University of Alberta

Physiological Responses to Breath Holding in Synchronized Swimming

by

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LIST OF ABBREVIATIONS

AI	Artistic impression mark
ANOVA	Analysis of variance
BH	Breath holding
CO	Cardiac output
EPBHOC	Excess post breath holding oxygen consumption
ERV	Expiratory reserve volume
EX	Execution mark
Fb	Frequency of breathing
F_ECO_2	Fraction of expired carbon dioxide
F_EO_2	Fraction of expired oxygen
$FEV_{1\,s}$	Forced expiratory volume in 1 s
FINA	Federation Internationale de Natacion amateur
FRC	Functional residual capacity
FVC	Forced expiratory vital capacity
HR	Heart rate
IC	Inspiratory capacity
IRV	Inspiratory reserve volume
MRF	Mental readiness form for performance
O_2 pulse	Oxygen pulse
OI	Overall impression mark
P_aCO_2	Arterial pressure of carbon dioxide
P_ACO_2	Alveolar pressure of carbon dioxide
P_aO_2	Arterial pressure of oxygen

LIST OF ABBREVIATIONS (cont.)

P_AO_2	Alveolar pressure of oxygen
PO_2	Partial pressure of oxygen
PCO_2	Partial pressure of carbon dioxide
$P_{ET}CO_2$	End tidal partial pressure of carbon dioxide
$P_{ET}O_2$	End tidal partial pressure of oxygen
RER	Respiratory exchange ratio
RV	Residual volume
S_aO_2	Arterial blood saturation
SS	Synchronized swimmers
SV	Stroke volume
TLC	Total lung capacity
TM	Technical merit mark
TPR	Total periferal resistance
TV	Tidal volume
VAS	Visual analog scale
VC	Vital capacity
$\dot{V}CO_2$	Carbon dioxide production per minute
$\dot{V}_E$	Minute ventilation
$\dot{V}O_2$	Oxygen consumption per minute
$\dot{V}O_2$ max	Maximum oxygen consumption per minute
$\dot{V}O_2$ peak	Peak oxygen consumption per minute
VT	Ventilatory threshold
WI	Water immersion

Chapter One: Introduction

Rationale

During the last decade, the sport of synchronized swimming has undergone many changes including a decrease in routine times, an increase in movement speed in routines, the introduction of acrobatic movements and the replacement of figures by technical routines at the senior level. These changes also affected solo routines and have likely shifted the demands of the sport including the dynamics of breath holding (BH) within a routine. Breath holding is the main focus of this series of studies. Synchronized swimming is one of the only sports where an athlete needs to perform high intensity work while BH for significant periods of time. This leads to a lack of oxygen (hypoxia) and an increase in carbon dioxide levels (hypercapnia) among other physiological responses (Davies, Donaldson & Joels, 1995), creating potentially unsafe situations in both training and competition. The physiological effects of BH in synchronized swimmers need to be understood in order to provide safe guidelines for training and competition. Understanding BH physiology will also lead to improvements in training and performance.

Synchronized swimming competitions are divided into two parts, figures and routines. Figures, now only performed by junior athletes, are standardized exercises of varied difficulty. In competition, each athlete performs a total of four figures one at a time, in front of a panel of judges. Routines are performed as solos, duets, teams, or in a combined program (a new event where solos, duets and teams are combined within a 5 min period) and are a combination of figures, strokes, and transitions choreographed to music. There are two different kinds of

routines: technical and free. Technical routines range in length from 2 min for solos to 2 min and 50 s for teams. They consist of compulsory figures and other core elements that must be choreographed into the routine. Free routines have no specific required elements and range from 3 min for solos to 5 min for the combined program at the senior level. Rule changes introduced in the early 1990s eliminated the figure event in international competitions at the senior level and replaced it with the technical routine, thus diminishing the importance of the figure event. Figures are still worth 50% of the total score in junior events.

To date, little research has examined breath holding in synchronized swimming. Those who have studied BH in synchronized swimming have restricted their studies to BH on land and the resulting alveolar partial pressures (Bjustrom & Schoene, 1987); the study of alveolar partial pressures after one single BH period in the water while performing figures (Gemma & Wells, 1987; Figura, Cama & Guidetti, 1993) or while performing part of a routine (Davies et al., 1995). Other research has examined blood lactate (bla) production during figures (Figura et al., 1993) or during a routine (Yamamura, Matsui, & Kitagawa, 2000; Figura et al.) and heart rate (HR) response during figures (Gemma & Wells; Figura et al.) or during routines (Figura et al.). Potential reasons for the lack of research in synchronized swimming include the uniqueness of the sport and the difficult mix of electronic monitoring equipment and the aquatic environment, both of which present challenges to researchers. There is a limited audience interested in the findings from synchronized swimming studies as the results will typically not be generalizable to other sports. In addition to electrical safety

precautions associated with monitoring equipment, immersion facilities, waterproof equipment and water safety protocols are all required. This makes research difficult and expensive.

The purpose of this thesis was to address some of the key gaps in the understanding of BH as it relates to synchronized swimming since there is limited published research in the subject area. Because synchronized swimming is a sport that relies on subjective marks, trends and attitudes within the sport are more important to identify than in other sports. Therefore it was important to identify how the length of breath holding periods influence a judge's mark for a routine, which in part is a reflection of the perceived difficulty of the routine. This was accomplished in the first study using a time-motion analysis. This study assessed the frequency and duration of BH in 11 solo routines presented at the Canadian championships, the BH pattern throughout these solo routines, including partial and total underwater times, and the impact of BH times on the marks received for each routine. After determining the amount of time spent underwater in a synchronized swimming routine, it was important to examine the cardiopulmonary responses to exercise in and out of the water, and the impact of training in the water for long periods of time over several years. This led to the second and third studies where some important physiological characteristics of synchronized swimming athletes were assessed.

Study two examined peak oxygen consumption for synchronized swimmers and the influence of water immersion on peak oxygen consumption. Heart rate and frequency of breathing were measured and oxygen pulse was

calculated for synchronized swimmers during incremental exercise in and out of the water. These exercise responses in the water were compared to on land results. Results showed that there were no differences in peak oxygen consumption in and out of the water but that there were significant decreases in HR in the wet condition and significant increases in the frequency of breathing and oxygen pulse in the wet condition as a result of the hydrostatic pressure.

The third study investigated whether adaptations in lung volumes and capacities in experienced synchronized swimmers had occurred through comparisons with an established reference population of non-synchronized swimmers. This study also examined the change in lung volumes and capacities in synchronized swimmers on land compared to in the water. Results showed that most of the lung volumes decreased from land to water as a result of the hydrostatic pressure. The results demonstrated that some pulmonary adaptation has occurred. The results corroborate the theory that training in the water for years can increase lung capacities.

Knowing that adaptation has occurred and a significant amount of breath holding is required for the sport, it was important to investigate the BH event itself in a manner relevant to synchronized swimming. Further, it was important to compare the cardiopulmonary adaptations in SS to other athletes who did not train or perform in the water. This was accomplished in study four which investigated breath holding with immersion at rest and study five which investigated breath holding with water immersion and exercise.

The fourth study addressed some of the key gaps in the literature with

respect to HR and arterial oxygen saturation during and after BH while immersed in water at rest. The additional oxygen required after BH to recover from BH, and the speed of recovery to pre BH values was examined for both synchronized swimmers and land based female athletes. The study also identified factors that lead to the cessation of BH at rest for BH trained subjects versus BH untrained subjects. Results showed HR decreased as BH progressed, oxygen saturation decreased as BH times increased and recovery from BH was achieved within 25 s after BH ceased for both SS and controls.

Finally, the fifth study examined BH and exercise with water immersion for a sequence of breath holding periods. The study evaluated HR changes during and after BH and compared oxygen consumption and ventilatory responses following BH with pre BH values. It also measured the oxygen conservation effect (Andersson, Liner, Fredsted, & Schagatay, 2004) and the recovery from BH as exercise progressed. One of the practical applications of the fifth study was to try to determine whether long BH periods at the end of an exercise period versus long BH periods at the beginning of exercise have an impact on HR and $\dot{V}O_2$ during BH and whether one is more physiologically advantageous for the choreography of a synchronized swimming routine. Results showed that positioning larger BH periods at the start of exercise was more demanding for the SS subjects based on the significant increase in oxygen consumption. Recovery after BH was achieved within 25 s after BH ceased. These results also showed a trend toward oxygen conservation during BH but were not conclusive.

The collective results of these five studies provide important information

to better understand BH in synchronized swimming and also provide some insight for coaches on how to most effectively plan routines and BH training activities.

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Chapter Two: A Time-motion Analysis of Elite Solo Synchronized Swimming: Relationship to Breath Holding and Technical Merit.[1]

Introduction

The length of time a synchronized swimmer remains underwater during performance is considered by many to be remarkable. Recently, health and safety concerns related to the negative effects of breath holding (BH) in swimmers have been suggested (Davies, Donaldson & Udoh, 1993; Davies, Donaldson & Joels, 1995; FINA, 1998). No records of fatalities have been reported in the literature but anecdotal knowledge of near drowning has been reported among competitors. Some criticism has been made about the length of time synchronized swimmers are underwater performing exercise while BH during routine competition events and there has been speculation as to whether judging is influenced by the time spent underwater during a routine (Davies et al., 1993; Davies et al., 1995). Davies et al. (1995) reported mean (± SD) BH times of 43.3 ± 10.2 s (range 33 - 66 s) in the initial sequence of nine solos from elite level swimmers studied during practice time. However this latter research did not present BH in the context of a solo swim in a competition and there has been little research investigating the relationship of BH portions of a competitive solo synchronized swimming routine and judging (Davies et al., 1995).

The primary purpose of this investigation was to determine the length of time spent underwater, the longest BH period and the location of the BH period

[1] This paper has been submitted for publication and is under review by the Journal of Sports Sciences (UK).

within a solo routine at a national championship. Since Davies et al. (1995) suggested there may be a positive relationship between technical merit scores (TM) received and the time spent underwater, this relationship was also investigated. The distance covered while performing was considered since the extra energy used to move the body through the water while BH requires more energy, consequently influencing the apnoeic work.

Methods

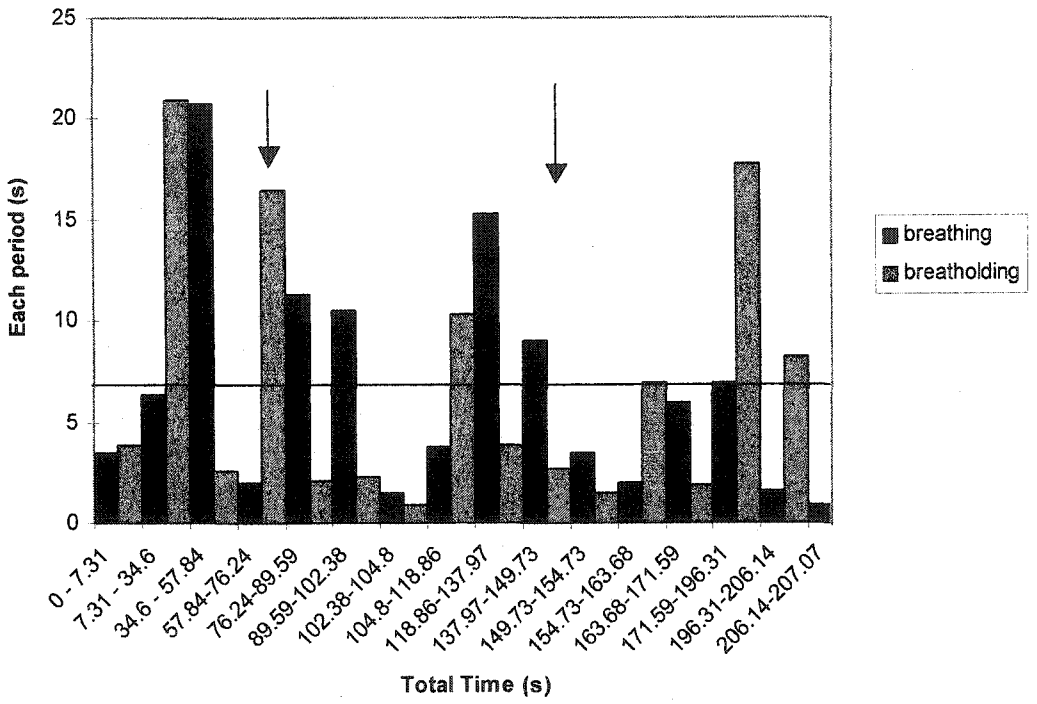
Subjects and Experimental Design

The data was collected during the final solo event at a Canadian Synchronized Swimming National Championship. Methodology included videotaping the 11 top soloists in Canada during finals. Each of the 11 solo performances was filmed using a video camera (JVC, Compact VHS GR-AX2) during the final events. A clock was started coincident to the performance. During the event, sketches were made by a trained individual to represent the pattern covered in the pool for each solo. A research assistant was provided with one sheet of paper for each solo, where a proportional rectangular area represented the 25 x 30m pool. The rectangular area was subdivided into four smaller rectangles to increase accuracy of the pattern drawing. The pathway of the swimmer during the routine was traced on the paper provided. The total distance traveled during each routine was estimated from the pathway taken by each athlete. Since solos may vary according to the rules from 3:15 to 3:45 min, the relative distance was also determined by dividing the total distance covered by the time taken to perform the solo.

The research procedures were approved by the Faculty of Physical Education and Recreation Research Ethics Board at the University of Alberta and each subject completed an informed consent form. Permission was also obtained from *Synchro Canada* and the coaches. Age, body mass, height and the length of time involved in the sport was recorded for each subject.

Time-motion Analysis

The analysis of time was made from the videotaped performance using a custom designed computer software package (STIMER, University of Alberta, Edmonton; see Bloxham et al., 2001). The total time out of the water, the number of times the swimmers had their face in or out of the water and the longest and the second longest BH period were determined for each solo event. For the purpose of this analysis, BH periods were considered as the time the swimmers were holding their breath or exhaling underwater. There is no literature providing information about the starting point of hypoxia in synchronized swimmers performing solos. A preliminary analysis demonstrated that the swimmers went underwater frequently for brief periods of time (i.e., less than 7 s) (Figure 2-1). Since this is one of the few studies that examines solo synchronized swimming in competition, two calculations of time underwater were made: a total time where the face was underwater; and a calculation of time where the face was underwater for more than 6.83 s (6.83 s was the group mean for all periods with face underwater). The latter is likely a more appropriate measure of BH in synchronized swimming, as frequent small periods of BH (i.e., < 6.83 s) could be considered as part of a normal breathing cycle (i.e. inspiring prior to face immersion, and expiring during immersion) or the BH may be small enough that the diving reflex is not initiated.



(The arrows indicate the first, second and third parts of the solo)

Figure 2-1. The time spent breathing or breath holding during a synchronized swimming solo (event for one athlete).

The total time under water consisted of the sum of each BH period for each swimmer. The percentage of time under water was calculated as the total BH time (s)/routine time (s). The longest and second longest BH time period was also recorded for each swimmer as was their placement within the routine. A choreography process in synchronized swimming tends to create a routine with a strong beginning, a middle and an ending climax. Thus, it was logical to divide the routine in three parts and determine where the longest BH period occurred.

Technical Merit Scoring

The technical merit (TM) score is the mark specifically related to the technical aspect of performance and is assigned to the performance by the judges after the routine. These scores were recorded by the investigator. The scoring system and judges were all accredited by the Federation Internationale de Natation Amateur (FINA).

Statistical Analysis

The statistical analysis was done using SPSS computer software. Descriptive statistics were calculated for the characteristics of the swimmers, the total length of BH time, the average length of BH time, and for the distance covered. Pearson product moment correlation coefficients were used to determine the relationship between years of training, the TM score, distance covered, total time of BH, total time of breath holding > 6.83 s, and the mean time of BH > 6.83 s. A t-test was used to compare the absolute and percentages of time spent under water by the top athletes (places $1^{st} - 6^{th}$) in comparison with the athletes placing 7^{th} to 11^{th}. Alpha level for all statistical tests was set a priori at $p \leq .05$.

Results

The mean age, height, and body mass for the 11 soloists was 20 ± 1.8 years, 173.3 ± 4.1 cm, and 58.3 ± 4 kg, respectively ($\bar{x}$ ± SD). They had been involved in synchronized swimming for an average of 10.7 ± 3 years ($\bar{x}$ ± SD), range 7 - 17 years.

The length of time, the number of times and the percentage of time the athletes had their face under and out of the water while swimming their solos is presented in Table 2-1. The two longest BH periods are also shown. There were

no significant differences between the top soloists and those placing 7th to 11th in any of the BH times measured. As expected, there was a significant difference for the TM scores (top group = 95.1 ± 1.7 vs. bottom group = 91.3 ± 1.0; $\bar{x}$ ± SD).

Table 2-1. Time-motion analysis of breathing and breath holding during synchronized swimming solo events

Variable	$\bar{x}$ ± SD	Range
Total time face under water	133.69 ± 27.1 s (59%)[a]	102.23 s - 166.18 s (50-65%)[a]
Total time face out of the water	87.13 ± 11.6 s (41%)[a]	71.15 s – 104.84 s (36-50%)[a]
Total time face under water for more than 6:83 s.	96.9 ± 11.4 s (46%)[a]	73.66 s – 106.88 s (36-52%)[a]
The longest time face out of the water	15.01 ± 4.9 s	8.62 s – 23.84 s
The longest BH period	25.45 ± 6.2 s	18.18 s - 38.72 s
Second longest BH period	17.3 ± 2.1 s	13.62 s - 21.09 s
# of times face in water	18 ± 3	15 – 24
# of times face out of water	19 ± 3	16 – 25
# of times when BH longer than 6:83 s	7 ± 1	6 – 8

[a](%) Indicates percentage of total solo time.

Figure 2-1 shows the BH pattern for one solo. Typically one of the longest BH periods was placed near the beginning of the solo and another large BH was placed near the end of the solo. The middle period of the solo tended to have shorter BH periods.

Table 2-2 shows the individual differences between each solo in relation to where the longest and the second longest BH periods occurred within a routine. The majority (10/11, 91%) of the longest BH periods occurred in the first third of the solo. Four out of 11 solos (36%) began their solos with the longest BH period. The second longest BH period varied considerably, with 27% (3) of the soloists having the second longest BH period in the first third of the solo; 45% (5) in the second third of the solo; and 27% (3) in the last third of the solo. There was also a wide variation with respect to where the longest breathing period occurred

during a routine. Four out of 11 (36%) occurred in the 1st third, 36% (4) occurred in the second third, and 27% (3) occurred in the last third of the routine. Unexpectedly, in most of the cases (73%, 8/11), the longest breathing period did not directly follow one of the longest BH periods.

Table 2-2. Appearance of BH and breathing periods during a synchronized swimming solo event

SOLOIST	Longest BH	2nd Longest BH	Longest Breathing Time
A	1st third of the solo	1st third of the solo	1st third of the solo[b]
B	1st third of the solo	2nd third of the solo	2nd third of the solo
C	3 third of the solo	2nd third of the solo	1st third of the solo
D	1st third of the solo	2nd third of the solo	3rd third of the solo
E	1st third of the solo	3rd third of the solo	3rd third of the solo[b]
F	1st third of the solo	3rd third of the solo	1st third of the solo[a]
G	1st third of the solo	3rd third of the solo	2nd third of the solo
H	1st third of the solo	2nd third of the solo	2nd third of the solo
I	1st third of the solo	1st third of the solo	3rd third of the solo
J	1st third of the solo	2nd third of the solo	1st third of the solo
K	1st third of the solo	1st third of the solo	2nd third of the solo

[a](Following 1st longest BH)
[b](Following 2nd longest BH)

The mean (± SD) total distance covered (absolute value) during the solo event was 57.61 ± 6.84 m, (range 48.61 - 68.2 m). The mean (± SD) for the total distance covered relative to time was 0.28 ± 0.03 $m \cdot s^{-1}$, (range 0.24 - 0.34 $m \cdot s^{-1}$). Table 2-3 contains the correlations between BH, distance and TM score. Not surprisingly, relative and absolute distances were significantly correlated ($r = .975$, $p \leq .05$), and the years of experience of the athletes correlated with the TM scores ($r = .693$, $p \leq .05$). No other significant correlations were found between any of the variables.

Table 2-3. Pearson Product Moment Correlation between TM, distance covered and BH and years of swimming

	TM	Absolute distance	relative distance	Max BH	BH	# times head was out of water	$\bar{x}$ time> 6:83 s	Years of swimming
TM	1.0							
Absolute distance	.260	1.0						
Relative distance	.231	.975[a]	1.0					
Max BH	-.076	-.025	.108	1.0	.			
BH[a]	-.129	-.518	-.471	.636[a]	1.0			
# times head was out of water	.079	-.508	-.429	.010	.444	1.0		
$\bar{x}$ time >6:83 s	.531	-.264	-.270	.365	.441	-.076	1.0	
years of swimming	.693[a]	-.066	-.059		-.169	.442	.182	1.0

[a] Statistically significant at $p \leq .05$ (TM = Technical Merit mark, BH = Breath holding)

Discussion

Breath holding is a safety issue in synchronized swimming. The Federation Internationale de Natation Amateur (FINA) recently recommended a discussion of the possible effects of BH in synchronized swimming to the FINA Medical Committee (1996). Davies et al. (1995) reported that synchronized swimming athletes could stay underwater for up to 50 s while performing strenuous exercise during solos at international competitions. Figura, Cama and Guidetti (1993) reported 20 to 30 s of BH periods followed by smaller breathing time periods during 3 min 30 s solo routines. FINA (1996) has suggested that BH periods longer that 40 s are dangerous to the athlete. There is no known literature that quantifies the total amount of time that synchronized swimmers stay underwater while performing a solo event.

In the present study, the athletes performed relatively long underwater sequences (greater than 6:83 s) that were repeated six to eight times during a solo

event (3:15 - 3:45 min). There was a wide variation for BH period times (6.87 - 38.72 s) and the longest time period of 38.72 s was shorter than the 50 s reported by Davies, et al. (1995). Most of the solos in the present study had two periods of BH similar to those reported by Figura et al. (1993) (20 to 30 s). These differential findings may be due to the new trends of the sport where BH is not emphasized as much or may be due to the individual characteristics of the athletes from different countries and/or the variety of choreography used. An interesting aspect demonstrated by the present video analysis was the frequent short periods during which the athletes submerged their faces in the water and almost immediately came out again (i.e., < 6.83 s). These short underwater periods corresponded to 13% of the total amount of the solo time (Figure 2-2) and 27% of the total time where the face was submerged. While these small BH periods may enhance the artistic impression of the routine or the swimmer's style, it is unclear what effect, if any, they have on the physiological responses of the swimmer.

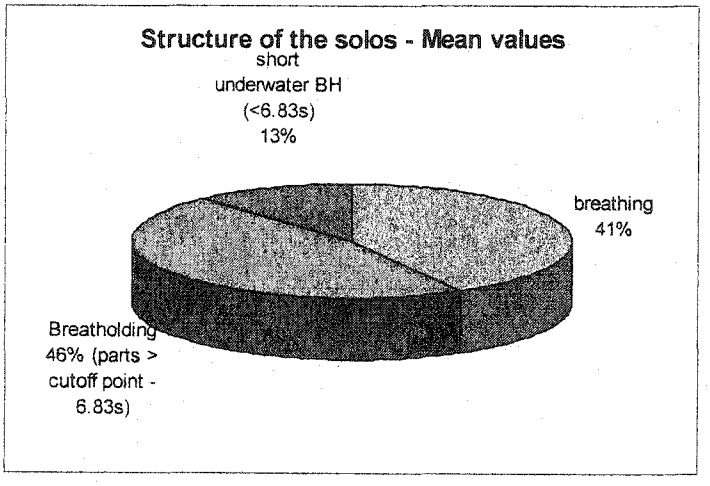


Figure 2-2 Mean percent of time spent performing different breathing patterns during a synchronized swimming solo event (BH = breath holding)

Davies et al. (1995) showed that in a Great Britain regional championship, the two highest scores were gained by swimmers that performed long initial periods of underwater work. Davies et al. (1995) found no correlation between BH and ranking but suggested that this was because only the first period of the solos were analyzed and not the entire solo event. In the present study, no significant correlation was found between TM scores and the longest BH period, the total BH time greater than 6.83 s or the total percentage of time spent BH. However, this could be partially due to a small sample size. The athlete that had the shortest maximum breath holding period (18:18 s) placed eighth (TM score) while the athlete that held her breath the longest amount of time in a single period (38:72 s) placed sixth (TM score). This is contrary to the suggestion by Davies et al. (1995). BH times did not appear to influence total TM score for Canadian judges. Alternatively, it was possible that the small differences in BH times observed between the athletes were not sufficient to impact the TM scores. Interestingly, in the present study, 36% (4/11) of the soloists began their solo with the longest BH period and 91% (10/11) of the athletes had their longest BH period in the first third of their solos. This tendency of longer BH periods earlier in a routine may have some physiologic basis (i.e., less fatigue at the beginning of routine), and/or it may be due to an artistic influence. For example, music selection plays an important role and influences the composition of the solo. The artistic impression and composition of the solo also influences the solo structure. Whatever the reason, there was a tendency for the longest BH period to be in the

first third of the solos.

Of note, 3 swimmers took a series of small breaths prior to their longest BH period, while another 3 swimmers showed this type of breathing pattern after their longest BH period. These types of breathing patterns should be explored further. Since hyperventilation can prevent the body from detecting a lack of oxygen (Astrand, 1960), this could lead to a potentially dangerous situation in the water.

Although the distance covered is considered important and represents a high level of difficulty and therefore a potential increase in TM score, there was no correlation between these variables in the present study. The distance covered did not appear to influence total TM score awarded by the Canadian Judges. Alternatively, it was possible that the small differences in the distance covered by each athlete was not sufficient to impact the TM scores. Although there was no significant correlation between distance covered and BH, all the correlations were negative. This is probably because during breath holding, the athlete is either performing a stationary exercise or uses mechanically less effective propulsion techniques in comparison to those used when breathing.

Another factor that influences BH is the level of difficulty of the maneuvers used in a solo event. Figura et al. (1993) reported that the solos chosen by the athletes in their study were comparable in difficulty although the method of assessing difficulty was not reported. The difficulty in the present study cannot be assessed since there was not enough agreement on the degree of difficulty for several movements between high level coaches and judges. An assumption could

be made that the increased difficulty would decrease BH because the energy expenditure required to do more difficult figures is greater. The degree of difficulty of figures in routines should be explored further in future research.

In summary, this study investigated BH patterns during competitive synchronized swimming solos at a national event and the relationship between BH and placing. The solos analyzed did not exceed the 40 s deemed to be dangerous by FINA (1996; 1998) suggesting that the athletes/coaches were cognizant of this limit and adhered to it. Findings further suggest a positive trend towards a decrease in the importance of long and dangerous BH periods in solo events, as BH time periods were not related to TM scores. Further research to determine if this is an international tendency would be interesting. In addition, the effects of a sequence of small breaths immediately preceding or following a long BH period should be explored to ensure which method is most effective and whether the most effective method introduces any safety concerns. Other research investigating the physiological consequence of breath holding exercise and water immersion in synchronized swimmers would also be recommended.

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Chapter Three : Arm cranking peak oxygen consumption in and out of the water

Introduction

Synchronized swimming is a unique sport where swimmers perform intermittent breath holding periods while training in the water for extended periods of time. There has been some controversy in the literature as to whether water immersion (WI) with the head out of the water influences the measurement of maximal oxygen consumption ($\dot{V}O_2$ max). Running studies have shown decreased $\dot{V}O_2$ max in the water versus out of the water (Frangolais & Rhodes, 1995; Svendenhag & Seger, 1992), while cycling studies have shown no difference in $\dot{V}O_2$ max in and out of the water (Chen, Kenny, Johnston & Giesbrecht, 1996; Connelly et al., 1990; Christie, Sheldahl, Tristani, & Clifford, 1990; Sheldahl et al., 1987). There are no reports to date of arm cranking comparisons between wet and dry conditions.

During exercise while submerged to the neck compared to exercise on land, research has reported no change in minute ventilation ($\dot{V}_E$) while cycling at 40, 60 and 80% of $\dot{V}O_2$ max based on a $\dot{V}O_2$ max test done on land (Sheldahl et al., 1987). However, others have shown increases in $\dot{V}_E$ during water running compared to land running (Frangolais & Rhodes, 1995). Different methodologies, exercise intensities and populations result in a variety of inconsistencies in the literature.

Because synchronized swimmers support their body with a continuous motion of their arms while upside down, the present study used arm peak oxygen consumption ($\dot{V}O_2$ peak) as a measure of power instead of some of the more common tests such as leg ergometry or treadmill running. We chose to term the test $\dot{V}O_2$ peak instead of $\dot{V}O_2$ max because of the difficulties in reaching the criteria for $\dot{V}O_2$ max (i.e., plateau of $\dot{V}O_2$ with the increase in workload) with arm cranking exercise in the water. Typically the arm ergometry $\dot{V}O_2$ peak will be lower than leg based tests because of the smaller muscle mass involved (Sawka, 1986). The smaller muscle mass results in a number of cardiovascular differences, including a lower $(a-\bar{v})O_2$ difference, higher peripheral resistance, lower HR, lower SV, and lower cardiac output, which result in lower $\dot{V}O_2$ during arm ergomery (Franklin, 1985, Bhambhani, Maikala & Buckley, 1998, Pendergast, 1989, Miles, Cox & Bomze, 1989, Reybrouck, Heigenhauser & Faulkner, 1975). Decreased oxygen extraction during arm cranking could also be a result of less developed oxidative capacity in the as a result of the reduced number and size of the mitocondria and lower enzimatic activity (Pendergast). The predominance of fast fiber type in the muscle, the lower vascular capacity for perfusion, and the greater intramuscular tension, which increases with exercise intensity and eventually impairs blood supply to the working muscles are also reasons for lower $\dot{V}O_2$ peak in arm ergometry (Sawka).

Since peak oxygen consumption ($\dot{V}O_2$ peak) is an important factor in the sport of SS, the primary purpose of the present study was to examine $\dot{V}O_2$ peak in

16 healthy, active, female synchronized swimmers (SS) who were tested in two different conditions: wet (submerged to the neck in water) and dry (out of the water). The specific hypotheses of the study were that heart rate (HR) would be lower, frequency of breathing (Fb), and oxygen pulse (O_2 pulse) would be higher and $\dot{V}O_2$ would be lower or the same in the wet versus dry condition. These hypotheses were based on previous pilot studies and published research not specific to synchronized swimming.

Previous research indicated that HR was lower in the water at submaximal and maximal exercise (Sheldahl et al., 1997), leading to the hypothesis that HR would be lower for synchronized swimmers and that oxygen pulse would be higher since it is the ratio between $\dot{V}O_2$ and HR. Tidal volume was expected to be lower in the water at rest. Based on the decrease in tidal volume (TV) at rest during WI it was hypothesized that Fb would be higher. With WI it is likely that Fb will increase at rest and will remain higher during exercise to compensate for the decrease in TV.

Despite the fact that there are inconsistent results reported for leg ergometry and running in the water (Frangolais & Rhodes, 1995; Svendenhag & Seger, 1992, Chen et al., 1996; Connelly et al., 1990; Christie, et al., 1990; Sheldahl et al., 1987), pilot work indicated that there was a tendency for a decrease in peak oxygen consumption but no significant changes from land to water for arm crank peak oxygen consumption which became the last hypothesis for this study.

Methods

Subjects

Sixteen volunteers were recruited from three local synchronized swimming clubs. Nine athletes were from non-elite synchronized swimming clubs who trained less than 10 hr·week^{-1}and 7 athletes were from an elite synchronized swimming club who trained for more than 20 hr·week^{-1}. None of the athletes were taking asthma medication on a regular basis nor had been diagnosed with any lung disease and all were non-smokers, which were pre-requisites for participation in this study.

The Faculty of Physical Education & Recreation Research Ethics Board granted ethics approval for this study. All subjects were informed of the proposed measures and procedures at a meeting prior to the start of the study. All subjects were volunteers and if they were under the age of 18 they were given time to discuss their potential involvement with their parents or guardians who were required to provide permission for their participation. Each subject or guardian signed a consent form prior to the athlete's participation (Appendix E).

Testing equipment and conditions

The experimental design included tests in two different conditions. Each subject performed an arm cycling $\dot{V}O_2$ peak test in the dry condition first, followed 1 week later by a $\dot{V}O_2$ peak test in the wet condition. Tests were not randomly determined because the equipment could not be easily moved from the wet to the dry condition. Subjects were tested on a custom designed cycle ergometer (Chen et al. 1996), with seat height and distance from the handle bars set for each of the subjects and maintained for both the dry and wet conditions. In

the wet condition, subjects were submerged to the clavicular notch in an underwater weighing tank while sitting on the cycle ergometer. The water temperature was 28 ± 1°C. Ankle weights were used to prevent the legs from floating. Each subject was strapped to the ergometer with a shoulder harness. A 4-kg weight belt was also positioned on top of the subject's thighs to stabilize their lower body. The same metabolic measurement cart (CPX/D, Medical Graphics Corporation, St. Paul, Minnesota, USA) was used in both conditions. The mouthpiece required some adaptation in order to make measurements in the water, which is described below (Figure 3-1).

To ensure that the pneumotach was not going to be in contact with water, a system of tubes connected to a Rudolph valve was developed. This custom set up was used for air sampling during testing in both the wet and dry experimental conditions (Figure 3-1). With this location of the pneumotach at the mouthpiece, the dead space for the Medgraphics cart was the same as for testing without the tubes, 50 ml. The dead space is the volume of expired gas that sits between the end of the pneumotach and the sample line (Lamarra & Whipp,1995).

For both testing days, subjects were asked to avoid food and caffeine 3 to 4 hr prior to reporting to the lab. They were instructed to report to the lab wearing comfortable clothing and a bathing suit. Subjects completed a history inventory questionnaire (Appendix D) and height was assessed with a setsquare and measuring tape to the nearest 0.2 cm. Body mass was determined to the nearest 0.2 kg using a beam balance scale (Health-O-Meter, Sunbeam Products, Inc.) with the subjects wearing their bathing suits. Body mass index (BMI; $kg \cdot m^{-2}$) was

subsequently calculated.

