The Effect of Training Load and Training Stress on the Lung Health of Competitive Youth Swimmers

by

Rachelle Dori Elizabeth Davies

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Faculty of Kinesiology, Sport, and Recreation

University of Alberta

Abstract

Background: Exercise-induced bronchoconstriction (EIB), airway hyperresponsiveness (AHR), airway inflammation, and respiratory symptoms are commonly observed in competitive swimmers. High ventilation during pool training with cumulative exposure to chlorine by-products likely influences such respiratory problems, however there is paucity of evidence to explain whether varying amounts of training influence the lung health of competitive swimmers. Therefore, the objective of the study was to determine the effect of increasing external training loads and internal training stress (the individual response to training) on AHR, inflammation, and respiratory symptoms of competitive youth swimmers.

Hypothesis: We hypothesized overall lung health status would worsen with increased training loads. We predicted lung health would be the worst following a high training load block compared to moderate or low training blocks.

Methods: Eight competitive youth swimmers (4 males, 4 females) from the same high-performance swimming group completed three blocks of training (three weeks in duration) classified as Low, Moderate, and High based on calculations of prescribed swimming distance and intensity. Swimmers completed a weekly self-report questionnaire to determine respiratory symptoms. Session Rating of Perceived Exertion (RPE) was reported daily to quantify internal training stress, which reflects the internal training load (product of RPE and training duration), internal training monotony (daily mean of training loads divided by the standard deviation), and internal training strain (product of load and monotony). Eucapnic Voluntary Hyperpnea (EVH) challenge, spirometry pre- and post-EVH, and Fractional Exhaled Nitric Oxide (FeNO) were completed to determine the extent of AHR, EIB, and inflammation. Data from the three training

were analyzed to determine whether an increase in training load resulted in significant differences in lung health measures across training blocks.

Results: Swimmers had significantly decreased resting FEV_1 after the Moderate training compared to Low, but there was no significant change after High. Maximum % decreases in FEV_1 did not differ significantly across training blocks. Post-EVH FeNO after the Moderate block was also significantly decreased compared to Low. Internal load was significantly decreased after the Moderate block compared to High, while internal monotony was significantly decreased after Moderate compared to Low. Recovery from the EVH test (FEV_1 at sampling intervals) was correlated with respiratory symptom frequency after training blocks.

Conclusion: Increases in training load and monotony influence airway obstruction and inflammation in competitive youth swimmers. Swimmers in our study also had hyperresponsive airways, as revealed by the consistent decreases in FEV_1 >10% upon provocation by EVH. Our results add to existing evidence that training with little variability in the daily training load (i.e. high monotony) may be a factor that facilitates the development of respiratory symptoms and could contribute to AHR and EIB in competitive swimmers. Thus, prescribing conservative increases in training load and maintaining low monotony in competitive swim programs may help reduce respiratory symptom frequency associated with EIB. However, further research is needed to determine the impact of varying training loads on long-term lung health and performance outcomes of swimmers over a season. Competitive swimming programs might benefit from implementing a lung health monitoring system that includes quantifying training loads, tracking respiratory symptoms, and measuring resting lung function.

Preface

This thesis is an original work by Rachelle Davies. The research project, of which this thesis is a part, received research ethics approval from the University of Alberta Research Ethics Board 2, Project Name “Effect of Training Load and Training Stress on Lung Health of Competitive Youth Swimmers”, Pro00066445, 8/25/2016.

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List of Abbreviations

Abbreviations

%	Percent
>	Greater than
<	Less than
≥	Greater than or equal to
≤	Less than or equal to
AED	Automated external defibrillator
AHR	Airway hyperresponsiveness
ANOVA	Analysis of variance
AQUA	Allergy Questionnaire for Athletes©
ASL	Airway Surface Liquid
ATS	American Thoracic Society
AU	Arbitrary units
BPT	Bronchoprovocation test
CC16	Clara cell secretory protein 16
CI	Confidence interval
cm	Centimetres
CO_2	Carbon Dioxide
CPR	Cardiopulmonary resuscitation
EIA	Exercise-induced asthma
EIB	Exercise-induced bronchoconstriction
ENO	Exhaled nitric oxide
ERS	European Respiratory Society
EVH	Eucapnic voluntary hyperpnea or Eucapnic voluntary hyperventilation
F	Females
FEF	Forced Expiratory Flow
FeNO	Fractional exhaled nitric oxide
FEV_1	Forced expiratory volume in one second
FVC	Forced Vital Capacity
HCl	Hydrochloric acid
HOCl	Hypochlorous acid
IOC-MC	International Olympic Committee – Medical Commission
kg	Kilogram

km	Kilometres
L	Litres
L/min	Litres per minute
L/s	Litres per second
M	Males
$mg \cdot m^{-3}$	Milligrams per metre cubed
min	Minutes
mL	Millilitres
mL/min	Millilitres per minute
mL/s	Millilitres per second
mmHg	Millimetres of mercury
mmol/L	Millimoles per litre
MVV	Maximal voluntary ventilation
n	Number of subjects
N_2	Nitrogen
NCl_3	Nitrogen trichloride
NHANES	National Health and Nutrition Examination Survey
NO	Nitric oxide
NOS2	Inducible nitric oxide synthase
O_2	Oxygen
PAR-Q	Physical Activity Readiness Questionnaire
PCO_2	Partial pressure of carbon dioxide
PEF	Peak Expiratory Flow
pH	Potential of hydrogen
PO_2	Partial pressure of oxygen
ppb	Parts per billion
RPE	Rating of perceived exertion
SD	Standard deviation
SP-A	Alveolar surfactant-associated protein A
SP-B	Alveolar surfactant-associated protein B
TLV	Threshold limited value
URTI	Upper respiratory tract infection
VE	Minute ventilation
VO_2	Volume of oxygen

VO_2max	Maximal oxygen consumption
yrs	Years

Chapter 1: Introduction

A potential problem when the respiratory system is under stress, such as during exercise, is the development of exercise-induced bronchoconstriction (EIB), defined as the "acute airway narrowing that occurs as a result of exercise." [1] EIB may be observed in individuals who do or do not have asthma – a chronic inflammatory disease of the airways – based on spirometry testing. [1] The term Exercise-Induced Asthma (EIA) is often used interchangeably in the literature with EIB; however, EIB should be made distinct in that it may occur in non-asthmatic athletes who have otherwise normal lung function. [2] It should also be underlined that exercise does not induce asthma, but rather it can trigger bronchoconstriction. [2] Prior to exercise, an individual may perform an FVC maneuver and obtain a normal flow-volume loop (solid black line, Figure 1), but after exercise could display a more obstructive pattern (red line, Figure 1). The diagnosis of EIB is typically defined by a decrease in FEV_1 after exercise of at least 10% of the pre-exercise value. [2]

Usually, EIB is triggered by inhaling large volumes of dry air during exercise, and is a manifestation of airway hyperresponsiveness (AHR), defined as "an abnormal susceptibility to airway narrowing following exposure to a wide range of bronchoconstricting stimuli." [3] Recently, it has been estimated the prevalence of EIB in athlete populations (11-50%) is higher than in the general population (4-20%), and largely depends on the environmental conditions in which training or sport participation occurs, which are factors that may enhance the development and severity of AHR and EIB. [2,4-8] Both EIB and AHR are especially common in elite athletes, and together are the most common chronic medical conditions experienced by Olympic athletes (8%). [9]

Although there are recognized benefits to health with swimming, respiratory symptoms and disorders associated with the sport have been identified, most of which concern the training environment and the amount of training completed. [3,10-15] EIB prevalence is 11-29% in competitive swimmers [1] and the swimming pool environment may influence the mechanism in which it occurs. Previously, swimming was recommended as a suitable activity for asthmatic children and adolescents due to the increased humidity and temperature of indoor swimming pools, which would theoretically be less likely to promote dehydration of the airways and thus protect against EIB and AHR. [16,17] However, the repeated inhalation of chlorine by-products (mainly trichloramines) likely contributes to chronic respiratory symptoms and inflammation in swimmers and might exacerbate EIB. [14,18] AHR is also prevalent in up to 79% of elite swimmers

compared to 4-35% in the general population.[3] Additionally, Langdeau et al[19] found in a cohort of 100 athletes, classified based on training environment consisting of dry air (long distance running, mountain biking), cold air (biathlon, cross-country skiing, speed skating), mixed air (triathlon), and swimmers (and 50 control subjects), that swimmers showed the highest prevalence of AHR – 76% of all the athletes. However, the age and years of training at which respiratory problems develop in swimming are not well understood. For example, while cross-country skiers develop AHR with increasing age,[20] an age-related increase in AHR has not been reported in swimmers, and most studies on elite athletes have generally been performed in adults with extensive training years and exposure to their sport-specific environmental and training conditions. Although youth swimmers have fewer of years of competition and strenuous exercise compared to adult athletes, they still train and compete several hours per day and undergo intense training. Therefore, examining the extent of lung health problems in competitive youth swimmers is worthwhile. Further, there is paucity of evidence that explains what overall volumes and intensities of swimming increase the risk of developing AHR and EIB.

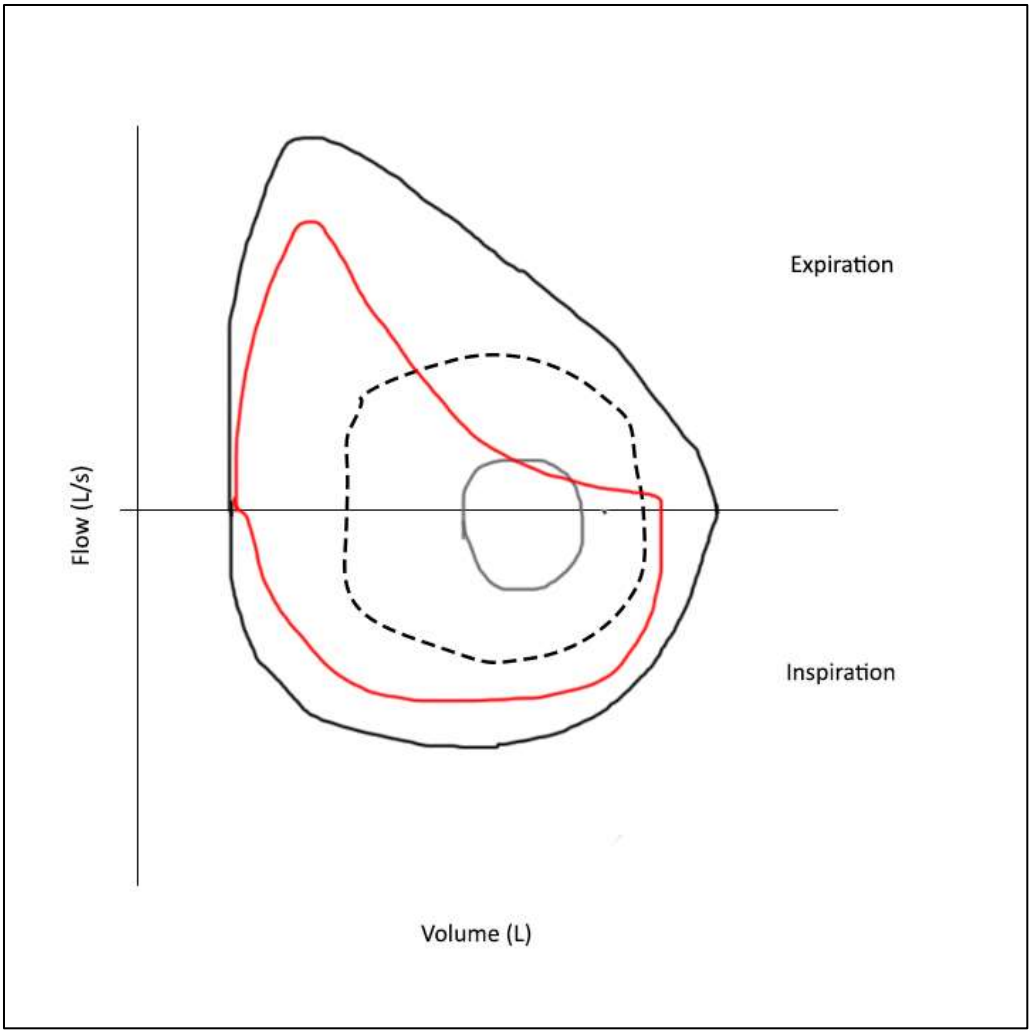

Figure 1. Flow-volume loop obtained with spirometry under various conditions. Solid grey line = normal breathing under resting conditions; dashed black line = increase in ventilation that occurs during submaximal exercise; solid black line = forced vital capacity (FVC) maneuver pattern in healthy persons; solid red line = typical obstructive pattern during FVC maneuver.

The frequency (days per week), duration, intensity, and volume (kilometres swum) of training that competitive swimmers undergo make up the external training load. [10,21] Competitive swimmers have generally high external training loads, primarily due to volume, which includes sustaining elevated ventilation rates in chlorinated pool environments – conditions that are unfavourable to lung health. [3,11,15,22] High ventilation in swimming influences the quantity of inhaled chlorine by-products, which are known to be irritants that contribute to upper- and lower-respiratory tract infections in swimmers. Infections may also be related to the acute alterations in immune function and tissue damage repair after intense exercise. [12,23] However, there is greater prevalence of airway dysfunction [24] and respiratory tract illness and symptoms, such as rhinitis, cough, wheezing, and chest tightness [4,24,25] in elite endurance athletes compared with non-endurance elite athletes. [9,26,27] In addition, higher frequency of reported illness occurs when training surpasses an athlete's individual threshold, known as the internal training stress, which is determined using a combination of internal training load, the product of perceived exertion post-workout and duration; training monotony, the variation in daily training loads, or the mean daily load divided by the standard deviation; and training strain, the product of training load and monotony. [28] Therefore, higher external training loads could influence greater internal training stress and the development of respiratory problems in competitive swimmers beyond merely their exposure to chlorine by-products. [24]

Monitoring training loads in athletes is largely regarded as useful for determining whether or not athletes are successfully adapting to the prescribed training program. In other words: are they improving performance by some measure? This can enhance the understanding of changes in performance by providing a scientific explanation for such changes. [29] Knowing how athletes respond to a given amount of training may help mitigate the risk of injury, illness, and non-functional overreaching or overtraining syndrome, characterized by fatigue lasting weeks to months with an associated decrement in performance. [29] However, reporting training loads in research is often insufficient in detail for it to be truly studied as an independent variable. For example, the loads are anecdotal: "10-12 workouts per week, according to normal program set by his/her coach" [30]or have vague qualifiers such as "intense training". [31] In studies of competitive youth swimmer populations, detailed reports on training load are scarce, but some have reported the average training volume (kilometres swum) and intensity quantified by Rating of Perceived Exertion (RPE) (or similar self-reported intensity ratings). [30,32]

Purpose and Hypothesis

Thus, the primary purpose of this study was to examine the effect of quantifiably low, moderate, and high training loads on the lung health of competitive youth swimmers. For the purpose of this study, lung health was operationally defined by the following components: airway hyperresponsiveness (AHR), exercise-induced bronchoconstriction (EIB), airway inflammation, and respiratory symptoms. The extent of AHR and EIB were determined with spirometry before and following a breathing provocation challenge termed Eucapnic Voluntary Hyperpnea (EVH); airway inflammation was assessed with Fractional Exhaled Nitric Oxide (FeNO) measurement; and self-reported respiratory symptoms were determined weekly via an online questionnaire. Each of these components and measurements are explained in further detail in Chapter 3.

We hypothesized that swimmers would have overall worsened lung health status following relatively high training loads later in the season compared to lower training loads training earlier in the season, which would also be representative of the cumulative effect of progressive overload typically found in periodized training plans.

Significance

Based on the 2016 Swim Alberta Annual Report, there were 32,061 registered competitive swimmers in Canada (compared to 19,606 in 2006/07), with 3,719 (11.5%) of the athletes being registered in Alberta. [33] The described research thus has the potential to influence thousands of athletes, especially if the research findings are translated to coaches at the provincial, national, and/or international level, and to various swimming organizations. The benefits of participating in competitive swimming should ideally outweigh the risks of developing respiratory illness or disease, but the training that competitive swimmers perform might elevate risk to the extent that their participation leads to lung health problems. Ultimately, the described study will enrich scientific discussion of the health risks imposed on swimmers undergoing heavy training.

In general, a need for further research on lung health and the diagnosis and management of EIB and related respiratory issues in athletes based on type of training and environmental irritants has been identified. [10,31] Thus, investigating the lung health of swimmers after different amounts of training in the season with varying external training loads will enhance knowledge and understanding of the lung health changes that may occur over a season, and potentially what threshold of volume and intensity of swimming is more likely to influence such changes.

This could assist swimming coaches and sport scientists in designing annual periodized training plans and monitoring adaptations to training, with the goal of optimizing the health and performance of the athletes.

Chapter 2: Literature Review

Introduction: A brief review of the respiratory system

The respiratory system is comprised of the lungs and a network of airways that connects them to the nasal passages and mouth. [34] The primary function of the lungs is gas exchange, whereby oxygen (O_2) is moved from the air into venous blood and carbon dioxide (CO_2) is moved out. [35] Other functions include filtering foreign material from the circulation and acting as a reservoir for blood.

The other parts of the respiratory system are air passageways connecting to the lungs, which are essentially branching tubes that become shorter and narrower as they reach the lungs. [34,35] The trachea (windpipe) divides into what is collectively termed the conducting airways, including the left and right bronchi, which divide further into lobar, then segmental bronchi, and finally the terminal bronchioles. The conducting airways serve to direct air into the gas exchanging portions of the lung or "transitional and respiratory zones" consisting of the respiratory bronchioles, and alveolar ducts which are lined with alveoli. [35] In this region of the lung, gas movement is mainly by diffusion, and is bounded by the blood-gas interface and the pulmonary capillary blood. [35]

During the process of inspiration, the diaphragm, a thin dome-shaped sheet of muscle separating the abdominal and thoracic cavities, contracts to allow expansion of the thoracic cavity and air to be drawn in through the nose and mouth, and the external intercostal muscles also serve to elevate the ribs. [34] Accessory muscles to inspiration include the sternocleidomastoid and scalene group, which also assist in elevating the ribs.

At rest, each inspiration allows approximately 500 mL of air to enter the lung, referred to as tidal volume, and upon expiration about the same quantity of the air leaves the lungs. [35] Inspiration and expiration at rest is a passive process that primarily involves contraction and relaxation of the diaphragm, and relies on the elastic properties of the lung and chest wall to return to resting positions. [35] In heavier breathing, such as during exercise or voluntary hyperventilation, the rectus abdominus, internal oblique muscles, and transverse abdominus help to raise abdominal pressure and forcefully exhale air from the lungs and decrease lung volume, while the external oblique muscles, sternocleidomastoid, and scalene group contract and help lift the thoracic wall, increasing lung volume. [35]

At rest, a normal breathing frequency is around 15 breaths/min, and supposing a tidal volume of 500 mL, the minute ventilation or total volume of air leaving the lungs each minute is

about 7.5 L/min.[35] When the respiratory system is under stress, such as during exercise, the gas exchange demands of the lungs are hugely increased and minute ventilation increases – as high as 150 L/min in elite athletes.[35] O_2 consumption can increase from 0.3 L/min to 3 L /min in a fit person or as high as 6 L/min in top elite athletes.[35] Additionally, resting CO_2 production is about 0.24 L/min and increases to 3 L/min.[35]

A simple way to examine respiration at rest and during exercise is with spirometry, which measures changes in lung volume during forced breathing maneuvers.[35,36] Visually, this can be represented by a flow-volume loop (Figure 1). Spirometry is an important tool for revealing patterns of impaired lung function, particularly when an individual performs a Forced Vital Capacity (FVC) maneuver, which is the volume of air that can be forcibly exhaled after a maximal inspiration.[35] The FVC test is arguably the most important pulmonary function test because during expiration, there is a limit to the maximal flow that can be reached at any lung volume that is unique to the individual being tested.[36] This limit is reached even with moderate expiratory efforts, so increasing the force of expiration generally does not increase flow.[36] From the FVC, there are several other variables related to flow or volume that can be determined: Forced Expiratory Volume in 1 second (FEV_1); measures of Forced Expiratory Flow (FEF) at different intervals of the FVC, usually at 50% and the average of 25-75% known as FEF 50% and FEF 25-75%, respectively; as well as the Peak Expiratory Flow (PEF), the maximum flow achieved during a forced expiration.[1,37] Of these, the most important variable for diagnosis of EIB is the FEV_1.

