

Physiology Of Drowning: A Review

Drowning physiology relates to two different events: immersion (upper airway above water) and submersion (upper airway under water). Immersion involves integrated cardiorespiratory responses to skin and deep body temperature, including cold shock, physical incapacitation, and hypovolemia, as precursors of collapse and submersion. The physiology of submersion includes fear of drowning, diving response, autonomic conflict, upper airway reflexes, water aspiration and swallowing, emesis, and electrolyte disorders. Submersion outcome is determined by cardiac, pulmonary, and neurological injury. Knowledge of drowning physiology is scarce. Better understanding may identify methods to improve survival, particularly related to hot-water immersion, cold shock, cold-induced physical incapacitation, and fear of drowning.

Joost J. L. M. Bierens,¹
Philippe Lunetta,² Mike Tipton,³ and
David S. Warner⁴

¹Maatschappij tot Redding van Drenkelingen, Amsterdam, The Netherlands; ²Department of Pathology and Forensic Medicine, University of Turku, Turku, Finland; ³Department of Sport and Exercise Science, Extreme Environments Laboratory, University of Portsmouth, Portsmouth, United Kingdom; and ⁴Departments of Anesthesiology, Neurobiology and Surgery, Duke University Medical Center, Durham, North Carolina
jbierens@euronet.nl

A recent report of the World Health Organization (WHO) labels drowning as one of the world's leading causes of death (164). Although standard WHO statistics report almost 375,000 persons drowning each year, the actual figure for worldwide drowning is probably four or five times as high. Low- and middle-income countries, where most drownings occur, have incomplete recording of drowning events. Furthermore, drowning as a result of flooding, ferryboat accidents, and accidents with boat-carrying refugees and migrants are not reported in the standard drowning statistics (140, 164).

Drowning is formally defined as the process of experiencing respiratory impairment from submersion/immersion in liquid (273). The exact physiological mechanisms of this process are complex and largely unknown, and have only been speculatively described in drowning reviews and studies over recent decades (29, 108, 132, 195, 257). Although there are clinical differences between submersion and immersion (30, 275), the details of the physiological processes have not been reviewed. The present work provides an overview of the current understanding of the physiological mechanisms that may occur during a submersion or immersion incident. Since human drowning mechanisms per se are difficult to study, observations from animal experiments, case series, and forensics have been included where helpful.

The objective of the review is to summarize the physiological mechanisms associated with drowning and to explore whether future physiological studies may contribute to the prevention, treatment, and forensic investigations of drowning.

Immersion

Hot-Water Immersion

“Thermoneutral” is the term for the water temperature at which heat loss equals heat production (53, 238). Most drowning events occur at water temperatures below the point of thermoneutrality, which is $35^{\circ}\text{C} \pm 0.5$. Some drownings, however, occur in hot-water tubs, while pouring hot water over the head, or during diving or competitive swimming in warm water.

Ofuro bathing is a component of Japan's national culture and identity. It is believed that healthy persons may benefit from the physiological effects of hot-water immersion (HWI) on the body's homeostatic systems (16, 25, 48, 53, 81, 118). People may sit and soak up to the shoulders or neck in deep hot ($38\text{--}43^{\circ}\text{C}$) tubs for 5–15 min (96, 118). The high incidence of Japanese hot-water tub fatalities suggests that HWI may lead to drowning (2, 109, 175, 191, 211, 291).

Thermoregulation during HWI differs from thermoregulation in hot ambient air. In ambient air, elimination of body heat occurs mainly by sweat evaporation. The phase-change from a liquid to a gaseous state removes heat from the skin and cools the body. In HWI, the high humidity of the ambient air around a hot tub, with only the head and neck skin above the water, allows limited evaporation of sweat above the water. Sweating, however, also occurs under water. The secretory pressure of sweat glands allows sweat to flow outward to dissolve in the water. This sweat fails to evaporate and thus does not contribute to body cooling. When skin temperature increases, cutaneous warm thermoreceptors located in sensory nerve (unmyeli-

nated C-type fiber) endings interact with keratinocytes through transient receptor potential vanilloid cation channels and convey signals, via the spinal dorsal horn and trigeminal nerve, to hypothalamic thermoregulatory centers mainly situated in the pre-optic area (220, 235, 237). From the pre-optic area, autonomic efferent information is forwarded to the skin and causes, among other effects, cutaneous vasodilatation (118, 169, 182). Under normal circumstances, external hydrostatic pressure results in bradycardia. In HWI, however, the temperature effects overcome this (16, 34, 236, 251), because decreased peripheral vascular resistance raises heart rate (34, 48, 175, 259, 284).

Increased HR may trigger ventricular arrhythmias, potentially hazardous in combination with peripheral vasodilatation and increased blood viscosity (229). The associated dehydration increases likelihood of thrombosis, particularly in the elderly (158, 239). HWI drowning is most likely to occur during protracted immersion at high temperature and when leaving the tub (1, 117). The loss of the hydrostatic squeeze on leaving a bath and assuming an upright posture can cause a gradual or sudden decrease in blood pressure (44, 109, 118, 185, 211, 229, 291). The HWI-related cardiovascular changes may be important in the elderly and in those with coronary artery disease, hypertension, or congestive heart failure (7, 25, 48, 81, 117, 175, 211, 291).

Drownings have also been attributed to pouring hot water (>39°C) over the head. Tactile and temperature stimuli can trigger reflex epilepsy in indi-

viduals with aberrant thermoregulation or genetic defects (24, 165, 228).

Competitive swimming in warm water can cause a marked increase in deep body temperature and insidious hyperthermia. The pathophysiology of endurance swimming in warm water has been considered after a death during warm-water competition (260). Hyperthermia during diving in tropical waters also can pose a drowning risk (208, 260).

Cold-Water Immersion

Most drownings occur in water colder than thermoneutral temperature, thus initiating physiological responses associated with cooling. In cold water, the responses that act as precursors to drowning are evoked by skin cooling (cold shock), then cooling of superficial nerves and muscles in the limbs, and finally cooling of deep body tissues (hypothermia).

Cold Shock

After a fall into cold water, any intention to breath-hold can be overcome by cold shock (261, 263). The response starts in water ~25°C and peaks somewhere between 15 and 10°C; it peaks in the first 30 s of immersion and attenuates during the next 2–3 min (268). It is evoked by cold receptors located in the superficial sub-epidermal layer of the skin; below ~19°C, cold nociceptors contribute to the response with a sensation of intense cold pain being experienced in water below ~5°C (40, 163). The cold-shock response may be decreased but is still present in those with a high body temperature (159).