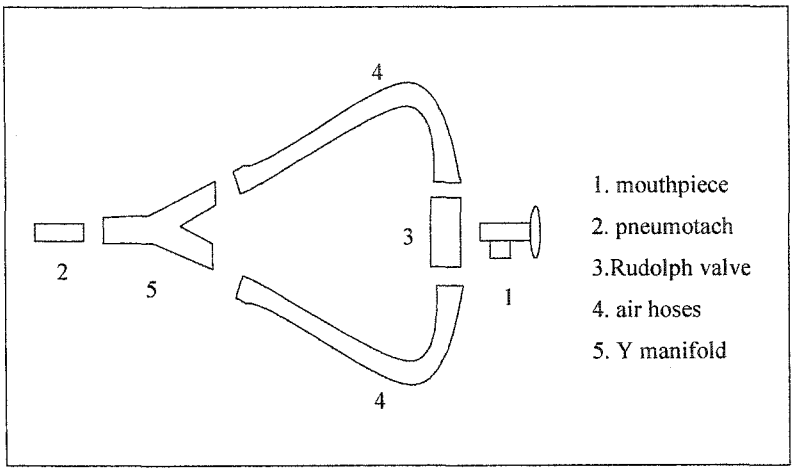

Figure 3-1 Mouthpiece schematic diagram – (VO_2 peak test)

Testing procedures

The cycle ergometer was calibrated each day with known weights. The metabolic measurement cart was calibrated with known gases prior to and at the end of each test, according to the manufacturer's specifications to ensure accuracy. HR was monitored throughout the tests, with a heart rate monitor positioned on the subject's chest (Polar Vantage, Polar, Kempele, Finland).

Peak oxygen consumption was measured with a continuous protocol recommended by the American College of Sports Medicine (ACSM) (1995). The subjects first sat on the cycle ergometer resting for 5 min with a nose clip while connected to the Medgraphics metabolic cart. Measured variables included $\dot{V}_E$, fraction of expired oxygen (F_EO_2), fraction of expired carbon dioxide (F_ECO_2) from which $\dot{V}O_2$, carbon dioxide production ($\dot{V}CO_2$) and respiratory exchange ratio (RER) were calculated and averaged over 15 s. A 4 to 5 min unloaded warm up was then provided. During testing, the initial workload for arm cranking was fixed at 0.5 Kp with an additional increment of 0.25 Kp every 2 min until

volitional exhaustion was reached. The initial load corresponded to a power output of approximately 30 W dry and 41 W wet (11 W of additional load to account for the drag in the water as determined in Appendix B). Each load increment corresponded to approximately 15 W. Subjects were instructed to pedal at 60 rpm, in time to a metronome set accordingly. The test was terminated when the subject volitionally fatigued or showed an inability to maintain the correct cadence. At this point the metabolic data collection was stopped and a cool down period was provided, consisting of 3 to 5 min of unloaded cycling. The following week the same procedures were repeated in the water (wet condition).

For the purpose of comparing exercise in the wet versus the dry condition, ventilatory threshold (VT) was detected for each subject. The VT was determined by the power output at which the $\dot{V}_E/\ \dot{V}CO_2$ ratio reached a minimum value and F_ECO_2 reached a maximum value during graded exercise (Bhambhani & Singh, 1985).

Prior to the start of this study, a pilot sample of 7 female subjects aged 24.6 ± 8.2 years ($\bar{x}$ ± SD), completed two arm crank tests in the wet condition, two days apart, to determine test retest reproducibility and a possibility of a learning effect. No significant differences were found between these two tests and the one way intraclass correlation coefficient (ICC) showed significant correlation between the data (absolute $\dot{V}O_{2peak1}$ = 2.1 ± 0.3 L·min^{-1}, absolute $\dot{V}O_{2peak2}$ = 2.0 ± 0.2 L·min^{-1}; $\bar{x}$ ± SD; p = .173, ICC=.619, sig.=.04; relative $\dot{V}O_{2peak1}$ = 32.3 ± 6.1 ml·kg·min^{-1} and relative $\dot{V}O_{2peak2}$= 30.5 ± 5.3 ml·kg·min^{-1}; $\bar{x}$ ± SD; p = .169, ICC=.840, sig.=.003). Thus, a preliminary water trial for this

study was deemed unnecessary.

Statistical Analysis

T-tests for dependent variables (repeated measures) were used to compare the results between the two conditions, wet and dry. A one-way analysis of variance was used to compare the differences between training hours for clubs. The alpha level was set a priori at $p \leq .05$. For the T-tests where families of contrasts involved nonorthogonal variables (e.g.; O_2 pulse, RER, absolute $\dot{V}O_2$ peak and relative $\dot{V}O_2$ peak), a Bonferonni correction was used to establish the appropriate alpha level (Myers & Well, 1995). As a result, the alpha level for oxygen pulse, RER, absolute $\dot{V}O_2$ peak and relative $\dot{V}O_2$ peak was set at $p \leq .0125$ (.05/4), and for all the other comparisons the alpha level was set at $p \leq .05$. All the analyses were done using the SPSS software program version 7.5 for Windows®.

Results

Physical and training characteristics

Table 3-1 contains the physical characteristics of the 16 swimmers that participated as subjects. Table 3-2 presents the typical program for each synchronized swimming club. There was a large variability in hours of swimming between clubs.

Table 3-1. Physical characteristics of the subjects - Values are $\bar{x} \pm$ SD (range).

Age (years)	BMI ($kg \cdot m^{-2}$)	Height (m)	Body mass (kg)
17.9 ± 2.0	21.3± 2.6	1.70 ± 0.06	61.8 ± 10.4
(15 – 22)	(18.3 – 26.2)	(1.61 – 1.82)	(47.4 - 83.1)

Table 3-2. Average training hours for the teams - Values are hr·week^{-1}.

Activity	Club 1 (n=7)	Club 2 (n=8)	Club 3 (n=1)
Water practice	21 or 25[ab]	6.5[a]	5.5[ab]
Weights:	3	0	0
Dryland:	1.5	1	0
Flexibility:	2.5	1	0
Pilates:	1	0	0
Land drill:	1	0.5	0.5
Team Meeting:	1.5	0	0
Psych. Meeting:	1	0	0
TOTAL	32.5 to 36.5	9	6

[a] Significantly different at $p \leq .05$.
[b] For athletes that train solos and duets.

Exercise parameters in the wet versus dry condition

Results reported for RER max, Fb max and $\dot{V}_E$ max are not necessarily from the same time point as $\dot{V}O_2$ peak because in some instances RER max, $\dot{V}_E$ max and Fb max values were not reached at the same exact time point as $\dot{V}O_2$ peak was achieved.

There was no significant difference in $\dot{V}O_2$ peak between the wet and dry condition. There was also no difference in the length of the exercise between conditions (Table 3-3).

Table 3-3. Exercise parameters - Values are $\bar{x} \pm$ SD (range).

	Wet	Dry
$\dot{V}O_2$ peak abs. (L·min^{-1})	2.0 ± 0.3 (1.4 - 2.4)	1.9 ± 0.3 (1.5 - 2.4)
$\dot{V}O_2$ peak rel. (ml·kg^{-1}·min^{-1})	33.2 ± 5.0 (26.3 – 42.5)	31.9 ± 5.4 (25.5 – 44.7)
Time length of exercise (s)	488 ± 113 (315 – 735)	486 ± 117 (315 – 690)
Where VT was detected (min)[a]	3.7 ± 1.1 (2.25 - 5.5)	3.9 ± 1.3 (2.75 - 7.25)

[a] Significant correlation at .01, r=.729

The maximal frequency of breathing (Fb max) in the wet condition was significantly higher than in the dry condition (**Table 3-4**).

Table 3-4. Frequency of breathing (Fb) at different exercise time points - Values are $\bar{x} \pm$ SD (range).

	Wet	Dry
Fb at the onset of exercise ($br \cdot min^{-1}$)	27 ± 7 (19 - 44)	25 ± 5 (14 – 32)
Fb at the VT (N= 15) ($br \cdot min^{-1}$)	32.3 ± 8.3 (21 – 45)	28.5 ± 6.7 (18 - 42)
Fb at $\dot{V}O_2$ peak ($br \cdot min^{-1}$)	52 ± 9 (34 - 65)	48 ± 10 (32 – 75)
Fb max ($br \cdot min^{-1}$)	58 ± 16 (31 –98)[a]	53 ± 14 (39 –97)[a]

[a] Significantly different at $p \leq .05$.

Heart rate in the dry condition was significantly higher than in the wet condition at all time points, except at the onset of exercise, where the difference did not reach significance. Table 3-5 contains HR at the onset, at VT and at $\dot{V}O_2$ peak in both conditions.

Table 3-5. Heart rate (HR) at different exercise time lengths – Values are ± SD (range).

	Wet	Dry
HR at the onset of exercise ($b \cdot min^{-1}$)	106 ± 14 (81 – 132)	115 ± 14 (92 - 139)
HR at the VT (N = 15) ($b \cdot min^{-1}$)	143 ± 15[a] (112 - 164)	155 ± 12[a] (136 - 173)
HR at $\dot{V}O_2$ peak ($b \cdot min^{-1}$)	171 ± 9[b] (157 – 187)	186 ± 9[b] (162 - 200)

[a, b] Significantly different at $p \leq .05$.

Oxygen pulse was significantly larger in the wet condition than in the dry condition at the onset of the exercise (32.1%) and at the VT (22.9%) (Table 3-6). There was no statistically significant difference in oxygen pulse between conditions at $\dot{V}O_2$ peak.

Table 3-6. Oxygen pulse - Values are $\bar{x} \pm$ SD (range).

	Wet	Dry
O_2 pulse at the onset of exercise ($ml \cdot HR^{-1}$)	7.4 ± 1.4^a (4.3 – 10.0)	5.6 ± 1.6^a (2.7 - 8.5)
O_2 pulse at the VT (N=15), ($ml \cdot HR^{-1}$)	10.2 ± 1.6^b (8.0 – 14.0)	8.3 ± 1.3^b (6.2 – 10.6)
O_2 pulse at $\dot{V}O_2$ peak ($ml \cdot HR^{-1}$)	11.8 ± 1.7 (8.0 – 15.1)	10.4 ± 1.4 (8.2 –13.0)

[a, b] Indicates significantly different from wet to dry at $p \leq .0125$.

RER max was significantly lower in the wet condition than in the dry condition. There were no differences for $\dot{V}_E$ at the onset of the exercise or $\dot{V}_E$ max between conditions (Table 3-7).

Table 3-7. Other parameters - Values are $\bar{x} \pm$ SD (range).

	Wet	Dry
$\dot{V}_E$ at the onset of exercise ($L \cdot min^{-1}$)	23.73 ± 4.86 (15.5 – 37.1)	22.23 ± 8.56 (13.4 - 52.3)
$\dot{V}_E$ max ($L \cdot min^{-1}$)	79.49 ± 14.92 (46.3 - 104.5)	83.11 ± 17.84 (47.9 – 111.4)
RER max	$1.05 \pm 0.06a^a$ (0.92 - 1.18)	1.11 ± 0.04^a (1.01 – 1.18)

[a] Indicates significantly different from wet to dry at $p \leq .0125$.

Discussion

This study examined peak and submaximal exercise parameters measured via arm cranking in synchronized swimming female athletes in and out of the water. The results support the main hypotheses that water immersion decreases HR and increases Fb and O_2 pulse compared to on land. However, there was no support for the hypothesis that $\dot{V}O_2$ peak would be lower in water.

The lack of difference reported between wet and dry conditions shown in Table 3-3 for $\dot{V}O_2$ peak while arm cranking in this study are comparable to lack of differences in leg crank comparisons reported by several researchers (Christie

et al., 1990; Sheldahl et al., 1984; Connelly et al., 1990). There are no reports in the literature on arm cranking in the water. Bhambhani, Maikala and Buckley (1998) reported $\dot{V}O_2$ peak of 1.77 L·min^{-1}and 27.3 ml·kg^{-1}·min^{-1} for female athletes performing arm crank exercise out of the water which are 14% lower than our findings. Thus, the physiological differences from dry to wet conditions such as the increase in stroke volume and cardiac output due to blood shift to central circulation (Arborelius , Balldrin, Lilja & Lundgren , 1972; Sheldahl et al., 1987) were not strong enough to significantly impact $\dot{V}O_2$ peak in the present study. Alternatively, peripheral mechanisms such as the specific characteristics of the muscle involved and intramuscular pressures exceeding perfusion pressure (Sawka, 1986) were solely responsible for determining $\dot{V}O_2$ peak in both conditions, with no advantage obtained from water immersion.

While there were no differences in peak $\dot{V}O_2$ between wet and dry condition in the present study, the values for $\dot{V}O_2$ peak may seem low. However, according to Franklin (1985), arm cycle ergometer $\dot{V}O_2$ peak tests result in values that are 20 to 30% lower and peak HR that are 10 to 15 b·min^{-1} lower than leg ergometer tests. A $\dot{V}O_2$ max test done on an inclined treadmill usually results in $\dot{V}O_2$ values that are 5 to 15% higher than those obtained on a cycle leg ergometer (McArdle & Magel, 1970). If one accounts for these differences, the peak $\dot{V}O_2$ test results from the present study are comparable with other $\dot{V}O_2$ test results found in the literature for healthy active female athletes.

Some authors explain the lower peak $\dot{V}O_2$ achieved during arm crank relative to running as being a result of central and peripheral differences (Sawka, 1986; Bhambhani et al., 1998). Central differences with arm cranking include a lower cardiac output and lower stroke volume. Peripheral differences with arm cranking, according to Sawka include: reduced potential to generate muscular tension due to smaller muscle mass and cross sectional area, reduced oxidative capacity due to smaller muscle mass, differences in fiber type composition, motor unit recruitment patterns and reduced blood perfusion of skeletal muscle due to the smaller total capillary cross sectional area, the vascular capillary bed differences (fiber type) and the intramuscular pressures exceeding perfusion pressure. The higher tension required to perform the work will increase pressure to a point that decreases blood flow, not allowing oxygen uptake to increase further.

Chen et al. (1996) studied males and females performing leg ergometry and found that the time of exercise in the wet condition was shorter than the time of exercise in the dry condition. This was not the case in the present study. There was no significant difference in the length of the peak test between wet and dry conditions and VT was detected at the same stage of the test in both conditions for most of the subjects (Table 3-3). This could be explained by the specificity of the work performed. Arm cranking in water has similarities to the sculling motion in synchronized swimming and is possible to perform under laboratory conditions. Drag is a known factor that contributes to some of the differences seen when comparing wet and dry conditions. Due to water resistance, the amount of work

done in the wet condition is increased and because of this, the extra work needed to move the arms at 60 rpm in the water was measured in the present study (Appendix B). Measurements were based on representative dimensions of arms and legs of synchronized swimmers and resulted in an 11 Watt higher power output for arm cranking in the water at 60 rpm. However, extra work due to drag varies with the exercise specificity. Most research has used metabolic rates to determine if drag had an impact on the physiological responses while pedaling (Chen et al., 1996; Christie et al., 1990). These studies concluded that drag was not measurable by physiologic or metabolic parameters at any submaximal power output. An explanation for this could be that the complex physiological changes that occur in WI, such as blood shift to central circulation, increase in central venous pressure, increase in stroke volume and cardiac output, decrease in heart rate and decrease in systemic vascular resistance (Arborelius et al., 1972; Yamazaki, Endo, Torii, Sagawa & Shiraki, 2000; Pan, Kinouchi, Yamagushi, Miyamoto, 1997; Begin et al., 1976) that override the increased drag in water compared to land, thereby producing similar results.

Sheldahl et al. (1987) reported greater frequency of breathing in the water as their male subjects reached 80% of $\dot{V}O_2$ max while leg cranking. In the present study the maximum frequency of breathing achieved by the subjects was significantly greater in the wet condition than in the dry condition. The increase in frequency of breathing is related to the lung tidal volume decrease that occurs in the water (See chapter 4). By increasing the frequency of breathing the subject is able to maintain the same minute volume and thus keep up with the demand for

oxygen uptake and carbon dioxide elimination. As a consequence of the frequency of breathing increase, the relative effect of the dead space ventilation (anatomical dead space) will increase (McClaran, Harms, Pegelow & Dempsey, 1998). This will gradually decrease the efficiency of the respiratory system.

Previous research has shown contrasting results with regards to HR variability during exercise in water. While at rest in thermoneutral water, Miwa, Sagiyama, Mano, Iwase and Matsukawa (1997) reported lower resting HR in the wet condition than in the dry condition (69.2 ± 2.7 b·min^{-1} vs. 88.2 ± 3.9 b·min^{-1}; $\bar{x} \pm$ SD) for males. Others have reported no difference in HR at rest between water immersion and land (Christie et al., 1990; Begin et al., 1976; Shedahl et al., 1987; Farhi & Linnardson, 1977; Kame & Pendergast, 1995). Similarly, in the present study there was no difference in HR at the onset of exercise in the wet versus dry condition. This may be explained as a combination of the thermoregulatory effect, which increases HR as a result of involuntary muscle work such as in shivering, and water immersion effect, which decreases HR as it increases central blood volume due to hydrostatic pressure. This counterbalancing effect produces no change in HR from land to water immersion. However, as exercise intensity increases, working muscles produce heat and release extra energy used to heat the body. Thermoregulatory adjustments are likely withdrawn and only the water immersion effect persists, including the increase in CO, the increase in SV, and the blood shift to central circulation. This could bring HR to a lower level, as seen at VT and peak $\dot{V}O_2$ in the water. Tikuisis , Ducharme, Moroz and Jacobs (1999) suggested that if exercise level is

high enough there will be no energy specifically expended to heat the body such as through shivering.

Heart rate at the VT and at $\dot{V}O_2$ peak was significantly lower in the wet condition compared to dry the condition. HR at $\dot{V}O_2$ peak achieved by the subjects in the dry condition was higher than HR at $\dot{V}O_2$ peak reported by Bhambhani et al. (1998) for female athletes performing arm cranking (160 ± 19.1 $b \cdot min^{-1}$; $\bar{x} \pm SD$ vs. 186 ± 9 $b \cdot min^{-1}$; $\bar{x} \pm SD$ in the present study). The decrease in HR seen at higher loads in the wet condition relative to dry condition in this study and in others (Shedahl et al., 1987; Christie et al., 1990; Chen et al., 1996) may be explained by the decrease in sympathetic stimulus or the withdrawal of the thermoregulatory mechanism as explained below.

There is a decrease of sympathetic stimulus activated by the baroreceptors to adjust for larger blood volumes that shift from the periphery to central circulation (Miwa et al., 1997; Shedahl et al., 1987). The larger central blood volumes are due to the hydrostatic pressure in the wet condition (Frangolais & Rhodes, 1995). With a larger SV, more oxygen can be delivered at any given HR.

Another possible factor is the withdrawal of thermoregulatory mechanism. It is also possible that the thermoregulatory mechanism acts when the body is cold, which would be the case when immersed in water at 28 °C, releasing more epinephrine and norephinephrine. Vasoconstriction occurs to reduce heat loss and shivering may be seen to produce heat, depending on the degree of fat insulation (Tikuisis et al., 1999). As the athlete begins exercising, extra heat is produced. The thermoregulatory effect decreases and the efforts to reduce heat loss and

produce heat are diminished (Toner, Sawka, Foley & Pandolf, 1986). The temperature of the water and enhanced heat exchange prevents body temperatures from increasing as much as when on land, reducing the need for extra blood flow to the skin as seen on land. As a result, HR would not increase as much compared to dry land exercise.

Oxygen pulse is the ratio between $\dot{V}O_2$ and HR (Bambhani, Norris & Bell, 1994) and is a measure of cardiovascular efficiency, indicating how much oxygen is available per heart beat. It can also be determined using the product of SV and the oxygen content difference between arterial and venous blood. Oxygen pulse was higher in water immersion. These changes likely reflect changes in SV and/or oxygen extraction. Water immersion increases SV between 32 and 79% at rest (Christie et al., 1990; Lin, 1984; Farhi & Linnarsson, 1977). Christie et al. reported an elevated SV when comparing water to land exercise but no changes in $\dot{V}O_2$. They concluded that the non-increase in $\dot{V}O_2$ at different levels of exercise from the dry to the wet condition suggests that the muscles do not use the extra oxygen available. This extra oxygen is available due to the significant increases in cardiac output at rest reported by Arborelius et al., (1972), Lin (1984), Farhi and Linnarsson, and Liner, (1994). The oxygen available may not be used due to a limitation in oxygen extraction by the working muscles involved in arm cranking or to poor blood flow (Pendergast, 1989). Blood may be flowing to non exercising muscles possibly due to the vascular compression in the arm region and/or fewer capillary beds. Less developed oxidative machinery in the arms could also explain lower oxygen extraction (Pendergast).

A similar conclusion can be derived from the data in this study. The increase of O_2 pulse at the onset of exercise (significant), at the VT (significant) but not at $\dot{V}O_2$ peak (despite increase) (Table 3-6), in the wet condition compared to the dry condition, suggests an additional delivery of oxygen. This extra oxygen seemed not to be used by the muscles, since there was no increase in $\dot{V}O_2$. The variability seen in the data for O_2 pulse is similar to the variability reported for SV at rest by different researchers (Christie et al., 1990; Lin, 1984; Farhi & Linnarsson, 1977).

There were no significant differences in $\dot{V}_E$ between the wet and the dry conditions during various time points of exercise. These results are consistent with the literature. Sheldahl et al. (1987) reported no differences in $\dot{V}_E$ at any point in time during graded leg cycle ergometry in dry and wet conditions in 19 male subjects. This result in Sheldahl et al.'s study was likely a result of the combined effects of frequency of breathing and tidal volume changes in WI. Maximal frequency of breathing significantly increased in the present study in the wet condition while the max tidal volume decreased in the wet condition (Wet: $\bar{x}$ = 1.43 L and dry: $\bar{x}$ = 1.64 L), maintaining a similar volume per minute.

Max RER in the dry condition in this study is comparable to the results reported by Bhambhani et al. (1998) for female athletes arm cranking under similar condition. There was a significantly lower max RER in the wet condition. That was consistent with the theory of Chang and Lundgren (1996), who postulated that the pressure generated by water immersion increases tissue perfusion, allowing non working muscles to absorb some CO_2, decreasing arterial

CO_2 tension. The body therefore will expel less CO_2, decreasing RER as observed in the present study.

Conclusion

The present findings indicate that arm cranking is a viable alternative method to measure peak oxygen consumption of water-based athletes. The arm cranking results are comparable to other studies and the smaller muscle mass involved in the activity is likely the primary reason for lower $\dot{V}O_2$ peak values compared to treadmill and cycle ergometer test protocols.

A practical finding that can be applied to the daily training of synchronized swimmers is to use lower target heart rates in the water than for on land or use water based exercise test heart rates to prescribe water training. These findings may provide guidance in establishing these target heart rates. It is reasonable to assume that the same effect is seen for other athletes who perform in the water environment, such as swimmers and water polo players.

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Chapter Four: Lung volumes and capacities in and out of the water

Introduction

Previous research has shown that elite synchronized swimmers perform breath holding periods of up to 38 s during a solo routine (Chapter 2) and train a considerable number of hours in the water (up to 25 hrs/week) (Chapter 3). However, the specific adaptations of synchronized swimmers to training and competing in the water have not been extensively studied. From another perspective, the effect of water immersion (WI) on the human body has been studied with other groups of subjects. It is well known that WI decreases lung volume (Agostini, Gurtner, Torri, & Rahn, 1966; Fahri & Linnarsson, 1977) and that the size of the decrease with WI was dependent on depth of immersion. The decrease in lung volume with water immersion is a direct consequence of a diaphragm shift towards the heart, an increase in thoracic blood volume decreasing pulmonary compliance (Sheldahl et al., 1987), and inward forces exerted by water against the chest wall that demand a higher chest wall muscle strength to overcome hydrostatic pressure (Agostini et al. 1966; Fahri & Linnarsson).

There are several factors that influence lung volumes and capacities, including body size, sex, age, race, level of physical activity, circadian rhythms, socio-economic status and exposure to high altitude (Neder, Andreoni, Castelo-Filho & Nery, 1999; Astrand & Rodahl, 1986). Doherty and Dimitriou (1997) showed that lung volume and ventilatory muscle endurance typically increase with training, especially if training is done in the water. Apnoeic training in the

water has been shown to decrease residual volume (Delapille, Verin, & Tourny-Chollet, 2002). It is also possible that training in the water for many consecutive years produces different physiological adaptations in synchronized swimmers that can lead to increased lung volumes and capacities. It is also possible that the breath holding periods that are part of the daily training of synchronized swimmers contribute to changes in lung volumes and capacities. Thus, the purpose of this study was to compare lung volumes and capacities in and out of the water in a group of synchronized swimmers that are accustomed to training in the water.

The hypotheses of this study were that lung volumes (residual volume [RV], expiratory reserve volume [ERV], tidal volume [TV] and forced expiratory volume in 1 s [FEV_1) and lung capacities (total lung capacity [TLC], inspiratory capacity [IC], functional residual capacity [FRC] and forced expiratory vital capacity [FVC]) would decrease when subjects were submerged in water due to water pressure. Further, it was hypothesized that when out of the water, lung volumes and capacities of synchronized swimming athletes will be larger than predicted lung volumes and capacities.

Methods

Subjects

Sixteen subjects were voluntarily recruited from three local synchronized swimming clubs. These subjects were the same as those described in Chapter 3 where they participated in a different experiment. None of the athletes had been diagnosed with any lung disease and all were non-smokers, which were pre-requisites for participation in this study.

The Faculty of Physical Education & Recreation Research Ethics Board granted ethics approval for this study. All subjects were informed of the proposed measures and procedures at a meeting prior to the start of the study. All subjects were volunteers and if they were under the age of 18 they were given time to discuss their possible involvement with their guardians who had to provide permission for their participation. Each subject and parent/guardian, if required, signed a consent form agreeing to participate in this study (Appendix E).

Testing conditions

On the same day, subjects were submitted to the "wet" and the "dry" condition. In the wet condition, subjects were submerged to the clavicular notch in the hydrostatic weighing tank while seated on a chair. The water temperature was 28 ± 1°C. A 4-kg weight belt was positioned on top of the subject's thighs to prevent them from floating. In the dry condition subjects were tested out of the water while seated. The test order was randomly assigned, with half of the subjects tested in the wet condition first, and half tested in the dry condition first. There was a 5 to 10 min break between the two testing conditions. Please note that tests described in this chapter occurred on different days than those described in Chapter 3.

Testing procedures

Subjects were asked to avoid food and caffeine 3 to 4 hr prior to reporting to the lab. They reported to the lab wearing comfortable clothing and a bathing suit. Subjects completed a history questionnaire (Appendix D) and then height and body mass was measured. Height was assessed with a setsquare and measuring tape to the nearest 0.2 cm in bare feet. Body mass was determined to

the nearest 0.2 kg using a beam balance scale (Health-O-Meter, Sunbeam Products, Inc.) with the subjects wearing their bathing suits. Body mass index (BMI; $kg \cdot m^{-2}$) was subsequently calculated.

Lung Function tests

When tested in the wet condition, a 5-min water adaptation period was allowed. The adaptation consisted of the subject sitting quietly in the chair with no activity, before the onset of the test. All other testing procedures were similar in the wet and dry conditions. In both conditions, wet and dry, the subjects were connected through a mouthpiece to the pulmonary function unit (Sensor Medics 2450). Nose clips were used to block nasal breathing. Forced expiratory vital capacity and FEV_1 were measured by asking the subjects to inspire to total lung capacity and force the air out as hard and as fast as they could until they squeezed it all out from their lungs. To calculate RV, TLC, and FRC, the helium dilution technique was used (Meneely, Ball & Kory, 1960). The spirometer was calibrated using a 3 L syringe. After a normal expiration the subject rebreathed a 10% helium mixture until a homogeneous gas mixture was attained with a new and lower helium concentration. Oxygen was added to the mixture to maintain a constant volume at the end of expiration since CO_2 was absorbed from the mixture. After helium equilibration the homogeneous lower helium concentration indicated FRC [$V_{FRC} = (V_{Spirometer} (He_1 - He_2) He_2^{-1})$, where He_1 is the helium concentration prior to mixing (10%) and He_2 is the helium concentration after being diluted by air in the lungs] (Astrand & Rodahl, 1986). After equilibration, the subject performed a maximal expiration followed by a maximal inspiration to TLC. This vital capacity manoeuvre was done once and permitted the calculation

of RV and TLC. This report also provided IC, TV and ERV. The values for FEV_1 and FVC were determined based on three trials. The spirometry trial that gave the largest sum of FEV_1 and FVC was used. Total lung capacity was calculated based on the trial that gave the best result for the sum of FEV_1 and FVC.

Statistical Analysis

One sample t-tests were used to compare the lung volumes and capacities of this group of synchronized swimmers to the normal predicted volumes for a population with similar physical characteristics. T-tests for dependent variables (repeated measures) were used to compare the results between the two conditions, wet and dry, for all the pulmonary function measures. Where families of contrasts involved nonorthogonal variables (e.g.; FVC and FEV_1), a Bonferonni correction was used to establish the appropriate alpha level (Myers & Well, 1995). As a result, the alpha level for the lung function tested by spirometry (FVC and FEV_1) was set at $p \leq .025$ (.05/2) and the alpha level for the other lung volumes and capacities was set at $p \leq .008$ (.05/6). Other alpha levels were set a priori at $p \leq .05$.

A Pearson Product Moment Correlation Coefficient was calculated to determine if there was any correlation between TLC out of the water and hours of training in the water per week, years of synchronized swimming training and age. These and the other statistical comparisons were made using the SPSS software program version 7.5 for Windows®.

Results

Physical characteristics

The physical characteristics of the 16 swimmers that participated as

subjects and their training profile are listed in Table 3-1, Chapter 3.

Lung volumes and capacities

Table 4-1 contains the lung capacities measured for the wet and dry conditions. Total lung capacity, FRC, and FVC in the dry condition were significantly larger than in the wet condition, while IC in the wet condition was significantly larger than in the dry condition. Total lung capacity in or out of the water did not significantly correlate with age, years of swimming or hours of swimming per week

Table 4-1. Lung capacities (BTPS) - Values are $\bar{x} \pm$ SD (range).

	Wet	Dry
TLC (L)	5.94±0.98[a] (4.81 – 8.06)	6.20±1.08[a] (4.97 - 8.36)
IC (L)	3.29±0.74[a] (2.41 – 5.06)	3.02±0.66[a] (2.11 - 4.57)
FRC (L)	2.41±0.30[a] (1.94 – 3.02)	2.94±0.45[a] (2.44 - 4.10)
FVC (L)	4.61±0.76[b] (3.72 – 6.27)	4.75±0.84[b] (3.69 - 6.61)

[a] Significantly different at $p \leq .008$.
[b] Significantly different at $p \leq .025$.

Table 4-2 contains the lung volume measurements for the wet and dry conditions. Forced expiratory volume in 1 s and ERV were both significantly larger in the dry condition than in the wet condition.

Table 4-2. Lung volumes (BTPS) - Values are $\bar{x} \pm$ SD (range).

	Wet	Dry
RV (L)	1.33 ± 0.31 (1.01 - 1.81)	1.45 ± 0.39 (1.00 - 2.43)
TV (L)	1.11 ± 0.45 (0.63 - 2.17)	1.04 ± 0.50 (0.60 - 2.41)
FEV_1 (L)	3.81 ± 0.52[a] (3.23 - 4.90)	4.00 ± 0.56[a] (3.32 - 5.25)
ERV (L)	1.08 ± 0.21[b] (0.69 – 1.46)	1.50 ± 0.23[b] (1.08 - 1.98)

[a] Significantly different at $p \leq .025$
[b] Significantly different at $p \leq .008$.

Predicted values were derived for different measures using the predictive

equations from the Morris/Polgar dataset (SensorMedics, 1988) as shown in Table 4-3. Table 4-4 contains the percent of normal predicted volumes calculated by dividing the measured volumes and capacities by the normal predicted values for each measure (x 100).

Table 4-3. Predictive equations from Morris/Polgar dataset (SensorMedics, 1988)

Equation		Reference
FVC = 0.115 H – 0.024 A – 2.852	(age >18)	Moris (1976)
= 0.113 H – 3.82	(age ≤ 18)	Polgar & Promadhat (1971)
TLC = 0.201 H – 0.008 A –7.49	(age > 18)	Goldman & Becklake (1959)
= 0.1493 H – 5.101	(age ≤ 18)	Polgar & Promadhat *
RV = 0.0813 H + 0.009 A – 3.9	(age > 18)	Goldman & Becklake (1959)
= 0.029 H – 0.9192	(age ≤ 18)	Kasik, Niden, Barclay (1961)
FRC = 0.135 H – 0.00771 B – 4.74	(age > 18)	Goldman & Becklake (1959)
= 0.069 H – 2.295	(age ≤ 18)	Polgar & Promadhat
FEV_1 = 0.0711 H – 0.021 A – 0.867	(age > 18)	Hollis, Kory & Syner (1966)
= 0.112 H – 3.91	(age ≤ 18)	Polgar & Promadhat (1971)

Where: H = height in inches, A = age in years and B = body mass in pounds
* Unpublished

Lung volumes and capacities measured in the dry condition showed a large positive percent difference compared with the predicted values for a population of the same age, height and sex (Table 4-4). The one sample t-test comparing predicted results for the population to the swimmers showed all results were significantly higher for the swimmers. Note that all values, except RV, are within the high normal values.

Table 4-4. Volumes and capacities in the dry condition - Values are $\bar{x} \pm$ SD (range).

Measure	Dry (% of predicted)	Normal values (95% confidence interval)[a]
TLC	120 ± 18 (91 –155)	80 to 120%
RV	126 ± 49 (61 – 208)	75 to 120%
FVC	120 ± 16 (97 – 162)	80 to 120%
FRC	116 ± 24 (76 – 153)	75 to 120%
FEV_1	110 ± 10 (98 – 130)	80 to 120%

[a]Salzman, S. (1999)

Discussion

This study examined pulmonary function in synchronized swimming female athletes in and out of the water. The outcomes of this study are important because they provide updated information about female synchronized swimmers after rule changes such as the decrease in routine times, the considerable increase in speed in routines and the recommendations from FINA demanding less importance of breath holding in judging routines. These changes have already impacted the sport and may have changed the characteristics of the swimmers, therefore this type of study is important.

The results partially support both main hypotheses. Water immersion resulted in a significant decrease in TLC, FRC, FVC, ERV and FEV_1 but the decrease was not significant for RV and TV. Contrary to the expected, inspiratory capacity significantly increased in the water. Inspiratory capacity was impacted by the decrease in ERV and RV that allowed for an increase in IC. All the predicted values were within normal ranges except for RV (Salzman, 1999) but the one sample t-test demonstrated that means of the synchronized swimmers were significantly larger than means of the normal population.

Total lung capacity has been reported to decrease with water immersion. Whithers and Hamdorf (1989) have reported decreases in TLC of 8.4% in male subjects while immersed to the neck in water. In the present study, TLC decreased an average of 4.3% in the water versus on land values. It is possible that training in water may have led to the development of additional respiratory muscle strength, which prevented a large TLC decrease when immersed. Possible differences in methods or the gender of the subjects might also have accounted for the differences. An important fact related to gender is the impact of the hydrostatic pressure on taller subjects. The lungs of male subjects would be immersed deeper in the water and therefore subjected to greater hydrostatic pressure. This could also have accounted for the difference between groups.