Potential mechanisms in the development of respiratory problems in swimmers

EIB is often an outcome of intense exercise in athletes and a manifestation of AHR. [2] Generally speaking, acute exercise stresses the respiratory tract through increased ventilation and induces epithelial stress, which has been demonstrated in athletes by increased urinary levels of Clara cell secretory protein 16 (CC16) after a breathing provocation challenge. [11,35,38] Acute AHR associated with EIB is likely initiated by water loss from the airway surface liquid (ASL), resulting in increased osmolarity[a]. [37] When ventilation rate decreases post-exercise, (i.e. as exercise intensity is reduced), water moves from cells and results in cell shrinkage, promoting the release of endogenous inflammatory mediators, namely leukotrienes, prostaglandins, and histamines. [39] These mediators cause airway smooth muscle contraction, as well as mucous formation and/or edema[b]. The chronic development of EIB may result from repeated, sustained periods of high ventilation exercise, which poses mechanical stress on the airways. [37] Furthermore, repeated high ventilation in noxious environments (particularly chemical irritants or cold air) is associated with epithelial cell activation, and smooth muscle and mucous gland proliferation that increase susceptibility to airway narrowing. [37] In the case of swimming, athletes inhale chlorine, a strong oxidizing chemical used to sterilize swimming pools, and its derivatives, such as trichloramines, present in the ambient air and near the water surface of indoor pool environments. [11] Inhalation of such compounds may promote EIB in addition to high ventilation exercise itself; however, further study is required to understand the mechanisms and subsequent cascade of events leading to EIB depending on the sport, training load, and training environment. [10,11]

Chlorine is widely used to sanitize the water of indoor swimming pools, although recently other methods have been employed. [40] Chlorine is typically added to pool water in either tablet, granular, liquid, or gas form. [3,40] When added in liquid form within the typical pH range of swimming pools (fairly neutral – around 7.2-7.6), chlorine reacts with water to form two acids, hypochlorous (HOCl) and hydrochloric acids (HCl), [41] and exposure to these acids may lead to injury of the eye membranes and the upper respiratory tract. [3] Chlorine in gas form may also trigger acute damage to the respiratory tract via formation of free oxygen radicals. [3] Swimmers and other pool users also carry various contaminants on their skin (such as cosmetics, dirt, sweat), and when brought in contact with chlorine in pool water these can

[a] The concentration of solutes in a solution.
[b] Build up of fluid.

produce chemical irritants that may be carcinogenic.[3] Of the chlorine derivatives, nitrogen trichloride (NCl_3) is the primary compound contributing to the chlorine odour in pools and is responsible for the ocular and respiratory symptoms experienced by pool users.[12] It has been further suggested that NCl_3 may be responsible for acute increases in lung permeability, as significantly elevated levels of alveolar surfactant-associated proteins A and B (SP-A and SP-B) were observed in trained and recreational swimmers after only 1 hour of exposure to pool air without exercising, and remained increased for a further 12 hours.[42] Additionally, increased lung permeability is a potential outcome of the mechanical stress on epithelial tissue via oral hyperventilation near the pool water surface, which may further augment the release of inflammatory mediators.[42]

As competitive swimmers may spend approximately 30 hours per week training while sustaining high levels of ventilation (often exceeding 100 L/min), they are inhaling large quantities of trichloramines in both training and competition.[3,15] Thus, increased ventilation during intense exercise may facilitate the transport of chlorine by-products to the lungs.[10,14] It has been estimated that their exposure to chlorine compounds is 20 times that of lifeguards, and 100 times that of recreational swimmers.[3] To determine the typical chlorine exposure of various pool users, Drobnic et al[11] measured chlorine gas concentration <10 cm above pool water surfaces (at the breathing level). The threshold limited value (TLV) of chlorine for work places during a typical 8-hour workday is 1.45 $mg \cdot m^{-3}$, however calculations determined that during a typical 2-hour training period, swimmers' exposure to chlorine (approximately 4-6 g) is close to the TLV. It is important to note that the TLV levels are based on average exposure to chlorine for sedentary workers or individuals engaging in low- to moderate-intensity activity, but not vigorous activity.[11] Competitive swimmers also tend to have low breathing frequency with high tidal volumes, which may facilitate the transport of large quantities of volatile chlorine by-products into the lungs.[43] Considering most competitive swimmers train at least 2 hours/day with a ventilation 10-12 times resting values, these ventilations would increase the amount of chlorine inhaled such that it approaches the TLV, which would be further increased if the training sessions were conducted twice daily, as is common in competitive training.[11] Thus, cumulative exposure to chlorinated compounds in indoor swimming pools combined with sustained high ventilation is likely an important factor in the development of respiratory problems in competitive swimmers.[3,10,11,40]

Illness related to training load

In the context of sport science, the term "load" can be used generally to describe "the sport and non-sport burden (single or multiple physiological, psychological or mechanical stressors) as a stimulus that is applied to a human biological system (including subcellular elements, a single cell, tissues, one or multiple organ systems, or the individual)." [44] Specifically, the "external load" applied to a biological system is dependant both on time, measured in seconds, minutes, hours to days, weeks, months and/or years; and magnitude, the combined duration, frequency, and intensity of training. [44] Each individual has a unique physiological and psychological response to any external load, often referred to as the "internal load" or training stress. To distinguish from the external load being applied to the athlete, internal training stress is the global term utilized in this thesis to encompass the following sub-components: internal training load (the product of perceived post-workout exertion and duration), internal monotony (reflects variation in training – the mean daily load divided by the standard deviation), and internal strain (the product of load and monotony).

It is well understood that the external training load is a key factor that determines training adaptations. [45] As such, elite swimmers often train 3-4 hours or more per day split into two, or even three separate swim training sessions of 1-2 hours each, totalling 7-9 swim training sessions per week. [21,45] The majority of training in swimming programs tends to involve high volume (around 4,000-10,000 metres total per day) for 3-4 hours, performed at intensities below the anaerobic threshold. [45,46] Mujika et al [21] found a positive correlation between external training load (estimated mean intensity of training calculated with distance and theoretical blood lactate zones) and performance improvements in a study of 18 elite swimmers; thus, it appears logical that coaches and athletes are continually modifying the external training loads to improve performance. [10,15] Costill et al [45] have suggested that swimmers might not require such a high volume of training to maximize fitness and competition performance. In their study, 24 male collegiate swimmers were studied for 25 weeks of training, split into two matched groups; for 6 weeks of the study, one group completed a second 1.5 hour training session in addition to regular training (1.5 hours/day), while the other group continued with regular training. The results suggested that the 6-week period of increased training did not enhance performance above the single 1.5 hour/day training, as the group who completed the extra training showed decreased sprint velocity and increased cortisol levels compared to the regular training group. Although both groups improved their aerobic or anaerobic capacities during the study, the extra training did not increase their capacities above the regular group. Therefore, further

investigation into the optimization of training load is justified, as this could have a meaningful impact on health and performance outcomes of swimmers.

There is an understanding amongst researchers that a relationship exists between total training load and the risk of illness, [44] with the prevailing hypothesis being that load and risk of illness forms a J-shaped curve. [47] According to this hypothesis, extremely low or no training is associated with a greater risk of illness, while moderate training load yields the lowest risk. In contrast, risk of illness increases with extremely high training loads, which actually present the highest risk of illness in this model. In a study of 24 competitive swimmers, [48] for example, training intensity was purposefully increased over 4 weeks, which resulted in 10 swimmers (42%) exhibiting self-reported symptoms of upper respiratory tract infection (URTI). The authors later suggested that increased risk of URTI might be an outcome of intense training in all athletes, [25] possibly in the presence of overtraining syndrome – "a decreased performance capacity despite increased or maintenance of training load." [49,50] It is likely that infections result from the cumulative effects of repeated, heavy training that can acutely alter immune function and tissue damage repair. [12,23]

Foster [28] has further explained this issue in that a higher frequency of reported illnesses occurs when training surpasses an athlete's individual threshold, calculated with internal training load, training monotony, and training strain. There is also some evidence that demonstrates a dose-response relationship between training volume and incidence of URTI, and that the risk is higher in endurance athletes – including swimmers – compared to other non-endurance athletes. [49] However, across all sport domains, there are few studies that have examined the effect of specific changes to the overall external training load (modifying frequency, intensity, duration, or a combination of these factors) and the risk of illness. In a study of 28 elite swimmers over a 4-year period, [51] it was revealed that intensive periods of training increased the odds of URTI by 1.10 times for every 10% increase in high-load training. Additionally, there is paucity of evidence with mixed results on the effect of internal training stress and risk of illness. Training monotony has been studied in cross-country skiers, and was associated with a lower risk of illness, [52] however another study of rugby league players [53] found the opposite – higher training monotony, along with increased internal load and internal strain – were all associated with an increased risk of illness. Although it is recommended to avoid high monotony in training programs [49], the relationship between monotony and risk of illness in competitive swimmers is not known and necessitates further investigation.

Considering this information, a potential implication of this study would be improving understanding of the risk and/or severity of respiratory illness in swimmers through carefully

monitoring training loads in relation to lung function and symptoms.[28] Furthermore, thinking critically about training variables is worthwhile, considering the difference between first place and fourth place (or making it to the podium or not) is often attributed to factors such as technical proficiency, mental resilience, and the effective planning of tapering periods, which usually include several weeks of significantly reduced training volume prior to competition.[54-56] Therefore, monitoring the training load of the swimmers in the current study is valuable to determining the relationship between training and lung health issues.

Current methods of evaluating airway hyperresponsiveness, exercise-induced bronchoconstriction, inflammation, and respiratory symptoms

Airway hyperresponsiveness (AHR) and exercise-induced bronchoconstriction (EIB)

According to the American Thoracic Society Guidelines,[1] the presence and severity of EIB can be determined with successive lung function measurements (spirometry) after a bronchoprovocation test (BPT), which triggers airway constriction. With spirometry, it has been suggested to obtain repeated measurements of forced expiratory volume in one second (FEV_1), which represents the ability to forcefully exhale air from the lungs, a procedure that also has high test-retest reliability.[57,58] The results are then expressed as percent decreases in FEV_1 at various sampling points up to 30 minutes post-challenge as compared to pre-challenge values. The criterion for the percent fall in FEV_1 used to diagnose EIB is >10%, and therefore a positive test would be indicated by this decrease.[2] The severity of EIB can be graded as mild, moderate, or severe if the percent fall in FEV_1 from the pre-exercise level is >10% but ≤25%; >25% but ≤50%; and >50%, respectively.[1] FEV_1 values typically return to 95% of the pre-challenge measurements within 30-90 minutes after a BPT.[1]

BPTs can be classified as direct or indirect challenges. Direct BPTs use pharmacological agents, such as methacholine, which act directly on the acetylcholine receptors of bronchial smooth muscle to cause narrowing of the airways that is independent of airway inflammation.[59] In contrast, indirect challenges are thought to provoke smooth muscle constriction through the

release of endogenous mediators from inflammatory cells, which cannot be inferred through a direct BPT.[37] Therefore, it is recommended to confirm diagnosis with an indirect challenge.[37]

There are several indirect BPTs that may be used to provoke airway narrowing. Osmotic stimuli, such as inhalation of dry powder mannitol (sugar alcohol), induce the release of bronchoconstricting mediators from inflammatory cells in the airways through a change in osmolarity, as described in the mechanisms of EIB above.[60] Inhalation of hyperosmolar (4.5%) saline, another osmotic stimulus, is also based on the premise that there is evaporative water loss during exercise. An exercise challenge, either laboratory or field-based, may also act as the stimulus, which typically consists of a rapid increase in exercise intensity over approximately 2-4 min to achieve a sustained, high level of ventilation that dries the airways and provokes AHR.[37] Lastly, a eucapnic voluntary hyperpnea (EVH) challenge aims to provoke EIB through hyperventilation of a dry gas mixture containing 5% carbon dioxide (CO_2), 21% oxygen (O_2), and balanced nitrogen (N_2).[1,58,61,62] These gas concentrations are safe for humans and stimulate ventilation, but partial pressure of CO_2 in the blood is kept constant around 40 mmHg throughout the test to prevent hypocapnia[63] and participant discomfort or syncope. The theorized mechanism for reproducing EIB is that voluntary hyperventilation of a gas mixture dries the airways leading to an increased inflammatory response, whereby airway narrowing occurs in a manner similar to exercise.[1] The increase in ventilation mimics (or exceeds) that achieved in high intensity exercise dehydrates the airways and induces airway constriction in hyperresponsive individuals.[59]

Currently, the International Olympic Committee - Medical Commission (IOC-MC) recommends a eucapnic voluntary hyperpnea (EVH) test as the “gold standard” for diagnosing EIB in athletes. This subsequently provides evidence to receive a therapeutic use exemption (TUE) for inhaled beta-2 (β_2) adrenoceptor agonists and inhaled corticosteroids, which are the most effective drugs for immediate inhibition of EIB and for long term control and prevention of EIB, respectively.[13,61,64] Although intuitively it would make sense that an exercise challenge would be the best and most specific provocation for EIB evaluation, it does not necessarily simplify the diagnosis or enhance sensitivity; the intensity, duration, mode, and environmental conditions of the exercise must all be considered.[65] Competitions may be used as the provoking stimulus, however those who have a positive non-exercise laboratory test (e.g. methacholine or EVH challenge) may be asymptomatic during their actual event. A major advantage of using EVH over an exercise challenge test to identify EIB is the relative ease of achieving and sustaining higher ventilation rates [85% of maximal voluntary ventilation (MVV) - the maximum rate of voluntary breathing] that may not be as easily reached with exercise.

[58]Further, the EVH test is also very effective at re-creating airway closure and determining EIB in comparison to the other BPTs because it controls for the temperature and humidity of air being inspired. [13,62,64] It may also have greater sensitivity than some direct measures for identifying AHR and EIB. For instance, in a study of 50 elite summer sport athletes, [66] all nine participants who had a positive methacholine challenge also had a positive EVH challenge. However, there were 25 participants overall who had a positive EVH challenge, with 16 (64%) of those showing a negative methacholine challenge result. EVH in-test performance has also been shown to be reproducible in varsity swimmers. [63] Therefore, the EVH test will be adopted in this study to identify the extent of AHR and EIB in competitive swimmers. [59]

Simplified methodology for EVH was established over 30 years ago in order to reproduce "the bronchial heat and water fluxes that occur with exercise challenge." [67] For any EVH challenge, it is suggested to first obtain baseline maximal lung function with spirometry. [68] Typically, MVV is calculated from baseline FEV_1 multiplied by 30 or 35. Since the introduction of the EVH, there are two basic protocols that have emerged – the Stepped Protocol and the Single-Stepped Protocol. [68]

The Stepped Protocol is recommended for individuals with severe or uncontrolled airway disease (e.g. Chronic obstructive pulmonary disease or severe asthma), and proceeds as follows:

- **Stage 1:** Three minutes at 30% MVV
    - Spirometry at 1, 5, 10, 15 and 20 minutes post-test or until stable
- **Stage 2:** Three minutes at 60% MVV
    - Spirometry at 1, 5, 10, 15 and 20 minutes post-test or until stable
- **Stage 3:** Three minutes at 90% MVV
    - Spirometry at 1, 5, 10, 15 and 20 minutes post-test or until stable

If a fall in $FEV_1 \geq 10\%$ from baseline occurs, the challenge is stopped and considered as positive.

The Single-Stage Protocol is recommended for individuals with mild or controlled airway disease (e.g. athletes), and proceeds as follows:

- **Stage 1** Six minutes at 85% MVV
    - Spirometry at 1, 5, 10, 15 and 20 minutes post-test or until stable

An observed fall in $FEV_1 \geq 10\%$ from pre-challenge spirometry indicates a positive test.

Recently, it has been suggested that the ≥10% fall in FEV_1 should be observed on at least two consecutive time points following the EVH test. [2,63] In addition to FEV_1, other lung function

parameters may provide further insight into EIB diagnosis in athletes.[7] For instance, a fall >12.5% in FEF 25-75% or FEF 50% can reflect small airway obstruction in athletes.[7]A fall in PEF >18% may also be an indication of EIB.[7,69] Additionally, a study of 20 asthmatic children[70] showed FEF 25–75% could be used in addition to FEV_1 as a measure to determine the occurrence of EIB, as well as to evaluate correlations between EIB and inflammation. For the current study, we chose to adopt the Single-Stepped Protocol (commonly used in athletes)[68,71] with additional parameters to FEV1 (FVC, FEF 25-75%, FEF 50%, and PEF) to gain further insight into the pattern of airway obstruction in swimmers following the EVH test. We expected the swimmers would present with mild/controlled airway disease (rather than severe or uncontrolled) especially if they are regularly training and competing at a high intensity of swimming and therefore the Single-Stage Protocol would be appropriate.

Inflammation

Regular intense swimming in a chlorinated environment may induce airway inflammation that is not always consistent with AHR or EIB,[3,72] but that is an important precursor of asthma or asthma-related symptoms.[73,74] As mentioned earlier in this chapter, competitive swimmers ventilate large amounts of air above pool water surfaces, and are thus exposed to a higher quantity of chlorine derivatives. This exposure likely contributes to mild eosinophilic[c] airway inflammation in competitive swimmers.[75] Evaluating airway inflammation, therefore, is important in the investigation of the lung health of swimmers.

Nitric oxide (NO) is a key molecule implicated in airway inflammation that is produced in human lungs and is present in exhaled breath.[76] However, the role of NO in the airways and lungs is complex given its wide array of biological functions as a vasodilator, bronchodilator, neurotransmitter, and inflammatory mediator.[76] NO originates in airway epithelial cells, and is produced by the inducible nitric oxide synthase (NOS2) enzyme,[77] both of which have been shown to be elevated in asthmatic profiles.[78] Regardless of the underlying mechanism of inflammation, measurements of exhaled nitric oxide (eNO) are valuable in understanding the intricate relationships between inflammatory responses and exposure to bronchoconstricting stimuli, and the progression of eosinophilic airway inflammation and AHR.[76,79] Thus, eNO is an important indirect marker of airway inflammation for swimmers who develop AHR and EIB.[37]

Although direct assessment of airway inflammation using bronchoscopy would objectively be more precise than eNO, it is an overly invasive procedure that requires advanced technical training.[80] Sputum collection, a mixture of saliva and mucus coughed up from the respiratory tract, is another method of obtaining cell samples from the lower airways, however can be quite uncomfortable for the participant (i.e. they must forcefully cough) and obtaining reliable measures for each sputum sample requires many hours of analysis by a trained individual.[80] An innovative and non-invasive method to measure airway inflammation is fractional exhaled nitric oxide (FeNO), which has been used in research in place of some of the more invasive techniques,[72,80-82] and may also be used as a surrogate for AHR.[76,83] FeNO has also been shown to correlate with AHR to a histamine challenge (r=-0.62), reversibility of airway obstruction (r = 0.51), serum eosinophil cationic protein levels (r=0.57) and blood eosinophil counts (r=0.69).[84] FeNO is currently regarded as the gold standard gas for evaluating airway inflammatory responses to high ventilation exercise.[37]

[c] Eosinophils are a type of white blood cell that are implicated in allergic responses and asthma pathogenesis

FeNO measurement techniques are typically categorized as online or offline. With online measurement, the participant exhales directly into a gas measurement device to display live NO breath profiles.[76] The participant also requires little technique to exhale the air; inhaling and exhaling generally occurs at a rate of 50 ml/s, which is low and generally does not produce undue discomfort or symptoms.[85] However, in offline methods participants breathe into a reservoir that can later be connected to a gas analyzer and would not provide a continuous sample of air in the same way as online measurement; there could be certain time-dependent processes (e.g. air being kept in receptacle for a number of hours) that introduce measurement error to the NO samples.[86]

Depending on methods used, the online technique can provide more information about exhaled NO in addition to other variables, such as air flow rate and pressure. This allows the researcher to monitor exhalation to ensure it meets the required flow rate and pressure parameters needed for accurate measurement. Thus, exhalations that do not meet the parameters can be immediately discarded.[76] The ATS Clinical Practice Guidelines[76] strongly recommend either offline or online measurements of exhaled NO in the diagnosis of airway inflammation, but online (which is simply referred to as FeNO in this thesis) is preferable, and therefore will be adopted as a marker of inflammation in the present study. It is recommended that FeNO <25 ppb (<20 ppb in children) serve as an indicator that, "eosinophilic inflammation and responsiveness to corticosteroids are less likely"; FeNO > 50ppb (>35 ppb in children) indicates that "eosinophilic inflammation and, in symptomatic patients, responsiveness to corticosteroids are likely"; and values between 25 ppb and 50 ppb (20–35 ppb in children) "be interpreted cautiously with reference to the clinical context."[76]

Respiratory symptoms

It is well established that competitive swimmers experience respiratory symptoms, which are usually classified as relating to the upper (nasal or throat region) or middle-to-lower respiratory tract (chest region). Nasal obstruction (stuffy nose), rhinorrhea (runny nose), sneezing, and nasal itching have been reported by up to 74% of competitive elite swimmers during the training season, which is also similar to the prevalence of AHR.[87-89] Other studies observed middle/lower respiratory tract symptoms, with approximately 25% of swimmers reporting cough during their training,[14,90] while work from Helenius et al[91] found as high as 57% of the 42 swimmers they studied experienced cough and asthma-like symptoms such as breathlessness, wheezing, and chest tightness. Another study[92] found a very high prevalence of lower respiratory symptoms (83%) in 24 adolescent swimmers, including cough, heavy breathing, wheeze, phlegm, and expectoration (coughing up spit/phlegm). Of those who reported symptoms, 15 (75%) had at least one positive provocation test (EVH or methacholine challenge) and 10 (50%) felt that the symptoms had undesirable effects on their sports performance.

