Regulation of Breathing
Introduction

Breathing involves a complex interaction between many important respiratory organs and the blood. Air is brought into the lungs through the active process of inhalation, then it goes through the process of gas exchange with the blood and then finally is passively exhaled. Inspiration occurs when the diaphragm and intercostal muscles (located in the chest cavity) contract and expand, which allows air to flow into the lungs. Specifically, the diaphragm contracts downward giving more space in the lungs. Once inspiration is at its peak, the gases in the inhaled air mix with the gases in the blood through the alveoli which are the smallest units in the lungs. Gases flow down a pressure gradient and the blood then transfers the gases to the tissues that need them. Once gas exchange is complete, exhalation can occur. While in a resting state, exhalation is passive because the originally contracted muscles are now able to relax. Inspiration is active during the resting state because work must be done to create a contraction in the muscles (Sherwood, 2013, p.461-463).

This lab studied static lung volumes, effects of inspired gas composition and lung volume on respiration, as well as the process of exercise hyperpnea. When measuring static lung volumes, it was expected that the sum of the inspiratory reserve volume (IRV), expiratory reserve volume (ERV) and then tidal volume (TV) would equal the vital capacity (VC). In Part 2, it was expected that re-breathing would produce a higher CO2 composition before the breath-hold and that hyperventilation would produce a lower CO2 composition, both being compared to the normal breathing. In terms of the CO2 composition after breath hold, it was expected that the compositions would all be the same, given that the breath was held to the same level of uncomfortableness. The duration of breath-hold was expected to be shorter for the re-breathing exercise and longer for hyperventilation, again both being compared to normal breathing.
When looking at the effects of lung volume on the duration of the breath-hold, it was expected that the larger lung volumes would have a longer corresponding breath-hold. Thus, the inspiration/inhalation before breath-hold would cause a longer breath hold than the expiration/exhalation. For Part 3, exercise was expected to cause higher tidal volumes, minute ventilation and minute CO2. CO2 content and respiratory rate were expected to stay roughly the same. It was expected to see that higher tidal volumes gave more effect on alveolar ventilation during exercise than an increase in the respiratory rate.

**Materials and Methods**

The procedure for this lab followed Lab 6: The Human Respiratory System, which is outlined in the *NPB 101L: System Physiology lab manual* written by Erwin Bautista and Julia Korber. There were no specific alterations made to the directions listed in the manual. Part 1 involved the use of a spirometer, nose clip, stopwatch, and mouthpiece. The subject was a 22 year old male student in good health. Biopac Student Analysis software was used to obtain data from his inhalation and exhalations. Part 2 involved the use of a plastic bag and two rubber bag, a stopwatch, nose clip and carbon dioxide analysis machine. The subject was a 21 year old female student in good health. The subject underwent three different breathing challenges, each one giving her a specific breathing style to undergo before blowing air into a bag. Following this, she held her breath and then blew into another bag. Both bags were then analyzed for CO2 content. In Part 3, the same female subject was used. The subject was put on an exercise bike and also breathed into a spirometer while her nose was clipped. While biking, the workload on the bike was incrementally increased. Throughout this entire experiment the subject continued biking. Data was then analyzed for CO2 content, tidal volume, respiratory rate, and airflow using the Biopac Student Analysis Software.
Results

Part 1: Measuring Static Lung Volumes

Table 1 displays the different static lung volumes that were observed when the subject breathed into a spirometer. The volumes measured and analyzed on the software were Inspiratory Reserve Volume (IRV), Expiratory Reserve Volume (ERV), Tidal Volume (TV), Vital Capacity (VC), Minute Ventilation (Ve), Dead Space volume (Vds), and Alveolar Ventilation (Va). The delta tool was used to calculate all volumes, as instructed by the lab manual. Minute ventilation, dead space ventilation and alveolar ventilation were all calculated using the equations from the lab manual. It was expected that the sum of IRV, ERV and TV would equal VC however there was some discrepancy.