The TLC value found in the present study (6.21± 1.08 L) was higher than the TLC found in the dry condition reported by Roby, Buono, Constable, Lowdon and Tsao (1983) and by Bjurstrom and Schoene (1987) for national calibre synchronized swimmers (5.58 ± 0.68 L; $\bar{x}$ ± SD and 5.74 ± 0.171 L; $\bar{x}$ ± SE respectively). The high variability found in the present study for TLC was likely due to the different calibre of synchronized swimmers in the sample or their height range (1.61 to 1.82 m). The difference in height between subjects in the present study (1.70 ± 0.06 m) and those of Roby et al. (1983)($\bar{x}$ ± SD = 166.2 ± 6.2 cm) and Bjurstrom and Schoene($\bar{x}$ ± SE = 167 ± 6.7 cm) does not account for the difference in TLC among these studies. The predicted values for TLC calculated for the subjects from Roby's et al. and Bjustrom & Schoene's studies using the equations listed in Table 4-3 were 106% and 104% respectively whereas

the subjects in this study presented a mean of 120% of the predicted values.

Bjurstrom & Schoene (1987) reported an average IC measured out of the water of 2.82 ± 0.15 L; ($\bar{x}$ ± SE) for national level synchronized swimmers, which was lower than what was measured for the dry condition in the present study (3.02 ± .66 L). Height difference and consequently a larger TLC, may explain the larger IC in the present study. In contrast to all the other capacities, IC was larger in the wet condition (8.2%) than in the dry condition. This increase in IC is explained as a compensation for the large decrease in ERV (Whithers & Hamdorf, 1989), where normal expiration approaches RV.

In three different studies examining men not accustomed to training in water, FRC decreased between 29 and 43% compared to values on land (Begin et al., 1976; Whithers & Hamdorf, 1989; Fahri & Linnarsson, 1977). In the present study, female synchronized swimmers had an average decrease in FRC of 18% from the dry to wet condition. Females that have lower FRC will likely have smaller changes in FRC from land to water.

Roby et al. (1983) reported the average FVC measured out of the water as 4.40 ± 0.54 L ($\bar{x}$ ± SD) (107% of the predicted value calculated from Table 4-3) for national calibre synchronized swimmers which is lower than the FVC measured in the dry condition of the present study (4.75±0.84 L) (120% of predicted). This may be due to an increase in training time currently spent in the pool compared to Roby et al.'s research. In the present study FVC decreased with water immersion by an average of 2.9%, reflecting the decrease in TLC as a result of hydrostatic pressure. However, this decreased value in the water was still

higher than that reported by Roby et al.

Residual volume decreases with water immersion as a result of hydrostatic pressure and pulmonary engorgement (Whithers & Hamdorf, 1989). Whithers and Hamdorf reported a decrease of 19.7% in RV measured in water versus land in male subjects (ages = 19.5 to 43.3 yrs) using the helium dilution technique. The present study showed an average decrease of only 8.3% in RV when comparing wet to dry conditions, and this difference was not statistically significant due to the Bonferonni correction ($p = .034$). The difference between results may be partially attributed to the quantity of air trapped behind closed airways in Whithers and Hamdorf 's subjects since they are older than the subjects in the present study. Age is associated with an increase air trapped behind closed airways and consequently is associated with an increase in RV (Neder et al., 1999). The extra hydrostatic pressure from the wet condition may have helped decrease RV by applying extra pressure to the airways, but comparison is difficult because of the different sex of the groups. Another possible explanation is that training in the water helped decrease RV out of the water (Delapille et al., 2002) and allowed for a smaller difference between the two conditions.

Differences in gender, height and age are known factors that contribute to the variations in RV in healthy subjects. The aging process reduces lung elasticity and increases airway closure volume (Neder et al., 1999). Apnoeic training in the water has been demonstrated to decrease residual volume by 10% due to increased chest wall muscle strength (Delapille et al., 2002). In the present study the average RV measured in the dry condition (1.45 ± 0.39 L) was lower than the

one reported for out of the water by Roby et al. (1983) (1.84 ± 0.32 L; $\bar{x}$ ± SD) but higher than the one reported by Bjurstron and Schoene (1987) (1.1 ± 0.15 L ($\bar{x}$ ± SE). When the predicted values were compared, results from the present study (126%) were slightly higher than those of Roby's et al. (119%) and much higher than Bjustronm and Shoene's (70%). The large difference in RV in the present study compared to Bjurstrom and Schoene's data could be due to less exposure to apnoeic training. Typically a synchronized swimmer will start to train at the age of 8 years. The absolute time that the swimmers in the present study were submitted to synchronized swimming training may possibly be lower than the older athletes from Bjurstrom and Schoene's study. An alternative explanation could be related to the trends of synchronized swimming at the time of Bjurstrom and Schoene's study. In the 1990's there were some educational programs from the International Federation of Swimming related to the potential dangers of large breath holding periods in synchronized swimming. The decrease in breath holding in routines, and consequently the reduction in apnoeic training on a daily basis in synchronized swimming since that time, could have impacted RV values in the present study. Differences in methods might also contribute to the differences between studies. Roby et al., used single breath carbon monoxide pulmonary diffusion that included 10% of helium in the gas mixture when determining RV and TLC whereas the present study and Bjurstrom and Schoene's study used the helium dilution technique as described previously. Posture is also known to contribute to differences in results for lung volumes.

Some authors reported TV as remaining constant at rest while immersed in

water (Whithers & Hamdorf 1989; Sheldahl et al., 1987), while Chang and Lundgren (1996) reported a decrease of 11% for TV in males when immersed at rest in thermoneutral water. In the present study there was no significant difference in TV between the wet and dry conditions (Table 4-2), supporting the findings of Whithers and Hamdorf and Sheldahl et al.

In the present study the comparison between the dry and wet conditions demonstrated a significant decrease in FEV_1 of 4.5% while immersed (Table 4-2). The ability to blow out air as fast as possible in 1 s is dependent on lung volumes, muscle strength and on airway resistance. TLC was reduced during immersion and therefore the amount of air that could be expired in 1 s was reduced. Since the subjects that participated in the present study were healthy, airway obstruction should not have been a factor. The resistance in the small airways can be expected to increase faster in the water than on land due to the fact that the volume of the lungs in the wet condition was smaller. The volume of the lungs while submerged is influenced by the external pressure (where more strength is needed to counterbalance the water pressure), extra blood pooled to the lungs from the extremities, and a shift of the diaphragm towards the surface that takes up some of the volume of the lung. Muscle strength counterbalances these changes, accounting for the variability seen (Agostini et al., 1966; Hong et al., 1971; Fahri & Linnarsson, 1977).

Previously reported FEV_1 values measured out of the water for synchronized swimmers were 114% (Roby et al., 1983), and 118% (Bjurstrom & Schoene, 1987) of the predicted values, both calculated based on the predicted

formula in Table 4-3. In the present study FEV_1 was 110% of the normative predicted value. The different calibre of swimmers and consequently the amount of time spent swimming could account for the difference between the three groups. The important finding is that all the three studies reported an average FEV_1 for SS that is in the upper range of the normal predicted values.

In the present study, ERV decreased in the wet condition by 28%. Whithers and Hamdorf (1989) reported a decrease of 61.9% in ERV from land to water for male subjects. The ERV decrease is attributed to the hydrostatic force pressing inwards on the chest wall and upwards on the diaphragm (Whithers & Hamdorf) and to the FRC decreases (Hong, Cerretelli, Cruz & Rahn, 1969).

The larger lung volumes and capacities observed in the present study than those expected by prediction equations may have been due to years of training in water, especially during the developmental years (Doherty & Dimitriou, 1997). Delapille et al. (2002) suggested that apnoeic training in the water is responsible for an increase of 5 to 10% in lung volume and a decrease of 10% in residual volume by increasing chest wall muscle strength. When immersed in the water, water pressure and the extra blood volume pooled from the extremities of the body contribute to the reduction in lung volumes and capacities. According to Hong et al. (1969), the work of breathing increases during immersion at rest. The increase in the work of breathing was a result of the smaller lung volumes and increased airways resistance. Training consistently under water pressure may lead to the development of additional respiratory muscle strength that may consequently lead to lung volume increases measured on land.

The results from the present study are consistent with the latter suggestions. The synchronized swimmers had a TLC that was 120% of the predicted value and a FVC that was 120% of the predicted value, both of which are in the upper range of the normal values for an average population of the same age and height (Table 4-4). (Statistical analysis showed that the means were significantly different). The FRC measured in the dry condition was 116% of the predicted value and was similar to that reported by Bjurstrom and Schoene (1987) for national level synchronized swimmers. Training in the water for the present group did not seem to decrease RV, which was 126% of the predicted volume, which is in opposition to what was suggested by Delapille et al. (2002). Residual volume in the present study seemed to have been consistent with the increases in lung volume seen for all other measurements.

Doherty and Dimitriou (1997) reported that swimmers had higher FEV_1's than land based athletes and untrained subjects. Female swimmers in their study ($\bar{x}$ height = 163 cm), had higher FEV_1's ($\bar{x}$ = 3.3 L) than land based athletes ($\bar{x}$ = 2.9 L) (n = 72, $\bar{x}$ height = 159 cm) and their sedentary counterparts ($\bar{x}$ = 2.7 L, $\bar{x}$ height = 157 cm). The higher FEV_1 for female swimmers corresponded to 11% higher values for FEV_1 measured out of the water for the swimmers than normative predicted values for females of the same age and height. Similarly, the synchronized swimmers in the present study had a 10% higher FEV_1 measured in the dry condition (Table 4-4) than what is predicted by normative values. Doherty and Dimitriou suggested that the superior FEV_1 was related to the amount of time swimmers exercised in the wet condition and the intensity of

training apart from subject's height. Without undertaking a long-term study it is not possible to conclude that training is responsible for this change, but it seems that the SS have either acquired a higher FEV_1 through years of training or they were genetically pre-disposed with this capability which is an asset for them in synchronized swimming.

Conclusion

The data from the present study reinforces the idea that training in the wet condition for several years will improve lung volumes and capacities but only a long-term study will be able to answer this question. An alternative explanation for the results is that there is a selection process where synchronized swimming attracts those athletes with naturally larger volumes and capacities. The benefits that the athletes gain from the increased lung volumes and capacities in their performance in synchronized swimming, especially while breath holding, is still to be determined in further research.

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Chapter Five: Breath holding at rest with water immersion

Introduction`

Breath holding (BH) is a unique feature of the sport of synchronized swimming. The swimmers train and compete while performing intermittent BH periods of varying length, as shown in Chapter 2. However, there is limited information available about the physiological responses that pertain to this sport and its athletes despite the numerous investigations of BH and water immersion (WI) without exercise (Hong, Rahn, D. Kang, Song & B. Kang, 1963; Masuda, Yoshida, Hayashi, Sasaki & Honda, 1982; Hentsch & Ulmer, 1984; Ferreti et al., 1991; Gooden, 1994; Chang & Lundgren, 1996; Schagatay & Holm, 1996; Pan, He, Kinouchi, Yamagushi & Miyamoto, 1997; Ferrigno et al., 1997; Delapille Verin, Tourny-Challot & Pasquis, 2001). Research has shown that BH times are prolonged in the water compared to on land (Sterba & Lundgren, 1985, Pan et al., 1997). The group of physiological responses (respiratory, vascular and cardiac) that lengthen BH time during WI have been termed the "diving reflex" or "diving response" (Gooden, 1994). The diving response is induced by apnoeic and can be enhanced by cold face immersion. The main aim of the diving response is to maintain adequate oxygen (O_2) levels for the brain and heart (Sterba & Lundgren, 1985).

Psychological factors are known to play an important role in BH with or without WI and the will to withstand physiological responses while BH will likely contribute to longer BH periods at rest (Hentsch & Ulmer 1984). As subjects train to hold their breath, they go through psychological adaptations such as

reduction in the fear associated with BH and increased ability to withstand breathing stimuli and motivation that allow them to withstand the urge to breathe for a longer period of time. Once this psychological training has occurred, physiological mechanisms become the most important factors affecting BH time (Hentsch & Ulmer, 1984).

Of the studies that have examined BH and synchronized swimmers (SS) at rest, all have limited themselves to reporting BH times and blunted responses to partial pressures of carbon dioxide (PCO_2) out of the water (Bjustrom & Schoene, 1987) and heart rate (HR) decreases while BH at rest during WI (Figura, Cama & Guidetti, 1993). This study was conducted to provide a better understanding of the cardiorespiratory responses during maximal BH at rest in synchronized swimmers. Differences in BH response between synchronized swimmers and active females from non-swimming sports were also examined.

There were two main hypotheses in this study. The first was that maximal BH times at rest would be larger for synchronized swimmers than for similarly fit subjects unaccustomed to BH and minute ventilation ($\dot{V}_E$) and oxygen consumption ($\dot{V}O_2$) after BH would be higher for SS due to the hypothesized higher BH times. The second hypothesis was that there would be an oxygen deficit created while BH that will be recouped during recovery. Recovery time would take longer for BH trained subjects due to the hypothesized longer time they would be breath holding and recovery to pre BH $\dot{V}_E$, and $\dot{V}O_2$ levels would happen within 25 s after BH ends for both groups as determined by previous pilot work.

Methodology

The subjects

The subjects were 15 female synchronized swimmers and 15 active females who served as controls (C). The SS were volunteers from two local elite and sub-elite synchronized swimming clubs. The C group subjects were volunteers from university varsity teams and physical education students. Recruitment of the C group followed the recruitment of the SS group. Control group subjects were matched to synchro subjects on the basis of sitting height, since sitting height is known to correlate well with lung volumes (Kivastik & Kingisepp, 1995). All the controls were comfortable being in the water. At the time of data collection, all the C subjects were physically active but were not participating in any swimming activity. Thirteen of the C group subjects had no competitive swimming experience and 2 of the C group subjects had previously competed in speed swimming but not above the Provincial level. All the subjects were non-smokers and could breath hold for at least 45 s out of the water at rest, a requirement of the study. None of the subjects had ever suffered from lung disease.

During the first contact with the C group, prior to the first orientation session, a pre screening of sitting height was done and the subjects were matched to a particular SS subject. Subjects were excluded if the sitting height did not match the required height of one of the SS athletes.

During the first orientation session a history inventory questionnaire to collect descriptive data on each subject was completed, the ability to breath hold for at least 45 s was verified and a spirometry test done. Subjects needed to have

a ratio of forced expiratory volume in 1 s to forced vital capacity (FEV_1/FVC) of at least 75%, which is comparable to normal levels for sedentary people (Leme, 1995). If all the criteria for participation were met, subjects were asked to familiarize themselves with the mouthpiece out of the water. The sitting height measurement procedure was repeated in the lab on the second orientation day (see measures section for a description of the procedures). Practice breath holding trials in the water were also performed at this time.

The Physical Education and Recreation Research Ethics Board granted ethics approval for this study. Each subject signed a consent form agreeing to participate in this study prior to her participation (Appendix E). All subjects were volunteers and if they were under the age of 18, a parent or legal guardian provided permission for participation.

Measures

The history inventory questionnaire provided information about main sport activity, degree of involvement in water training, ease with being in the water, present participation in water activities, lung diseases including asthma, menstrual cycle status and smoking status. Following the completion of this questionnaire the subjects proceeded to perform the spirometry test.

Forced expiratory vital capacity and FEV_1 were measured using a hand held spirometer (Micro Spirometer - Micro Plus – Vacumed Inc. Ventura, California, USA). The spirometry test was done in a sitting position with the back straight. The subjects were asked to take a large maximal breath (total lung capacity; TLC) and then exhale through the spirometer as fast and as continuously as possible with the researcher encouraging a fast and hard expiration. Three trials

were done and the best result for FVC was used to determine the trial to report.

Standing height of subjects with shoes removed, was measured to the nearest 0.2 cm using a setsquare and measuring tape (Gordon, Chumlea & Roche, 1991). Sitting height was measured with a setsquare and a measuring tape to the nearest 0.2 cm while the subject was sitting against a wall on a bench that allowed a 90 degree angle at the hip joint (Martin, Carter, Hendy & Malina, 1991). Body mass was measured with the subject in a bathing suit using a beam balance scale (Health-O-Meter, Sunbeam Products Inc.) to the nearest 0.2 kg (Gordon et. al. 1991).

For the ventilation measures (BH responses at rest) a metabolic cart was used (CPX/D, Medical Graphics Corporation, St. Paul, Minnesota, USA). Prior to the test, the metabolic cart was calibrated with known gases and a 3 L syringe according to the manufacturer's protocol. The metabolic cart was calibrated again at the end of each test to verify accuracy. The metabolic cart was operated in breath by breath mode and continuously monitored the expired air of each subject for $\dot{V}_E$, fraction of expired oxygen (F_EO_2), fraction of expired carbon dioxide (F_ECO_2), end tidal partial pressure of oxygen ($P_{ET}O_2$), end tidal partial pressure of carbon dioxide ($P_{ET}CO_2$) and calculated $\dot{V}O_2$, and carbon dioxide production ($\dot{V}CO_2$).

The standard mouthpiece was modified to ensure continuous data collection. During pilot work it was determined that the metabolic cart data collection process stopped after 12 to 15 s of BH. In order to ensure continuous data collection an adaptor was attached to the mouthpiece to fit a dummy

breathing line connected to a valve and a breathing filter (Figure 5-1). The researcher breathed through the dummy breathing line to ensure continuous data collection while the subject was breath holding (the lack of a breath for 12 s caused the cart to switch to stand by thus preventing post BH data collection). A pneumotach connected the mouthpiece to a two- way Rudolph valve (2700, Hans Rudolph Inc., Kansas City, Missouri, USA) and a pair of hoses which conducted expired air from and fresh air to the subject were also part of the custom made mouthpiece. All connections were sealed using a combination of Teflon tape, vinyl tape, nylon safety ties and metal hose clamps. For each test the mouthpiece seal was tested by immersing it in water and blowing through the inspiration hose (using a filter) with the end of the mouthpiece sealed. The dead space of the system was calculated and determined to be 120 ml and was inputted to the metabolic systems software.

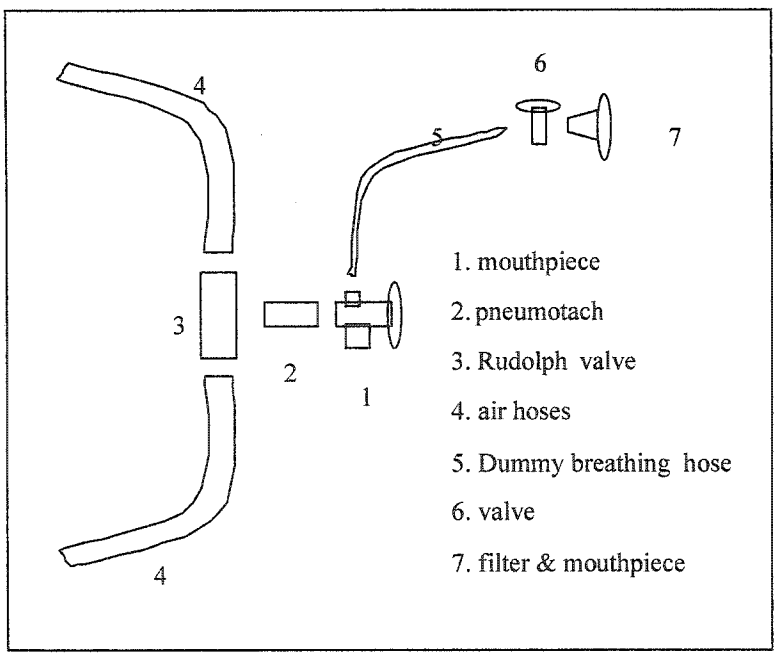


Figure 5-1. Mouthpiece schematic (BH study)

In all tests HR was monitored with a monitor (Polar Vantage, Kempele, Finland). Heart rate was recorded every 5 s and downloaded to a personal computer for further analysis.

During BH tests a hand held oximeter (8000K2, Nonin Medical Inc., Plymouth, Minnesota, USA) was used to measure arterial blood saturation (S_aO_2). Oximetry is an indirect method that measures S_aO_2 in a non-invasive way (ACSM, 1995). A probe positioned on the subject's forehead detected the difference between infrared light diffusion through the tissues. This method is considered to provide an accurate measurement of the quantitative change in S_aO_2 (Benoit et al., 1997). In the range of 70 to 100%, the accuracy is generally around 2 to 3%, provided that the equipment is positioned properly. Fast decreases in saturation, movement and hypothermia decrease accuracy. Finger probes tend to be more accurate than others (Clayton, Webb, Ralston, Duthie & Runciman, 1999).

The mental readiness form for performance (MRF) (Murphy, Greespan, Jowdy & Tammen, 1989) is a visual analog scale (VAS) that is used to grade subjective feelings and efforts. The MRF was used in this study to determine the level of anxiety associated with the BH periods at rest. The MRF has been tested for its validity against the competitive state anxiety inventory 2 and results supported the MRF as a brief and accurate measure of competitive anxiety (Krane, 1994). The MRF consists of three scales. The first scale corresponds to cognitive anxiety (calm vs. worried), the second scale corresponds to somatic anxiety (relaxed vs. tense), and the third scale corresponds to self confidence

(confident vs. scared). Before the first breath hold and after each of the BH periods at rest, the lifeguard asked the subjects to select a value on the scale that best represented their anxiety towards BH and a research assistant recorded these numbers.

Procedures

All measures were conducted in the laboratories of the Faculty of Physical Education and Recreation. The study required three visits to the lab, beginning with two orientation sessions and ending with one testing session (Figure 5-2). All subjects were tested out of their luteal menstrual cycle phase to avoid interference in chemosensitivity (Bjurström & Schoene, 1987). Menstrual cycle was assessed through a questionnaire (Appendix D). During the first orientation session, the subjects completed the history inventory questionnaire (Appendix D), a spirometry test, and a verification of their ability to meet the inclusion criteria by performing two maximal BH trials. If a subject was unable to hold their breath for 45 s the subject was excluded from the research group. In order to become familiarized with the mouthpiece (Figure 5-1), the subjects who qualified performed two additional maximal BH trials out of the water at the command of the researcher with the mouthpiece in place. The interval between the first and second trial was between 1 to 2 min, at the subjects' volition. When the subject was ready to hold their breath, they were instructed to exhale maximally [to residual volume (RV) and inhale maximally to TLC], and then hold their breath. Hyperventilation prior to BH was discouraged.

On the second visit to the laboratory, sitting height was verified and the mouthpiece refitted. Following this, subjects were asked to enter the water and sit

on the same underwater cycle ergometer chair where they would perform the maximal BH tests during the following visit. They then performed two maximal BH trials at the command of the researcher using the mouthpiece and the same techniques as in the first visit to the lab except that this time they were immersed to the clavicular notch. Following inspiration they were instructed to lean forward and put their face in the water to ear level, while breath holding. The subjects performed two training trials in the water. The interval between the first and the second trial was from 1 to 2 min, based on the subjects' volition.

Pre – orientation session:		
• Contacting subjects • Sitting height check		
Sessions:		
Day 1 – Orientation session:	Day 2 – Orientation session:	Day 3 – Testing session:
• History inventory questionnaire • Spirometry • 45 s BH out of the water (1 to 2 trials) • 2 BH trials with the mouthpiece out of the water	• Sitting height • 2 BH trials in the water	• Height • Body mass • BH at rest in the water

Figure 5-2. Data collection summary

Testing procedures were conducted on the third visit to the laboratory. Subjects wore bathing suits and were instructed to avoid food and caffeine 3 to 4 hr prior to reporting to the lab. Since WI and BH involved a risk of unconsciousness or drowning, a certified lifeguard was on duty for the testing procedures. Subjects were weighed and their height measured. A HR monitor transmitter was positioned around their chest and held in place with an elastic strap. The oximeter probe was taped to the forehead. A headpiece apparatus was attached to the mouthpiece and positioned comfortably on the subject's head. The pneumotach was connected to the metabolic measurement cart. Ankle weights

were fitted to the subjects' ankles to prevent subjects from floating. Subjects entered the water and sat on a cycle ergometer bench. To further prevent the subject from floating, a 4-kg weight belt was positioned on their lap and they were strapped to the cycle ergometer chair. The water level was adjusted so that each subject was submerged to the clavicular notch and the temperature of the water was kept constant at 28 ± 1°C. A nose clip was worn by each subject. Use of swim goggles was optional.

At the command of the researcher, the lifeguard (in the water) started the HR monitor. At this same moment the metabolic measurement cart was started. A research assistant started recording information from the oximeter on a regular basis (every 10 s during BH and during the first 30 s of recovery and every 30 s afterwards). The study consisted of five intermittent periods of maximal BH at rest with the face immersed using the time line shown in Figure 5-3.

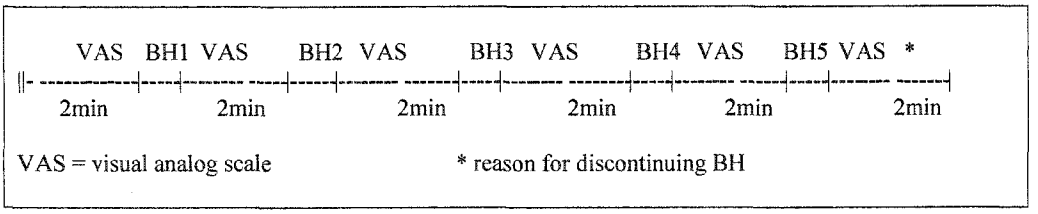


Figure 5-3. BH at rest test timeline

At the command of the researcher the subjects expired and then inspired deeply. The subjects leaned forward to put their face in the water to the ear level. A stop watch was started when each subject initiated their forward lean to put their face in the water. While the subjects were BH the researcher opened a valve and started breathing through a filter into the pneumotach to maintain the flux of air through the pneumotach so that the metabolic cart would continue to sense

normal breath by breath data collection and not trigger a software error (see Appendix C for the full validation of this procedure). Approximately 5 s before they began breathing again the subjects rang a bell to inform the researcher that they were going to exhale. The researcher stopped breathing through the pneumotach, closed the valve and the subject exhaled and then resumed normal breathing. It was important to obtain results from the first breath, as this breath closely represents the alveolar gas concentration following BH. At this point the stopwatch was stopped. Subjects rested between BH periods for 2 min. Heart rate was continuously recorded. The VAS was used to determine the anxiety levels of the task performed prior the start of the test and after each BH period (Appendix F). At the end of the BH at rest test the subjects were asked to identify the reasons why they had to stop breath holding in general. In the event that the researcher found, by visual inspection, that the metabolic cart lines were gaining moisture, the test was stopped, the lines changed and the test re-started.

Data analysis

One sample T-tests were used to determine if the net oxygen consumption was significantly different from 0. T-tests were also used to determine if there were differences in oxygen consumption, HR and ventilation from one point in time to another during the recovery period. T – tests were also used to compare group characteristics. Apha level was set a priori at $p \leq .05$.

A series of two-way (2x5) analysis of variance (ANOVA) tests for repeated measures (group x condition) were used to compare a number of parameters for each successive BH period at rest (there were a total of 5 BH

periods). The parameters were BH time, baseline rate of $\dot{V}O_2$ prior to BH, excess post breath holding oxygen consumption (EPBHOC) during recovery, S_aO_2, and HR as well as the respiratory parameters (pre $\dot{V}_E$, post $P_{ET}CO_2$ and $P_{ET}O_2$). For all the comparisons the alpha level was set a priori at $p \leq .05$.

A Pearson Product Moment Correlation Coefficient was calculated to determine if there was any correlation between sitting height and BH time, sitting height and FVC, BH time and hours of training in the water, years of synchronized swimming training and VAS. These and the other statistical comparisons were made using the SPSS software program version 7.5 for Windows®.

The $\dot{V}O_2$ needed to maintain homeostasis without BH is termed the 'baseline rate'(Figure 5.4). Excess post breath holding oxygen consumption (EPBHOC) is the term used to describe the oxygen consumption measured above the baseline rate during the recovery period. The baseline rate was calculated based on a 30 s period prior to BH. The time period used to determine the baseline rate began at 45 s prior to BH and ended at 15 s before BH. This time period was used to avoid possible O_2 consumption increase in anticipation of BH, which was observed in some subjects during a pilot study. The area above the baseline in this anticipatory response to BH was termed A. The estimated oxygen consumption during BH measured in litres based on the baseline rate was termed B. (Figure 5-4). [B= baseline(ml/min)/60 s* BH (time in s)].

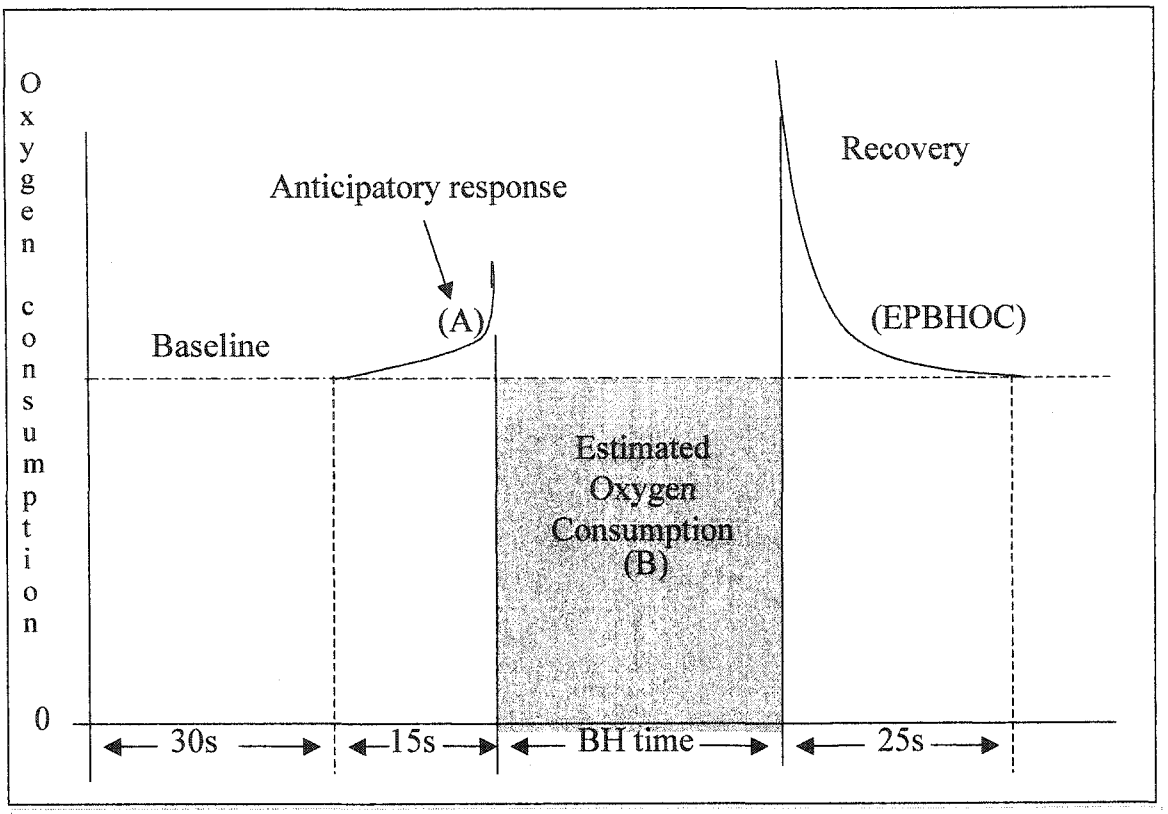
To determine if there was an oxygen conservation effect, the estimated values for oxygen consumption during BH were calculated based on the baseline

rate (B) and this was compared to the oxygen consumption immediately prior to and following BH based on the metabolic data collected (EPBHOC + A). The sum of the area above the baseline during recovery (EPBHOC) and the area above the baseline in the anticipatory 15 s before BH (A) was subtracted from the estimated oxygen requirement (B) to find a net value that indicates whether a conservation effect occurred or not (Net = (A + EPBHOC) – B). The anticipatory 15 s before BH (A) was included in the equation because pilot work showed that some subjects hyperventilated and increased their $\dot{V}O_2$ prior to BH, possibly storing some O_2 that is used during BH. If the net result of this comparison is positive, the measured O_2 consumption is larger than what was estimated from the baseline. If the net result is negative, the measured O_2 consumption is smaller than that estimated from the baseline demonstrating economy while breath holding. To summarize:

Net result = 0 → no conservation effect (the baseline amount of oxygen was used during BH).

Net result > 0 → no conservation effect (more oxygen was consumed than what was predicted by the baseline).

Net result < 0 → there is an oxygen conservation effect (less oxygen was consumed than what was predicted by the baseline).



Where: A = Anticipatory phase
B = Estimated oxygen deficit due to BH
EPBHOC = oxygen measured above baseline during recovery

Figure 5-4. Phases of BH.

To examine the pattern of recovery at rest after BH, data from the maximal BH period for each subject was compiled and analysed. The analysis focused on HR, $\dot{V}O_2$ and $\dot{V}_E$ during the recovery phase.

There were some cases where parts of the results were eliminated. Oxygen saturation, as measured by the oximeter, was eliminated if the difference between HR provided by the oximeter and HR generated by the HR monitor was greater than 10 b·min^{-1}. The data generated by the metabolic cart was not used if numbers did not follow the characteristic response of the same subject during previous tests. This occurred because the data was collected in the water and

sometimes moisture got into the lines and the machine failed to respond as it normally would. These points were eliminated, which is why the "n" values sometimes differ when reporting results.

Results

Subject characteristics

Subject's characteristics are shown in Table 5-1. The SS were significantly younger than the C group. Synchronized swimming experience and swimming hours were significantly higher for SS. There were no other statistically significant differences between groups for height, body mass, sitting height and FVC.

Table 5-1. Group characteristics – ($\bar{x} \pm SD$)

	SS (n=15)	C (n=15)
Age (years)	18 ± 2[a]	22 ± 3
Height (cm)	170.6 ± 5.2	169.2 ± 8.9
Body mass (kg)	60.5 ± 6.9	65.0 ± 8.8
Sitting height (cm)	89.8 ± 3.3	90.1 ± 3.3
FVC (L)	4.4 ± 0.7	4.1 ± 0.5
Water training per week (hr)	20.4 ± 8.7[a]	0
Synchronized swimming experience (years)	9 ± 4[a]	0

[a] Significantly different at $p \leq .05$.

Breath holding times

Results revealed a significant main effect showing that SS group BH times were significantly larger than the C group. There was also a significant difference in BH times independent of the groups. BH times increased significantly in both groups from BH 1 to BH 5 (Table 5-2).

Table 5-2. BH times (s) - Values are $\bar{x} \pm$ SD and (range).

	SS (n=15) [a, b]	C (n=15) [a,b]
BH 1 (s)	75.48 ± 27.89 (36 – 135)	56.94 ± 11.49 (38 – 77)
BH 2 (s)	86.22 ± 27.63 (56 – 155)	63.77 ± 14.36 (39 – 90)
BH 3 (s)	95.36 ± 29.84 (59 – 151)	68.96 ± 16.27 (47 – 99)
BH 4 (s)	97.16 ± 33.16 (55 – 162)	73.54 ± 19.69 (45 – 114)
BH 5 (s)	109.79 ± 39.31(52 – 168)	78.28 ± 24.96 (31 – 138)

[a] Indicates significantly different from BH1 to BH 5 at $p \leq .05$.
[b] Indicates significant difference between SS and C at $p \leq .05$.