Methods to obtain data on respiratory symptoms were quite variable in the studies mentioned above. For example, Helenius et al[91] used a "respiratory symptoms questionnaire" and interviewed athletes; however the questionnaire was specially designed for a previous study they conducted[93], and few details were given on the development process. Lévesque[90] developed a questionnaire based on other questionnaires used by Potts[14] and the International Study of Asthma and Allergies in Childhood.[94] In contrast, Gelardi et al[88] obtained a more detailed medical history of their participants, which was integrated with a modified version of the European Community Respiratory Health Survey (ECRHS). This survey is used primarily to understand the prevalence of asthma, asthma-like symptoms, and exposure to risk factors for asthma, as well as differences in medication used for asthma diagnoses in the European community.[95] However, the questionnaire is comprehensive and meant for a one-time use (and then perhaps a follow-up), but given the context of our study in Canadian swimmers and collecting weekly data on respiratory symptoms for the analysis, the ECRHS tool did not appear to be relevant.

For athletes, it has been recommended to use the Allergy Questionnaire for Athletes (AQUA©), as it is the first validated questionnaire for screening atopic status[d].[96] Self-reported symptoms are adjunctive in informing diagnosis, therefore implementing screening questionnaires such as the AQUA© may be valuable in understanding susceptibility to AHR and

[d] The tendency to develop allergic diseases.

EIB. The questionnaire has a high positive predictive value (0.94) of individuals who require additional allergy testing, yet the relationship between allergy and respiratory problems in athletes requires further investigation. We have chosen to adopt this questionnaire for the purpose of identifying athletes who may be more susceptible to AHR and EIB due to atopy.

It should be noted that the prevalence of respiratory symptoms may not agree with measurements of AHR, EIB, and inflammation, however more research is needed to understand the relationship between these variables and respiratory symptoms in swimmers. One possible explanation is that swimmers do not recognize or report symptoms for a variety of reasons, such as the expectation that symptoms occur with intense training, which therefore may be missed if not diagnosed by a physician. [3]An alternative explanation could be that the perception of sensory stimuli has been altered in the airways, possibly from damaged sensory receptors following chlorine exposure, however, this mechanism is not understood. [3] Rundell et al [4] compared the utility of a self-reported symptoms questionnaire for EIB following an exercise challenge test. It was concluded that questionnaires could provide reasonable estimates of exercise-induced bronchoconstriction, but that they should not be relied upon as a single measure, as there may be many false positives or false negatives. It was suggested that a questionnaire is helpful in identifying symptoms, but should be used in combination with spirometry and other laboratory measures to illustrate a better overall picture of lung health status.

There is no single relied upon questionnaire for monitoring respiratory symptoms. In addition to the AQUA©, we have chosen to adopt the Alberta Swim Fatigue and Health questionnaire, which our Athlete Health laboratory has developed previously for weekly health and fatigue monitoring of University of Alberta varsity swimmers. The questionnaire collects information about the athletes' overall health and wellbeing in addition to specific respiratory symptoms experienced within the past week of training, which would help determine whether symptoms change with increased training loads. As the AQUA© inquires mainly about past allergy and allergy diagnosis, we reasoned a weekly questionnaire that monitors changes in respiratory symptoms is compatible with the study's repeated measures design. It is also designed for online use on the Survey Monkey platform, and is therefore quite pragmatic in the life of a student-athlete as it can be opened from a smartphone or other electronic device that has Internet access. On a weekly basis, swimmers will receive a link via e-mail or text message to complete the questionnaire, which can be done in less than a minute.

Conclusion

Using a wide range of measurement techniques to measure lung health resists against the mono-method bias threat to construct validity. [97]As lung health is a construct operationally defined by several components in this thesis, it was beneficial to the research design to have several types of measurements, both objective and subjective measures. [97] Objective measures will be used to determine AHR, EIB, and inflammation, and include: spirometry, the EVH test, and FeNO measurement. The external training load will also be an objective measure as it is the training prescription imposed upon the athletes. Internal training stress will be determined using a subjective measure – that is session RPE. This will provide useful information about individual tolerance to the external training loads, and highlights the idea that each athlete has a unique response and adaptation to training. [29]

To our knowledge, no study has investigated changes in lung health in relation to specific, quantified training loads during a training season in competitive swimmers. An existing gap in the literature is that training loads are generally not documented in sufficient detail to quantify how much training was done, so it presents a challenge when studies suggest that "intense", "heavy", or "vigorous" training in swimmers might influence AHR/EIB. Therefore, the goal of this thesis is to show detailed quantification of both external and internal training loads, in combination with a battery of tests to provide a whole picture of "lung health" (i.e. extent of AHR and EIB, airway inflammation, and respiratory symptoms) in swimmers, and how this might change with different amounts of training. Although there are many tests available to assess lung health, we believe those described in this chapter are reproducible and have sufficient evidence in the literature for their use for measuring the variables that we believe define lung health.

Chapter 3: Research Study

Effect of Low, Moderate, and High Training Loads and Internal Training Stress on the Lung Health of Competitive Youth Swimmers

Abstract

Background: Exercise-induced bronchoconstriction (EIB), airway hyperresponsiveness (AHR), airway inflammation, and respiratory symptoms are commonly observed in competitive swimmers, however there is paucity of evidence that explains whether the volume and intensity of training exacerbates these problems. We aimed to determine the effects of different training loads on AHR, inflammation, and respiratory symptoms in competitive youth swimmers. We hypothesized overall worsened lung health status would be observed following high training load compared to low or moderate training loads.

Methods*:* Competitive youth swimmers (n=8) completed nine weeks of training split into three blocks, consisting of "Low" [(47 arbitrary units (AU), "Moderate" (75 AU), and "High" (114 AU)] loads, which was determined with prescribed distance and intensity of workouts. Eucapnic Voluntary Hyperpnea (EVH) challenge, spirometry, and Fractional Exhaled Nitric Oxide (FeNO) tests were repeated at the end of each training block to determine extent of AHR, EIB, and inflammation. A weekly self-report questionnaire was used to determine respiratory symptoms. Session Rating of Perceived Exertion (RPE) was used to quantify internal training stress.

Results: Pre-EVH FEV_1 was significantly decreased after Moderate compared to Low, but no significant change occurred after High load. Maximum % decreases in FEV_1 post-EVH did not differ significantly across training blocks. Post-EVH FeNO after Moderate was significantly decreased compared to Low load. Internal load was significantly lower for Moderate load compared to High load, while internal monotony was significantly lower after Moderate load compared to Low load. Percent decrease in FEV_1 20 mins post-EVH was significantly correlated with respiratory symptom frequency after Low and Moderate loads. Respiratory symptom

frequency after High load was significantly correlated with % reduction in FEV_1 at 10, 15, and 20 mins post. All other correlations with spirometry sampling points were not significant.

Conclusion: Low to moderate training loads influenced airway obstruction, inflammation, and respiratory symptoms in swimmers, yet the high training block did not result in significant changes to chronic airway obstruction or inflammation. Our results suggest relatively large increases in training loads early in a swimming season may negatively influence lung health, however more research is needed to determine whether manipulating variables such as training monotony in competitive swimming programs may favour better lung health outcomes.

Introduction

Exercise-induced bronchoconstriction (EIB), known as the "acute airway narrowing that occurs as a result of exercise" [1] and airway hyper responsiveness (AHR), defined as "an abnormal susceptibility to airway narrowing following exposure to a wide range of bronchoconstricting stimuli" [3] are the most common chronic medical conditions experienced by Olympic athletes (8%). [9] In particular, elite endurance athletes have greater airway dysfunction and respiratory tract illness and symptoms compared with non-endurance elite athletes. [9,24,26,27,49] A distinguishing feature is the high ventilation requirement, a phenomenon ascribed as "high ventilation sport dysfunction". [5,39]

Competitive swimmers undergo high volume, high intensity training while sustaining elevated ventilation rates in chlorinated pool environments. [10,21] Such ventilation rates combined with several hours of pool training per week have been associated with increased exposure to chlorine by-products and unfavourable changes to lung health compared to recreational swimming. [3,11,15,22] The prevalence of EIB is 11-29% in competitive swimmers, [1,91] however the pool environment may influence mechanism in which it occurs. AHR is a key characteristic associated with EIB and is prevalent in up to 79% of elite swimmers, [59,87] however further investigation is needed to establish how AHR, airway inflammation, and EIB are interrelated. Competitive swimmers have high incidence of respiratory tract infections, likely due to acute alterations in immune function and tissue damage repair after intense swimming exercise. [12,23] Higher frequency of reported illness also occurs when training surpasses an athlete's individual threshold, usually indicated by their internal training stress, which can be calculated with post-workout perceived exertion and training duration (as detailed in Foster's seminal work). [28] It is generally accepted that a combination of factors contribute to illness and development of overtraining syndrome, such as sudden increases in training volume or intensity, lack of periodization or programmed recovery in training schedule, and highly monotonous training. [49] Thus, higher training loads could influence the development of respiratory problems in competitive swimmers beyond exposure to chlorine by-products. [24]

A Eucapnic Voluntary Hyperpnea (EVH) challenge has been recommended as the gold standard to understand AHR status for EIB diagnosis, [68] however it is typically done only once. To our knowledge, serial administration of EVH to understand AHR status after differing training loads of swimming volume and intensity has not been investigated. Additionally, Fractional Exhaled Nitric Oxide (FeNO) may assist in predicting AHR, as FeNO levels tend to increase in response to allergen exposure and the onset of respiratory symptoms. [76]

AHR may be reversible by transitioning to "light" / no training after a period of "intense" training, as Bougault et al [31] found in 67% of swimmers who were previously hyperresponsive. However, intensity of training was not objectively quantified, and to our understanding no study has quantified external or internal training loads to determine what influence training has on AHR, inflammation, and respiratory symptoms in competitive swimmers. Further, most studies on elite athletes have been performed in adults with greater training years than in younger athletes.

Thus, the primary purpose of this study was to examine the effect of quantifiably low, moderate, and high external training loads and resulting internal training stress on lung health in competitive youth swimmers. Lung health was determined by airway inflammation, AHR, EIB, and respiratory symptoms. We hypothesized that swimmers' lung health would worsen with each increase in training load from low, to moderate, to high. Specifically, we predicated swimmers would have greater % decreases in FEV_1 post-EVH challenge (i.e. more hyperresponsive to provocation), increased FeNO levels (more inflammation), and increased frequency of respiratory symptoms determined by a self-reported questionnaire.

Methods

Study Population

Eight competitive swimmers (four males, four females) aged 14-17 volunteered to participate in the study. They were recruited from one high performance training group consisting of 12 swimmers from a local competitive swimming club. All were training for the same key provincial and national competitions and had similar previous years of involvement in a competitive swim program. The head coach allowed the swim training loads to be determined in length and intensity for the study. The study received Institutional Research Ethics Board approval, and all participants provided informed consent (Pro00066445). Participants were included if they were currently training and free of any diagnosed illness, such as flu or fever, respiratory infection, or musculoskeletal injury prohibiting participation in this training group; however, no invited swimmer was excluded based on this criteria. Swimmers with a history of asthma or respiratory symptoms associated with exercise were not excluded, as these individuals could help better understand the profile of swimmers with lung health problems, and we are interested in lung health changes that occur with training.

Experimental design

This study utilized a single group, within-subjects, quasi-experimental design. Participants completed the same tests three times, on the last day of Low, Moderate, and High training load blocks in the first nine weeks of their program from September-November.

Measurements completed during laboratory visits (Fig. 1) included FeNO, spirometry, and EVH challenge testing. The Alberta Swim Fatigue and Health Questionnaire was completed once per week to determine respiratory symptoms. Session RPE was reported once or twice daily. As per previous recommendations, [64] participants did not complete any training or strenuous exercise 24 hours prior to the start of the test for each testing day. The Allergy Questionnaire for Athletes (AQUA©) [96] was completed at the first testing session to screen for previous respiratory symptoms and atopy. The Physical Activity Readiness Questionnaire (PAR-Q) [65] ensured participants had no contraindications to exercise, as the EVH test involves high ventilation.

Procedures

For each testing day, participants were assigned a 45 minute-one hour time slot to complete testing at the laboratory, with the first appointment beginning at 8:00am. Laboratory measures were performed at the same time of day at each of the three testing sessions adhering to standard procedures of the laboratory. Participants received an e-mail several days before the first testing session to describe pre-test requirements (Appendix C). Testing was completed on their day off from training (Sunday). Participants were also asked to complete no further exercise or training after their morning swim on Saturday (typically 8:00am-10:00am). Upon arrival to the laboratory they were asked to confirm they had adhered to the pre-test requirements.

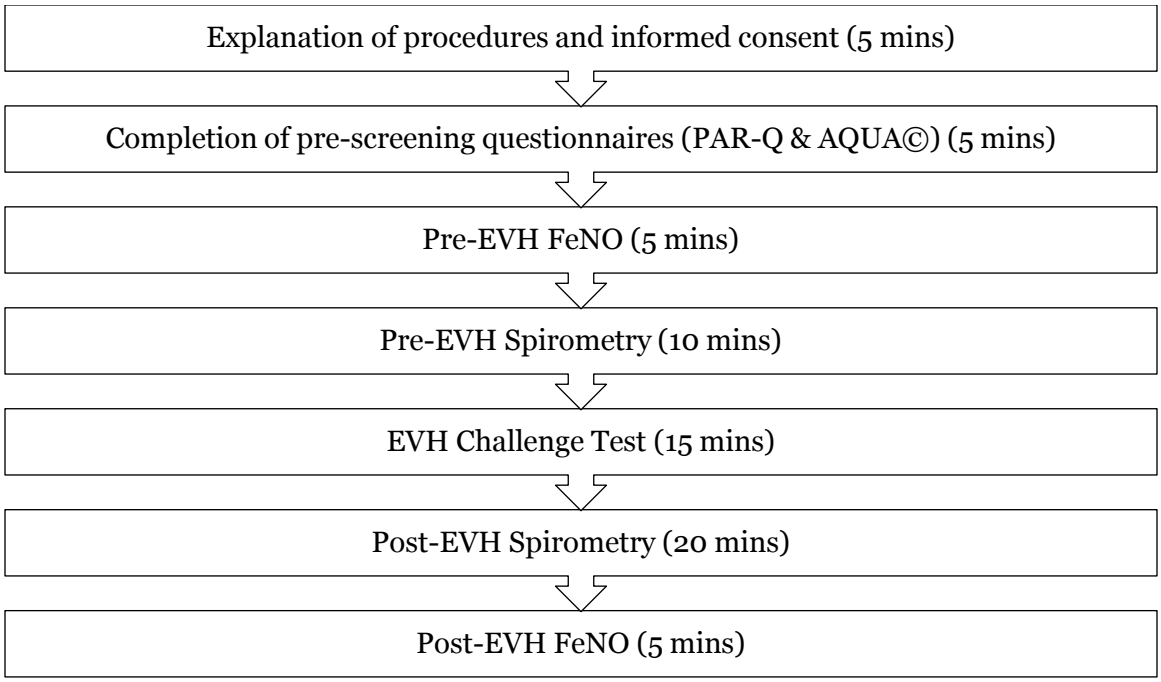

Figure 2. Flow-chart timeline for testing sessions. The process remained the same on all three sessions, except the first two steps were completed on the first session only.

Measures

Individuals involved in conducting the laboratory measures (Rachelle Davies and Michael Kennedy) were trained in Standard First Aid & CPR/AED, administration of the specific test procedures, and proper equipment operation in order to ensure safety of the participants.

FeNO

The NIOX MINO® (Aerocrine AB, Solna, Sweden) portable monitor and accompanying equipment were used to measure FeNO in participants' exhaled breath (online). Measurements followed the National Health and Nutrition Examination Survey (NHANES) Respiratory Health ENO Procedures Manual, American Thoracic Society (ATS)/European Respiratory Society (ERS) Recommendations for Standardized Procedures for the Online and Offline Measurement of Exhaled Lower Respiratory Nitric Oxide and Nasal Nitric Oxide, and standard laboratory procedures.[74,98] FeNO is expressed in parts per billion (ppb) and represents nitric oxide (NO) levels in exhaled breath. A high level of inflammation is marked by ≥50ppb, while moderate/low inflammation is <50ppb but ≥25ppb; and <25 ppb is considered normal/healthy.[76]

The NIOX MINO® was calibrated once per day by the same individual, once per day three days prior to testing days, as per device instructions to ensure accurate readings.[99] To complete the test, each participant was seated in a non-rolling chair, held the device with two hands, and the mouthpiece placed at a comfortable height and position (such that normal upright posture can be maintained throughout the test). A nose clip was not used, as this may promote accumulation of nasal NO and leakage of this NO via the posterior nasopharynx.[98]

A single-breath online technique was used, following current guidelines and recommendations for measuring exhaled nitric oxide.[76,98] Participants inhaled to total lung capacity and exhaled at constant pressure (10-20 cm H_2O) for 10 seconds, guided by visual and auditory aids to stabilize flow rate (50 ± 5 ml/s).[99] The test requires low flow and maximum inhalation one time and thus does not aggravate the airway prior to the EVH test. No participant reported the FeNO measurement as difficult or undue symptoms related to the test.

Online FeNO measurement procedure[76]:

- Ensure the NIOX MINO® display indicates it is ready for use, with sterile mouthpiece inserted at the back of the device
- Explain and demonstrate the test to the participant
- Participant performs manoeuvre

- Insert mouthpiece and inhale over 2 to 3 seconds through the mouth to total lung capacity (TLC), avoiding breathing through the nose.
- Once TLC is reached, the participant immediately exhales, as breath holding may affect FeNO. The exhalation phase is approximately 10 seconds.
- Participants complete as many attempts as necessary (with 1-2 minutes between attempts) to obtain a sample with standard exhalation pressure of 10 - 20 cm H_2O and to maintain a fixed flow rate of 50 ± 5 mL/s, however on average participants only required one attempt. The last three seconds of the 10-second exhalation are analysed by a calibrated electrochemical sensor to give a definitive result in ppb. Flow and pressure parameters are pre-set on the device, so the device provides a definitive result only if the sample meets the required parameters. [99]
- On the exhalation, the researchers coach the participants to push out air at the standard rate described above, with audio/visual assistance from the device. An image of a cloud on the device screen moves up and beeps rapidly to indicate flow is too high, and moves down with slow beeping to indicate flow is too low. If the participant is able to respond to the cues to correct the flow rate to obtain an adequate sample, then the device records a successful attempt.

Spirometry

Pulmonary function was determined pre- and post-EVH testing with a portable handheld spirometer (Spirodoc Touchscreen Spirometer, Medical International Research, Rome, Italy) according to the ATS/ERS standardisation of spirometry guidelines. [100] Participants performed three trials (or as many as necessary) of a forced vital capacity (FVC) manoeuvre, with 1-2 minutes between trials, until three values within 150mL were obtained. The following additional measures were obtained automatically by the spirometer as part of the FVC manoeuvre: forced expiratory flow in one second (FEV_1); forced expiratory flow at 25-75% of FVC (FEF 25-75%); forced expiratory flow at 50% (FEF 50%); and peak expiratory flow rate (PEF).

