Don't Waste Your Breath

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Abstract

Our lungs are membrane system that allows the exchange of O_2, CO_2, and H_2O between the body and the air. When air is inhaled, oxygen is transported to the blood by diffusion through the alveolar membrane of the lungs. Carbon dioxide, a waste product produced by cells, is simultaneously removed from the blood by diffusion through this membrane to the air in the lungs, and is then exhaled. During breathing, the air in the lungs becomes saturated with water, and water is therefore removed from the body through respiration. Breathing also plays a role in heat transfer and thermal regulation, since heat transferred to the air in the lungs is removed during exhalation. We have developed a hands-on experiment to introduce freshman engineering students to chemical engineering principles through the exploration of the breathing process. The objectives of this module are (1) to analyze the lungs as a mass transfer device, (2) to use gas analysis to investigate the rate of O_2 consumption and CO_2 production, (3) to perform simple mass and energy balances on the lungs, (4) to prepare a simple process flow diagram, and (5) use a process simulator to perform mass and energy balances.

Introduction

Rowan's two-semester Freshman Clinic sequence introduces all freshmen engineering students to engineering in a hands-on, active learning environment. Engineering measurements and reverse engineering methods are common threads that tie together the different engineering disciplines. Previous reverse engineering projects have involved common household products such as automatic coffee makers [1,2,3] hair dryers and electric toothbrushes [4]. Recently, the human body was added to the repetoire of familiar machines to be reverse engineered. In a semester-long project, freshmen engineering students explore the interacting systems of the human body in a hands-on, active learning environment. They discover the function, interaction, and response to changing demands of various systems in the human body: the respiratory, metabolic, cardiovascular, electrical, and musculoskeletal systems. This paper describes a laboratory experiment in which students are introduced to engineering measurements and calculations, estimations and unit conversions through their application to the respiratory system.

Students measure physiologic variables such as breathing rate, and respiratory gas compositions at rest and during moderate exercise on an exercise bicycle ergometer. Using their data, students perform mass balances to determine the rates of oxygen consumption and carbon dioxide production. This enables them to estimate the rate of energy expenditure, and determine the mechanical efficiency of the human body. They apply energy balances to determine the rate of heat transfer through respiration, and compare this to the total resting energy expenditure. Finally, students create a process flow diagram using HYSYS [5] process simulator, and perform mass and energy balance calculations on the lungs.

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Background

The air we inspire (inhale) is approximately 21% O_2 and 79% N_2 on a dry basis, while the expired (exhaled) gas from the lungs contains approximately 75% N_2, 16% O_2 and 4% CO_2 and 5% H_2O [6,7]. The inspired air is at ambient pressure, temperature and humidity, while the expired air is saturated at body temperature and ambient pressure. The lungs serve as a mass transfer device that allows rapid and efficient exchange of O_2, CO_2, and H_2O. The key to efficient gas exchange in the lungs is the tremendous surface area provided by the alveoli, the 300 million tiny sacs representing the terminal ends of the branched air-flow passages. The volume of the lungs is about the size of a basketball, but their surface area is about 80 m^2! Oxygen and carbon dioxide are moved in and out of the lungs, through the respiratory airways, by a process known as ventilation. Oxygen and carbon dioxide are exchanged between the alveoli and the blood in the pulmonary capillaries by diffusion [8].

A material balance on the lungs relates the oxygen consumption rate **(**$\dot{V}_{O_2}$, L O_2/min**)** to the total air flow rate ($\dot{V}$, L/min), and molar oxygen compositions of the inspired and expired air ($y_{O_2}^{in}$ and $y_{O_2}^{out}$):

$$\dot{V}_{O_2} = \dot{V}^{in} y_{O_2}^{in} - \dot{V}^{out} y_{O_2}^{out} \qquad \textbf{(1)}$$

An analogous component balance can be written for carbon dioxide, nitrogen and water. Nitrogen is known to be inert, so that the net rate of transfer with the body is zero. The gas exchange data ($\dot{V}^{out}$, $y_{O_2}^{out}$, $y_{CO_2}^{out}$) are reported at BTPS (Body Temperature and Pressure, Saturated) conditions. Since the ambient temperature and humidity conditions are different, the material balances involve Ideal Gas Law and relative humidity calculations.

