Physiological Adaptations of Apnea-Conditioned Athletes and their Implications for Synchronized Swimmers’ Performance

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Introduction

Synchronized swimming (SS) is an Olympic sport that encompasses swimming, dancing and gymnastics combined with repeated water submersions. SS programs are performed in solos, duets, trios, combos or in teams of men and women athletes. SS demands excellent swimming and sport-specific skills e.g. sculling, aerobic endurance and anaerobic power and strength, extraordinary flexibility and agility [1-3]. Performance is scored equally for technical and artistic skills by a panel of judges [4].

SS athletes’ ability to control their breath while in motion to perform routines and figures is vital for achieving high scores. Figures are specific lifts, throw and move while routines are divided into (a) technical and (b) free.

Technical routines are compulsory rudiments executed in a specific order though; “free routines” are open to athletes’ creativity. Routine duration increases with the number of competitors but it is also determined by their age and skill level. It ranges from 2.5 min to 5 min i.e.,

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Received: February 16, 2017; Accepted: May 05, 2017; Published online: May 08, 2017


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As both apnea and hypoxia might lead to loss of consciousness [6], we hypothesize that adjustments to hypoxic conditions might involve risks. Understanding the mechanisms concerning apnea adaptations should ensure safe training [7,8]. The overarching aim of this review is to establish how apnea and hypoxia training can safely improve SS athletes’ performance (Figure 1).

Undoubtedly SS athletes’ progress is heavily dependent on their water skills coupled with apnea training. Therefore, both apneas and swimming drills form the backbone of their daily training programs.

We analyze the impact of acute apneas and apnea training via the examination of individuals’ short-term responses and long-term physiological adaptations to conditions of hypoxia (Figure 1).

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Evidence Acquisition

This review is based on scientific articles in Sport Discus, Google Scholar and PubMed electronic search engines using as keywords apnea, hypoxia, diving response and synchronized swimming.

Evidence Synthesis

Apnea and hypoxia

Apnea relates to breath control causing retention of carbon dioxide (CO₂) within the body and an increase of its partial pressure (PCO₂) in the alveoli faster than in the venous blood [9]. Peripheral chemo-receptors in carotid and aortic bodies subsequently release afferent messages to the brainstem respiratory centre to restore oxygen (O₂) homeostasis [10]. Triggers would be (a) the fall in the oxygen’s partial pressure (PO₂) and/or (b) an increase in hydrogen ions (H⁺) caused by the increased CO₂ in the blood [11]. Apnea terminates in the “struggle phase” where respiration restarts involuntarily after respiratory muscles’ contraction [12-14]. Interestingly, psychological factors may also determine individual’s tolerance to an increased breathing drive [14]. Increased apnea duration can be achieved by either delaying physiological conditions leading to the breakpoint and/or increasing individuals’ tolerance to such conditions [15].

Apnea characteristics resemble conditions of hypoxia experienced in high altitudes. At sea level, barometric pressure is 760 mmHg. As oxygen constitutes 20.93% of the atmospheric air, its partial pressure (PO₂) is ~ 159 mmHg. Although the association between partial pressures of air gases remains stable, at high altitudes, their absolute values are reduced. Boyle’s Law states: “in stable temperature, gas volumes are inversely related to their pressure”. Therefore, at high altitude, gas volumes increase due to the fall in the barometric pressure, e.g., at mountain Everest - 9000 m it is ~ 250 mmHg and accordingly, PO₂ equals to one third of its value at sea level [16]. The reduced barometric pressure is translated for human respiration as a diminished PO₂ in the alveoli and reduced oxygen saturation in the arterial blood [17]. Semenza [18], proposes that apnea relates to oxygen deficiency in the blood and tissues irrespective of changes in the barometric pressure as opposed to Millet, et al. [19]. We adopt Semenza’s terminology of apnea as more generic.

Trained divers demonstrated increased tolerance to lower PO₂ and a corresponding higher PCO₂ in their arterial blood as opposed to non-divers i.e., 35 mmHg-50 mmHg and 60 mmHg-45 mmHg respectively [20]. These results along with additional longer-term adaptations to apnea are systematically discussed in the sections that follow. Furthermore, conditions of apnea-hypoxia cause a rise in PCO₂ and a corresponding fall in pH, i.e., characteristics of the diving reflex or diving response - a more generic term including several reflexes as discussed below.

