American Red Cross
Advisory Council on
First Aid, Aquatics,
Safety and Preparedness

ACFASP Scientific Review

Voluntary Hyperventilation

Preceding Underwater Swimming

Questions to be addressed:

Does the evidence available on voluntary hyperventilation preceding underwater swimming support the conclusion that over breathing can lead to a sudden loss of consciousness with or without exercise, and therefore must be prohibited at aquatic facilities?

Introduction/Overview:

Grimaldi J. (1993) notes that over breathing or hyperventilation is breathing at rate and depth higher than necessary to meet the metabolic needs of the body. Despite the incontrovertible neurophysiology findings that hyperventilation prior to underwater swimming can lead to a sudden loss of consciousness and death due to decreased carbon dioxide level, and has been identified as a contributing factor to drowning. This dangerous practice is still used in varying degrees by swimmers at aquatic facilities.

Review Process and Literature Search Performed

A National Library of Medicine, MEDLINE, PubMed and PsychInfo database search was conducted for the period of 1905 to 2007. Medline searched using the terms (1) the MeSH headings Search headings included combinations of the terms: exercise and hypercapnia; voluntary overbreathing; hyperventilation and hypercapnia; hyperventilation and breath holding; hyperventilation and decreased cerebral function; hyperventilation and underwater swimming; hyperventilation and loss of consciousness; hyperventilation preceding breath holding and unconsciousness; physiology of breath hold diving; physiology of underwater swimming, cardio-respiratory functions and breath hold diving; hyperventilation, breath holding, exercise, and unconsciousness; hypoxia and loss of consciousness; peripheral vasoconstriction reduced cardiac output and bradycardia; bradycardia and breath holding; oxygen apnea

This search yielded 1,789 citations. Journal references were obtained and articles consistent with the research questions were reviewed. Additional articles were identified from references cited in the selected articles “hyperventilation” AND ‘breath holding’ AND ‘loss of consciousness’ (2) MeSH headings ‘hyperventilation” AND ‘respiration’ (3) “overbreathing” as a text word, and then hand searched all articles including review articles was conducted. There were 262 abstracts reviewed and 46 papers obtained and reviewed plus papers identified by the hand searches.

Additional Medline search using “hyperventilation only” (textword); 400 titles were screened and 49 articles reviewed and references hand searched. Cochrane Database of Systematic Reviews searched using terms “hyperventilation,” “overbreathing” and “underwater swimming” each separately, yielding 4,370 and 12 results.

Scientific Foundation

The principal function of the respiratory system is to extract oxygen (O_2) from the air that enters the lungs, transport it to the body tissues, and evacuate excess carbon dioxide (CO_2) and water vapor. Neurophysiological control of breathing originates in the respiratory centers located in the brain stem, the pons, and the medulla oblongata. The limbic system and the pre-frontal cortex also regulate breathing.

The medulla oblongata is responsible for the involuntary autonomic nervous system regulatory processes of heart rate, breathing, and blood pressure. The axons in the medulla oblongata transmit signals based on the information received from the respiratory system. The carbon dioxide level, rather than the oxygen level, is the major stimulus for inspiration. The medulla oblongata sensors make certain that an increase in carbon dioxide level beyond normal limits triggers the urge to breathe before decreased oxygen levels leading to hypoxia occur.

The medulla oblongata activates respiratory reflex loops if the concentration of carbon dioxide exceeds normal limits. The increase of carbon dioxide (CO_2) levels and the acidity (H+) bloodstream levels are the primary stimuli for the inspiratory phase of respirations. The necessary amount of oxygen is then inhaled and the level of CO_2 is monitored during expiration to prevent red blood cell respiratory acidosis. Maintaining the proper level of CO_2 exhalation prevents the excessive buildup of either carbonic acid or hydrogen ions thus maintaining the appropriate acid -- base balance crucial to all metabolic processes.

There are two major physiological sensors for detecting oxygen and carbon dioxide levels. Oxygen sensors detect low arterial oxygen (PO_2) concentration. The oxygen level indicator is a weak signal and is easily suppressed especially during competition. Neurons in the solitary nucleus of the brain stem constantly sample the blood in the brain for CO_2 levels. The CO_2 sensors respond to rising carbon dioxide levels which trigger the urge to breathe. This process insures that arterial blood oxygen is adequate to provide the brain with sufficient oxygen to maintain consciousness and not drop below levels incompatible with higher level cerebral functioning.