FVC procedure using an open circuit method (handheld spirometer) [100]:

- Check the spirometer calibration and equip spirometer with sterile disposable mouthpiece
- Explain and demonstrate the test to the participant, including:

    - Correct posture - seated upright with feet flat on the floor, legs uncrossed, and head slightly elevated
    - Attach nose clip
    - Inhale completely and rapidly with a pause of 1 second at total lung capacity (TLC)
    - Place mouthpiece in mouth and form seal with lips around the mouthpiece (past the teeth)
    - Exhale maximally until no more air can be expelled while maintaining an upright posture
- Participant performs manoeuvre. Participants were coached to exhale vigorously when performing the test and were allowed as many additional attempts as necessary if incorrect technique was used (e.g. incomplete seal around mouthpiece).

EVH Test

Once the pre-test spirometry values were obtained, participants were equipped to complete the EVH test, which was performed based on previous laboratory procedures and the IOC-MC recommendations for identifying EIB. [61,64,101] For this test, participants were also asked to refrain from caffeine, alcohol, and any medications that might influence lung function (24 hours for short-acting β2-agonists and 72 hours for inhaled corticosteroids).

EVH Protocol. Each participant was seated in a non-rolling chair and equipped with a sterilized mouthpiece and nose clip (Vacumed #1001, Ventura, California). The mouthpiece was connected to a three-way-valve and had gas sampling at the mouth (ADI gas analyzer; ML206, ADInstruments, Colorado Springs, USA) to determine end-tidal partial pressure of O_2 (PO_2) and partial pressure of CO_2 (PCO_2). All variables were exported into Lab Chart 7 Pro (Lab Chart, ADI) via Powerlab 16/35 data acquisition system (Powerlab, PL3516, ADI) and stored for offline analysis.

We employed a single-stage protocol which requires hyperpnea (hyperventilation) for six minutes at a target ventilation rate equivalent to 30 × FEV_1, which approximates 85% of Maximal Voluntary Ventilation (MVV), corrected with body temperature, pressure, and ambient conditions. [64] We designed an apparatus with biomedical supplies (Appendix B) to act as an air reservoir with at least a 120L capacity. The reservoir is filled initially with approximately 90L and then continuously filled at a rate close to the target ventilation rate during the challenge. Visual feedback was provided from a digital chart recorder (LabChart, ADInstruments, Colorado Springs, USA) and projected onto a white wall to aid with maintaining target rate and depth of

breathing. An inspired dry gas mixture of 21% O_2, 5% CO_2, and balance N_2 was used to avoid hypocapnia. [63]

Before beginning hyperpnea, participants were asked to breathe normally to show their breath tracing via the feedback from the digital chart recorder. An individual marker line was set for each participant to indicate the volume equal to his or her highest pre-EVH test FEV_1, which helped illustrate the depth of breathing necessary for the test. When participants were cued to begin hyperpnea, a metronome application on a smartphone (Pro Metronome, EUMLab, Xanin Technology GmbH, Germany) was used to guide the frequency of respiration (one click for each inspiration and expiration) that matched with 30 x FEV_1. Participants were continually coached throughout the test to reach the target depth and rate of breathing.

Once the six minutes had elapsed, serial FVC manoeuvres were completed in duplicate within 30 seconds (referred to as "immediately post"), as well as 5, 10, 15, and 20 minutes post-test. If FEV_1 measures at a given time point differed by ≥ 150ml, an additional FEV_1 trial was performed. A fall of 10% in FEV_1 observed at two consecutive time points within 20 minutes post-test was considered a positive indication of EIB. [63,102]

Total external training load and internal training stress determination

To determine and quantify training load experienced by the athletes, the load units can be considered external or internal. [29] External load can be defined as "the work completed by the athlete, measured independently of his or her internal characteristics." [103] In swimming, for example, the external load would be represented by the number of kilometres swum at a particular intensity. [21] The internal training stress represents the subjective load on the individual athletes, and provides insight into the physiological and psychological stress imposed.

External Training Load. A traditional linear periodization approach was applied over a period of nine weeks and was divided into three training blocks consisting of three weeks each, classified as low, moderate, and high training load, as mentioned in 2.2 Experimental Design (Figure 3). [104] Prescribed pool and dryland training volume were calculated individually and then summed to determine total external load (the training prescribed to the athletes) per week (Appendix D). External monotony (variation in daily loads) and external strain (product of load and monotony) were also calculated. Methodology used to determine external load followed that of Mujika et al [21], which multiplies total kilometres swum by corresponding intensity factors. Mean training load for each block was 47 AU, 75 AU, and 114 AU for Low, Moderate, and High training blocks, respectively. External load was calculated retrospectively in the first two weeks of training (30 AU and 55 AU), and prospective participant data collection for the study began in

the third week of training. Laboratory tests were completed on the last day of each training block.

Internal Training Stress. Foster [28] developed the session rating of perceived exertion (RPE) method of quantifying internal training stress, which represents the individual response to training and is a simple means that can eliminate the need to use heart rate monitors or other methods/equipment to assess exercise intensity. This method multiplies the athlete's session RPE on a 1–10 scale by the duration of the session in minutes. Participants in the current study were asked to report their session RPE via text message link within 30 minutes of finishing their training session. A single value representing total internal training load for each session was calculated as a product of RPE and approximate training session duration (estimated by the coach) in minutes. This was then used in the calculation of total weekly internal training load, training monotony, and training strain (Appendix E). The weekly internal load is the sum of the daily internal loads, from which monotony can be calculated – the daily mean divided by the standard deviation of the training loads. Strain represents the product of the weekly training load and monotony. [28] Previous research shows session-RPE is a valid and reliable tool for determining internal stress, with individual correlations between session RPE and summated heart rate zone scores ranging between $r = 0.75$ and $r = 0.90$. [28,103,105,106] In a study of 12 competitive swimmers, [107] session-RPE scores were significantly correlated to heart rate-based methods for measuring internal training load as well as training distance (external load) for each swimmer.

Alberta Swim Fatigue and Health Questionnaire

A weekly online self-report questionnaire was completed every Sunday. The questionnaire identifies the presence of physical symptoms and irregularities in the past week of training. Aspects of the questionnaire we used in the statistical analysis were symptoms in Nose/Sinuses, Throat, and Chest categories, which were then summed up to provide a score of Total Respiratory Symptoms each week.

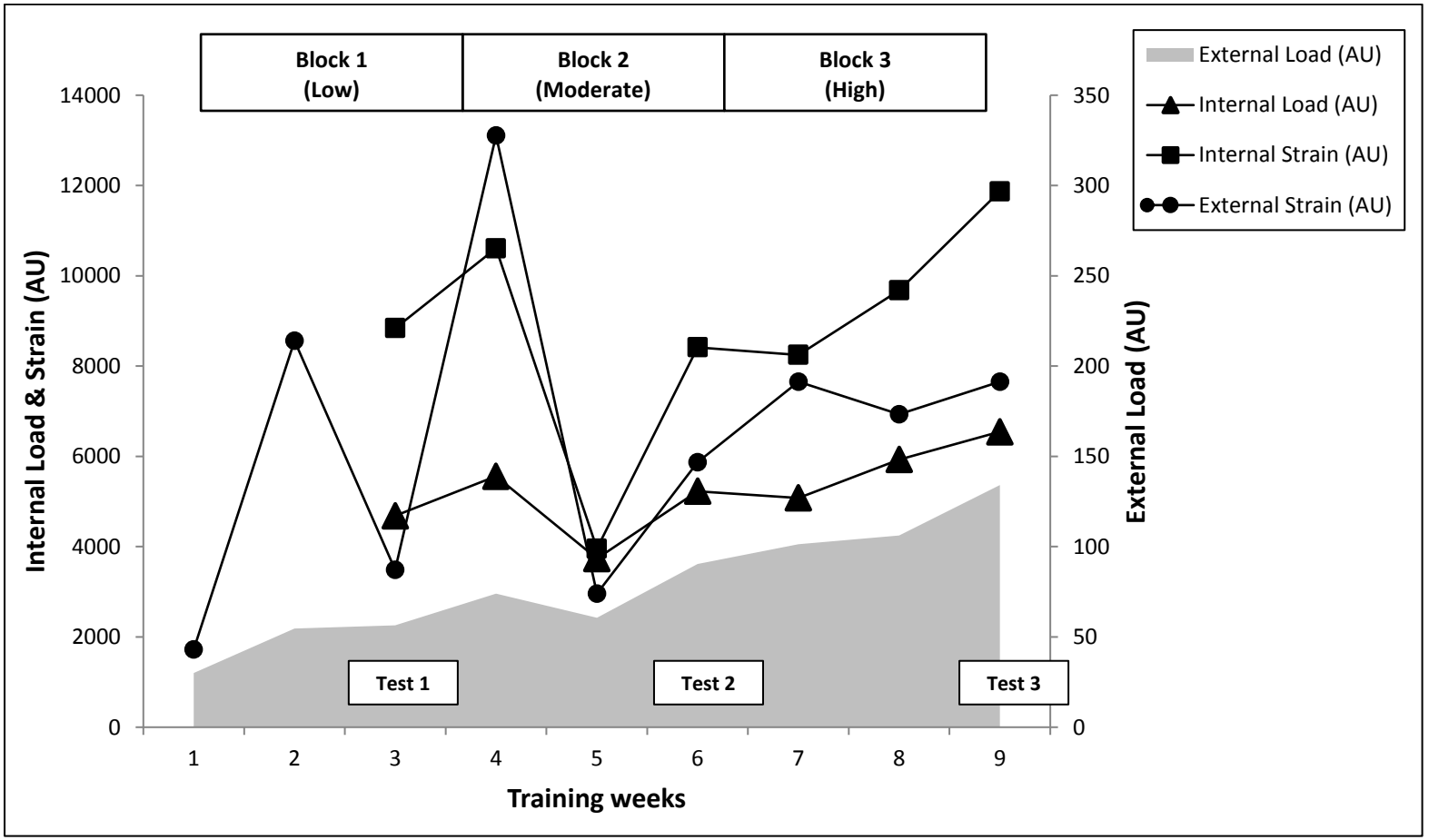

Figure 3. Weekly external load, external strain, internal load, and internal strain over nine weeks of swim training. Training loads are indicated for three-week blocks, with tests occurring at the end of the blocks. Data on internal load and strain were not collected until Week 3. External Load was calculated retrospectively in for the first two weeks of training.

Statistical analysis

Statistical analysis was performed using the IBM Statistical Package for Social Sciences (SPSS) for Macintosh, Version 22.0.0 (SPSS Inc., Chicago, IL). An alpha level (α) of 0.05 was chosen to indicate significance for all analyses, as this study has a small sample size and is a novel approach to understanding the relationship between different training loads and lung health in swimmers.

In order to effectively test the primary hypothesis, it was necessary to have the ability to a) have a quantifiable method to monitor external training load; b) ensure that these training loads could differ in intensity and volume enough to be categorized as low, moderate, or high and c) swimmers in the study would be prescribed approximately the same external training loads. One high performance training group from a local competitive swimming club was able to satisfy these criteria in order for the research team to have sufficient control over the study design. Thus, the number of swimmers that registered for the 2016/17 training season with the club influenced the recruitment of study participants. Considering our hypothesis that swimmers would have greater AHR after higher training loads (determined with the EVH test), it was important to know the mean fall in FEV_1 of swimmers in other studies who were found to have positive EVH tests. Based on a previous study of elite female swimmers and their responses to airway provocation tests, [108] 5 of 16 (31%) had positive EVH tests, with a mean fall of 0.70L (SD = 0.35L) in FEV_1 post-EVH, equivalent to 18% (SD = 8.4%). Another study [109] revealed 18 of 33 elite swimmers (55%) had a positive EVH challenge, with a mean fall in FEV_1 of 20.4 (SD = 11.7%) from baseline. [110]Using this information, 11-21 participants[e] would be required to detect a similar change with a 95% confidence level and 5% allowable error. It was not feasible to obtain the number participants within the estimated range as we were limited by the aforementioned criteria. However, considering the novel design and exploratory nature of the study it was concluded 8 participants would be sufficient.

A single-group repeated measures (1 group x 3 training intensities [Low, Moderate, High]) ANOVA was the primary test used to detect differences in spirometry values pre-/post-EVH, internal training stress, and mean respiratory symptoms between training loads. Before conducting the repeated measures ANOVA, three primary assumptions were made underlying the analyses: 1) There are no significant outliers in the group; 2) the distribution of the dependent variables should be approximately normally distributed; and 3) the variances across the levels of the independent variable are equal (homogeneity of variance). [111] Normality

[e] Determined using the SD of the % fall in FEV_1 reported in previous studies that was associated with positive EVH tests. Sample size was then estimated with $n = (z)^2 \times (SD)^2 / (E)^2$ where n = sample size, z = z-score for confidence interval, SD = standard deviation, and E = expected or allowable error.

was assessed using the Shapiro-Wilk test of normality, and sphericity was assessed with Mauchly's Test of Sphericity. If data violated these assumptions or outliers were detected (using the Explore>Statistics function for detecting outliers), a Friedman's ANOVA was used.

A single-group repeated measures ANOVA (1 group x 3 training loads [Low, Moderate, High]) examined differences in raw values for pre- and post-EVH FVC, FEV_1, FEF 25-75%, FEF 50%, and PEF (at immediate, 5 min, 10 min, 15 min, 20 min), as well as maximal % decreases in FEV_1 post-EVH between training blocks ($\alpha = 0.05$). Repeated measures ANOVA (1 group x 3 training loads [Low, Moderate, High]) also evaluated differences between training blocks in mean respiratory symptoms, and means of each internal load, internal monotony, and internal strain. LSD pairwise comparisons were used to evaluate differences in each variable between training blocks.

An outlier was detected for FeNO measurements, therefore a Friedman's ANOVA (1 group x 3 training loads [Low, Moderate, High]) was used to determine differences in pre- and post-EVH FeNO across training blocks. Wilcoxon Signed Rank Tests were used to determine pairwise differences between blocks, as well to evaluate differences in FeNO within testing days between pre- and post-EVH.

Pearson correlation coefficients with 95% confidence interval (CI) (two-tailed) were calculated between External and Internal Load estimates, as we expected there would be a proportional, linear relationship between these two variables. Spearman rank order correlation coefficients with 95% CI (two-tailed) were calculated between spirometry measurements and corresponding weekly respiratory symptoms. (e.g. Week 3 respiratory symptoms during the last week of the Low block were reported in the corresponding week of Test 1). Spearman correlation was chosen in place of Pearson, as we were interested in evaluating whether participants who ranked higher on symptom frequency also ranked higher on % decreases in FEV_1, as there is paucity of evidence for a linear relationship between these variables.

Results

Participant Characteristics

Participant characteristics are shown in Table 1. Swimmers had a wide range of years participating in competitive swimming (2-10 years). One female swimmer was diagnosed with mild asthma and was prescribed a short-acting beta-agonist, a long-acting corticosteroid, and a metered corticosteroid nasal spray by a physician and had a positive AQUA© score. No other swimmers had a history of asthma, however four other also swimmers had positive (≥5) AQUA© scores and reported they had previously experienced respiratory symptoms (shortness of breath, chest tightness, cough, and/or itching of the throat) during and/or following training sessions. The training program consisted of 7-9 swim sessions, 3-4 dryland sessions, and 1 day off per week during the study period. All participants had normal FEV_1, FVC, and FEV_1/FVC values for their age, height, and gender (Appendix F).

Table 1. Participant characteristics.

Part.	Gender (M/F)	Age (yrs)	Weight (kg)	Height (cm)	Competitive swimming (yrs)	Weekly training (h)	Low (h)	Moderate (h)[b]	High (h)[b]	AQUA©	EIB positive tests
1	F	16	61.4	178	3	15	16	15	16	13[a]	Low, Mod
2	F	16	59.1	175	3	13	16	15	11	15[a]	Low, Mod, High
3	M	17	79.5	183	10	16	16	14	19	5[a]	None
4	F	14	58.2	165	8	19	16	19	21	0	Low, High
5	M	17	95.0	175	4	19	16	19	21	2	Mod
6	F	17	59.1	170	9	19	16	19	20	8[a]	Mod, High
7	M	16	70.9	191	5	19	16	19	20	2	Low, Mod, High
8	M	16	76.2	178	2	19	16	19	21	5[a]	Low, Mod, High
Mean ± SD		16.1 ± 1.0	69.9 ± 13.1	176.9 ± 7.9	5.5 ± 3.1	17.4 ± 2.4	16	17.4 ± 2.3	18.6 ± 3.5	6.3 ± 5.4	2[c]

cm = centimetres; F = female; h = hours, kg = kilograms; L = low; M = male; part. = participant; yrs = years; [a] = positive score (≥5) on Allergy Questionnaire for Athletes (AQUA ©); [b] = presented as mean hours of training per three week training block; [c] = median number of positive tests

FeNO

Friedman's test revealed pre-EVH FeNO did not differ across training loads (p = 0.42), however post-EVH FeNO was significantly different (p = 0.006) (Table 2, Fig. 4). Wilcoxon Signed Ranks Test showed post-EVH FeNO after Low (15.4 ± 3.6 ppb) was significantly higher than after Moderate training loads (9.4 ± 4.9 ppb) (Z = -2.5, p = 0.012). Wilcoxon Signed Ranks Test also showed post-EVH FeNO was significantly lower than pre-EVH after Moderate (pre = 16.6 ± 7.4 ppb, post = 9.4 ± 4.9 ppb, Z = -2.5, p = 0.011) and High training loads (pre = 16.8 ± 3.5 ppb, post = 13.6 ± 4.5 ppb, Z = -2.1, p = 0.034).

Table 2. Pre- and post-EVH FeNO after Low, Moderate, and High training loads.

	Low	Moderate	High
FeNO Pre-EVH (ppb)	19.0 ± 8.4	16.6 ± 7.4	16.8 ± 3.5
FeNO Post-EVH (ppb)	15.4 ± 3.6*	9.4 ± 4.9*‡	13.6 ± 4.5‡

* = Wilcoxon Signed Ranks between training blocks p < 0.05; ‡ = Wilcoxon Signed Ranks pre- to post-EVH p < 0.05; ppb = parts per billion

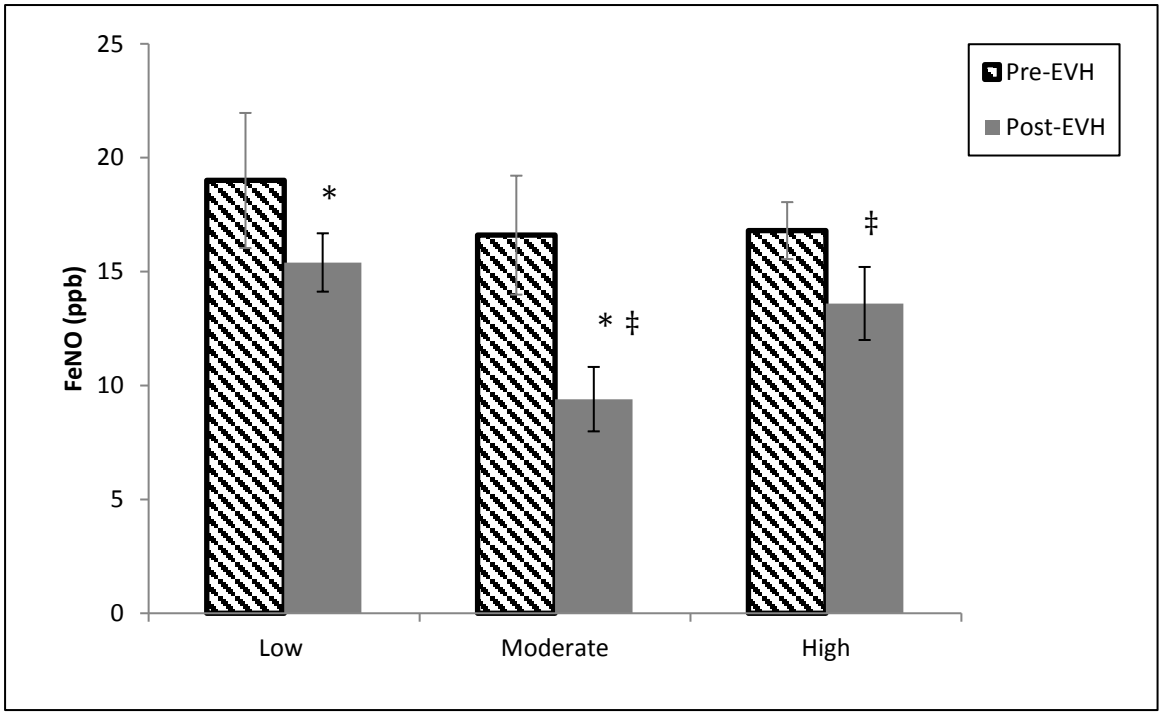

Figure 4. Pre- and post-EVH FeNO values. * = Wilcoxon Signed Ranks between training blocks p < 0.05; ‡ = Wilcoxon Signed Ranks pre- to post-EVH p < 0.05; ppb = parts per billion.