Cold receptors respond to the sudden decrease in skin temperature resulting from immersion in cold water with a dynamic response that evokes gasping, hyperventilation, increased cardiac output, peripheral vasoconstriction, and hypertension. These responses, along with a generalized increase in muscle tension, can increase metabolic rate on initial immersion by a factor of four (98). This would, on its own, decrease breath-hold time during initial immersion because the hypoxic and hypercapnic thresholds for the breakpoint of breath-holding would be reached earlier (FIGURE 1). More important, thermo-afferents from the peripheral cold receptors dramatically increase respiratory drive via direct stimulation of the respiratory center (121), with a reflex stimulation at the spinal level of α -motoneurons innervating the intercostal muscles and diaphragm (166, 263). As a consequence, the gasp response and hyperventilation cause an inability to breath-hold. Maximum breath-hold time generally is 60–90 s at a comfortable air temperature and is reduced to just a few seconds in water colder than ~15°C. The inability to breath-hold represents the most hazardous response to cold-water immer-

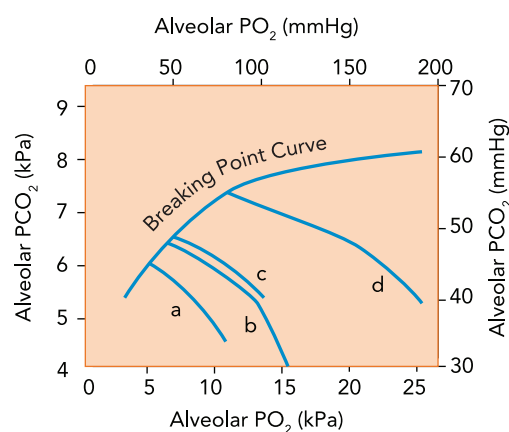


FIGURE 1. The breaking points of breath-holding in different settings

The “breaking point curve” defines the values of alveolar PO_2 and PCO_2 at the breath-hold breakpoint when starting from different states. The normal alveolar starting point is shown. This point is displaced by different maneuvers, and the length of the arrows gives an indication of the changes of the breath-hold duration. See Refs. 73, 196. a, After breathing 15% oxygen; b, after hyperventilation; c, normal alveolar point; d, after breathing 30% oxygen.

sion, increasing the chance of aspiration and drowning.

At the same time, upon initial immersion in cold water, the incidence of arrhythmias increases from 2% during cold water immersion with head-out-of-water free-breathing to 82% if the cold immersion is associated with face immersion and maximum breath-holding (see section *Diving Response and Autonomic Conflict* below).

Superficial Tissue Cooling

After the skin has been exposed to cold water, the next tissues to cool are superficial nerves and muscles. Those in the arms are particularly susceptible due to the surface area-to-mass ratio of the arms and the relatively superficial anatomical location of nerves and muscles. Low muscle temperature can affect chemical and physical processes at the cellular level. This includes metabolic rate, enzymatic activity, calcium and acetylcholine release and diffusion rate, and series elastic components of connective tissues (278). At muscle temperatures below 25°C, fatigue occurs because cooling impairs superficial muscle fibers leaving a smaller number of fibers to produce the same force (50). Maximum dynamic strength, power output, jumping, and sprinting performance have been related to muscle temperature with reductions ranging from 4 to 6% per degree fall in muscle temperature down to 30°C (27, 213).

At nerve temperatures below ~20°C, nerve conduction is slowed and action potential amplitude is decreased (62). Ulnar nerve conduction velocity falls by 15 m/s per 10°C decrease of local temperature. Nerve block may occur at a local temperature of between 5 and 15°C for 1–15 min and lead to a dysfunction that is equivalent to peripheral paralysis (22, 50).

The detrimental influence of peripheral and deep-tissue cooling on physical performance has recently been reviewed (43). It is noteworthy that drowning caused by physical incapacitation can occur before deep body tissue temperature falls below 35°C.

Deep-Tissue Cooling: Hypothermia

With regard to drowning, the most significant consequence of hypothermia is the loss of consciousness (LOC) with deep body cooling. This prevents individuals from undertaking physical activity to maintain a clear airway.

The progressive signs and symptoms are shivering (36°C), confusion, disorientation, introversion (35°C), amnesia (34°C), cardiac arrhythmias (33°C), clouding of consciousness (33–30°C), LOC (30°C), ventricular fibrillation (VF) (28°C), and death (25°C). Below a cardiac temperature of 28°C, the heart may suddenly and spontaneously

arrest. VF may result from rough handling of the casualty at deep body temperature of ~28°C (88, 89). Hypothermia affects cellular metabolism, blood flow, and neural function. In severe hypothermia, the patient will be deeply unconscious. The decreased oxygen requirement of cold cells and organs causes decreased respiratory and heart rates. This makes it difficult to detect vital signs in the field. Tendon reflexes are absent and the pupils dilated: this may give the appearance of death (88).

A distinction should be made between induced hypothermia for clinical purposes and accidental hypothermia. Successful resuscitation has occurred following induced hypothermia down to deep body temperatures as low as 5°C (32). In contrast, in accidental hypothermia, it is not uncommon for death to occur at a body temperature of 24–28°C. Therefore, the circumstances of cooling and rewarming resuscitation, and associated changes in physiology in themselves, can be important determinants of survival. In addition, different physiological functions have different susceptibilities to cooling. The Q_{10} temperature coefficient is a measure of the rate of change of a biological or chemical system as a consequence of increasing/decreasing temperature by 10°C. For example, metabolic and rhythmic processes are particularly depressed by hypothermia (Q_{10} of ~3); contractile processes have a Q_{10} of ~2. As hypothermia progresses, metabolic and rhythmic processes are depressed two to three times more than the rates of diffusion of different metabolites (152). Some of the mechanisms underpinning the functional changes associated with hypothermia are briefly outlined in (see Table 1). Although presented separately, it should be apparent that these changes are interrelated.

The signs and symptoms of progressive hypothermia are not strongly correlated with temperature. The temperatures above in parentheses are only rough approximations. Great variation exists between individuals in both the rate of cooling and the lowest deep body temperature compatible with life or consciousness (5). The rate of cooling depends on a wide range of internal thermal factors including subcutaneous fat thickness (119, 213) or nonthermal factors like motion illness (167) and external factors such as water temperature and sea state (88). Table 2 provides an overview of the risk factors for development of immersion hypothermia.

