Biomechanics Instrumentation Design Laboratory II

Pulmonary Physiology

Abstract

Biomedical engineering field requires understanding of mechanisms of pulmonary system and analyzing lung functions such as lung volumes and capacities. Also energy expenditure index should be considered with heart rate to perform exercise test. In this experiment, a spirometer was used to evaluate volumes and capacities such as tidal volume, inspiratory reserve volume, expiratory reserve volume, residual volume, respiratory dead space, vital capacity, etc. Lung volume test with multiple nitrogen washout tests, exercise test, and energy expenditure index test are useful tools to diagnose Asthma, Bronchitis emphysema, Fibrosis, and other chronic pulmonary diseases. This lab is focused on comparisons and contrast of male and female (both are non smokers). However, result could be varies with different subjects due to different lifestyle, environment, and pathology. Subject, who is an athlete with normal humidity, and no pulmonary disease, could have higher lung capacity than other subjects who is smoking at high altitude with Asthma. According to results, overall data show that male subject had higher volumes and capacities. Female subject had higher tidal volume, expiratory reserve volume and expiratory reserve volume. Frequency of breathing of male is less than female in resting situation. Both predicted vital capacity for male and female were less than actual values. Vital capacity varies with height due to oxygen consumption of body. Male subject showed less energy expenditure index than female subject.

Introduction

Biomedical engineers should understand mechanisms of pulmonary system to analyze pulmonary diseases for example Asthma, Bronchitis, etc. The purpose of this lab is for understanding the importance of mechanisms of pulmonary system. The objective of this lab is to allowing students to analyze and compare the lung functions such as lung volumes and capacities, oxygen consumption, and heart rate of female and male (non smokers). Also energy expenditure index at resting and after exercising were measured to accomplish lung volume and exercise tests. A spirometer was used in the lab to evaluate volumes and capacities. The spirometer is one of the simplest, most common pulmonary function tests and may be necessary to determine how well the lung receive, hold, and utilize air, to monitor a lung disease, to monitor the effectiveness of treatment, to determine the severity of a lung disease, and to determine whether the lung disease is restrictive or obstructive.

Lung volume test is dynamic information include tidal volume (TV), inspiratory reserve volume (IRV), expiratory reserve volume (ERV), residual volume (RV), respiratory dead space (RDS), and vital capacity (VC). TV is the volume that air moving in and out of the lungs with normal inspiration and expiration. Inspiratory reserve volume (IRV) is volume that air inspired with maximum inspiratory effort in excess of TV. Expiratory reserve volume (ERV) is the volume that air expired by active expiratory effort after passive expiration. RV is volume that air left in lungs after maximum expiratory effort. RDS is the volume that conducting zone of airways that do not exchange gas with blood. VC is the greatest amount of air that can be expired after a maximum inspiration.

VC is equal to addition of IRV, TV, and ERV. Inspiratory capacity is equal to IRV plus TV. Functional residual capacity is equal to ERV plus RV.

Asthma, Bronchitis emphysema are examples of chronic obstructive pulmonary disease. Fibrosis is an example of chronic restrictive pulmonary disease. Chronic obstructive pulmonary disease increases residual volume, vital capacity is normal, but total lung capacity increases. Chronic restrictive pulmonary disease decreases reserve volume, decreases vital volume, and decreases lung capacity.

Crouched or toe tipping gait can increase energy expenditure which can increase oxygen consumption of muscles. This can increase heart rate and frequency of breathing. Crouched or toe tipping gait need more energy to support body due to imbalanced posture during a gait.