Oxygen consumed during respiration is transported by blood to the body, where it is used by cells to produce energy through the oxidation of carbohydrates and fats from food. The reaction stoichiometry and thermodynamics are well known, and the rate of energy production may be calculated from the rate of O_2 consumption [6]. For instance, energy is released in the oxidation of glucose (evaluated at STP [9]):

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6H_2O + 6CO_2 \quad + \quad 673 \text{ kcal}$$

The heat of reaction for a mixed diet is equivalent to approximately 4.862 kcal per liter of oxygen consumed. This energy is used to maintain the function of the body (basal metabolism) and to do external work (exercise). The rate of energy expenditure (EE) is related to the rate of O_2 consumption ($\dot{V}_{O_2}$) and heat of reaction:

$$\text{EE} = \dot{V}_{O_2} \times 4.862 \frac{\text{kcal}}{\text{L O}_2} \quad \textbf{(2)}$$

The First Law of Thermodynamics reveals that if the energy equivalent of consumed food exceeds the energy expended, the result is a net storage of energy in the form of fat. The human body doing exercise can be analyzed as a machine doing mechanical work. To do mechanical work such as bicycling or running, the body consumes energy supplied by oxidation of food. Because the body is not perfectly efficient, the energy consumed is greater than the actual mechanical energy expended. The efficiency, η, of this human machine or a human is expressed by the following equation:

$$\eta = \frac{\text{mechanical work done}}{\text{energy consumed}} \cdot 100 \quad \textbf{(3)}$$

Respiration also contributes significantly to the thermal regulation system of the body. Inspired air is warmed from ambient temperature to body temperature prior to being exhaled. In addition, water evaporates from the wet alveolar membranes to saturate the air in the lungs prior to expiration. The humid exhaled air removes heat from the body in the form of latent heat of vaporization. The rate of cooling (q, kcal/min) achieved through the process of respiration is:

$$q = \dot{m}_{air} C_{p\,air} \left(T^{out} - T^{in} \right) + \Delta H_{vap,w} \left(\dot{m}_w^{out} - \dot{m}_w^{in} \right) \quad \textbf{(4)}$$

In Equation 5, m is the molar flowrate (mol/min), C_p is the molar heat capacity (kcal/mol K), T is temperature (K) and ΔH_{vap} is the latent heat of vaporization of water (kcal/mol). Subscripts represent components air air or water, and superscripts represent inlet or outlet air. Under normal conditions, about 14% of the body's total cooling is accomplished through respiration, and this percentage increases during exercise [10].

Equipment

The equipment used for all cardiorespiratory measurements was a gas exchange system, coupled with a cycle ergometer. The MedGraphics CPX/D cardiorespiratory gas exchange system includes capability for direct oxygen and carbon dioxide measurement and ventilation (flow). The system interfaces with a cycle ergometer (Lode Corvial) for exercise testing. To prevent cross contamination between patients (students), disposable PreVent™ pneumotachs were used once and then discarded. This system was purchased from MedGraphics, St. Paul, MN for approximately $35,000. While this price may be prohibitively expensive for an engineering program to purchase if not used for research purposes, many universities have such equipment available in a physiology or exercise science laboratory.

Experiment

Prior to commencing the experiment, the MedGraphics CPX/D system pneumotach is calibrated for air flow rate using a calibration syringe. Gas calibrations for oxygen and carbon

dioxide are performed using a reference gas (21% oxygen, balance nitrogen) and a calibration gas (12% oxygen, 5% carbon dioxide). In addition, the barometric pressure and ambient relative humidity are entered manually, and these values are stored by the software.

One student per team of four students is selected as the test subject for the experiment. Using the MedGraphics CPX/D cardiorespiratory test system coupled with the Corvial Cycle ergometer, measurements are taken at rest (for four minutes) and during exercise (for four minutes, pedaling at 70-80 rpm at 30 W braking power). A student is shown performing the experiment in Figure 1.