During voluntary or involuntary hyperventilation excessive carbon dioxide exhalation occurs. This over breathing results in hypocapnia (low levels of carbon dioxide) and respiratory alkalosis (acid – base imbalance). Woodson (1979) found that insufficient CO_2 changes the pH level towards alkalosis and inhibits the functioning of the breathing centers in the brain. Laffey & Kavavagh (2002) reported hyperventilation induced hypocapnia causes vasoconstriction, increases blood pressure, constricts the cerebral and peripheral arteries, reduces the blood flow to the brain, and the capacity of hemoglobin to bind and release oxygen. Inadequate CO_2 reaction with the red blood cells leads to lower production of carbonic acid/hydrogen ions. Respiratory alkalosis (pH level higher than normal) caused by respiratory over breathing lowers the body's CO_2 level significantly below their normal range causing dizziness and unconsciousness.

Hyperventilation lowers the CO_2 levels without increasing arterial oxygen level (PO_2) above the level necessary to maintain consciousness. Fried and Grimaldi (1993) indicated that low CO_2 pressure causes constriction of the blood vessels that supply the brain, tremors, decreased brain blood flow, and lightheadedness. Ley (1987) noted that double vision, vertigo, epileptic like seizures, EEG and EKG changes, coldness of arms and legs, and irritability can occur during hyperventilation. Siesjo, Berntman & Rehncrona (1979) indicate vasoconstriction of peripheral vessels, and the decreased ability to concentrate may occur during overbreathing. A reduction in alveolar CO_2 pressure reduces the diameter of the small pulmonary arteries thereby further restricting the blood flow to body tissues. The increased blood pH reduces the amount of oxygen in the blood delivered to the body's cells. Concurrently, the heart must pump blood with greater force and frequency to compensate for the decrease in alveolar CO_2 pressure and the increase in the pH level.

Summary

Proper breathing regulates body chemistry by providing appropriate levels of carbon dioxide based on the metabolic and other physiological requirements dictated by activities and personal factors. Voluntary hyperventilation deregulates breathing chemistry and brings about a carbon dioxide deficit in the blood through rapid and deep over breathing. The shift in the CO_2 chemistry associated with over breathing causes physiological changes such as hypoxia, cerebral constriction, coronary constriction, blood and cellular alkalosis, cerebral glucose deficit, ischemia, buffer depletion, bronchial constriction, calcium imbalance, magnesium deficiency, muscle spasms, and fatigue. When a person hyperventilates and then swims underwater, the oxygen level in the blood drops below the point needed to maintain higher cerebral functioning. The person will then become unconscious before the CO_2 level raises to the level that triggers the urge to breathe. Drowning then occurs if the person is not rescued.

Standards:

Voluntary hyperventilation prior to underwater swimming and underwater breath holding is a dangerous activity. Swimmers should not engage in hyperventilation prior to either practice. Aquatic managers, lifeguards, and swim instructors should prohibit all persons from hyperventilating prior to underwater swimming and breath holding activities. All aquatic facilities should have a policy of actively prohibiting hyperventilation.

Guidelines: None.

Options: None.

Level	Description	Implication
I	Convincingly justifiable on scientific evidence alone	Usually supports Standard
II	Reasonably justifiable by scientific evidence and strongly supported by expert opinion	Usually supports Guideline or Option but if volume of evidence is great enough and support from expert opinions is clear may support standard
III	Adequate scientific evidence is lacking but widely supported by available data and expert opinion	Usually supports Option.
IV	No convincing scientific evidence available but supported by rational conjecture, expert opinion and/or non peer-reviewed publications	May support option