There was no correlation between maximal BH time and sitting height ($r = .029$). Sitting height was positively correlated with FVC ($r = .637$, $p \leq .01$). There was also a significant correlation between BH times and hours of water training independent of group ($r_{bh1} = .424$, $r_{bh2} = .513$, $r_{bh3} = .600$, $r_{bh4} = .476$ and $r_{bh5} = .562$, all at $p \leq .05$) because controls did not train in the water. When SS were analyzed separately, no significant correlation was found between BH times and hours of swimming or years of experience.

The mental readiness form for performance

There was no correlation between BH times and the mental readiness form for performance (MRF) for SS, for C or for the groups collapsed. The reasons described by the subjects stopping BH were compiled and are listed in Table 5-3.

Table 5-3. Reasons for ending BH - Values are numbers of respondents and (%).

Reasons given after the last BH took place	SS (n=15)	C (n=15)
Involuntary lung movements – could not control	6 (40%)	3 (20%)
Needed to breathe	3 (20%)	3 (20%)
Panic	1 (6.6%)	5 (33.3%)
Chest was tight/started to burn	2 13.2%)	1 (6.6%)
Getting dizzy	1 (6.6%)	1 (6.6%)
Urge to cough	1 (6.6%)	-
Loss of will	1 (6.6%)	-
Head started to hurt	-	1 (6.6%)
Legs started to shake	-	1 (6.6%)

End tidal oxygen and carbon dioxide partial pressures

Results from the first exhaled breath showed that there was no significant interaction effect (BH x group) or main effect when $P_{ET}O_2$, and $P_{ET}CO_2$ post BH were compared. Results are given in Table 5-4. The first breath was chosen since it closely represents the alveolar gas concentration following BH.

Table 5-4. $P_{ET}O_2$ and $P_{ET}CO_2$ post BH at rest - Values are $\bar{x} \pm$ SD and (range).

	SS		C	
	$P_{ET}O_2$ (mmHg)	$P_{ET}CO_2$ (mmHg)	$P_{ET}O_2$ (mmHg)	$P_{ET}CO_2$ (mmHg)
BH 1 (n_{ss}=14, n_c=14)	71.8± 11.8 (54-85)	43.9 ± 4.3 (35-51)	72.7 ± 8.9 (56-88)	44.0 ± 3.3 (38-49)
BH 2(n_{ss}=15, n_c=14)	69.7 ± 10.0 (55-86)	44.1 ± 4.7 (35-52)	70.8 ± 8.7 (57-85)	43.9 ± 3.2 (38-49)
BH 3(n_{ss}=14, n_c=13)	67.8 ± 12.0 (49-85)	44.8 ± 7.8 (32-54)	67.1 ± 9.6 (54-83)	44.1 ± 2.8 (39-49)
BH 4(n_{ss}=13, n_c=11)	67.9 ± 12.9 (52-86)	43.5 ± 6.7 (34-56)	70.5 ± 11.2 (54-88)	43.2 ± 3.1 (31-47)
BH 5(n_{ss}=13, n_c=9)	68.1 ± 13.4 (49-87)	43.9 ± 6.5 (40-57)	71.0 ± 8.5 (55-86)	44.8 ± 1.9 (33-48)

Heart rate

There was no significant interaction effect between group and time in relation to HR. There was a significant difference between groups for HR 15 s prior to BH (SS > C), at the onset of BH (SS > C), at 30 s during BH (SS < C) and at 45 s during BH (SS < C) (Table 5-7).

Figure 5-5 shows the trend for HR based on mean HR results during each subject's maximal BH. Differences between groups were not significant at $p \leq .05$ when comparing only the maximal BH for each subject.

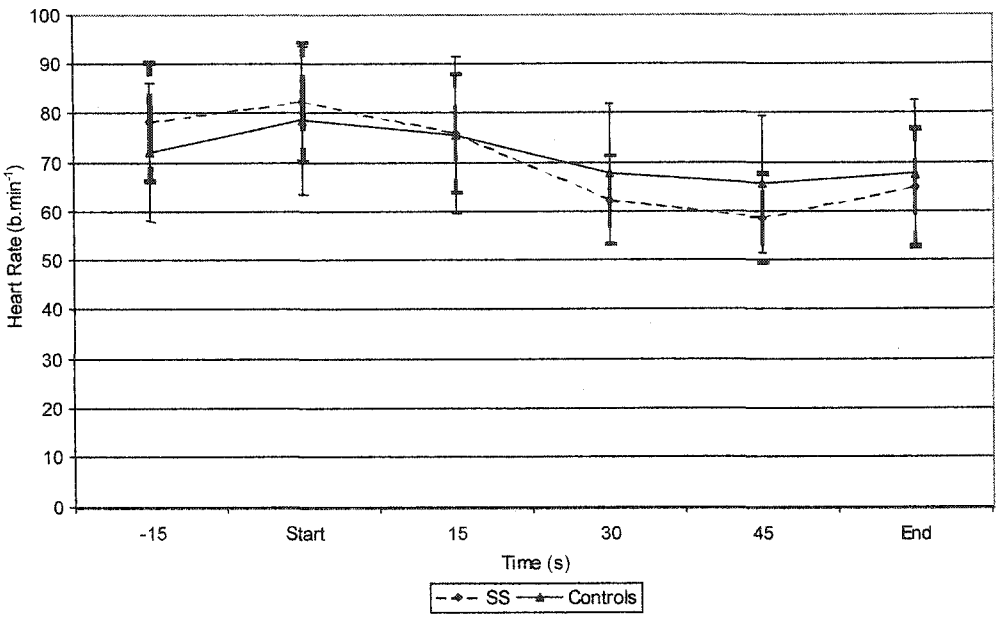


Figure 5-5. Heart rate trends during maximal BH at rest

Oxygen saturation

Oxygen saturation did not significantly change for either group during BH. There were no significant differences in S_aO_2 between groups but there was a significant main effect for S_aO_2 with respect to BH time independent of group, indicating that S_aO_2 decreased as BH times increased (Table 5-5).

Table 5-5. S_aO_2 after BH - Values are $\bar{x} \pm$ SD and (range).

	SS (%)$^{\alpha}$	C (%)$^{\alpha}$
BH 1 (n_{ss} =14, n_c=15)	95 ± 3 (89 – 99)	95 ± 3 (89 – 98)
BH2 (n=14)	95 ± 3 (88 – 99)	94 ± 3 (87 – 99)
BH3 (n_{ss}=12, n_c=14)	94 ± 5 (86 – 100)	94 ± 3 (87 – 99)
BH 4 (n=14)	92 ± 6 (74 – 98)	94 ± 3 (89 – 99)
BH 5 (n=13)	89 ± 6 (77 – 97)	93 ± 5 (83 – 99)

$^{\alpha}$ Indicates S_aO_2 decreases from BH1 to BH 5

Oxygen consumption during breath holding

The estimated oxygen consumption during BH was calculated based on

the baseline rate (Figure 5-7). The estimated oxygen required, the oxygen consumption measured and the difference between these values (net result) for each group during each BH period is reported in Table 5-6. The SS group oxygen consumption during BH ranged from 5.2 to 44.5% lower than the estimated values, but in only one case (BH 4 for SS) was the net result significantly different than zero. The C group had an oxygen consumption of only 6.7 and 6.8% lower for two out of five trials, but none of the net results were significantly different than zero.

Table 5-6. Estimated VO_2 (L) and excess VO_2 (L) at rest -Values are in L ($\bar{x}$) and (%).

	SS			C		
	Estimate (Area)	Surplus	Net	Estimate (Area)	Surplus	Net
BH 1 (n_{ss}=14,n_c=12)	0.503	0.477	- 0.026 (5.2)	0.368	0.428	0.060 (-14)
BH 2 (n_{ss}=14,n_c=13)	0.617	0.506	- 0.111 (17.9)	0.416	0.388	- 0.028 (6.7)
BH 3 (n_{ss}=13,n_c=13)	0.686	0.448	- 0.238 (34.7)	0.409	0.449	0.040 (-8.9)
BH 4 (n_{ss}=14,n_c=13)	0.676	0.374	- 0.301 (44.5)[a]	0.449	0.510	0.061 (-12.0)
BH (n_{ss}=15,n_c=13)	0.786	0.666	- 0.120 (15.3)	0.465	0.433	- 0.032 (6.8)

[a] Significantly different from zero.

Table 5-7. HR (b.m^{-1}) during BH - Values are $\bar{x} \pm$ SD and (range).

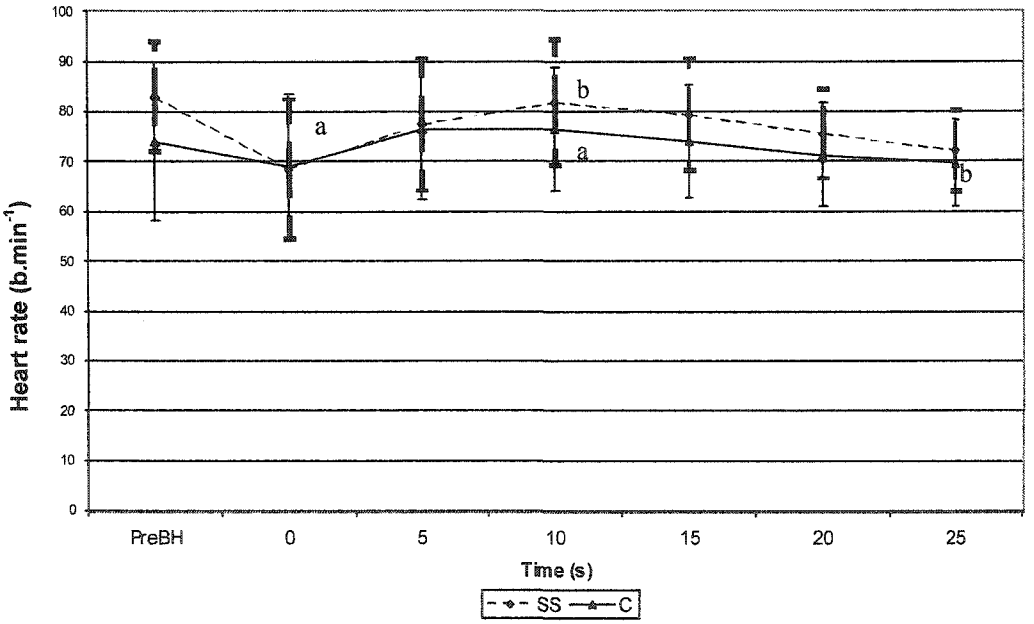
	SS (n =15)						C (n=15)					
	15 s Before [a]	Start[b]	15 s	30 s[c]	45 s[d]	End	15 s Before[a]	Start[b]	15 s	30 s[c]	45 s[d]	End
BH 1	79 ± 13 (59-100)	80 ± 13 (57-99)	78 ± 13 (60-103)	64 ± 10 (50-86)	62 ± 10 (46-78)	63 ± 12 (40-80)	77 ± 18 (50-111)	80 ± 19 (54-112)	81 ± 19 (53-107)	70 ± 13 (48-97)	67 ± 12 (48-4)	66 ± 11 (55-94)
BH 2	80 ± 15 (46-104)	83 ± 16 (45-106)	76 ± 16 (39-96)	63 ± 10 (42-82)	59 ± 9 (43-72)	63 ± 11 (41-79)	75 ± 15 (48-93)	78 ± 16 (49-103)	78 ± 17 (49-106)	69 ± 14 (45-89)	67 ± 16 (45-96)	67 ± 16 (49-102)
BH 3	81 ± 9 (70-104)	85 ± 11 (64-106)	77 ± 12 (57-101)	63 ± 8 (51-74)	59 ± 8 (46-73)	63 ± 12 (40-82)	72 ± 13 (49-95)	80 ± 15 (50-101)	74 ± 15 (52-94)	67 ± 15 (49-92)	65 ± 14 (49-96)	67 ± 15 (51-102)
BH 4	78 ± 11 (55-100)	82 ± 10 (63-100)	75 ± 8 (59-90)	63 ± 7 (52-83)	60 ± 10 (46-85)	68 ± 15 (45-91)	74 ± 15 (48-104)	77 ± 16 (52-109)	76 ± 16 (51-99)	68 ± 14 (46-89)	66 ± 16 (46-98)	67 ± 14 (51-100)
BH 5	76 ± 14 (59-103)	82 ± 11 (58-97)	78 ± 11 (59-98)	64 ± 9 (54-90)	61 ± 11 (46-90)	65 ± 13 (44-90)	69 ± 12 (49-104)	73 ± 14 (52-106)	72 ± 14 (50-101)	66 ± 13 (45-90)	63 ± 11 (45-83)	66 ± 11 (54-93)

[a,b,c,d] Significantly different at $p \leq .05$

Recovery after breath holding

HR during recovery

Figure 5-6 shows HR recovery after the maximal BH period at rest in both groups. Heart rate before the BH for SS was 83 ± 11 b·min^{-1} and for C was 74 ± 16 b·min^{-1}. Similar values were observed within 5 s of recovery (77 ± 13 b·min^{-1} for SS and 76 ± 14 10 b·min^{-1} for C). Heart rate significantly increased for SS when comparing HR at the end of the BH to HR at 10 s after BH ended and significantly decreased between 10 s after BH and 25 s after BH. No differences were observed for controls with respect to HR.



[a] Indicates HR is significantly different from time = 0 to time = 10 s for SS
[b] Indicates HR is significantly different from time = 10 to time = 25 s for SS

Figure 5-6. Heart rate recovery trend after maximal BH at rest

Oxygen uptake during recovery

The baseline rate was used to assess recovery following BH. There was no difference in baseline rates (mean $\dot{V}O_2$) between groups or from BH 1 to BH 5 within groups (Figure 5-7). This implies that there was not any carry over effect from BH 1 to BH 5 and there was a full recovery between BH periods.

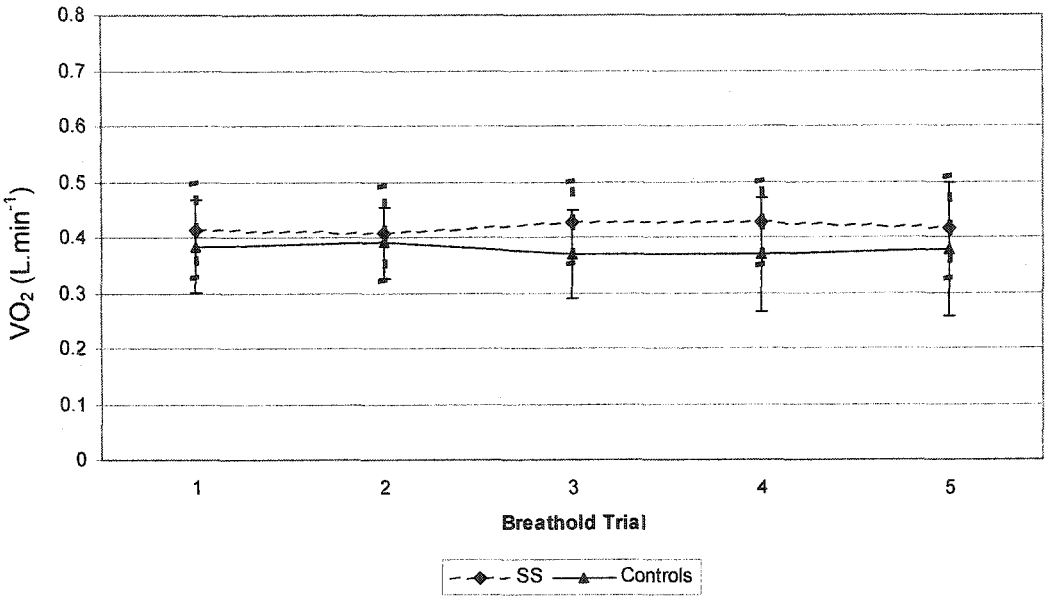
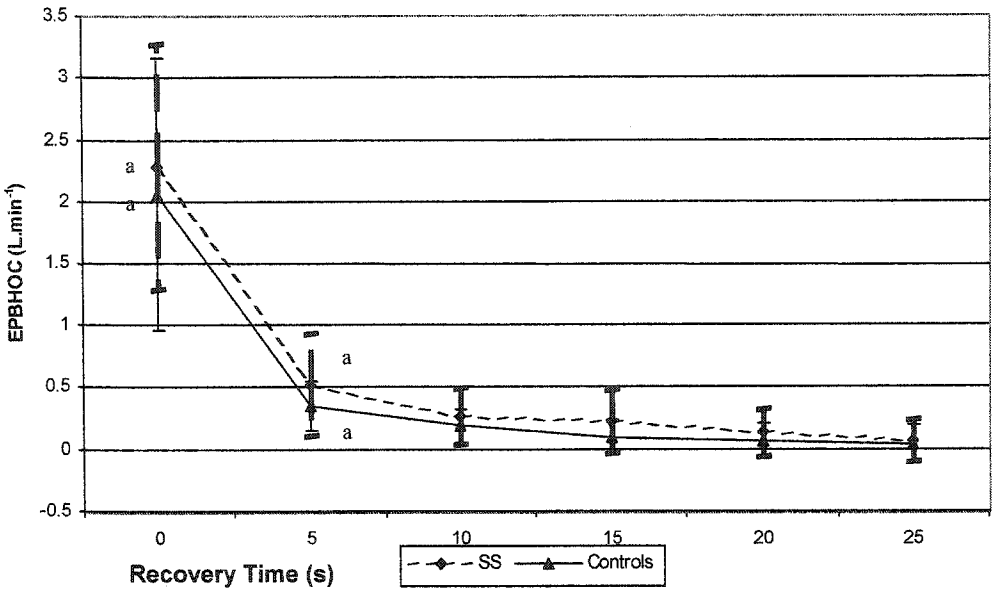


Figure 5-7. Mean $\dot{V}O_2$ at rest prior to each BH

The excess post breath holding oxygen consumption is presented in Figure 5-8. Trends for EPBHOC were very similar independent of the groups and their respective BH training level, independent of the significantly different length of BH and independent of the calculated net result (i.e. estimated economy) (Table 5-6). Both groups were very near total recovery (in reaching the baseline relative to $\dot{V}O_2$) by 25 s into recovery. Note that from 5 s into recovery onward there is no significant difference between baseline values and recovery values.

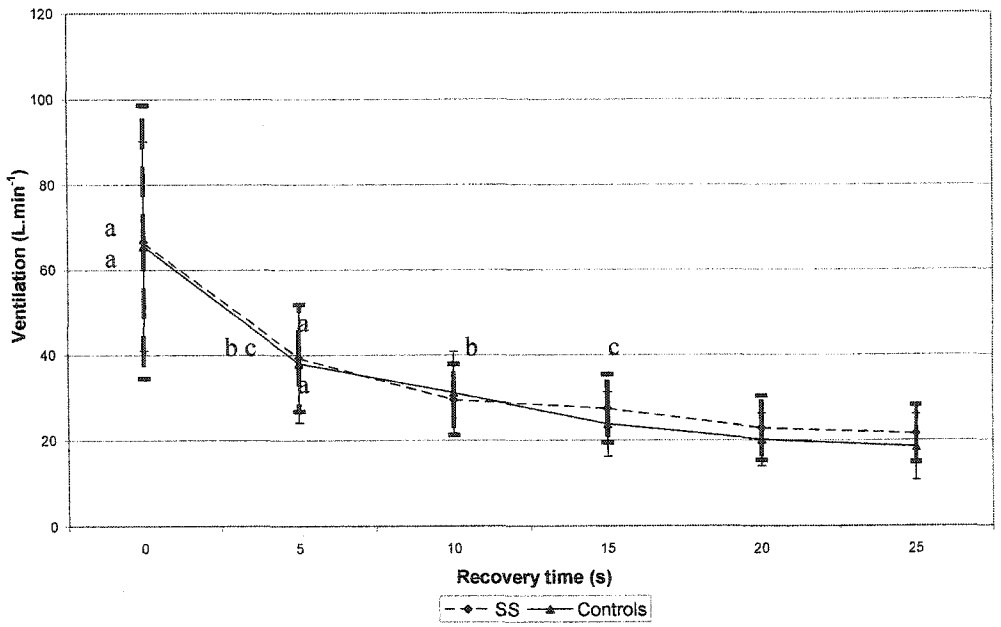


[a] Indicates EPBHOC is significantly different from time = 0 s to time = 5 s for both groups.

Figure 5-8. Excess $\dot{V}O_2$ after maximal BH at rest

Minute ventilation during recovery

Figure 5-9 provides an overview of ventilation responses after maximal BH at rest. The ventilatory trends for both groups were very similar. Despite the fact that BH periods were larger for SS, at the onset of recovery $\dot{V}_E$ was essentially the same at 66.5 L for SS and 65.5 L for C. Between 20 to 25 s of recovery, $\dot{V}_E$ changes were less than 2 L·min^{-1}.



[a] Indicates $\dot{V}_E$ is significantly different from time = 0 s to time =5 s

[b] Indicates $\dot{V}_E$ is significantly different from time = 5 s to time = 10 for SS

[c] Indicates $\dot{V}_E$ is significantly different from time = 5 s to time = 15 s for C

Figure 5-9. $\dot{V}_E$ response post maximal BH at rest

Discussion

Subject characteristics

There was a significant difference in age between SS and C. There was no difference in all other characteristics such as height, body mass, sitting height and FVC other than those chosen to maximize differences between groups such as water experience and current training in the water.

Breath holding times

Supporting the research hypothesis, synchronized swimmers in the present study were able to hold their breath for significantly longer periods of time during the maximal BH trials and this is well documented in literature. Pan et al. (1997),

Chang and Lundgren (1996), Sterba and Lundgen (1985) among others have demonstrated that trained breath holders can hold their breath for longer periods than untrained breath holders. Delapille et al. (2001) hypothesized that the larger BH times for trained subjects were related to non-chemical stimulus sent to the respiratory center. These stimuli would be supplementary to the chemical stimulus and would decrease the sensory mechanisms by which respiratory muscle contractions are detected, or act on the respiratory center to modify the distress stimulus. Schagatay, Kampen, Emanuelsson and Holm (2000) suggested that the larger BH capacity of trained subjects was related to the ability to withstand the discomfort of the struggle phase for a longer period of time and thus delay the end of BH. They also hypothesized changes to the processing of chemoceptor information or decreases of arterial partial pressure of carbon dioxide (P_aCO_2) accumulation as reasons for increased BH times with long-term training. In the present study, even though the $P_{ET}CO_2$ following BH was similar in both groups, the time to achieve this $P_{ET}CO_2$ for SS was longer than for the controls. Alternatively $P_{ET}CO_2$ may have leveled off due to the pressure gradient decrease before BH ended for the SS as suggested by Hong et al. (1971), giving the impression that it took a longer time to achieve the breaking point value.

All subjects in both groups demonstrated a significant increase in BH time from trial 1 through trial 5. SS increased their BH times by 33% from BH1 to BH 5 and C increased their BH times by 27%. This trend is also supported by literature. Hentsch and Ulmer (1984) found up to 160% increases in BH times due to short-term trainability. In the present study 11 of the 15 maximal BH times for

SS occurred in the fifth BH period while 10 of the 15 maximal BH periods occurred in the fifth BH period for the C. No swimmers had their maximal BH time in the first BH period and only one control had her maximal time during the first BH period. Schagatay et al. (2000) suggested that short-term training reduces the anxiety levels and increased the self-confidence of the subjects, therefore increasing BH times. Schagatay, Andersson Hallen and Palsson (2001) compared splenectomized and intact human subjects and described a spleen contraction and an increase in hematocrit after BH. These physiological effects described allowed progressively longer BH periods. Spleen contraction as part of the diving response has also been described by Bakovic et al. (2003). These authors were able to compare BH trained subjects, non-BH trained subjects and splenectomized non-BH trained subjects. They observed a continuous decrease in size of the spleen from the onset of BH for all the intact subjects, increasing the red blood cell pool in the circulating blood and allowing for larger blood gas storage during subsequent BH periods. The spleen did not relax for 2 min following BH and persisted throughout the following BH performed by the intact subjects.

Forty percent of the SS declared the inability to control their involuntary respiratory muscle action as the reason for ending BH. Thirty three percent of the C group reported panic as being their reason for stopping BH. These subjective answers characterize the differences between groups. The SS group justified ending BH more due to the physiological effect on their body (40% due to involuntary chest wall contractions, chest burning 13.2%, urge to cough 6.6%) while the C group had more psychological factors associated with their reasoning

(panic 40%, need to breathe 20%). Hentsch and Ulmer (1984) tested swimmers and non-swimmers and reported that 31% of all subjects stopped BH before respiratory movements started. This group was considered less ready psychologically to hold their breath. The authors described these subjects as being cautious, or fearful. Thirty percent were described as capable of enduring the unpleasant feeling of the need to breathe even after the involuntary respiratory movements started. These subjects were described as having a higher psychological tolerance and results from the present study are consistent with these observations.

End tidal oxygen and carbon dioxide partial pressures.

Despite the fact the BH times were significantly larger for the SS there were no significant differences for $P_{ET}CO_2$ and $P_{ET}O_2$ between SS and C, which is contrary to what was hypothesized. These findings are similar to those reported by Bjurstrom and Schoene (1987) who tested SS and C while BH out of the water in a sitting position. The $P_{ET}O_2$ values reported by Bjurstrom and Schoene were higher than the means found for SS and for the C in the present study. Because subjects in the present study were BH in the water, the increased ventilation typical of WI could explain the difference. Hyperventilation leads to a decrease in CO_2 before BH, allowing more CO_2 to accumulate during the breath hold and thus more O_2 can be consumed (Hill, 1973). Another reason for this could be the increase in tissue perfusion due to WI that would decrease arterial CO_2 tension allowing for a lower $P_{ET}O_2$ before the end of BH (Chang & Lundgren 1996). Chang and Lundgren reported an increase in CO_2 storage capacity of 26.9% from air to WI calculated through the use of rebreathing technique. These authors

suggested that with the increase in central blood volume due to the increase in hydrostatic pressure, perfusion to the poorly perfused, hypometabolic tissues increased. This led to the increase in CO_2 storage capacity in those sites. As PCO_2 gradient decreased, storage capacity similarly decreased explaining the smaller changes that occur to PCO_2 towards the end of BH. Another factor that could add to the decrease in the rate of CO_2 accumulation towards the end of BH is the vasoconstriction that occurs near the end of BH (Pan et al., 1997; Sterba and Lundgren, 1985; Lin, 1984). Vasoconstriction will decrease blood flow and consequently reduce the ability to transport CO_2 to the lungs.

The $P_{ET}CO_2$ values from the present study were similar to values reported by Bjusrstrom and Schoene (1987). Most of the BH research suggests hypercapnia has a greater impact on ending BH than $P_{ET}O_2$. Therefore it is logical that levels of $P_{ET}CO_2$ are similar at the breaking point despite different levels of $P_{ET}O_2$ (Schagatay et al., 2000, Bjurstrom & Schoene, Astrand & Rodall, 1986). Since the SS and C groups are similar with respect to levels of $P_{ET}CO_2$ at the breaking point, one might infer that SS do not have any delay in a breaking point due to decreased sensitivity to CO_2. This is in accordance with Delapille et al. (2001) who studied divers and non-divers while BH at rest, but contrary to the findings of Bjurstrom and Shoene who tested national level synchronized swimmers. It is possible that SS did have a decreased sensitivity to CO_2 and were able to BH for longer due to this decreased sensitivity. Hong et al. (1971) suggested that CO_2 increases in the first 30 s of BH and levels off after 30 s into BH. Chemoceptors may be sending neural impulses of less magnitude if the

subjects are trained in BH, allowing them to hold their breath for longer. An alternative explanation is the suggestion that arterial-alveolar CO_2 exchange decreases due to the decrease in pressure gradient between the blood and the lungs, but does not level off (Anderson & Schagatay, 1997). This could have contributed to the fact that SS had a similar $P_{ET}CO_2$ at the breaking point despite BH times that were longer. The pre BH $P_{ET}CO_2$ for all BH periods were not significantly different between groups and therefore do not account for the longer BH times between SS and C.

The maximal BH periods found in the present study do not appear to be long enough to cause risk to the swimmers. It is interesting to note that the lowest $P_{ET}O_2$ found at the breaking point was 49mmHg (BH 5) in one of the SS subjects. This value is not as low as the arterial pressures reported by Davies, Donaldson and Joels (1995). This value is well away from critical arterial pressures of O_2, which are around 25 to 30mmHg (Astrand & Rodall, 1986). It is important to mention that end tidal partial pressures of oxygen and carbon dioxide are the non-invasive measurements that best approximate arterial values. Barton and Wang (1995) reported that end tidal pressure of CO_2 was 3.5mmHg lower than arterial partial pressure of CO_2 and the correlation between those measurements was r =.772. Subjects were patients admitted to a university hospital.

Heart rate

Bradycardia can be defined as HR at or below 60 $b \cdot min^{-1}$ (Arnold, 1985). The SS as a group achieved an average HR below 60 $b \cdot min^{-1}$ for BH 2, 3 and 4 towards the end of BH (at 45 s), while the control group did not have an average HR below 60 $b \cdot min^{-1}$ at any point in time for the five maximal BH events. This

result supports the hypothesis that HR would be lower for SS. It is important to note that some individuals from the C group did reach bradycardia (Table 5-7). According to Schagatay et al. (2000) BH trained subjects tend to show a more pronounced bradycardia than non-BH trained subjects. Bradycardia and longer BH periods can be linked to an O_2 conservation effect which is characterized by a reduction in oxygen uptake during BH (Andersson & Schagatay, 1997, Andersson. Liner, Fredsted & Schagatay, 2004).

Bradycardia during BH is thought to be a result of an increase in vagal activity (Sánchez & Sébert, 1983; Arnold, 1985). Diving bradycardia is connected to the accumulation of blood in the aorta and arteries at end-diastole and to the decreased venous return due to an increase peripheral resistance (Pan et al., 1997). Bradycardia can be influenced by BH training, anxiety, water temperature, lung volume, intrathoracic pressure (Valsalva maneuver), levels of physical activity, and age (Shagatay & Holm, 1996). An interesting result of the analysis of the HR data is the fact that SS decreased HR at a much faster rate while the control group maintained a similar HR up to 15 s after BH began (Figure 5-5) This may be a result of long term BH training by the SS group.

The analysis of HR also shows a tendency for an increase in HR prior to BH for both groups. This physiological response has been reported previously in literature (Sanchez & Sébert, 1983; Schagatay & Holm, 1996; Schagatay, Kampen & Andersson, 1999). Anticipatory tachycardia just before and at the beginning of BH is explained by Ferrigno et al. (1997) as anticipatory excitement for BH or hyperventilation.

Analyzing the HR of the SS during BH revealed three different phases which are slightly different from the increase in HR slope for 5 to 10 s at the onset of BH followed by a decline and then by a plateau described by Schagatay et al. (2000) and Schagatay et al. (1999). In the present study the first phase was a decrease in HR followed by a plateau in the second phase and an increase in HR during the third phase, which occurred towards the end of BH (Figure 5-5). The increase in HR during the third phase detected in the present study was also reported by Schagatay et al. (1999). Heart rate changes for C were much less pronounced than for SS. At the beginning of BH there was a plateau with a slight decrease after 15 s of BH. This was followed by either a second plateau or a slight increase towards the end of BH.

Oxygen saturation

Oxygen saturation decreased from BH 1 to BH 5 (Table 5-5) independent of group. This result was expected and is consistent with the significantly increasing BH time between trials (Table 5-2). It was expected that S_aO_2 would decrease as BH time increased. The drop in S_aO_2 was more marked in SS but was not significantly different between groups, which is surprising due to the significantly different BH times between groups. One explanation for the lack of significant difference in saturation between groups could be an oxygen conservation effect which is the decrease in oxygen consumption during apnea (Andresson et al., 2004). Lindholm, Sundblad & Linnarsson (1999) suggested that there is a causal relationship between intensity of the cardiovascular responses to apnea (hypertensive response and bradycardia) and the decrease in oxygen consumption during BH, which is reflected in a less steep decline in

saturation.

Oxygen consumption during breath holding

Oxygen consumption and BH time have been shown to have a relationship. Bjusrstrom and Shoene (1987) suggested that the larger BH times found in their study for synchronized swimmers were related to larger lung volumes. In this study lung volume differences were minimized by matching the subjects for sitting height. There was no significant difference between SS and C for FVC. Therefore if one considers Bjusrstrom and Shoene's suggestion that the mass balance equation ($F_AO_{2\ final}=F_AO_{2\ initial} - \dot{V}O_2 \cdot$ BH time/lung volume) can explain larger BH times, there should be a stronger O_2 conservation effect in the SS group in this study.

The O_2 conservation effect theory had a mild impact on the estimated net O_2 consumption. All the SS trials had negative net results while two out of the five control group trials had net negative results. A negative net result means that the amount of O_2 consumed during BH was slightly smaller than the estimated value, which is based on pre BH $\dot{V}O_2$ at rest. Only 1 of the 10 net O_2 values achieved significance when tested for their difference from zero as seen in Table 5-6. Therefore it is not conclusive that there was an oxygen conservation effect at rest, however, there is a trend towards a net conservation effect at rest. If there is an oxygen conservation effect, the variability of the data for each EPBHOC was great enough that it would have made significance difficult to achieve. The O_2 conservation effect is achieved mainly by selective vasoconstriction and decrease in HR and consequently cardiac output. Blood flow is diverted from organs that

can function anaerobically and is maintained for the brain and the heart (Schagatay & Holm, 1996; Andersson, Liner, Runov & Schagatay, 2002).

Recovery after breath holding

Heart rate recovery trends for SS show a sharp increase in HR in the first 10 s of recovery followed by a decrease in HR to levels below the pre BH HR values after 15 s of recovery. Controls showed a faster recovery of HR. It took these subjects 5 s to return to pre BH levels while for SS the time of recovery was 10 s. This difference may be due to the longer times of BH (109.79 ± 39.31 vs. 78.28 ± 24.96) and/or the larger decrease from pre BH to end BH (15 $b \cdot min^{-1}$ for SS vs. 5 $b \cdot min^{-1}$ for C). These HR changes following BH coincide with the period when the body is in great demand for more oxygen, which has been named the EPBHOC phase.

Oxygen consumption did not increase as subsequent BH events took place. The subjects were able to fully recover from the BH stress after 2 min of rest recovery. There was a tendency for $\dot{V}O_2$ to increase for SS but it was not significantly different from pre BH 1 to pre BH 5.