As noted, during accidental hypothermia, the deep body temperature associated with death is ~25°C (5), but the lowest deep body temperature recorded to date following accidental exposure to cold air and with a beating heart and full recovery was 12.7°C in a 28-mo-old child (19,

Table 1. Overview of the physiological changes with moderate-severe hypothermia compared to normothermia

Decreased spontaneous depolarization of heart pacemaker cells	Progressive bradycardia that accompanies increasing hypothermia is characterized by a relatively greater prolongation of systole than diastole. It affects both atrial and ventricular rates and is approximately linearly related to the fall in body temperature. There is a direct effect of cold on the pacemaker tissue (18, 75). Myocardial conductivity is uniformly and progressively depressed (103).
Altered activity of membrane ion channels	Alterations in the myocardial membrane action potential are thought to be due to changes in ion fluxes across the myocardium sarcolemma (153). Such alterations are thought to produce the characteristic J-deflection recorded in both induced and accidental hypothermia (186, 241).
Renal function and glomerular filtration depression, augmented by osmotic diuresis	Hypothermia has a depressant effect on all aspects of renal function. There is a progressive fall in renal blood flow and increase in renal vascular resistance. At a deep body temperature of 28°C, renal blood flow may have been reduced by as much as 50% (221). Decreased renal tubular function appears to be a result of the direct effects of cold (12). Hypothermia inhibits many of the enzymatic processes in the renal tubular cells, negating the kidneys' role in acid-base control (221). Increased sodium excretion during hypothermia is evidence of depressed tubular transport of sodium; this also impacts the ability of the kidneys to contribute to acid-base regulation (sodium-hydrogen exchange) (221). There is a cold-induced inhibition of the tubular reabsorption of water, which contributes to the diuresis seen on cooling (222).
Fluid shift into the extravascular compartment	Hypothermia depresses many of the mechanisms involved in the regulation of body fluid balance and causes abnormal fluid shifts between body compartments (107).
Impaired hepatic metabolism	The hypothermic liver is less able to utilize glucose or remove excess lactate or other products of muscle metabolism; this contributes to the metabolic acidosis seen in hypothermia (221).
Impaired respiratory function	At deep body temperature below ~32°C, spontaneous respiratory activity is decreased. This, plus the increased solubility of carbon dioxide in the body fluids, may combine to produce respiratory acidosis (249).
Diminished endocrine function	The release of adrenocorticotrophic hormone (ACTH) from the anterior pituitary is depressed in proportion to the severity of hypothermia; the action of ACTH on the adrenal cortex also falls in proportion to deep body temperature below 32.2°C (79). The depression of human adrenocortical function intensifies at a deep body temperature of 28°C (112). The adrenal medulla production of adrenaline and noradrenaline become significantly depressed at a deep body temperature of 28°C (113). Endogenous production of insulin falls (23, 52). Below a deep body temperature of 30°C, the glucose carrier mechanisms of the cell membrane appear to be inhibited, and glucose utilization is severely reduced, resulting in hyperglycemia even in the presence of insulin (35). Conversely, hypoglycemia can increase the likelihood of hypothermia by inhibiting metabolism (202).
Impaired cerebral function	Cerebral blood flow decreases due to falling cardiac output and blood pressure, and a rise in blood viscosity and cerebrovascular resistance. The metabolic rate of the brain and spinal cord are depressed. There is a progressive slowing of electrical activity, with cerebral electrical activity ceasing in some individuals at 17°C (197).
Impaired peripheral neural function	When expressed as a semi-logarithmic function, all peripheral motor and sensory nerve fibers have a Q ₁₀ of 1.51 (59); voluntary grip strength has a Q ₁₀ of 1.2 (64).
Decreased gastrointestinal motility and function	Multiple acute submucosal hemorrhages are common in the region of the pylorus (155, 183). The absorption of drugs from the bowel is impaired during hypothermia (193, 219).
Blood alterations	Hypothermia results in increased blood viscosity (120), which can interfere with the microcirculation. There is a severe fall in leukocyte count below a deep body temperature of 28°C (269). There is a linear fall in platelet count with deep body cooling. Thrombocytopenia becomes pronounced at a deep body temperature below 28°C. The fall in the number of platelets is associated with a tendency for abnormal bleeding (282).
Collapse of the microvasculature	Hypothermia can result in a loss of microcirculatory control, vasomotor paralysis, and hypoperfusion (similar to "shock"). Capillary sludging and microcirculatory stasis can result and threaten survival (100). Circulatory failure prevents acids formed in the tissues, due to hypothermia-induced hypoxic metabolism, from being buffered. When the microcirculation improves with rewarming, metabolic acidosis may rapidly increase as the acid products of anaerobic metabolism are returned to the circulation (187).

217). The coldest adult survivor of cold-water immersion followed by submersion had a body temperature of 13.7°C (86).

The variation in the rates at which people cool in water below thermoneutral temperatures, and

the poor association between the signs and symptoms of hypothermia and actual deep body temperature, make the determination of time of useful consciousness and survival time "more of an art than a science" (88). It also follows that the

signs of hypothermia may be unreliable indicators of deep body temperature. For example, the presence and absence of shivering have variously served as indicators that body temperature is normal, under threat, or profoundly hypothermic. However, shivering is dependent on functioning neuromuscular pathways, blood glucose levels, and a local supply of substrate (82); these factors may change, independent of deep body temperature. Hypoglycemia following consumption of alcohol, a common factor in immersion victims, can suppress shivering independent of body temperature (94). Substrate depletion is more likely in chronic hypothermia than in the acute hypothermia observed in immersion victims.

A final problem with hypothermia is that, in the field and sometimes in the emergency department, the absence of a reliable measure of deep body temperature makes the direct and accurate assessment of the degree of hypothermia in an immersion victim difficult (150, 258).

Submersion

Sympathetic Activation, Fear of Drowning

Fear of drowning as a mechanism that results in drowning is most often reported in the gray literature and social media. Several triathletes mention excessive panic, notably during the mass start of swimming. The panic is accompanied by complete inability to swim. The fear of drowning urges them to go back to shore or get attached to a buoy or lifeboat. Approximately 80% of triathlon deaths occur during the swim, and it is speculated that several drownings during triathlon swimming may be due to the results of these panic attacks (39, 260, 264). Also, competitive swimmers may panic when swimming in open water where they are confronted with a different setting than the Olympic pool and the need to use different swimming strokes than the strokes they are trained for (260, 264). Recreational swimmers in open water encounter similar panic experiences when suddenly confronted with cold water, rip currents, or unexpected underwater objects. Some swimming instructors have experienced students who refused to enter the water or almost drowned when in the water, paralyzed by this fear of drowning. Special training programs have been developed for these students and are also recommended for experienced swimmers (114, 181). Divers with self-contained underwater breathing apparatus (SCUBA) also may panic when experiencing the sensation of cold and streaming water, losing visual contact with the bottom (blue orb syndrome), observation of large or dangerous fish,

Table 2. Risk factors for immersion hypothermia (88, 119, 167, 213)