The following quantities are measured directly and displayed using Med Graphics Breeze Suite software: $\dot{V}^{out}$, $y_{O_2}^{in}$, $y_{O_2}^{out}$, $y_{CO_2}^{in}$, $y_{CO_2}^{out}$, and breaking power. The gas exchange data are reported at BTPS (Body Temperature and Pressure, Saturated) conditions. The software offers many options for the convenient display of automatically-calculated values; however, these direct measurements at BTPS conditions are the only values necessary to perform the calculations involved in this experiment. The calculation/display options may be exercised in order to provide numbers against which students may check their calculations.

For their laboratory report, students perform all calculations by hand. In a subsequent laboratory period, students are introduced to the process simulator, HYSYS. In an in-class activity, students use HYSYS to draw a simple process flow diagram of the respiration cycle. They provide their data and allow HYSYS to perform material and energy balances on the respiration process, and they compare the results of the simulation to their hand calculations.

Results

Gas exchange measurements were taken at rest and during exercise as described above. Nearly everyone is aware of the body’s physiologic responses to exercise: The body’s increased demand for energy is met with an increased breathing rate and heart rate. By comparing the resting and exercise gas exchange measurements, students quantify this physiologic response. Table 1 shows gas exchange measurements and calculated values for the respiration experiment, for an 18 year female student (120 lb, 64 in). Comparison of exercise data to resting data reveals that the rate breathing rate is substantially faster during exercise, the oxygen concentration of expired air is slightly lower than its resting value. This translates into higher rates of oxygen consumption and carbon dioxide production during exercise. The energy expenditure as calculated by Equation 2 is higher during exercise, as expected by our knowledge that exercise “burns calories”. The mechanical efficiency of cycling is only 23.4%, because a significant amount of energy is required to overcome internal and external friction [6].

There are three sources of variance in their measurements that are examined by students in the experiment: (1) accuracy and reproducibility of the equipment used for experimental measurement; (2) breath-by-breath variation on a single subject; and (3) person-to-person physiologic variations. The first is illustrated by taking five consecutive measurements of the ambient air composition and determining the average and standard deviation. The second is explored by observing ten consecutive breath-by-breath analysis of flow rate and gas compositions for a single subject. The third is explored by examining software-predicted results and experimental results between different students. Factors such as gender, height and weight are considered. These are explored in more depth in a follow-up experiment in which students use correlations to predict results for body surface area and energy expenditure.

Table 1. Gas exchange measurements and calculations at rest and during cycling exercise. : $\dot{V}^{out}$, $y_{O_2}^{in}$, . $y_{O_2}^{out}$, $y_{CO_2}^{in}$, and $y_{CO_2}^{out}$ are measured experimentally at BTPS conditions. $\dot{V}_{O_2}$ and $\dot{V}_{CO_2}$ are calculated at STP. (Ambient Conditions: T=21°C, P=755 mm Hg, RH=50%)

Measured variables				Calculated Variables			
Power (W)	$\dot{V}^{out}$ (L/min)	$y_{O_2}^{out}$	$y_{O_2}^{out}$	$\dot{V}_{O_2}$ (L/min)	$\dot{V}_{CO_2}$ (L/min)	EE (kcal/min)	**η (%)**
0	7.99	0.174	0.035	0.25	0.23	1.23	--
30	20.50	0.171	0.035	0.63	0.54	3.07	23.4

Using HYSYS process simulator, the experimental gas exchange resting measurement data are used to simulate the process of respiration. The feed stream represents inspired air at ambient temperature, pressure and relative humidity. In the first unit, the air is heated to body temperature, and in the second unit it is humidified to saturation. The HYSYS respiration process flow diagram is shown in Figure 1. Material and energy balance calculations are performed and compared with hand-calculated values. The overall rate of heat transfer through respiration at rest (and at ambient conditions of the experiment) is about 10.3 kcal/h, or 14% of the total resting energy expenditure.