Summary of Key Articles

Author(s)	Full Citation	Summary of Article (provide a brief summary of what the article adds to	Level of Evidence (Using table below)
Schneeberger J, Murray W.B, Mouton W.L, Stewart R. I. (1986)	Breath holding in divers and non-divers--a reappraisal. *South African Medical Journal. 21;69(13):822-834*	The two phases of breath holding, the voluntary inactive and involuntary active phases, were identified by non-invasive methods using the induction plethysmograph. Eight trained divers and 7 non-diving control subjects familiar with respiratory apparatus were studied. During breath holding from normocapnia and total lung capacity it was not possible to distinguish between the two groups in respect of the pattern or duration of breath holding or alveolar gas tensions at the breakpoint. Divers could, however, hold their breath much longer after hyperventilation (165 +/- 40.0 and 121 +/- 31.4 seconds; P less than 0.01). This was associated with a longer second phase than occurred in non-divers (78.0 +/- 29.7 and 17.6 +/- 13.1 seconds; P less than 0.01) and more severe alveolar hypoxia (percentage oxygen 7.6 +/- 1.8 and 10.9 +/- 1.7%; P less than 0.01). It is concluded that these divers had a hyperventilation-dependent attenuated hypoxic ventilatory response. Subjects could also be identified who have either a very short (less than 10 seconds) or very long (greater than 45 seconds) second phase. They were considered to be at risk of developing underwater hypoxia and unexpected loss of consciousness. It is further suggested that analysis of the phases of breath holding holds promise as a screening test of both novice and experienced divers.	2a

Landsberg P.G. (1975)	Bradycardia during human diving. *South African Medical Journal;49(15):626-30*	The bradycardial response to the diving reflex, which occurs in man and in diving animals, is thought to be a physiologically protective oxygen-conserving mechanism whereby the animal is kept alive during submergence. The physiology and nervous pathways are not yet fully understood, but several investigators have pointed out the potentially fatal outcome of an accentuated diving reflex. The CO_2 content of the peripheral venous blood has been proved variable and unpredictable during the hyperventilation-breath-hold dive cycle in man. A group of 8 male divers (average age 34 years) was investigated during breath hold dives to 3.3 m in a swimming pool. Heart rates were recorded and compared at various stages during breath-hold and SCUBA (self-contained underwater breathing apparatus) dives, viz. when resting on the surface, breath holding, hyperventilating and swimming underwater. Two divers performed extreme breath hold endurance tests lasting 135 seconds underwater. All divers had a tachycardia after hyperventilation and a bradycardia after breath hold diving, lasting 80-100 seconds. Extra asystoles were recorded during some of the breath hold dives. Prolonged submergence caused extreme bradycardia (24/min) with central cyanosis. Bradycardia during diving may be a physiological conserving reflex or the start of a pathophysiological asphyxial response.	2a

Craig, A.B. (1961)	Causes of loss of consciousness during underwater swimming. *Journal of Applied Physiology,16,583-586*	Four types of breath holding were executed; a) at rest, b) after hyperventilation, c) during mild exercise, and d) after hyperventilation and during exercise. At the breaking point the subject made maximal expiration, and the end title air was analyzed for O_2 and CO_2. It was found that when the breaking point was reached, the PCO_2 was higher and the PO_2 lower during exercise than at rest. The lowest PO_2 was observed after the subject had exercised following hyperventilation; the PO_2 was 34 mm or below in four of the 12 subjects, a degree of hypoxia often associated with unconsciousness. Other experiments including underwater swimming support the conclusion that the loss of consciousness after hyperventilation and during exercise is possible and is probably due to hypoxia.	2a
Fink, B. R. (1961)	Influence of cerebral activity in wakefulness on regulation of breathing. *Journal of Applied Physiology 16(1):15-20*	13 healthy men, unaware of the objectives of this study, underwent passive or active over ventilation lowering the end expansion carbon dioxide tension to 25 mm Hg or below. At the end of the period of hyperventilation, rhythmic respiration continued uninterrupted at approximately the control frequency. The volume of ventilation was above control during the first minute of recovery and then stabilized at about two thirds of the control volume; it continued at this level for over two minutes during which time the end expiration PCO_2 gradually rose towards the control level. No incidents of periodic breathing occurred. The absence of over ventilatory apnea in the waking condition contrasts with its easy elicitation during general anesthesia. It is concluded that cerebral activity associated with wakefulness is a component of normal respiratory drive and that carbon dioxide acts by augmenting the effects of this	2a

