THE PULMONARY PROFILE OF COMPETITIVE SWIMMERS

by

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Abstract

**Purpose:** The purpose of this thesis was to investigate the nature of the following conditions in competitive swimmers: the occurrence of exercise-induced arterial hypoxemia (EIAH), and the relationship to gender and exercise-induced bronchoconstriction (EIB) (Study 1), and the development of exercise-induced pulmonary edema (PE), and changes in oxyhemoglobin saturation (Study 2).

**Methods:**

*Study 1:* Twenty-one well-trained swimmers (10 male, 11 female) completed a eucapnic voluntary hyperpnea test and an incremental swim test to exhaustion with pre and post-exercise spirometry. Metabolic data (VO₂, VCO₂, ventilation and heart rate) along with oxyhemoglobin saturation (SpO₂) were collected throughout exercise.

*Study 2:* Baseline lung density was obtained in eight well-trained male swimmers using computerized tomography after 24 hours rest. After a standard warm-up, subjects performed 6 x 50m maximal effort intervals on 90 s. Oxyhemoglobin saturation (SpO₂) and heart rate were collected across exercise intervals. Scans were repeated at 45-60 min post-exercise.

**Results:**

*Study 1:* Eleven of the twenty-one subjects tested positive for EIB. No subjects fulfilled our criteria for EIAH (SpO₂ ≤95% or ≥3% drop from resting values) despite a small mean drop in SpO₂ from rest to maximal exercise in both males and females. There was no correlation between EIAH and EIB (p=0.21).
**Study 2:** For the duration of the intervals, mean saturation levels remained close to resting values. Mean lung density significantly increased (p<0.05) from pre to post-exercise, with no significant changes in lung volume between scans (p=0.28).

**Conclusions:** Our findings suggest that the swimming environment provides some protection against the development of EIAH in this population regardless of sex or presence of EIB. Furthermore, the development of pulmonary edema does occur and appears to be independent from oxyhemoglobin saturation. These results are likely attributable to the physiological response to water immersion and the horizontal body position associated with this form of exercise.
Preface

This thesis contains original data collected and analyzed for partial fulfillment of the author’s Doctor of Philosophy degree. All protocols were approved by the Clinical Research Ethics Board (Approval numbers: H11-00504, H11-00550) at the University of British Columbia.

**Study #1:** Conducted at the UBC Aquatic Centre by Jane Labreche and Eric Carter. Eric Carter (UBC graduate student) assisted with handling of the metabolic equipment during data collection of the maximal swim test. I was responsible for preparing the subject, explanation of protocols, collection of spirometry, oximetry, and all other descriptive variables. Dr. Walter Karlen (UBC Department of Electrical and Computer Engineering) provided the equipment and expertise for the oximeter data collection. The Canadian Sport Center Pacific provided the metabolic cart for use during swim testing. I conducted the EVH testing protocol as a whole. Results analyzed and all written work related to Study #1 in this document was completed by Jane Labreche.

**Study #2:** Conducted in collaboration with Dr. John Mayo (UBC Faculty of Medicine, Department of Radiology). The swim tests were conducted at the UBC Aquatic Centre by Jane Labreche. I was responsible for all data collection and results analysis of the swim test. Walter Karlen provided the equipment and expertise for the oximeter data. The CT scans were completed by Ron Chitsaz (certified CT scan technologist) at Vancouver General Hospital. The analysis of the CT scans was provided by Dr. Harvey Coxson and graduate students Tara Candido and Lauren Wierenga (UBC Department of Radiology, VGH Hospital & James Hogg Research Centre, St Pauls Hospital Institute for Heart and Lung Health). All written work related to Study #2 in this document was completed by Jane Labreche.
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<th>Definition</th>
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<tbody>
<tr>
<td>A-aDO2</td>
<td>Alveolar to arterial oxygen difference</td>
</tr>
<tr>
<td>AA</td>
<td>Aortic arch</td>
</tr>
<tr>
<td>AE</td>
<td>Alveolar edema</td>
</tr>
<tr>
<td>AHR</td>
<td>Airway hyperresponsiveness</td>
</tr>
<tr>
<td>BGB</td>
<td>Blood gas barrier</td>
</tr>
<tr>
<td>CO</td>
<td>Cardiac output</td>
</tr>
<tr>
<td>CT</td>
<td>Computed tomography</td>
</tr>
<tr>
<td>DL</td>
<td>Pulmonary diffusion</td>
</tr>
<tr>
<td>EI AH</td>
<td>Exercise-induced arterial hypoxemia</td>
</tr>
<tr>
<td>EIB</td>
<td>Exercise-induced bronchoconstriction</td>
</tr>
<tr>
<td>EFL</td>
<td>Expiratory flow limitation</td>
</tr>
<tr>
<td>EVH</td>
<td>Eucapnic voluntary hyperpnea</td>
</tr>
<tr>
<td>EVLW</td>
<td>Extravascular lung water</td>
</tr>
<tr>
<td>f</td>
<td>Breathing frequency</td>
</tr>
<tr>
<td>FEF25-75</td>
<td>Average forced expiratory flow from 25-75% forced vital capacity</td>
</tr>
<tr>
<td>FEV1</td>
<td>Forced expiratory volume in 1 second</td>
</tr>
<tr>
<td>FVC</td>
<td>Forced vital capacity</td>
</tr>
<tr>
<td>HR</td>
<td>Heart rate</td>
</tr>
<tr>
<td>IE</td>
<td>Interstitial edema</td>
</tr>
<tr>
<td>MVV</td>
<td>Maximal voluntary ventilation</td>
</tr>
<tr>
<td>PaO2</td>
<td>Partial pressure of oxygen in arterial blood</td>
</tr>
<tr>
<td>PE</td>
<td>Pulmonary edema</td>
</tr>
<tr>
<td>PEF</td>
<td>Peak expiratory flow</td>
</tr>
<tr>
<td>PO2</td>
<td>Partial pressure of oxygen</td>
</tr>
<tr>
<td>RER</td>
<td>Respiratory exchange ratio</td>
</tr>
<tr>
<td>SpO2</td>
<td>Oxyhemoglobin saturation measured via pulse oximetry</td>
</tr>
<tr>
<td>SaO2</td>
<td>Arterial oxyhemoglobin saturation</td>
</tr>
<tr>
<td>SIPE</td>
<td>Swimming-induced pulmonary edema</td>
</tr>
<tr>
<td>STPD</td>
<td>Standard temperature pressure dry</td>
</tr>
<tr>
<td>SV</td>
<td>Stroke volume</td>
</tr>
<tr>
<td>TC</td>
<td>Tracheal carina</td>
</tr>
<tr>
<td>T10</td>
<td>Tenth thoracic vertebrae</td>
</tr>
<tr>
<td>V/A/Q</td>
<td>Ratio of alveolar ventilation to capillary perfusion</td>
</tr>
<tr>
<td>VE</td>
<td>Ventilation</td>
</tr>
<tr>
<td>VE/VO2</td>
<td>Ventilation per oxygen consumption</td>
</tr>
<tr>
<td>VE/VCO2</td>
<td>Ventilation per carbon dioxide expired</td>
</tr>
<tr>
<td>VO2max</td>
<td>Maximal oxygen consumption</td>
</tr>
<tr>
<td>VT</td>
<td>Tidal volume</td>
</tr>
</tbody>
</table>
Chapter 1: Introduction

The traditional concept of an oxygen transport system, adequate to meet the demands imposed by exercise, is challenged by the occurrence of exercise-induced arterial hypoxemia (EIAH). Highly trained athletes who fail to maintain blood oxygen levels at or near resting values during exercise may also experience a performance limitation. The mechanisms identified as pulmonary system limitations to exercise include, but are not limited to, EIAH and flow limitation (29). Swimmers are an interesting population to examine these respiratory constraints as the environment they experience provides unique demands of the human body during exercise.

Exercise-Induced Arterial Hypoxemia

Exercise-induced arterial hypoxemia, by definition, is a decrease of 1 kPa in PaO\textsubscript{2} (44) or a decrease to <95% SaO\textsubscript{2}. To assess severity, it can be further categorized into mild (SaO\textsubscript{2} = 93-95%), moderate (SaO\textsubscript{2} = 88-93%) and severe (SaO\textsubscript{2} <88%) conditions (30). This physiological response to intense exercise has been shown to occur in highly trained athletes with an incidence rate of approximately 50% (91). There is evidence of sex differences with a higher prevalence of EIAH in females occurring at relatively lower fitness levels when compared to their male counterparts (47, 96). These differences have been attributed to smaller lung volumes, lower maximal expiratory flow rates, and smaller diffusion surface areas in women (41, 49).

A review by Nielson et al. (86) showed that evidence of EIAH have been reproducible in various sports such as rowing, cycling, and running, though data on swimmers is limited. Most test
sessions document EIAH via an incremental test to maximal exertion. However, PaO$_2$ has also been shown to fall within the initial 30-60 seconds of exercise maintained throughout the rest of a 4-5 minute intense interval (28). In an athlete population this is of concern as low blood oxygen saturation is associated with negative effects on oxygen transport and VO$_2$max (68). For this reason EIAH has potential to affect both training and competition in this population.

Incomplete gas exchange has been shown to limit VO$_2$max, in those who desaturate at maximal exercise, with a 1% decrease in aerobic capacity (males) and a 2% decrement (females) for each 1% decrease in SaO$_2$ (47, 92). In high-level sport, this decrement could be substantial. Athletes with an altered blood-gas-barrier could be more susceptible to EIAH.

EIAH has been associated with an abnormal widening of alveolar-to-arterial oxygen tension difference (A-aDO$_2$) during maximal exercise. Possible mechanisms for this occurrence include shunts, diffusion limitation, relative alveolar hypoventilation, and ventilation-perfusion (V$_A$/Q) mismatch (29). In asthmatic athletes, two variables contribute equally to decreases in PaO$_2$ during exercise: 1) a widened alveolar-to-arterial PO$_2$ difference (A-aDO$_2$) and 2) insufficient ventilatory response (50). High airway resistance and inflammation could negatively affect gas exchange. Constriction and inflammation of the bronchial tree frequently develops in swimmers (12) possibly causing flow limitation and a subsequent relative hypoventilation.

**Airway Dysfunction**

Asthma is a common airway disorder that is described by an elevated response of the bronchii to stimuli. It can include 3 main variables: airflow obstruction, airway hyperresponsiveness (AHR) and airway inflammation (15, 84). In athletes with high minute ventilations and flow rates, a
transient airway narrowing during or following exercise termed exercise-induced bronchoconstriction (EIB) can occur. The main stimulus is water loss by evaporation causing drying and cooling of the airway surface leading to a cascade of events. An increase in osmolarity (Na\(^+\), Cl\(^-\), Ca\(^{2+}\), K\(^+\) concentration) causes a release of inflammatory mediators (leukotrienes, histamine, prostaglandins) inducing bronchoconstriction, and subsequent airway narrowing or obstruction (5, 99). Exposure to cold, dry air, particulate matter and/or chlorine by-products trigger AHR increasing the degree to which the airways constrict upon exposure to stimuli (18, 69). At high work rates, the large airways can no longer humidify the air appropriately and the small airways are recruited. This recruitment further contributes to hyperosmolarity and dryness of the bronchial surface, amplifying airway narrowing.

In an elite athlete under chronic chemical exposure, continuous inflammation can lead to an abnormal healing process, resulting in structural changes or airway “remodeling” (95). Remodeling can include hypertrophy and hyperplasia of airway smooth muscle, increased mucous glands, thickening of reticular basement membrane from collagen deposits, blood vessel proliferation, and alterations to the extra cellular matrix, all of which lead to airway wall thickening and a reduction in airway caliber (18).

The eucapnic voluntary hyperpnea (EVH) test is the current gold standard for the assessment of EIB in athletes (98). Other recommended diagnostic tests include bronchodilator reversibility (post-bronchodilator response compared to baseline airway measure), direct (methacholine), or indirect (exercise, EVH, mannitol, hypertonic saline) provocation (78). Treatment often involves inhaled corticosteroids or leukotriene receptor antagonists (targeting the inflammatory response) and \(\beta_2\)-adrenergic agonist therapy (targeting vessel constriction). These treatments are
recommended to athletes with EIB not only for their respiratory health during training, but also to improve what may be viewed as impaired performance. With moderately intense exercise, bronchospasm has been shown to increase alveolar-arterial oxygen gradient sustained through exercise (64). These results suggest an oxygen transport limitation in asthmatics. Treating a group of asthmatics with corticosteroids has been shown to increase gas exchange efficiency as well as improving performance (51).

**Pulmonary Edema**

Pulmonary edema can be described as an abnormally high volume of extravascular lung water (EVLW) collected between the alveolar epithelium and the capillary endothelium (interstitial space). Starling forces are thought to govern the movement of fluid in this area (107). Should fluid accumulation exceed that of drainage by the lymphatic system, edema will occur. With extreme cases, capillary compression and/or changes in the permeability or structure of the membrane can take place (115). In highly trained athletes where oxygen delivery is of great importance to training and racing, exercise performance could be impaired.