<table>
<thead>
<tr>
<th>Volume</th>
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<tbody>
<tr>
<td>IRV</td>
<td>1.62 L</td>
</tr>
<tr>
<td>ERV</td>
<td>0.76 L</td>
</tr>
<tr>
<td>TV</td>
<td>1.25 L</td>
</tr>
<tr>
<td>VC</td>
<td>3.4 L</td>
</tr>
<tr>
<td>Ve</td>
<td>20 L/min</td>
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<tr>
<td>Vds</td>
<td>2.8 L/min</td>
</tr>
<tr>
<td>Va</td>
<td>17.2 L/min</td>
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Part 2: Effects of Inspired Gas Composition and Lung Volume on Respiration

Figure 1 displays the effects that different ventilation types had on CO2 percentages in air that was breathed out before and after a breath-hold. It is observed that compared to normal breathing, re-breathing had a higher end tidal CO2 percentage at 5.8%. In contrast, hyperventilation had a lower amount at 2.59%.
The post breath-hold composition for normal breathing and hyperventilation were almost identical, however the re-breathing amount was lower at 4.6% compared to 5.1% for normal breathing and 5.16% for hyperventilation. This result was slightly unexpected and will be discussed later.

**Figure 2** demonstrates the effects of different ventilation types on how long the subject could hold her breath afterwards. The observation shown is that compared to normal breathing (34.71 seconds), the post re-breathing breath hold (11.5 seconds) was significantly shorter.

For hyperventilation compared to normal breathing, the breath hold was significantly longer at 85.8 seconds.

**Figure 3** displays the effects that different lung volumes had on how long the subject could hold her breath. It is observed that the length of breath hold is higher when there was an inspiration before it than when there was an exhalation. In
terms of inhalation, forced inhalation allowed for a longer breath hold at 51.5 seconds compared to normal inhalation at 47 seconds. In terms of exhalation, the forced exhalation caused a significantly shorter breath hold at 9 seconds compared to the normal exhalation which was followed by a 30.7 second breath-hold. All of these results were expected.

**Part 3: Exercise Hyperpnea**

![Figure 4](image)

**Figure 4** illustrates the changes in tidal volume as the workload is increased. To calculate the data points, four values were taken from the last 30 seconds of each workload on the analysis software. These values were then averaged and gave the final value. Overall there is a steady increase in tidal volume from 1.03 L at the rest workload to 2.1 L at the final workload of 2.0. However, there is a slight decrease at the workload of 0.5 kPa as it has a tidal volume of 1.39 L. As can be observed, there was a direct correlation between and increase in workload and an increase in tidal volume.
Figure 5 illustrates the changes in respiratory rate in response to the increase in workload. As can be observed, there is an initial increase in respiratory rate from 31.8 breaths/min at the rest period up to 35.2 breaths/min at a workload of 1.5 kPa. Then there is a sharp drop to 26.8 breaths/min at workload 1.5 and a small increase to 28.2 breaths/min at workload 2.0. Respiratory rate was obtained by taking the average of the last 30 seconds during each workload period. These results loosely followed the expected results and will be discussed further in the discussion.

Figure 6 illustrates the changes in minute ventilation compared to an increase in workload. Minute ventilation is calculated by multiplying respiratory rate by the tidal volume. As can be observed, there is an increase up until a workload of 1 kPa where the
minute ventilation peaks at 60.9 L/min. After this there is a slight decrease to 51.19 L/min at a workload of 1.5 kPa. Following this there is an increase to 59.22 L/min at the final workload of 2.0 kPa. These results mirrored the trend seen in respiratory rate which makes sense because respiratory rate is part of the calculation.

**Figure 7** illustrates the changes in carbon dioxide content (CO2), in relation to increases in workload. To calculate these numbers, 4 traces were measured for the percent CO2 content in the last 30 seconds of each workload. As can be observed, there is an initial slight increase in the percent CO2 with the increase in workload. It levels out around workload 1.0-1.5 and then there is a slight decrease. Overall, there is no significantly large changes in the percentages which was an expected result.

**Figure 8** gives an explanation for the effects that increasing the workload had on minute CO2. Minute CO2 is the CO2 volume that was cycled through the body per minute. There is an increase from 1.65 L/min at rest to 3.67 L/min at a workload of 1.0 kPa.
Following this there is a slight decline to 3.1 L/min at workload 1.5 kPa and then an increase again to the final output of 3.48 L/min at the workload of 2.0 kPa. Data was obtained by averaging out 4 selections of minute CO2 output during the last 30 seconds of each work period. The data loosely follows the expected data.
Discussion

This lab took an in depth look at control of lung ventilation and how it effects lung volumes and rate of breathing in the human. The lungs are capable of holding several different volumes at different times in the breathing process. Tidal volume (TV) is the amount of air that is breathed in and out during a normal respiratory cycle. Inspiratory reserve volume (IRV) is the amount of air that can be forcefully inhaled passed the tidal volume. In contrast, expiratory reserve volume (ERV) is the amount of air that can be forcefully exhaled passed the tidal volume. Residual volume (RV), is the volume of air that remains in the lungs at all times and can never be removed which is a reason why the lungs cannot fully deflate. Functional residual capacity(FRC) is the air that remains in the lungs after a normal breathing cycle, this air is important because it interacts with the blood during the brief period that the lungs are not being filled with air. Lastly, vital capacity (VC) is the sum of IRV, ERV, and TV and is classified as the max volume change allowed within in the lungs (Sherwood, 2013 p.474).