		component	
Craig, A.B. (1961)	Underwater swimming and the loss of consciousness. *The Journal of the American Medical Association, 176 (4), 87 -- 90*	Under certain circumstances a person swimming underwater may lose consciousness. Eight incidents here described indicate that hyperventilation before breath holding and exercise may delay the onset of the urge to breath. Before the partial pressure of CO_2 increases significantly, the O_2 may decrease to a degree incompatible with higher level cerebral functioning. In five cases of drowning also reported, this chain of events is likely to have occurred. Discussion of the details suggest that certain preventive steps can be taken without discouraging swimmers from learning to handle themselves underwater.	5
Craig, A.B. (1961)	Underwater swimming and the loss of consciousness. *The Journal of the American Medical Association, 176 (4), 87 -- 90*	<u>Report of Cases: Survivors</u> <u>Case 1</u> An excellent swimmer, age 27, set as his goal an underwater swim of over of 200 feet in distance, two laps of the pool. Before beginning he hyperventilated for about two minutes, took a full inspiration, and dove in. After the first few feet, during which he was dizzy, he felt he could have swam underwater "forever." He negotiated the turn and started back before he noted the urge to breathe. As this sensation became more pronounced, he made continuous swallowing movements, a common trick for relief from the pressure of breath holding. The last thing he remembered was passing a ladder which was later measures as 40 feet from the end, or 160 feet from the beginning of the swim. When he reached the end of the pool, he surfaced, regained consciousness, climbed out of the pool, and	5

		lay down to rest. His friends, who were following the progress of the swim, noted nothing amiss, and when informed of what the swimmer had experienced they could recall nothing unusual.	

Craig, A.B. (1961)	Underwater swimming and the loss of consciousness. *The Journal of the American Medical Association, 176 (4), 87 -- 90*	<u>Report of Cases: Survivors</u> <u>Case 2</u> Another good swimmer, age 18, decided to repeat a previous performance he had achieved by swimming underwater for three laps of a 75 foot pool, i.e. 225 feet. He hyperventilated for one minute at which time he was dizzy. A significant urge to breathe was not apparent until the beginning of the third lap, when he reminded himself that his goal was 225 feet. He did not remember swimming most of the third lap. When he reached the end, a fellow student who was specifically watching the swim reported that the subject surfaced but failed to raise his head. He began to cough and gasp, but regained consciousness in two or three breaths after his head was held above the surface. The subject did not recall any after effects other than being slightly tired.	5

Craig, A.B. (1961)	Underwater swimming and the loss of consciousness. *The Journal of the American Medical Association, 176 (4),*	<u>Report of Cases: Survivors</u> <u>Case 3</u> Another boy, age 18, was practicing underwater swimming with mask, fins, and snorkel a short distance offshore. Before one dive he "hyperventilated hard" for	5

	87 -- 90	about two minutes. Careful questioning failed to reveal that he had not set any time or distance goal on this particular dive nor was he competing against another diver. He went under "… feeling great. I thought I could hold my breath forever." He estimated that he was 5 feet under the surface propelling himself slowly. He did not remember having any urge to breathe before seeing "spots" before his eyes. This was a transient sensation, and his next memory was being on the surface breathing hard. He started to swim for shore, but felt dizzy and exhausted. When he reached shallow water, he tried to stand but was still dizzy and "shaky." He recovered during the next minute or so and had a slight headache for about an hour. Further questioning revealed that he did not call or gasp when he found himself conscious. There was no hint that he has aspirated water. Most interesting was the observation that he could not remember making any decision to surface.	

Craig, A.B. (1961)	Underwater swimming and the loss of consciousness. *The Journal of the American Medical Association, 176 (4), 87 – 90*	<u>Report of Cases: Survivors</u> <u>Case 4</u> A subject related that at the age of 14 he was a participant in an underwater swimming event at a local club. As he was the first to swim, he wished to make a maximal effort. He hyperventilated for "quite a long time," enough to feel dizziness and tingling in the extremities. At the end of the first lap of a 60 foot pool he felt himself	5

		"tired." However, after the first turn he recovered and during the second and third lengths he thought that "this was great." The last event he remembered was making the turn at 180 feet and pushing off the wall. He did not recall swimming another three or four strokes only that he regained consciousness while being pulled to the edge of the pool. No artificial resuscitation was necessary.	