The canine model demonstrates that fluid accumulation occurs initially in the interstitial space and as pressure rises, eventually floods the alveoli (108). Cases described as interstitial edema (IE) and alveolar edema (AE) have been reported in the human sport setting, but remain controversial (1, 6, 22, 77, 80). The range is from no symptoms, in cases of mild interstitial edema, to severe signs including pink froth in sputum (hemoptysis), cough, cyanosis and dyspnea. The pressures generated in the pulmonary system due to exercise or environment, are likely responsible for the severity of this condition.
The blood-gas-barrier (BGB) must be thin enough to allow for passive diffusion, but strong enough to withstand pressure increases introduced by the environment and/or exercise. Cardiac output in excess of 30 L/min is not uncommon in athletes with maximal exercise (34) generating high pulmonary arterial pressures. These pressures can lead to capillary leakage or stress failure (115). Evidence of an impaired BGB with intense exercise has previously been demonstrated in elite athletes using bronchoalveolar lavage (60). These findings are consistent with capillary damage and possible diffusion limitation. Further to this, both animal and human studies have suggested that pulmonary edema promotes ventilation-perfusion inequality (75, 100). These variables contribute to a widening of A-aDO2 and can lead to the development of EIAH in athletes.

Evidence for the occurrence of pulmonary edema in humans include both direct and indirect methods. Measurement tools suggesting the development of edema include non-invasive technologies such as radiography (77), ultrasonography (38), computed tomography (CT) (22), and magnetic resonance (MR) (80). More invasive procedures such as bronchial lavage provide evidence of damaged capillaries (60). Indirect evidence implying the existence of edema via VA/Q mismatch has been reported using multiple inert gas elimination technique (21, 100).

Conversely, a number of studies using similar methods have been unable to document pulmonary edema (39, 42, 54, 73). The current body of work uses varying methodology with conflicting results and consequently continues to be debated in the literature.

**Competitive Swimmers**

Swimming produces a unique set of circumstances challenging the human body. At the elite
level, aerobically trained athletes are capable of high cardiac outputs and ventilations. There are three major characteristics that make swimming distinct from other forms of exercise: chemical inhalation, water immersion and a horizontal body position.

Exposure to chlorine plays a large role in the development of airway dysfunction in swimmers. Although other disinfectants are available, chlorine remains the treatment of choice among experts and is a Public Health requirement. Seawater swimming does not appear to have the same deleterious effects on airway cells as seen in chlorinated pools (11). Adolescent swimmers with minimal training fail to show significant signs of airway damage, indicating that EIB and associated inflammation develop over time with exposure (87). Furthermore, when swimming athletes were tested following retirement, inflammatory markers were shown to be reversible once exposure was reduced or eliminated (53, 90).

Swimmers inhale the layer of air directly above the water surface where the mean chlorine concentration is 0.42mg/m$^3$ (32). A 2hr training session would expose the athlete to 4-6g, exceeding the restrictions for an 8hr day of work. Alveolar air and plasma chloroform levels in swimmers have been correlated with pool water, air concentration, intensity of exercise, and length of time swimming (2, 3). Associated inflammation has been indicated by elevated leukotriene levels reported in sputum samples of athlete populations (14, 87, 106) with an exaggerated response in swimmers (13, 16, 17, 89). In athletes, high ventilation rates expose the airway epithelium to increased shear stress and transmural pressure gradients which can amplify epithelial injury (65). A compromised epithelium in swimmers promotes penetration of aeroallergens therefore increasing the susceptibility to airway hyperresponsiveness (52).
Immersion, in the case of competitive swimming, can be described as partial body submersion. The body is held horizontally near the surface of the water with part of the head and upper chest or back above the water line during clean swimming. With the forces of buoyancy acting on the body, peripheral muscle no longer needs to generate the same pressure to overcome gravitational forces. Immersion therefore enhances return of fluid from the limbs to the heart, altering the distribution of blood flow and increasing cardiac preload. Research in dogs has shown increases in blood flow specifically to respiratory and cardiac muscle with immersion (44). Cardiac output and stroke volume have been shown to be significantly higher (during exercise) underwater compared to on-land (102).

Redistribution of blood volume is not only altered by immersion, but also by body position. A horizontal body position encourages pooling of blood in the thorax. Findings of increased pulmonary extravascular water volume from sitting to supine, amplified with exercise, suggests that elite athletes exercising in a horizontal position could be predisposed to pulmonary edema associated with elevated central blood volumes (76).

Swimming-induced pulmonary edema (SIPE) has been documented in the literature (1, 70, 103, 114). These data, largely clinical in nature, have been collected on open water swimmers involved in navy training where cold water, wind, tides and currents play a role. These results are difficult to compare to the swimming athlete competing in controlled waters and therefore warrant further investigation.
Purpose

1. To investigate the occurrence of exercise-induced arterial hypoxemia in competitive swimmers, to highlight any sex differences, and to examine the relationship between this condition and the clinical expression of bronchoconstriction.

2. To assess and describe the occurrence of exercise-induced pulmonary edema in this population, and to examine the relationship between this condition and the development of EIAH.

Hypothesis

1. Exercise-induced arterial hypoxemia and bronchoconstriction
   a. Subjects will have a high incidence of EIB similar to previous reports in elite swimming populations
   b. Swimmers will exhibit EIAH with a corresponding prevalence similar to that seen in other athletes (~%50)
   c. Those with EIB will have a high incidence of EIAH

2. Pulmonary edema
   a. Swimmers will have an increased lung density (as measured by CT scan) post-exercise
   b. Increases in lung density will be associated with decreases in oxyhemoglobin saturation
Chapter 2: Exercise-Induced Arterial Hypoxemia and Exercise-Induced Bronchoconstriction in Competitive Swimmers

Introduction

Pulmonary Limitations to Exercise and Exercise-Induced Arterial Hypoxemia

It is generally accepted that in most individuals, the lung is overbuilt for the demands placed on the human body during exercise. However, in very fit athletes the respiratory system may be unable to match the large metabolic demand during maximal effort, potentially having a negative effect on performance. Dempsey and colleagues identify the primary causes of respiratory system limitation to exercise: 1) exercise-induced arterial hypoxemia, 2) ventilatory limitation as a result of narrowed, hyperreactive airways, 3) respiratory muscle fatigue from sustained high intensity exercise, 4) expiratory flow limitation (29).

Exercise-induced arterial hypoxemia (EIAH), by definition, is a decrease of 1 kPa in PaO$_2$ (44) or a decrease to <95% SaO$_2$. This physiological response to intense exercise has been shown to occur in highly trained athletes with an prevalence of approximately 50% (91). Data have been reproducible in various sports such as rowing (46, 85), cycling (59, 91), and running (28), but not appropriately documented in swimmers. Further studies have shown a higher prevalence of EIAH in females occurring at relatively lower fitness levels when compared to their male counterparts (47, 96). It has been suggested that these sex differences are due to smaller lung volumes, lower maximal expiratory flow rates, and smaller diffusion surface areas in women (41, 49). EIAH has been shown to negatively affect performance making it a concern in athlete population for both males and females (68).
EIAH is associated with an abnormal widening of alveolar-to-arterial oxygen tension difference (A-aDO₂) during maximal exercise. Possible mechanisms for this occurrence include R-L or intra-pulmonary shunts, diffusion limitation, relative alveolar hypoventilation, and ventilation-perfusion mismatch (29). In asthmatics, two variables contribute equally to decreases in PaO₂ during exercise: 1) a widened A-aDO₂ and 2) insufficient ventilatory response (50). Constriction and inflammation of the bronchial tree frequently develops in swimmers causing flow limitation and a subsequent relative hypoventilation.

Airway Dysfunction in Swimmers

Clinical presentation of asthma in athletes includes dyspnea, coughing, and sputum production (36). The highest prevalence in summer sport Olympians has been shown in cycling, triathlon, and swimming (~11-13%). In winter sport, endurance ski events and speed skating (~13-16%) were most affected (37). These sports demand high minute ventilation combined with exposure to cold air, or irritants such as particulate matter or chlorine by-products. The main mechanism of exercise-induced bronchoconstriction (EIB) is drying and cooling of the airway surface. This leads to an increase in osmolarity and a release of inflammatory mediators inducing bronchoconstriction (5, 99). At high work rates, inflammation amplifies airway narrowing with an exaggerated response in swimmers specifically (13, 16, 17, 89). Under chronic exposure, continuous inflammation can lead to structural changes or airway “remodeling” (95) resulting in airway wall thickening and a reduction in airway caliber (18).

Early work by Katz et al. showed that with moderately intense exercise, children with bronchospasm had an immediate, large increase in alveolar-arterial oxygen gradient sustained through exercise as compared to controls (64). It was suggested that there is an oxygen transport
limitation in asthmatics. In 2007, Haverkamp et al. treated a group of asthmatics with corticosteroids to reduce bronchial inflammation (51), which not only increased gas exchange efficiency, but also improved performance in these individuals.

Accordingly, the purpose of this investigation was to characterize the occurrence of exercise-induced arterial hypoxemia in competitive swimmers, to highlight any sex differences, and to examine the relationship between this condition and the clinical expression of bronchoconstriction. We hypothesized that swimmers would a) exhibit EIAH with a similar prevalence to other endurance-trained athletes (~50%), b) have a high incidence of EIB, and c) be more likely to display EIAH with a positive EIB test.

Methods

**Subjects:** Twenty-one healthy (10 males and 11 females), non-smoking competitive swimmers were recruited from the University of British Columbia varsity program or the Canadian National swim team for testing. Subjects trained regularly (6 days/week) including swim sessions and dry land sessions (resistance training or conditioning outside of the pool). Total swim training volume was 12-18 hours/week (35-70km). All testing sessions were completed during the competitive season. All subjects were competitive at either national or international levels. Female subjects were tested randomly throughout the menstrual cycle and the use of oral contraceptives did not result in exclusion from this investigation. Five subjects (4 female, 1 male) were diagnosed with asthma via eucapnic voluntary hyperpnea (EVH) provocation prior to entering the study. These five subjects were prescribed short-acting inhaled bronchodilators and corticosteroids.
**General Protocol:** The experimental protocol included two test days separated by a minimum of 24h. Subjects were asked to refrain from 1) short acting bronchodilators for 8h prior, 2) vigorous exercise and caffeine for 12h prior, and 3) long acting bronchodilators or antihistamines 48h prior to each testing session. A leukotriene antagonist and corticosteroid washout period of four days was observed. On day 1, subjects reported to the pool and underwent basic anthropometric measures followed by baseline spirometry testing, an incremental swim test (IST) to maximal aerobic capacity (VO$_2$max) and subsequent post-exercise spirometry. Pool deck (indoor) air conditions were between 19-23°C and 744-769 mmHg. Water temperature was between 25-28°C (within international sport body mandates), typical of competitive pool standards. On day 2, subjects reported to the laboratory to complete an EVH test including baseline spirometry, a non-exercise ventilatory challenge, and post-challenge spirometry assessment for bronchoconstriction.

**Spirometry and VO$_2$max (Day1):** Basic pulmonary function measures (MIR Spirolab II, Medical International Research, Rome, Italy) were performed according to the American Thoracic Society specifications (82). Predicted spirometric values were defined according to Knudson et al. (66). Values were recorded prior to the swim test, as well as at 5 and 10 minutes post test. Maximal voluntary ventilation (MVV) was calculated as 35 x FEV$_1$ (baseline) for the purposes of evaluating provoking stimulus.

Horizontal resistance was applied to the subjects during swimming via a tethering apparatus located ten feet behind them on the pool deck. The tethering apparatus was calibrated (r=0.992) over a range of weights at this distance using a force meter (model BG50, Mark-10 Corporation, Copiague, NY). The calibration equation (y=0.5309x + 8.8641, $r^2 = 0.97175$) was used to
calculate force data. Force production in this context can be described as “the force necessary to maintain swimming position”. These data were converted to Newtons (N) post-test for reporting purposes. Swimmers were attached to a nylon belt, connected to nylon rope, fed through a pulley system attached to a bucket, where weighted plates were added to provide resistance (Appendix A). All subjects were familiar with this apparatus and had used it regularly as a training tool. Subjects completed a three-phase warm-up consisting of 200m free-swimming, followed by 4 x 30 seconds tethered swimming (without snorkel), and finally 4 x 30 seconds tethered swimming (with snorkel). The tethered swim warm-up was used to practice maintaining position in the pool, as well as to determine starting load for the incremental test based on swimming technique. Starting loads (kilograms placed in the bucket of the tethering apparatus) ranged from 45-90kg for males and 45-60kg for females. The incremental swim test (IST) began at the pre-determined starting load and increased by 5kg each 2 minutes until the swimmer could no longer hold position. Swim position was marked by a static pole submerged in front of the swimmer, and markings on the floor of the pool. Colored markers were attached to a pole and inserted in front of the swimmer to indicate the 1-minute (blue marker) and 2-minute (red marker) time points of each stage. During exercise, subjects wore a nose clip and breathed through a mouthpiece connected to a low-resistance non-rebreathing Y-shaped valve (model 1420, Hans Rudolph, Kansas City, MO). The valves and hoses were fixed to a custom L-shaped, weighted PVC pipe structure that was buoyancy neutral (Appendix A). The Y-shaped valve was oriented vertically to allow for a clean arm stroke without interference. Subjects were familiar with breathing through a mouthpiece and snorkel for training purposes. Breathing frequency was unrestricted (self-selected) throughout the test. Mixed expired gas concentrations and ventilatory parameters were measured continuously using an automated gas analysis system (TrueOne 2400, Parvo Medics, Provo, UT) and values were recorded over 15s epochs. The gas
analyzers were calibrated using a 3-litre syringe over a range of flow rates to ensure linearity. All subjects swam until exhaustion and each displayed a plateau in VO$_2$ whereby an increase in final workload did not further increase VO$_2$. Data are reported as averages of the two highest consecutive 15s epochs.

