></td>
<td>20</td>
<td>40</td>
<td>24</td>
</tr>
</tbody>
</table>

It is interesting to note that the total lung capacity stays relatively constant with age, while the residual volume increases. Therefore, the vital lung capacity decreases with age. Spirometric and radiographic measurements have shown a strong correlation of both with square of height and weight, such that predictive formulas can be created.\(^1\) For men:

\[
\text{TLC} = (-0.0282 + 0.0162 h - 0.0013 w)^2
\]

\[
\text{RV} = (-0.2096 + 0.0088 h - 0.0028 w + 0.0043 a)^2
\]

where \( h \) = height (cm), \( w \) = weight (kg), and \( a \) = age (years).

For women:

\[
\text{TLC} = (-0.0934 + 0.0162 h - 0.0013 w)^2
\]

\[
\text{RV} = (-0.0732 + 0.0088 h - 0.0028 w + 0.0092 a)^2
\]

https://www.ncbi.nlm.nih.gov/pmc/articles/PMC463861/
These formulas vary somewhat with medical condition and smoking history.

**Procedure: Measurement of lung volumes and capacities.**

Each subject should be assigned a unique identifier that consists of the lab section, randomly assigned group number, and letter for each member. For example, a particular subject in lab section B might be B2a (section B, group 2, member a).

For each of the following procedures, every person in the lab section should take measurements, and post the data to the lab section discussion board in an Excel, csv or text file. Please use the standard abbreviations to head the columns in your spreadsheet. Optional: provide your weight, height, sex, and relative fitness level; you may choose to omit any or all of these factors if you choose.

The spirometer is an instrument that can be used to measure various lung volumes. Our Ohio 822 spirometers have a piston with an internal diameter of approximately 29.6 cm. Calculate the displacement ratio in L/mm for the pen traces produced by this spirometer.

The Koko spirometer is a USB device that performs a variety of lung volume calculations for you. You do not need to recalculate these values if you have already done this set of calculations for the Ohio spirometers – just include them in your table of data.

For parts (a) through (d) set the chart recorder speed to the slower setting. In order to avoid wasting paper, the operator should start the machine just before the subject starts the described breath.

   a) **Vital Capacity (VC).** Set the spirometer pen at zero on the graduated scale. The subject inhales to maximum capacity, and holds his breath. After the mouthpiece is inserted, the subject blows air into the spirometer to his or her maximum capacity. Record the volume. Repeat the procedure two more times allowing a few seconds rest between successive measurements.

   b) **Tidal Volume (TV).** Have the subject remove and hold the mouthpiece. Move the pen to the chart record that indicates 3 liters. The subject will replace the mouthpiece while the cylinder is being held in place. Once the mouthpiece is in place, the cylinder is released. Allow the subject to breathe normally for 4-5 breaths.

   c) **Inspiratory Reserve Volume (IRV).** At the end of a normal inspiration, have the subject inhale maximally. Determine the additional volume of air inspired.

   d) **Expiratory Reserve Volume (ERV).** Allow the subject to breathe normally for 2-3 breaths and at the end of a normal expiration continue to exhale until maximum capacity is attained.

For part (e) set the chart recorder speed to the faster setting. The operator should start the machine just before the subject starts the described breath.

   e) **Forced Expiratory Volume (FEV₁).** As in part (b), take as deep a breath as possible before placing the mouthpiece in the mouth. Hold your nose and expel air into the mouthpiece as rapidly and completely as possible.
Record your group’s measurements in a spreadsheet in the following order. Note that you will need to divide the volume expelled in one second by the total volume expelled to determine the percentage expelled in the first second.

<table>
<thead>
<tr>
<th>Subject</th>
<th>VC</th>
<th>TV</th>
<th>IRV</th>
<th>ERV</th>
<th>FEV₁</th>
<th>RR</th>
<th>Sex</th>
<th>Height</th>
<th>weight</th>
<th>age</th>
</tr>
</thead>
</table>

**Upload your group’s spreadsheet of measurements to the discussion board.** Do it as soon as you have compiled the data. Whether you include the personal characteristics is up to you, but if you do not then include your calculated RV.

**For Lab Report**

a) Provide the purpose, methods, and raw results.

b) Compare your results with expected values as tabulated in the introduction. Explain why you might observe differences from the expected values.

c) Calculate the volumes and capacities listed in the second table below. Use the formulas provided above to estimate the residual volume. Tabulate them in the order shown.

<table>
<thead>
<tr>
<th>Subject</th>
<th>RV</th>
<th>TLC</th>
<th>FRC</th>
<th>IC</th>
<th>RMV</th>
<th>VC</th>
<th>100*FEV₁/VC</th>
</tr>
</thead>
</table>

d) For each of the values you measured and calculated, provide the mean and standard deviation over the entire lab section. Compare the mean TLC for those subjects who provided their weight and those who did not.

e) Use Excel’s or MATLAB’s linear regression tool to determine the correlation between TLC and height, and TLC and weight.

f) In what types of disorders would you expect an abnormally low fraction of the vital capacity to be exhaled in one second?