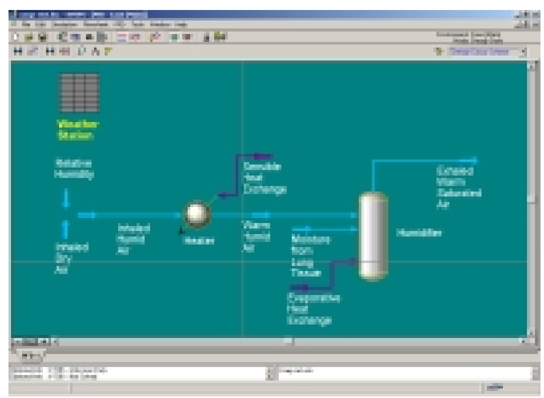

Figure 1. The HYSYS Respiration process flow diagram.

Conclusions

This paper describes a simple and exciting laboratory experiment in which a wide range of chemical engineering principles are introduced through application to the process of respiration. Students take measurements of physiologic variables both at rest and during exercise, and then perform calculations involving mass and energy balances, chemical reaction stoichiometry and heats of reaction, work and efficiency. Through these calculations, students apply the Ideal Gas Law and partial pressure, relative humidity, and Henry's law relationships. Students are also introduced to chemical process simulation software when they simulate the process of respiration using HYSYS.

Basic physiologic responses are already familiar to students through "common knowledge" and sensory experiences, and most students have a natural curiosity to learn how their own bodies work. In a series of hands-on experiments that use engineering measurements and reverse engineering methods, these physiologic responses are quantified. This establishes a framework within which new engineering concepts are introduced through the analysis of the data. Using a familiar system, sensory experiences, and hands-on active learning is thought to increase understanding and retention of the new concepts.

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References

1 Hesketh, R. and C. Stewart Slater, Demonstration of Chemical Engineering Principles to a Multidisciplinary Engineering Audience, Proceedings of the 1997 Annual Conference of the American Society for Engineering Education, Session 2513, June 15-18, 1997.

2 Marchese, A.J., R.P. Hesketh, K. Jahan, T.R. Chandrupatla, R.A. Dusseau, C.S. Slater, J.L. Schmalzel, Design in the Rowan University Freshman Engineering Clinic, Proceedings of the 1997 Annual Conference of the American Society for Engineering Education, Session 3225, June 15-18, 1997.

3 Hesketh, R.P., K. Jahan, Marchese, A.J., C.S. Slater, J.L. Schmalzel, T.R. Chandrupatla, R.A. Dusseau, Multidisciplinary Experimental Experiences in the Freshman Engineering Clinic at Rowan University, Proceedings of the 1997 Annual Conference of the American Society for Engineering Education, Session 2326, June 15-18, 1997.

4 Ramachandran, R., J. Schmalzel and S. Mandayam, Proceedings of the 1999 Annual Conference of the American Society for Engineering Education, Session 2253, June 20-23, 1999.

5 HYSYS, version 2.4.1, Hyprotech Ltd. 2001.

6 McArdle, W.D., F.I. Katch, and V.L. Katch, *Exercise Physiology: Energy, Nutrition, and Human Performance*, 4th edition, Lea and Febiger, Philadelphia, PA 1996.

7 Adams, Gene, Exercise Physiology Laboratory Manual, W.C.B. McGraw Hill, NY, 1998.

8 West, John B.(ed.), Bioengineering Aspects of the Lung, Marcel Dekker, Inc., NY, 1977.

9 Cooney, David O., Biomedical Engineering Principles, Marcel Dekker, 1976.

10 Cameron, J.R., J.G. Skofronick, and R.M. Grant, *Physics of the Body*, 2nd edition, Medical Physics Publishing, Madison, WI, 1999.

Biographical Information

Stephanie Farrell is Associate Professor of Chemical Engineering at Rowan University. She received her Ph.D. (1996) from NJIT. Stephanie has developed innovative classroom and laboratory materials in biomedical, food, and pharmaceutical engineering areas. She is the recipient of the 2000 Dow Outstanding Young Faculty Award, the 2001 Joseph J. Martin Award, and the 2002 Ray W. Fahien Award.

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Rachel Specht is a Junior Chemical Engineering Student at Rowan University. Rachel has an interest in biomedical engineering and is planning to pursue a masters degree in this field. She has been a member of the Dean's List at Rowan University. She is the current president of the Society of Women Engineers student chapter at Rowan University and plays an active role in the American Institute of Chemical Engineers.