Examining results from the analysis of EPBHOC it was observed that the groups reacted in a very similar way. Despite the fact that maximal BH times were much larger in the SS group, it appears that this group does not need a longer recovery phase than controls. It also reinforces the idea that SS have higher average O_2 conservation during BH which helps decrease the need for larger volumes of oxygen during the recovery phase.

Ventilation responses after BH were very similar for both groups despite

the fact that BH times for SS were larger. This result combined with the fact that $P_{ET}O_2$ and $P_{ET}CO_2$ were similar, suggests that SS were more efficient during BH.

Conclusion

It is clear that there is a training adaptation to BH at rest. Breath holding trained subjects have an advantage versus subjects who are untrained at BH. Breath holding trained subjects were able to reduce their HR faster and to a lower level than control subjects and appear to be able to conserve more O_2. It is inconclusive if there is an oxygen conservation effect at rest. There is a trend for this latter suggestion since all the net results for the synchronized swimmers were negative but with the current methodology used it was not possible to confirm. Since BH in synchronized swimming happens with much smaller intervals than the 2 min in the present study, it would be valuable to know the minimum amount of time to fully recover from maximal breath holding at rest without impacting oxygen consumption over time. Establishing this lower bound would be useful in planning interval training for breath holding.

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Chapter Six: Breath holding with arm crank exercise during water immersion

Introduction

Breath holding (BH) and water immersion (WI) with exercise have not been studied substantially (Butler & Woakes, 1987; Paulev et al., 1990) except in the case of the "Ama", who have been studied extensively. The "Ama" are female divers who harvest pearls in deep waters while BH (Scholander, Hammel, LeMessurier, Hemmingsen & Garey, 1962; Hong, Rahn, Kang, D., Song, & Kang, B., 1963, Masuda, Yoshida, Hayashi, Sasaki & Honda, 1981; Stanek et al., 1993). The applicability of these studies to synchronized swimmers (SS), a group that is also required to exercise while BH under water, is limited due to the deep dives the "Ama" perform and the resulting pressure differences. Of the studies that have examined BH and synchronized swimmers under exercise conditions, all have been limited to reporting the partial pressure of oxygen (PO_2) and carbon dioxide (PCO_2) (Davies, Joels, & Udoh, 1993; Davies, Donaldson & Joels, 1995), or heart rate (HR) decreases while BH and performing figure exercises (Gemma & Wells, 1987; Figura, Cama & Guidetti, 1993).

One of the first studies published examining BH with exercise was by Astrand (1960) who studied subjects cycling out of the water. Since then only a few papers have been published (Ahn et al., 1989; Sanchez & Sebert, 1983;Fujitsuka, Ohkuwa & Miyamura, 1980) until the last five years when other studies examining BH and exercise with or without face immersion have appeared (Andersson Liner, Fredsted & Schagatay, 2004; Irzhak & Oskolkova, 2003; Lindholm Nordh & Linnarsson, 2002; Delapille, Verin, Chollet & Pasquis, 2002;

Andersson, Liner Runov & Schagatay, 2002; Linholm, Sundbland & Linnarsson, 1999). The collective results from these latter studies suggest that the physiological changes that occur during BH and exercise are suggested to be linked to an oxygen conserving effect theory which is characterized by the decrease in HR which is vagally mediated; the decrease in arterial saturation; the increase in peripheral vasoconstriction; the increase in diastolic pressure and mean arterial pressure, and the increase in partial pressure of carbon dioxide.

Studies have also shown large inter-individual variability in apnea responses with BH and exercise (Linholm et al., 1999) and it is possible that individuals with experience and training in BH in water such as SS would be more likely to exhibit these responses. Since none of the above studies investigated synchronized swimmers, the present study was devised to provide a better understanding of the cardiorespiratory responses during BH when exercising at a controlled intensity while in water immersion.

Differences in BH response between synchronized swimmers and active females from non-swimming sports were examined. Since previous work has demonstrated that synchronized swimmers tend to use a combination of short and long breath holding periods throughout a routine (Chapter 2), the responses to a sequence of variable length breath holding trials were investigated. In Chapter 2 it was found that the average of maximal BH times for top soloists in Canada was 25.45 s. Consequently this study examined the effect of a series of six BH periods of 10, 20 and 25 s in length in either ascending or descending order.

There were three main hypotheses in this study. The first was that there

would be an oxygen deficit created while BH that would be recouped during recovery. Recovery time after 25 s of BH would be shorter and minute ventilation ($\dot{V}_E$) and oxygen consumption per minute ($\dot{V}O_2$) would be lower for the SS than for non-SS. The second hypothesis was that recovery to pre BH $\dot{V}_E$ and $\dot{V}O_2$ levels would happen within 25 s after breathing resumes as determined by previous pilot work. The third hypothesis was that the order of breath holding periods would affect HR and $\dot{V}_E$. A 25 s breath hold at the end of the exercise session would result in a smaller increase in $\dot{V}_E$ and faster decrease in HR following the start of BH compared with a 25 s breath holding period at the beginning of the exercise session.

Methodology

The subjects

The subjects were 15 female synchronized swimmers and 15 active females who served as controls (C). These same athletes previously participated in a different BH experiment (Chapter 5). Further information on the subjects is reported in Chapter 5.

Measures

Most measures are reported in Chapter 5. A metabolic measurement system was used (CDX/D, Medical Graphics Corporation, St. Paul, Minnesota, USA) for all ventilation and gas exchange measures. Prior to each test, the metabolic cart was calibrated with known gases and a 3 L syringe according to the manufacturer's protocol. The metabolic cart was calibrated again at the end of each test to ensure accuracy. The metabolic cart was operated in breath by breath

mode to continuously monitor the expired air of each subject for $\dot{V}_E$, (fraction of expired oxygen (F_EO_2), fraction of expired carbon dioxide (F_ECO_2), end tidal partial pressure of oxygen ($P_{ET}O_2$), end tidal partial pressure of carbon dioxide ($P_{ET}CO_2$) and calculate $\dot{V}O_2$ and carbon dioxide production ($\dot{V}CO_2$). For the $\dot{V}O_2$ peak during arm crank exercise only, the data was averaged over 15 s. The same modified mouthpiece used in Chapter 5 was used in the present study.

Arm $\dot{V}O_2$ peak was measured with a continuous protocol recommended by the American College of Sports Medicine (ACSM) (1995). The cycle ergometer was calibrated with known weights prior to each day of testing to ensure correct power outputs for $\dot{V}O_2$ peak tests and exercise. The subject was connected to the metabolic cart, wore a nose clip and completed a 4 to 5 min unloaded warm up. At the command of the researcher the test was started. Initial power output was fixed at approximately 40 W (29.4 W from the cycle ergometer resistance plus 11 W from water resistance, see Appendix B) with an additional increment of approximately 15 W every 2 min until volitional exhaustion occurred. Cranking rate was kept constant at 60 rpm using a metronome. The test was terminated when the subject volitionally fatigued, or showed an inability to maintain the correct cadence. A cool down period consisting of 3 to 5 min of unloaded cycling was provided. The ventilatory threshold (VT) was determined as the power output when the ratio of $\dot{V}_E/\dot{V}CO_2$ reached a minimum value coincident with F_ECO_2 reaching a maximum value during graded exercise using the averaged data from the breath by breath data (Bhambhani & Singh, 1985).

Procedures

All measures were conducted in the laboratories of the Faculty of Physical Education and Recreation. The study required four visits to the lab, beginning with two orientation sessions and ending with two testing sessions. The pre orientation sessions were the same as for Chapter 5. Figure 6-1 outlines the research steps.

Pre – orientation session: (Preferably within 5 days of the test)	
• Contact subjects	• Sitting height check
Orientation sessions:	
Day 1: Preliminary procedures • History inventory questionnaire • Spirometry • 45 s BH out of the water Orientation session • 2 BH trials with mouthpiece, out of the water	Day 2: • Sitting height • 2 BH trials with mouthpiece, in the water • Cycle ergometer familiarization
Testing sessions (3 to5 days apart):	
Day 3: • Height • Body mass • Arm cranking VO_2 peak test	Day 4: • Height • Body mass • BH and exercise

Figure 6-1. Data collection summary

Testing procedures started on the third visit to the laboratory. Subjects wore bathing suits and were instructed to avoid food and caffeine 3 to 4 hr prior to reporting to the lab. All subjects were tested out of their luteal menstrual cycle phase to avoid interference in chemosensitivity (Bjurström & Schoene, 1987). Menstrual cycle was assessed through the history inventory questionnaire completed during the preliminary procedures (Appendix D). Since WI, BH and exercise involves a risk of unconsciousness or drowning, a certified lifeguard was on duty for all testing procedures. Subjects were weighed and their height

measured. A HR monitor transmitter was positioned around the chest and held in place with an elastic strap. An oximeter probe was taped to the forehead. A headpiece apparatus was attached to the mouthpiece and positioned comfortably on the subject's head. The pneumotach was connected to the metabolic measurement cart. Ankle weights were fitted to the subjects' ankles to prevent floating. Subjects entered the water and sat on the cycle ergometer. The horizontal seat distance was adjusted so that the subject had their arms slightly bent in the extended position. To further prevent the subjects from floating, a 4-kg weight belt was positioned on their lap and a shoulder harness was used to strap them to the cycle ergometer chair. The water level was adjusted so that each subject was submerged to the clavicular notch and water temperature was kept constant at 28 ± 1°C. A nose clip was worn by each subject. Use of swim goggles was optional.

At the command of the researcher, the lifeguard (in the water) started the HR monitor. At this same moment the metabolic measurement cart was started. A research assistant started recording information from the oximeter every 30 s. After 2 min of acclimatization to the water during which the subjects were seated at rest, the subjects were asked to start arm cranking for a 4 to 5 min unloaded warm up period. The arm crank peak oxygen consumption ($\dot{V}O_{2\,peak}$) test followed at the command of the researcher. The test served as the basis for determining the VT for the exercise and BH experiment, which was conducted 3 to 5 days later.

On the fourth visit to the laboratory, the same subjects performed a series of six BH trials of various lengths (Figure 6-2) over an exercise period of 16 min

and 50 s while immersed to the clavicular notch and with the face tilted in water when BH and exercising. The series of BH trials started after a 3-min exercise warm up period with a power output approximately 15 W below the point where the VT was previously detected. Exercise intensity was maintained from warm up through to the end of the recovery period for the sixth BH period. Exercise pace was controlled by a metronome set at 60 $b \cdot min^{-1}$. Breath holding intervals were either 10, 20, or 25 s in length, and were followed by a 2-min active recovery period (Figure 6-2). The safety of the subjects would have been put at risk by having them breath hold maximally during exercise, given that some researchers have reported subjects fainting at the end of maximal BH while exercising out of the water (Astrand & Rodalh, 1986). Therefore, for safety reasons, it was decided to limit BH to a maximum of 25 s while exercising. This value also corresponds to the mean BH value previously reported for 11 elite synchronized swimming solos (Chapter 3).

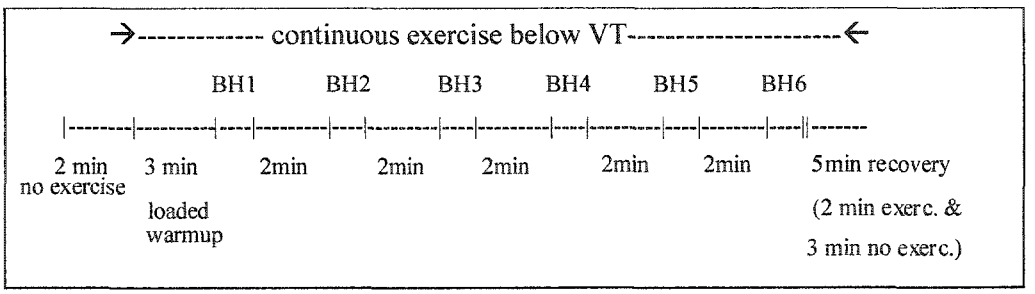


Figure 6-2. BH and exercise timeline

Seven subjects in each group (SS and C) performed the 25 s breath hold first and continued in order of descending length that is: BH 1= 25 s, BH 2 = 25

s, BH 3 = 20 s, BH 4 = 20 s, BH 5 = 10 s and BH 6 = 10 s. These groups were named *SS 25 s initial and C 25 s initial*. The remaining 8 subjects in each group (SS and C) performed the 10 s breath hold first and continued in order of ascending length that is: BH 1 = 10 s, BH 2 = 10 s, BH 3 = 20 s, BH 4 = 20 s, BH 5 = 25 s and BH 6 = 25 s and were named *SS 10 s initial and C 10 s initial.* Synchronized swimming subjects were randomly assigned to either the 25 s initial or the 10 s initial group while the C group was matched based on the sitting height of the subjects in the two SS groups.

All BH started at total lung capacity (TLC). While BH, the subjects leaned forward to put their face in the water to the ear level. When subjects were BH for either 20 s or 25 s the researcher used the dummy breathing procedure described earlier (Chapter 5) in order to ensure continuous data collection by the metabolic cart before breathing was resumed. In the event of the researcher finding by visual inspection that the metabolic cart lines were filling with water or accumulating moisture, the test was stopped, the lines changed and the test re-started. Following the BH trials, the subjects performed a 5-min recovery, the first 2 min while still exercising at the same load and the final 3 min with no exercise after which the metabolic data collection was stopped.

Data analysis

A series of one way ANOVAs for repeated measures were used to compare $P_{ET}CO_2$ and $P_{ET}O_2$ at 10 s, 20 s and 25 s. One way ANOVA was also used to compare the subjects' characteristics.

Two way ANOVAs (group x time) with repeated measures across time points (2x4) were used to compare HR between SS and C at 4 different points in

time (pre BH, start of BH, 15 s into BH and end of BH) for the 25 s and the 20 s BH periods and a 2x3 two way ANOVA for repeated measures across time points was used to compare HR between SS and C at 3 different points in time (pre BH, start of BH and end of BH) for the 10 s BH period. T-tests were used as post hoc to determine where differences occurred.

The calculations for the 'baseline rate' which is the rate of $\dot{V}O_2$ needed to maintain homeostasis without BH are described in Chapter 5. The process used to calculate the deficit of oxygen during BH, the EPBHOC and the net oxygen consumption was also described in Chapter 5 (Figure 5.4).

A series of 4x6 (group x condition) two way ANOVAs for repeated measurements (group: *SS 25 s initial, C 25 s initial, SS 10 s initial, C 10 s initial* x 6 BH tests) were used to compare baseline values. A series of 2x6 two way ANOVAs for repeated measurements were used to compare the differences between baselines for *SS 10 s initial* vs. *SS 25 s initial* and between *C 10 s initial* vs. *C 25 s initial*. A series of 4x3 (group x condition: 10 s, 20 s, 25 s) were used to compare estimated oxygen consumption between groups. The alpha levels were set a priori at $p \leq .05$.

For the purpose of analyzing the effect of BH on $P_{ET}CO_2$, $P_{ET}O_2$, HR and EPBHOC where the impact of the order of BH did not show any significant difference, the data was collapsed into two groups, SS and C. For ventilation, baseline values and to specifically address one of the research questions about the relationship of the sequence of shorter and longer BH periods and its effects on efficiency, the groups remained split.

One sample T-tests were used to determine if net oxygen consumption was significantly different from 0. Independent T tests were used to compare subject characteristics, $\dot{V}_E$, estimated oxygen consumption and EPBHOC for each BH period (10 s, 20 s, 25 s) when the groups were collapsed. T-tests were used to determine if there were differences in EPBHOC and ventilation from one point in time to another during the recovery period and HR during BH and the recovery period. Apha level was set a priori at $p \leq .05$. Statistical comparisons were made using the SPSS software program version 7.5 for Windows®.

Some of the statistical tests have a smaller sample than the number of subjects in each group. Heart rate was eliminated if there was no fluctuation in the data generated by the HR monitor for more than 3 min. In these cases it was deemed that the device was not responding. Because the data was collected in the water, equipment malfunction due to lines retaining moisture or the HR monitor band loosing contact with the subject, occurred at times. If a malfunction of the equipment was detected while the subject was performing the test the malfunction was fixed and the test was repeated. If the malfunction was only detected as the analysis of the data was being performed the test was not repeated and the faulty tests were eliminated (e.g., when a value was widely out of range and not following the characteristic response of the subject during previous tests).

Results

Subject characteristics

Subject characteristics are shown in Table 6-1. The SS were significantly younger than C. There were no statistically significant differences between groups

for height, body mass, sitting height, forced vital capacity (FVC), and arm $\dot{V}O_2$ peak. The only other significant differences were the ones imposed by the inclusion criteria such as synchronized swimming experience and swimming hours. Note that sitting height was the matching criteria between groups, therefore these values are very similar.

Table 6-1. Group characteristics – ($\bar{x} \pm SD$)

	SS 25 s initial (n=7)	*SS 10 s initial (n=8)*	*SS groups combined (n=15)*	*C 25 s initial (n=7)*	*C 10 s initial (n=8)*	*C groups combined (n=15)*
Age (years)[a]	18 ± 2.2b[b]	18 ± 2.3[c]	18 ± 2.0[a]	23 ± 2.9[b]	21 ± 2.1[c]	22 ± 3.0[a]
Height (cm)	169.9 ± 7.0	171.2 ± 3.2	170.6 ± 5.2	166.6 ± 9.0	172.7 ± 8.7	169.2 ± 8.9
Body mass (kg)	58.0 ± 6.1	62.6 ± 6.1	60.5 ± 6.9	66.6 ± 11.9	65.3 ± 7.1	65.0 ± 8.8
Sitting height (cm)	88.3 ± 4.1	91.1 ± 1.8	89.8 ± 3.3	88.7 ± 3.8	91.4 ± 2.2	90.1 ± 3.3
FVC (L)	4.3 ± 0.8	4.5 ± 0.7	4.4 ± 0.7	4.0 ± 06	4.2 ± 0.4	4.1 ± 0.5
$\dot{V}O_2$ peak (L·min)	1.9 ± 0.4	2.0 ± 0.4	2.0 ± 0.4	2.2 ± 0.3	2.1 ± 0.4	2.1 ± 0.4
$\dot{V}O_2$ peak ($ml \cdot kg \cdot min^{-1}$)	33.0 ± 6.0	31.6 ± 5.6	32.2 ± 5.6	34.2 ± 5.3	32.0 ± 6.2	32.8 ± 5.7
Water training (hr/Week)	19 ± 7.4[b]	21.3 ± 9.8[c]	20.4 ± 8.7[a]	0[b]	0[c]	0[a]
Synchro experience (years)	7.5 ± 2.2[b]	10.1± 4.4[c]	9.0 ± 4.0[a]	0[b]	0[c]	0[a]

[a, b, c] significantly different at $p \leq .05$.

Exercise and breath holding while immersed

End tidal oxygen and carbon dioxide pressure

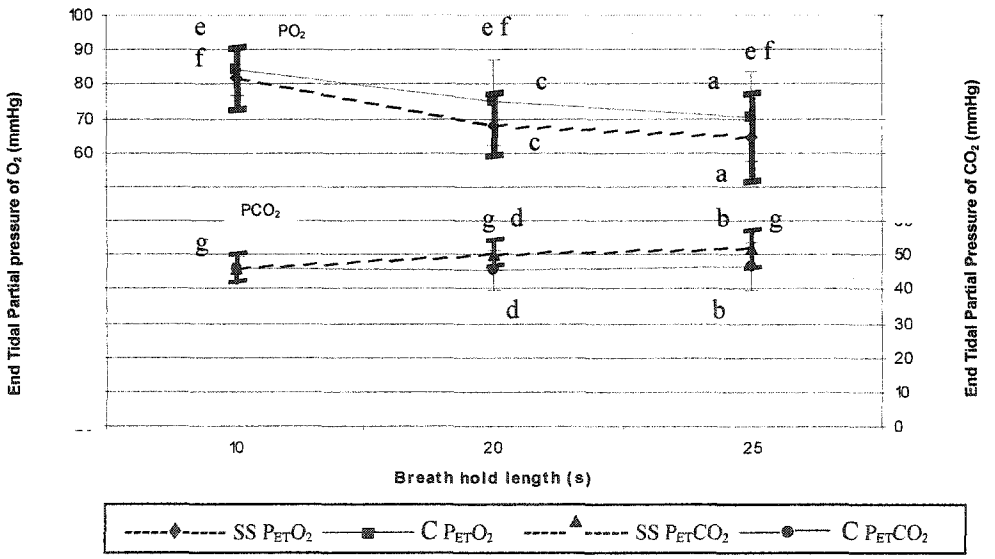
Results showed there was a significant difference between SS and C when comparing $P_{ET}CO_2$ and $P_{ET}O_2$ after 25 s or 20 s BH (Figure 6-3, Table 6-2). For both 25 s and 20 s, $P_{ET}CO_2$ was significantly higher for SS than for C while $P_{ET}O_2$ was significantly lower. There was no difference when comparing the groups after

10 s of BH. Results also showed a significant decrease in $P_{ET}O_2$ for both groups as breath holding time increased (10 s, 20 s, 25 s), while a significant increase in $P_{ET}CO_2$ as BH time increased was only seen in the SS group.

Table 6-2. $P_{ET}O_2$ and $P_{ET}CO_2$ post BH during exercise - Values are $\bar{x} \pm$ SD and (range).

	SS (2 BH combined: n = 30)		C (2 BH combined: n=30/28[h])	
	$P_{ET}O_2$[e] (mmHg)	$P_{ET}CO_2$[f] (mmHg)	$P_{ET}O_2$[g] (mmHg)	$P_{ET}CO_2$ (mmHg)
25 s BH*	62 ±10.1 (45 – 84)[a]	52 ± 4.3 (40 – 59)[b]	70 ± 13.2 (50 – 92)[a]	47 ± 7.2 (30- 55)[b]
20 s BH	68 ± 8.8 (49 – 84)[c]	50 ± 3.8 (44 – 57)[d]	75 ± 12.5 (59 – 95)[c]	45 ± 6.1 (33 – 53)[d]
10 s BH	84 ± 7.3 (66 – 96)	46 ± 4.5 (40 – 59)	84 ± 7.2 (72 – 97)	46 ± 3.5 (39 – 52)

[a, b, c, d] Indicates significant difference between SS and C at $p \leq .05$
[e, f, g] Indicates significantly different dependent on BH time $p \leq .05$
[h] Two controls were only able to BH for 1 of the 2 25 s BH periods

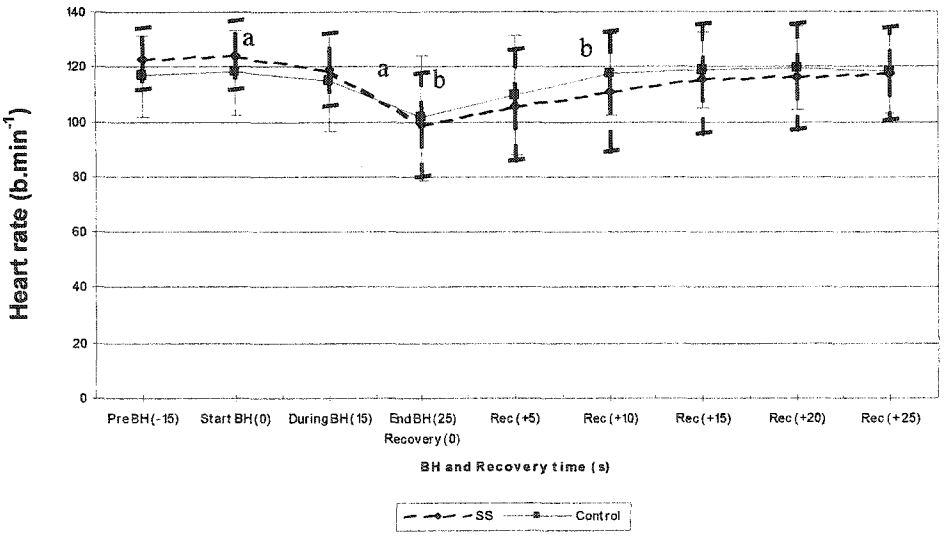


[a, b, c, d] Indicates significant difference between SS and C at $p \leq .05$
[e, f] Indicates significantly different dependent on BH time $p \leq .05$ for SS and C
[g] Indicates significantly different dependent on BH time $p \leq .05$ only for SS

Figure 6-3. $P_{ET}O_2$ and $P_{ET}CO_2$ post 10 s, 20 s and 25 s of BH

Heart rate

Heart rate values while BH during exercise are shown in Table 6-3. There was no interaction and no significant difference between groups. Figure 6-4, Figure 6-5 and Figure 6-6 show the average effect on HR (both trials combined for each 10 s, 20 s and 25 s trials) from the pre BH phase (15 s before BH) to the end of BH for SS and C. The HR response was tested to determine if the HR drop from the start of BH to the end of BH was significant. For 25 s of BH and for 20 s of BH the decrease in HR from the start of BH to the end of BH was significant in both groups. During 10 s of BH there was no significant difference between HR at the start of BH to the end of BH. Heart rate during the 25 s trial increased significantly between the end of the BH period to the first 10 s of recovery for both groups. During the 20 s trials, HR increased significantly in the first 10 s of recovery for SS and in the first 15 s of recovery for C.



[a] Indicates HR is significantly different from start to end of BH for SS and C
[b] Indicates HR is significantly different from time =0 s (Rec) to time=10 s (Rec) for SS and C

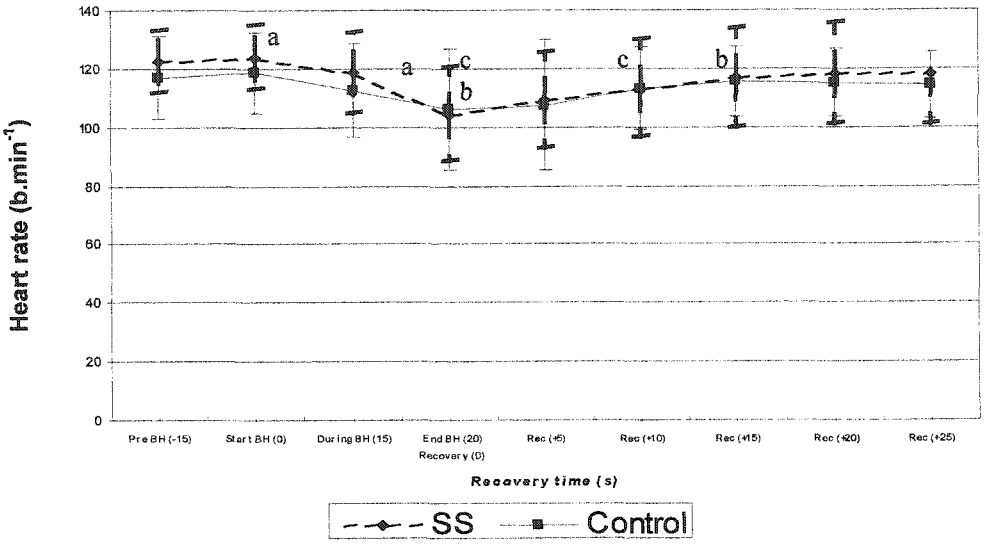
Figure 6-4. HR before and during 25 s BH with exercise

Table 6-3. HR during BH and exercise - Values are $\bar{x} \pm$ SD and range.

	SS (2 BH combined)				C (2 BH combined)			
	- 15 s	Start	15 s	End	- 15 s	Start	15 s	End
25 sBH (n_{ss}=28,n_c=24[b])[a]	123±11 (100-140)	124±13 (98-141)	119±13 (101-146)	99 ±18 (74- 146)	117±15 (95 – 150)	118±16 (97-156)	115±18 (95-161)	101±23 (65-149)
20 sBH (n_{ss}=28,n_c=26)[a]	122±11 (102-146)	124±11 (103-146)	119±14 (100-147)	104±14 (74-144)	117±14 (93-150)	118±14 (98-150)	112±16 (94-149)	106±19 (74-144)
10 sBH (n_{ss}=28,n_c=26)	121±10 (104-136)	122±10 (105-139)	-	114±12 (97-142)	116±12 (99-144)	115±13 (98-144)	-	114±17 (88-152)

[a] Indicates significantly different from –15 s to end of BH for SS and C

[b]Two controls were only able of BH for 1 of the 2 25 s BH periods. Other "n" decreased due to failure of equipment



[a] Indicates HR is significantly different from start to end of BH for SS and C
[b] Indicates HR is significantly different from time =0 s (Rec) to time=15 s (Rec) for C
[c] Indicates HR is significantly different from time =0 s (Rec) to time=10 s (Rec) for SS

Figure 6-5. HR before and during 20 s BH with exercise

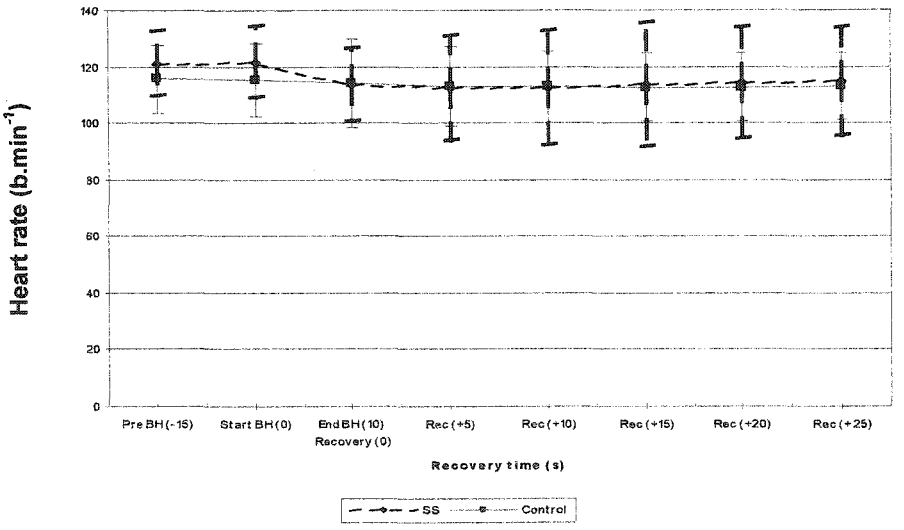


Figure 6-6. HR before and during 10 s BH with exercise

Recovery after breath holding during exercise

Estimated baseline values and estimated oxygen consumption during BH were significantly different dependent on the order of BH, 25 s initial or 10 s initial, therefore the data will be presented divided into 4 groups (SS 25 s initial, SS 10 s initial, C 25 s initial and C 10 s initial).

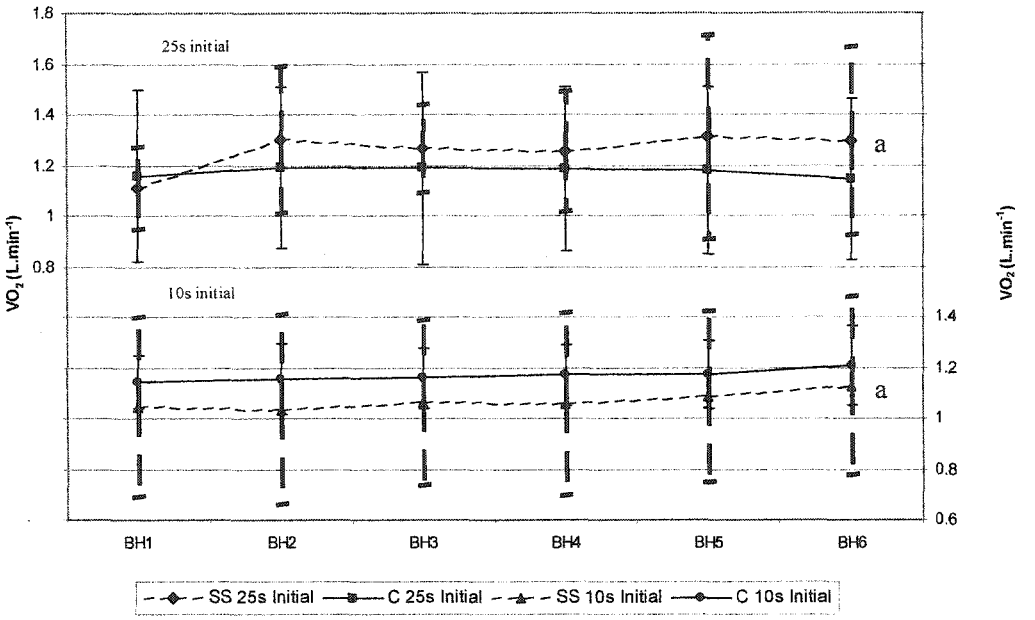
Figure 6-7 shows the estimated baseline rates ($\dot{V}O_2$, $L \cdot min^{-1}$) for each condition and each group. The *SS 10 s initial* group had the lowest baseline $\dot{V}O_2$, while the *SS 25 s initial* group had the highest $\dot{V}O_2$ from the second baseline measurement and beyond. There was no significant difference in baseline rate across BH time for each group.

Table 6-4. Estimated O_2 consumption for each group - Values are $\bar{x} \pm$ SD.

	SS 10 s initial	*SS 25 s initial*	*C 10 s initial*	*C 25 s initial*
	(n=14)	(n=16)	($n_{25\,s}$=12, $n_{20\,s,10\,s}$=14)	(n=16)
For:	Estimate	Estimate	Estimate	Estimate
25 s	0.468 ± 0.179	0.537 ± 0.164	0.518 ± 0.084	0.542 ± 0.140
20 s	0.384 ±0.121[a]	0.473 ±0.082[a]	0.450 ± 0.067	0.444 ± 0.123
10 s	0.235 ± 0.046b[b]	0.297 ± 0.096[b]	0.250 ± 0.027	0.248 ± 0.055

[a,b] Indicates estimate is significantly different between 10 s initial and 25 s initial at $p \leq .05$

The estimated oxygen consumption calculated based on the baseline rates for each group and each BH period are reported in Table 6-4.The estimated oxygen consumption was calculated as explained previously (Chapter 5, Figure 5-4). The estimated value was significantly different between the two SS groups when BH for 10 s and 20 s, showing greater oxygen consumption for the *SS 25 s initial group.*



[a] Indicates baseline values are statistically different between groups (just for SS)

Figure 6-7. $\dot{V}O_2$. baselines - $\dot{V}O_2$ prior to BH

Table 6-5 - Net oxygen consumption (L) - Values are $\bar{x} \pm$ SD and (% of estimated).

	SS (2 BH combined)	C (2 BH combined)
25 s BH(n_{ss}=30,n_c=28)	- 0.088 ± 0.29 (82.6)	-0.018 ± 0.32 (96.6)
20 s BH(n_{ss}=30,n_c=30)	-0.065 ± 0.11(84.9)[a]	-0.089 ± 0.15 (80.0)[a]
10 s BH(n_{ss}=30,n_c=30)	-0.034 ± 0.13 (87.4)	-0.004 ± 0.07 (98.4)

[a] Indicates net oxygen consumption is significantly different than 0 at $p \leq .05$

The calculated net oxygen consumption values are reported in Table 6-5. Two of the negative net result volumes (estimated O_2 minus calculated O_2 for SS and C) were significantly different than zero, indicating that the O_2 consumed in these two cases was significantly lower than what was estimated for the period. The percentages of estimated O_2 consumption for the significantly different

results ranged from 85% (SS, 20 s BH) to 80% (C, 20 s BH) of the estimated oxygen consumption. Note that SS net consumption ranged from 83% (25 s BH) to 87% (10 s BH) of what was estimated while C ranged from 80% (20 s BH) to 98% (10 s BH).