Control of breathing is strongly affected by levels of arterial gases in the blood. In particular, carbon dioxide (CO2) is often considered the primary gas in control of respiration. The medulla in the brain contains central chemoreceptors that are responsible for sensing changes in CO2 content. They are able to sense these changes by detecting a change in pH which is caused by a change in the CO2 content. When there is an increase in CO2 in the brain, it interacts with water to create bicarbonate and free hydrogen which in turn lowers the ph. This change in the hydrogen ion content tells the chemoreceptors to stimulate an increase in ventilation. The stimulation involves stimulating the dorsal respiratory group (DRG) which is a group of inspiratory neurons that signal for the inspiratory muscles to contract (Sherwood, 2013, p.496). The central chemoreceptors are deemed specific to CO2 because they lie across the blood
brain barrier which only CO2 can freely cross. When there is a drop in CO2 the chemoreceptors respond accordingly and stimulate a decrease in ventilation. Peripheral chemoreceptors are less utilized during breathing but relate to oxygen (O2) concentrations. They are located in the aortic and carotid bodies in the heart and neck respectively. They only respond to significant drops in O2 meaning an arterial concentration of less than 60 mm Hg which only occurs under unusual circumstances (Sherwood, 2013 p.495).

In the first part of the lab, a simplistic look was taken at the different static lung volumes and how to calculate them from the analysis software. Table 1 lists the values for IRV, ERV, TV, and VC as being 1.62 L, 0.76 L, 1.25 L, and 3.4 L respectively. Vital capacity typically equals the combination of IRV, ERV and TV, in this case that would be 3.63 L. However, the vital capacity obtained during lab was 3.4 L. An explanation for this discrepancy could be error in the analysis of the volumes when looking at the software. Also, it was challenging to coordinate the timing and breaths between the subject and the student using the student analysis software, so incorrect marks could have been made. From these volumes, calculation of minute and alveolar ventilation (Va) were possible. Minute ventilation (Ve) explains the amount of volume that circulates through the lungs per minute (Sherwood, 2013, p.475). Table 1 lists minute ventilation as 20 L/min, alveolar ventilation as 17.2 L/min and dead space ventilation as 2.8 L/min. Physiologically, dead space is any air that does not contribute and participate in alveolar gas exchange. This includes air that is in the mouth, throat and pharynx as well as the upper areas of the respiratory tract (Lumb and Nunn 2005, p.118-119). When you breathe in, part of the tidal volume goes to the dead space and thus, minute ventilation is defined by the dead space ventilation (Vds) plus the alveolar ventilation. Alveolar ventilation being the gas per minute that is used for gas exchange (Sherwood, 2013, p.477). Changes in alveolar ventilation
would initially affect the plasma pH but the chemoreceptors would subsequently help return the pH to normal. For example, an increase in respiratory rate would increase alveolar ventilation causing less CO2 to be in the brain per unit of time and thus the pH would raise. However, this would be regulated shortly after and inspiration would be slowed. If respiratory rate were to decrease alveolar ventilation, a buildup of CO2 would occur and the pH would lower but again this would be regulated and inspiration would increase.