- Water temperature: effects being most significant during cold water immersion
- Water movement: faster-moving liquids increase convective heat loss
- Surface area-to-mass area: the higher this ratio, the more cooling is facilitated
- Age: children cool faster than adults due to their lower levels of subcutaneous fat and higher surface area-to-mass ratio
- Body stature: tall, thin individuals cool faster than do those short and obese
- Body morphology: body fat and nonperfused muscle are good insulators
- Gender: females tend to have more subcutaneous fat than men but a weaker shivering response
- Fitness: high fitness level enables greater heat production
- Fatigue: exhaustion results in decreased heat production
- Nutritional state: hypoglycemia attenuates shivering and accentuates cooling
- Intoxication: alcohol and other drug depressants affect metabolism
- Lack of appropriate/specialized clothing

entanglement, entrapment, or equipment malfunction. This is sometimes combined with a reduction of muscle force (see below). An unknown, but probably significant, contributor to SCUBA drowning may be panic that completely incapacitates the diver both mentally and physically (181, 210).

The psychological aspects in these situations also includes concern by the person in the water about a sudden onset of previously diagnosed and treated minor physical problems (such as cardiac problems, hypertension, diabetes) and other frightening thoughts, leading to sensory deprivation, illusions, flashbacks, and thoughts of catastrophic outcome. It is well known that panic leads almost instantaneously to irrational logic and cognition. Problem-solving capacities are decreased.

There is limited physiological literature on this phenomenon, although many reports also mention a physical component, most of all paralysis or loss of muscle strength. This may be due to the hyperarousal of the sympathetic activation during panic in the water. This will lead to a combination of physical and psychological stressors that could potentiate cold shock, disable swimming ability, or at least create the feeling that swimming ability has seriously decreased. Notable in people with an overreactive anxiety state, the stressful or unexpected event may result in a panic-induced hyperarousal, resulting in submersion.

Breath-Holding

Breath-holding has served as an intervention to discover more about control of breathing and determinants of breath-hold time. A long history of excellent work has examined breath-holding physiology (78, 104, 200). Under normal circumstances in air, an initial period occurs with little respiratory afferent activity and therefore also with little effort required to maintain a breath-hold (“easy going phase”). This ends due to afferent neural input to the respiratory centers arising from the respiratory musculature, creating an increasing drive for respiratory movement: the struggle phase (FIGURE 2). Respiratory movement, in the form of rebreathing into a bag at the point of maximum breath-hold, can double the time spent without fresh air (78). The respiratory movement associated with rebreathing decreases the afferent neural input arising from the respiratory musculature and extends the breath-hold time to the point where blood oxygen and carbon dioxide tensions drive respiration. Swallowing can extend breath-hold time by causing some movement of the respiratory musculature, perhaps explaining why some drowning victims have water in their stomachs when rescued.

Under normal circumstances, typical alveolar PCO_2 at the breakpoint ranges between 43 and 53 Torr and occurs 60–90 s after breath-holding with ambient air (FIGURE 2). The breath-holding time can be influenced by several factors, including those listed in Table 3 (196).

In water, important additional physiological factors decrease breath-holding duration, including alcohol intoxication, water temperature below $\sim 15^\circ C$, and the cold shock response that intensifies respiratory drive. Other factors that can influence breath-hold time include voluntary liquid aspiration such as occurs in suicides.

As with many physiological responses that involve a combination of autonomic and conscious

input, the variation between individuals in maximum breath-hold time is large. Even in the same cold water temperature, the breath-hold time can range from <10 to >100 s (262). In warm water, the average maximum breath-hold time is ~ 45 s, but some trained breath-hold divers can achieve over 20 min (149, 252a).

Diving Response

Whereas there is evidence that the diving response conserves oxygen during apneic diving or cold exposure of the face, only limited and indirect evidence defines the role of the diving response during drowning. The diving response is one of the commonly proposed mechanisms to explain why some drowning victims survive for prolonged periods underwater (91). However, the response is probably much less important as a protective mechanism than is rapid selective brain cooling caused by the supply of cold carotid blood to the brain and cooling of the heart caused by the aspiration and ingestion of ice-cold water (51, 90, 266, 270).

Research into diving birds, reptiles, mammals living in or underwater, and other hypoxia-tolerant animals shows that the diving response is an autonomic response that serves as an endogenous hypoxia defense mechanism to preserve life. The diving response is better developed and has a faster onset in diving mammals and children than in adult humans (47, 77, 91, 106, 137). Rats have been trained to dive to allow study of the diving response (106, 161, 162, 198).

Studies with infants reveal that, up to 6 mo of age, all children have the ability to achieve the diving response. This is decreased to 90% of all children at 12 mo of age (87, 207). The diving response could be triggered in 66% of adult volunteers, but with large interindividual differences in its effects (99).

Human studies are mostly related to breath-hold diving (9, 95, 97, 102, 133, 134, 137) and facial immersion in cold water (38, 126). The diving response is considered one of the most powerful autonomic responses, particularly in children (42, 198). For this reason, clinically relevant studies on the diving response have involved treatment of paroxysmal atrial tachycardia, diabetic cardiovascular autonomic neuropathy, and rheumatoid arthritis (42). Because the diving response is an oxygen-conserving response, it is also used as a potential model to study endogenic neuronal protection effects at the molecular level (105, 227). It is also used to teach integrative physiology to students (45).

The diving response can be activated by apnea alone or by facial immersion alone, but their combination enhances the response (4, 11, 42,

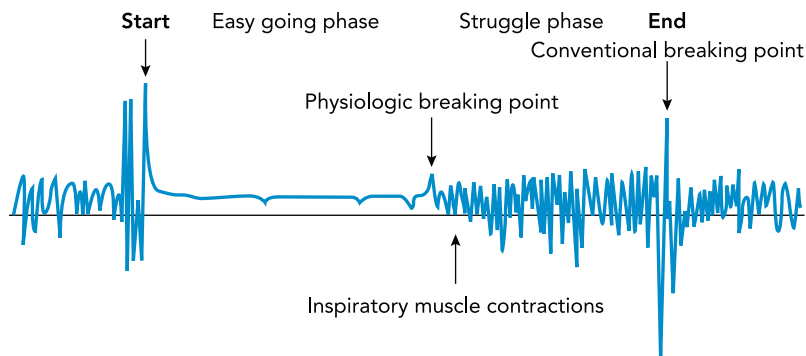


FIGURE 2. Human thoracic movements measured by electromyography (EMG) during maximal breath-holding in an untrained, non-immersed subject
 “Easy going phase” and “struggle phase” are distinguished by the absence or presence of respiratory muscle activity that must be suppressed during breath-holding. Figure is from Ref. 72 and used with permission from Saunders.