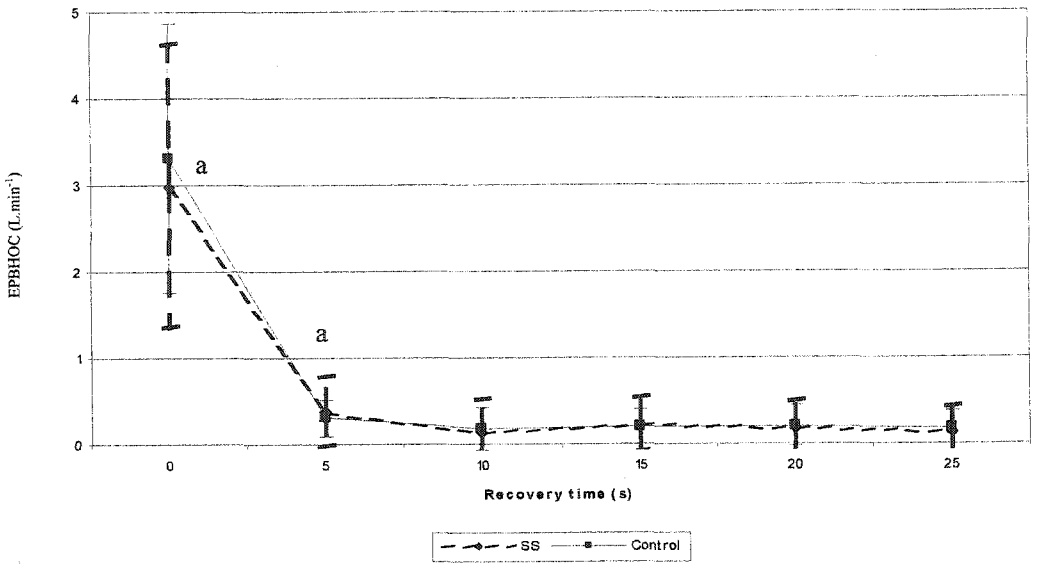
Table 6-6 shows the peak EPBHOC for SS and C. The EPBHOC for SS was significantly lower compared to the C group after 10 s of BH. There were no other significant differences between groups.

Figure 6-8, Figure 6-9, and Figure 6-10 show EPBHOC for each BH time period for SS and C. Recovery was plotted for 25 s, based on results from an earlier pilot study that showed $\dot{V}O_2$ returned to a steady state within 25 s of recovery. Mean oxygen consumption after BH stabilized rapidly post BH. All groups achieved oxygen steady state within 5 s after BH was completed, independent of the groups, the length of the breath hold and of the net O_2 result at BH. After this fast decrease, EPBHOC decreased at a slower rate but mean values were not significantly different than baseline rates.

Table 6-6. Peak EPBHOC for SS and C ($L.min^{-1}$) - Values are $\bar{x} \pm$ SD and (range).

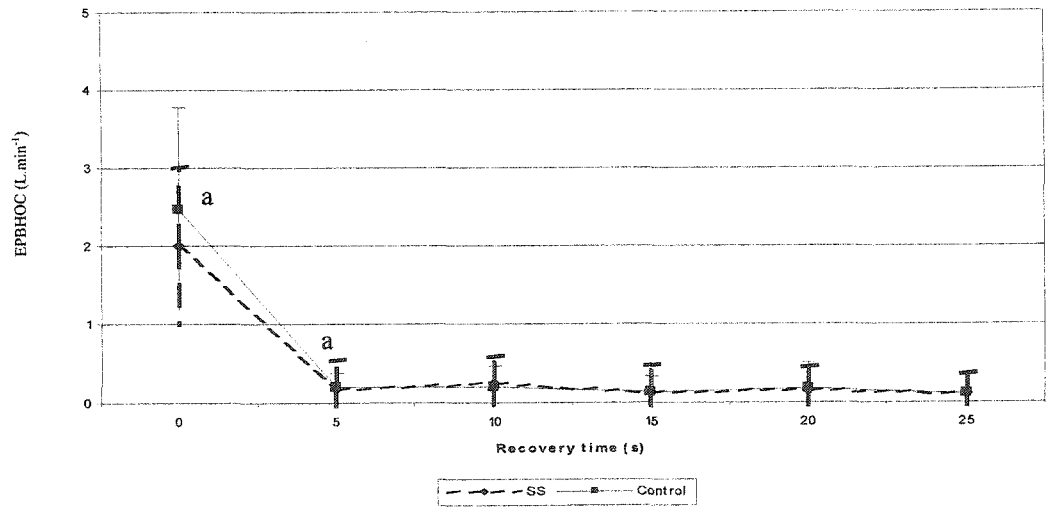
	SS (2 BH combined)	C (2 BH combined)
25 s BH(n_{ss}=30,n_c=28)	3.0 ± 1.6 (-0.4 – 6.44)	3.3 ± 1.5 (1.4 – 7.1)
20 s BH(n_{ss}=30,n_c=29)	2.0 ± 1.0 (0.3 – 5.18)	2.5 ± 1.3 (0.9 – 6.32)
10 s BH(n_{ss}=30,n_c=30)	0.6 ± 0.7 (-1.0 – 2.7)[a]	1.1 ± 0.8 (-0.3 – 3.1)[a]

[a] Indicates estimate is significantly different between C and SS at $p \leq .05$



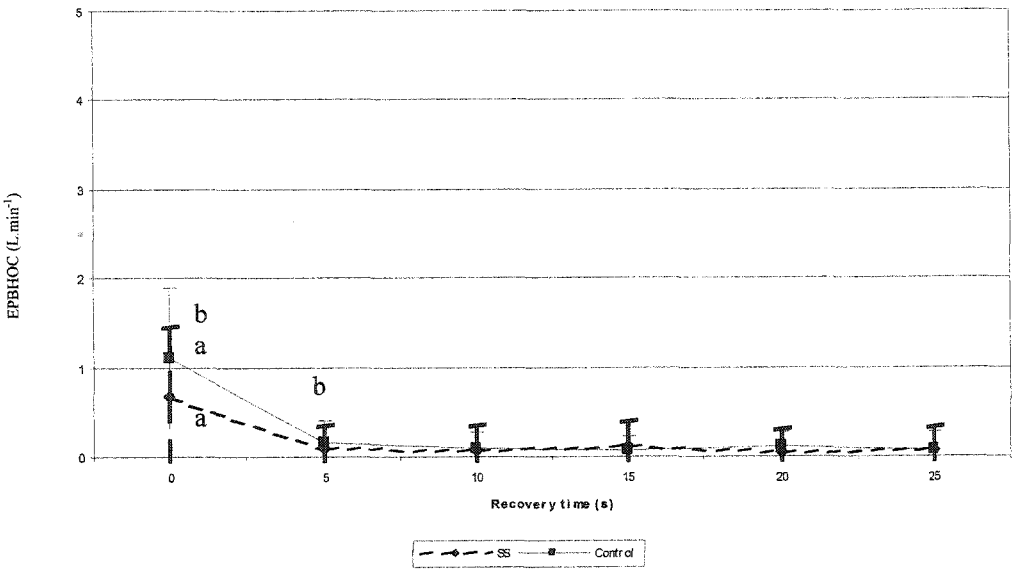
[a] Indicates EPBHOC is significantly different from time = 0 s to time =5 s for SS and C.

Figure 6-8. EPBHOC for SS and C after 25 s of BH during exercise



[a] Indicates EPBHOC is significantly different from time = 0 s to time = 5 s for SS and C

Figure 6-9. EPBHOC for SS and C after 20 s of BH during exercise



[a] Indicated EPBHOC is significantly different from SS to C
[b] Indicates EPBHOC is significantly different from time =0 s to time = 5 s for SS and C

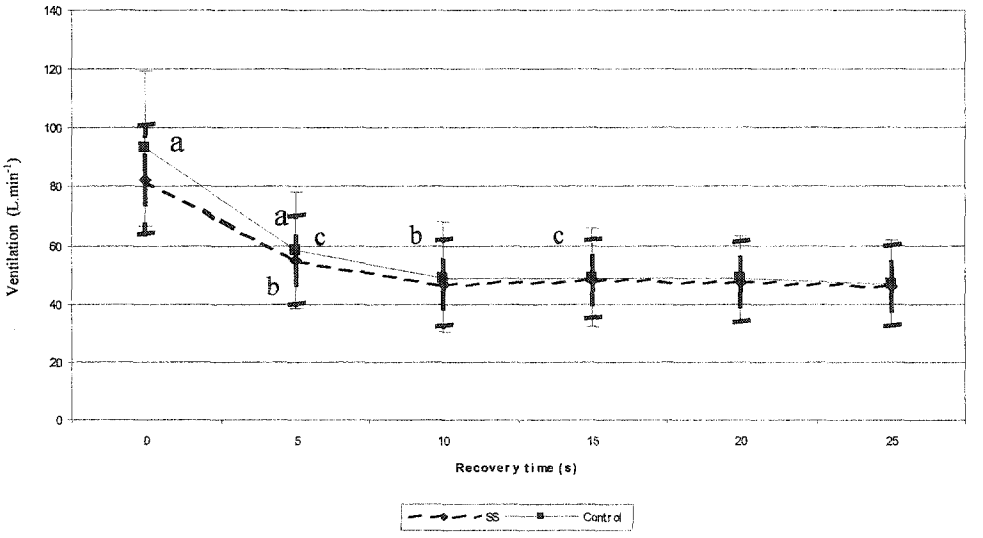
Figure 6-10. EPBHOC for SS and C after 10 s of BH during exercise

Peak $\dot{V}_E$ following BH is shown in Table 6-7. There was only one significant difference between C and SS: $\dot{V}_E$ was significantly lower for SS compared to C after 20 s of BH. Ventilation responses for 25 s into recovery for SS and C after different BH times are shown in Figure 6-11, Figure 6-12 and Figure 6-13. Ventilation decreased significantly within 5 s for SS and C in all cases (10 s, 20 s, 25 s). Following the fast 5 s decrease at the onset of recovery there was a significant drop within 10 s and 15 s of recovery for SS and C respectively when BH for 25 s. The only other significant difference noted was in the 20 s BH trial, where SS had a significantly lower $\dot{V}_E$ post BH than C.

Table 6-7. Post BH peak $\dot{V}_E$ for SS and C ($L.min^{-1}$) - Values are $\bar{x} \pm$ SD and (range).

	SS (2 BH combined)	C (2 BH combined)
25 s BH(n_{SS}=30,n_C=28)	82.2 ± 18.6 (37.0 – 112.2)	93.1 ± 26.3 (44.5 – 138.3)
20 s BH(n_{SS}=30,n_C=29)	67.8 ± 14.6[a] (41.7 – 99.0)	81.4 ± 23.3[a] (42.8 – 121.3)
10 s BH(n_{SS}=30,n_C=30)	49.6 ± 16.6 (24.8 – 81.4)	57.6 ± 22.1 (17.9 – 108.4)

[a] Indicates estimate is significantly different between C and SS at $p \leq .05$

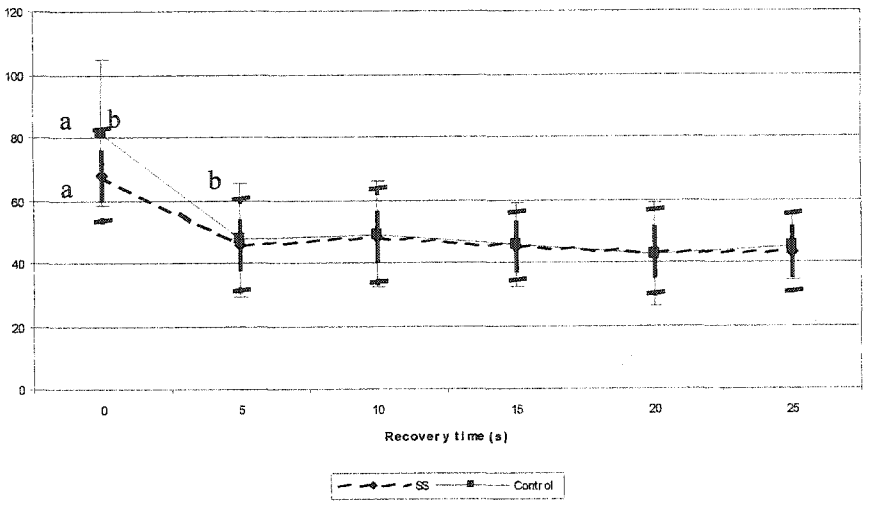


[a] Indicates $\dot{V}_E$ is significantly different from time=0 s to time=5 s for SS and C

[b] Indicates $\dot{V}_E$ is significantly different from time=5 s to time=10 s just for SS

[c] Indicates $\dot{V}_E$ is significantly different from time=5 s to time=15 s just for C

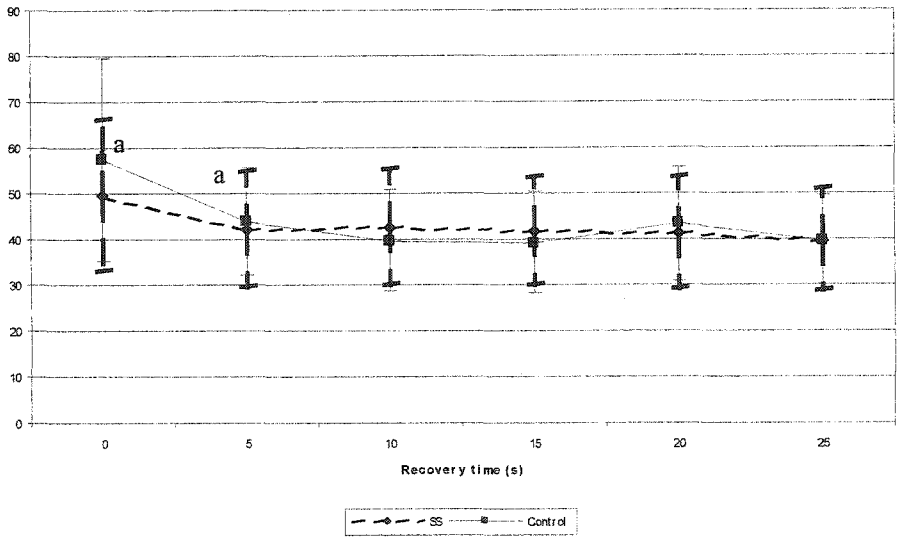
Figure 6-11. Recovery $\dot{V}_E$ for SS and C after 25 s of BH during exercise



[a] Indicates $\dot{V}_E$ is significantly different between SS and C

[b] Indicates $\dot{V}_E$ is significantly different from time =0 s to time = 5 s for SS and C

Figure 6-12. Recovery $\dot{V}_E$ for SS and C after 20 s of BH during exercise



[a] Indicates $\dot{V}_E$ is significantly different from t=0 s to t=5 s for SS and C

Figure 6-13. Recovery $\dot{V}_E$ for SS and C after 10 s of BH during exercise

Discussion

The results of the present study partially supported the hypotheses stated at the outset. An oxygen deficit was created during BH and recouped during recovery as hypothesized. Recovery for all variables in all groups happened within 15 s. After 25 s of BH, synchronized swimmers returned to steady state faster than controls since $\dot{V}_E$ stabilized 5 s faster than C. But there was no difference between SS and C in the initial recovery values of $\dot{V}_E$, HR and EPBHOC. The length of time for the first BH periods significantly influenced oxygen consumption in the SS during exercise. The group that breath held for 25 s at the start of exercise had a higher oxygen consumption (baseline) than the group that breath held for 10 s at the start of exercise; however there were no differences in $\dot{V}_E$ and HR due to the length of the first BH periods.

Subject characteristics

There was a significant difference in age between SS and C. All the other characteristics such as height, body mass, sitting height, FVC, and arm $\dot{V}O_2$ peak were similar. Arm $\dot{V}O_2$ peak results were similar to previous results (2.0 ± 0.3 $L \cdot min^{-1}$, Chapter 3) but were higher than those reported by Bhambhani, Maikala and Buckley (1998) for $\dot{V}O_2$ peak of female athletes (1.77 L·min-^{1}).

Exercise and breath holding while immersed

End tidal oxygen and carbon dioxide pressure

The present results showed that there was a relationship between the decrease in $P_{ET}O_2$ and the increase in BH times for both SS and C. An increase was observed for $P_{ET}CO_2$ with increasing BH times in the SS group. Chang and

Lundgren (1996) reported that tissue storage of CO_2 would increase in water immersion due to increased cardiac output and tissue perfusion. It is also known that BH produces vasoconstriction. It is possible that trained subjects had a faster reaction to BH and had less time to accumulate CO_2 in peripheral tissue before the effects of BH decreased blood supply to the periphery. This would have led to the results seen in the present study where $P_{ET}CO_2$ was higher for SS than for C. It would have also led to an increase in $P_{ET}CO_2$ for the C group following BH when blood flow was re-established, which is an alternative explanation to the difference in energy sources being used during BH, hypothesized below.

Hong et al. (1971) reported that at rest, CO_2 levels increase rapidly during the first 30 s of BH and level off or decrease their rate of increase while rates of O_2 transfer in the lungs remain constant throughout BH. Astrand (1960) reported the same tendency with exercise except that the decrease in build up of CO_2 was identified 10 s into BH and exercise. It is possible that the C group reached the leveling off phase at a faster rate even though their absolute values were lower than SS.

It can also be speculated that the significantly higher CO_2 levels for SS at 20 and 25 s could be related to differences in energy sources to maintain exercise. Synchronized swimmers may have utilized a different proportion of energy from aerobic, glycolytic and high energy phosphogens compared to C. This difference could be a result of adaptation to training. In fact there are conflicting results about lactate accumulation during BH. Ferreti et al. (1991) reported no lactate increase following BH out of the water despite high desaturation while Ferrrigno

et al. (1997) and Andersson et al. (2004) reported an increase in blood lactate following BH for deep divers and active BH divers performing steady state exercise respectively. This issue requires further research.

There was no greater increase in minute ventilation due to the higher $P_{ET}CO_2$ found in SS as might have been expected. The estimated alveolar ventilation [$\dot{V}_A$ =Fb x(TV - 0.15)] at time 0 post BH followed similar trends as those seen for $\dot{V}_E$ post BH. Therefore $\dot{V}_A$ for the SS is similar or lower than for C and there was no difference in $\dot{V}_A$ that would explain the higher $P_{ET}CO_2$. This is probably another adaptation seen in synchronized swimmers. It is possible that SS have decreased sensitivity to high levels of CO_2, as reported by Bjurstrom and Schoene (1987) and as a result minute ventilation following BH was either similar or lower than C.

Heart rate

The hypothesis that the 10 s initial groups were going to exhibit a faster decrease in HR during BH was not supported. Therefore the data was collapsed into two groups, SS and C. Heart rate decreased significantly during 20 s and 25 s BH periods, but not during the10 s period of time. In general SS decreases were sharper than for the C but there were not significant differences between the groups. The sharper decrease may show that SS are more efficient in their response to BH. It is very likely that this efficiency will translate into a better conservation of O_2.

Oxygen consumption

The present study hypothesized that after each breath hold there is an O_2

deficit that will be recouped through the EPBHOC following BH. The present findings demonstrated that the size of the O_2 deficit depends on the length of the BH time period and on the length of the first BH time period. Assuming the two SS groups were similar, results showed that beginning the sequence of BH periods with breath holds of shorter duration decreased the tendency towards higher $\dot{V}O_2$ at the end of the exercise period compared to beginning the sequence with breath holds of longer duration (Figure 6-7). For the C groups there was no such trend, therefore there was no difference between performing the shortest or the longest breath hold first. This observation could represent a BH training effect. This result suggests that it is better for BH trained subjects to perform shorter BH periods at the onset of exercise and longer ones towards the end of the exercise period. This would be different from what is normally done in elite solos, according to the time-motion analysis study (Chapter 2), which showed that larger BH periods were more common at the beginning of the solos.

Table 6-5 shows the net oxygen consumption for SS and C. Even though all results were negative, only two of the O_2 net values achieved significance. There was a significant net economy of O_2 while BH for 20 s in the SS and C groups. All other net values were negative and ranged from 82.6 to 87.4 % of the estimated oxygen consumption for SS and from 96.5 to 98.4% for C but were not significantly different than 0. The variability of the data was in part responsible for the lack of significance. The negative net results are similar to those reported by Andersson, Liner, Fredsted, and Schagatay (2004). They studied male subjects performing steady state cycle ergometry with eight 40 s BH periods. By

calculating the rate of oxygen consumption and carbon dioxide production during BH based on the change in volumes of oxygen and carbon dioxide in the lungs divided by the corresponding BH times, they concluded that BH on land reduced alveolar gas exchange compared to eupnoeic controls performing similar steady state exercise. With face immersion the reduction was even larger and lung oxygen storage was depleted at a slower rate. Stanek et al. (1993) proposed that the bradycardia and the hypoperfusion to non-essential organs and tissues during BH might provide an oxygen conservation effect. The net result in the present study approaching the 100% seen in 10 s and 25 s in the C group could be explained by the combination of psychological factors, such as fear influencing the response of the subjects and increasing HR or decreasing it less at the start of BH, which is supported by Finley, Bonet and Waxman, (1979). When the subjects reported their reason for ending BH at rest in a previous study (chapter 4), most of the reasons given by the C group were emotional as opposed to the more physiological reasons described by the SS group.

An interesting finding that was observed in the present study was that 25 s of recovery provided more than enough time for HR, $\dot{V}_E$ and EPBHOC to return to a steady state. But in some of the cases, oxygen consumption returned to a steady state that was slightly higher, from the previous baseline to the steady state achieved post BH, but this change was not statistically significant. The longer the recovery period used to calculate EPBHOC, the more this increase in steady state would diminish the conservation effect calculated in the present study. This tendency for oxygen consumption to increase over time could be a result of BH

but seems more likely to be a confounding effect from exercise. In Chapter 5 oxygen consumption fully returned to baseline before the following baseline was calculated when BH was performed under resting conditions. Thus the increase in baseline values appears to be a result of exercise. Other research has shown that there is a trend towards increase in oxygen consumption and a decrease in efficiency as steady state exercise progresses (Prince & Campbell, 1999). If the increase in oxygen consumption were not a confounding effect of exercise, it would imply that the oxygen conservation effect is only transient and that on a long term basis the oxygen that was not consumed during BH would in fact be gradually recouped. Nonetheless, results would still show a short term oxygen conservation effect for 20 s of BH in both the SS and C groups (Table 6-5).

Recovery after breath holding

Two parameters were used to study recovery after BH during exercise: $\dot{V}O_2$ and $\dot{V}_E$. Oxygen consumption following BH increased compared to pre BH $\dot{V}O_2$, resulting in an EPBHOC. When mean $\dot{V}O_2$ reached a steady state and EPBHOC reached the baseline value following BH, the group was considered recovered. Even though there was a tendency for the baseline to increase from BH1 to BH6, as expected, baseline rates were not significantly different. Therefore $\dot{V}O_2$ recovery or at least the fast component of recovery was on average fully achieved after each BH within 5 s for both the SS and the C groups. Andersson, et al. (2004) reported similar oxygen uptake behaviour after BH and exercise with face immersion for the first 15 s of recovery. Their results showed a sharp decrease in oxygen consumption during the first 15 s but it was followed by

a transient increase in oxygen consumption from 15 s post BH to 45 s post BH, which was not seen in the present study between 10 to 25 s of recovery. This could be due to the difference in BH time (25 s x40 s) or testing conditions (WI versus face immersion).

Minute ventilation increased after BH to provide adequate oxygen for recovery and proper CO_2 elimination. Both groups had a significant drop in $\dot{V}_E$. within 5 s from the start of recovery following 10 s, 20 s and 25 s of BH. After this initial 5 s drop that was observed for both groups there was no more significant changes in $\dot{V}_E$. following BH for 10 s and 20 s. Minute ventilation significantly decreased further following 25 s of BH for both groups and reached a steady state within 10 s of recovery for SS and 15 s within recovery for C. These results demonstrate a possible training effect that reduces the time of recovery for SS following a longer BH period and that the repetitive exposure to BH has helped SS become more efficient in recovering from BH.

Synchronized swimmers had a significantly lower $\dot{V}_E$. response after BH for 20 s compared to C as shown in Figure 6-12, which is in accordance with Bjurstrom & Shoene, (1987). The difference between C and SS at the start of recovery for all the other comparisons did not reach significance even though the trend was similar. It appears that the SS were able to eliminate higher amounts of CO_2 with similar ventilation rates. This depressed $\dot{V}_E$ response could be the result of a blunted response from the chemoceptors because these subjects are routinely under similar hypoxic condition while training. Masuda, Yoshida, Hayashi, Sasakim and Honda (1981) demonstrated the lower hypoxic sensitivity

of the "Ama" divers associated with an attenuation of the ventilatory response. The lower hypoxic sensitivity was hypothesized to be due to decreased peripheral chemosensitivity in these "Ama" subjects. In analyzing the ventilation response in association with CO_2 response, it seems clear that BH trained subjects perform differently. According to Sanchez and Sebert (1983) when higher levels of CO_2 are present there should be an increase in $\dot{V}_E$ response. This did not hold true for SS subjects when compared to the C group in the present study. Even though the SS group had significantly higher $P_{ET}CO_2$ values than controls following BH for 20 s and 25 s their ventilatory responses were either higher than or similar to C which seems to be related to decreased sensitivity of the chemoceptors to increased partial pressures of carbon dioxide.

Sánchez and Sébert (1983) studied men and women BH and exercising at 30 and 50% of $\dot{V}O_2$ max and concluded that ventilation speed of recovery was three times faster when maximal BH was performed before steady state had been achieved. They also observed a decrease in ventilatory response with subsequent BH periods. In the present study ventilation did not significantly vary between the start and the end of exercise. These findings are contrary to what Sánchez and Sébert reported but BH periods in the present study started after steady state exercise was achieved, which may have made a difference.

Conclusion

The results in the present study seem to lead to the conclusion that there is a possible training adaptation to BH while exercising, but a long term training study is needed to determine if that is really the case. Breath hold trained subjects

have an advantage versus subjects who are not trained in breath holding. Breath hold trained subjects are less sensitive to CO_2 since ventilation did not increase more due to the elevated levels of CO_2 following BH and were even reduced following 20 s of BH.

Synchronized swimmers are possibly able to conserve more O_2 than breath hold untrained subjects, but data is inconclusive since not all results were significant. It is tempting to suggest from the present results that it is more efficient for trained breath holders, specifically SS subjects, to perform larger BH periods at the end of their exercise sets rather than at the start of the exercise period, which is the exact opposite of what was observed in study the time-motion analysis (Chapter 2), where 91% of the swimmers had their largest BH during the first part of their routines. However future research is required exploring the effect of exercise and BH above the ventilatory threshold.

Further research to determine if there are differences in energy sources used during BH periods dependent on the level of BH training of the subjects is needed. There is also a need for further research to identify if the significant oxygen conservation effect that occurred for 2 out of the 6 groups analysed was only a transient effect or whether they were an effect of the physiological changes that pertain to BH and water immersion.

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Chapter Seven: General Discussion and Conclusion

Introduction

During the last decade, the sport of synchronized swimming has undergone many changes including the decrease in the time limits for routines, the increase in speed of movement, the introduction of acrobatic movements, and the replacement of figures by technical routines at the senior level. Solo routines have also undergone time limits and speed of movement changes during this time period. All these changes have likely altered the demands of the sport including the dynamics of breath holding (BH) within a routine. Breath holding, the main focus of this series of studies, is of great importance in synchronized swimming since not much was previously known about this aspect of the sport. The question of how much breath holding should be done, the impact of BH on judges' marks, and the physiological characteristics and responses associated with breath holding were all addressed in this series of studies. The issue of breath holding safety has also been addressed because it has been raised by Davies, Donaldson, and Joels (1995) and Davies, Joels and Udoh (1993) as well as being questioned in some of the Federation Internationale de Natation Amateur (FINA) reports (1996 &1998). The collective results of this research provide a more comprehensive profile of swimmers who have been conditioned to breath holding and water training over many years. These results also provide insight into new coaching strategies as well as training guidelines based on the new information gathered, advancing the previously limited knowledge about breath holding physiology in synchronized

swimmers.

The first of the five studies was a time-motion analysis of solo synchronized swimming performances in competition. As expected, the time spent underwater by the best Canadian synchronized swimmers did not reach the 40 s considered dangerous by Davies et al. (1995) and FINA (1996 & 1998). Time-motion analysis showed that underwater times for Canadian soloists were much smaller than the ones reported by Davies et al. (1995) and none of the breath holding periods was greater than 39 s. The study was unable to provide any information about the levels of $P_{ET}CO_2$ to compare with the values reported by Davies et al., but based on the maximal times found, the levels of CO_2 should not have reached those considered dangerous **(Chapter 2).**

Contrary to what was expected, there was no positive relationship between the time of breath holding and the technical merit (TM) scores received for routines. The TM score was not significantly correlated with time spent underwater, maximal BH time or mean time for breath holds greater than 6:83 s. This finding suggests decreasing importance of long and dangerous BH periods in solo events. This trend may be a result of the effort of FINA to educate judges and coaches to de-emphasize maximal BH time **(Chapter 2).**

The second study compared peak oxygen consumption tests on land (dry) versus immersed in water (wet). As expected, heart rate (HR) was significantly lower in the wet condition at the ventilatory threshold and at $\dot{V}O_2$ peak, oxygen pulse in the wet condition was significantly higher at the onset of the exercise, and at the ventilatory threshold; the maximal frequency of breathing was greater

in the water compared to out of the water and there was no difference in maximal $\dot{V}O_2$ in and out of the water during exercise in any of the timelines analysed. This result for HR offers further information on HR behaviour in the water and may be useful in providing guidelines for training based on HR in the water **(Chapter 3).**

The third study investigated adaptations in lung volumes and capacities in synchronized swimmers and compared differences in lung volumes and capacities from land to water. Most of the lung volumes and capacities were lower in the wet condition. Forced expiratory volume in one second (FEV_1), expiratory reserve volume (ERV), total lung capacity (TLC), functional residual capacity (FRC) and forced expiratory vital capacity (FVC) were all significantly decreased in the wet condition than in the dry condition. In contrast to these decreases, inspiratory capacity (IC) in the wet condition was significantly larger than IC in the dry condition. These findings are in agreement with previous research that showed them to be a direct result of hydrostatic pressure. The observed volumes on land were significantly larger for the swimmers than the mean predicted volumes for the normal population of similar height, age and sex (SensorMedics, 1988) although SS lung volumes were within the upper range of normal. These high normal volumes support the possibility that the swimmers have benefited from their training in the water due to the extra strength needed to work against water resistance (Doherty & Dimitriou, 1997) or at least from the high level of physical activity (Neder, Andreoni, Castelo-Filho & Nery, 1999; Astrand & Rodahl, 1986); however, only a long-term study will be able to will be able to confirm this

possibility **(Chapter 4)**.

Study four examined breath holding in water immersion at rest for synchronized swimmers (SS) versus a non-swimming active female control group (C). Maximal BH times at rest for SS were significantly larger than for C. Minute ventilation and $\dot{V}O_2$ following BH was not significantly different between SS and C and post BH $P_{ET}CO_2$ and post BH $P_{ET}O_2$ were also similar for SS and C despite the maximal BH time difference. As predicted, there was an oxygen deficit that was recouped during recovery. Contrary to what was expected, there was no difference in recovery time between groups. The excess post breath holding oxygen consumption (EPBHOC) during recovery was very similar from SS to C, and returned to baseline values within 25 s of recovery breathing. Excess post breath holding oxygen consumption was only significantly different from the baseline for the first 5 s of recovery breathing for both groups Minute ventilation recovered to pre BH values within 10 s for SS and 15 s for C. Results for the oxygen conservation effect were inconclusive **(Chapter 5).**

The fifth study examined BH and exercise with water immersion for a sequence of breath holds. A synchronized swimming group and a control group were again compared. Results confirmed the hypothesis that there was an oxygen deficit that was developed during BH and needed to be recouped during recovery while the subjects were exercising but not holding their breath. Recovery trends were very similar between SS and C. As expected, recovery for both EPBHOC and $\dot{V}_E$ returned to baseline values within 25 s following BH. Minute ventilation response for the two groups was also very similar but at 20 s BH $\dot{V}_E$ was

significantly lower for SS than for C. This shows a possible adaptation to BH.

The normal stimulation to ventilate appears to be decreased for the SS due to their continuous exposure to BH. There was no difference in HR response between SS and C. There was a HR decrease for both groups when BH for 25 and 20 s but not when BH for 10 s. It seems that 10 s of BH was not enough to trigger a significant HR decrease.

An oxygen conservation effect represented by the difference between estimated oxygen consumption and measured oxygen consumption was significant for two of the six groups analysed (20 s of BH for SS and for C). This result corroborates the theory that there is an oxygen conservation effect during BH (Andersson, Liner, Fredsteed, & Schagatay, 2004) but because all the other four results were not significant, further research is required. The estimated oxygen consumption during BH was lower for the *SS 10 s initial group* compared to the *SS 25 s initial* due to the fact that baseline values were significantly lower for *SS 10 s initial.* This finding will have an impact on the understanding of the best order to do BH while exercising. If SS had their shortest breath holding periods at the beginning of the exercise period they needed less oxygen over the entire exercise period than if the largest breath holding periods were done at the beginning of the exercise period **(Chapter 6).**

Limitation

A major limitation of this series of investigations was the size of the sample. In the City of Edmonton there is only one elite club and one sub-elite club that would have been exposed to high levels of synchronized swimming training. As a result of the small number of subjects, the likelihood of achieving statistical

significance from the analysis was considerably decreased.

Conclusion

This thesis supports a number of important conclusions:

1. Correlational analysis of BH times and marks show that, at least for Canadian soloists, it is no longer important to perform long periods of breath holding to get top marks in the sport.

2. It has been suggested that swimming during developmental years would help increase lung volumes and capacities (Doherty & Dimitriou, 1997). The larger volumes presented in the present study support the possibility of a training effect but only a long-term study could confirm this hypothesis.

3. The BH at rest study (Chapter 5) shows that there are some adaptations that allow synchronized swimmers to breath hold for longer than controls. Whether the adaptations are mainly psychological or physiological or a combination of both is inconclusive, but the study did show different physiological outcomes between groups. Recovery trends were similar between groups despite the breath holding time differences, concurring with the idea that there is a physiological adaptation achieved through BH training.

4. The possibility of an oxygen conservation effect needs further investigation but the results show a trend towards a possible reduction of oxygen consumption during breath holding, for exercise below the ventilatory threshold. The trend was more noticeable for the SS than for the controls.