Equations

Functional Residual Capacity: $\text{FRC} = \text{Total volume expired } \text{N2} \times \frac{100}{79}$

Energy Expenditure Index:

$$\text{EEI} = \frac{\text{Average Walking Heart Rate - Average Resting Heart Rate}}{\text{Walking Speed}}$$

Predicted Vital Capacity:
VC for Males (in liters) = 0.052 (Height in centimeters) – 0.022*(Age in years) – 3.60
VC for Females (in liters) = 0.041* (Height in centimeters) – 0.018*(Age in years) -2.69

Predicted Total Lung Capacity:
TLC for Males (in liters) = 0.0799*(Height in centimeters) -7.08
TLC for Females (in liters) = 0.066*(Height in centimeters) -5.79

Predicted Residual Volume:
RV for Males (in liters) = 0.0131*(Height in centimeters) + 0.022*(Age in years) – 1.23
RV for Females (in liters) = 0.0181*(Height in centimeters) + 0.016*(Age in years) – 2

Predicted Functional Residual Capacity:
FRC for Males (in liters) = 0.0234*(Height in centimeters) + 0.009*(Age in years) – 1.09
FRC for Females (in liters) = 0.0224*(Height in centimeters) + 0.001*(Age in years) – 1

Total Lung Capacity (TLC):
TLC = Inspiratory reserve volume (IRV) + Tidal volume (TV) + Expiratory reserve volume (ERV) + Residual volume (RV)
Inspiratory Capacity (IC):
IC = Tidal volume (TV) + Inspiratory reserve volume (IRV)
Vital Capacity (VC):
VC = Inspiratory reserve volume (IRV) + Tidal volume (TV) + Expiratory reserve volume (ERV)

Expiratory Capacity (EC):
EC = Tidal volume (TV) + Expiratory reserve volume (ERV)
Functional Residual Capacity (FRC):
FRC = Expiratory reserve volume (ERV) + Residual volume (RV)

Method

For the spirometric tests, slow vital capacity, two volunteers who were female and male were needed. Each volunteer obtained a mouth piece. Once the system was ready, each volunteer breathes normally into the mouth piece for at least 10 breaths to measure tidal volume. On the next breath, the volunteer slowly took a deep breath in and then slowly exhales out as much air as possible to measure total lung capacity and residual volume. Once the slow breath was accomplished, the volunteer returned to normal breathing for few times again. The lung volume test involves breathing in pure oxygen to wash out the nitrogen gas in the lung and in the blood. The system measures the nitrogen gas concentration in the exhaled air. The test is stopped once the nitrogen concentration is less than 2.5%. For this test, the same volunteers are needed again. Once the system is ready, each volunteer was breath normally. When a volunteer was breathing, two bars were displayed. One bar measured the depth of breathing and the other measure the frequency of breathing. If bar turns different color then red, then the volunteer should take deeper breath or faster frequency. Then repeated a same procedure for exercise test. A resting heart rate and oxygen consumption measurement were initially recorded. Once the volunteers were ready, they walked a set distance as measured by the students and then immediately obtained a heart rate and oxygen consumption reading.

Results

General information

Volunteer	Age(years)	Height(feet inches)	Weight
Male	22	5’ 10’’	164.9lbs
Female	20	5’ 6’’	164 lbs

Table 1. Spirometric test

Volunteer	IRV	TV	ERV	RV	VC	EC	IC	FRC	TLC
Male	3.19	0.88	1.09	2.06	5.16	1.97	4.07	3.15	7.22
Female	1.67	1.30	1.61	0.89	4.58	2.91	2.97	1.73	5.46

*****Units are L (liters)**
Tidal volume (TV), inspiratory reserve volume (IRV), expiratory reserve volume (ERV), residual volume (RV), respiratory dead space (RDS), and vital capacity (VC), functional residual capacity (FRC), Total lung capacity (TLC)

Table 2. Exercise test

Volunteer	Average Resting Heart Rate	Average Walking heart rate	Distance Traveled	Volume of oxygen Resting	Volume of oxygen after exercise	Time Traveled
Male	76 beats/min	113bpm	900 ft	309.2ml/min	1492ml/min	3:06 min
Female	90 beats/min	150bpm	900 ft	163.5ml/min	1040.7ml/min	3:00 min

Table 4. Energy Expenditure Index (EEI)

Volunteer	Walking speed	EEI (beats/meter)
Male	88.39m/min	0.419
Female	91.44m/min	0.656