45, 97). Most important is the presence of cold water and a large ambient air-to-water temperature gradient (77, 233). The diving response involves simultaneous activation of sympathetic and parasympathetic responses leading to peripheral vasoconstriction, hypertension, and bradycardia (FIGURE 3) (42, 203). Individual papers debate whether apnea, laryngospasm, or contractions of the spleen are part of the response (87, 232). The effects have been consistently observed in studies, with large individual differences. The diving response decreases metabolism selectively, mainly in the vasoconstricted tissues and heart, resulting in an overall decrease in oxygen consumption and a slower desaturation during apnea. This is in contrast to protective hypothermia that decreases the metabolism and oxygen consumption of all organs. The factors that influence the effects of the diving response are summarized in Table 4.

Small involuntary breathing movements during the struggle phase of prolonged apnea do not influence the response in the presence of hypoxia and hypercapnia (9). Animal and human experiments have shown that the sympathetic and parasympathetic components of the diving response can be separately influenced by atropine and va-

Table 3. Factors influencing breath-holding duration in air

Metabolic rate during breath-holding
Prebreathing with hyperoxic or hypoxic gas mixtures
Carbon dioxide and oxygen storage capacity
Prior hyperventilation
Experience and psychological tolerance of unpleasant sensations arising during breath-holding

sodilators. No chemoreceptor influence comes from acidic, asphyxic blood (203). The sympathetic effects, occurring within 10–40 s after cold water touches the face in humans, are affected by input from facial cold-receptors and chemoreceptors. Next comes selective vasoconstriction, with less perfusion measured in the peripheral vascular beds of the skin, muscles, and viscera (9, 77, 102). Metabolism in these organs is decreased, and they shift to anaerobic metabolism, leading to increased lactate. Vasoconstriction causes hypertension (77). Increased carotid artery blood flow and vasodilatation in the brain results in better cerebral perfusion. Brain hypoxia also enhances cerebral perfusion. The result is that the oxygenation of this most oxygen-sensitive organ remains preferentially sustained underwater (38, 126).

Central Nervous System Centers

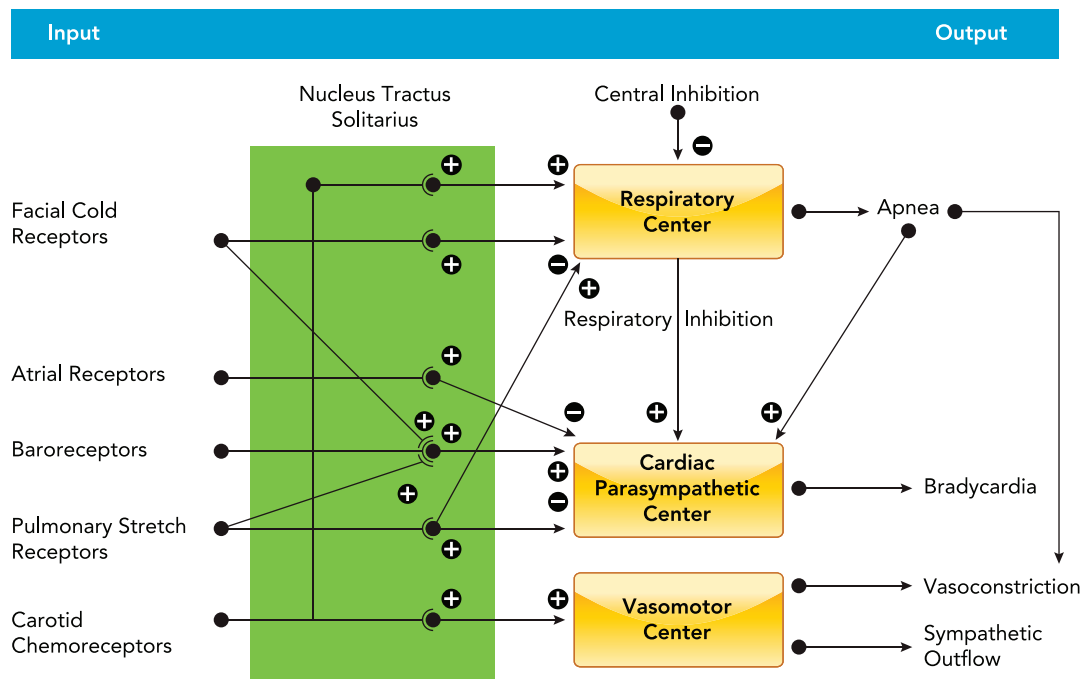


FIGURE 3. Schematic figure of the diving response Input appears on the left and output at the right. In between are the neural connections located in the nucleus tractus solitarius and central nervous system control centers. The response is activated through the chemoreceptor sensitivity of the cold receptors of the skin and the unmyelinated C-fibers of the ophthalmic branch of the nervus trigeminus. For more details on the neurological pathways of the diving response, see also Refs. 162, 199, 226, 234. +, Excitatory neural connections, -, inhibitory neural connections. Figure is from Ref. 77 and used with permission from *Scandinavian Journal of Medicine and Science in Sports*.

Table 4. Factors that increase effects of the diving response (10, 11, 17, 42, 77, 134, 231, 233)

Precooling of the face
Contact of cold material with the face (water, air, cold packs)
Large air/water temperature gradient
Increased hypoxia
Prolonged or deeper submersion
Posture in the water
Smaller vital capacity lung volume
Previous breath-hold diving experiences
A series of repeated apnea dives or apnea exercises
Physical fitness

In addition, the diving response induces, after ~30 s, vagal-mediated bradycardia. Initially, bradycardia is a baroreceptor response due to vasoconstriction and later a chemoreceptor response due to hypoxia. Bradycardia also results from the decreased cardiac output related to decreased oxygen demand in vasoconstricted tissue. Heart rate can decrease to 30–40% of resting levels. During underwater diving competitions, heart rates as low as 20 beats/min have been attributed to the diving response. Bradycardia adds to the oxygen-saving effects through decreased myocardial oxygen consumption (17). The rate-dependent fall in contractility can be counterbalanced by the increase in sympathetic tone. Sometimes ectopic beats occur, either as escape arrhythmias or due to the simultaneous co-activation of the sympathetic and parasympathetic nervous systems. This may result in a vagal cardiac arrest (95, 102, 133).

Human studies with experimental head immersion in cold water and during apneic diving have shown that the diving response decreases oxygen consumption, slows arterial desaturation, and prolongs the duration of breath-holding or diving and the duration before asphyxia becomes life-threatening (9, 77, 134, 137). In the context of drowning, some consider the reflex fantastic physiology, others physiological fantasy.