5. There is a widely held belief that it is more efficient to have a large BH period at the start of the routines. In contrast to this, this study showed that it may be better to start with a small BH period and build to a larger BH period at the

end. However further research exploring exercise intensity and BH is needed before this conclusion can be made.

Future research

This thesis has developed and validated equipment and techniques for using a metabolic cart in breath by breath mode to study breath holding in and out of the water. The arm and leg cyclergometer adapted from another study (Chen, Kenny, Johnston, & Giesbrech, 1996), and built for this series of studies can be used to further develop the understanding of water exercise.

The development of an oximeter that could be used underwater similar to a heart rate monitor would be a very useful tool to monitor the training of synchronized swimming since it would allow for the measurement of arterial blood saturation while performing either a routine or compulsory figures. Such equipment would result in a much safer training environment for the swimmers and would allow them to push more towards their limits without the risk of loosing consciousness in the water. This kind of equipment will also help the development of routines that have suitable recovery periods from BH that maximize the level of performance and therefore increase marks obtained by the swimmers.

It would be interesting to see the International swimming Federation (FINA) apply a methodology similar to the one used in study one to randomly test synchronized swimming routines and determine if long periods of BH are an issue. This would allow them to conclude whether the sport of synchronized swimming is safe and would provide further data on the influence of breath holding on technical merit scores.

The suggestion that there is an oxygen conservation effect during BH, especially when the subjects are breath holding trained individuals, seems to be a highly promising research direction. It is possible that a larger sample size, and a specific protocol to examine only this hypothesis will produce positive and conclusive data on this issue. If the oxygen conservation effect is indeed confirmed, it would be interesting to determine if this conservation is a transient effect while the body is in danger of lacking oxygen for their most important body functions and whether the oxygen saved is recouped following the BH period. Alternatively, it would be interesting to determine if oxygen conserved is never needed by the body.

Further studies investigating higher intensities of exercise combined with a series of BH trials would be very useful to help coaches plan their routines. The present study identified that larger BH periods at the end of steady state exercise were more economical for the swimmers, but the intensity studied did not represent the intensity at which SS swim their routines. Thus, a breath holding study mimicking the intensity of routines is required. Muscle fatigue is potentially a serious detriment performance at the end of a routine. If the intensity of the exercise is above the ventilatory threshold, it would possibly provide coaches with a different result than what was found in this study.

An analysis of breath holding and synchronized swimming entirely at higher levels of exercise will also provide further knowledge for coaches and allow them to train swimmers near acceptable limits of breath holding without endangering their athletes. The proper identification of the most important

sources of energy during a routine and specifically during breath holding parts of the routine could improve the current knowledge used to develop training programs.

Small sequential BH periods were identified by the time-motion analysis as often either preceding or succeeding larger BH periods. It would be beneficial to have some further information on how swimmers react to these small sequences of breath holding that could potentially lead to hyperventilation and consequently loss of consciousness in the water.

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Appendix A - Review of literature

Physiological changes to water immersion and breath holding at rest and during exercise

To date little research has been done on the physiological requirements to compete in the sport of synchronized swimming; however, the physiological effects of water immersion, breath holding and breath holding with water immersion have all been studied. Some of this research has been done in conjunction with exercise but the majority of studies done to date on water immersion have been completed without exercise. Collectively this literature provides an indirect body of research on the physiology of synchronized swimming.

Water immersion

There has been increased interest by the scientific community in studying the effects of water immersion in a variety of settings. These studies have served several different purposes, including examining the specific effects of water immersion on divers, swimmers, and scuba divers (Ferreti et al., 1991; Liner, 1994; Thorsen, Skogstad & Reed, 1999; Leddy, Roberts, Moalen, Curry & Lundgren, 2001; Delapille, Verin Tourny-Chollet & Pasquis, 2001a); the beneficial effects of water immersion for physiotherapy treatments (Frangolais & Rhodes, 1995) the detrimental effects for cardiac patients (Hall, Macdonald, Maddison & O'Hare, 1998); and the miscellaneous effects of water immersion after boating accidents (Tipton, 1989). Finally, water immersion has been examined as a potential scenario to partially reproduce reduced gravity and

therefore simulate the conditions of space flights (Koryak, 2002).

Physiological changes in water immersion without exercise

When immersed in water, subjects are affected by cardiovascular changes that occur due to a change in pressure. Water immersion to the neck led to a shift of approximately 700 ml of blood from the periphery to the central circulation in men (Arborelius, Balldrin, Lilja & Lundgen, 1972), an increase of central venous pressure (8 to 12 mmHg), and a 10 to 28% increase in stroke volume (SV) (Arborelius et al., 1972; Begin et al., 1976; Pan, He, Kinouchi, Yamaguchi & Miyamoto, 1997) at rest. There was also an increase in cardiac output (CO) (Arborelius et al.; Farhi & Linnarsson, 1977; Lin, 1984), and either a decrease (Miwa, Sugiyama, Mano, Iwase & Matsukawa, 1997; Pan et al., 1997) or no change in heart rate (HR) (depending on temperature) (Arborelius et al.; Farhi & Linnarsson; Lin). Yamazaki, Endo, Torii, Sagawa and Shiraki (2000) observed a decrease of 13% in total peripheral resistance (TPR) from air to water immersion and when water temperature increased from 32 to 36 °C and Arborelius et al. observed a 30% decrease in TPR from air at 28°C to water at 35°C. Temperatures below 33°C have been described as the threshold for the increase in peripheral vasoconstriction (Tipton, 1989).

Water temperature plays an important role in respiratory changes when immersed without exercise. Marino and Booth (1998) investigated the responses to 60 min of water immersion at rest. Water temperature started at 28°C and reached 23°C by the end of the test. They reported an increase in oxygen consumption (from 0.34 to 0.54 $L.min^{-1}$; $\bar{x}$) and an increase in minute ventilation

($\dot{V}_E$)(from 6.2 to 11.6 $L.min^{-1}$; $\bar{x}$) during water immersion. These changes were associated with the decrease in temperature. Oxygen consumption increase with water temperature decrease could be due to thermoregulatory effects such as shivering thermogenesis that increases metabolic activity in the muscles and causes the increase in heat production (McArdle, Magel, Lesles, & Pechar, 1976). Oxygen consumption increase may also be related to non-shivering thermogenesis mechanisms of unknown origin (Marino & Booth, 1998).

Water immersion influences lung volumes and capacities at rest. Vital capacity decreases in water immersion, as do almost all other lung capacities and volumes, except for inspiratory capacity. Inspiratory capacity increases due to a drastic decrease in expiratory reserve volume, which is due to pressure changes (Withers & Hamdorf, 1989; Hong, Cerreletti, Cruz & Rahl, 1969; Agostini, Gurtner, Torri, & Rahn, 1966). Tidal volume either decreases in water as a result of pressure changes due to immersion (Chang & Lundgren, 1996) and/or temperature changes that provoke hyperventilation (Cooper et al., 1976), or stays the same as on land (Hong et al., 1969, Whiters & Hamdorf, 1989). It is also known that many years of training with water immersion minimize the change in lung volumes and capacities from land to water due to the repetitive muscle work done over the years against a higher pressure which leads to an increase in muscle strength (Doherty & Dimitriou, 1997). Changes due to training with immersion and the effect of immersion itself both play an important role in exercise in the water with breath holding and deserve careful consideration.

Yamazaki et al. (2000) also investigated hemodilution and other

cardiovascular changes during water immersion in males, sitting in water at rest. Mean arterial pressure increased between 2 and 7 mmHg after 10 min of water immersion, cardiac output increased 5 to 20% depending on water temperature (36 vs. 34.5 °C). Hematocrit, blood density and plasma density decreased during the first 25 min of water immersion and remained low throughout water immersion. These reduced values were linked to the fluid shift from the interstitial space to intravascular space during water immersion.

Thus water immersion causes important cardiovascular, respiratory and blood content changes. Water temperature is a critical variable affecting oxygen consumption, frequency of breathing, mean arterial pressure, HR, SV and vascular resistance (Marino & Booth, 1999; Arborelius et al., 1972; Yamazaki et al., 2000). Temperature must therefore be considered when reporting or comparing data with previous research and must be carefully controlled in any study of water immersion.

Physiological changes in water immersion with exercise

During water immersion to the shoulders, HR significantly decreased by approximately 10 $b \cdot min^{-1}$ at maximal and submaximal exercise above 75% of $\dot{V}O_2$ max in men, compared to exercise on land (Sheldahl et al., 1987). These changes are due to CO and SV changes. Cardiac output and stroke volume significantly increased during water immersion (Sheldahl et al.). Since water immersion causes more oxygen to be stored in blood and tissue than in the dry condition, this increase in oxygen lessens the need for external respiration to take in oxygen for the working muscles (Hayashi & Yoshida, 1999). Some of the

other differences detected such as peripheral vasoconstriction, are mostly due to water temperature (Shagatay & Holm, 1996; Sterba & Lundgren, 1985).

During water immersion to the shoulders, breathing frequency increased during maximal and submaximal exercise versus exercise on land and there was a decrease in tidal volume (Sheldahl et al., 1987). Frangolais and Rhodes (1995) and Sterba and Lundgren (1985) reported increases in $\dot{V}_E$ during exercise at and above the ventilatory threshold when immersed in water. Conversely, others reported no change in $\dot{V}_E$ (Sheldahl et al.). The discrepancy in results may be due to the increase in water resistance to movement that changed the absolute intensity of exercise from land to water (Brechat et al., 1999) or buoyancy that changed muscle recruitment (Frangolais and Rhodes, 1995).

$\dot{V}O_2$ max measured during water immersion did not differ from that measured on land in most of the cycle ergometer studies (Christie et al., 1990; Sheldahl et al., 1987; Conelly et al., 1990), but running studies have shown a decrease in $\dot{V}O_2$max in water immersion compared to dryland running (Frangolais & Rhodes, 1995). The differences have been attributed to the effect of buoyancy and to the different muscle recruitment pattern during water immersion vs. land (Nakanishi, Kimura & Yokoo, 1999).

Brechat et al. (1999) investigated males performing steady state exercise on a cycle ergometer in water immersion compared to on land. They concluded that absolute tidal volumes were similar in both conditions, despite the decreased vital capacity and the lower ergometric workload in water immersion (60% of power for the same $\dot{V}O_2$). They also reported higher frequency of breathing in

water immersion. Oxygen consumption achieved steady state after 2 min in both water immersion and dryland at 59% of $\dot{V}O_2$ max. Subjects exercising while immersed in water need to overcome lung volume changes due to the external hydrostatic pressure and muscle recruitment differences due to the difference in the density of the water compared to air. This may have accounted for the difference in maximal load achieved described in results obtained by Brechat et al.

Connelly et al. (1990) reported lower blood lactate (Bla) at maximal exercise during water immersion in men suggesting less contribution of anaerobic glycolitic energy production. Plasma norepinephrine was lower at and above 80% of $\dot{V}O_2$ max and epinephrine was lower at maximal work. These investigators concluded that the lower epinephrine concentration could have reduced glycogenolysis and therefore reduced Bla. Another alternative presented was the potential for increased blood flow to aid in the removal of Bla from blood by other tissues.

Thus there are a number of factors to consider when studying exercise with water immersion. Temperature is again an important variable, although less so than for water immersion without exercise, provided that water temperature is kept below thermoneutral temperature but not cold to the point that it would increase oxygen consumption. Water resistance and the possibility of differing muscle recruitment in the water versus on land must be considered in studies that attempt to compare exercise under the two conditions. Maximal oxygen consumption tends to be the same on land and in the water when using cycle

ergometers. This type of equipment is therefore good to use in studies that compare exercise with and without water immersion.

Breath holding

A number of important general variables influence the ability to breath hold. These may be grouped into the broad categories of chemical, non-chemical and psychological factors. Chemical factors refer to the ability to withstand hypoxia and hypercapnia, or decreased sensitivity to lower levels of oxygen or/and carbon dioxide (Hong et al.1971; Courteix, Bedu, Fellmann, Heraud & Coudert, 1993). Non-chemical factors are either the existence or absence of respiratory movements while breath holding (Delapille et al., 2001a). Psychological factors are related to the motivation to breath hold.

The main chemical factors involved in determining breath holding times are related to pH, arterial partial pressure of carbon dioxide (P_aCO_2) and to a lesser extent arterial partial pressure of oxygen (P_aO_2) (Henstsch & Ulmer, 1984). The most important stimulus to breathe is P_aCO_2 , more specifically the hydrogen ions dissociated from carbonic acid once carbon dioxide diffuses through the blood brain barrier to the cerebral fluid, combines with water and dissociates to ions of hydrogen and hydrogencarbonate and is detected by the central chemoreceptors. Hypercapnia stimulates the chemoceptors, which send messages to the ventilatory centre of the brain to increase ventilation. The carotid bodies are also important organelles in detecting the lack of oxygen. They are responsible for producing the drive to breathe based on oxygen, hydrogen ions, and to a lesser extent carbon dioxide (Astrand & Rodalh, 1986). The central

chemoceptors account for 75% of carbon dioxide (CO_2) induced increases in ventilation, while the carotid bodies account for 25% of human sensitivity to CO_2. Once there is a drive for breathing, respiration may still be delayed by the psychological will to prolong diving (Hentsch & Ulmer). In extreme O_2 deprivation (30 to 25 mmHg), loss of consciousness occurs as a self protection mechanism. If the loss of consciousness happens in the water, a person may drown.

Breath holding is composed of two distinct phases. The first phase, known as the "easy going phase", is from the beginning of breath holding to the point where involuntary respiratory movements occur, which is the physiological breaking point. The physiological breaking point is defined as the point where elevated partial pressure of carbon dioxide triggers involuntary breathing movements (Henstsch & Ulmer, 1984), and occurs at approximately 45 to 50 mmHg (Delapille et al., 2001a). The second phase or "struggling phase" goes from the end of the first phase to where the "strength of will" determines the end of breath holding (Henstsch & Ulmer). The "strength of will" is a psychological predisposition to withstand discomfort. As the person continues to breath hold during the second phase, motivation to continue breath holding is higher than the fear of running out of air.

Breath holding times are highly influenced by psychological factors, especially maintaining breath holding after the struggle phase starts (Henstsch & Ulmer, 1984). A short-term training effect has also been observed for breath holding. That is, as the person practices breath holding, an accustomization to the

discomfort occurs and breath holding times increase (Henstsch & Ulmer). Hentsh & Ulmer stated that involuntary contractions are present during the struggling phase that occurs during the latter stages of breath holding. They found that the resumption of breathing movements accelerated HR, even when gas tension was maintained at a constant levels (Gooden, 1994).

Thus chemical, non-chemical and psychological factors all influence the physiological response to breath holding. Any study of breath holding needs to consider that the psychological effect can overcome other factors. Short term training effects, breath holding experience and strength of will need to be considered in studies of breath holding.

Physiological changes with breath holding on land without exercise

Research done on land is easier to conduct than research done in water. Therefore there is a considerable amount of research done on land without exercise that contributes to the understanding of the physiology of breath holding.

Hong et al. (1971) studied diving and non-diving male subjects, and reported a decrease in HR and an increase in SV during breath holding on land. Hong et al. also reported an increase in blood pressure toward the end of breath holding (after 1 min on land). This led to the conclusion by the authors that HR changes were not elicited by the baroreflex stimulus. Swift et al. (2003) and Leuemberger, Hardy, Herr, Gray & Sinoway, (2001) postulated that the increase in blood pressure and vascular resistance seen during breath holding are due to an increase in muscle sympathetic nerve activity, which is activated by chemoreflex activity during breath holding and therefore mediated in part by the sympathetic

nervous system.

Pan et al. (1997) suggested that as breath holding time increases HR decreases. However, according to Gooden (1994), the HR decrease is observed in only 2% of the population and the younger fit individuals present a much higher percentage of the response (18%), primarily because the aging process reduces parasympathetic tone. The heart rate decrease is due to vagal stimulation (Gooden) or to peripheral vasoconstriction (Sterba & Lundgren, 1985) through the baroreceptor reflex (Lin, 1984; Pan et al.). With the decrease in venous return, peripheral vasoconstriction triggers the HR response towards bradycardia (Pan et al.). Some authors base their explanation of HR decrease on vasoconstriction (Lin, Pan et al.) while others dissociate the decrease of HR with vasoconstriction Hong et al. (1971). It is possible that both explanations are correct. The main rationale for those who do not associate HR decrease and vasoconstriction is the time frame of both phenomena. Heart rate may decrease at the onset of breath holding, though not elicited by baroreflex; but as vasoconstriction builds, the baroreflex causes an additional HR decrease.

Hong et al. (1971) reported that as breath holding times increase, the alveolar and arterial levels of CO_2 increase. The increase was rapid during the first 30 s of breath holding on land, after which CO_2 increased at a slower rate. There could even be a reversed CO_2 gradient across the alveolar-capillary membrane due to a decrease in lung volume since the rate of O_2 transfer remains higher than CO_2 transfer. The volume loss concentrates CO_2 in the lungs. This pattern of gas exchange will lead to an increase in tissue CO_2 accumulation, which

in turn will increase the stimulation of the respiratory centre (Ferreti et al., 1991). It was estimated that the lungs and the blood accumulate 70% of the CO_2 and the other tissues such as brain and muscles accumulate the remaining 30% (Hong et al., Ferreti et al.).

Irzhak and Oskolkova (2003) studied non-athletes, swimmers and skiers (type of skiing not stated) while performing max breath holding at rest and during exercise on land. At rest maximal breath holding was 88 ± 8 s ($\bar{x}$ ± SE) for untrained, 91 ± 6 s ($\bar{x}$ ± SE) for swimmers and 95 ± 7 s ($\bar{x}$ ± SE) for skiers (if means were different was not reported). $\dot{V}_E$ following breath holding significantly increased 30% for untrained and skiers and 60% for swimmers. The authors also reported a significant increase in respiratory heat loss in response to apnea (5% of the total heat loss) and a significant increase in the frequency of breathing following breath holding for the untrained group. The heat loss was positively related to the duration of breath holding and to $\dot{V}_E$.

Hong et al. (1971) studied divers and non-diving male subjects and reported Bla increases after 2 min of breath holding. Blood lactate also continued to increase for 20 s after breathing resumed. The author associated this increase with a similar phenomenon observed in diving mammals where circulatory shunts bypass the muscle capillaries and other vascular beds. As a consequence, Bla is trapped until the end of breath holding, and then is released with the return of perfusion following breath holding.

Thus we expect to see a decrease in HR while breath holding and increases in $\dot{V}_E$ during recovery. Non-athletes will have lower maximal breath

holding times but the breath holding experience of swimmers does not necessarily give them the advantage when breath holding on land at rest. This is perhaps surprising.

Physiological changes with breath holding on land during exercise

Breath holding times during exercise have been shown to be inversely correlated to the intensity of exercise (Sanchez & Sebert, 1983). Sanchez and Sebert investigated men and women performing max breath holding periods on land within a continuous 6-minute cycle ergometer exercise period. Intensity of the exercise was either 30 or 50% of $\dot{V}O_2$ max. Duration of breath holding decreased as exercise intensity increased, and breath holding was longer for men than for women. The limited amount of oxygen accounts for the decrease in BH times as exercise increases. Mean HR decreased throughout all breath holding periods at both 30% and 50 % of $\dot{V}O_2$ max. However, some subjects also showed an increase in HR during breath holding, which was also reported by others (Gooden, 1994). The mean HR decrease was found at the onset of breath holding for men while for women HR decrease was found more towards the end of the breath holding period.

Sanchez and Sebert (1983) suggested $\dot{V}_E$ could be used as an index of recovery from breath holding. Ventilation kinetics showed that when breath holding started at steady state (4th min of exercise) $\dot{V}_E$ mean values were 3 times lower than when breath holding started 30 s after the onset of exercise, before steady state was achieved. They attributed the results to a transient effect on $\dot{V}_E$

at the onset of exercise. They linked the higher $\dot{V}_E$ stimulus to the O_2 deficit developed. They also observed that $\dot{V}_E$ recovery was slower during steady state exercise due to a decreased stimulus to ventilate. No data was available with respect to oxygen consumption post breath holding or the possible cumulative effects of intermittent breath holding. To date this information does not seem to be available in the literature.

Irzhak and Oskolkova (2003) also investigated the effect of breath holding on respiration while exercising. They reported that swimmers did not considerably increase their $\dot{V}_E$ following breath holding while exercising compared to following breath holding at rest, which was explained by the somewhat similar activity the swimmers are involved in while training. For non-swimmers the increase was 1.5 to 2 times higher than for breath holding at rest. The authors suggested that the increase in $\dot{V}_E$ following apnea could be transformed into an index of adaptation to breath holding.

Astrand (1960) reported that during breath holding on land P_ACO_2 increased rapidly following the first 10 s of breath holding at the start of a 147 W exercise period. The P_ACO_2 increased from 43 to 60 mmHg and then leveled off at around 65 mmHg. These results are similar to other results for breath holding with no exercise reported by Hong et al., (1971). The difference between Hong et al. and Astrand is that due to the influence of exercise in Astrand's research, CO_2 reached a plateau at a much faster rate (10 vs. 30 s). P_AO_2 decreased from 95 to 25 mmHg after 40 to 45 s of breath holding during a 147 W exercise on a cycle ergometer (Astrand). Below a P_AO_2 of 25 to 30 mmHg, a safety mechanism to

maintain available O_2 for the main functions of the body exists that reduces any non-primary function, including consciousness, to preserve oxygen flow to essential body tissues (Astrand & Rodalh, 1986). Astrand also observed that if breath holding was performed at the beginning of exercise, the P_ACO_2 decreased to the same values as those found during breath holding at rest, independent of the workload. During steady state exercise and breath holding, the P_ACO_2 was higher if the workload was greater. An interesting observation was that when breath holding was performed during exercise there was an increased ability to withstand higher P_ACO_2 which was explained by a decrease in sensitivity (or greater tolerance) to higher levels of CO_2 or a distraction from the need for air (Astrand).

Andersson, Liner, Fredsteed, and Schagatay (2004) investigated divers performing steady state exercise on a cycle ergometer for 50 min while performing intermittent 40 s breath holding periods with cold face immersion on land or without face immersion on land. Without face immersion, the authors reported a decrease in arterial hemoglobin saturation to 88% (measured with an oximeter) or 80% (by arterial blood sample), decreases in HR, skin blood flow and increases in mean arterial blood pressure. The collective changes seen with breath holding and exercise on land may be enough to show that the diving response triggered by breath holding has an oxygen conserving effect (Andersson et al., 2004).

Fujitsuka, Ohkuwa and Miyamura (1980) determined Bla in males exercising while running and breath holding. They concluded that Bla is lower when breath holding, refuting the theory that an oxygen deficit was compensated

for by anaerobic energy production. They hypothesized that the lower levels of Bla could be related to the balance between disappearance and production of lactate. They also suggested that there could be an enhancement of lactate utilization by the working muscles as an energy source during breath holding.

The physiological changes that occur during exercise and breath holding support the theory of an oxygen conserving effect. The decrease in HR, the decrease in skin blood flow and the increase in mean arterial pressure corroborate the decrease in oxygen utilization. The main differences in breath holding with exercise on land compared to breath holding at rest is that exercise results in a higher P_ACO_2 and consequently a lower P_AO_2. This increases the danger of losing consciousness during exercise if the levels of P_AO_2 reach 25 to 30 mmHg (Astrand & Rodalh, 1986).

Breath holding and water immersion or face immersion

Breath holding with water immersion elicits a group of physiological responses (respiratory, vascular and cardiac) that have been termed the diving reflex or diving response. Liner (1994), West, Mc Culloch and Browne (2001) and Andersson, Liner and Runow (2002), among others, described the diving response as a phenomenon induced by apnoea, consisting mainly of vagally mediated bradycardia, decreased cardiac output, vasoconstriction and redistribution of peripheral blood flow. The diving response can also be enhanced by face immersion in cold water. Face immersion in cold water is known to provide a stronger response to breath holding than breath holding without face immersion (Andersson et al., 2002). Facial cold receptors and/or arterial

chemoceptors trigger peripheral vasoconstriction. Both bradycardia and vasoconstriction are oxygen conservation strategies. The blood flow to the brain is maintained or even increased (Pan et al., 1997). The main aim of the diving response is to conserve oxygen for the brain and heart (Sterba & Lundgren, 1985).

Physiological changes with breath holding and water immersion or face immersion without exercise

Figura, Cama and Guidetti (1993) studied elite synchronized swimmers while breath holding upside down for 50 s in the water at rest and during exercise. During breath holding while resting upside down, the authors reported a decrease in HR from 98 ± 14 to 70 ± 7 $b \cdot min^{-1}$; ($\bar{x}$ ± SD). The HR decreases reported for synchronized swimmers are similar to others reported for breath holding at rest in water immersion (Pan et al., 1997).

Among the respiratory changes with breath holding and water immersion is that there is a transient alveolar CO_2 decrease as a person is immersed in water, changing the O_2 and CO_2 stores of the tissues, including blood. The decrease in alveolar CO_2 is related to the increase in cardiac output, a decrease in peripheral blood flow and venous blood volume (Liner, 1994), and/or hyperventilation due to water temperature (Tipton, 1989). The CO_2 decrease in water immersion could account for the differences in maximal breath holding time in and out of the water. It may also slightly change the time frame for CO_2 accumulation while immersed. Sterba and Lundgren (1985) studied male scuba divers and reported P_ACO_2 values of 40 mmHg at the onset of breath holding on land. Alveolar carbon dioxide tensions showed a tendency to decrease in water immersion

compared to land. The tendency to decrease was greater as the water temperature decreased ($\bar{x}$ =36.9 at 35 °C and 36.2 mmHg at 32°C). This decrease in P_ACO_2 is due to the hyperventilation that occurs following cold water immersion (Tipton).

Breath holding times are prolonged during water immersion in thermoneutral water (Sterba & Lundgren 1985, Pan et al., 1997) but post breath holding CO_2 levels are not different in comparison to on land (Sterba & Lundgren). Higher water immersion temperatures (35°C & 32°C) increased oxygen consumption by 16% during breath holding compared to on land (Sterba & Lundgren), but there was no difference in breath holding times. If water temperature is reduced to 20 °C, breath holding time is reduced possibly because cold face receptors stimulate respiration. There is also a reported increase of 256% in $\dot{V}O_2$ (on land control at 28 °C), which contributes to the decrease in breath holding time when the water temperature is low (Sterba & Lundgren).

Delapille, Verin, Tourny-Chollet, and Pasquis (2001b) investigated the sensitivity to hypercapnia in trained divers and untrained controls while performing maximal breath holding and water immersion. Rebreathing tests revealed a less pronounced ventilatory response of 42.7% for the trained divers. This led to the conclusion that lower CO_2 sensitivity was an adaptation to breath holding and a result of decreased respiratory center activity, which allowed a delay in the breath holding physiological breaking point.

Researchers were recently able to include spleen contraction as part of the diving response. Bakovic et al. (2003) tested intact persons and splenectomized persons and Schagatay, Andersson, Hallen and Palsson (2001) tested healthy

subjects and splenectomized subjects and their ability to breath holding. Intact subjects were able to increase breath holding times after the first breath holding trial. These authors established a relationship between a larger number of red blood cells ejected from the spleen leading to a larger blood gas storage and the ability to breath hold for a longer period of time.

Cold temperature, even simple face immersion in cold versus warm water, clearly enhances the diving response. Thus temperature is an important factor to control in any research involving the diving response.

Physiological changes with breath holding and water immersion or face immersion with exercise

Research has provided important information about physiological changes to water immersion and exercise. This pool of information was developed mainly with male subjects. Nevertheless the changes that happen with water immersion and exercise such as vasoconstriction when water temperature is low, (Sterba & Lundgren, 1985; Shagatay & Holm, 1996) decreases in HR, and increases in CO and SV (Sheldahl et al., 1997) allow longer breath holding periods and can be extrapolated to the female population. The number of subjects involved in each of the research projects that deal with exercise, water immersion and breath holding is surprisingly low. Most of the breath holding water immersion with exercise studies had less than 10 subjects involved in the data collection (mean 6.6). This may reflect the difficult and laborious process of conducting research under these conditions. It is very possible that water immersion limits the use of regular equipment demanding the development of specialized equipment. Face

immersion is an alternative method that produces a diving response and allows the study of exercise and breath holding without water immersion.

The most studied population while breath holding and exercising is the "Ama". The "Ama" are women diving experts that hyperventilate and harvest pearls by swimming to the bottom of the sea (Scholander, Hammel, LeMessurier, Hemmingsen & Garey 1962; Hong, Rahn, Kang, D., Song & Kang, B., 1963; Masuda, Yoshida, Hayashi, Sasaki & Honda, 1981; Stanek et al., 1993). The main findings of these studies were that the "Ama" have developed a respiratory adaptation to hypoxia and/or hypercapnia due to their diving activity (Masuda et al., 1981) and that there is not any risk of severe desaturation if the length of the dive is within their normal diving time (oxygen saturation mean of 92%) (Stanek et al). Oxygen saturation recovered in 10 s, which is considered fast (Stanek et al.). The researchers also found a different adaptation depending on how the divers were customarily brought to the surface. Divers who typically came back to the surface by their own means showed a decreased response to hypercapnia and hypoxia. Divers who were usually pulled to the surface showed a lower hypoxic sensitivity expressed by lower ventilatory response and no respiratory adaptation to hypercapnia (Masuda et al.). Other important findings were that the "Ama" deliberately performed hyperventilation before their diving and that they purposely decreased their inspiratory volume to cope with the extra pressure and need to reduce buoyancy (Hong et al., 1963). The effect of deliberate hyperventilation and the effect of depth on their physiological responses may make this type of deep sea diving unique, making comparisons to the others who

exercise and breath hold while immersed (eg. synchronized swimmers) difficult. It is likely that part of the physiological changes seen in the "Ama" may not be reproducible in synchronized swimmers, since they do not encounter the large atmospheric pressure changes that the "Ama" do.

Exercise adds additional stress to breath holding in water immersion or with face immersion. Andersson et al. (2002) investigated divers under conditions of breath holding and steady state exercise on a cycle ergometer in air and with face immersion. They reported a lower decrease in arterial SO_2 with face immersion (5.2 vs. 6.8%; $\bar{x}$) than in air, a decrease in HR, an increase in mean arterial blood pressure, and a decrease in arterial hemoglobin oxygen saturation with face immersion (90% measured by pulse oximeter and 84% measured by end-apnoeic arterial blood sample). They concluded that the difference was part of the diving response and related to an oxygen conserving effect. The oxygen conserving effect in breath holding with water immersion at rest and exercise has been quantified just recently by Andersson et al. (2004) and deserves further investigation.

Butler and Woakes (1987) investigated men who performed sub maximal exercise (flutter kicks) in water immersion at 28 °C. They reported an increase in HR to 106 ±5.7 $b \cdot min^{-1}$, ($\bar{x} \pm$ SE) followed by a decrease after 10 s of activity with the HR eventually reaching 48 ± 4.4 $b \cdot min^{-1}$ ($\bar{x} \pm$ SE) at around the 33rd s of breath holding, after breath holding from the beginning of exercise. They hypothesized that the decrease in HR was correlated with the decrease in O_2 saturation and the increase in vasoconstriction. Vasoconstriction is associated not

only with breath holding but also with water immersion below thermoneutral temperatures (McArdle, Magel, Lesmes & Pechar, 1976). Paulev et al. (1990) found no decrease in HR in males while doing stationary flutter kicks during a 15 s breath holding period. They noticed no changes in SV nor CO, except when a Valsalva manouver was performed. They concluded that with the water immersion induced changes in SV and CO, there was enough O_2 available and therefore no anaerobic work was done. When a Valsalva maneuver was performed, SV and CO were reduced and total peripheral resistance increased. Neither study (Butler & Woakes; Paulev et al.) quantified exercise load. Delapille et al. (2001a) examined HR during breath holding and water immersion with exercise (kicks with fins) and reported higher HR values during exercise for non-breath holding trained subjects at the end of breath holding ($\bar{x}$ =147 vs. 135 beats.min^{-1}).

Carotid blood flow and diastolic blood pressure increases with breath holding time (Pan et al., 1997). On the other hand, peripheral blood flow decreases as bradycardia progresses during breath holding (Gooden, 1994; Pan et al.). These changes are triggered by the increase in CO_2 concentration in the blood during breath holding. As the higher levels of CO_2 are detected, these changes ensure O_2 availability to the brain (Pan et al.; Scholander et al., 1962).

Finley, Bonet & Waxman (1979), suggested a dissociation between bradycardia and blood pressure increase with breath holding. The authors studied a mixed group of swimmers while breath holding with face immersion only at temperatures of 4 to 6 °C. They noted a considerable HR decrease (26 ± 9 b·min^{-1};

$\bar{x} \pm$ SD) within 20 s from the onset of breath holding, with complete absence of change in blood pressure. Pan et al., (1997), investigated untrained male subjects while in head out immersion and reported an increase in diastolic blood pressure of 4% after 30 s of breath holding and 15.4% after 60 s of breath holding. It is possible that breath holding with facial immersion produced different results than breath holding in water immersion. Alternatively there is a time delay of 20 s into breath holding before diastolic blood pressure decreases in contrast with HR decrease, which commences much earlier.

Figura et al. (1993) studied breath holding in synchronized swimmers who were upside down and performing support sculling and found that HR increased up to 132 $\pm$ 11 b·min^{-1} ($\bar{x} \pm$ SD) followed by a decrease to 87 $\pm$ 6 b·min^{-1} ($\bar{x} \pm$ SD) while still breath holding. Breath holding time was 50 s. This same pattern was also seen when performing figures. It took 10 to 15 s for HR to recover to starting values after breath holding was interrupted. After 1 minute of rest, HR was lower than values before the start of breath holding.

Gemma and Wells (1987) studied elite synchronized swimmers and demonstrated that during synchronized swimming figures, HR increases just after face immersion and then decreases after three to six body positions. The amount of HR decrease was time dependent, and was to some extent effort dependent. Gemma and Wells also detected anticipatory bradycardia (followed by the increase mentioned above), prior to face immersion in 9 out of the 10 subjects, which was associated with unknown psychological processes. These are the only studies that describe cardiovascular changes to breath holding and water

immersion or face immersion in synchronized swimmers, and they limit their physiologic reporting to HR.

Stanek et al. (1993) mentioned a considerable drop in the P_aO_2 of the "Ama" (values not reported) at the surface after returning from a dive. Others have reported decreases in P_aO_2 to a level of 28 mmHg for the same kind of divers executing a 50 s dive (Hong et al., 1963). A partial pressure of 28 mmHg was lower than the partial pressures detected by Davies, Donaldson and Joels (1995) at the end of figures for synchronized swimmers (see below), but higher than what was reported by Davies, Joels and Udoh (1993).