Craig, A.B. (1961)	Underwater swimming and the loss of consciousness. *The Journal of the American Medical Association, 176 (4), 87 – 90*	<u>Report of Cases: Survivors</u> <u>Case 5</u> Several other swimmers had preceded an 18-year-old boy in an event to see how far they could swim underwater. This subject recalls telling a friend that he was going to make two laps of the 60 foot pool and at least complete the second turn. Before starting he made "four or five" maximal expirations and inspirations but did not feel dizzy. He noted the urge to breathe during the middle of the second lap, but "I bit my lip and pumped my lungs." By the latter statement he meant that he made inspiratory and expiratory efforts against a closed glottis. Within the next few feet he reminded himself that his goal was 120 feet and a turn. As he saw the end of the pool, "things turned dim" his next memory was lying on the edge of the pool with "someone pushing on my back." The person watching the swim reported that nothing seemed to be amiss until the swimmer pushed off from the second turn. He made no further swimming movements but began to sink feet first. He was immediately pulled from the water and regained consciousness after two or three cycles of artificial resuscitation.	5

		Although his color was not noted, it was observed that he was flaccid when taken out of the pool. There was no coughing when spontaneous respirations were resumed.	

Craig, A.B. (1961)	Underwater swimming and the loss of consciousness. *The Journal of the American Medical Association, 176 (4), 87 – 90*	<u>Report of Cases: Survivors</u> <u>Case 6</u> A 17-year-old male swimmer had participated in a water polo game about 20 minutes before entering an underwater swimming contest. Before beginning he took 10 or 12 "very deep breaths" and for the first few feet on the water, he felt "very dizzy". He completed the first lap, 75 feet and about half way back "my mind went blank." Spectators said that he continued to swim, completed the second lap, turned, and appeared to surface (about 160 feet). He then began to sink and was immediately pulled out. Artificial resuscitation was carried out for two or three minutes before spontaneous respirations were adequate.	5

Craig, A.B. (1961)	Underwater swimming and the loss of consciousness. *The Journal of the American Medical Association, 176 (4), 87 – 90*	<u>Report of Cases: Survivors</u> <u>Case 7</u> At the conclusion of the lifesaving class the students were asked to swim one length of a 75 foot pool underwater. Most of these college students swam one length and did get out, but one man in a lane at the edge of the pool made the turn and started back. The instructor reached over the edge of the pool with his foot and pushed the swimmer	5

		on the back. The swimmer then climbed up, sat on the edge, but did not seem to know "where he was." A short time later the student told the instructor that he did not remember getting out of the pool but only that he had " a wonderful feeling that he could go, go, go," while swimming the length of the pool.	

Craig, A.B. (1961)	Underwater swimming and the loss of consciousness. *The Journal of the American Medical Association, 176 (4), 87 – 90*	<u>Report of Cases: Survivors</u> <u>Case 8</u> A medical student recounted that he had worked as a lifeguard at a large outdoor pool. A favorite game of a group of 14 to 16-year-olds was to swim underwater. The pool was 75 feet wide. They would each do this repeatedly during a swim, and many of them could make the distance without much apparent effort. They routinely hyperventilated before starting. The victim had attempted to swim several times but on this occasion was pulled from the water at a point indicating that he had gone 120 feet. He was found on the bottom but could not have been there more than 30 seconds. When taken from the water he was flaccid, and "very cyanotic." Manual artificial resuscitation was effective in reducing the degree of cyanosis and was continued for five to seven minutes before spontaneous respirations were noted. The subject reported "I don't know what happened," but no further history was obtained	5

Craig, A.B. (1961)	**Underwater swimming and the loss of consciousness.** ***The Journal of the American Medical Association, 176 (4), 87 -- 90***	Case 1 Drowning. A young college sophomore who was a good swimmer and was known to be in good condition borrowed his roommates flippers and went to the pool. It was known that the victim intended to swim laps underwater (150 feet). Those of the pool recall that he swam for some time before he presumably attempted the underwater distance. There were only six or seven other people in the pool during this period. The guards suddenly saw the subject on the bottom of the deep end; the maximal time he could've been there was no more than one minute. The body was recovered and back pressure -- arm lift resuscitation was begun immediately. Bloody froth appeared at the mouth with the first positive pressure. Within a minute another instructor began mouth-to-mouth breathing but reported that despite maximal expiratory effort he was unable to move any air. The victim's cyanosis did not decrease. Other efforts were made with a "machine resuscitator" but this merely "chattered." Autopsy revealed the lungs were full of water but there were no contents of the stomach in the airway	5