Oxyhemoglobin saturation (SpO$_2$), perfusion index and heart rate were measured using a customized waterproof oximeter system (Phone Oximeter, Electrical and Computer Engineering in Medicine Group, University of British Columbia, Vancouver, BC). The system was composed of a forehead sensor probe (TF-I transflectance) placed under the swim cap, attached to a pulse oximeter module (SET Low Power Module, Masimo Corporation, Irvine, CA) with the signal transmitted through a cable to a laptop on the pool deck where data were recorded and stored. The raw signal was sampled at 1-second intervals, recorded to a text file and processed in a customized software program (iRecord2, Electrical and Computer Engineering in Medicine Group, University of British Columbia, Vancouver, BC). For quality control purposes the raw photoplethysmogram waveforms were also recorded to a file. Data with a perfusion index > 0.8 was discarded. The lowest value for SpO$_2$ was reported. To account for the industry standard of 1% error for motion artifact, exercise-induced arterial hypoxemia was defined using a SpO$_2$ value of $\leq 94\%$, or a drop of 4% or more from resting values. These values are in agreement with previous classifications for exercise data (96).

**Eucapnic Voluntary Hyperpnea Challenge (Day 2):** The EVH challenge was performed according to the method of Anderson et al. (4). Subjects inhaled a compressed dry gas mixture (21%O$_2$, 5%CO$_2$, balance N$_2$) at room temperature for 6 minutes. Target ventilation was 30xFEV$_1$ equivalent to 85% of MVV. The gas flowed from a cylinder, controlled by a high-
pressure regulator (model 500, CONCOA, Virginia Beach, VA), via a 120L reservoir bag to the subject. From the bag, the subjects breathed through a two-way non-rebreathing valve (Hans-Rudolph, Kansas City, MO) attached to a mask. Exhaled air passed through a calibrated, heated pneumotachometer (Hans Rudolph, Kansas City, MO). Ventilation data for the challenge portion of the test was recorded continuously at 200Hz using a 4-channel data acquisition system (model ML866, Powerlab 4/30, ADI, Colorado Springs, CO). Subjects were instructed to try to attain the highest ventilation possible, with a consistent rhythm over 6 minutes, using the target as a guideline. Time (min:sec), ventilation (L/min) and breathing frequency (bpm) were displayed as feedback for the subject during the challenge. Ventilation (VE) was averaged over six minutes post-test. Forced expired volume in 1 sec (FEV$_1$) was measured before the test and at 5, 10, 15, and 20 minutes post-challenge. Immediately after the 20min post-challenge maneuver, subjects were given 200 micrograms of an inhaled, short-acting β-agonists (salbutamol). A post-dilator FEV$_1$ maneuver was completed at 25min post-challenge.

Three values (agreeing within 150ml) were obtained for baseline FEV$_1$. The highest measurement was used to calculate airway response. At each interval post-challenge, FEV$_1$ was measured in duplicate. Additional maneuvers were added if there was a difference larger than 150ml. The highest of the two values was used to represent the FEV$_1$ at each interval as previously suggested (63). The lowest of the four post-challenge values was used to calculate drop in FEV$_1$. Percentage fall in FEV$_1$ was calculated as follows: 100 X (FEV$_1$ (pre-challenge) – lowest FEV$_1$ (post-challenge)) / FEV$_1$ (pre-challenge). A drop in FEV$_1$ of 10% or more was considered a positive test based on the recommendations of Anderson et al. and Hurwitz et al. (4, 63).
A subject was deemed to have exercise-induced bronchoconstriction if he/she fit either of the following two criteria:

1) A decline in FEV\textsubscript{1} of 10% or more as calculated after the non-exercise challenge (EVH test)

2) A decline in FEV\textsubscript{1} of 10% or more as calculated after the exercise challenge (VO\textsubscript{2}max test)

**Statistical Analysis:** Multivariate analysis of variance (MANOVA) was run by sex and by EIB grouping (positive or negative) on descriptive characteristics and metabolic data. Linear regression analysis using Pearson correlations were performed to test associations between specific pulmonary function parameters and metabolic data to investigate relationships between variables. The α level was set a-priori at 0.05 for all statistical comparisons. Values are presented throughout the manuscript as means ±SD unless otherwise stated.

**Results**

**Spirometry and VO\textsubscript{2}max:** Table 2.1 shows anthropometric and spirometry data obtained on day one. In accordance with the difference in body height and weight, males displayed larger absolute values for forced vital capacity (FVC) and FEV\textsubscript{1}. There were no differences between sexes for age, race experience, or percent predicted lung values. It is noteworthy that both FVC and FEV\textsubscript{1} values are well above 100% of predicted in each group. Table 2.2 is a summary of the data obtained at maximal exercise during the incremental test to exhaustion. Males exhibited higher values for VO\textsubscript{2}, VCO\textsubscript{2}, VE, VT, RER, force, and heart rate (HR) at maximal exercise (p<0.05). There were no differences between sexes for respiratory efficiency (VE/VO\textsubscript{2},
VE/VCO₂, respiratory rate (f), stroke rate (SR), or saturation level (SpO₂) (p>0.05).

**Table 2.1** Subject characteristics and spirometry data

<table>
<thead>
<tr>
<th></th>
<th>Males (n=10)</th>
<th>Females (n=11)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age, yr</td>
<td>20.7±1.1</td>
<td>20.9±2.9</td>
</tr>
<tr>
<td>Height, cm</td>
<td>187.3±5.4</td>
<td>171.9±6.0*</td>
</tr>
<tr>
<td>Mass, kg</td>
<td>79±8.3</td>
<td>61.5±7.2*</td>
</tr>
<tr>
<td>Race experience, yrs</td>
<td>11.4±3.7</td>
<td>12.5±4.2</td>
</tr>
<tr>
<td>FVC, L</td>
<td>7.5±0.9</td>
<td>5.4±0.5*</td>
</tr>
<tr>
<td>FVC, % predicted</td>
<td>131±12</td>
<td>128±15</td>
</tr>
<tr>
<td>FEV₁, L</td>
<td>5.8±0.6</td>
<td>4.4±0.8*</td>
</tr>
<tr>
<td>FEV₁, % predicted</td>
<td>117±11</td>
<td>120±22</td>
</tr>
<tr>
<td>FEV₁/FVC, %</td>
<td>76.9±4.5</td>
<td>80.9±9.2</td>
</tr>
</tbody>
</table>

*Significantly different from males (p<0.05). Values are means ±SD. FVC, forced vital capacity; FEV₁, forced expiratory volume in 1 s. Predicted values are based on Knudsen et al. (66)

**Table 2.2** Maximal ventilatory, metabolic, saturation and force data

<table>
<thead>
<tr>
<th></th>
<th>Males (n=10)</th>
<th>Females (n=11)</th>
</tr>
</thead>
<tbody>
<tr>
<td>VO₂ ml/kg/min</td>
<td>60.5±6.0</td>
<td>54.5±5.5*</td>
</tr>
<tr>
<td>VO₂ L/min</td>
<td>4.8±0.6</td>
<td>3.3±0.3*</td>
</tr>
<tr>
<td>VCO₂ L/min</td>
<td>5.1±0.7</td>
<td>3.4±0.3*</td>
</tr>
<tr>
<td>VE l/min</td>
<td>121.2±19.2</td>
<td>80±8.6*</td>
</tr>
<tr>
<td>VE/VO₂</td>
<td>25.8±3.3</td>
<td>24.5±2.4</td>
</tr>
<tr>
<td>VE/VCO₂</td>
<td>24.0±2.8</td>
<td>23.8±2.7</td>
</tr>
<tr>
<td>VT, l</td>
<td>3.4±0.4</td>
<td>2.4±0.5*</td>
</tr>
<tr>
<td>f, breaths/min</td>
<td>50.2±7.1</td>
<td>46.6±10.9</td>
</tr>
<tr>
<td>RER</td>
<td>1.08±0.03</td>
<td>1.04 ±0.05*</td>
</tr>
<tr>
<td>HR, beats/min</td>
<td>179±10</td>
<td>189±12*</td>
</tr>
<tr>
<td>SpO₂, %</td>
<td>97.1±1.1</td>
<td>97.5±1.1</td>
</tr>
<tr>
<td>SR, strokes/min</td>
<td>66.8±7.1</td>
<td>71.6±4.9</td>
</tr>
<tr>
<td>Force, N</td>
<td>60.9±6.0</td>
<td>51.6±3.4*</td>
</tr>
</tbody>
</table>

* Significantly different from males (p<0.05). Values are means ±SD. VO₂, oxygen consumption; VCO₂, carbon dioxide production; VE, minute ventilation; VT, tidal volume; f, breathing frequency; RER, respiratory exchange ratio; HR, heart rate; SpO₂, lowest arterial oxyhemoglobin saturation; SR, stroke rate expressed per minute.
**Oxyhemoglobin Saturation:** Table 2.3 (males) and 2.4 (females) show SpO₂ values expressed at rest, at maximal exercise, and as a drop from resting value. Although there was a statistically significant difference from rest to maximal exercise for both males and females (p=0.00), on an individual basis, no subjects fulfilled our criteria for EIAH. All individual maximal exercise values were >95.0%, and all values for drop in SpO₂ were <4%.

**Table 2.3** Individual arterial oxyhemoglobin saturation values for male subjects

<table>
<thead>
<tr>
<th>Subject #</th>
<th>SpO₂ at rest (%)</th>
<th>SpO₂ at maximal exercise (%)</th>
<th>Drop in SpO₂ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>100.0</td>
<td>98.4</td>
<td>1.6</td>
</tr>
<tr>
<td>2</td>
<td>99.5</td>
<td>96.5</td>
<td>3.0</td>
</tr>
<tr>
<td>3</td>
<td>99.4</td>
<td>96.9</td>
<td>2.5</td>
</tr>
<tr>
<td>4</td>
<td>100.0</td>
<td>97.7</td>
<td>2.3</td>
</tr>
<tr>
<td>5</td>
<td>98.5</td>
<td>95.5</td>
<td>3.0</td>
</tr>
<tr>
<td>6</td>
<td>100.0</td>
<td>98.3</td>
<td>1.7</td>
</tr>
<tr>
<td>7</td>
<td>99.9</td>
<td>97.7</td>
<td>2.2</td>
</tr>
<tr>
<td>8</td>
<td>100.0</td>
<td>96.5</td>
<td>3.5</td>
</tr>
<tr>
<td>9</td>
<td>99.6</td>
<td>98.1</td>
<td>1.5</td>
</tr>
<tr>
<td>10</td>
<td>98.8</td>
<td>95.3</td>
<td>3.5</td>
</tr>
</tbody>
</table>

**Mean ± SD**

99.6 ± 0.5  *97.1 ± 1.1  2.5 ± 0.8

* Significantly different from resting values (P<0.05). Drop in SpO₂ is the absolute drop calculated as the difference between resting values and maximal exercise for each subject.