*****Units are L(liters)**

Table 5. Predicted lung capacity

	Predicted Vital Capacity	Predicted Total Lung Capacity	Predicted Residual Volume	Predicted Functional Residual Capacity
Male	5.16	7.12	1.58	3.27
Female	3.82	5.27	1.35	2.77

*****Units are L (liters)**

Male has higher inspiratory reserve volume, residual volume, vital capacity, inspiratory capacity, functional residual capacity, and total lung capacity. Female has higher tidal volume, expiratory reserve volume and expiratory reserve volume. The maximum difference between female and male is 1.52L from inspiratory reserve volume. Frequency of breathing of male is less than female in resting situation. According to calculation, predicted vital capacity for male is 5.16L and for female is 3.82L. However, results show that vital capacity for male is 5.16L and for female is 4.58L. Vital capacity varies with height due to oxygen consumption of body. Male subject showed less energy expenditure index. Female subject shows 0.237beats/meter higher than male subject.

Example of calculation with male subject data

Functional residual capacity (FRC), where $\text{FRC} = \text{Total volume expired } N2 \times \frac{100}{79}$

= 2.504 x 100/79 = 3.14L

EEI (in beats/meter) $= \frac{\text{Average Walking Heart Rate - Average Resting Heart Rate}}{\text{Walking Speed}}$

= (113-76)/88.39 = 0.419 beats/meter

Predicted Vital Capacity:

VC for Males (in liters) = 0.052 (Height in centimeters) – 0.022*(Age in years) – 3.60

= 0.052*177.8-0.022*22-3.6 = 5.16L

Predicted Total Lung Capacity:

TLC for Males (in liters) = 0.0799*(Height in centimeters) -7.08
=0.0799*177.8-7.08=7.12L

Predicted Residual Volume:

RV for Males (in liters) = 0.0131*(Height in centimeters) + 0.022*(Age in years) – 1.23
=0.0131*177.8+0.022*22-1.23=1.58L

Predicted Functional Residual Capacity:

FRC for Males (in liters) = 0.0234*(Height in centimeters) + 0.009*(Age in years) – 1.09
=0.0234*177.8+0.009*22-1.09=3.23L

Total Lung Capacity (TLC):

TLC = Inspiratory reserve volume (IRV) + Tidal volume (TV) + Expiratory reserve volume (ERV) + Residual volume (RV)= 3.19+0.88+1.09+2.06 =7.22L

Inspiratory Capacity (IC):

IC = Tidal volume (TV) + Inspiratory reserve volume (IRV) = 0.88+3.19 = 4.07L

Vital Capacity (VC):

VC = Inspiratory reserve volume (IRV) + Tidal volume (TV) + Expiratory reserve Volume (ERV) =3.19+0.88+1.09=5.16L

Expiratory Capacity (EC):

EC = Tidal volume (TV) + Expiratory reserve volume (ERV)=0.88+1.09=1.97L

Functional Residual Capacity (FRC):

FRC = Expiratory reserve volume (ERV) + Residual volume (RV) = 1.09+2.06 = 3.15L

**Appendix A. Subdivisions of lung volumes
**Appendix B, Nitrogen washout and measurement of FRC
**Appendix C, Spirometric tests results of both male and female

Discussion

1. Male has higher inspiratory reserve volume, residual volume, vital capacity, inspiratory capacity, functional residual capacity, and total lung capacity. Female has higher tidal volume, expiratory reserve volume and expiratory reserve volume. The maximum difference between female and male is 1.52L from inspiratory reserve volume. This explains that male has higher capacity than female. Frequency of breathing of male is less than female in resting situation. In the experiment, tidal volume of female was higher than male one. This can be varied with subjects due to life pattern, health conditions, and activities that performed before testing. Expiratory reserve volume of female was higher which explains that volume of air that can be maximally exhaled after tidal expiration was larger than male. This can be varies with age of subject. Since female is younger than male subject, elasticity of alveoli of female could be better than male. This factor can be exhale larger volume of air. Also different height of subjects can make differences of total lung capacity.