Craig, A.B. (1976)	Summary of 58 cases of loss of consciousness during underwater swimming and diving. *Medicine and Science in Sports.*	It is well accepted that hyperventilation before breath hold swimming and skin diving makes it possible for a person to extend the time under water. Less well known is the fact that this maneuver can cause loss of consciousness due to hypoxia. This accident happens almost exclusively to males (56 cases). The most common age group was 16-20 years (range 12-33 years). All were known to be good swimmers or	3b

	8 (3):171-175.	divers. Approximately 80% of the cases occurred in guarded pools. Thirty-five subjects survived the accident and of the twenty-three fatalities, there was only one good autopsy report. In this instance the findings were those associated with classical drowning preceded by hypoxia and hypercapnia. Breath holding experiments indicated that the times between loss of consciousness and death may be no longer than 2.5 minutes. The patterns associated with these cases suggest that those who are responsible for aquatic safety as supervisors or guards of pools could prevent most accidents by watching for young male swimmers who are practicing hyperventilation and underwater swimming in competition with themselves or with others.	

United States Navy. (2008)	United States Navy Dive Manual Revision 6, pages 3-19 – 3-20 (SS521-AG-PRO-010 Washington,DC, United States Commander,Naval Sea Systems Command	Most people can hold their breath approximately 1 minute, but usually not much longer without training or special preparation. At some time during a breathholding attempt, the desire to breathe becomes uncontrollable. The demand to breathe is signaled by the respiratory center responding to the increasing levels of carbon dioxide in the arterial blood and peripheral chemoreceptors responding to the corresponding fall in arterial oxygen partial pressure. If the breathhold is preceded by a period of voluntary hyperventilation, the breathhold can be	5

		much longer. Voluntary hyperventilation lowers body stores of carbon dioxide below normal (a condition known as hypocapnia), without significantly increasing oxygen stores. During the breathhold, it takes an appreciable time for the body stores of carbon dioxide to return to the normal level then to rise to the point where breathing is stimulated. During this time the oxygen partial pressure may fall below the level necessary to maintain consciousness. This is a common cause of breathholding accidents in swimming pools. Extended breathholding after hyperventilation is not a safe procedure. **3-20 U.S. Navy Diving Manual—Volume 1** **WARNING Voluntary hyperventilation is dangerous and can lead to unconsciousness and death during breathhold dives.** Another hazard of breathhold diving is the possible loss of consciousness from hypoxia during ascent. Air in the lungs is compressed during descent, raising the oxygen partial pressure. The increased ppO_2 readily satisfies the body's oxygen demand during descent and while on the bottom, even though a portion is being consumed by the body. During ascent, the partial pressure of the remaining oxygen is reduced rapidly as the hydrostatic pressure on the body lessens. If the ppO_2 falls below 0.10 ata (10% sev), unconsciousness may result. This danger is further heightened when hyperventilation has eliminated normal body warning signs	

		of carbon dioxide accumulation and allowed the diver to remain on the bottom for a longer period of time. The US Navy Dive manual describes a warning as follows: **WARNING** **Identifies an operating or maintenance procedure, practice, condition, or statement, which, if not strictly observed, could result in injury to or death of personnel.**	

Level of Evidence	Definitions **(See manuscript for full details)**
Level 1a	Population based studies, randomized prospective studies or meta-analyses of multiple studies with substantial effects
Level 1b	Large non-population based epidemiological studies or randomized prospective studies with smaller or less significant effects
Level 2a	Prospective, controlled, non-randomized, cohort or case-control studies
Level 2b	Historic, non-randomized, cohort or case-control studies
Level 2c	Case series: convenience sample epidemiological studies
Level 3a	Large observational studies
Level 3b	Smaller observational studies
Level 4	Animal studies or mechanical model studies
Level 5	Peer-reviewed, state of the art articles, review articles, organizational statements or guidelines, editorials, or consensus statements
Level 6	Non-peer reviewed published opinions, such as textbook statements, official organizational publications, guidelines and policy statements which are not peer reviewed and consensus statements

Level 7	Rational conjecture (common sense); common practices accepted before evidence-based guidelines
Level 1-6E	Extrapolations from existing data collected for other purposes, theoretical analyses which is on-point with question being asked. Modifier E applied because extrapolated but ranked based on type of study.

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