Apnea and the diving response

The Diving Response (DR) is intrinsically linked with apnea, particularly when accompanied with face immersion in cold water [21]. It is characterized by bradycardia and increased peripheral vasoconstriction. It is found in all mammals but also in birds and constitutes a survival mechanism against hypoxia [22]. Factors such as face immersion or otherwise [23], depth of water immersion and body position [24], water and environmental tem-
The diving response and respiration

DR is presumed an oxygen conservation mechanism protecting humans from conditions of hypoxia [28]. The redirection of blood flow from periphery to our vital organs is an indisputable proof of this allegation [29]. The rise of the central blood flow might be attributed to the rise in $P_{CO_2}$ and a corresponding fall in $P_{O_2}$; but also to the simultaneous increase in arterial blood pressure [30]. Bradycardia may be the result of a rise in the total peripheral resistance followed by a blood accumulation in the aorta and the arteries which in turn might be activating baroreceptors leading to a reduced venous return [31].

Researchers initially noticed a direct relationship between DR and a lower rate of fall in the arterial blood oxygen saturation [28,32,33] but, adjusted experimental designs revealed a causal relationship between these two parameters [34,35]. Apnea with face immersion leads to greater oxygen conservation via a more intense DR and a higher oxygen saturation [23,36]. Under conditions of dynamic apnea-cycling on an ergometer - an increased anaerobiosis and a greater fall of venous oxygen led to an oxygen conservation mechanism [33]. This mechanism delays the fall of the $P_{O_2}$ both in the alveoli and in the arterial blood and it consequently delays hypoxia to vital organs. The percentage of oxygen saturation confirmed the activation of the DR in these experiments.

Although divers and underwater hockey players exhibited reduced chemo-sensitivity under conditions of hypoxia, results are inconclusive concerning hypoxic adaptations to their respiratory drive [37,38].

The diving response and cardiovascular variables

Bradycardia and an elevated arterial blood pressure form DR’s primary characteristics [23,39-42]. Heart rate changes due to the DR appear far more intense compared to those in the arterial blood pressure [37,43] although contradictory evidence exists [44]. Increases in the arterial blood pressure are manifested only in humans and not in aquatic mammals [21]. DR causes arterial blood pressure increases as high as 280 mmHg and 200 mmHg for systolic and diastolic respectively [41]. However, contradictory evidence exists concerning arterial blood pressure during water submersion partly due to the water temperature per se [9] and partly possibly due to methodological differences [45]. For example, Ferrigno, et al. [41] measured changes in arterial blood pressure using invasive methods during simulated dives of 10 m in hyperbaric chamber whereas Sieber, et al. [46] used non-invasive blood pressure measurement methods during actual dives of ≥ 10 m. It should be noted also that “pulse pressure” i.e., the difference between systolic and diastolic pressure depends on stroke volume and its ejection speed, but also on arterial compliance [10]. Although the first two factors may be influenced by DR, arterial compliance is a characteristic of each individual.
and particularly it relates to his/her state of health e.g., atherosclerosis.

Breath-hold divers exhibited a drop in their heart rate of 20-30 beats·min⁻¹ [41] and a reduction in the limb blood flow due to peripheral vasoconstriction [44,47].

Low water temperature is inversely related to the intensity of the DR particularly for fit individuals [48,49]. However, the “Cold Shock like Response” might overshadow the DR when the water is below 10 °C [48,50]. The “Cold Shock like Response” and/or the “cold shock response” cause an increase in both heart rate and blood arterial pressure via the arousal of the sympathetic nervous system [51]. Arguably, the simultaneous activation of both “Cold Shock like Response” and DR might lead to an “autonomic conflict” [52,53]. Others suggest a synergistic effect on the parallel activation of these two systems leading to an “oxygen conservation breaking point” [54].

Dry apnea i.e., apnea in the air as opposed to wet apnea - apnea with face immersion-causes only minor [55] or no bradycardia [44]. On the contrary, wet apnea leads to maximum bradycardia particularly when the water is cold [56]. Environmental temperature is positively related to the intensity of the DR particularly when accompanied with face immersion in cold water [9,48]. Lung volumes and intrapleural pressure might also be influencing the degree of bradycardia [57].