2. Predicted vital capacity varies with height because vital capacity for female and male has a direct relationship with height of subjects. According to calculation, predicted vital capacity for male is 5.16L and for female is 3.82L. However, results show that vital

capacity for male is 5.16L and for female is 4.58L. Vital capacity varies with height due to oxygen consumption of body. Taller people have more muscles and need more energy to move than shorter people. Thus, vital capacity should be larger to possess enough oxygen.

3. Both female and male showed higher capacity values than predicted values. This can be due to lifestyle, pathology, and environment.

When subjects exercise regularly, then lung capacity can be higher than predicted value because more oxygen is needed during exercise. Also people who exercise have more muscles that need more oxygen during resting. Thus, tidal volume could be higher than predicted value. When subjects smoke, then lung capacity can be less than predicted value due to losing elasticity of alveoli.

When subjects have Asthma and Bronchitis emphysema which are examples of chronic obstructive pulmonary disease, results show that increasing residual volume, vital capacity is normal, but total lung capacity increasing. When subjects have Fibrosis which is an example of chronic restrictive pulmonary disease, results show that decreasing reserve volume, vital volume, and lung capacity. Also subjects have difficulties to obtain normal gait then it can also increase frequency of breathing increases. Because subjects need more energy to support their position with for example, crouched position needs to keep up with oxygen consumption due to desire of more energy.

When pulmonary testing was performed at higher altitude of mountain, subjects might have less lung capacity due to less pressure at the mountain. Also subjects would not be comfortable to breathe regularly. Tidal volume would be higher to possess enough oxygen, but if it does not satisfy oxygen level, then people could be in danger. High humidity or high temperature could affect pulmonary testing.

4. If a person has an airway obstruction, the forced expiratory vital capacity would increase to get rid of an airway obstruction. Inspiratory capacity would be increasing after the person does not have any more air in the lungs for the forced expiratory vital capacity. However, inhale and exhale action would be performed in very high frequency.

5. Male subject who is taller and heavier and walked slower than female subject, showed less energy expenditure index. Female subject shows 0.237 beats/meter higher than male subject. This explains that female subjects needed more oxygen during exercise than male subject. This could be due to female subject walking speed which was 10 ft/min higher than male subject. Due to height difference, male subject could move same distance in a short time period which can save energy during walking.

Overall, pulmonary tests have potential errors due to different health condition, environment, and life styles of subjects. However, general ideas of pulmonary test supports that lung capacity has a direct relationship with height. And energy expenditure

index could be different due to height and oxygen consumption. This can be related with pulmonary tests to analyze patients.

Conclusion

This lab was successful to understand pulmonary system and analyze data to distinguish obstructive and restrictive pulmonary diseases. Male has higher inspiratory reserve volume, residual volume, vital capacity, inspiratory capacity, functional residual capacity, and total lung capacity. Female has higher tidal volume, expiratory reserve volume and expiratory reserve volume. The maximum difference between female and male is 1.52L from inspiratory reserve volume. Frequency of breathing of male is less than female in resting situation. According to calculation, predicted vital capacity for male is 5.16L and for female is 3.82L. However, results show that vital capacity for male is 5.16L and for female is 4.58L. Vital capacity varies with height due to oxygen consumption of body. Male subject showed less energy expenditure index. Female subject shows 0.237beats/meter higher than male subject. Overall, pulmonary tests have potential errors due to different health condition, environment, and life styles of subjects. However, general ideas of pulmonary test supports that lung capacity has a direct relationship with height. And energy expenditure index could be different due to height and oxygen consumption. This can be related with pulmonary tests to analyze patients. In this lab, there was an error to set the gender wrong. Therefore, female data for resting increased the predicted values. The limitation of this lab was that students could not change pressure or humidity of environment to test how pressure and humidity might affect breathing patterns or volumes.

Reference

[1] Harris, Gerald, "BIEN 192, class notes", Marquette University, Spring 2006

[2] Winters, D. A. *Biomechanics and Motor Control of Human Movement Second Edition.* New York 1990.