**Table 2.4** Individual arterial oxyhemoglobin saturation values for female subjects

<table>
<thead>
<tr>
<th>Subject #</th>
<th>SpO₂ at rest (%)</th>
<th>SpO₂ at maximal exercise (%)</th>
<th>Drop in SpO₂ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>99.8</td>
<td>97.7</td>
<td>2.1</td>
</tr>
<tr>
<td>2</td>
<td>100.0</td>
<td>98.9</td>
<td>1.1</td>
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<td>3</td>
<td>100.0</td>
<td>98.5</td>
<td>1.5</td>
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<td>4</td>
<td>99.5</td>
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<td>1.5</td>
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<td>1.5</td>
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<td>99.6</td>
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<td>1.2</td>
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<td>98.4</td>
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<td>95.5</td>
<td>3.2</td>
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<tr>
<td>10</td>
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<td>97.0</td>
<td>2.9</td>
</tr>
<tr>
<td>11</td>
<td>100.0</td>
<td>97.0</td>
<td>3.0</td>
</tr>
</tbody>
</table>

**Mean ± SD**

99.7 ± 0.4  *97.5 ± 1.1  2.1 ± 0.9

* Significantly different from resting values (P<0.05). Drop in SpO₂ is the difference between resting values and those at maximal exercise
**Exercise-Induced Bronchoconstriction:** Four of ten males (Table 2.5) and seven of eleven females (Table 2.6) tested positive for exercise-induced bronchoconstriction. Therefore occurrence of EIB for this pool of subjects is 52%. One of the four males, and four of the seven females testing positive via our methods had been previously diagnosed as asthmatic. Similar ventilations were achieved for males (146.8±22.4, 140.7±23.3 l/min) and females (97.1±10.2, 108.1±17.5 l/min) at maximal exercise and during the non-exercise hyperpnea respectively. With a target of 30 x FEV\textsubscript{1} during the challenge portion of the EVH test, subjects were able to attain a mean of 72.5 %MVV or 25 x FEV\textsubscript{1} (range 20.3-30.5 for EVH and 19.3-37.0 for IST) in agreement with athlete population standards (82).

**Table 2.5** Individual airway responsiveness for male subjects

<table>
<thead>
<tr>
<th>Subject #</th>
<th>Decrease in FEV\textsubscript{1} after EVH (%)</th>
<th>Decrease in FEV\textsubscript{1} after IST (%)</th>
<th>Average baseline FEV\textsubscript{1}/FVC</th>
<th>Percent of MVV (EVH)</th>
<th>Percent of MVV (IST)</th>
<th>Diagnosis of EIB</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4.9</td>
<td>11.1*</td>
<td>77.3</td>
<td>58</td>
<td>69</td>
<td>+ve*</td>
</tr>
<tr>
<td>2</td>
<td>1.3</td>
<td>9.6</td>
<td>67.3</td>
<td>63</td>
<td>57</td>
<td>-ve</td>
</tr>
<tr>
<td>3</td>
<td>9.2</td>
<td>4.2</td>
<td>81.8</td>
<td>79</td>
<td>88</td>
<td>-ve</td>
</tr>
<tr>
<td>4</td>
<td>4.8</td>
<td>-13.6</td>
<td>81.8</td>
<td>75</td>
<td>83</td>
<td>-ve</td>
</tr>
<tr>
<td>5</td>
<td>11.4*</td>
<td>6.0</td>
<td>79.6</td>
<td>75</td>
<td>69</td>
<td>+ve*</td>
</tr>
<tr>
<td>6</td>
<td>1.5</td>
<td>-1.7</td>
<td>70.7</td>
<td>82</td>
<td>71</td>
<td>-ve</td>
</tr>
<tr>
<td>7</td>
<td>6.2</td>
<td>-0.3</td>
<td>77.9</td>
<td>77</td>
<td>84</td>
<td>-ve</td>
</tr>
<tr>
<td>8</td>
<td>16.2*</td>
<td>8.0</td>
<td>73.2</td>
<td>63</td>
<td>82</td>
<td>+ve*</td>
</tr>
<tr>
<td>9</td>
<td>9.7</td>
<td>1.4</td>
<td>79.6</td>
<td>87</td>
<td>74</td>
<td>-ve</td>
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<tr>
<td>10</td>
<td>13.5*</td>
<td>6.5</td>
<td>78.9</td>
<td>63</td>
<td>52</td>
<td>+ve*</td>
</tr>
<tr>
<td><strong>Mean ± SD</strong></td>
<td><strong>7.9±5.0</strong></td>
<td><strong>3.1±7.2</strong></td>
<td><strong>76.8±4.9</strong></td>
<td><strong>72±10</strong></td>
<td><strong>73±12</strong></td>
<td></td>
</tr>
</tbody>
</table>

*Indicates a positive test for EIB.

Negative values represent an improvement in FEV\textsubscript{1}. Baseline FEV\textsubscript{1}/FVC is reported an average of the two pre-test values (EVH and IST). FEV\textsubscript{1}, forced expired volume in 1s; EVH, eucapnic voluntary hyperpnea test; IST, incremental swim test; FVC, forced vital capacity; MVV, maximal voluntary ventilation; EIB, exercise-induced bronchoconstriction; +ve, positive for EIB; -ve, negative for EIB
**Table 2.6** Individual airway responsiveness for female subjects

<table>
<thead>
<tr>
<th>Subject #</th>
<th>Decrease in FEV(_1) after EVH (%)</th>
<th>Decrease in FEV(_1) after IST (%)</th>
<th>Average baseline FEV(_1)/FVC</th>
<th>Percent of MVV (EVH)</th>
<th>Percent of MVV (IST)</th>
<th>Diagnosis of EIB</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>11.7*</td>
<td>0.0</td>
<td>78.3</td>
<td>68</td>
<td>63</td>
<td>+ve*</td>
</tr>
<tr>
<td>2</td>
<td>20.7*</td>
<td>-5.3</td>
<td>56.1</td>
<td>84</td>
<td>106</td>
<td>+ve*</td>
</tr>
<tr>
<td>3</td>
<td>12.6*</td>
<td>4.2</td>
<td>80.9</td>
<td>75</td>
<td>62</td>
<td>+ve*</td>
</tr>
<tr>
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<td>11.1*</td>
<td>10.5*</td>
<td>92.3</td>
<td>82</td>
<td>51</td>
<td>+ve*</td>
</tr>
<tr>
<td>5</td>
<td>13.8*</td>
<td>5.2</td>
<td>90.0</td>
<td>67</td>
<td>57</td>
<td>+ve*</td>
</tr>
<tr>
<td>6</td>
<td>9.7</td>
<td>4.5</td>
<td>82.2</td>
<td>77</td>
<td>61</td>
<td>-ve</td>
</tr>
<tr>
<td>7</td>
<td>25.7*</td>
<td>-0.2</td>
<td>80.1</td>
<td>71</td>
<td>55</td>
<td>+ve*</td>
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<td>8</td>
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<td>2.5</td>
<td>80.9</td>
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<td>+ve*</td>
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<td>11</td>
<td>2.4</td>
<td>5.8</td>
<td>85.1</td>
<td>72</td>
<td>69</td>
<td>-ve</td>
</tr>
</tbody>
</table>

*Indicates a positive test for EIB. Negative values represent an improvement in FEV\(_1\). Baseline FEV\(_1\)/FVC is reported an average of the two pre-test values (EVH and IST). FEV\(_1\), forced expired volume in 1s; EVH, eucapnic voluntary hyperpnea test; IST, incremental swim test; FVC, forced vital capacity; MVV, maximal voluntary ventilation; EIB, exercise-induced bronchoconstriction; +ve, positive for EIB; -ve, negative for EIB

**Discussion**

The purpose of this study was to examine the occurrence of EIAH and its relationship to EIB in swimmers. This is the first study to compare the development of EIAH in male and female swimming athletes. We reasoned that EIAH would occur based on evidence in other endurance-trained athletes and a well-documented history of airway dysfunction in swimmers. The main findings of this study are: 1) EIAH did not occur in this population of competitive swimmers, 2) EIB was shown at similar levels as reported in the literature, 3) EIB was not related to the development of EIAH. This study suggests that EIAH is unlikely to occur in well-trained swimmers despite a high incidence of bronchoconstriction in this group of athletes.
Swimming Population

Well-trained swimmers easily exceed predicted values (up to 130%) for FVC and FEV\textsubscript{1}. These individuals are capable of high minute ventilation (>150L/min) during exercise (55). Swim flumes, tethering apparatuses and modified snorkel systems allow monitoring of gas exchange during swim exercise. Early work by Holmer et al. reported swim specific VO\textsubscript{2max} values in males (5.05L) and females (3.42L) using a flume (55, 57). In males, additional studies have reported maximal data during tethered swimming (10, 31) with more recent work providing data collected during free swimming with a portable gas analyzer system (88, 97). Our descriptive data are characteristic of a well-trained athlete and are similar to previously reported swim-specific tests.

Exercise-Induced Arterial Hypoxemia

Contrary to our hypothesis, we found no evidence of EIAH in this population of swimmers. In athletes, EIAH has been demonstrated via arterial blood sample values below 94mmHg (33, 59) and via pulse oximeter values below 91% (79, 110). In females, EIAH has also been reported in similar ranges for each of these methods (48, 96). Holmer et al (1974) collected arterial blood samples in a small sample (n=5) reporting a SaO\textsubscript{2} of ~91% during maximal swimming (30). However, given the low resting SaO\textsubscript{2} in this group (~95%), it is unlikely that these samples were temperature corrected. Therefore, these results may be overestimating the level of desaturation and are more in agreement with our findings. More recently, Miyasaka et al. measured SpO\textsubscript{2} via Masimo components (finger probe) in 3 male swimmers during sprint exercise (100m) and reported a fall of 6-14% in SpO\textsubscript{2} (83). The subjects were not well-trained with relatively slow 100m times reported (1min 15s), compared to those posted in competitive sprinters around the world (<55s). It is possible these three swimmers lacked a trained physiological response to
breath-hold and perhaps even intense exercise, resulting in desaturation. Furthermore, evidence for sustained hypoxemia with appropriate scientific rigor would be required to support these findings. The discrepancy between our study and those reporting EIAH in other sports could be explained by the aquatic environment itself. Two main characteristics differentiate swimming from other modes of exercise: water immersion and a horizontal body position.

Immersion, in the case of competitive swimming, can be described as partial body submersion. The body is held horizontally near the surface of the water with part of the head and upper chest or back above the water line. The ambient pressure associated with surface swimming contributes to a larger thoracic blood volume and increases in pulmonary arterial pressure. At rest, head-out immersion has been shown to increase cardiac output by 32% and central blood volume by 700mL with noticeable increases in pulmonary artery pressure and a decline in vital capacity (7). Research in dogs has shown increases in blood flow specifically to respiratory and cardiac muscle with immersion (44). Furthermore, cardiac output and stroke volume have been shown to be significantly higher underwater when compared to on-land exercise (102). Head-out immersion studies showing increases in cardiac output (CO), stroke volume (SV) and central blood volume, and pulmonary arterial pressure also report a blunted HR response at maximal exercise (7, 93, 102) consistent with our data. It has been proposed that a decrease in sympathetic nerve outflow (via blood pressure-induced baroreflex) is responsible for a blunted maximal HR with immersion (24), while the increase in pulmonary arterial pressure is due to the hydrostatic pressure of the aquatic environment. In humans, both ventilation and cardiac output increase with exercise. At maximal exercise however, VE increases out of proportion to CO such that the severity of V̇_A/Q mismatch is larger during heavy exercise (111). It has been shown that V̇_A/Q mismatch accounts for ~50% of A-aDO₂ under maximal loads (45, 59).
Therefore in swimmers, a relatively lower ventilation and higher cardiac output caused by immersion, would reduce \( V_A/Q \) mismatch and minimize the widening of A-a\( \Delta O_2 \) often seen during high intensity exercise in athletes (59). This is supported by the work of Holmer et al., where lower A-a\( \Delta O_2 \) values at maximal exercise were found when subjects were swimming (~25 mmHg) versus running (~33 mmHg) (56). No differences in A-a\( \Delta O_2 \) were found between exercise modes at submaximal loads. In addition, immersion likely provides a more homogenous distribution of pulmonary blood flow (20, 93). Increasing blood flow to alveoli normally under-perfused (due to gravity), should tend to favor gas exchange. We can then reason that the increases in pulmonary arterial pressure, along with a more homogenous distribution of pulmonary blood flow, likely attenuate the widening of A-a\( \Delta O_2 \), thus explaining in part, the maintenance of blood saturation levels in our subjects during progressively intense exercise.

Redistribution of blood volume is not only altered by immersion, but also by body position. Marshall (1971) examined the effects of posture and exercise on the pulmonary system. Moving from sitting to a supine position at rest was associated with increases in mean pulmonary arterial pressure and extravascular water volume. These two values were further increased when subjects transitioned from rest to exercise in the supine position (76). It has been reported that a change in body posture from upright to supine, shifts central blood volume, increasing cardiac pre-load resulting in a higher stroke volume (SV) and cardiac output (CO) at rest and during exercise (9). Therefore, body position can potentially further increase thoracic blood volume pulmonary arterial pressures during exercise underwater.

The influences of immersion and body position may also help to explain why there were no
SpO$_2$ differences detected been our male and female groups. There is no difference between sexes in this physiological response to immersion when body size is taken into account (112). If males and females respond similarly to immersion, this may contribute to our findings of almost identical saturations of the two groups at maximal exercise. Increases in blood flow and pulmonary arterial pressure should enhance gas exchange in females who have a smaller surface area for diffusion.

