RESPIRATION

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ENGINEERING OBJECTIVES

1. To determine the rate of oxygen consumption and carbon dioxide production using gas analysis

2. To analyze the breathing process using engineering principles

3. To investigate rates of CO_2 production and O_2 consumption under various breathing conditions

4. To perform mass balances on the lungs

5. To use the Ideal Gas Law in engineering calculations

INTRODUCTION

The air we breathe in is 21% O_2 and 79% N_2, (neglecting humidity). When the air reaches the lungs, some of this oxygen is transferred from the lungs to the blood, and is then transported throughout the body to be used for energy. In addition, the blood contains some carbon dioxide (a waste product) that is transferred to the air in the lungs, which is then exhaled. The result is that the exhaled air contains less oxygen and more carbon dioxide than the inhaled air.

The air in the lungs also becomes humidified with water before it is exhaled. In fact, exhaled air is completely saturated with water – it contains the maximum amount of moisture, and is therefore has a relative humidity of 100%. We lose water as we breathe! The typical composition of exhaled air is about 18% O_2, 78% N_2, and 4.0% CO_2.

With each breath, approximately 0.5 L of air travels deep into the lungs, into tiny sponge-like sacs called alveoli, where the exchange of oxygen, carbon dioxide, and water between the air and the body occurs. A typical rate of breathing (at rest) is about 12-20 breaths per minute.

The rates at which oxygen, carbon dioxide, and water are exchanged with the body are very important. (We will later see how these rates are related to both energy production and cooling). Engineers working on the design of an artificial lung must develop a system capable of achieving these rates of gas transfer.

Gas analysis equipment is capable of measuring the amounts of oxygen, carbon dioxide and water that is inhaled and exhaled. In order to calculate the rate at which these gases are transferred to the body, a **mass balance** is used. In its simplest form, a mass balance states: input = output.

It is that simple--just what goes in must come out. Inhaled oxygen (input) comes out of the lungs (output) by exhalation and by transfer to the body.

Mass of oxygen inhaled = Mass of oxygen exhaled + Mass of oxygen transferred to the body
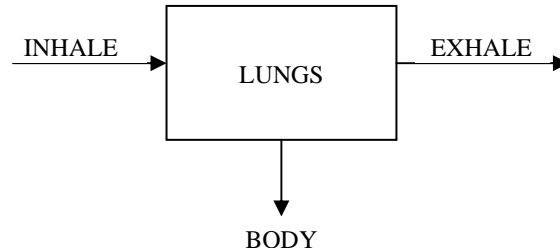
In this experiment we will measure flow rates and concentrations of the air that is inhaled and exhaled. We will calculate the flow rates of oxygen and carbon dioxide inhaled and exhaled during respiration. We will also calculate their rates of exchange between the lungs and body. The calculations will employ **the Ideal Gas Law and mass balances**.

Recall that the Ideal Gas Law states

$$PV = nRT$$

Where

   P = pressure

   V = volume or volumetric flowrate

   n = moles or molar flowrate

   R = ideal gas constant

   T = Temperature

We will use the following units for P, V, and T: P(mm Hg), V(L) and T(K). The value of the gas constant in these units is

$$62.36 \frac{L \cdot mm\,Hg}{mol \cdot K}$$

The pressure in the lab is measured using the pressure gauge on the wall behind the row of computers. It is displayed in inches of mercury (in. Hg), the Breeze software displays pressure as a unit of mm Hg. To convert a pressure from in Hg to mm Hg, multiply by 25.4 mm/in.