EVH Test / Spirometry

Seven swimmers (88%) were positive for EIB (>10% fall in FEV_1 on two consecutive time points post-EVH) for at least one testing session (Table 1). Five (63%) swimmers were positive for EIB after Low load; six (75%) after Moderate; and five (63%) after High. The mean maximum % falls in FEV_1 after low, moderate, and high training loads were -14.3±9.2%, 13.9±4.1%, and -12.0±7.6%, respectively.

Repeated measures ANOVA showed a main effect of training load on pre-EVH FEV_1 values (p = 0.041). LSD pairwise comparisons revealed significantly lower mean pre-EVH FEV_1 after Moderate (4.52 ± 0.69 L) compared to after Low (4.74 ± 0.63 L) (p = 0.025) (Table 3, Fig. 5), while pre-EVH FEV1 values after High (4.52±0.63 L) were not significantly different from Low (p = 0.083) or Moderate (p = 1.00). There was also a main effect of training load on 20-min post FEF 25-75% (p = 0.044). These values after Moderate (3.73 ± 0.94 L/s) were significantly lower than after High (4.07 ± 1.02 L/s) (p = 0.02) (Table 3). Maximum % changes in FEV_1 did not differ significantly across training blocks (p = 0.763) (Fig. 6). None of the other spirometry measures at pre- or post-EVH sampling points differed between training blocks.

Table 3. Spirometry pre-EVH testing and at each post-EVH sampling point after low, moderate, and high training load

		Pre-EVH	Immediately Post	5 mins	10 mins	15 mins	20 mins
FVC (L)	Low	5.84 ± 0.74	5.70 ± 0.76	5.54 ± 0.58	5.43 ± 0.75	5.41 ± 0.84	5.49 ± 0.98
	Moderate	5.65 ± 0.86	5.48 ± 0.82	5.44 ± 0.84	5.24 ± 0.77	5.44 ± 1.29	5.41 ± 1.04
	High	5.56 ± 0.94	5.31 ± 0.80	5.36 ± 0.75	5.34 ± 0.70	5.31 ± 0.76	5.31 ± 0.78
FEV_1 (L)	Low	4.74 ± 0.63	4.48 ± 0.63	4.26 ± 0.45	4.14 ± 0.46	4.15 ± 0.54	4.22 ± 0.64
	Moderate	4.52 ± 0.69*	4.26 ± 0.62	4.12 ± 0.61	3.99 ± 0.42	4.12 ± 0.72	4.18 ± 0.68
	High	4.52 ± 0.63	4.15 ± 0.69	4.13 ± 0.56	4.14 ± 0.53	4.23 ± 0.50	4.25 ± 0.54
FEF 25-75% (L/s)	Low	4.69 ± 1.12	4.08 ± 0.87	3.72 ± 0.62	3.42 ± 0.66	3.52 ± 0.80	3.81 ± 0.83
	Moderate	4.34 ± 1.04	3.80 ± 0.89	3.52 ± 0.94	3.43 ± 0.58	3.51 ± 0.57	3.73 ± 0.94
	High	4.47 ± 1.05	3.82 ± 1.04	3.67 ± 0.91	3.69 ± 1.07	3.93 ± 0.77	4.07 ± 1.02*
FEF 50 % (L/s)	Low	5.23 ± 1.39	4.35 ± 0.98	4.27 ± 0.89	3.96 ± 0.80	4.09 ± 0.97	4.21 ± 0.85
	Moderate	4.71 ± 1.12	4.30 ± 1.14	4.08 ± 1.10	3.85 ± 0.71	4.02 ± 0.75	4.20 ± 1.11
	High	4.90 ± 1.22	4.25 ± 1.26	3.88 ± 1.16	4.26 ± 0.98	4.39 ± 0.95	4.45 ± 1.03
PEF (L/s)	Low	8.91 ± 1.30	8.32 ± 1.34	7.83 ± 1.36	7.55 ± 1.08	7.65 ± 1.26	7.56 ± 1.25
	Moderate	8.43 ± 1.52	7.92 ± 1.29	7.76 ± 1.18	7.49 ± 1.24	6.92 ± 3.12	8.05 ± 1.70
	High	8.42 ± 1.53	7.98 ± 1.63	7.78 ± 1.58	7.76 ± 1.62	7.93 ± 1.72	7.80 ± 1.61

FEF 25-75% = mean forced expiratory flow at 25-75% of FVC; FEF 50% = forced expiratory flow at 50% of FVC; FEV_1 = forced expiratory volume in 1 second; FVC = forced vital capacity; PEF = peak expiratory flow; mins = minutes; * = LSD pairwise comparison between training blocks for corresponding time points $p < 0.05$.

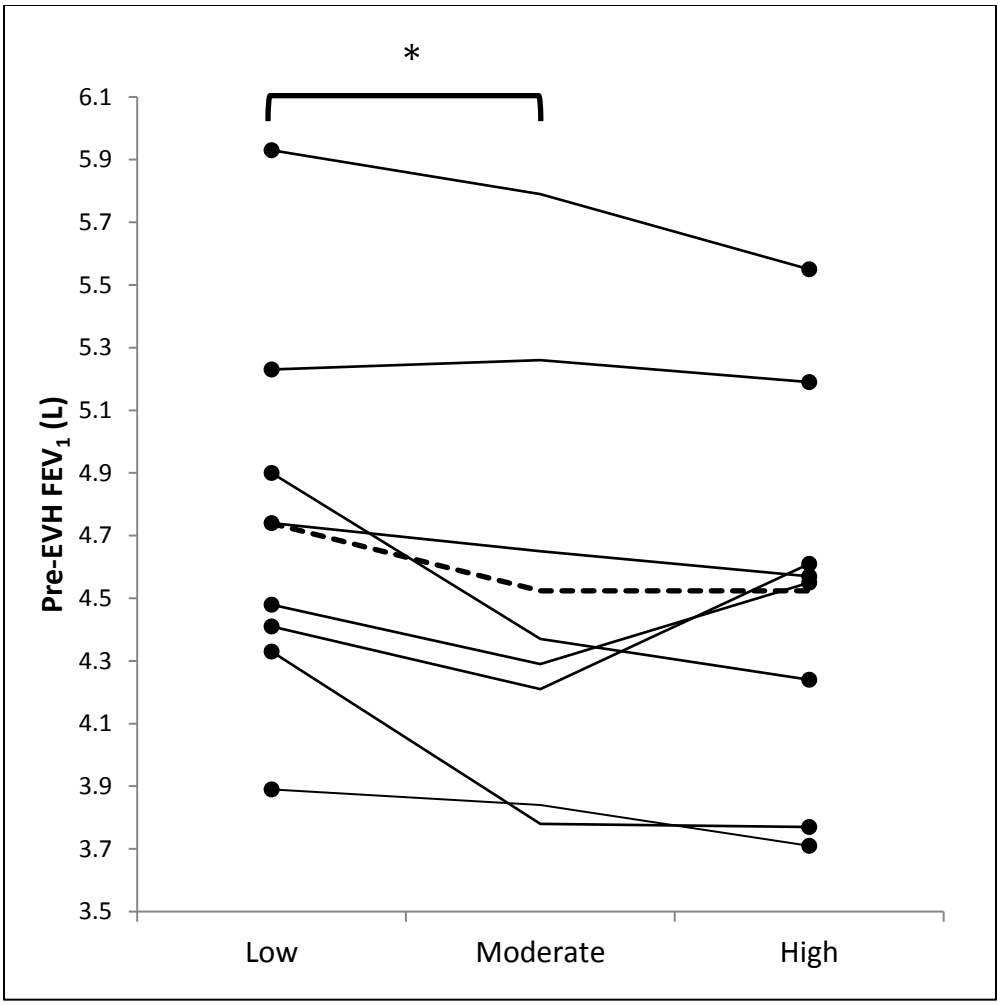

Figure 5. Individual FEV_1 values prior to the EVH test for each testing session. Mean indicated by thick dashed line. * = LSD pairwise comparison between training blocks $p < 0.05$.

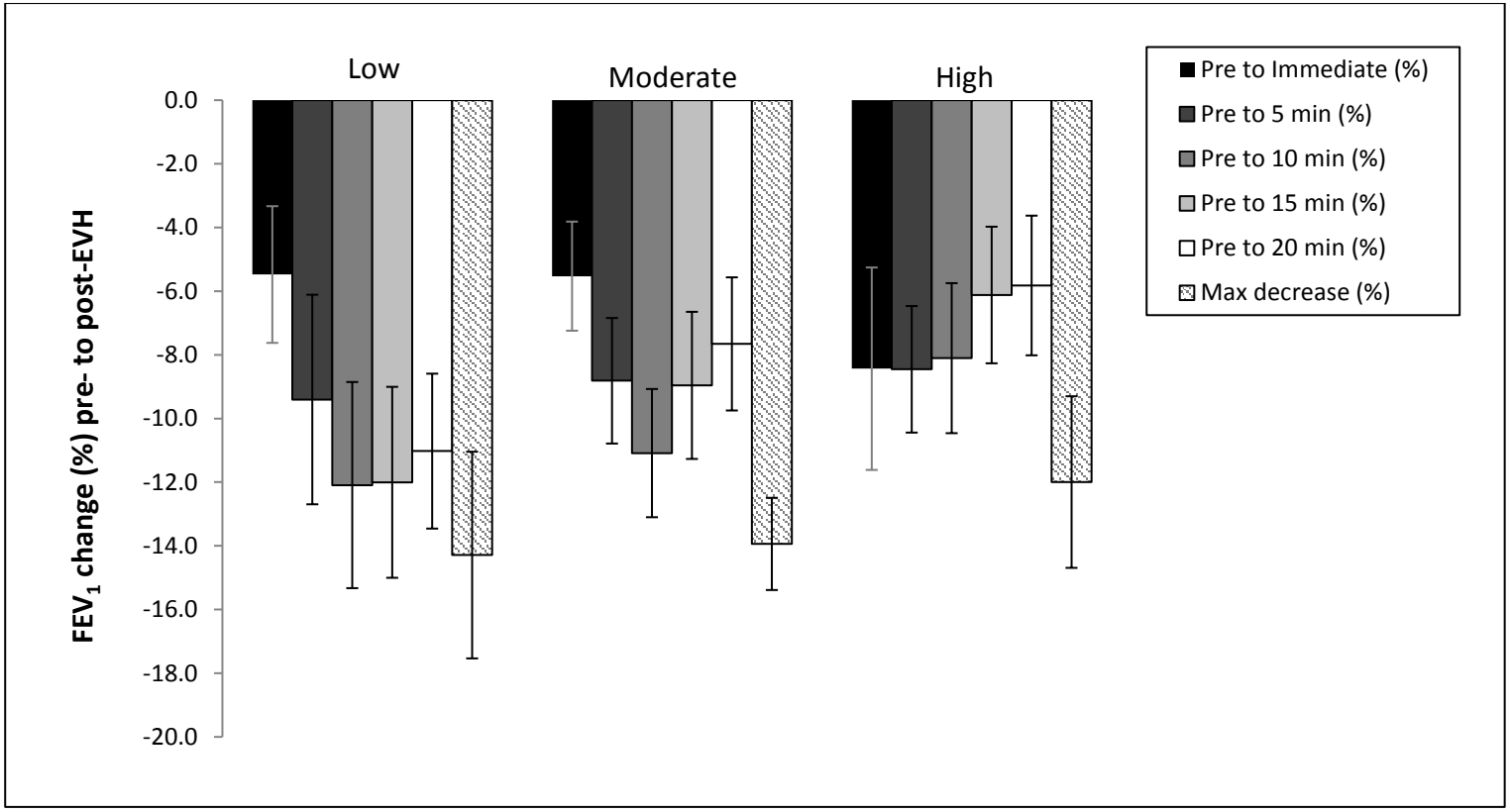

Figure 6. Percent changes in FEV_1 (L) from pre-EVH to each post-EVH sampling point after low, moderate, and high training loads, displayed as means with standard error bars. Maximal FEV_1 decreases did not differ significantly across training loads. Max = maximum; min = minute.

Respiratory Symptoms

Mean respiratory symptoms did not significantly differ by training block. Spearman correlations revealed total respiratory symptoms in the last week of the low training load were significantly negatively correlated with % change in FEV_1 20 minutes post ($\rho = -0.71$, $p = 0.05$) in the corresponding week. Respiratory symptoms in the last week of the moderate training load were also significantly negatively correlated with % change in FEV_1 20 minutes post ($\rho = -0.71$, sig = 0.05) in the corresponding week. Respiratory symptoms in the last week of the high training load were significantly negatively correlated with % change in FEV_1 at 10 minutes post ($\rho = -0.74$, sig = 0.03), 15 minutes post ($\rho = -0.91$, sig = 0.00), and 20 minutes post ($\rho = -0.75$, sig = 0.03) in the corresponding week. All other sampling points and spirometry values tested were not significantly correlated with symptoms.

External training load and internal training stress

There was a positive Pearson correlation between weekly external load and weekly internal load ($r = 0.83$, $p = 0.02$) (Table 4, Fig. 7). Repeated measures ANOVA revealed significant differences among training blocks on internal load ($p = 0.02$) and internal monotony ($p = 0.02$), but not internal strain. LSD pairwise comparisons showed internal load was lower in the Moderate block (4840 ± 971 AU) than in the High block (5852 ± 737 AU) ($p = 0.02$). Internal monotony was lower in the Moderate block (1.5 ± 0.4 AU) than the Low block (1.9 ± 0.3 AU) ($p = 0.01$) (Table 4).

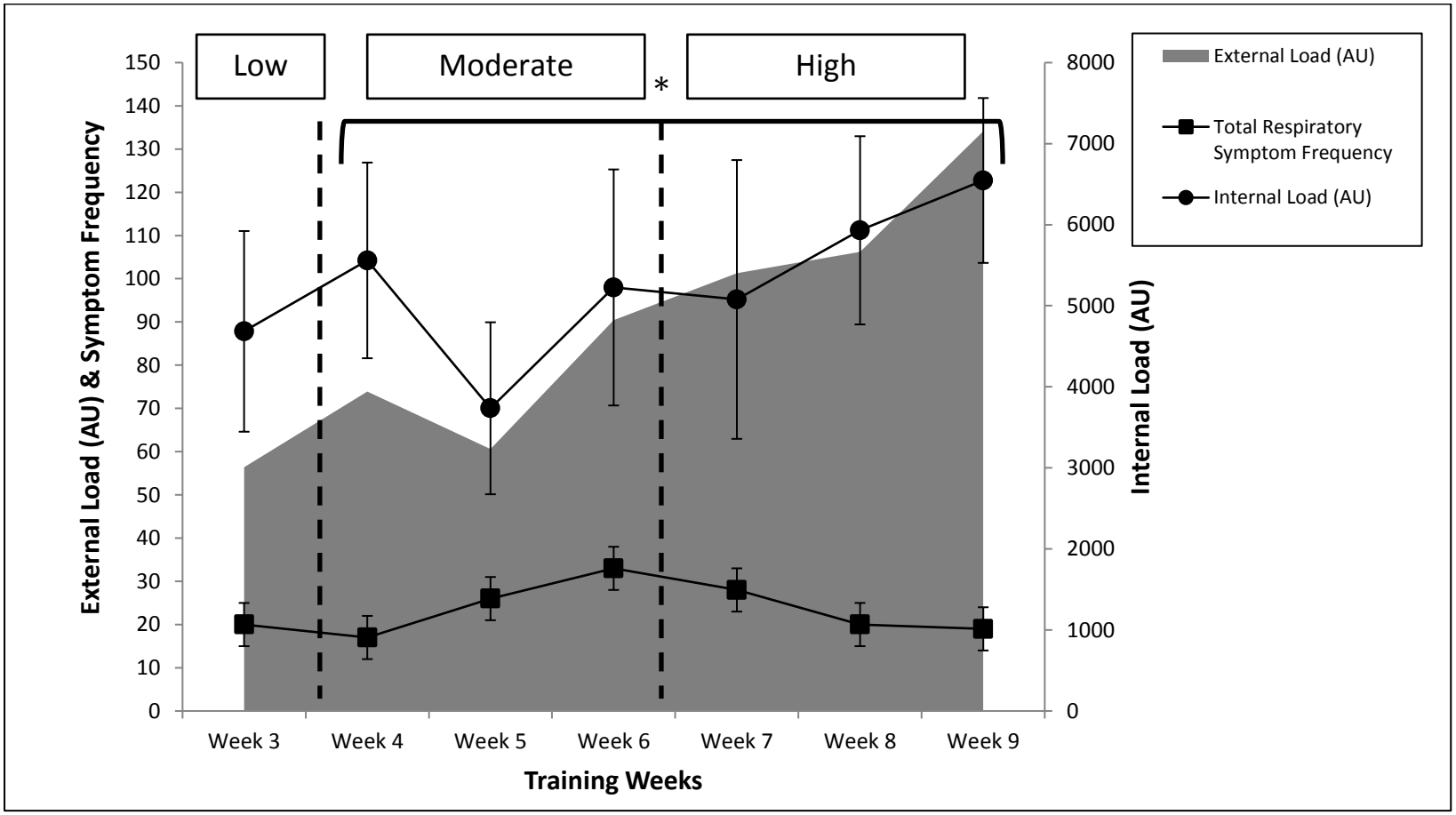

Figure 7. External training load, internal training load, and total respiratory symptom frequency over Weeks 3-9 displayed with standard deviation error bars. Training blocks are separated by dashed line. Symptom frequency was calculated as a group sum of reported upper and lower respiratory tract symptoms. AU = arbitrary units. * = LSD pairwise comparison of internal between training blocks $p < 0.05$

Table 4. External training load and internal training stress summary.

		External Training Load			Internal Training Stress			
Training Block	Week	External Load* (AU) [b]	External Monotony (AU)	External Strain (AU)	Session RPE	Internal Load * (AU) [b]	Internal Monotony (AU) [b]	Internal Strain (AU) [b]
Low	1[a]	30 ± 3	1.4	43				
	2[a]	55 ± 2	3.9	214				
	3	56 ± 5	1.5	87	5.2 ± 1.1	4684 ± 1238	1.9 ± 0.3	8839 ± 2954
Block Mean ± SD		47 ± 17	2.3 ± 1.4	115 ± 89				
Moderate	4	74 ± 2	4.4	328	4.9 ± 1.4	5559 ± 1207	1.9 ± 0.2	10608 ± 2368
	5	61 ± 7	1.2	74	4.8 ± 0.8	3735 ± 1062	1.1 ± 0.3	3956 ± 1932
	6	90 ± 7	1.6	147	5.1 ± 1.1	5226 ± 1456	1.5 ± 0.4	8416 ± 3922
Block Mean ± SD		75 ± 15	2.4 ± 1.8	183 ± 131	5.0 ± 1.0	4840 ± 971‡	1.5 ± 0.4‡	7660 ± 3390
High	7	101 ± 6	1.9	191	5.6 ± 1.0	5078 ± 1721	1.6 ± 0.5	8248 ± 4309
	8	106 ± 7	1.6	173	5.8 ± 1.1	5931 ± 1161	1.6 ± 0.4	9679 ± 3686
	9	134 ± 7	2.1	280	6.5 ± 1.0	6547 ± 1017	1.8 ± 0.3	11872 ± 3290
Block Mean ± SD		114 ± 18	1.9 ± 0.2	215 ± 57	6.0 ± 0.5	5852 ± 737	1.7 ± 0.1	9933 ± 1825

AU = Arbitrary Units; RPE = Rating of Perceived Exertion; [a] = internal stress data not collected, and external load calculated retrospectively in these weeks; [b] = weekly mean ± SD; * = Pearson correlation $p < 0.05$; ‡ = LSD pairwise comparison between blocks $p < 0.05$

Discussion

This aim of this research was to determine whether systematic increases in external training load would increase airway responsiveness to an EVH challenge, affect airway inflammation, and exacerbate respiratory symptoms in competitive youth swimmers. An existing gap in the literature was that training loads are generally not documented in sufficient detail to quantify how much training was done, therefore with the training blocks imposed, we hoped not only to evaluate how external training load affects lung health, but also gain insight into how changes in training volume and intensity may influence lung health.