Dynamic exercise causes more intense DR as opposed to isometric exercise or rest [40,58,59] although there also exist inconclusive results [60,61]. Jay, et al. [50], attributed DR’s cardiovascular shifts to the cold shock response, by demonstrating that the lower the water temperature - for face immersion - the higher the heart rate response and the lower the apneic time. Short intensive exercise followed by face immersion in cold water (10 °C) led to a reduction of apneic time by 75% compared to apnea at rest [62]. This might be due to competing needs for an increased blood flow between muscles and vital organs resulting in: a) an abrupt cessation of apnea, and b) an exaggerated rise of systolic blood pressure.

The diving response and biochemical variables

The DR is directly related to the rise of anaerobiosis and the consequent increase of lactic acid and a fall in pH [23,33,34]. Individuals’ familiarity with conditions of apnea such as divers is confirmed through an augmented DR [59,63]. Elite divers demonstrate higher anaerobic metabolism during DR activation as opposed to controls [20]. However, trained divers also exhibit lower oxidative stress after dynamic apnea as opposed to controls [58]. Divers’ and endurance athletes’ physiological adjustments to apnea appear to lead to lower acidosis i.e., plasma lactate analogous to altitude acclimatization [58,59].

Synchronized swimming athletes’ adaptations to apnea

SS athletes exhibited physiological adaptations during apnea sessions similar to those of professional divers such as longer apnea durations, more intense bradycardia and greater oxygen conservation compared to controls [4,74]. DR was more intense in SS athletes during static and dynamic apneas vs. controls [75]. There were no differences between the two groups on respiratory variables such as oxygen consumption, oxygen saturation etc. at the end of apneas [74]. During a static apnea of 50 seconds, in a reverse body position, SS athletes exhibited a remarkable fall in heart rate from 98 ± 14 bpm to 70 ± 7 bpm [76]. It should be noted that, SS athletes exhibited an anticipatory tachycardia before competition followed by a bradycardic response both of which are evidenced on the variability of their performance [77-79].

Researchers advocate that, SS athletes had augmented...
lunge volumes and vital capacity compared to controls. Further, their respiratory response to hypoxia was lower [4]. However, hypercapnic i.e., ventilation in liters per minute to alveolar PCO₂, was similar for both groups. Naranjo, et al. [80], stress the importance of functional respiratory adaptations induced by apnea for boosting SS athletes’ performance. Consequently in the long-term apnea training may favourably alter the DR as follows: (Figure 3).

Discussion

Trained divers have bigger lungs and stronger respiratory muscles compared to controls. We may hypothesize that apnea training delays respiratory muscles’ fatigue during prolonged and peak exercise [81]. Similar respiratory adaptations were confirmed for swimmers including improved lung elasticity leading to an improved forced vital capacity [82]. Elite divers develop protective mechanisms against hypoxia in conjunction with mechanisms that reduce total oxygen consumption [73]. Prolonged exposure to hypobaric hypoxia is found to cause an increase in brain capillaries improving tolerance to hypoxia [83]. Divers exhibit more intense DR and a higher blood circulation in their brain during apneas [71]. Individuals involved with breath holding activities demonstrate a reduced chemo-sensitivity to hypoxia and hypercapnia leading to a reduced respiratory drive and corresponding increases in cardiovascular re-

### Table 1: Responses to dry or wet static or dynamic apneas for divers, swimmers, U/W rugby players & healthy individuals.

<table>
<thead>
<tr>
<th>Researchers</th>
<th>Participants &amp; Type of Exercise</th>
<th>HR (bpm)</th>
<th>MAP (mmHg)</th>
<th>SaO₂ (%)</th>
<th>SBF Conclusions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lindholm, et al. [28]</td>
<td>9 healthy males Cycle ergometer for 45 minutes at 120 Watt</td>
<td>Apnea_Cycle (44 ± 8)</td>
<td>49 ± 4</td>
<td>Apnea_Air (32 ± 5)</td>
<td>NA</td>
</tr>
<tr>
<td>Andersson, et al. [33]</td>
<td>8 breath-hold divers/underwater rugby players</td>
<td>Apnea_FI (39 ± 5%)</td>
<td>42 ± 6%</td>
<td>Apnea_Air (35 ± 5%)</td>
<td>NA</td>
</tr>
<tr>
<td>Andersson, et al. [34]</td>
<td>10 breath-hold divers led to wet dynamic apneas</td>
<td>Apnea_FI (39 ± 5%)</td>
<td>42 ± 5%</td>
<td>Apnea_Air (35 ± 5%)</td>
<td>NA</td>
</tr>
<tr>
<td>Kiviniemi, et al. [60]</td>
<td>9 elite divers Underwater swimming</td>
<td>Apnea: (42)</td>
<td>65 ± 4</td>
<td>Apnea: (20)</td>
<td>NA</td>
</tr>
<tr>
<td>Konstantinidou &amp; Soultanakis [62]</td>
<td>10 swimmers Treadmill for 3 minutes - max load at 85% of VO₂max</td>
<td>AAE (30.7 ± 12.5)</td>
<td>40 ± 4</td>
<td>AAR (16.6 ± 11.9)</td>
<td>NA</td>
</tr>
</tbody>
</table>