Davies et al. (1993) measured breath holding times and P_AO_2 and P_ACO_2 in synchronized swimmers and suggested that synchronized swimmers reach undesirable levels of hypoxia (P_AO_2 as low as 27.5 mmHg) at the end of breath holding periods. In further research, Davies et al. (1995) studied elite synchronized swimmers. Four of the subjects performed two different figures and showed a negative relationship between breath holding times and PO_2. One of the swimmers, who held her breath the longest (≅ 54 s for the figure Albatros), reached a partial pressure of 33 mmHg. During solo routines, the subjects were monitored for breath holding time during their first underwater sequence. They reported values of 43 ± 10.2 s ($\bar{x}$ ± SD) (range = 33 to 66 s). The PO_2 was 38 ± 8.4 mmHg, ($\bar{x}$ ± SD) but these values were not related to breath holding times. The difference of intensity (not quantified) performed while breath holding may have accounted for the lack of correlation.

Only limited information on the measurement of alveolar gases in

synchronized swimmers is available in the literature. After a 45 s breath holding period at rest, Figura et al. (1993) showed no significant changes in partial pressures of CO_2 and O_2 in 6 elite synchronized swimmers. After the execution of one figure (heron) they reported decreases in PO_2 from about 100 to about 60 mmHg, while PCO_2 had risen from about 40 to 48 to mmHg. As far as it is known, the above data and Davies et al. (1995) are the only such data available specific to synchronized swimming to date. Andersson et al. (2004) reported a decrease in end tidal partial pressure of oxygen (from 99 to 53mmHg; $\bar{x}$) and increases in carbon dioxide (from 44 to 61 mmHg; $\bar{x}$) during breath holding for 40 s with face immersion and steady state exercise. Due to the lack of similar research it is not possible to establish comparison between this data and other studies.

There is little information available about blood lactate changes while breath holding and exercising in the water. Figura et al. (1993) studied elite synchronized swimmers. After an average breath holding length of 45 s during the execution of a figure, blood lactate increased about 1.3 mM (from a pre test value of 1.46 $\pm$ 0.4 mM; $\bar{x} \pm$ SD), and after a 3 min routine chosen by each athlete the mean total Bla value was 3.37 mM. Yamamura, Matsui and Kitagawa (2000) reported mean Bla values of 4.7 $\pm$ 1.1 $mmol \cdot L^{-1}$ ·and 4.3 $\pm$ 1.1 $mmol \cdot L^{-1}$ ($\bar{x} \pm$ SD) for team technical routines and free routines respectively (4 elite athletes). The relatively low Bla levels may be indicate that the predominant sources of energy during these routines were phosphocreatine stores through he anaerobic alactic metabolism and ATP through the aerobic metabolism. An

alternative explanation may be that breath holding enhanced the utilization of lactate as an energy source through glyconeogenesis as proposed by Fujitsuka et al. (1980) due to a reasonably low anaerobic level of exercise, or some other unknown factor.

In the last few years two main issues may have considerably influenced knowledge about breath holding, water immersion and exercising. These are the increase in hemoglobin concentration as breath holding trials are repeated (Bakovic et al., 2003, Schagatay et al., 2001), and the evidence of the existence of an oxygen conserving effect as seen in diving mammals (Andersson et al., 2004). The first allows for an increased oxygen availability and consequently a lengthening of breath holding periods which was previously explained solely by a psychological training effect, whereas the second provides new ideas for breath holding research. These two topics have just been published lately and deserve further investigation.

Conclusion

There are multiple conditions under which breath holding has been investigated. Six different combinations of water or face immersion, breath holding and exercise produce contrasting results thus must be carefully analysed and understood. Table A-7-1 provides the summary of the physiological changes reported in literature and the multiple combinations that elicit different responses. The table summarizes exercise and resting conditions with water immersion and breath holding with face immersion or water immersion, breath holding on land and water immersion.

Table A-7-1 - Summary of the physiological changes reported in literature

	Water immersion: Rest	Water immersion: Exercise
Cardiovascular changes	• Blood shift to central circulation[24] (up to 700ml) [1] • ↑ Central venous pressure (8 to 12 mmHg) [1,2,20] • 10 to 28% ↑ SV [1,2,20] • CO ↑ [1,3,4, 22] • HR = [1,3,4] or ↓ [2,5] • ↓ Systemic vascular resistance [1,24]	• HR↓ at submax & max exercise [6] • CO ↑ [6] • SV ↑ [6] • Peripheral vasoconstriction if water is cold [11,21]
Respiratory changes	• O_2 consumption ↑ as temp. ↓ [29] • TV ↓ [27] or = [28] • VC & other LV and LC ↓ except IC [26, 28] • IC ↑ [26]	
Blood changes	• Hematocrit↓[24] • Blood density↓[24] • Plasma density↓[24]	• Epinephrine ↓ max work [30] • Norepinephrine ↓ above 80% work[30] • Bla ↓[30]
	With BH on land: Rest	**With BH on land: Exercise**
Cardiovascular changes	• = [8] or↑ Blood pressure [7] • HR ↓ [7,8]	• HR ↓ [1, 23] or ↑ [12] • S_aO_2 ↓ [23] • ↑ Blood pressure [23]
Respiratory changes	• Post BH V_E↑ 30 to 60% [31] • Resp. heat loss ↑ [31] • Post Fb ↑ [31]	• P_AO_2 ↓ & P_ACO_2↑ [9] • Post V_E steady state < onset exercise [10] • Post V_E rec. onset exercise < steady state [10]
Blood changes	• Bla after BH ↑ [33]	• Bla ↓ [32]
	BH with WI or FI : Rest	**BH with WI or FI : Exercise**
Cardiovascular changes	• Peripheral vasoconstriction [2] • HR ↓ [2] • = or ↑ Blood flow to the brain [2] • ↓ Venous return [2] • ↓ Peripheral blood flow [11,19,2] • ↑ Blood pressure (DBP ↑) [2] • ↑ Hematocrits & Hemoglobin [25]	• HR ↓ [16, 23] • HR ↑ at the start of BH & ↓ as BH persists [18] • Pre BH HR ↑ [18] • S_aO_2 ↓ [17, 15,23] • Peripheral vasoconstriction [15] • SV = [16] or SV↓[36] • CO= [16] or CO↓[36]
Respiratory changes	• Pre BH CO_2↓ [22]	
Blood changes	• # RBC ↑ [34, 35]	

(1) Arborelius et al. (1972), (2) Pan et al. (1997), (3) Lin (1984), (4) Farhi & Linnarsson (1977), (5) Miwa et al. (1997), (6) Sheldahl et al. (1997), (7) Hong et al. (1972), (8) Finley et al. (1979), (9) Astrand (1960), (10) Sanchez & Sebert (1983), (11) Sterba & Lundgren (1985), (12) Gooden (1984), (13) Scholander et al. (1962), (14) Figura et al. (1993), (15) Butler & Woakes (1987), (16) Paulev et al. (1990), (17) Stanek et al. (1993), (18) Gemma & Wells (1987), (19) Lin (1984), (20) Begin et al. (1976), (21) Schagatay & Holm (1996), (22) Liner (1994), (23) Andersson et al. (2004), (24) Yamazaki et al. (2000), (25) Schagatay et al. (2001), (26)Whithers & Hamdorf (1989), (27) Chang & Lundgren (1996), (28) Hong et al. (1969), (29) Marino & Booth (1998), (30) Connely et al. (1990), (31) Irzhak & Oskolkova (2003), (32) Fijitsuka et al (1980), (33) Hong et al. (1971), (34) Bakivic et al. (2003, (35) Andersson et al. (2001) (36)Andresson et Al. (2004) .

WI = Water immersion, FI = face immersion, BH = breath holding, SV = stroke volume, CO = cardiac output, DBP = diastolic blood pressure, HR = heart rate, S_aO_2 = arterial oxygen saturation RBC = red blood cells, CO_2 = carbon dioxide, P_AO_2 = Alveolar Partial pressure of oxygen, P_ACO_2 = Alveolar partial pressure of carbon dioxide, Bla = blood lactate, TV = tidal volume, VC = vital capacity, LV = lung volumes, LC = lung capacities, IC= inspiratory capacity, VE = minute ventilation, Fb = frequency of breathing

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Appendix B - Out of the water versus in the water work on an arm crank and leg crank cycle ergometer - Is drag a factor?

Teresa Alentejano, Doug Kaweski

Introduction

It is well known that the body is influenced by water pressure while immersed in water (Arborelius, Balldrin, Lilja, & Lundgen 1972; Christie, Sheldahl, Tristani, & Clifford 1990;, Sheldahl et al. 1987). Performance testing of athletes in sports such as swimming, water polo and synchronized swimming and feedback from these tests is becoming more and more important to achieve excellence. The more closely matched the tests are to the actual activity performed, the better the comparison and the more useful the test becomes. But testing athletes in the water is always a challenge. Vulnerability of equipment to water damage and a limited budget prevent most labs from having an appropriate equipment to measure underwater power and work. Bikes (cycle ergometers) are a comparatively low cost piece of equipment, making them a good option. Several researchers have developed underwater cycle ergometers (Craig & Dvorak 1969; Morlock & Dressendrfer 1974; McArdle Magel, Lesmes & Pechar 1976; Sheldahl et al. 1987; Chen, Kenny, Johnston & Giesbrecht 1996; and others). As far as it is known, the equipment developed in this paper is the first to enable athletes to perform underwater arm and leg exercise, either at the same time or separately, while being monitored.

Underwater ergometer apparatus

The cycle ergometer is similar to the one described by Chen et al. (1996). The wood platform was kept but another Monark® bike was added to permit

simultaneous arm crank exercise. To allow for both bikes to fit together on top of the platform, the original Monark® pedals were removed and one of the bikes had the load panel reversed to allow the researcher to control loading with the flywheel turning in the revere direction (Figure B 7.1). The arm crank stainless steel chain is shorter in length to match the arm position. The 1:1 gear ratio was kept by using the same sized sprocket. Plastic handles serve as handgrips.

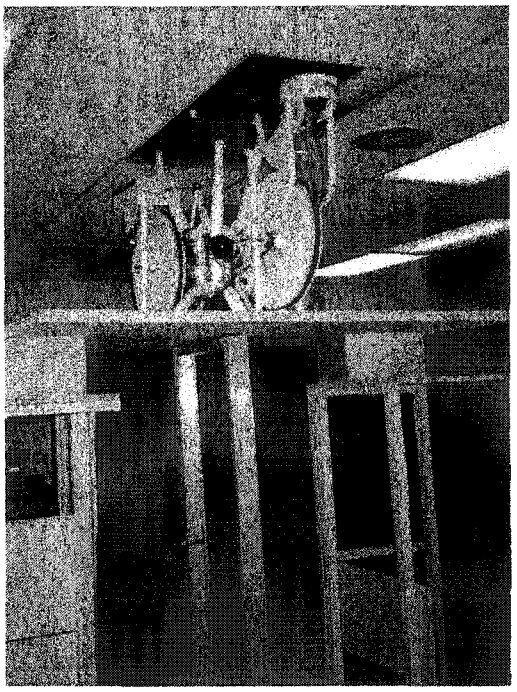

Figure B-7-1: Bike under construction

A wood platform rested on top of the walls of the hydrostatic weighing tank. A wood structure was built to support the structure out of the water so that equipment could be tested and used out of the water. A coating of epoxy paint was added to prevent corrosion and pitting of the aluminum. Acrylic guards were added to prevent the subjects' fingers and toes from being caught in the arm and leg crank sprockets. The seat structure was also slightly modified from the original project. Holes in both the seat post and the horizontal bar of the bike

allow adjustment for the subject's height and arm/leg length. The bike seat was surrounded by a fiber glass chair seat with cutouts to allow thigh motion. The chair provides the pedaling reaction (force), which is usually provided by gravity when pedaling out of the water. Velcro seat belts were made which attach to the back of the chair and go over the subject's chest in an "x" pattern. The seat belts prevented the subjects from floating and are made of Velcro to facilitate quick detaching, if necessary. A lap weight belt was also used to help prevent the subjects from floating while arm cranking. A chest harness with lead weights attached to it was used if the subjects were to perform leg cranking or a combination of arm and leg cranking.

Drag changes from air to land

Some researchers have disregarded water resistance (drag) while comparing dry land to underwater bike exercise, as long as the rpm were kept at or below 60 rpm (Chen et al.,1996). Perini, Milesi, Biancardi, Pendergast and Veiesteinas (1998) used VO_2 max result differences to determine the drag increase in the water. The authors estimated the increase in power output required from air to water for leg cycling to be 25 W (no reference to how this conclusion was reached). Others have used water drag as their method of increasing loads in the water (Craig & Dvorak 1969; Shapiro, Avellini, Toner, & Pandolf 1981; Christie et al. 1990; Connely et al. 1990).

After roughly calculating the drag through fluid dynamics calculations considering inertia only (Roberson & Crowe 1985), it was found that the effect of drag on power output may potentially be considerable (60 W for legs only) and

therefore worth investigating further. It was decided to measure drag to determine the difference between air and water biking

A device was built to mimic subjects' arm and leg movements: The Arm and Leg Motion Apparatus (ALMA) (Figure B-7.2). ALMA was built with flat aluminum bars, threaded steel axles, bike pedals and cylindrical plastic bottles. An aluminum structure was created to mimic each limb with the "hands" and " feet" bolted to a bike pedal connected to the underwater bike arm and leg cranks. At the other extremity of the legs and arms, a 14 inch rectangular piece of steel was built to resemble a swimmer' s torso in size. The torso was painted with rust inhibiting paint to prevent corrosion. The bottles were taped to an aluminum structure to represent the lower and upper portion of each limb. The arms and legs were bolted to the torso. The shoulder joints were created using pieces of heat shrink tubing which served as bushings and nylon washers to minimize friction between the bars and fasteners. When the parts were bolted together, double nuts were used in a locking fashion to allow the aluminum bars to remain loose and minimize friction. Similar joints were created to represent the knees. To measure drag and determine the difference between air and water biking exercise a 110 W, 30 V DC motor was used. Other equipment included three 12V batteries, two fluke multi-meters and resistors to place in series with the motor to vary voltage.

The length of the legs and arms and the frontal area of thighs, legs, feet and arms and forearms were calculated based on representative values for synchronized swimmers (Table B-7-2). Cylindrical plastic bottles were chosen to model arms and legs since they have a similar coefficient of drag due to their

rounded profile. The feet were represented using rectangular metal plates. The projected area was sized to be representative of the subjects to be tested.

Figure B-7-2: ALMA

The water bottles were filled with air while testing out of the water and filled with water while testing in the water. Filling the bottles with water made them more rigid in testing and gave them neutral buoyancy, which allowed parts to be disconnected underwater without floating.

A 72- tooth sprocket was added to one of the Monark® bikes on top of the platform. An aluminum cylinder was built and bolted to the Monark® bike allowing the original sprocket and the 72-tooth sprocket to work simultaneously. Another chain connected the 72- tooth sprocket to a 15- tooth sprocket bolted to the motor shaft. This gave a gear ratio of 4.8:1.

Table B-7-2 : Typical synchronized swimmer and representative values

	Athlete's dimensions		ALMA dimensions
	Small (cm and cm^2)	Large (cm and cm^2)	(cm and cm^2)
Thigh length	37	42	50
Calf length	36	39	48.5
Thigh frontal cut	13.4	17.18	11.14
Thigh frontal area	*400.9*	*588*	*497*
Knee frontal cut	8.27	10.82	8.9
Heel frontal cut	6.36	7.64	8.9
Shin frontal area	*263*	*359.9*	*NA*
Foot length	21	24	21
Arm length	27	34	31
Forearm length	22	26.5	30
Arm frontal cut	7	8.59	7.5
Arm frontal area	*186.4*	*265*	*253*
Elbow frontal cut	6.36	7	NA
Wrist frontal cut	4.45	5.05	NA
Forearm frontal area	*118.8*	*162.07*	*154.75*

Measuring Drag - Results and discussion

After measuring the DC motor properties, the bike power measurements began. By knowing the motor properties, the following formulas were used to determine rpm and output power:

- Current draw of motor: I=[V-(Kb · kRPM)] / Rm
- Torque output of motor: J=(Kt · I) - (Kt · Inl)
- rpm of motor: kRPM = (V-RmI)/Kb
- Power output of motor: Po=(J ·rpm)/ 1345

Where:

Inl = no load current,

J= Torque(oz-in/A),

Kb=Voltage constant(Volt/1000RPM),

Kt=Torque constant(oz-In/A),

Rm=Terminal resistance.

The first measurements taken were out of the water. The number of watts necessary to move the arm crank and the leg crank without the legs/arms attached was measured at different rpm (Table B-7-3 & Table B-7-4). The measurement of power required to move the bike apparatus out of the water without the arms attached was the same as with the arms attached to within a 1 W difference, indicating that frictional loss in the elbow and shoulder joints was very low. Since legs and arms were built the same way, the same was assumed to be true for the legs.

Table B-7-3. Arm Crank

Rpm	Loaded (W)	No load (W)	Water resitance (W)
53	22.25	11	11.25
60 *	25.1	13.3	11.8*
63	25.88	14	11.88
66	28.81	14.8	14.01

* Estimate includes measured friction loss of 1 W in ALMA joints.

Table B-7-4. Leg Crank

Rpm	Loaded (W)	No load (W)	Water resistance (W)
41	24.52	8.2	16.32
47	33.2	9.5	23.7
55.6	47	12.1	34.9
60*	54	13.3	41.7*

* Estimate includes measured friction loss of 1 W in ALMA joints.

After finishing these measurements, equipment was moved to the water to redo the measurements done out of the water. The number of watts that were necessary to move the arm crank or leg crank ergometer without the legs/arms attached was measured at different rpm. The results showed the power necessary

to move the bike out of the water and in the water was the same within 1W. The arm and leg apparatus was then connected and the power required to move the arms underwater as well the arm ergometer was measured. This was repeated for the legs. The rpm was varied by changing voltage applied to the motor using resistors in placed in series with the motor.

Limitations

Motor properties vary somewhat with rpm. The gel batteries used were not a very good current source and as a result the current varied slightly. This was minimized by trying to wait until the system stabilized. Notwithstanding, a somewhat dynamic measurement was obtained, due to the energy stored on the flywheel and difficulty in stabilizing the current.

The increase in drag for legs was considerable compared to arms. The water surface was not smooth anymore. The tank where the bike was immersed is a small 3 by 1.8 m area. The drag may have increased due to waves and currents reflecting off the walls and back against the arms and legs, possibly producing some additional drag effects. There was no system of damping reflected waves.

Conclusions

Resistance increases when comparing exercise in water to exercise in air on a cycle ergometer for both arms and legs. An increase of 11 W was found for arm cranking and 41 W for leg cranking at 60 rpm. Measurements were based on representative dimensions of arms and legs of female synchronized swimmers who will be part of the next step of the project. Depending on the size of the subject drag would vary. It was concluded that drag must be taken into account

when comparing out of the water testing to underwater testing.

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Appendix C - Reliability of the Medgraphics metabolic measurement system while collecting post breath holding data

Introduction

The studies in this thesis required considerable adaptation of the normal Medgraphics mouthpiece set up as well as operation of the cart during and after breath hold. Because this is considerably different then the typical testing done with the device the cart and procedures needed to be tested to verify accuracy.

Procedures

A Tissot tank was used to collect post breath holding expired air for 30 s as the Medgraphics measurement system (MMS) cart was simultaneously analyzing the expired air in a breath by breath mode. To enable data collection the MMS was connected to the Tissot tank through a Rudolph Valve, connected downstream of the pneumotach. In doing this, the dead space was increased to 160ml[2], which accounts both for the pneumotach and the Rudolph Valve. The new dead space was entered in the MMS setup.

The pneumotach was connected to the Rudolph valve and the Rudolph valve to the Tissot tank input line. This changed the volume calibration of the pneumotach, particularly for expiration. The MMS was calibrated using the 3 L syringe and the Medgraphics calibration program until the changes caused by the Rudolph valve and the Tissot tank line were accounted for. Once calibration was achieved normal data collection began.

After series of breath by breath data was collected, the MMS was used to

[2] Previous testing and theory define dead space as the volume of expired gas that sits between the end of the pneumotach and the sample line.

read F_eO_2 and F_eCO_2 in the expired gas captured in the Tissot tank. Gas concentrations from the tank were measured by removing the Rudolph valve, reversing the pneumotach to allow gases to flow out, and using the "P-wave" mode setting of the cart.

After numerous tests it was concluded that some artificial method was needed to prevent the MMS from losing the first data point after BH was completed. The method chosen prevents the machine's software from stopping data collection during BH and achieved very similar results for gases captured in the Tissot tank and what was measured by the MMS. In this method, a research assistant removes the pneumotach and blows through it to maintain breathing and prevent the machine treating the breath hold as an error condition and losing the first data point after BH. This method decreased error in the order of 10 to 20% for the 30 s after BH versus calculating O_2 consumption based on cart output with a lost initial data point.

Another alternative would have been to blow some known gas concentration through the pneumotach to keep the machine working. Although viable, this alternative method would lead to extra CO_2 in the environment, and would also lead to a series of complicated maneuvers to close valves and open valves that would increase the data collection difficulty. There would also be a safety concern in that the subject's air inlet tube would have to be closed during the BH period. In the event that the subject needed to breathe unexpectedly, she could not. Thus the first option was used. The research assistant needs to be trained to expire first and than inspire through the pneumotach and through a

mouthpiece positioned at the end of the long hoses. The last phase of his/her respiration into the pneumotach will be inspiration. The cart then measures the expiration of the research subject after BH in the normal manner.

When a maximum BH test is conducted at rest, the assistant will be instructed to breathe through the pneumotach until he/she hears a bell signal coming from the subject indicating that the subject is near maximal BH time. During the exercise protocol, the assistant breathes through the pneumotach only when the BH times are 20 or 25 s. In those cases he/she stops breathing and reconnects the pneumotach 5 to 10 s before breathing is again resumed by the subject. (Previous tests indicated that the machine stops registering the first breath after BH only after 13 s of no flow through the pneumotach).

Analysis

By applying the method described above, the post BH volumes collected for 30 s showed a volume difference of 0.16 to 5.5% (Table C-1) between the cart result and the volume of exhaled gas captured in the Tissot tank. Result differences for O_2 consumption ranged from 0.87 to 6.8 % (Table C- 2) between the cart output and analysis of the gas captured in the Tissot tank. Sources of error include expired gas from previous experiments in the Tissot tank input lines prior to gas capture, uncollected expired gas from the pneumotach and Rudolph valve after gas capture, and incomplete mixing of the gases in the tank.

Table C-1 Volume for 30 s after BH measured by the MMS versus collected in the Tissot tank

	Test 1	Test 2	Test 3	Test 4	Test 5
Tissot volume (L) (STPD)	8.602214	7.040843	9.707876	10.38669	7.11288
Medgraphics volume (L) ($\dot{V}E$) (STPD)	9.106657	6.857682	9.534422	10.37303	7.351024
Medgraphics Volume (L) (Vt) (STPD)	9.081121	6.875059	9.526867	10.40325	7.358579
% difference (Tissot / Medgraphics $\dot{V}E$)	5.539277	2.601407	1.786735	0.131514	3.239603
% difference (Tissot / Medgraphics Vt)	5.273655	2.354604	1.864558	0.159181	3.338946

All volumes were corrected to STPD. All volumes were collected after BH at rest for 30 s. Tests 1, 2 and 3 used the standard MMS mouthpiece and tests 4 and 5 used the longer hoses that will be used during the water testing (Chapter 3, figure 3-1).

Table C-2 O_2 consumption for 30 s after BH measured by the MMS versus calculated from expired gases captured in the Tissot tank.

	Test 1	Test 2	Test 3	Test 4	Test 5
VO_2 (Tissot) (ml)	0.339843	0.279899	0.431658	0.423306	0.28318
VO_2 (MMS) (ml)	0.364536	0.286147	0.427867	0.408	0.302
% difference	6.773817	2.183493	0.878242	3.615824	6.231788

Tests 1, 2 and 3 used the standard MMS mouthpiece and tests 4 and 5 used the longer hose that will be used during the water testing (Chapter 3, figure 3-1).

Tests involving normal breathing and no BH showed similar differences to those with breath holding (Table C-3). Differences found between the two ways of calculating O_2 consumption may be attributed in part to the residual volume that was previously in the Tissot tank hose system, and lost air from pneumotach and valve. To minimize the difference, post BH expired air was collected in the Tissot tank prior to data collection. During exercise, volumes are larger, leading to decreased significance of residual volume in Tissot tank inlet line valves and

hoses.

Table C-3 O_2 consumption for 2 min at rest with no BH

	Test 1	Test 2
VO_2 (Tissot) (ml)	0.490682	0.56298
VO_2 (MMS) (ml)	0.468	0.57227
% difference	4.622546	1.62336

Conclusion

According to Lamarra and Whipp (1995) it is difficult to achieve significantly better than a 5% difference between breath by breath analysis and gases captured in a Tissot tank or in Douglas bags. It was concluded that the results are accurate and can be used to determine post BH O_2 consumption.

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Appendix D - History inventory questionnaires

University of Alberta
Faculty of Physical Education and Recreation

History Inventory Questionnaire Date ___/____/___

Name:_____ Date of Birth ____/_____/_____

Main Sport/Activity:_____ Years of practice:_____

frequency of practice: _____ days/week, _____ hours/week

Do you suffer from any diseases? ( )No ( )Yes List: _____

_____

Do you suffer from any lung disease? ( )No ( )Yes List:_____

_____

Do you suffer from asthma or have you ever suffered from asthma?

( ) No ( ) Yes my last attack was_____

Did you swim as a child? Yes ( ) No ( ) From age ____ to age ____

Do you swim regularly now? Yes ( ) No ( ) # Hr Week____

Do you regularly practice any physical activity (not a sport)Yes ( ) No ( )
Hr Week____

Are you taking any medication? ( )No ( )Yes List:_____

_____

Are you allergic to any medication? ( )No ( )Yes List:_____

_____

Is your menstrual cycle regular? ( ) No ( ) Yes
Starting date of last period ___/ ___
Typical length of cycle (i.e time between periods eg. 28 days) _____
Frequency of menstrual cycle(#/times/years)_____

University of Alberta
Faculty of Physical Education and Recreation

Water immersion and breath holding with or without exercise (cycling: arm cranking) in a hydrostatic tank.
History inventory Questionnaire

Name:_____ date of birth ____/____/___

Do you practice any sport? No ( ) Yes ( ) Main Sport/Activity:_____

Years of practice:_____ frequency of practice: _____ days a week _____ hours
Other activities: _____

Were you a speed swimmer or a synchronized swimmer in the past? No ( ) Yes ( )
If you answered "yes", please describe what level of competition you were involved at:

Provincial ( ) Regional ( ) National ( ) International ( )

Are you afraid of going into a pool? No( ) Yes( )

Do you swim nowadays? No( ) Yes ( )

If you answered "yes", please define the amount of time per week:
( ) 30min/week or less ( ) 31 min/week or more

Do you suffer from asthma or have you ever suffered from asthma? ( ) No ( ) Yes.

If you answered "yes", please inform when was your last crisis ___/ ___

Are you taking use of any asthma medication? ( )No ( )Yes List:_____

Are you under any other medication? No ( ) Yes ( ) List:_____

Is your menstrual cycle regular? No ( ) Yes ( ) last cycle started _____/_____
day/month

Do you smoke? No ( ) Yes ( )

These questions will be answered by the researcher:

Breath holding time _____ *sitting height* _____ *subject #* _____

Appendix E – Consent forms

Faculty of Physical Education and Recreation
University of Alberta
Edmonton, Alberta
Phone and Fax: (403) 439 55 85

A Time-motion Analysis of Elite Solo Synchronized Swimming: Relationship to Breath Holding and Technical Merit.

Investigators:

D. Marshal (PhD)
Phone: (403) 492 1035

G. Bell (PhD)
Phone: (403) 4921018

Teresa Alentejano
Fax and Phone: (403) 439-5585
e-mail: tca@gpu.srv.ualberta.ca

Informed consent for videotaping the solo

I, _____(please print your name) agree to participate in a research project conducted by the above named investigators studying the time-motion analysis of elite synchronized swimmers soloists. I understand that the solo performed during the Canadian Nationals or American Nationals are going to be taped for further study. I also understand that my own results will be kept confidential and are going to be sent to me after the conclusion of research. I also know that any eventual doubts I have in concern with the research procedures will be promptly answered by the evaluator. I understand I may decline to participate in the research project or withdraw from it at any time, for any reason and without consequences.

About the research and the time-motion analysis:

- The videotaping of the solos for the time-motion analysis will take place during the Solo Finals on the American and Canadian National championships in 1997.
- The participant will be asked to provide their body mass, height, age and years of experience in Synchronized swimming.
- There is no risk involved with the research

- The breath holding period during the solo is the primary purpose of the time-motion analysis
- The investigation is related to the amount of time spent in each of the different kind of exercises performed during the solo swimming, the difficulty of each movement the length swam during performance and the scores received.

I acknowledge that I have read this form and I understand the test procedure I may expect a copy of this consent form and the report of my personal results after the study is complete and understand that the data collected will be used in a research publication and will remain in possession of the investigator to ensure confidentiality. I also understand that I may make any inquiries concerning any procedure that I do not completely understand. Furthermore, I acknowledge that there will be no financial remuneration for participation in this study. I freely consent to participate in this research project.

Name:_____ signature:_____

Weight:_____ Height: _____ date of birth ____/____/____

Years of experience in Synchro: _____ years and months_____

Address:_____ Postal code:_____

Phone: _____

Witness:_____ Investigator: _____ date:_____

Faculty of Physical Education and Recreation
University of Alberta
Edmonton, Alberta
T6G 2H9

Dry and wet pulmonary function tests and VO_2 max tests: Is there a difference?

Investigators: D. Marshall (PhD)
Phone: (780) 492-1035
Teresa Alentejano
Fax and Phone: (780) 439-5585 / e-mail: tca@gpu.srv.ualberta.ca

Informed Consent

I, _____(please print your name) agree to participate in a research project conducted by the above named investigators studying lung volumes and capacities and aerobic fitness in and out of the water.

Physiological Assessment and Time Commitment

I understand that I will need to go to the University for testing on three different occasions for the following tests:

1. Lung Function Tests (to be done in the underwater weighing lab, room E-451, Faculty of Physical Education and Recreation) - I will be connected to a machine by a mouthpiece and I will also wear a nose clip. I will be asked to take big breaths and blow them out rapidly into the machine several times. I will be given some practice trials prior to the actual data collection. I will also breathe normally during and after the test. I will be coached throughout the tests. These tests will be done both in and out of the water on the same day. When I am in the water, I will be submerged to the neck. This test will require a total of approximately 45 min.

2.Fitness test out of the water (to be done in the Sport Performance Unit, room P-344, Faculty of Physical Education and Recreation) - I will be connected to a different machine through a mouthpiece and will be wearing a nose clip. I will be asked to cycle with my arms. I will be working to exhaustion. I will warm up with light cycling and as the test starts the load will be progressively increased every 2 min. I will be asked to maintain the pedal revolutions constant (at 60 Revolutions per minute) by pedaling to a metronome. My heart rate will be monitored and the oxygen level in my blood will be measured by a sensor placed on my forehead. This test will require approximately 45 min and will be done on a different day from the lung function tests.

3.Fitness test in water (to be done in the underwater weighing lab, room E-451, Faculty of Physical Education and Recreation) - The same procedures above will be repeated on a different day, while I am submerged to my neck in water. There will be a 1 week interval between the two fitness tests. This test will also require approximately 45 min.

Risks and Benefits

The maximal oxygen consumption test requires a maximal physical and mental effort in order to go to exhaustion. This test represents little risk to healthy active subjects.

The water tests will be strictly supervised by trained personnel. One research assistant will be responsible for observing and ensuring the safety of the subject. As the head and neck will be out of the water, the risks of inhaling water are minimal. In addition, the use of the nose clip will further reduce the possibility of inhaling water.

There may be no direct benefit to participants, however, individual results will be provided for information.

Consent

I understand that my own results will be kept confidential and are going to be sent to me after the conclusion of the research. I also know that any questions I have related to the research procedures will be promptly answered by the investigator. I understand I may decline to participate in the research project or withdraw from it at any time, for any reason and without consequences. If I decline to continue or withdraw from the study, my data will be removed from the study upon my request.

I understand that I will be submerged to my neck in a small pool and I feel at ease being in the water.

I acknowledge that I have read this form and I understand the test procedures. I may expect a copy of this consent form, as I sign it, and the report of my personal results after the study is complete. I understand that the data collected will be used in a research publication and will remain in possession of the investigator to ensure confidentiality. The University of Alberta creates and collects information for the purposes of research and other activities directly related to its educational and research programs. All participants in research projects are advised that the information they provide, and any other information gathered for research projects, will be protected and used in compliance with Alberta's Freedom of Information and Protection of Privacy Act. I also understand that I may make any inquiries concerning any procedure that I do not completely understand. Furthermore, I acknowledge that there will be no financial remuneration for participation in this study.

Name:_____Signature:_____date___/____/__

Parent/Guardian

name_____Signature_____ date___/____/___

Address:_____Postal code:_____Phone_____

Witness:_____ Investigator_____ Date:___/____/__

Teresa Alentejano

Faculty of Physical Education and Recreation
University of Alberta
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Title of Project: Water immersion and breath holding with and without exercise (cycling: arm cranking) in a hydrostatic tank.

Principal Investigator(s):Teresa Alentejano (MSc)
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Co-Investigator(s): Dr. Dru Marshall (PhD)
Phone: (780) 492 3615
e-mail:dru.marshall@ualberta.ca

CONSENT FORM

Do you understand that you have been asked to be in a research study?	Yes	No
Have you read and received a copy of the attached consent and information sheet?	Yes	No
Do you understand the benefits and risks involved in taking part in this research study?	Yes	No
Have you had an opportunity to ask questions and discuss this study?	Yes	No
Do you understand that you are free to refuse to participate, or to withdraw from the study at any time, without consequence, and that your information will be withdrawn at your request?	Yes	No
Has the issue of confidentiality been explained to you? Do you understand who will have access to your information?	Yes	No

This study was explained to me by: _____

I agree to take part in this study.

_____ ___/___ _____ ___/___
Signature of participant Date Witness Date

_____ _____
Printed Name Printed Name

I believe that the person signing this form understands what is involved in the study and voluntarily agrees to participate.

_____ _____/____
Signature of Investigator or Designee Date

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Appendix F – Mental readiness form for performance (MRF)

Visual Analog Scale
Mental readiness form for performance (MRF)
(Adapted from Murphy et al., 1989)

Name:_____ date: ___/____/____

Below are three 10-centimiter lines. With a vertical line please indicate how you feel at this present moment on the scale provided.

Mentally calm *Worried*
|-------|-------|-------|-------|-------|------|--------|-------|------|-------|

Relaxed *Tense*
|-------|-------|-------|-------|-------|------|--------|-------|------|-------|

Confident *Scared*
|-------|-------|-------|-------|-------|------|--------|-------|------|-------|