BACKGROUND PHYSIOLOGY

LUNGS

The primary function of the lungs is to supply oxygen to the blood, which in turn transports it to the rest of the body. The lungs also assist in the removal of carbon dioxide and water. The lungs can be looked at from an engineering standpoint as a mass transfer device: they have an efficient design that facilitates the rapid exchange of these gases between the lungs and the blood. The volume of the lungs is about the size of a basketball and weighs about 1 kg. If the lungs were spread out they would cover a surface area of 60 to 80 m^2. This is about 35 times greater than the surface area of a person, and is large enough to cover more than half a tennis court! (Cameron[1], p. 145)

THE ALVEOLI

The actual transfer of oxygen and carbon dioxide occurs in tiny sacs called alveoli, which comprise the terminal ends of the whole branched network of flow passages in the lungs. There are more than 300 million alveoli, which are the final branchings of the respiratory tree and act as the primary gas exchange units of the lung. The gas-blood barrier between the alveolar space and the pulmonary capillaries is extremely thin, allowing for rapid gas exchange. Diffusion occurs through the extremely thin barrier of the alveolar and capillary cells.

MECHANICS OF BREATHING

At rest, during normal breathing the pressure in the alveoli is about 60 mm Hg greater than in the venous blood that enters the pulmonary capillaries. This pressure differential is what causes a person to breathe and air to enter the lungs.

During inhalation, the **diaphragm** and **intercostal muscles,** the muscles between your ribs, contract to expand the chest cavity. This expansion lowers the pressure in the chest cavity below the outside air pressure. Air then flows in through the airways from high pressure to low pressure and inflates the lungs. When you exhale, the diaphragm and intercostal muscles relax and the chest cavity gets smaller. The decrease in volume of the cavity increases the pressure in the chest cavity above the outside air pressure. Air from the lungs at high pressure then flows out of the airways to the outside air at low pressure. The cycle then repeats with each breath. (*How Your Lungs Work*[2])
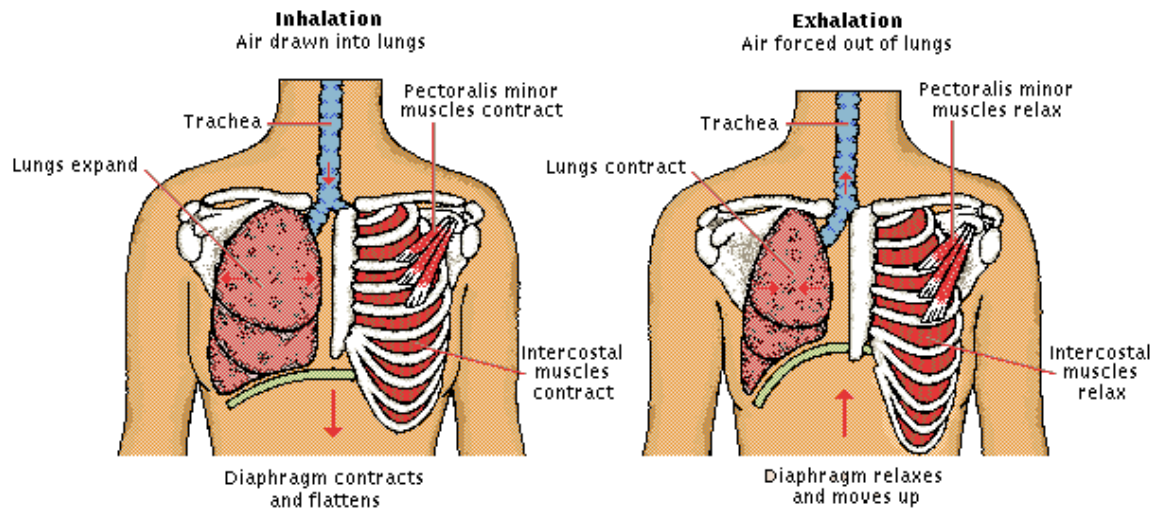
Inhalation
Air drawn into lungs

Trachea
Pectoralis minor muscles contract
Lungs expand
Intercostal muscles contract
Diaphragm contracts and flattens

Exhalation
Air forced out of lungs

Trachea
Pectoralis minor muscles relax
Lungs contract
Intercostal muscles relax
Diaphragm relaxes and moves up

Figure 1. Mechanics of Breathing. Picture taken from Encarta3.