Apnea_air: apnea in the air; Apnea_cycle: apnea during cycling at a standardised volume; AAE: apnea after exercise; Apnea_FI: apnea with face immersion; DR: diving reflex; HR: heart rate; MAP: mean arterial pressure; NA: not available; Re-BB: breathing in a re-breathing bag with an equivalent volume; SAp: static apnea; SBF: peripheral blood flow; U/W: underwater.

*Numbers in brackets () denote a decrease.
...ing causes increases in lung volumes and vital capacity and improves the performance of respiratory muscles by delaying fatigue during prolonged intensive exercise. It also delays blood acidosis during static and/or dynamic apneas but it also increases tolerance to hypoxia. In-

Table 2: Effects of apnea training on healthy individuals and athletes.

<table>
<thead>
<tr>
<th>Researchers</th>
<th>Participants</th>
<th>Protocol</th>
<th>Conclusions</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Schagatay et al. [63]</td>
<td>AP group: 13 M, 11 F CC: 2 M, 9 F</td>
<td>2-month aerobic gymnastic training programme</td>
<td>Training effects are specific to the actual training protocol therefore, apnea training promotes characteristics such as bradycardia</td>
<td>• ↑ aerobic power</td>
</tr>
<tr>
<td>Joulia et al. [59]</td>
<td>8 male triathletes</td>
<td>Repeated apneas of 20 sec with breathing intervals of 40 sec during one hour exercise on cycle ergometer at 30% of their VO₂max x 3 times per week for 3 months</td>
<td>Training improves tolerance to hypoxemia, the duration of static apnea and eliminates oxidative stress during dynamic apnea</td>
<td>• ↑ VO₂ peak</td>
</tr>
<tr>
<td>Lemaitre, et al. [73]</td>
<td>Four male swimmers</td>
<td>3-month apnea training: 1 hr cycling x 3 times/week with apneas of 30 sec and a breathing interval of 30 sec</td>
<td>Training improves performance in maximal and sub-maximal exercise and swimming technique and continuous propulsion</td>
<td>• ↑ FEV, RCP</td>
</tr>
</tbody>
</table>

AP: aerobic power; CC: control group; CERgo: cycle ergometer; CO: cardiac output; DR: diving reflex; F: females; FEV: forced expiratory volume; HCVR: hypercapnic ventilatory response; HR: heart rate; K: unchanged; M: males; Min SaO₂: minimal arterial oxygen saturation; RAs: repeated apneas; RCP: respiratory compensation point; RI: rest interval; RPD: rating of perceived dyspnea; RPE: rating of perceived exertion; SL: stroke rate (swimming); V̇ₗₘₕₖ: ventilation threshold; V̇ₗₖₒₐₓ: absolute oxygen uptake/body weight; >: greater; <: less; ↑: increase; ↓: decrease.
individuals’ trained in apneas exhibit longer apnea durations, elevated DR responses and arguably a rise in their maximum oxygen consumption (VO$_{2\text{max}}$) i.e., their aerobic capacity. However, hypoxic compared to normoxic training in swimmers did not enhance their aerobic or anaerobic ability [84].