Expiratory flow limitation (EFL) occurs during exercise when maximal expiratory flow is achieved during tidal breathing. EFL can cause alterations in breathing patterns increasing work of breathing. It may therefore contribute to EIAH and could also be influenced by immersion. As immersion decreases tidal volume and expiratory reserve volume, it is conceivable that exercise flow-volume loops during swimming were within maximal flow volume loop and therefore expiratory flow limitation was not present. Although hydrostatic pressure on the chest wall increases inspiratory muscle demand, it may also decrease demand during expiration. This would be advantageous for someone with bronchoconstriction where expiration is compromised. Furthermore, considering the larger cardiac output due to pre-load, it is feasible that an increased respiratory muscle demand is met with adequate blood supply.

**Airway Dysfunction**

Our finding of a 52% prevalence is similar to values previously reported ranging from 50-65% in competitive swimmers (15, 64, 78). When compared to winter athletes most commonly affected by EIB and AHR, the occurrence in swimmers in the literature is almost double (14). In our study both females (7/11) and males (4/10) tested positive for EVH. It is also of note that two males with negative test results had baseline FEV$_1$/FVC values of 67.3 and 70.7, suggesting
airway constriction at rest. There was no clear relationship between the two EVH and IST results indicating poor sensitivity of these tests. Frequent, sustained exposure to pool chemicals best explains the differences between swimmers and other athletes. By-products associated with chlorine are largely volatile in nature (113). Swimmers inhale the layer of air directly above the water surface where the mean chlorine concentration is 0.42mg/m³ (32). A 2hr training session would expose the athlete to 4-6g, exceeding the restrictions for an 8hr day of work. Alveolar air and plasma chloroform levels in swimmers have been correlated with pool water, air concentration, intensity of exercise, and length of time swimming (2, 3). Elite, competitive swimmers spend 15-25h per week completing in-water training. Wheezing, coughing, and dyspnea with intense training or racing are frequently reported in this population. Swimming in seawater does not appear to have the same deleterious effects on airway cells as seen in chlorinated pools (11). In examining a swimmer’s career, it is of note that adolescent swimmers with few years of training, fail to show significant signs of airway damage indicating that EIB and associated inflammation develop over time with chlorine exposure (87). This airway narrowing may occur during or after exercise. Longitudinal results indicate that symptoms and inflammatory markers are reversible or eliminated all together, once exposure is minimized (53, 90). However, there is evidence to suggest that the associated inflammation of the bronchial tree is transient. Stickland found that induced sputum cell count returned to normal 12hrs or more after the previous training session (109). As a typical elite swimmer has <6hrs between swim training sessions within a day, chronic inflammation due to chlorine exposure is likely contributing to elevated levels of airway dysfunction in this population.

Despite the high prevalence of EIB among our subjects, there was no significant relationship to EIAH. We hypothesized that airway narrowing due to bronchoconstriction and inflammation
would result in a relative hypoventilation making these individuals susceptible to EIAH. The most probable explanation is that the physiological response to immersion, resulting in decreases in ventilation, increases in pulmonary arterial pressures, and a redistribution of blood flow, must outweigh the negative effects of EIB on gas exchange. Interestingly, male subjects #8 and #10, and female subject #7 all had the largest drops in the EVH test corresponding with the largest drops in SpO$_2$. However, statistical analysis does not support this as a general trend in the group. Therefore we assess the risk of desaturation in this population as low, despite clear evidence of airway dysfunction.

**Exercise Protocol and Data Collection**

Pulse oximetry is an indirect method of measuring the oxygen content of the blood. Direct blood sampling is the most appropriate procedure/method for reporting oxyhemoglobin saturation and the incidence of EIAH. However, data collection in the aquatic environment presents challenges for such procedures, therefore our method of acquiring this variable is a limitation of this study. However, it can be noted that recent improvements in oximeter technology have increased precision and reduced both bias and motion artifact. Studies have shown the Masimo unit with forehead sensor to be the most accurate device with a bias of only -0.24%, and a correlation factor $r^2=0.90$ when compared to corresponding ECG lines and arterial samples (8, 120). As the error in oximetry tends to underestimate true saturation, considering our results, this would further substantiate our findings.

Another limitation of our study is the procedure involved in measuring metabolic variables such as VO$_2$, VCO$_2$ and VE. Our snorkel system allowed for free-breathing conditions with unrestricted ventilation. This is atypical in comparison to the stroke-dependent breathing pattern
adopted during freestyle (prone) swimming. Our results however, can be compared to previous studies where EIAH was reported in athletes exercising on land where ventilation was also unrestricted. Nonetheless, we cannot fully extend our findings to prone swimming exercise when coupled breathing patterns are employed. Elite swimmers often reduce their breathing frequency for the purpose of hypoxic adaptation in training, or to maintain speed under race conditions. During cycle exercise, it has been shown that reduced frequency of breathing results in arterial hypoxemia (119). In swimming, dives and turns require breath-holding further compromising ventilation. While providing valuable descriptive data, the use of the snorkel system confines the application of our results to the effects of the aquatic environment on the body, without extending it to true swim training/racing conditions.

Despite the absence of the development of EIAH in any of our subjects, our small sample size is also a limiting factor. To appropriately detect sex differences and to contribute to the literature on prevalence in the swimming population, additional subjects and studies are required.

Conclusions

This study is novel in its assessment of EIAH during swimming exercise in a pool. It is the first to provide data comparing the occurrence of EIAH in both male and female swimmers. We found no evidence of EIAH in swimmers regardless of sex and/or presentation of EIB. Our data is contradictory to that found in other elite athlete populations. This finding may be attributable to two variables, water immersion and horizontal body position, uniquely associated with swimming. These conditions promote redistribution of blood flow and ultimately improved gas exchange. While data were collected in an exercise-specific environment, additional studies are required to examine the effect of restricted breathing patterns on EIAH. In addition, efforts must
be made to collect temperature-corrected blood samples during swimming exercise to confirm the absence of EIAH in this population.
Chapter 3: Pulmonary Edema in Competitive Swimmers

Introduction

Pulmonary edema (PE) can be described by a sequence of fluid accumulation progressing from mild to severe (108). Interstitial edema (IE) is characterized by fluid accumulation in the interstitial space, where collection eventually exceeds removal, creating a net fluid influx. As pressure continues to rise, the interstitial space reaches capacity and the alveolar wall eventually concedes flooding the alveolar space resulting in alveolar edema (AE). In extreme cases, capillary compression and/or changes in the permeability or structure of the endothelial or epithelial membranes can take place (115). More severe symptoms and signs include pink froth in sputum (hemoptysis), cough, cyanosis and dyspnea. Conversely, interstitial edema could be transient and occur without obvious symptoms.

There has been recent debate in the literature as to whether pulmonary edema occurs in athletes during exercise at sea level. Hopkins (62) provided a series of case reports of pulmonary edema exacerbated under conditions including prolonged exercise (77), psychological stress (1), cold (118), moderate altitude exposure (21) and water immersion (1, 104) as evidence this condition does occur in response to exercise. Studies reporting severe symptoms likely reflect alveolar flooding particularly when coupled with radiographic evidence of lung fluid accumulation. While indirect evidence such as $V_A/Q$ mismatch increasing with exercise and persisting into recovery are thought to be consistent with interstitial pulmonary edema (30), Sheel and McKenzie (101) argue that the case reports likely contain technical errors in measurement, and the clinical presentation could be due to underlying pathophysiology. The validity of the
measurement of PE has been questioned with studies that fail to show pulmonary edema using
sensitive tools such as computerized tomography (CT) or magnetic resonance (MR) (42, 54, 71).
A variety of diagnostic imaging techniques remain at the core of this debate. Radiographic
images require large changes in magnitude (~35%) of extravascular water (105) to detect PE,
making this unlikely to detect interstitial edema. MR imaging shows accuracy in vitro (35) but
requires further validation in vivo. It is a powerful tool with a variety of techniques to assess
regional lung function that need to be explored further (58). CT scan technique is validated and
has shown consistencies with diagnosis of pulmonary edema in divers, chronic obstructive
pulmonary disease, and emphysema (19, 26, 27) making it an attractive tool for use in the
athletic population.

Interstitial edema is more likely to occur in human athletes as overt signs of injury to the blood-
gas barrier (associated with alveolar edema) are rarely presented in sport. There are several
human studies on runners, cyclists and triathletes showing increases in lung water post-exercise
(22, 77, 80), however swimmers have yet to be investigated formally. Marshall (76)
demonstrated an increase in pulmonary extravascular water volume from sitting to supine that
was amplified with exercise. This suggests that athletes exercising in a horizontal position could
be predisposed to the development of pulmonary edema. Clinical cases of swimming-induced
pulmonary edema (SIPE) have been documented in endurance open water swimmers (1, 70, 103,
114). In many cases, the clinical assessment of pulmonary edema was linked with hypoxemia
(SaO₂ ~85-95%) indicating impaired gas exchange. The mechanism implicated in the
development of PE associated with immersion is pulmonary overperfusion (67). Swimming in
the lateral position has shown an increase in infiltrates in the dependent (submerged) side of the
lung, indicating increased perfusion and pulmonary capillary pressures causing immersion-
induced stress failure in these cases (70, 72). At rest, head-out immersion increases cardiac output, central blood volume and pulmonary arterial pressure (7). During exercise, cardiac output and stroke volume are significantly higher underwater compared to on-land values (102). Furthermore, canine studies have shown a decrease in lymph flow maintained for the duration of immersion (81). As lung fluid movement reflects the dynamic between hydrostatic and osmotic pressures, if pulmonary arterial pressures are high and the lymphatic system is unable to compensate with an increased clearance rate, the result will be pulmonary edema. While the pool environment is less strenuous in terms of temperature and water movement, the physiological effects of immersion apply to both conditions. Increases in pulmonary blood volume and pressures, coupled with decreases in lymph flow, could make pool swimmers susceptible to this condition. Therefore, the purpose of this study was to assess and describe the occurrence of exercise-induced pulmonary edema in competitive swimmers, and to examine the relationship between this condition and oxyhemoglobin saturation. We hypothesized that there would be an increase in lung density post-exercise, and that these changes would be associated with a decrease in blood oxygen saturation levels during exercise.

Methods

Subjects: Eight, non-smoking, male competitive swimmers were recruited from the University of British Columbia varsity program or the Canadian National swim team for testing. Subjects trained regularly (6 days/week). Total swim training volume was 12-18 hours/week (35-70km). Testing sessions were completed in-season. Competition level of all subjects was either national or international level. Five subjects (4 female, 1 male) were diagnosed with asthma via EVH provocation prior to entering the study. These five subjects were prescribed short-acting inhaled
bronchodilators and corticosteroids.

**General Protocol:** The experimental protocol included four test days separated by a minimum of 48h. Subjects were asked to refrain from 1) short acting bronchodilators for 8h prior, 2) vigorous exercise and caffeine for 12h prior, and 3) long acting bronchodilators or antihistamines 48h prior to each testing session. A leukotriene antagonist and corticosteroid washout period of four days was observed. On day 1, subjects reported to the pool and underwent basic anthropometric measures followed by baseline spirometry testing, an incremental swim test to maximal aerobic capacity (VO$_{2\text{max}}$). On day 2, subjects and underwent a baseline limited low-dose CT scan of their lungs. On day 3, subjects completed an interval swim training session at the pool followed by another CT scan using the same slice locations and acquisition parameters. Pool conditions were consistent with water temperature between 25-28°C (within international sport body mandates) typical of competitive pool standards.

**Spirometry and VO$_{2\text{max}}$ (Day1):** Basic pulmonary function measures (MIR Spirolab II, Medical International Research, Rome, Italy) were performed according to ATS specifications prior to the swim test (82). Predicted spirometric values were defined according to Knudson et al. (66). Horizontal resistance was applied to the subjects during swimming via a tethering apparatus located ten feet behind them on the pool deck. The tethering apparatus was calibrated (r=0.992) over a range of weights at this distance using a force meter (model BG50, Mark-10 Corporation, Copiague, NY). The calibration equation ($y=0.5309x + 8.8641$, $r^2 = 0.97175$) was used to calculate force data. Force production in this context can be described as “the force necessary to maintain swimming position”. These data were converted to Newtons (N) post-test for reporting purposes. Swimmers were attached to a nylon belt, connected to nylon rope, fed
through a pulley system attached to a bucket, where weighted plates were added to provide resistance (Appendix A). All subjects were familiar with this apparatus and had used it as a training tool regularly. Subjects completed a three-phase warm-up consisting of 200m free-swimming, followed by 4 x 30 seconds tethered swimming (without snorkel), and finally 4 x 30 seconds tethered swimming (with snorkel). The tethered swim warm-up was used to practice maintaining position in the pool, as well as to determine the starting load for the incremental test. Starting loads (kilograms placed in the bucket of the tethering apparatus) ranged from 45-90kg for males and 45-60kg for females. The incremental swim test (IST) began at the pre-determined starting load and increased by 5kg every 2 minutes until the swimmer could no longer hold position. Swim position was marked by a static pole submersed in front of the swimmer, and markings on the floor of the pool. Colored markers were attached to a pole and inserted in front of the swimmer to indicate the 1-minute (blue marker) and 2-minute (red marker) time points of each stage. During exercise, subjects wore a nose clip and breathed through a mouthpiece connected to a low-resistance non-rebreathing Y-shaped valve (model 1420, Hans Rudolph, Kansas City, MO). The valves and hoses were fixed to a custom L-shaped, weighted PVC pipe structure that was buoyancy neutral (Appendix A). The Y-shaped valve was oriented vertically to allow for a clean arm stroke without interference. Subjects were familiar with breathing through a mouthpiece and snorkel for training purposes. Breathing frequency was unrestricted (self-selected) throughout the test. Mixed expired gas concentrations and ventilator parameters were measured continuously using an automated gas analysis system (TrueOne 2400, Parvo Medics, Provo, UT) and values were recorded over 15s epochs. The gas analyzers were calibrated using a 3-litre syringe over a range of flow rates to ensure linearity. All subjects swam until exhaustion and each displayed a plateau in VO\textsubscript{2} whereby an increase in final workload did not further increase VO\textsubscript{2}. Data are reported as averages of the two highest
consecutive 15 s epochs.