**Calculations & Questions**

a) Determine the volumetric flow rate of air during the first second. Assuming that the diameter of the trachea is 2 cm, calculate the Reynolds number of the air flow in the trachea. $Re = \text{density} \times \text{diameter} \times \text{velocity} / \text{viscosity}$.

b) Air is compressible, but in fluid dynamics the term “compressible flow” is used when the flow speed is greater than about 20% of the speed of sound. This ratio of velocity to speed of sound is called the Mach number. Find the Mach number in the trachea at the time of maximal flow.

c) The air in the lungs provides a large portion of the buoyant force on our bodies when submerged. Calculate the difference in buoyancy provided by the air in your lungs after a forced inspiration at the surface of the water (depth = 0.2 m) to the force when submerged to a depth of 3 m.
Part 3: Physiologic Control of Breathing

Introduction
The second part of this experiment is designed to demonstrate the effects of changes in the amount of oxygen inspired on breathing rate, heart rate, and blood pressure. Low blood $pO_2$ is known as hypoxia; low blood $pCO_2$ as hypocapnea; high blood $pCO_2$ as hypercapnea. This will be demonstrated by rebreathing into a plastic bag, holding the breath, hyperventilation, and hypoventilation.

There are various physiologic conditions that can change breathing rate, heart rate, and blood pressure, such as a change in the length or diameter of the airways that changes the airway resistance. Additionally, there can be changes in the patterns of ventilation, as listed in Table 3.1, adapted from Silverthorn’s Human Physiology.

<table>
<thead>
<tr>
<th>NAME</th>
<th>DESCRIPTION</th>
<th>EXAMPLES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eupnea</td>
<td>Normal quiet breathing</td>
<td></td>
</tr>
<tr>
<td>Hyperpnea</td>
<td>Increased respiratory rate and/or volume in response to increased metabolism</td>
<td>Exercise</td>
</tr>
<tr>
<td>Hyperventilation</td>
<td>Increased respiratory rate and/or volume without increased metabolism</td>
<td>Emotional hyperventilation; blowing up a balloon</td>
</tr>
<tr>
<td>Hypoventilation</td>
<td>Decreased alveolar ventilation</td>
<td>Shallow breathing; asthma; restrictive lung disease</td>
</tr>
<tr>
<td>Tachypnea</td>
<td>Rapid breathing; usually increased respiratory rate with decreased depth</td>
<td>Panting</td>
</tr>
<tr>
<td>Dyspnea</td>
<td>Difficulty breathing</td>
<td>Various pathologies or hard exercise</td>
</tr>
<tr>
<td>Apnea</td>
<td>Cessation of breathing</td>
<td>Voluntary breath-holding; depression of CNS control centers</td>
</tr>
</tbody>
</table>

Procedures
Set-up:
1. Plug everything in before connecting the USB cable.
2. Open LoggerPro.
3. The respiratory monitor belt should be detected automatically. Otherwise, go to Experiment → Setup sensor → Resp. Monitor Belt or Gas Pressure Sensor.
4. Attach the respiratory monitor belt around the chest and the blood pressure cuff on the left arm.
5. Set sampling rate to 10 sec$^{-1}$ and use Continuous data collection.
For each of the following steps, one person in each group should get measurements and share the data with all in your group. Provide the measurements to the group that did not have time to conduct these experiments. Choose one of the optional tasks.

a) Record the normal breathing for one minute. During that time, determine the normal pulse rate and blood pressure.

b) Have the subject be seated in a chair or on the horizontal table. The subject should hold breath until a level of discomfort is reached, then breath normally until comfortable again. Repeat twice. Note how long the breath is held, how long the recovery time is, and the breathing, pulse and blood pressure throughout. If a pulse oximeter, respirometer, or heart rate monitor is available, include those measurements with this experiment.

c) Repeat the breath-holding experiment but precede the cessation with hyperventilation (rapid, deep breathing) for about 30 seconds. Be certain that the subject stays seated or lies down! Record the same values as before.

d) Optional: choose a sleep-deprived member of the team, take baseline readings while seated, then allow the subject to lie down and possibly to sleep, perchance to dream (aye, there’s the rub!). Record the relaxed values of breathing, heart rate and blood pressure.

e) Optional: Sterilize the end of a long tube with alcohol. Have the subject breathe through this tube while monitoring the physiological conditions as well as O2 and CO2 content in the breath until conditions can no longer be tolerated. Repeat with a tube of a different volume.

f) Optional: record BR, BP and HR before and after running to the 5th floor.

For Lab Writeup
Include purpose, methods and results as usual, focusing on the following information.

a) What is the resting value of the breathing rate, pulse rate and blood pressure?

b) Graph the HR, BR, and BP as a function of time.

c) Compare the length of time that the breath could be held after normal breathing and after hyperventilation. Do they match your expectations? To what factors do you ascribe each change in breathing, heart rate and blood pressure that occur?

d) Comment on the changes you would expect in blood flow to the brain, and what factors you considered in your estimate. Can you provide a physiological explanation of the benefit or consequence of these changes?

e) Comment on your observations and suggest causes. Is there a difference with small vs. large diameter tubes? Explain why you think this would be.

f) Of the three values measured, which appears to be the most affected by exercise?

This is a GROUP REPORT but I would like each of you to write up one section. You may come up with answers to the questions as a team, but the writing should be individual. See the online calendar for the due date.