Apnea and face immersion in cold water, alone or in combination, may occur in some drowning scenarios. Under these circumstances, the diving response may occur. But many drowning scenarios will involve neither voluntary apnea nor cold water. Other mechanisms may also cause interference. For example, when a drowning victim is able to take a full breath before disappearing under water, the increased intrathoracic pressure may result in decreased cardiac output and hypotension (9). Also, the physical effort associated with the predrowning struggle to maintain the airway clear of the water may significantly decrease breath-holding and negate the diving response.

Bradycardia and hypertension may be indicators that the diving response has been active, information rarely available at the rescue site. Therapeutic

interventions at the scene, in the emergency department, and in the intensive care department will limit exploration of the diving response in clinical settings.

Despite these reservations, the possibility remains that the diving response has a role in the prevention of fatal drowning, notably in very young children. It is important to realize that not all persons who engage in the struggle of drowning will experience the physiological processes of a diving mammal or human.

Autonomic Conflict

Interplay between sympathetic and parasympathetic components of the autonomic nervous system has led to the theory of “autonomic conflict” to account for the genesis of cardiac arrhythmias and dysrhythmias (244, 265). Arrhythmias arise due to simultaneous and conflicting positive and negative chronotropic signals to the heart. Human data, and data from isolated hearts, indicate that arrhythmias are most likely to occur in a situation of cyclical vagal stimuli to the heart, for example, with the reinstatement of breathing post-breath-holding, against a background of sympathetic stimulation due to cold, exercise, anger, or anxiety (264) (FIGURE 4).

Arrhythmias are usually observed within 10 s of the cessation of breath-holding. The fact that they occur on cold immersion without face immersion (57) indicates that the release of breath-holding is, in itself, an arrhythmogenic trigger, due to neural responses associated with the release of stimulation of the cardiac vagal neurons. The incidence of an arrhythmia increases further if breath-holding is coincident with submersion in cold water (57, 267). This is probably due to the greater vagal drive seen with face immersion and trigeminal nerve stimulation. This is a powerful pro-arrhythmic stimulus that, on initial immersion, occurs at a time when the QT interval does not match the underlying heart rate, further increasing the likelihood of cardiac arrhythmias (286). Cardiac arrhythmias are predominantly supraventricular and junctional but can include short bursts of ventricular tachycardia interposed between periods of bradycardia, supraventricular ectopic beats, or even atrio-ventricular blocks. Arrhythmias tend to occur when heart rhythm changes from tachycardia (sympathetic predominance) to bradycardia (vagal predominance) (57, 267). The appearance of arrhythmias immediately post-breath-holding on immersion in cold water may also depend on the timing or magnitude of this rhythm in relation to the cessation of breath-holding. While autonomic conflict commonly results in arrhythmias, these descend into fatal arrhythmias much less commonly and probably only in the presence of a

range of predisposing factors that may include ischemic heart disease, long QT, channelopathies, and atherosclerosis (FIGURE 4) (244).

It is possible that arrhythmias caused by cold water submersion could result in death but go undiagnosed, mainly because electrical disturbances to the heart that result in fatal arrhythmias are undetectable postmortem. Also, even if the primary problem on immersion is cardiac, spontaneous terminal gasping may result in water entering the lungs, giving the appearance of drowning.

Upper Airway Reflexes

The upper airway is composed of the nose, pharynx, larynx, and extrathoracic portion of the trachea, and has many reflexes relevant for life, including maintenance of an open airway and airway defense. Mild irritation of the laryngeal mucosa may lead to a laryngeal closure reflex as a protective reflex against materials entering the tracheobronchial tree. Laryngospasm is the closure of the aryepiglottic folds, false vocal cords, and true vocal cords. This reflex responds to direct laryngeal stimulation from secretions, blood, or a foreign body (41, 188–190, 285). Other upper-airway reflexes include the pharyngoglottal closure reflex, esophagoglottal closure reflex, and aerodigestive reflex (65, 243).

During the drowning process, laryngospasm may prevent the entrance of water into the lungs, but this remains controversial. The existence of laryngospasm, also known as glottis spasm, was mentioned in the earliest drowning studies to explain why 10–20% of all dead drowning victims had macroscopically dry lungs (147, 178). Laryngospasm as an explanation for dry lungs seems logical (131). However, dry-drowning and dry-lung have been variably explained not only by laryngospasm but also by vago-vagal cardiac inhibition, pulmonary reflexes, absorption of aspirated fresh water into the circulation, and various reflexes triggered by contact of the body with water (36, 61, 178, 230, 250). Some of these deaths were also labeled “hydrocution” or “atypical drowning” in the early medical literature (288). Critical appraisal of the original literature from the 1930s, as well as clinical observations, has concluded that dry-drowning as result of a laryngospasm is nonexistent. If a laryngospasm may initially have occurred, it will cease to operate as a result of progressive hypoxia of the laryngeal muscles while under water breathing efforts are sustained (178, 194).

Some morphological forensic studies, also using microscopic tracers of the drowning liquid, indicate that penetration of liquid into the lungs occurs in almost all drowning deaths (148), even in those with macroscopically apparent dry-lung. Actually, dry-lungs with no evidence of liquid penetration

can be found only in bodies dumped into water after death on land (148, 178). Mechanisms other than aspiration may, however, also lead to lung changes mimicking liquid aspiration. Case studies describe mild pulmonary edema after swimming, snorkeling, and diving, especially in cold water (144). Subclinical pulmonary edema has resulted from marginal hyperbaric stress under hypoxic conditions (83), from intense exertion by athletic and military swimmers (144) and from an increase in catecholamines due to hypoxemia and stress, leading to pulmonary vascular overload. Another potential mechanism is negative-pressure pulmonary edema caused by extreme negative intrathoracic pressure from inspiration efforts against a