Oxygen saturation (SpO$_2$), perfusion index and heart rate were measured using a customized waterproof oximeter system (Phone Oximeter, Electrical and Computer Engineering in Medicine Group, University of British Columbia, Vancouver, BC). The system was composed of a forehead sensor probe (TF-I transfectance) placed under the swim cap, attached to a pulse oximeter module (SET Low Power Module, Masimo Corporation, Irvine, CA) with the signal transmitted through a cable to a laptop on the pool deck where data were recorded and stored. The raw signal was sampled at 1-second intervals, recorded to a text file and processed in a customized software program (iRecord2, Electrical and Computer Engineering in Medicine Group, University of British Columbia, Vancouver, BC). For quality control purposes the raw photoplethysmogram waveforms were also recorded to a file. Data with a perfusion index > 0.8 (indicating a poor signal) was discarded. The lowest value for SpO$_2$ was reported. To account for the industry standard of 1% error for motion artifact, exercise-induced arterial hypoxemia was defined using a SpO$_2$ value of ≤94%, or a drop of 4% or more from resting values. These values are in agreement with previous classifications for exercise data (96)

**Interval Swim Test (Day 2):** Subjects performed a 2km free-swimming, standard warm-up consisting of drills and mild-to-moderate intensities of varying distances in a 25m pool. Subjects were then fitted with a customized, portable, waterproof oximeter system (Phone Oximeter, Electrical and Computer Engineering in Medicine Group, University of British Columbia, Vancouver, BC). The system was placed entirely under the swim cap and was composed of a forehead sensor probe (TF-I transfectance), attached to a pulse oximeter module (SET Low Power Module, Masimo Corporation, Irvine, CA) connected to a portable storage device (iPod
Touch 4th Generation, Apple Inc, Cupertino, USA). The raw signal was sampled at 1-second intervals, recorded to a text file and processed in a customized software program (iRecord2, Electrical and Computer Engineering in Medicine Group, University of British Columbia, Vancouver, BC). To allow for real time monitoring during the test, the oximeter system conditioned the parameters for wireless broadcasting over a web server whereby the experimenter inspected the data using a web browser on a laptop (located on the pool deck) connected to the same wireless network. For quality control purposes the raw photoplethysmogram waveforms were also recorded to a file. Data with a perfusion index > 0.8 was discarded. For comparison between intervals, exercise data were pooled and averaged. The lowest \( \text{SpO}_2 \) sampled during exercise, and highest \( \text{SpO}_2 \) sampled during rest were also recorded at each interval for the purpose of commenting on fluctuations between exercise and recovery.

Following the warm-up and oximeter fitting, subjects performed 6 x 50m (from a push) on 90s time intervals in their most comfortable stroke (N=7 freestyle, N=1 backstroke). Subjects were instructed to hold the fastest average speed over all six intervals. Performance times were measured by an expert coach using a stopwatch marking the time of foot departure from the wall and finger touch at the finish. During each interval, six strokes were timed by the coach, and via a function on the stopwatch, stroke rates were reported per-minute. Breaths were counted as totals per 50m effort and converted to breathing rates (per-minute) post-test. This warm-up and interval swim protocol was utilized to be consistent with a typical training session. All subjects drank 500mL of water post-exercise (standard practice) to minimize dehydration.

**Computed Tomography Scans (Day 2, 3):** Subjects reported to the Department of Radiology at Vancouver General Hospital where they underwent baseline and post-exercise limited low-dose...
CT scans. Baseline scans were completed after a minimum of 24 hours rest. Post-exercise scans were completed within 60 minutes of the completion of the 6 x 50m effort. Lying supine, scans were acquired from three regions of the lung using a single-turn 360° acquisition on a Siemens “Sensation 16”, 16 detector row CT scanner (Siemens AG Medical Solutions, Erlangen, Germany) and images were transmitted to a workstation for quantitative analysis. The CT parameters were identical to those described in a previous study examining lung density in male cyclists (71). Briefly, scanner parameters included: 120kVp, 80 mA, 0.5 s rotation time, and a field of view of 380mm. Automatic tube current modulation was applied in the x, y plane with an average dose length product per acquisition of 34 ± 1.4 mGy/cm yielding an effective dose for the pre- and post-exercise scans of 0.95 mSev. This is equal to approximately one half of the yearly background radiation exposure in Vancouver, BC. To minimize variability as previously specified (42), subjects were directed to hold their breath at maximal inspiration for the duration of the scan, while the CT technician based slice position on easily identified non-lung anatomical landmarks (see Appendix B for topographical image). Subjects were familiar with performing maximal inspiration routinely in training due to the nature of their sport. At each of the 3 levels (aortic arch, the tracheal carina, the superior end plate of the tenth thoracic vertebrae), ten 1mm thick images were obtained. Images were reconstructed using a 180° linear interpolation algorithm and an intermediate (B45) special frequency reconstruction algorithm. The lung parenchyma was segmented and the x-ray attenuation values of the lung were analyzed using custom software (EmphylxJ) as previously described (25, 27). The slices were matched pre-post for location and were selected on this basis for the purpose of analysis (see Appendix B for examples). The overall or total data for volume and mass are the summation of these matched slices. Raw density data for the selected slices in each individual were first pooled together, then analyzed as a whole to produce average density across the image. CT lung volume was
calculated by summing the voxel dimensions of the lung tissue following segmentation from the chest wall and mediastinum. The mean CT attenuation of the lung was calculated and converted to a density value in g.ml\(^{-1}\) using the relationship: density = [(lung attenuation (in Hounsfield units (HU)) + 1000)/1000. To examine inter-subject lung density differences, the mean, median, standard deviation, variance, and skewness of the CT density histograms were calculated.

**Statistical Analysis:** Descriptive characteristics were compared between pre and post-exercise tests using unpaired T-tests. Linear regression analysis using Pearson correlations were performed to test associations between specific pulmonary function parameters and metabolic data. The \(\alpha\) level was set a-priori at 0.05 for all statistical comparisons. Values are presented throughout the manuscript as means ±SD unless otherwise stated.

**Results**

**Spirometry and VO\(_{2}\)max:** Table 3.1 shows anthropometric and spirometry data obtained on day 1. Typical to this population, both FVC and FEV\(_1\) values are well above 100% of predicted in this group. Table 3.2 is a summary of the data obtained at maximal exercise during the incremental test to exhaustion. The VO\(_2\)max results indicate a well-trained group of male athletes. The mean absolute drop in SpO\(_2\) from resting was 2.7% (range 1.7-3.5%). The resting SpO\(_2\) (99.5±0.6) was significantly different from that recorded at maximal exercise (p=0.00). Despite this statistic, no individual subjects fulfilled our criteria for EIAH. All individual maximal exercise values were >95.0%, and all values representing a decrease in SpO\(_2\) were <4%.
Table 3.1 Subject characteristics and airway data

<table>
<thead>
<tr>
<th></th>
<th>Value</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age, yrs</td>
<td>20.5±1.9</td>
<td>(18-23)</td>
</tr>
<tr>
<td>Height, cm</td>
<td>186.9±5.6</td>
<td>(181.1-195.2)</td>
</tr>
<tr>
<td>Mass, kg</td>
<td>79.2±9.3</td>
<td>(67.2-89.4)</td>
</tr>
<tr>
<td>Race experience, yrs</td>
<td>11.8±3.8</td>
<td>(6-17)</td>
</tr>
<tr>
<td>FVC, L</td>
<td>7.4±0.9</td>
<td>(6.2-8.7)</td>
</tr>
<tr>
<td>FVC, % predicted</td>
<td>129.8±12.7</td>
<td>(116-150)</td>
</tr>
<tr>
<td>FEV₁, L</td>
<td>5.6±0.6</td>
<td>(5.0-6.9)</td>
</tr>
<tr>
<td>FEV₁, % predicted</td>
<td>114.8±10.1</td>
<td>(106-138)</td>
</tr>
<tr>
<td>FEV₁/FVC</td>
<td>77±5</td>
<td>(69-82)</td>
</tr>
</tbody>
</table>

Values are means ±SD. FVC, forced vital capacity; FEV₁, forced expiratory volume in 1 s. Predicated values are base on Knudsen et al. (66).

Table 3.2 Maximal ventilatory, metabolic, saturation and force data

<table>
<thead>
<tr>
<th></th>
<th>Value</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>VO₂ ml/kg/min</td>
<td>60.5±6.8</td>
<td>(51.2-73.9)</td>
</tr>
<tr>
<td>VO₂ L/min</td>
<td>4.8±0.7</td>
<td>(3.8-5.8)</td>
</tr>
<tr>
<td>VCO₂ L/min</td>
<td>5.1±0.8</td>
<td>(3.8-6.2)</td>
</tr>
<tr>
<td>VE l/min</td>
<td>118.1±19.9</td>
<td>(89.8-142.2)</td>
</tr>
<tr>
<td>VT, l</td>
<td>3.4±0.4</td>
<td>(2.8-4.1)</td>
</tr>
<tr>
<td>f, breaths/min</td>
<td>50.2±7.9</td>
<td>(41.5-65.7)</td>
</tr>
<tr>
<td>RER</td>
<td>1.08±0.03</td>
<td>(1.04-1.13)</td>
</tr>
<tr>
<td>HR, beats/min</td>
<td>179±11</td>
<td>(164-202)</td>
</tr>
<tr>
<td>SpO₂, %</td>
<td>96.8±1.1</td>
<td>(95.3-98.3)</td>
</tr>
<tr>
<td>SR, strokes/min</td>
<td>68±7</td>
<td>(56-80)</td>
</tr>
<tr>
<td>Force, N</td>
<td>61.6±6.3</td>
<td>(51.3-69.9)</td>
</tr>
</tbody>
</table>

Values are means ±SD. VO₂, oxygen consumption; VCO₂, carbon dioxide production; VE, minute ventilation; VT, tidal volume; f, breathing frequency; RER, respiratory exchange ratio; HR, heart rate; SpO₂, arterial oxyhemoglobin saturation by pulse oximetry; SR, stroke rate expressed per minute

**Swim Intervals:** Table 3.3 summarizes the mean performance data for all intervals. The average combined duration of all intervals was 159.4±5.9 sec. Figure 3.1 shows mean performance time, heart rate and SpO₂ response for each 50m interval. Performance times were consistent across intervals as requested. Due to the sprint nature of the set, heart rates show a
slow climb over time with a mild plateau by interval #5 and #6.\(\text{SpO}_2\) decreased slightly across the intervals but remained above our cut-off of 95%, and was therefore not considered to be evidence of exercise-induced arterial hypoxemia.

**Table 3.3** Mean performance, metabolic and stroke parameters for all intervals

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Mean Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time, s</td>
<td>26.6±1.0</td>
<td>(25.2-28.1)</td>
</tr>
<tr>
<td>(\text{SpO}_2), %</td>
<td>99.0±1.4</td>
<td>(97.5-100)</td>
</tr>
<tr>
<td>HR, beats/min</td>
<td>139±8.1</td>
<td>(130-151)</td>
</tr>
<tr>
<td>HR, % max</td>
<td>87.6±6.4</td>
<td>(79-98)</td>
</tr>
<tr>
<td>BR, breaths/min</td>
<td>19.0±3.4</td>
<td>(15.1-25.0)</td>
</tr>
<tr>
<td>SR, strokes/min</td>
<td>46.1±3.3</td>
<td>(42.8-52.0)</td>
</tr>
</tbody>
</table>

Values are means ±SD. \(\text{SpO}_2\), arterial oxyhemoglobin saturation by pulse oximetry; HR, heart rate; BR, breathing rate calculated as breaths taken converted to /min; SR, clean swimming stroke rate
Figure 3.1 Mean performance time, heart rate (HR), oxyhemoglobin saturation (SpO₂) for all intervals
**CT:** The post-exercise CT scans were obtained 47.9±7.2min (range 40-60min) following the completion of the last interval. Table 3.4 shows the total volume, mass, and density of the three regions that were imaged and matched for location on each individual. The volume changes between scans were minimal as measured by the CT tracing (Appendix B). The percent volume change for the aortic arch (AA), tracheal carina (TC), tenth thoracic vertebrae (T10), and the slice total were -1.9, -0.6, -1.3, -1.2% respectively indicating consistency in breath size. There was no significant change in total volume between scans (p=0.28). The mean percent density increases for AA, TC, T10 and the slice total was 3.6±10.6%, 6.4±7.6%, 7.9±6.0%, 6.3±6.3% respectively. There was a significant increase in both total mass (p=0.05) and total density (p=0.03) following exercise. The majority of subjects (7/8) showed increases in slice total density. As density values are based on the amount of Hounsfield units absorbed in each voxel, and mass is calculated from volume and density, the concurrent increase in mass is as expected.