The second part of the lab looked at three different breathing techniques and how they affected CO2 composition in tidal volume pre and post breath hold. As seen in Figure 1, the percent CO2 before breath-hold for normal breathing was 3.65% and the composition after the breath hold was 5.1%. Now taking a look at the rebreathing section, the percent CO2 at the end of rebreathing and before the breath-hold was significantly higher at 5.8%. This was an expected result because as the subject was breathing into a bag, no fresh air/oxygen was entering into the bag. Instead, the bag was used as a CO2 recycler and each time she breathed in, more and more CO2 was being put into her lungs instead of oxygen. Thus, compared to normal breathing when she was breathing in new oxygen, it make sense that she had a higher end CO2 volume. When the subject underwent hyperventilation prior to the breath-hold, the end tidal CO2 was lower than normal breathing, presenting at 2.59% (Figure 1). This was an expected result because when you are hyperventilating, large amounts of CO2 are being eliminated by the body and being replaced with larger volumes of oxygen. This can be seen through the process of respiratory alkalosis as was observed in a study on hyperventilation syndrome. When researchers looked at the effects of hyperventilation on the ECG, blood gases, and electrolytes they saw a significant association with hyperventilation and mean CO2 content (Yu et al, 1959 p.904&907).
When analyzing the CO2 content post breath-hold, an unexpected result was presented. Theoretically, if the subject held her breath to the same level of uncomfortableness after each breathing challenge, all of the post breath-hold CO2 values should be the same. This is because the same amount of gas exchange would have occurred to get to this level of uncomfortableness. As seen in Figure 1, the post breath hold CO2 contents for normal breathing, hyperventilation, and re-breathing were 5.1%, 4.6%, and 5.16% respectively. While, the re-breathing and normal breathing values line up almost identically, the hyperventilation percentage is lower. A possible explanation for this lower value is that the subject did not hold her breath to the same level of uncomfortableness during the hyperventilation trial. Figure 2 gives the times for breath-hold after each breathing challenge. The values for normal breathing, hyperventilation and re-breathing were 34.71, 11.5, and 85.8 seconds respectively. Because hyperventilation had the lowest percent CO2 before the breath-hold it makes sense that the subject was able to hold her breath longer because she had more time to equilibrate to the normal CO2 levels. The opposite is seen with the re-breathing challenge, because she already had a high volume of CO2 in her lungs it did not take much to get back to the same amount of uncomfortableness and CO2 level. By taking a deep breath of oxygen after the rebreathing, this may have overcompensated and cause the discrepancy in the post breath hold CO2 as well.

The final portion of part 2 studied the effects lung volume on breath-holding time. The expected result was that with larger lung volumes, there would be a longer breath-hold time in seconds. This trend was seen in a study done on middle-aged males in 1955 (Chapin 1955, p.88&90). The study involved subjects holding their breath at their functional residual capacity and their full vital capacity. It became clear that at the higher lung volume, subjects were able to hold their breath longer than at the functional residual capacity. The data from this experiment
was in line with both the hypothesis and study results. **Figure 3** shows the time for forced inhalation breath hold to be 51.5 seconds. This was the longest breath hold and also the largest lung volume because air was being forced to enter and thus the inspiratory reserve capacity to be breathed in addition to the tidal volume. The breath-hold time for forced exhalation was 9 seconds. This was the shortest breath-hold time and also the lowest lung volume because not only was the tidal volume expelled but also the expiratory reserve capacity, leaving a small lung volume. Normal expiration and normal inspiration values were 30.7 seconds and 47 seconds respectively. These also aligned with the hypothesis because at an inspiration there is going to be a higher lung volume than expiration so the breath-hold should be longer for the inspiration as observed.

During exercise the mechanisms for increasing ventilation are not completely defined. However, it is believed that the chemoreceptors are not the main causes of change in ventilation (Lumb and Nunn, 2005, p.243). A main driving force in the increase in ventilation, is the metabolic requirements of the organism. During exercise the muscle tissues need more oxygen and thus, an increase in ventilation can provide that. There is often seen a direct relationship between oxygen consumption and ventilation during exercise (Grodins, 1950, p.220). In an attempt to analyze the mechanisms behind breathing regulation during exercise, a paper by Fred S. Grodins at Northwestern University Medical School suggests that there is an additive exercise stimulus at work. Additive meaning one that does not alter the sensitivity to blood gases by the respiratory system (Grodins, 1950, p.223). After taking a multi-factorial approach at analyzing many studies done on breathing regulation, this paper suggests that chemical actions alone cannot trigger the ventilation changes we see during exercise and thus, that there is a stimulus that adds to and increases ventilation to meet the metabolic needs of the body (Grodins, 1950,
No matter the cause for ventilation changes during exercise, there are a few outcomes that are expected and that the data from this experiment support.