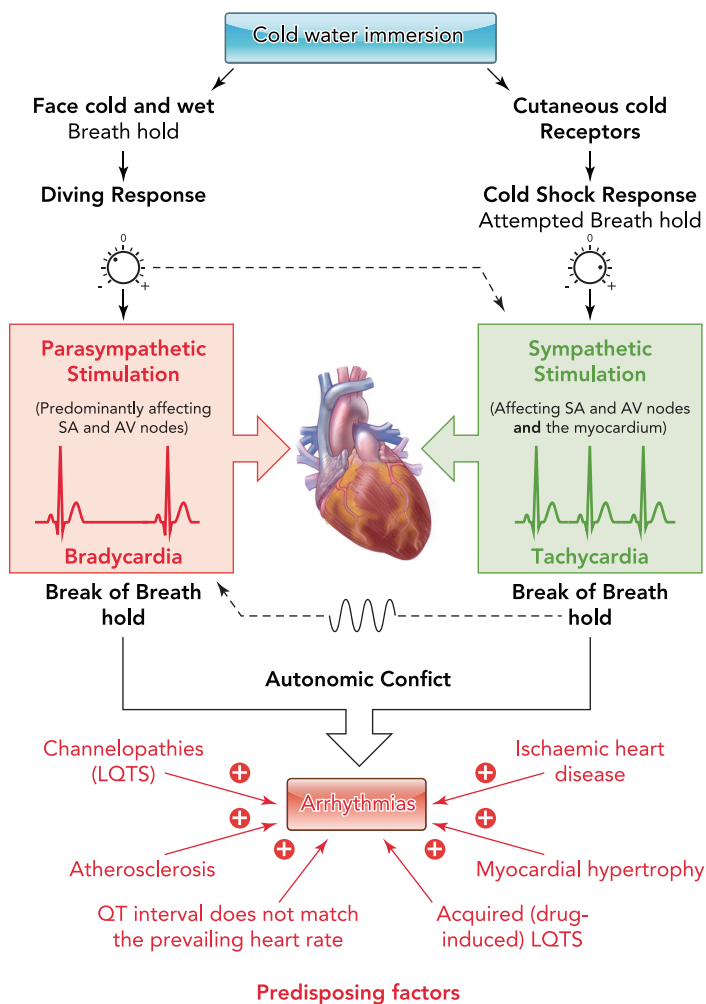


FIGURE 4. Autonomic conflict
Cold-water immersion activates two powerful responses: the diving response (on facial immersion) and the cold shock response (on the activation of cutaneous cold receptors). The magnitudes of these responses can vary with a range of factors including water temperature, clothing, and habituation. The diving response triggers a parasympathetically driven bradycardia, whereas cold shock activates a sympathetically driven tachycardia. It is hypothesized that together these conflicting inputs to the heart can lead to arrhythmias, particularly at the break of breath-hold, which increases parasympathetic tone that varies with respiration. The substrate for arrhythmias is enhanced by various predisposing factors. Figure is from Ref. 244 and used with permission from *The Journal of Physiology*.

closed glottis (60, 184, 279). On the other side, clinical studies report that the majority of drowning resuscitation survivors, whom can be assumed to have been under water for a sustained interval, have no clinically relevant pulmonary complications (76, 274).

One problem in gathering evidence for this debate on upper airway reflexes is that knowledge of laryngeal muscle function is limited. Some information can be extracted from studies on speaking, singing, and swallowing (65, 243, 292). The muscles of the larynx have largely involuntary medulla-mediated tasks during swallowing, breathing, and coughing, and volitional cortex-mediated tasks during speaking and crying for help. For each of its functions, the different vocal-fold movements need rapid and precise control by intrinsic and extrinsic laryngeal muscles. All these muscles can be actively controlled.

Older studies assume that the afferent end-organs in the larynx can respond to pressure, flow, respiratory drive, osmolarity, temperature, and chemical irritants (285). More recent studies on the pharyngoglottal closure reflex, relevant for prevention of food aspiration, show that the laryngeal vocal folds close when water is injected rapidly toward the posterior pharyngeal wall (65, 243). Anatomic coordination exists between the larynx muscles, respiratory reflexes, and cough control through stimulation of the same internal branches of the superior laryngeal nerve (8, 242). Because all four functions of the laryngeal muscles (swallowing water, breathing, coughing, crying for help) are relevant to the drowning process, these muscles must play an active but still poorly studied role in drowning (142).

Although there is on-going discussion about the existence of laryngospasm during drowning, it will only be protective in those few patients where the spasm has been activated and is still active at the moment of rescue from the water.

Aspiration of Water

The lung is an immediately vulnerable target during the drowning process. During laryngospasm, forceful ventilatory movements against a closed glottis may cause mechanical damage. Furthermore, during the drowning process, both hypertonic and hypotonic aspirated liquids cause changes to the pulmonary surfactant and to the alveolocapillary barrier that result in systemic hypoxemia.

Confusion exists about the volume of water aspirated in drowning and how these volumes contribute to respiratory impairment. Speculative extrapolations of data from experimental and post-mortem studies to clinical settings have contributed to this confusion. Aspirated volumes are also

reported in milliliters per pound in some studies and in milliliters per kilogram in others (90, 177, 179, 180).

Hypotonic liquid, when reaching the alveoli, damages and dilutes pulmonary surfactant. The increase in the alveolar surface tension, along with diminution of pulmonary compliance, causes alveolar instability and atelectasis that alters the ventilation-to-perfusion ratio. Because a large part of the lung is not adequately ventilated, more venous blood bypasses the lungs, and the shunt fraction increases. Aspiration of 2.5 ml/kg of sea water causes the pulmonary shunt fraction to increase by 75% (206). Hypotonic fresh water tends to be absorbed into the pulmonary circulation and distributed throughout the body. Aspiration of hypertonic seawater draws liquid from the plasma into the alveoli and also causes damage to surfactant (215). In both situations, the supra-normal hydrostatic forces over the alveolar-capillary membrane will disrupt its integrity. Plasma enters the alveoli, incapacitating normal gas exchange. Plasma in the alveoli may also generate foam that further decreases pulmonary efficiency (147). This results in a local adult respiratory distress syndrome-like clinical picture (85, 92, 176, 274).

Spontaneous ventilation persists after submersion and causes liquid penetration into the lungs. Moreover, terminal shock induced by a variety of natural causes can produce pulmonary stasis and edema mimicking a wet lung indistinguishable from that observed in actual drowning. It is therefore impossible macroscopically or microscopically to assert whether a lung contains or does not contain aspirated liquid. One way to assess, and eventually quantify, the penetration of drowning liquid into the lungs is to study the presence of microscopic tracers of the drowning liquid (147).

Swallowing of Water

Swallowing water during the drowning process may increase the risk for vomiting, spontaneously or during resuscitation, eventually leading to aspiration of gastric content. Swallowing water may also contribute to life-threatening electrolyte disorders.

Under normal conditions, the process of swallowing liquid includes an oral phase, a pharyngeal phase, and an esophageal phase (69, 160, 174, 252). Swallowing is triggered by cortical inputs integrated into the swallowing central pattern generator (SCPG) of the brain stem (69, 70, 115, 129, 174). The SCPG sends efferent innervations to over 30 muscles involved in swallowing. Afferent pathways originate from chemical or mechanical receptors in the upper-airway mucosa and from lung and intercostal muscles. Information is conveyed via

cranial nerves V, IX, and X to the brain stem and the nucleus tractus solitarius. The main efferent pathways are via the ambiguous and hypoglossal nuclei (XII) (189).