**Table 3.4** Individual total lung volume, total lung mass, and average density pre- and post-exercise

<table>
<thead>
<tr>
<th>Subject #</th>
<th>Total volume, ml</th>
<th>Total mass, g</th>
<th>Avg density, g/ml</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pre</td>
<td>Post</td>
<td>Pre</td>
</tr>
<tr>
<td>1</td>
<td>94.53</td>
<td>88.63</td>
<td>14.64</td>
</tr>
<tr>
<td>2</td>
<td>82.46</td>
<td>84.33</td>
<td>13.94</td>
</tr>
<tr>
<td>3</td>
<td>75.10</td>
<td>74.30</td>
<td>10.47</td>
</tr>
<tr>
<td>4</td>
<td>82.37</td>
<td>81.24</td>
<td>13.47</td>
</tr>
<tr>
<td>5</td>
<td>101.95</td>
<td>104.16</td>
<td>12.73</td>
</tr>
<tr>
<td>6</td>
<td>100.77</td>
<td>96.40</td>
<td>16.27</td>
</tr>
<tr>
<td>7</td>
<td>85.43</td>
<td>83.93</td>
<td>15.08</td>
</tr>
<tr>
<td>8</td>
<td>91.73</td>
<td>92.04</td>
<td>13.07</td>
</tr>
<tr>
<td><strong>Means ± SD</strong></td>
<td><strong>89.3±9.5</strong></td>
<td><strong>88.1±9.4</strong></td>
<td><strong>13.7±1.7</strong></td>
</tr>
</tbody>
</table>

* Significantly different from pre-exercise values p=0.05
Slice location has been matched pre-post at each region (aortic arch, tracheal carina, superior end-plate of T10). Density values are the average of matched slices. Mass data are the summation of three slices (one per region).
Table 3.5 breaks the density data down into three separate regions from the apex of the lung to the base of the lung in each individual subject. There was no change in density at the level of the aortic arch (p=0.48). The density at the tracheal carina approached significance (p=0.06) but did not satisfy our a priori alpha level. A significant increase in density is shown at T10 (p=0.01). Table 3.6 shows results of the histogram analysis. The standard deviation and variance were both significantly larger post-exercise at each the tracheal carina and the tenth thoracic vertebrae (p=0.01). In addition, the median value at T10 also reached significance (p=0.03). These indicate a rightward shift in the curve of the histograms from pre-post demonstrating a change in distribution of these data and a concurrent increase in density. Upon inspection of the histogram curves (Appendix C), subjects #1 and #3 have the most pronounced rightward shift, while subjects #4, #5, and #8 have much smaller, yet visible shifts. These observations correspond with the magnitude of percent density increases in these subjects.

**Table 3.5** Individual mean density (g/ml) at the aortic arch, tracheal carina, and superior end plate of T10 pre- and post- exercise

<table>
<thead>
<tr>
<th>Subject #</th>
<th>Aortic Arch</th>
<th>Tracheal Carina</th>
<th>T10</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pre</td>
<td>Post</td>
<td>Pre</td>
</tr>
<tr>
<td>1</td>
<td>0.1493</td>
<td>0.1836</td>
<td>0.1577</td>
</tr>
<tr>
<td>2</td>
<td>0.1854</td>
<td>0.1780</td>
<td>0.1625</td>
</tr>
<tr>
<td>3</td>
<td>n/a</td>
<td>n/a</td>
<td>0.1361</td>
</tr>
<tr>
<td>4</td>
<td>0.1695</td>
<td>0.1726</td>
<td>0.1517</td>
</tr>
<tr>
<td>5</td>
<td>0.1207</td>
<td>0.1270</td>
<td>0.1212</td>
</tr>
<tr>
<td>6</td>
<td>0.1538</td>
<td>0.1711</td>
<td>0.1555</td>
</tr>
<tr>
<td>7</td>
<td>0.1895</td>
<td>0.1770</td>
<td>0.1632</td>
</tr>
<tr>
<td>8</td>
<td>0.1489</td>
<td>0.1412</td>
<td>0.1342</td>
</tr>
<tr>
<td>Means±SD</td>
<td>0.1596±0.024</td>
<td>0.1644±0.021</td>
<td>0.1478±0.015</td>
</tr>
</tbody>
</table>

* Significantly different from pre-exercise values p<0.05

Slice location has been matched pre-post at each region (aortic arch, tracheal carina, superior end-plate of T10). Density values are the average of matched slices. Mass data are the summation of three slices (one per region).
Table 3.6  Group mean values for median, SD, variance and skewness of the lung density histograms pre- and post- exercise by region

<table>
<thead>
<tr>
<th>Region</th>
<th>Aortic Arch</th>
<th>Tracheal Carina</th>
<th>T10</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pre</td>
<td>Post</td>
<td>Pre</td>
</tr>
<tr>
<td>Median (g/ml)</td>
<td>0.129±0.023</td>
<td>0.133±0.021</td>
<td>0.121±0.016</td>
</tr>
<tr>
<td>SD (g/ml)</td>
<td>0.150±0.011</td>
<td>0.155±0.009</td>
<td>0.135±0.006</td>
</tr>
<tr>
<td>Variance (g/ml)</td>
<td>0.023±0.003</td>
<td>0.024±0.003</td>
<td>0.018±0.002</td>
</tr>
<tr>
<td>Skewness (g/ml)</td>
<td>3.282±0.199</td>
<td>3.091±0.377</td>
<td>3.209±0.391</td>
</tr>
</tbody>
</table>

* Significantly different from pre-exercise values p<0.05

Values are group means ±SD per region (aortic arch, tracheal carina, superior end-plate of T10).
Discussion

The purpose of this study was to evaluate whether pulmonary edema occurs following sprint swimming and to examine the relationship between this condition and oxyhemoglobin saturation. This is the first study to measure lung density in competitive swimmers. We found short intense swimming exercise caused significant increases in lung density suggesting the development of transient pulmonary edema in these athletes. Despite an increase in density, desaturation was not associated with exercise, implying that pulmonary gas exchange was not impaired.

Several studies have shown increases in lung water measured post-exercise in athletes (22, 77, 80). Early work by McKechnie (77) documented overt signs and radiographic evidence in runners after ~3hr ultramarathon effort. Reports in triathletes, with both radiographic (23) as well as CT images, have demonstrated a 19% increase in lung density post-race with a concomitant 5% decrease in pulmonary diffusion (DL) (22). Similar results in cyclists were seen with MR imaging after 45 min of exercise at 76% VO$_2$max where a 9.4% increase in lung density, and a 12% decrease in DL was observed (80). In the latter, decreases in DL observed were associated with decreases in pulmonary capillary volume (VC) implying that these changes were a result of blood redistribution and not specifically related to PE. Further to this, no strong correlation was found between diffusing capacity and pulmonary extravascular water. This could be explained if the edema measured was interstitial and therefore concentrated away from the alveolar-arterial tissue barrier. Due to logistical reasons involved with timing of the scans, DL was not measured in our study. Despite the variation in measurement techniques and exercise protocols, these studies support the theory that pulmonary edema can occur in athletes.
following strenuous endurance exercise at sea level. Alternatively, additional studies have failed to show changes in lung water after both running (75%VO₂max) and cycling (60% VO₂max) exercise bouts 1-2 hr in duration (54, 73). There is evidence to show that the blood gas barrier is impaired in intense exercise, but not in submaximal exercise as a possible explanation of the lack of edema post-exercise at 60%VO₂max (61). Two hours of treadmill running at a higher intensity (75%VO₂max) also showed no significant change in density, however a significant increase in lung volume was reported (73). As lung volume is a function of density, it is possible that a true increase in density was overlooked if the subjects took larger breaths during the scans post-exercise vs. pre-exercise.

Studies examining the effects of high intensity interval exercise also show conflicting results. Zavorsky et al (121) reported increases in chest radiograph scores following 5 x 3 min intense interval exercise in female cyclists. The 3-point scale used to interpret the data lacked objective analysis, however given the results, the effects of short interval bouts deserve further investigation. Two additional studies utilizing more sensitive measures (CT scans) failed to show pulmonary edema in both males (71) and females (42) following 5 x 4.5 min exercise intervals (breathing 15% inspired O₂). It was reasoned that hypoxia would increase susceptibility to PE via increases in pulmonary arterial pressure. In contrast, our findings showed increases of 6.3% in lung density using the same sensitive measurement technique after shorter intervals (5 x 26 s). This discrepancy is likely attributable to the effect of immersion on the body.
**Immersion**

The aquatic environment provides a unique set of circumstances in both rest and exercise. Immersion enhances return of fluid from the limbs to the heart, altering the distribution of blood flow, increasing cardiac preload. Head-out immersion at rest has been shown to increase cardiac output by 32% and central blood volume by 700mL, with increases in pulmonary artery pressure of 12mmHg (7). Cardiac output and stroke volume have been shown to be significantly higher (during upright exercise) underwater compared to on-land (102). Reflective of this, arterial blood pressures have been reported to be higher in swimming vs. running (55). The interstitial space acts as a protective mechanism when blood pressure rises. It can increase its volume up to 40% in efforts to remove fluid and conserve gas exchange (43). However in immersion, this mechanism may be compromised. Canine studies have compared the effects of head-out immersion on lymph movement. At rest an initial decrease in lymph flow, maintained for the duration of immersion was observed (81). It was deduced that water immersion compresses the lymph vessels, increasing lymph resistance and could therefore counteract the pressure gradient that normally encourages lymph flow. Increased thoracic blood volume, high pulmonary arterial pressures and reduced lymph flow during exercise can create a net fluid efflux. Therefore, if V/Q distribution is altered through the regions of the lung and the lymphatic system’s capacity to clear fluid accumulation, edema occurs. Furthermore, the horizontal body position unique to swimming exercise, may also contribute, in part, to these conditions. At rest, increases in mean pulmonary arterial pressure and extravascular water volume have been associated with moving from a seated to supine body position (76). These values further increased with exercise showing concomitant changes with cardiac output.
The clinical expression of swimming-induced pulmonary edema (SIPE) has been well-documented in open-water swimmers (1, 70, 103). In navy trainees, swim tests (2-4km) were conducted in calm seas with a temperature range of 19-23 degrees. Most trainees exhibited some combination of the following clinical symptoms or signs: shortness of breath, coughing, sputum production with pink froth (hemoptysis), chest pain, inspiratory crackles on chest auscultation, and/or wheezing. Quantitative data revealed arterial desaturation (SpO₂ often <90% measured at the ear), a decrease in pulmonary function (post-exercise FVC and FEV₁ values lower in SIPE), and, in some cases, infiltrate present in the submerged lung (visual inspection of radiograph). Theses cases are consistent with more severe symptoms of edema related to capillary stress failure and alveolar flooding (115) and could be a result of the additional stress of cold causing peripheral vasoconstriction further increasing pulmonary pressures. The indoor pool environment is more forgiving (indoor pool = 25-28°C, open water = 15-20°C) and as expected, none of the athletes in our study displayed severe symptoms indicating that the integrity of their alveolar-capillary wall was maintained. In well-trained pool-swimmers we reason that the increases in lung density are reflective of mild interstitial edema (without consequence to the alveolar space). It has been shown that fluid accumulation is unlikely to affect the alveolar wall until edema is advanced (108), consistent with our findings of high oxyhemoglobin saturation levels. Given the training frequency and intensity (10 training sessions per week, <6 hours between daytime sessions), the IE observed is most probably intermittent and recurrent. Remodeling of the blood-gas barrier is thought to be a continual process in response to stressors (116); it is therefore possible that repeated transient IE is accommodated by this structural reorganization.
Protocol

Previous reports of pulmonary edema in swimmers were clinical in nature with data collected in an uncompromising, outdoor environment. We overcame this weakness in design by conducting our study in a well-controlled environment to examine the development of pulmonary edema following swimming exercise. While our subjects underwent an exercise protocol commonly seen in a competitive swimmers training program, it can be argued that the interval length was insufficient to induce arterial desaturation, and is therefore considered a limitation to this study. While the swimming velocity and exercise intensity required for each interval was very high, average heart rates (130-151 bpm) reflect the duration limitation we imposed. These average values reported are not typically categorized as high-intensity. Further investigation is required to determine whether interval length plays a role in PE development in swimmers and whether this is correlated to magnitude of changes in lung density.