We hypothesized that an increase in external training load would worsen overall lung health status. In support of this, we found that resting lung function (as described by pre-EVH FEV_1) decreased from 4.74 ± 0.63 L to 4.52 ± 0.69 L (p = 0.04) between Low and Moderate training loads (60% load increase). Pre-EVH FEV_1 was not significantly different (4.52 ± 0.63 L) after the High training load (52% load increase from Moderate). This does not support our hypothesis, and could be that the change in training load was not large enough to detect significant changes. The swimmers could also be more susceptible to airway changes are potentially greater at the beginning of a training season when athletes are adjusting to a new training program, while later in the season they are able to tolerate higher training loads without concomitant changes in airway obstruction.

Seven swimmers (88%) had positive EVH tests during at least one of the testing sessions (median was 2 sessions), with a median change in FEV_1 greater than 10% for each testing session. Swimmers in our study tended to reach their maximum % decreases in FEV_1 at 5-10 minutes post-EVH, comparable to other research. [71] Such responses have been found in adult elite swimmers, [31,108] while much less is known about youth swimmers. A previous study [110] suggested youth involvement in competitive swimming for approximately two years is not sufficient for development of respiratory symptoms or airway inflammation, but could possibly result in minor increases in AHR. Our swimmers were on average two years older (16.1 ± 1.0 compared to 14.3 ± 1.2) and had been in competitive swimming for three years longer (5.5 ± 3.2 compared to 2.7 ± 1.3) than the swimmers in the Pedersen et al [110] study, and presented a more vigorous response to provocation. Thus, our results suggest that three additional years of competitive swimming (about 2,700 total hours) may influence AHR and could mark an important transition to severity and prevalence of AHR reflective of adult elite swimmers with extensive training years.

Although not statistically different between blocks, we also observed mean decreases in mid-expiratory flow rates post-EVH, suggesting presence of expiratory airflow restriction in the

smaller airways. [69] These decreases were accompanied by mean falls in FVC, which Dickinson et al [69] have suggested may be influenced by the discomfort of exhaling to residual volume during bronchoconstriction. Reduced mid-expiratory flow rates combined with falls in FEV_1 >10% on average after each training block suggests that approximately 17 hours/week of competitive swimming may facilitate AHR and the likelihood of a positive response to EVH, but changes in training load might not produce linear increases in AHR.

Competitive swimming itself can induce eosinophilic airway inflammation via chloramine-induced changes to the lung epithelium. [72] Moreover, high ventilation sustained in swimming may negatively affect the airway epithelium by promoting mucus dehydration and increased shear stress on the epithelial wall of the lungs. [3,72] We included FeNO measurements because eosinophilic inflammation is a characteristic feature of asthma, [73] and we predicted that individuals with positive EVH tests would have elevated FeNO levels. We found a lack of differences in resting levels of inflammation across training loads (as indirectly indicated by pre-EVH FeNO), which do not support our hypothesis. This is consistent with previous findings indicating FeNO is not elevated in adolescent elite swimmers, [110] adult elite swimmers compared to controls [112] or elite cross-country skiers compared to controls. [113] However, post-EVH FeNO (9.4 ± 4.9 ppb) and 20-min mid-expiratory flow (FEF 25-75%) (3.73 ± 0.94 L/s) were significantly lower after Moderate training, which supposes post-EVH FeNO might decrease due to increased airway obstruction from provocation. This contrasts a previous study that found airway provocation counteracts the fall in expired NO that is observed after repeated spirometry alone, and could therefore be associated with further increased NO production. [114] However, significant differences in post-EVH FeNO between training blocks suggests swimmers who are hyperresponsive may additionally express lower FeNO values after provocation rather than high expired NO levels at rest.

Our correlation data shows swimmers who were more hyperresponsive and slower to recover from the EVH test also had greater respiratory symptom frequency. Closer examination of individual symptoms (not shown) revealed more hyperresponsive swimmers tended to report at least one upper respiratory symptom in the week coinciding with the EVH test, primarily rhinorrhea (runny nose) and/or phlegmy throat. Thus, monitoring symptoms on a regular basis could provide additional insight into the development of AHR, despite previous research indicating AHR may be observed in the absence of symptoms or vice versa. [115] A previous study[116] also determined training 1.5-4 hours a day, 3-5 times per week (similar to our study) is associated with high prevalence (74%) of rhinitis symptoms. Thus, participation in competitive swimming at this frequency and volume is perhaps enough of a stimulus to provoke chronic

respiratory symptoms, and warrants regular monitoring due to the association we found with AHR post-EVH. Hyperresponsive, symptomatic swimmers may then need special consideration where a set or race involving high ventilation rates could influence subsequent sets. What measurable effect symptoms and AHR have on performance requires further investigation, but it can be hypothesized that coaches would observe speed or time-related decrements given the linear relationship that exists between oxygen consumption and swimming velocity. [117]

In the recent IOC consensus statement on load in sport and risk of illness, [44] only two studies have examined the changes in training load and the risk of illness in swimmers. [51,118] Furthermore, training monotony as a risk factor for illness has only been studied recently in elite cross-country skiers [52] and rugby league players. [53] Our data supports the idea that monotony can negatively impact athlete health. A novel finding within the Moderate block is that total respiratory symptom frequency was highest with a concomitant decrease in pre-EVH FEV_1, and training was also highly monotonous (2.43 ± 1.76 AU), with the highest monotony score occurring in Week 4 (4.43 AU). This reinforces that little variation in training load might exacerbate illness symptoms [119] and perhaps worsen lung function. Moreover, in the Moderate block the coaching staff increased training frequency to achieve higher volume (i.e. two-a-day workouts), while maintaining similar training intensity as the Low block. Surprisingly, in the Moderate block internal load (4840 ± 971 AU) and internal monotony (1.50 ± 0.42 AU) were significantly lower than the High block, which might theoretically favour better lung health outcomes. [28] In contrast, persistent respiratory symptoms may cause swimmers to purposefully ease off in training to allow sufficient rest and to prevent overreaching, resulting in lower RPEs. [49] Low internal load and monotony with Moderate training – yet obstructed airways at rest – suggests prescribed increases in external training load could negatively influence lung health more than internal markers of training stress. [25]

Recognizing the potential limitations of this study is important. First, we had a small sample of eight swimmers from the same training group and club; therefore external validity is limited to swimmers at a similar competitive level with comparable training loads and schedules. It could also be challenging to measure whether swimmers in other clubs similar training if there is no method employed to quantify training loads. Second, a 48% increase in load from Week 5 (61 ± 6.7 AU), to Week 6 (90 ± 6.9 AU) within the Moderate block might have negatively influenced the swimmers, speaking to the importance of microcycle variation for load increases). Upon reflection, although we did not plan for such a large increase from Week 5 to 6, it helped illustrate how load increases may affect lung health. Training load also decreased 18% from Week 4 (74 ± 2.4 AU) to Week 5 prior the High block, which may have facilitated recovery

from training and improved tolerance to increased training loads in the High block. Lastly, we did not include a control group, however in our repeated measures design the participants acted as their own controls to determine changes in lung health.

It appears that increases in training load may affect the development of chronic airway obstruction, inflammation, and respiratory symptoms in swimmers, yet determining whether swimmers have worsened lung health that could impact performance outcomes is challenging. A simple, cost-effective method to monitor overall lung health status in competitive youth swimmers could incorporate tracking respiratory symptoms, quantifying training load, and performing resting spirometry measurements and/or a standard EIB lab test. Based on our results, seemingly minor symptoms such as a runny nose or phlegmy throat that persist over several weeks may be early indicators of AHR, and therefore should not be disregarded. Additionally, having a means of quantifying both external and internal training loads has merit, as it could help coaches manage the overall variation in the training prescription. Microcycles could be adjusted to reduce monotony and possibly lower the risk of undue fatigue and illness. Implementing a monitoring system could allow coaches to enhance relationships and communication with athletes and support staff not only in day-to-day swimming practice, but also in regards to overall health and wellness that impacts swimming performance.

Chapter 4: General Discussion

Main Findings

In summary, our findings indicate the swimmers showed airway obstruction after an increase from low to moderate training load and had hyperresponsive airways throughout the entire study, which are arguably the most meaningful findings when reflecting on the potential implications of training on the lung health of competitive swimmers. Furthermore, we found weekly monitoring of respiratory symptoms may be useful in identifying early indicators of AHR, despite previous research suggesting athletes with AHR do not always present with symptoms. Our results also add new evidence for showing when the onset of AHR and EIB occur in swimmers, since most studies are done in adult competitive swimmers and less so with younger swimmers.

This study provides unique insight into the influence of training loads on the lung health status of competitive swimmers. We believe a key reason for this is that training loads (both internal and external) are generally not documented in sufficient detail to quantify how much training was done, so in this respect we have innovated the way that sport science research is conducted. We observed that higher external training monotony coincided with greater airway obstruction and respiratory symptoms. It is generally agreed that monotony is a training factor that increases risk of illness in elite athletes, [49] and thus could play a role in development of EIB in addition to the overall training load. However, training monotony has not been extensively studied in swimmers, and to our knowledge this was the first study to examine how training variables influence the specific indicators of lung health that we measured. We did not expect that internal load and monotony would be significantly lower – yet with greater airway obstruction – with a moderate external training load. It seems, then, that the training prescription (i.e. what is the external load, and how does it vary day to day?), along with the time spent in chlorinated pools (i.e. 17 hours/week on average) may be more important in the development of AHR and EIB, inflammation, and respiratory symptoms than markers of internal training stress.

Although not statistically significant, we have emerging evidence that swimmers actually had *better* airway recovery from provocation after high training loads. While the largest % decreases in FEV_1 seemed to occur around 10-15 minutes post-EVH after low and moderate training, this pattern was not evident after high training loads – the decreases seemed to occur earlier and return close to baseline in a shorter amount of time. This was not what we expected - we hypothesized AHR would be the *worst* after a high training block. There are many factors

that could influence this finding, but it is possible that the timing of the EVH test and adaptation to training affect lung health measurements.

Limitations

Recognizing the potential limitations of this study is important. First, we had a small sample of eight swimmers from the same training group and club; therefore external validity is limited to swimmers at a similar competitive level with comparable training loads and schedules. The alpha level used for statistical analyses was set at 0.05, where there would be a 5% chance of committing a Type 1 Error (that is, rejecting the null hypothesis when it should have been accepted). Further, our small sample size certainly inflates the risk of Type 2 error as small samples reduce statistical power in detecting significant differences.

Seven of 8 swimmers were positive for EIB (>10% drop in FEV_1) after at least one of the three training load intensities. Yet with only 8 swimmers in the sample, there is the possibility of selection bias where perhaps the more symptomatic swimmers were interested in participating and the lesser or non-symptomatic swimmers did not have a desire to participate. The positive findings were also not consistent for each swimmer in the study – some swimmers were positive on one test, yet negative on the next (when we hypothesized that lung health gets worse); therefore, we cannot completely reject the null hypothesis. Some positive findings may have been false and affected by something other than the training load (Type 1 Error), such as a more complex mechanism in the EIB phenotype of swimmers. We also did not measure markers of the airway remodelling process – that may be influenced by the possible reversibility of airway hyperresponsiveness – which could affect whether a swimmer is positive or negative for EIB at the time of measurement. [31] Additionally, the lack of significant differences between training loads on levels of chronic airway inflammation and respiratory symptoms relates to Type 2 error. We may have needed more participants, different measurement tools to detect significant changes in these variables, or a greater magnitude of change in training load imposed for more than nine weeks. This group of swimmers is from one club who train at multiple pools around the city, so it is not known whether swimmers at other clubs have similar training environments or training loads, especially if no method is employed to quantify training loads. However, we do know some of the common characteristics of competitive swim training – it is a high volume, high ventilation sport with several hours of the day spent in chlorinated swimming pools.

Another limitation is that changes in external training load were based on a linear periodization approach, meaning that our testing only shows the effect of increasing training load from Low, to Moderate, to High over nine weeks duration – while we might have reached a

different conclusion had we tested a different order of training load with more testing sessions over a longer period of training. Additionally, there was a 60% increase in load from Low to Moderate, and a 52% increase from Moderate to High. Thus, we do not know whether a different magnitude of change between training blocks would have produced different results; it may be that the magnitude of change from Moderate to High was not great enough to detect a significant change in lung health.

The weekly changes in training load could have also affected the results. For instance, a 48% increase in load from Week 5 (61 ± 6.7 AU), to Week 6 (90 ± 6.9 AU) within the Moderate block may have negatively influenced the swimmers. Upon reflection, although we did not plan for such a large increase from Week 5 to 6, perhaps it (and possibly the timing of laboratory testing) contributed to the lowered resting FEV_1 we observed. Thus, more research is needed to understand how microcycle variation might affect changes in lung health.

A potential explanation for the lack of changes after the High block of training is that swimmers adapt to their worsened airway status because of improved tolerance to higher training loads, where they respond to the EVH test with less AHR. This might also be supplemented by increased strength in respiratory muscles. Swimming involves water immersion and horizontal body positioning, which increases hydrostatic pressure around the chest and pushes the chest wall inward when the inspiratory muscles are relaxed. [120] Swimmers also tend to have lower breath frequency combined with higher tidal volumes that encroach upon the end-inspiratory reserve volume. Thus, completing a relatively greater amount of high intensity training would involve rapidly inspiring air when the face leaves the water and high velocity inspiratory muscle shortening, which results in significant demand placed upon the inspiratory muscles. In other words, the muscles they use to breathe may become stronger such that they have an improved ability to inspire air on the inspiratory phase of the FVC maneuver, thus moving more air out during the forced expiration. We did not measure respiratory muscle strength and thus cannot make this type of conclusion, but we can consider the possibility that it could mask negative changes to the airways.

Exposure to chlorine by-products during pool training with high ventilation was considered an important confounding variable in this study. As per the literature review, chlorine and its by-products likely influence the development of AHR, inflammation and respiratory symptoms in swimmers. However, measuring chlorine exposure would require a separate investigation to determine exact exposure while exercising in a pool (especially if training occurs in multiple pools around the city), and whether or not the intensity at which the exercise was performed and the overall volume significantly influences exposure. Although

previous research has measured chlorine above the surfaces of swimming pools, quantifying the exposure in relation to volume and intensity could elucidate how the exposure to chlorine differs in competitive swimmers compared to recreational or casual swimming pool users. Furthermore, comparing newer pool sanitation methods (such as salt water chlorination or bromine treated pools) to older methods and determining frequency of respiratory symptoms could be a possible future direction from the current study.

Lastly, we did not include a control group, however in our repeated measures design the participants acted as their own controls to determine changes in lung health. There were many additional potential extraneous variables that were not controlled for, such as mental or social stressors, or sleep disturbances that could influence how an athlete responds to and recovers from training, as well as how they recover from illness. Certain months of the year could influence illness (e.g. September – going back to school and having increased exposure to bacteria and viruses), however swimmers are more susceptible to developing respiratory symptoms at any time of year. With the Alberta Swim Health and Fatigue questionnaire, we gained some additional insight into these potential stressors, although they were not used in the statistical analysis. Gender, years of training, and changes in health unrelated to respiratory problems (e.g. musculoskeletal injury) over the course of the study were other potential confounding variables in this investigation that could have influenced the response to training and progression of fatigue and illness.

Application to coaching practice and further insights

An important aspect to decision making in sport is an understanding of the training factors that are likely to influence the health and performance of athletes. It is generally accepted that a combination of factors contribute to the development of overtraining syndrome, such as sudden increases in training volume and/or intensity, lack of periodization or programmed recovery in training schedule, and highly monotonous training. [49] Considering the results of the current study, it is quite likely that highly monotonous training had more dramatic effects in the first 6 weeks of training (September 12-October 23). Although it would be wise to impose low total external training loads in the beginning of a season assuming a short period of detraining over the summer months, it also appears important to maintain a varied daily training stimulus to minimize training monotony and strain, as well as fatigue from the adjustment to new training schedules on top of beginning a new academic year. This could signify that coaching staff should reflect on when, how, and why to implement two-a-day training, for instance, if the idea is to cycle between "hard" and "easy" days to reduce external monotony. [28]

Assuming high monotony is to be avoided in the future, there are some specific programming considerations that coaches may find helpful. For the swimmers in our study, and like many other swimming programs with high school-aged or varsity athletes, two-a-day training can lead to undue fatigue due to reduced sleep from waking up for early morning practice, on top of a rigorous school schedule followed by an evening workout. Given the other responsibilities many student athletes must attend to Monday to Friday, a possible solution to the problem would be to schedule two-a-day training on weekends when the athletes would have more free time available for training and adequate sleep and recovery, then plan for at least one day mid-week (such as Wednesday) with absolutely no training. This modification may not be possible with the current structure of many swimming programs, but over time could be a variable that individual coaches may want to consider for their youth athletes.

Reflecting upon the meaning of our results, it is important for swimming coaches to consider not only the training variables can impact overall health, but also how changes in lung health (that may result from higher training loads) could affect training and performance. For example: in discussion with the head coach, an aerobic power (VO_2max) set in swimming practice involving 10 x 100m on 2:00min aiming for best average with 45-60 seconds rest *might* provoke airway obstruction similar to what was revealed in the EVH test. We could hypothesize that a stimulus of a 10 x 100m aerobic power set triggers lower airway obstruction in the more hyperresponsive athletes, and affect their ability to maximally expire air from the lungs in

following sets that involve maximal exertion. However, in a recent study [121] comparing AHR in varsity swimmers in practice, swim field challenge, and race-pace conditions, it was shown intense swimming exercise may not induce acute AHR. Further, it was suggested that swimming at race-pace intensity with maximal ventilation is less likely to provoke AHR than a lab test such as EVH where humidity is low (inhaling dry air as opposed to humid pool environment air). It is possible, though, that there is some accumulated effect of heavy ventilation in chlorinated swimming pools over time that influences airway obstruction in some – but maybe not all – swimmers.

We were able to demonstrate in the current study that a change in training load does influence airway obstruction, but what is not as well understood is the fluctuating displays of AHR and inconsistent EIB results (i.e. one swimmer was positive on the first test, negative on the second test, positive on the third test). Why is it that some swimmers who are EIB positive can be negative on the next test three weeks later? Of course we can consider the possibility of measurement error given the small sample size, but what other factors are going to influence day-of performance of the EVH test? Is the EVH test even an appropriate evaluation of EIB in swimmers given the environmental differences of air in indoor swimming pools (warm and humid) versus air used for the EVH test (room temperature and dry)? Future studies might consider designing and evaluating a controlled hyperventilation challenge that mimics the unique environmental conditions of indoor swimming.

Changing from EIB positive to EIB negative over a relatively short time period could also have implications for therapeutic use exemption (TUE). Considering an approved TUE for an inhaled beta-2 agonist is valid for 4 years, [122] testing athletes more frequently – such as once or twice a year – to determine the need for an IBA may be more appropriate. We still do not fully understand what kind of effects variable AHR could have on training and performance, however in the future coaches could benefit from taking the AHR status of their athletes into account, and consider what type of recovery they plan within training sets and between training days in order to optimize performance. Ideally, lung health assessment would be integrated into a component of health and fitness testing, however communicating the results in a timely fashion (that is also comprehensible for coaches) could be challenging in a high performance sport setting.

If we examine airway obstruction further, we found that post-EVH FVC and FEV_1 were on average 200-300ml (~5%) lower after the Moderate training block as compared to the Low training block in our study. Knowing a competitive swimmer aged 14-17 would typically have a maximum ventilation rate (VE) of at least 80 L/min and an absolute maximum VO_2 of around 3

L/min, [123] and assuming the same 5% decrement was applied to overall ventilation, it would result in approximately a 4 L drop in maximum VE and 150 mL drop in VO_2. Although a 5% decrease might seem meaningless for non-athletes, in elite athletes small improvements or decrements in performance make a difference between making it to the podium or not. [56] Consider the effect of tapering interventions, which have been shown to improve performance by 0.5-1% in swimming [56,124] and that the minimum performance enhancement that has a meaningful effect on an athlete's chance of reaching the podium is about one third of the expected variation of performance in competition. To put into context: at the 2000 Sydney Olympics, taper-induced improvements in performance in swimming events (2.2%) were similar to the differences between the gold medalist and fourth place (1.62%), and between third and eighth place (2.02%), with a total of 91 of the 99 analyzed performances being faster after the final three weeks of training, and only 8 were slower. [55] Therefore, the magnitude of change in the ability to ventilate could potentially translate to relatively large decrements in performance or missing the chance of a medal.