An oxygen conservation effect during apneas is evident through a reduced arterial oxygen desaturation coupled with a reduced rate of oxygen store depletion in the lungs [34,55,85]. Further, an elevated haematocrit, haemoglobin and erythropoietin have been confirmed in apnea trained individuals [23,64,86]. These characteristics found in trained divers also appear in SS athletes. The physiological adaptations to apnea are extremely valuable for SS athletes performing repeated and occasionally prolonged dynamic apneas during competitive events. Arguably, half of the time during a competitive event is underwater [87]. Therefore, long apnea duration, tolerance to hypoxia, delayed blood acidosis coupled with increased lung volumes and vital capacity are essential for

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**Figure 3:** Diving reflex cycle in the long-term.

**Figure 4:** The long-term physiological adaptations to apnea-conditioned individuals.
their successful performance. Synchronized swimming requires aerobic and anaerobic power [88] in conjunction with extraordinary breath control [89]. Therefore, an exaggerated DR combined with structural lung adaptations are essential for succeeding in competitions.

Rodriguez-Zamora, et al. [78], highlight the impact of psychological factors in SS athletes’ performance and particularly the anticipatory tachycardia due to their perceived intensity of exercise demands. They suggest an interrelationship exists between psychological factors and the physiological stress that SS athletes undergo during competitive events. An anticipatory tachycardia was evidenced as a response to specific routines to be performed during training or competition according to their perceived difficulty (RPE) [79]. Therefore arguably, this stress-related anticipatory tachycardia may blunt athletes’ habituation to hypoxia on their performance in SS competitions.

In brief, apnea-conditioned individuals, exhibit the following characteristics that undoubtedly account for their increased tolerance to hypoxia and possibly their enhanced aerobic and anaerobic power. (Figure 4).

Concerning the possible dangers involved in apnea training, one relates to extreme breath-hold divers’ reduced ventilatory response to breathing CO₂ due to their frequent exposure to high PCO₂ [90]. However, is the alleged reduced chemo-sensitivity to hypoxia and hypercapnia that characterizes divers and other apnea-trained athletes unsafe [15,21,38]? According to Grassi, et al. [91], divers exhibit a diminished ventilatory response only to hypercapnia but not to hypoxia. Further, as the former might not represent an adaptive mechanism but an inherited characteristic [92], thus, it should not raise any issues of concern. On the contrary, what could be life threatening is the commonly used hyperventilation prior to apnea and it should be applied with caution [6,15].

Conclusions

Apnea induces spleen contraction and a rise in hematocrit and hemoglobin lasting up to ten minutes [65,68,69], sufficient for SS athletes to successfully perform their competition program. In essence, repeated apnea sessions before competition would be a legitimate and a safe way to boost performance [93]. In the long-term, apnea training not only increases its duration but it also boosts tolerance to hypoxia [71]. Apnea training reduces blood acidosis and oxidative stress, factors that may clearly influence SS athletes’ performance [58,59]. Allegedly, apnea training may also increase VO₂max, i.e., individuals’ aerobic capacity [73].

In conclusion, apnea training causes physiological adaptations allowing individuals not only to exert an improved breath control but also, to cope with conditions of hypoxia in an effective and efficient manner. These adaptations may be described as aquadicity [94]. They are manifested in an elevated DR coupled with other structural and functional changes such as increased lung volumes and vital capacity. SS athletes’ ability to control their breath definitely affects both their functional performance and their artistry. Caution should be taken as apnea training arguably reduces the chemically initiated drive to breathe [95]. Further research should meticulously examine the implications of this suspected respiratory adaptation.

Postscript

This review highlighted the differences in apnea responses between non-apnea trained individuals and athletes familiar with hypoxic conditions. It also identified the similarities among apnea-trained athletes. The underlying mechanisms of these differences/similarities are yet not fully understood although researchers attribute those to the diving response and hypoxia conditioning. Others claim that there is no discernible interrelationship between respiration and hemodynamic variables under various conditions of breathing-apnea [96]. Future research should clarify those physiological mechanisms that lead to altered responses to hypoxia between apnea-trained and non-apnea trained individuals. The purpose of such research should be not only with a view of boosting athletes’ performance but foremost to ensure their safety. A robust theoretical framework is required to guide research but also, to render empirical evidence comparable and most importantly, to facilitate its interpretation. So far, three related yet not fully understood reflexes have been identified in this context namely, the diving response, the cold shock response and the trigemino-cardiac reflex. Research may attempt to clarify these reflexes, their interrelationships including their similarities and differences. Finally, as apnea-training adaptations resemble altitude acclimatisation future research may compare the impact of the exposure to these two conditions on athletes’ performance.

References