Using computed tomography (CT), extravascular lung water is measured via calculations of density. The physical density of lung parenchyma can be determined by CT scans because the attenuation value of a pixel has been shown to have a linear relationship to the physical density of the tissue (22). Following exercise, pulmonary edema persists as drainage through the lymphatic system is relatively slow (117). This allows for measurement of edema by means of chest radiography, CT, or MR imaging post-effort. Timing must allow for the balance of two issues: 1) heart rate and blood pressure to return to baseline so that increases in blood volume are not misinterpreted as increases lung water, 2) capturing measurements prior to the lymph system clearing any accumulated fluid that should reflect edema. Our data, measured ~48 min post-exercise, do not reflect increases in thoracic blood volume as it has been previously documented that pulmonary capillary blood volume returns to near resting levels ~ 30 min following maximal
exercise (74). Our protocol detected changes in lung density post-exercise consistent with CT measures by Caillaud et al. (22) who observed lung density increases ~90 min post-exercise in triathletes. While these two studies provide evidence that PE can be detected by CT scan post-exercise, optimal timing will remain under debate in the literature until a protocol can be developed to explore the response time-course in subjects with reproducible pulmonary edema.

Another limitation of this study is that we did not scan the entire lung. To minimize radiation exposure to our subjects, we selected three anatomical regions to represent the superior, inferior and middle portion of the lung. It can be argued that this small total region may not reflect an accurate assessment of lung changes following exercise. However, it is unlikely that the increases in density observed in both this study and that of Caillaud et al. (22) using a limited slice profile, could be constrained to the small areas measured and not occur across larger portions of the lung as a whole. Although we did not see uniform increases in density across the 3 selected regions as compared to the total density increase, these data findings are consistent with the osmotic discrepancy from the apex to base of the lung as described by West (117). In efforts to minimize technical error and ensure accuracy, we performed all CT scans using the same scanner, technician and technical parameters. In addition, only matched slices were selected to ensure that any changes observed were not due to slice location differences.

Conclusions

Our main finding is an increase lung density after high-intensity exercise in well-trained swimmers. Our data supports the argument that pulmonary edema does occur in athletes exercising at sea level, and contradicts studies failing to show lung density increases in athletes using CT scan technology. This finding may be attributable to the effects of immersion on the
human body during exercise. It is possible that immersion and body position cause increases in pulmonary arterial pressure that induce interstitial edema, but are insufficient to cause more severe symptoms consistent with alveolar edema. Additional studies are required to examine the relationship of interval length on oxyhemoglobin saturation and the severity of PE in this population.
Chapter 4: Conclusion

Summary, Major Findings and Significance

The purpose of this thesis was to describe the pulmonary profile of competitive swimmers. We examined the occurrence of exercise-induced arterial hypoxemia in relation to exercise-induced bronchoconstriction in males and females. We also assessed the development of exercise-induced pulmonary edema and the association to oxyhemoglobin saturation in this population.

Instances of exercise-induced arterial hypoxemia at sea level have been reported in the literature over the last 40 years. A comprehensive description of this condition provided by Dempsey and Wagner (30) creates the framework for research in this area. This condition has been well documented in a variety of sports (94) with a high prevalence in the athletic population. These findings have been extended to both males and females (28, 48, 91, 96). More recently, reports of pulmonary edema following intense exercise have fueled debate in the literature regarding fluid movement in the lung and its effect on gas exchange (62). The documentation includes a variety of exercise stressors and measurement techniques making it difficult to draw conclusions from the compilation of data. The work of this thesis contributes to the characterization of the pulmonary systems response to swimming exercise. It provides a unique perspective of the development of EIAH and PE in a population facing environmental challenges during exercise. Specifically, we have shown that EIAH does not occur in competitive swimmers, yet pulmonary edema does develop following intense exercise in this population. This is likely due to the effects of immersion and the horizontal body position associated with this form of exercise. Our findings suggest that swimming provides some protection against EIAH due to redistribution of
blood flow and increases in pulmonary arterial pressures. The development of PE appears to be limited to the interstitial space, without signs or symptoms of severe alveolar edema as seen in cases of open water swimmers. The increases in EVLW detected in our subjects versus the description of SIPE reported in open water studies are associated in terms of basic mechanisms, but should be considered separate conditions. Overt signs and symptoms reported with arterial hypoxemia are considered to be on the extreme end of the spectrum (open water cases). Interstitial edema with no obvious signs or symptoms of the clinical expression of SIPE, with little or no consequence to oxyhemoglobin saturation can be considered to be a mild development of edema (pool swimmers). Not only do these two conditions have different physiological outcomes, but they will also require individualized treatment and/or recommendations for health and performance.

This thesis is the first to compare EIAH in males and female swimmers. Contrary to our original hypothesis, subjects did not develop this condition, regardless of gender. Sex differences have previously been shown in the literature (47, 48), yet these were not evident in swimmers. There was no difference in oxygen saturation levels between males and females at maximal exercise despite smaller lung volumes, lower expiratory flow rates and smaller diffusion surface area in women. The finding of no sex differences in swimmers is significant as it highlights the impact of immersion and body position on blood saturation levels during exercise. $V_A/Q$ mismatch and diffusion limitation have been shown to each contribute ~50% to the widening of A-aDO$_2$ during exercise (45, 59). We reason that a larger thoracic blood volume and small increases pulmonary arterial pressure help reduce $V_A/Q$ mismatch during intense exercise in the swimming athlete. However, if pulmonary arterial pressures continue to rise to the point where the capillary-alveolar barrier is compromised, PE could then have the opposite affect on A-aDO$_2$. If
immersion and intense exercise generate pulmonary pressures that are too high and a more severe edema develops, subsequent diffusion limitation could lead to a widening of A-aDO$_2$ and EIAH. Very high cardiac outputs and pulmonary arterial pressures also have the potential to reduce transit time and increase $V_A/Q$ mismatch, or possibly contributing to intrapulmonary shunts further compromising SaO$_2$.

This thesis also provides the first evidence of pulmonary edema in pool swimmers. Measurement tools and exercise protocols for the assessment of edema in the literature remain controversial (62). Studies utilizing hypoxia as a stimulus to induce arterial hypoxemia have failed to detect pulmonary edema with sensitive lung imaging techniques (42, 54, 71). However, we were able to demonstrate increases in lung density using swimmers as a model to evaluate the role of immersion in the development of pulmonary edema. Redistribution of blood flow, with increased blood volume and pressure in the pulmonary system, provide rational for these results. This finding is significant as it indicates that PE can develop in athletes at sea level without signs or symptoms associated with the clinical expression of this condition. In addition, these athletes were not found to develop EIAH during an incremental test to maximal exertion, nor did they desaturate with the short, intense interval exercise bouts we required for this study. This calls into question whether PE should be indicated as a mechanism for EIAH? What remains unknown is the severity of PE in swimmers, its relationship to interval length and intensity, and the point at which we consider this condition relevant to performance and/or health.
Strengths and Limitations

Studies examining EIAH in rowers, cyclists and runners use ergometers and treadmills to control for confounding variables that may influence measurement outcomes. This laboratory environment provides a certain ease of data collection in a dry environment. Lab ergometers for swimming exist, but their use eliminates the influence of water immersion and therefore alters the physiological response to exercise. The scientific evaluation of swimming exercise should be completed in a flume or pool where conditions can be manipulated. A strength of this thesis is the relatively well-controlled environment in which we collected our data. The standards of pool conditions (temperature, chlorine content, and water movement) were maintained across collection days, while the tethering system provided discrete stages during the incremental test and allowed for the measurement of metabolic variables. In addition, the confounding variables associated with open water swimming (tides, currents, and water temperature) were eliminated in our assessment of swimming-induced pulmonary edema.

However, it is that same testing environment from which we draw our study limitations. The protocol set-up (tethered apparatus and free-breathing condition) can be criticized for failing to appropriately mimic typical swimming conditions. Multiple elements should be considered: 1) the snorkel potentially allowed for higher overall minute ventilation as breathing frequency was not restricted to stroke frequency, 2) the ventilation pattern (inspiratory and expiratory lengths) may have been altered as it was not necessary to incorporate these into the stroke, 3) stroke technique was altered as the swimmer did not need to turn their head to breathe, 4) the tethered swimming protocol eliminated dives and turns and therefore, did not include breath-hold periods commonly employed in the sport.
Another limitation of this thesis is the use of pulse oximetry. Our system consisted of Masimo components that have previously been validated against hypoxic, normoxic, and hyperoxic conditions (120), and have demonstrated minimal motion artifact (8) imperative to data collection during exercise. The raw signal produced by these components was then filtered and used to provide a real-time screen display for data collection with the option to export data to a secondary software program for analysis. While we have confidence in the accuracy of the data, it remains that arterial hypoxemia can only truly be confirmed with an arterial blood sample.

**Future Directions**

There are unanswered questions related to the swimming environment that require specific methodology. For example, does EIAH occur in swimmers in a free swimming condition (untethered) when typical ventilatory patterns (stroke-dependent side breathing, and breath hold on flip turns) are employed? There is evidence that reduced frequency breathing induces arterial hypoxemia in subjects (cyclists) who do not regularly utilize these techniques (119). However, well-trained swimmers have been shown to have a reduced CO₂ sensitivity and VE/VO₂ compared to untrained counterparts (40). Perhaps then, our results would not have been altered under swim-specific breathing patterns. Carefully designed studies are required to examine the effect of ventilatory patterns and hypoxic periods (breath-hold) on blood oxygen saturation in swimmers. If either of these have a measurable effect on SaO₂, there is potential for these to be manipulated to produce a training stimulus in athletes.
The occurrence and magnitude of pulmonary edema in this population also warrant further investigation. The continuum of severity of PE is difficult to ascertain from the current data available. Certainly studies documenting the severe end of the spectrum report clinical signs and symptoms associated with AE (1, 77, 104). Research showing evidence of IE (80, 121) document a statistical significance from baseline or resting measures, but the range and quantification of severity have yet to be defined. The relationship between duration of exercise interval and severity of response (change in lung density or % change in lung density) requires attention. Can we use sensitive tools such as CT and MR to measure and quantify the progression of interstitial edema to alveolar edema? Can we identify the point at which PE becomes relevant to athletes in terms of impeding performance? Efforts to mimic race and training duration and intensity are necessary to provide the scientific basis associated with real demands of the sport. Furthermore, conflicting results in females between less sensitive measures (121) and more sensitive tools (42) need clarification. Additional research is required to build our knowledge surrounding the existence and description of PE in female swimmers.

**Overall Conclusion**

The purpose of this thesis was to provide an assessment of the pulmonary response to swimming exercise. We found that EIAH does not occur in either male or female competitive swimmers despite a high incidence of EIB. We also observed the development of PE in well-trained swimmers after intense interval exercise. These results are likely related to the effects of water immersion and horizontal body position on hemodynamics associated with this particular form of exercise. Future work is required to expand our knowledge of oxyhemoglobin saturation variation with the ventilatory parameters involved in swimming. The direction of research in PE
should aim to quantify severity and relevance of the development of this condition in both male and female athletes.
References


51. Haverkamp HC, Dempsey JA, Pegelow DF, Miller JD, Romer LM, Santana M, Eldridge MW. Treatment of airway inflammation improves exercise pulmonary gas...


Appendices

Appendix A

*Incremental Swim Test Equipment Set-Up*

The top image shows the tethering apparatus on the left and the distance from the apparatus where the swimmer performed the test. The bottom image shows a close up view of the swimmer, valve and hosing set-up, stationary pole for spatial orientation in front of the subject, and metabolic cart on the left.
Custom Breathing Apparatus

Photo of the custom L-shaped, weighted PVC pipe structure attached to a non-rebreathing Y-shaped valve.
Appendix B

*Topogram Image of Whole Lung*

This image shows an overhead view of the torso of a subject lying supine. From this image, location was selected for the thirty 1mm slices provided for analysis.
Individual CT Images (Single Slice)

Below are four images used to calculate density. All images were taken at the level of the aortic arch as these are the most clear for visual purposes. Colored highlighting indicates right (red) and left (green) sides of the lung. The top set of scans are from subject #1 and represent a relatively large increase in density from pre (left) to post (right). The bottom set of scans are from subject #5 and represent a small or minimal increase in density from pre (left) to post (right).
Appendix C

**Histogram Graphs**

Individual histograms comprised of the pooled data (3mm total) for each subject pre and post-exercise (listed by subject #). The bottom graph labeled “pre vs post” is the histogram comprised of the pooled data of all subjects at all slice sites pre and post-exercise.
Subject 7 Pre vs Post

Subject 8 Pre vs Post