Finally, given our study measured several variables relating to a construct variable we termed "lung health", more research is needed to establish an overall score which may be attached to lung health, so that coaches and scientists can gauge the lung health of swimmers. The development of such a score would involve determining which sub-constructs are important, i.e. is there something else besides airway inflammation, airway hyperresponsiveness, EIB, and respiratory symptoms? Then, deciding upon the relative weight or contribution of each variable to the score, and which measurement tool(s) will be used to evaluate each variable. Each categorical variable would then result in a sub-score that contributes to a total "swim lung health score". For example, a high lung health score could result if the swimmer obtained a "high" score for inflammation (relative to an expected normal value for the test used); was positive for EIB with a decrease in FEV_1 >10%, and presented with multiple respiratory symptoms. Further investigation is needed to determine swimming-specific thresholds or clinical significance for each variable to determine when swimmers may be at risk of developing lung health issues.

Conclusion

Although there are recognized benefits to health, lung health problems are prevalent in competitive swimmers, which are likely related to the training environment (chlorinated swimming pools) and the amount of training they do. Determining if swimmers have worsened lung health as a result of training, and whether it impacts long-term health outcomes are important questions in sport science research. Ideally, the benefits of participation in swimming should outweigh the risk of undesirable lung health outcomes. Based on our results, there are simple modifications to training plans that may optimize the health and performance of swimmers. Quantifying weekly training loads, implementing a means of monitoring of respiratory symptoms, and possibly additional lung function assessments or a standard EIB lab test as a part of athlete health and fitness testing are just a few examples that could benefit swimmers. The inclusion of a weekly questionnaire tracking respiratory symptoms and regular lung health assessments, such as those used in our study, could lead to greater athlete awareness and seeking medical treatment - in fact, two of the swimmers in our study sought medical treatment after study participation, based on the advice of the principal investigators. Of course there is the issue of resources – athlete monitoring comes with a cost. Not all swimming organizations may have the budget for recruiting a sport science team to assess and analyze all of the data that would be part of a lung health testing battery, however with continued research in this area we hope to improve levels of evidence such that a lung health monitoring system becomes a more standardized component of competitive swimming.

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Appendix A

Research Question & Hypotheses

Broad research question: What effect does training load have on the lung health of competitive swimmers?

Table 5. Hypotheses for determining the effect of training load on the lung health of competitive swimmers.

Hypotheses	*Description*	*Dependent Variables*	*Independent Variables*
Null	There will be no significant changes in *lung health* and internal training stress (DV) with different *external training loads* (IV)	*1)* Airway hyperresponsiveness (no change) *2)* Lung Inflammation (no change) *3)* Respiratory Symptoms (no change) *4)* Internal Training Stress (no change)	External load (Low, Moderate, and High)
Alternative 1	*Lung health* and *internal training stress* (DV) will be worse when assessed post-*high external training loads* (IV). Post-*moderate training,* lung health and internal training stress will be worse than post-*low training* but to a lesser extent than high training. Following a *low training load* swimmers will have better lung health and lower internal stress than following *moderate* or *high*.	*1)* Airway hyperresponsiveness (increase) *2)* Lung Inflammation (increase) *3)* Respiratory Symptoms (increase) *4)* Internal Training Stress (increase)	External load (Low, Moderate, and High)

Appendix B

Equipment

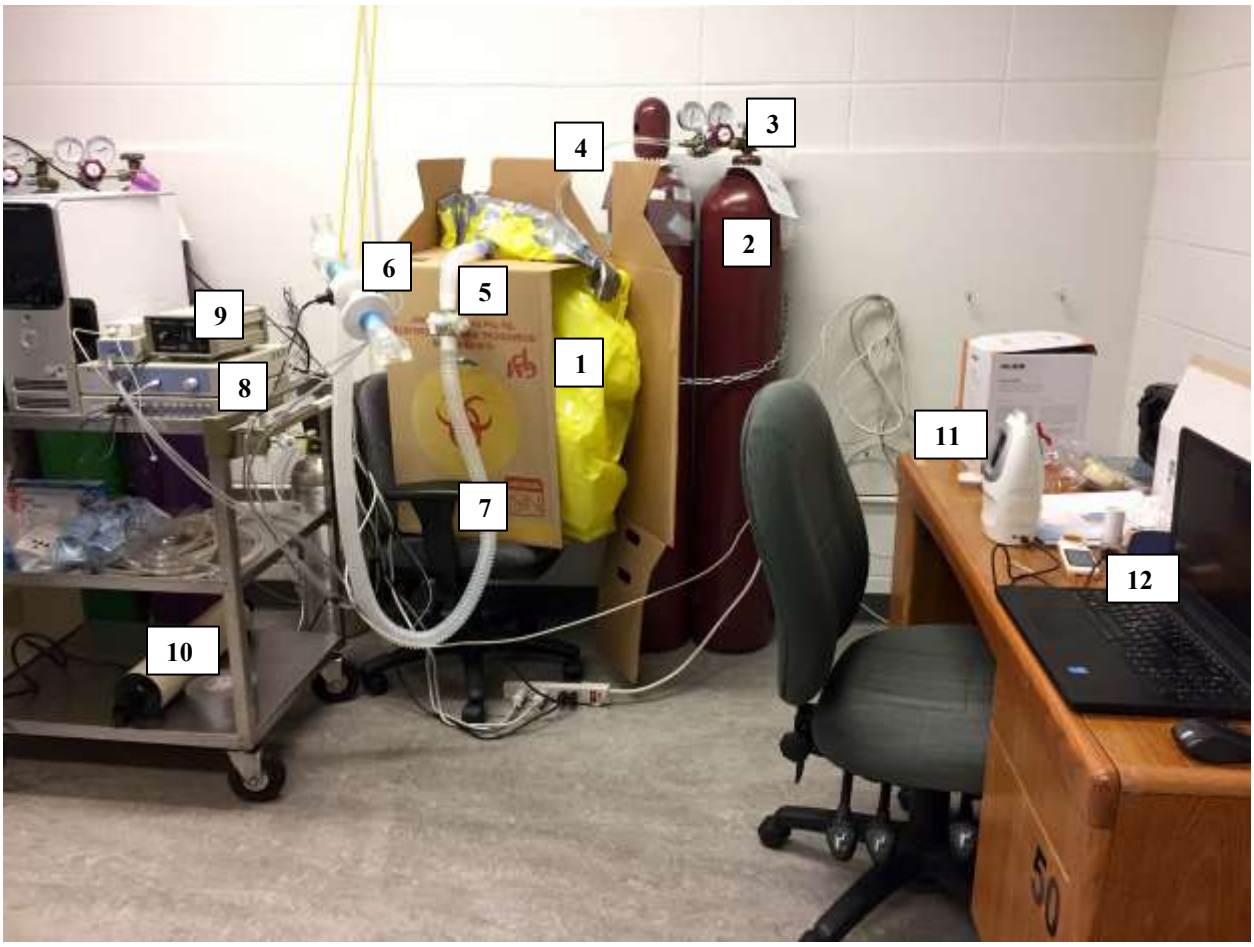


Figure 8. Equipment setup for FeNO, spirometry, and EVH test. The chair pictured above was not used in the test but rather a stationary (non-rolling) chair. 1: air reservoir with minimum 120L capacity; 2: compressed gas mixture (5% CO_2, 21% O_2, balanced N_2); 3: regulator; 4: high pressure tubing; 5: valve to allow gas to simultaneously enter and leave air reservoir; 6: pneumotachometer with flow head, clean tubing, filter and mouthpiece; 7: air hoses (1.25 inch diameter); 8: Powerlab and gas analyzer; 9: pneumotachometer heater control; 10: 3L calibration syringe; 11: NIOX MINO® device; 12: Spirodoc Touchscreen Spirometer with disposable mouthpiece.

Appendix C

Pre-Test Requirements For Lung Health Testing

1. **DO NOT** exercise on the day of the test. Please refrain from engaging in any further exercise after your training on Saturday morning. This is **very** important because it could affect your test on Sunday.
2. **DO NOT** consume caffeine-containing beverages or foods, such as coffee, tea, cola, and chocolate on the day of the test.
3. **DO NOT** smoke or consume alcohol on the day of the test.
4. **DO NOT** consume very heavy meals 2-3 hours prior to the test, however **DO** make sure you eat regular meals that will not upset your stomach and that you drink water throughout the day.
5. **DO** bring comfortable exercise clothes to wear, such as what you would wear for dryland. Make sure the clothes are not extremely tight or restricting.
6. You must be free of any serious respiratory tract infection on the day of as well as 6 weeks prior to the test (e.g. bronchitis).
7. If you are sick or not feeling well on testing day or the day before, please contact Rachelle as soon as possible.
8. If you use any medication for asthma, asthma-related symptoms, or for any other purpose, please inform Rachelle what you take, and bring the medication with you to your test.
    - If you have medication for asthma or asthma-related symptoms, please follow the guidelines in the chart below.

Table 2
Medications and their required withholding times before challenge by exercise, EVH, or mannitol to reduce the possibility of a false-negative test result and optimize the possibility of finding a positive test result

Time to Withhold	Medication
8 h	Short-acting β_2 agonists (eg, *albuterol, salbutamol, levalbuterol terbutaline*) Inhaled nonsteroidal antiinflammatory agents Cromones (eg, *sodium cromoglycate, nedocromil sodium*)
12 h	Inhaled corticosteroids (eg, *beclomethasone dipropionate, budesonide, fluticasone propionate, ciclesonide*) Ipratropium bromide
24 h	Inhaled corticosteroids plus long-acting β_2 agonists (eg, *fluticasone and salmeterol, budesonide and formoterol*) Long-acting β_2 agonists (eg, *salmeterol, eformoterol*) Theophylline
72 h	Tiotropium bromide Antihistamines (eg, *cetirizine, fexofenadine, and loratadine*)
4 d	Leukotriene-receptor antagonists (eg, *montelukast sodium*) Nonsteroidal antiinflammatory (eg, *indomethacin, ibuprofen*)

Anderson & Kippelen [71]

Appendix D

External Training Load Determination

As recording only the distance swum in a training session is not reflective of the overall training load, Mujika et al.[21] established a stress index scale according to theoretical blood lactate accumulation levels during different training sets in swimming, as follows:

> "Values 2, 4, 6, and 10 mmol/L corresponds to Intensity Levels 1, 2, 3, and 4, respectively. The corresponding value for Intensity 5 was estimated as 16, since sprint training is a very hard mode of training. These values were then divided by 2 in order to make them more manageable. Thus the resulting estimated stress index scale was 1, 2, 3, 5, 8, to be multiplied by the distance swum at each intensity level."

Coaches and swimmers have also previously estimated 1 hour of dryland training as equivalent to 1 km swum at Intensity 1, 0.5 km at Intensity 4, and 0.5 km at Intensity 5. Therefore, distance swum at particular intensities was estimated based on the swimming coach's prescription in each training session.

Calculations are shown below:

Training load calculations are expressed in arbitrary units (AU)

Swim training load

Daily Swim training load = (km intensity 1 * 1) + (km intensity 2 * 2) + (km intensity 3 * 3) + (km intensity 4 * 4) + (km intensity 5 * 8)

Dryland training load

Daily dryland training load = hrs x [1 + (0.5*4) + (0.5*8)] = hrs * 7

Daily total external training load = Swim training load + Dryland training load

Weekly external training load

Weekly external training load = Sum of daily external training loads

External Training Monotony (weekly)

Training Monotony = Mean of Daily External Training Loads / Standard Deviation

External Training Strain (weekly)

Training Strain = Weekly External Training Load * Training Monotony

Appendix E

Internal training stress determination

Table 6. Modified rating of perceived exertion (RPE) scale used for athletes to classify their perceived intensity of each training session.

Rating	Descriptor
0	Rest
1	Very, Very Easy
2	Easy
3	Moderate
4	Somewhat Hard
5	Hard
6	
7	Very Hard
8	
9	
10	Maximal

Weekly Internal Training Load

Daily Internal Training Load = session RPE x duration (minutes)

e.g. Daily Internal Training Load = 7 * 90 minutes = 630 arbitrary units (AU)

If two or more sessions were performed:

Daily Internal Training Load = Session 1 (Session RPE x duration) + Session 2 (Session RPE x duration) + Session 3 (Session RPE x duration) +….

Total Internal Training Load = sum of all Daily Training Loads for one week

Mean Daily Internal Training Load = (sum of all Daily Training Loads for one week) / 7

Internal Training Monotony (weekly)

Training Monotony = Mean of Daily Internal Training Loads / Standard Deviation

Internal Training Strain (weekly)

Training Strain = Weekly Internal Training Load * Training Monotony

Appendix F

Individual Data

Table 7. Individual pre-EVH spirometry measurements taken before the EVH challenge on each testing day and main EVH test outcomes. Predicted values for FVC and FEV_1 are shown in columns 7 & 8, which were calculated based on height, weight, age, and gender. [125] Maximum change in FEV_1 across all sampling points post EVH is shown in column 9, and the corresponding result for exercise-induced bronchoconstriction is indicated in the rightmost column.

	Low									
	FVC (L)	*FEV1 (L)*	*FEF 25-75% (L/s)*	*FEF 50% (L/s)*	*PEF (L/s)*	*FEV1/FVC (%)*	*Age Pred. FVC (%)*	*Age Pred. FEV1 (%)*	*Max FEV1 diff. (%)*	*EIB (Pos/Neg)*
Participant	6.13	4.90	4.64	5.08	7.15	79.93	132.68	120.39	-18.98	Pos
Participant	4.85	4.41	5.95	6.44	8.85	90.93	108.74	112.50	-16.55	Pos
Participant	6.15	4.48	3.48	3.89	9.58	72.85	107.14	91.80	-6.92	Neg
Participant	5.52	4.33	3.83	4.14	8.13	78.44	136.21	121.29	-21.48	Pos
Participant	6.19	5.23	5.48	6.22	10.42	84.49	117.23	115.20	-1.91	Neg
Participant	4.85	3.89	3.53	3.79	7.18	80.21	115.48	105.42	-4.11	Neg
Participant	5.97	4.74	4.23	4.68	9.65	79.40	96.29	90.46	-16.03	Pos
Participant	7.06	5.93	6.36	7.63	10.29	83.99	128.83	126.17	-28.33	Pos
Mean	*5.84*	*4.74*	*4.69*	*5.23*	*8.91*	*81.28*	*117.83*	*110.40*	*-14.29*	
SD	*0.74*	*0.63*	*1.12*	*1.39*	*1.30*	*5.30*	*13.87*	*13.43*	*9.18*	
	Moderate									
	FVC (L)	*FEV1 (L)*	*FEF 25-75% (L/s)*	*FEF 50% (L/s)*	*PEF (L/s)*	*FEV1/FVC (%)*	*Age Pred. FVC (%)*	*Age Pred. FEV1 (%)*	*Max FEV1 diff. (%)*	*EIB (Pos/Neg)*
Participant	5.54	4.37	4.22	4.87	6.82	78.88	119.91	107.37	-11.67	Pos
Participant	4.78	4.21	4.92	5.45	7.63	88.08	129.60	107.40	-16.55	Pos
Participant	6.33	4.29	3.06	3.27	8.64	67.77	110.28	87.91	-7.93	Neg
Participant	4.57	3.78	3.53	3.59	6.84	82.71	112.56	105.88	-10.32	Neg
Participant	6.13	5.26	5.75	6.47	10.03	85.81	116.10	115.86	-19.96	Pos
Participant	4.85	3.84	3.46	3.82	7.20	79.18	115.48	104.07	-11.98	Pos
Participant	6.02	4.65	4.01	4.57	9.61	77.24	97.10	88.74	-15.48	Pos
Participant	6.98	5.79	5.78	5.66	10.66	82.95	127.37	123.19	-17.62	Pos
Mean	*5.65*	*4.52*	*4.34*	*4.71*	*8.43*	*80.33*	*116.05*	*105.05*	*-13.94*	
SD	*0.86*	*0.69*	*1.04*	*1.12*	*1.52*	*6.25*	*10.22*	*12.06*	*4.09*	
	High									
	FVC (L)	*FEV1 (L)*	*FEF 25-75% (L/s)*	*FEF 50% (L/s)*	*PEF (L/s)*	*FEV1/FVC (%)*	*Age Pred. FVC (%)*	*Age Pred. FEV1 (%)*	*Max FEV1 diff. (%)*	*EIB (Pos/Neg)*
Participant	5.24	4.24	4.01	4.46	6.77	80.92	113.42	104.18	2.12	Neg
Participant	4.95	4.61	6.42	6.84	8.60	93.13	110.99	117.60	-16.55	Pos
Participant	6.17	4.55	3.69	3.96	9.02	73.74	107.49	93.24	-6.59	Neg
Participant	4.55	3.77	3.59	3.80	7.28	82.86	112.07	105.60	-22.55	Pos
Participant	6.09	5.19	5.52	6.13	10.8	85.22	115.34	114.32	-8.29	Neg
Participant	4.37	3.71	3.68	3.74	6.32	84.90	104.05	100.54	-15.09	Pos
Participant	5.92	4.57	3.90	4.27	8.85	77.20	95.48	87.21	-12.25	Pos
Participant	7.15	5.55	4.93	5.97	9.70	77.62	130.47	118.09	-16.76	Pos
Mean	*5.56*	*4.52*	*4.47*	*4.90*	*8.42*	*81.95*	*111.16*	*105.10*	*-12.00*	
SD	*0.94*	*0.63*	*1.05*	*1.22*	*1.53*	*6.04*	*10.04*	*11.29*	*7.62*	

Table 8. Raw individual values for spirometry measures pre-EVH and immediately, 5 minutes, 10 minutes, 15 minutes, and 20 minutes post-EVH test for Test 1.

	FVC						FEV1						FEF25-75%						FEF50%						PEF					
Part.	Pre	Im	5	10	15	20	Pre	Im	5	10	15	20	Pre	Im	5	10	15	20	Pre	Im	5	10	15	20	Pre	Im	5	10	15	20
1	6.13	6.13	4.96	5.09	5.12	4.98	4.90	4.95	3.97	4.14	4.14	4.25	4.64	4.68	3.76	2.82	2.98	4.20	5.08	4.12	4.11	3.52	3.44	4.35	7.15	7.22	5.79	6.62	6.64	6.47
2	4.85	4.93	4.91	4.72	4.35	4.48	4.41	4.25	4.04	3.81	3.71	3.68	5.95	4.68	4.03	3.56	3.79	3.76	6.44	5.45	5.45	4.44	5.08	4.53	8.85	8.12	8.12	8.07	7.95	7.06
3	6.15	6.12	6.08	6.57	6.57	6.94	4.48	4.36	4.26	4.17	4.17	4.18	3.48	3.32	3.20	2.64	2.64	3.00	3.89	3.64	3.45	3.12	3.12	3.57	9.58	9.20	8.31	7.06	7.06	7.20
4	5.52	4.47	5.42	4.44	4.44	4.34	4.33	3.56	4.26	3.56	3.56	3.40	3.83	3.22	3.78	3.28	3.28	2.96	4.14	3.61	3.94	3.54	3.54	3.21	8.13	6.77	7.48	6.46	6.46	6.56
5	6.19	6.22	6.46	6.34	6.34	6.26	5.23	5.17	5.26	5.13	5.25	5.20	5.48	5.14	5.04	4.86	5.24	5.29	6.22	5.87	5.87	5.70	5.88	5.73	10.42	10.19	10.35	9.61	10.03	9.82
6	4.85	5.10	4.95	5.06	5.04	4.95	3.89	3.80	3.73	3.89	3.85	3.73	3.53	3.14	3.15	3.41	3.30	3.12	3.79	3.30	3.54	3.68	3.59	3.43	7.18	6.67	6.60	6.59	6.49	6.41
7	5.97	5.99	5.75	5.47	5.35	5.45	4.74	4.40	4.22	4.14	3.98	4.21	4.23	3.43	3.23	3.42	3.09	3.60	4.68	3.71	3.83	3.94	3.55	3.87	9.65	8.76	8.42	8.19	8.78	8.19
8	7.06	6.62	5.80	5.77	6.03	6.55	5.93	5.33	4.34	4.25	4.55	5.08	6.36	4.99	3.58	3.34	3.86	4.54	7.63	5.07	3.98	3.75	4.53	4.95	10.29	9.65	7.60	7.83	7.78	8.78

Table 9. Percent changes from pre-EVH for spirometry measures on Test 1.