EXERCISE PHYSIOLOGY TERMS

The computer software used in this laboratory uses a system of nomenclature that is standard to exercise physiology. Common terminology is given below. In Engineering, the standard nomenclature is sometimes different. The engineering terminology and nomenclature is explained after each definition.

BTPS – Body Temperature Pressure Saturated. 37°C and barometric pressure, saturated with water. The vapor pressure of water at 37°C is 47 mm Hg. The fraction of water in air at 37°C is 47 mm Hg/P_B.

STPD – Standard Temperature Pressure Dry. 0°C and 760 mm Hg, dry.

VO2 ($\dot{V}_{O2}$) = calculated volumetric rate of oxygen consumption, (L/min or ml/min) – calculated by software. The software presents VO2 values at in L/min at STPD – remember that the volume would be different at a different temperature or pressure.

VCO2 ($\dot{V}_{CO2}$)= calculated volumetric rate of carbon dioxide production, (L/min or ml/min) – calculated by software. The software presents VO2 values at in L/min at STPD.

V_E = measured volumetric flow rate of air (L/min) moving out of the lungs at the designated conditions, either BTPS or STPD. We have chosen BTPS for the Freshman Clinic report.

V_I = calculated volumetric flow rate of air (L/min) moving into the lungs, at BTPS.

V_t = tidal volume, the measured volume of air exhaled in a single normal breath (L).

O$_2$ % (FEO$_2$ mix) = percent oxygen expired, on a dry basis – measured. (In engineering we commonly work with fractions instead of percentages. We will use $y_{O2}^{out,dry}$ to denote the mole fraction of oxygen in the exhaled gas on a dry basis.)

CO$_2$ % (FECO$_2$-mix) = percent carbon dioxide expired, on a dry basis – measured. (In engineering we commonly work with fractions instead of percentages. We will use $y_{CO2}^{out,dry}$ to denote the mole fraction of oxygen in the exhaled gas on a dry basis.)

EXPERIMENTAL PROCEDURE

1. Select one member from the group to control the computer and another to be the test subject. Each test subject will receive a pneumotach. Please **do not** share pneumotachs. The rest of the group members are responsible for recording the information and instructing the computer controller and the test subject as per the procedure.

2. Record the Temperature (°F), Pressure (in Hg), and Relative Humidity (%RH) of the laboratory in a laboratory notebook.

3. Open the program named "Breeze".

4. Select **File**, **New**, **Patient**.

5. Input the test subject's **last name**, **ID** (initials), **DOB** (date of birth), **Race**, **Sex**.
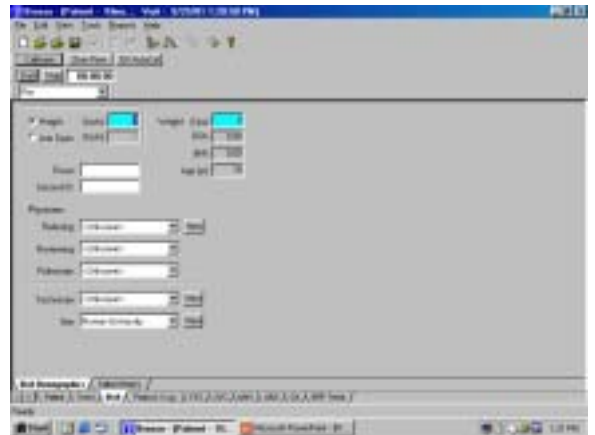
6. Select **Add Visit**.

7. Fill in the test subject's **height** (in inches, ex. 5'5"=65 inches) and **weight** (lbs).

8. Select the **GX** tab at the bottom of the screen.

9. Ensure that the following options are set:

   a. Choose Bike for the Scriptname
   b. Clear all boxes for external devices
   c. Choose freewheel 0 minutes and 15 W ramp exercise test

10. Make certain that the gas sample line (pink wire) is connected to the Cal/Port.

11. (Only if instructed by professor) Select **Zero Flow**, then **GX AutoCal**. These buttons are located at the top of the screen. Allow system to recalibrate.