As stated earlier, during exercise there is a clear increase in oxygen consumption. Data in Figure 4 displays the changes in tidal volume related to increase in workload in part 3 of the lab. As can be seen, at rest the tidal volume is 1.03 liters and at the final workload of 2.0 kPa tidal volume is 2.1 liters. An increase in tidal volume, allows for more air to be interchanged during each breath and thus, more oxygen can be brought into the body. The Hering-Breuer reflex is a reflex that stops the lungs from overinflating. It is particularly important during exercise because as the body is trying to increase oxygen to the muscles the tidal volume can increase quite a bit as seen in our data. Thus, the reflex is important in preventing over inflation. The reflex is activated by stretch receptors in the smooth muscles that send negative feedback to stop inspiration (Sherwood, 2013, p.494). Data in Figure 5 displays an initial increase in respiratory rate from 31.8 breaths/min at rest to 35.2 breaths/min at a workload of 1.0 kPa. After this, there is a drop in the rate to 26.8 breaths/min at 1.5 kPa and then a stabilization at 28.2 breaths/min for workload 2.0 kPa. These results line up with what was expected almost completely. After about three minutes an equilibrium in ventilation is expected (Lumb and Nunn, 2005, p.242). The data shows the initial increase but does not completely stabilize at the end as seen by the drop in breaths/min. Respiratory rate increases at the beginning of exercise are useful because more breaths/min means increasing air that is going into the lungs and an increase in minute ventilation. When comparing a 50% increase in tidal volume versus a 50% increase in respiratory rate, increasing tidal volume is much more effective. Tidal volume does not include the dead space air and thus any increase in tidal volume, means all that air is going directly to alveolar ventilation for gas exchange. When the respiratory rate is increased, one is just breathing
quicker but this does not mean all air is making it to gas exchange. Typically, breathing faster just means more exchange with dead space air and not as much air making it to the alveoli. Thus, while increasing both cause an increase in minute ventilation it is only tidal volume that has a significant effect on alveolar ventilation. Data from this lab supports this conclusion because as described earlier there are larger more significant changes in tidal volume as opposed to changes in respiratory rate.

Because there is an increase in tidal volume and respiratory rate during exercise, it is clear that there will be an increase in minute ventilation (L/min). In a study done on physiological mechanisms of breathing during exercise, minute ventilation (Ve) increased during exercise in response to the overall increased need for oxygen (Wasserman et al., 1967, p.80). Because there is a larger need for oxygen, there is going to be more output of CO2, however this was not evident in the differences between the end tidal CO2 at the beginning of exercise and the end tidal CO2 at the cessation of exercise (Wasserman et al., 1967, p.83). By increasing the minute ventilation not only is more air coming in but more air is leaving, allowing the CO2 concentration to be the same. This also allows for the protection against metabolic acidosis by allowing the CO2 content to remain stable (Wasserman et al., 1967, p.81).

The data from this experiment almost directly relates to the data observed in the above study. Figure 6 illustrates the changes in minute ventilation in response to changes in workload. At rest, the minute ventilation is 32.75 L/min and this increases up to workload 1.0 kPa where it is 60.90 L/min. After this, there is a decline to 51.19 L/min at workload 1.5 kPa, and then an increase again to 59.22 L/min at the final workload of 2.0 L/min. This trend is similar to the one illustrated in Figure 5 which described the respiratory rate changes. Overall, the increase in minute ventilation is expected and fulfilled in order to address the changes oxygen
consumption. As seen in the study, end tidal CO2 should not change that much because minute ventilation changes to eliminate more of it. (Wasserman et al., 1967, p.81). Figure 7 shows the changes in end tidal CO2 versus increases in workload. While the percentages do not stay exactly the same throughout the exercise they are pretty close together. The percent CO2 at rest is 5.04%, this then increases up to 6.05% at workload of 1.5 kPa. Following this there is a slight decrease to 5.87% at 2.0 kPa. A reason for the increase could be a general effect in response to exercise and not being able to regulate quick enough. Figure 8 demonstrates minute CO2 changes during the increase in workload. Theoretically these would increase because minute CO2 is the amount of CO2 breathed out per minute. Because there was an increase in minute ventilation during exercise, there is going to be an increase in CO2 expended even though the content of each breath should have stayed relatively the same. As can be seen, the initial minute CO2 at rest is 1.65 L/min and increases to 3.67 L/min at a workload of 1.0 kPa. Following, it drops to 3.1 L/min at workload of 1.5 kPa and then increases again to 3.48 L/min at workload 2.0 kPa. The minute CO2 trend mirrors the minute ventilation trend because minute ventilation multiplied by end tidal CO2 is equal to the minute CO2. The increase in minute CO2 was expected because as tidal volume and minute ventilation increased so would the amount of CO2 per minute. The decrease may have been due to the stabilization and drops in minute ventilation and could have been a function of the subjects breathing rate stabilizing.

In conclusion, there are many forces at work when regulating breathing whether it is at rest or during exercise. Chemoreceptors and blood gases play a crucial part in controlling the breathing process and during exercise, the need for oxygen in the muscles drives the increase in respiration. Different lung volumes and breathing challenges produce varying effects on how...
long ones breath can be held and this can be observed in many real life situations. Thus, these are the properties of breathing regulation.
Works Cited