	FVC						FEV1						FEF25-75%						FEF50%						PEF					
Part.	Im	5	10	15	20	Max	Im	5	10	15	20	Max	Im	5	10	15	20	Max	Im	5	10	15	20	Max	Im	5	10	15	20	Max
1	0.0	-19.1	-17.0	-16.5	-18.8	-18.8	1.0	-19.0	-15.5	-15.5	-13.3	-19.0	0.9	-19.0	-39.2	-35.8	-9.5	-39.2	-18.9	-30.7	-30.7	-32.3	-14.4	-32.3	1.0	-19.0	-7.4	-7.1	-9.5	-9.5
2	1.7	1.2	-2.7	-10.3	-7.6	-10.3	-3.6	-8.4	-13.6	-15.9	-16.6	-16.6	-21.3	-32.3	-40.2	-36.3	-36.8	-40.2	-15.4	-15.4	-31.1	-21.1	-29.7	-31.1	-8.3	-8.3	-8.8	-10.2	-20.2	-20.2
3	-0.5	-1.1	6.8	6.8	12.9	-1.1	-2.7	-4.9	-6.9	-6.9	-6.7	-6.9	-4.6	-8.1	-24.1	-24.1	-13.8	-24.1	-6.4	-11.3	-19.8	-19.8	-8.2	-19.8	-4.0	-13.3	-26.3	-26.3	-24.8	-26.3
4	-19.0	-1.8	-19.6	-19.6	-21.4	-21.4	-17.8	-1.6	-17.8	-17.8	-21.5	-21.5	-15.9	-1.3	-14.4	-14.4	-22.7	-22.7	-12.8	-4.8	-14.5	-14.5	-22.5	-22.5	-16.7	-8.0	-20.5	-20.5	-19.3	-20.5
5	0.5	4.4	2.4	2.4	1.1	0.5	-1.2	0.6	-1.9	0.4	-0.6	-1.9	-6.2	-8.0	-11.3	-4.4	-3.5	-11.3	-5.6	-5.6	-8.4	-5.5	-7.9	-8.4	-2.2	-0.7	-7.8	-3.7	-5.8	-7.8
6	5.2	2.1	4.3	3.9	2.1	2.1	-2.3	-4.1	0.0	-1.0	-4.1	-4.1	-11.1	-10.8	-3.4	-6.5	-11.6	-11.6	-12.9	-6.6	-2.9	-5.3	-9.5	-12.9	-7.1	-8.1	-8.2	-9.6	-10.7	-10.7
7	0.3	-3.7	-8.4	-10.4	-8.7	-10.4	-7.2	-11.0	-12.7	-16.0	-11.2	-16.0	-18.9	-23.6	-19.2	-27.0	-14.9	-27.0	-20.7	-18.2	-15.8	-24.2	-17.3	-24.2	-9.2	-12.8	-15.1	-9.0	-15.1	-15.1
8	-6.2	-17.9	-18.3	-14.6	-7.2	-18.3	-10.1	-26.8	-28.3	-23.3	-14.3	-28.3	-21.5	-43.7	-47.5	-39.3	-28.6	-47.5	-33.6	-47.8	-50.9	-40.6	-35.1	-50.9	-6.2	-26.1	-23.9	-24.4	-14.7	-26.1

If no decrease occurred, then the lowest percentage was chosen. Im = immediately post; Max = maximum percentage change (decrease) from pre-EVH that occurred.

Table 10. Raw individual values for spirometry measures pre-EVH and immediately, 5 minutes, 10 minutes, 15 minutes, and 20 minutes post-EVH test for Test 2.

	FVC						FEV1						FEF25-75%						FEF50%						PEF					
Part.	Pre	Im	5	10	15	20	Pre	Im	5	10	15	20	Pre	Im	5	10	15	20	Pre	Im	5	10	15	20	Pre	Im	5	10	15	20
1	5.54	4.80	4.89	4.65	4.69	4.61	4.37	3.87	4.11	3.90	3.86	3.88	4.22	3.68	4.09	3.93	3.88	3.99	4.87	4.30	4.84	4.32	4.32	4.58	6.82	6.52	6.59	6.20	6.20	6.26
2	4.78	4.86	4.84	4.65	4.29	4.42	4.21	4.06	3.86	3.64	3.54	3.51	4.92	3.87	3.33	2.94	3.13	3.11	5.45	4.61	4.61	3.76	4.30	3.83	7.63	7.00	7.00	6.96	6.85	6.09
3	6.33	6.06	6.05	6.18	6.22	6.17	4.29	4.11	3.95	4.05	4.33	4.29	3.06	2.97	2.69	2.79	3.18	3.14	3.27	3.18	2.88	2.90	3.39	3.39	8.64	8.76	8.55	9.10	9.25	9.25
4	4.57	4.38	4.40	4.31	4.20	4.32	3.78	3.56	3.65	3.45	3.39	3.54	3.53	3.27	3.46	3.08	3.14	3.25	3.59	3.43	3.79	3.34	3.34	3.38	6.84	6.78	6.90	6.39	6.01	6.74
5	6.13	6.16	6.15	5.07	5.24	6.04	5.26	5.28	5.22	4.21	4.34	5.21	5.75	5.62	5.42	4.27	3.99	5.79	6.47	6.56	6.13	4.96	5.25	6.53	10.03	10.10	10.00	9.44	10.10	9.36
6	4.85	5.01	4.74	4.87	4.91	4.78	3.84	3.88	3.38	3.71	3.67	3.71	3.46	3.40	2.56	3.13	3.05	3.22	3.82	3.60	3.14	3.36	3.33	3.43	7.20	6.93	6.74	6.57	6.66	10.91
7	6.02	5.93	5.74	5.92	5.86	5.69	4.65	4.20	3.93	4.23	4.15	4.08	4.01	3.08	2.77	3.20	3.11	3.08	4.57	3.53	3.10	3.54	3.46	3.49	9.61	8.38	8.35	7.99	7.85	7.87
8	6.98	6.66	6.75	6.28	8.10	7.22	5.79	5.16	4.83	4.77	5.67	5.18	5.78	4.53	3.84	4.13	4.59	4.25	5.66	5.22	4.11	4.61	4.77	4.95	10.66	8.90	7.91	7.26	8.62	7.89

Table 11. Percent changes from pre-EVH for spirometry measures on Test 2.

	FVC						FEV1						FEF25-75%						FEF50%						PEF					
Part.	Im	5	10	15	20	Max	Im	5	10	15	20	Max	Im	5	10	15	20	Max	Im	5	10	15	20	Max	Im	5	10	15	20	Max
1	-13.4	-11.7	-16.1	-15.3	-16.8	-16.8	-11.4	-6.0	-10.8	-11.7	-11.2	-11.7	-12.8	-3.1	-6.9	-8.1	-5.5	-12.8	-11.7	-0.6	-11.3	-11.3	-6.0	-11.7	-4.4	-3.4	-9.1	0.0	-8.2	-9.1
2	1.7	1.2	-2.7	-10.3	-7.6	-10.3	-3.6	-8.4	-13.6	-15.9	-16.6	-16.6	-21.3	-32.3	-40.2	-36.3	-36.8	-40.2	-15.4	-15.4	-31.1	-21.1	-29.7	-31.1	-8.3	-8.3	-8.8	-10.2	-20.2	-20.2
3	-4.3	-4.4	-2.4	-1.7	-2.5	-4.4	-4.2	-7.9	-5.6	0.9	0.0	-7.9	-2.9	-12.1	-8.8	3.9	2.6	-12.1	-2.8	-11.9	-11.3	3.7	3.7	-11.9	1.4	-1.0	5.3	7.1	7.1	-1.0
4	-4.2	-3.7	-5.7	-8.1	-5.5	-8.1	-5.8	-3.4	-8.7	-10.3	-6.4	-10.3	-7.4	-2.0	-12.8	-11.1	-7.9	-12.8	-4.5	5.6	-7.0	-7.0	-5.9	-7.0	-0.9	0.9	-6.6	-12.1	-1.5	-12.1
5	0.5	0.3	-17.3	-14.5	-1.5	-17.3	0.4	-0.8	-20.0	-17.5	-1.0	-20.0	-2.3	-5.7	-25.7	-30.6	0.7	-30.6	1.4	-5.3	-23.3	-18.9	0.9	-23.3	0.7	-0.3	-5.9	0.7	-6.7	-6.7
6	3.3	-2.3	0.4	1.2	-1.4	-2.3	1.0	-12.0	-3.4	-4.4	-3.4	-12.0	-1.7	-26.0	-9.5	-11.9	-6.9	-26.0	-5.8	-17.8	-12.0	-12.8	-10.2	-17.8	-3.8	-6.4	-8.8	-7.5	51.5	-8.8
7	-1.5	-4.7	-1.7	-2.7	-5.5	-5.5	-9.7	-15.5	-9.0	-10.8	-12.3	-15.5	-23.2	-30.9	-20.2	-22.4	-23.2	-30.9	-22.8	-32.2	-22.5	-24.3	-23.6	-32.2	-12.8	-13.1	-16.9	-18.3	-18.1	-18.3
8	-4.6	-3.3	-10.0	16.1	3.4	-10.0	-10.9	-16.6	-17.6	-2.1	-10.5	-17.6	-21.6	-33.6	-28.6	-20.6	-26.5	-33.6	-7.8	-27.4	-18.6	-15.7	-12.5	-27.4	-16.5	-25.8	-31.9	-19.1	-26.0	-31.9

If no decrease occurred, then the lowest percentage was chosen. Im = immediately post; Max = maximum percentage change (decrease) from pre-EVH that occurred.

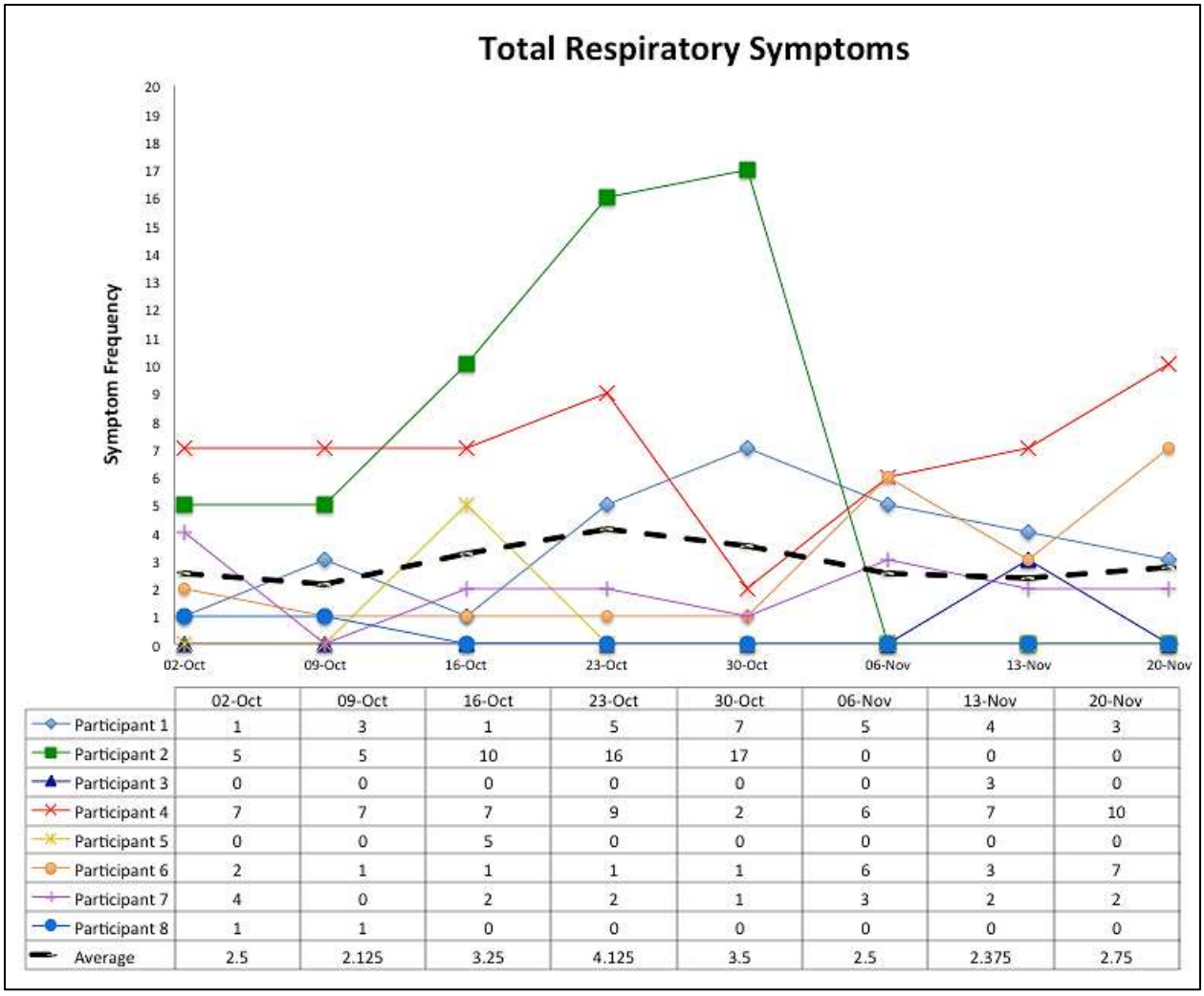
Table 12. Raw individual values for spirometry measures pre-EVH and immediately, 5 minutes, 10 minutes, 15 minutes, and 20 minutes post-EVH test for Test 3.

	FVC						FEV1						FEF25-75%						FEF50%						PEF					
Part.	Pre	Im	5	10	15	20	Pre	Im	5	10	15	20	Pre	Im	5	10	15	20	Pre	Im	5	10	15	20	Pre	Im	5	10	15	20
1	5.24	5.45	5.10	5.10	4.94	5.22	4.24	4.57	4.33	4.35	4.34	4.38	4.01	4.59	4.40	4.29	4.46	4.43	4.46	5.11	4.77	4.88	4.65	4.67	6.77	6.71	6.66	6.53	6.49	6.37
2	4.95	5.03	5.01	4.82	4.44	4.57	4.61	4.44	4.22	3.98	3.88	3.85	6.42	5.05	4.35	3.84	4.09	4.06	6.84	5.79	4.72	4.72	5.40	4.81	8.60	7.89	7.84	7.84	7.73	6.86
3	6.17	6.19	6.38	6.31	6.12	6.39	4.55	4.25	4.26	4.33	4.46	4.57	3.69	3.15	3.04	3.24	3.53	3.48	3.96	3.31	3.18	3.31	3.74	3.75	9.02	8.95	8.44	8.01	8.85	9.20
4	4.55	3.79	4.33	4.45	4.49	4.39	3.77	2.92	3.50	3.66	3.70	3.58	3.59	2.72	3.27	3.61	3.57	3.34	3.80	2.91	3.51	3.95	3.87	3.74	7.28	6.71	6.42	6.09	6.42	6.73
5	6.09	5.61	5.62	5.57	5.75	5.19	5.19	4.84	4.88	4.76	4.83	4.82	5.52	5.15	5.11	5.58	5.34	6.27	6.13	5.83	5.58	6.09	5.86	6.43	10.80	10.25	9.85	9.94	10.22	9.88
6	4.37	4.60	4.48	4.62	4.64	4.62	3.71	3.24	3.20	3.15	3.46	3.51	3.68	2.53	2.48	1.74	2.92	3.06	3.74	2.80	2.84	3.06	3.15	3.14	6.32	5.49	5.58	5.58	5.47	5.74
7	5.92	5.84	5.85	5.85	6.04	5.86	4.57	4.24	4.01	4.30	4.36	4.34	3.90	3.26	2.85	3.43	3.29	3.51	4.27	3.56	2.11	3.69	3.58	4.01	8.85	8.11	7.53	8.23	8.35	7.95
8	7.15	5.99	6.12	6.04	6.10	6.26	5.55	4.67	4.67	4.62	4.81	4.93	4.93	4.09	3.87	3.82	4.26	4.45	5.97	4.69	4.36	4.37	4.88	5.07	9.70	9.73	9.94	9.85	9.91	9.70

Table 13. Percent changes from pre-EVH for spirometry measures on Test 3.

	FVC						FEV1						FEF25-75%						FEF50%						PEF					
Part.	Im	5	10	15	20	Max	Im	5	10	15	20	Max	Im	5	10	15	20	Max	Im	5	10	15	20	Max	Im	5	10	15	20	Max
1	4.0	-2.7	-2.7	-5.7	-0.4	-5.7	7.8	2.1	2.6	2.4	3.3	2.1	14.5	9.7	7.0	11.2	10.5	7.0	14.6	7.0	9.4	4.3	4.7	4.3	-0.9	-1.6	-3.5	-4.1	-5.9	-5.9
2	1.7	1.2	-2.7	-10.3	-7.6	-10.3	-3.6	-8.4	-13.6	-15.9	-16.6	-16.6	-21.3	-32.3	-40.2	-36.3	-36.8	-40.2	-15.4	-15.4	-31.1	-21.1	-29.7	-31.1	-8.2	-8.2	-8.8	-10.2	-20.2	-20.2
3	0.3	3.4	2.3	-0.8	3.6	-0.8	-6.6	-6.4	-4.8	-2.0	0.4	-6.6	-14.6	-17.6	-12.2	-4.3	-5.7	-17.6	-16.4	-19.7	-16.4	-5.6	-5.3	-19.7	-0.8	-6.4	-11.2	-1.9	2.0	-11.2
4	-16.7	-4.8	-2.2	-1.3	-3.5	-16.7	-22.6	-7.2	-2.9	-1.9	-5.0	-22.6	-24.2	-8.9	0.6	-0.6	-7.0	-24.2	-23.4	-7.6	4.0	1.8	-1.6	-23.4	-7.8	-11.8	-16.3	-11.8	-7.6	-16.3
5	-7.9	-7.7	-8.5	-5.6	-14.8	-14.8	-6.7	-6.0	-8.3	-6.9	-7.1	-8.3	-6.7	-7.4	1.1	-3.3	13.6	-7.4	-4.9	-9.0	-0.7	-4.4	4.9	-9.0	-5.1	-8.8	-8.0	-5.4	-8.5	-8.8
6	5.3	2.5	5.7	6.2	5.7	2.5	-12.7	-13.8	-15.1	-6.7	-5.4	-15.1	-31.3	-32.6	-52.7	-20.7	-16.9	-52.7	-25.1	-24.1	-18.2	-15.8	-16.0	-25.1	-13.1	-11.7	-11.7	-13.4	-9.2	-13.4
7	-1.4	-1.2	-1.2	2.0	-1.0	-1.4	-7.2	-12.3	-5.9	-4.6	-5.0	-12.3	-16.4	-26.9	-12.1	-15.6	-10.0	-26.9	-16.6	-50.6	-13.6	-16.2	-6.1	-50.6	-8.4	-14.9	-7.0	-5.7	-10.2	-14.9
8	-16.2	-14.4	-15.5	-14.7	-12.5	-16.2	-15.9	-15.9	-16.8	-13.3	-11.2	-16.8	-17.0	-21.5	-22.5	-13.6	-9.7	-22.5	-21.4	-27.0	-26.8	-18.3	-15.1	-27.0	0.3	2.5	1.5	2.2	0.0	0.0

If no decrease occurred, then the lowest percentage was chosen. Im = immediately post; Max = maximum percentage change (decrease) from pre-EVH that occurred.



	02-Oct	09-Oct	16-Oct	23-Oct	30-Oct	06-Nov	13-Nov	20-Nov
Participant 1	1	3	1	5	7	5	4	3
Participant 2	5	5	10	16	17	0	0	0
Participant 3	0	0	0	0	0	0	3	0
Participant 4	7	7	7	9	2	6	7	10
Participant 5	0	0	5	0	0	0	0	0
Participant 6	2	1	1	1	1	6	3	7
Participant 7	4	0	2	2	1	3	2	2
Participant 8	1	1	0	0	0	0	0	0
Average	2.5	2.125	3.25	4.125	3.5	2.5	2.375	2.75

Figure 9. Individual respiratory symptom frequency.