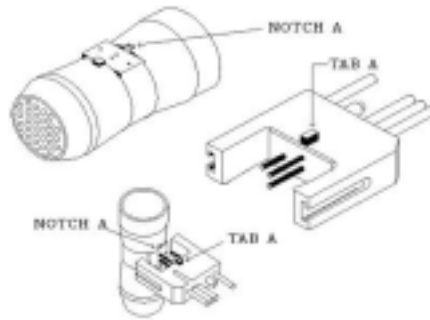12. The test subject should prepare the pneumotach (Figure 2) for testing.

Figure 2. The MedGraphics Pneumotach.

    a. Inspect the pneumotach for any abnormalities or cracks.

    b. Place the pneumotach into the umbilical clip, aligning the clip tab with the notch in the pneumotach.

    c. Undo the gas sample line from the Cal/Port and insert it into the pneumotach. Ensure that the gas line (pink wire) can be seen in the pneumotach but is not touching the crossbars (Figure 3).
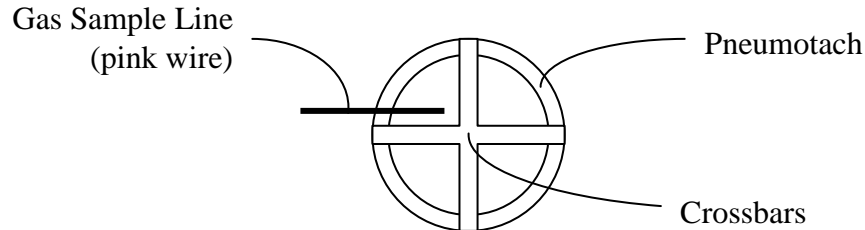

Figure 3. Proper Placement of Sample Line

    d. Insert pneumotach, grated side first, into saliva trap mouthpiece.

13. Test subject should sit on the bicycle and make certain that his/her feet are strapped in. For the at rest portion, the test subject should remain still. Position the pneumotach in mouth so that the sample line enters from the top of the pneumotach. Place the nose clips over the test subject's nose and continue to breathe normally.

14. Select the **BxB** tab at the bottom of the screen.

15. Select **Tools** and **PWave**. Verify that the compute program is accepting data.
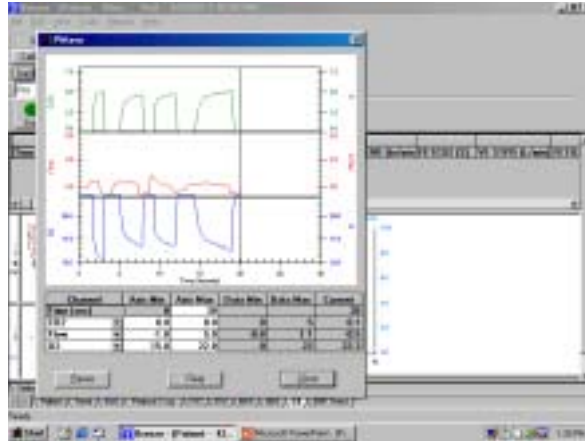
16. Close the **PWave** box.

Figure 4 Verification of PWave Accepting Data

17. Click **Start** (the big green button) on the test pad to begin data collection. Allow data to be collected for four minutes while the test subject is at rest (time recorded on computer screen). The patient should relax and breathe normally.

18. When four minutes have passed, select **Exercise** on computer screen. The test subject should now begin to pedal, maintaining the bicycle speed between 70-80 rpm (rpms can be determined from the face of the bicycle). While exercising, the pneumotach should be held steady in the mouth.

19. Continue data collection during exercise for four more minutes. When the time reaches 8 minutes on the screen, select **Stop**. The test subject can now remove the pneumotach and the nose clip and dismount the bicycle. **(Note: Group members should have paper towels ready for when the test subject has finished using the equipment.)**

20. To retrieve the data, select **Reports**, **Report Switchboard**, and click **OK** on the pop-up window.

21. Choose the Freshman Clinic Report format.

22. Select page to print and then press "print page" button. Then Close the Access window.

23. Wash pneumotach and mouthpiece in chlorine bleach solution in the sink.

HOMEWORK

To be turned in on the due-date: (1) Lab notebook page, (2) calculations and (3) answers to follow-up questions. The calculations should be neatly written on engineering paper (show all steps and show units throughout your calculations). The answers to the follow-up questions should be typed. Also hand in your evaluation/feedback form for this lab.

Lab Notebook

The report generated by the software will provide many data points corresponding to many sampling times. For your calculations, you will choose data from only two sampling times. The first point will be at two minutes into your breathing cycle at rest and the second point will be at two minutes into your breathing cycle while exercising on the bike.

In your laboratory notebook, record the temperature, pressure, and relative humidity in the room. Find the rows of data corresponding to the two sample times above (2 minutes into the normal breathing cycle and 2 minutes after the start of exercise. Record your values of %O_2 (FEO$_2$), %CO_2 (FECO$_2$) and V_E for each.

Temperature (°C)	
Pressure (cm Hg)	
Relative Humidity (%)	

Time (min)	"FETO2" (% oxygen)	"FETCO2" (%CO$_2$)	$\dot{V}_E$ (L/min)
2 min after start			
2 min after start of exercise			

Calculations

Refer to the supplemental handout with the sample calculations for respiration. Follow the calculation procedure outlined in the handout to answer the following questions.

1. Find the total <u>molar</u> flow rate of exhaled air at BTPS conditions($\dot{n}_{out}^{BTPS}$, mol/min).

2. Find the molar flow rate of exhaled <u>dry</u> air at body temperature and barometric pressure ($\dot{n}_{out}^{dry}$, mol/min).

3. Find the molar composition of nitrogen in the dry outlet gas (y_{N2}^{dry})

4. Find the flowrate of oxygen, nitrogen, and carbon dioxide in the exhaled breath ($\dot{n}_{O2}^{out}, \dot{n}_{CO2}^{out}, \dot{n}_{N2}^{out}$)

5. Find the flowrate of inhaled nitrogen ($\dot{n}_{N2}^{in}$)

6. Find the total flowrate of the dry air inhaled ($\dot{n}^{in,dry}$)

7. Calculate the molar flowrate of oxygen in the inhaled air ($\dot{n}_{O2}^{in}$)

8. Find the rates of oxygen and carbon dioxide transfer to the body ($\dot{n}_{O2}^{body}, \dot{n}_{CO2}^{body}$)

Follow-up Questions

1. The CPX/D system that was used in the lab is produced by MedGraphics and has a CO_2 and an O_2 analyzer. The O_2 analyzer is made from zirconia and the CO_2 analyzer uses NDIR.

    a. In your own (concise words) how do these two analyzers work? A few sentences on each is sufficient. (Hint: visit the websites www.k2bw.com and www.servomex.com. Each website has a site map to help you find information on these technologies.

2. The pneumotach, which you used in the lab has a more technical name; which is a pneumotachometer. Its U.S. patent number is 4,905,709.

    a. Who invented the pneumotachometer?

    b. In your own words, describe the "FIELD OF THE INVENTION"(hint: www.uspto.gov and search by patent number.)

3. List two important **functions** of an artificial lung. Be quantitative.

4. List three other features that you consider important in the design of an artificial lung

REFERENCES

1 Cameron, J., J. Skofronick,. and R. Grant, Physics of the Body, Medical Physics Publishing, Madison, WI, 1999.

2 *How Your Lungs Work*. http://www.howstuffworks.com/lung.htm. December 21, 2001.

3 Encarta online Encyclopedia: www.encarta.com