Coordination between breathing and swallowing prevents liquid aspiration (189). During swallowing, elevation of the soft palate, tilting of the epiglottis, and SCPG-mediated inhibition of airway reflexes interrupt respiration for 0.5–1.5 s during the inspiration-expiration transition or the expiratory phase (37, 63, 127, 190, 205, 240).

During drowning, swallowing of liquid usually occurs during partial head-out immersion or during breath-holding (see *Sympathetic Activation, Fear of Drowning* above). Under these circumstances, active and passive swallowing differ from the normal physiological processes (56). Uncontrolled premature entry of liquid into the pharynx can cause aspiration and swallowing, accentuated by a cough reflex. Stress, increased P_{CO_2} , decreased P_{O_2} , respiratory- and lung-volume changes, and unconsciousness hamper coordination between swallowing and respiration may cause swallowing during inspiratory and expiratory phases, with a consequent risk for aspiration (123, 124, 173, 188–190, 223).

Water swallowing during drowning has long been a subject of investigation (71, 218), but with little high-quality data. Experiments in the 1970s in rats, when electrolyte disorders were considered important for drowning outcome, suggested that the ratio of aspirated to swallowed liquid differed between fresh (1:1) and salt water (1:3) (58). The relevance of this to conscious humans is unknown.

Some authors maintain that drowning victims swallow much more water than they inhale (195). At this moment, autopsy data are still inconclusive (141, 230). Based on one of the author's (P. Lunetta) investigation of over 2,000 fatal drownings, the stomach of a drowning victim is either empty, or contains watery fluid, liquid mixed with food, or exclusively food. Postmortem liquid penetration into the stomach or its leakage into the small intestine impedes reliable prospective studies. Presence of water-borne particles in the stomach, such as plankton, is also not conclusive, because they can penetrate postmortem or can be present in food and beverages consumed before the incident (101, 146, 290). One postmortem computerized tomography (CT) study on 28 retrieved drowning bodies revealed gastric distension in 89%, but high-attenuation sediment in only 21% (135). Another series of 10 fatal fresh-water drowning cases examined by postmortem CT, reported a gastric volume ranging from 50 to 1,200 ml, with an average density of gastric contents less than the control group (49). Although some drowning victims clearly have swallowed water, data are limited as to

the incidence and clinical relevance, and whether differences exist between fatal and non-fatal drowning.

Emesis

Detailed data on the occurrence of emesis in drowning are also lacking. One study, reported 25–60% of drowning victims vomited (151). Another study revealed that emesis occurred in 86% of drowning victims who required cardiopulmonary resuscitation and in 50% of those who required no intervention (154). Autopsy series have disclosed aspiration of gastric contents in 24% of drowning victims (80). In a large series on out-of-hospital cardiac arrest (CA) with a cardiac and non-cardiac etiology, emesis occurred in 30–35% of all patients (247). The trigger can be the condition underlying the arrest, CA itself, gastric distension caused by artificial ventilation, or improper chest compression that increases intra-abdominal pressure.

The main vagal sensory afferents responsible for emesis originate from mechano-, osmo-, and chemoreceptors activated by gastric distension or mucosal irritation (14, 21). Mucosal chemoreceptors in the stomach can be stimulated by hydrochlorides or hypertonic saline (13). These afferents relay information to the nucleus tractus solitarius and then to the medulla oblongata, where a neural network (central pattern generator) coordinates the efferent response (21, 110). This integration area receives afferents also from the cerebral cortex, the vestibular region, and a chemoreceptor trigger zone located between the medulla and the floor of the fourth ventricle. The chemoreceptor trigger zone detects, within the blood, emetic stimulants, including hypoxia and ketoacidosis. The efferent motor pathways innervate the upper gastrointestinal tract via cranial nerves V, VII, IX, X, and XII, the diaphragm and abdominal muscles via spinal nerves (21, 26, 110).

Emesis includes retroperistaltic activity from the small intestine, relaxation of the pyloric sphincter, downward contraction of the diaphragm with decreased intrathoracic pressure, increase in intra-abdominal pressure, contraction of the abdominal wall muscles, squeezing and contraction of the stomach with elevation of intragastric pressure and closure of the pylorus, relaxation of the esophageal sphincter, and expulsion of gastric contents (130, 172). The extent to which these classical reflex mechanisms explain emesis in drowning is undefined.

During drowning, gastric contents can be aspirated into the airways, resulting in pulmonary infection and chemical irritation (68, 274). Emesis can also interfere with pulmonary resuscitation. In drowning, both vomiting and cardiopulmonary resuscitation may cause gastric mucosal tears, the

frequency of which varies widely among studies but has been detected in as many as 21% of patients (15, 33, 55, 145).

Electrolyte Disorders

Experiments during the 1940s and 1950s have long influenced the concepts of drowning pathophysiology (254–256). These experiments stressed the role of liquid osmolarity in drowning, especially the penetration of hypotonic liquid into the circulation, causing hypervolemia, erythrocyte hemolysis, intravascular potassium release, and subsequent VF. Studies beginning during the 1960s (179, 180) suggested that the volume of aspirated water rather than its osmolarity is the critical factor. Pathophysiological differences between freshwater or saltwater drowning are observable in experimental models. However, in most drowning victims, serum electrolyte changes are of limited importance because liquid redistribution within the body rapidly restores electrolyte balance. Hypo- and hypertonic liquid cause a ventilation/perfusion shift and hypoxemia and metabolic acidosis. These, in turn, cause myocardial depression, pulmonary vasoconstriction, and changes in capillary permeability that worsen pulmonary edema (148). The final common pathway is hypoxemia.

In most environments, drowning is not associated with clinically important electrolyte changes. When such changes do occur, it can be impossible to disentangle the roles of ingestion and aspiration (136). The small intestine absorbs ~80% of ingested liquid via concentration gradients and complex molecular mechanisms (84). When seawater reaches the small intestine, sodium moves mainly through the jejunal mucosal cells of the villi into capillaries. Water diffusion follows the osmotic gradient (245).

In sporadic cases, such as in protracted immersion while wearing a malfunctioning or poorly designed lifejacket, sea-water ingestion following the breath-holding breaking-point directly causes hypernatremia (67). Serum sodium concentrations higher than 145 mM have occurred in pediatric drownings (111). Chlorine ions may also pass the intestinal barrier by concentration gradient, causing metabolic acidosis (67, 111). In specific environments such as the Dead Sea, with its high magnesium and calcium concentration, ingestion of as little as 200 ml may have a significant clinical impact (136). Conversely, swallowing hypotonic liquid thus far has not been reported to result in water intoxication, although swallowing fresh water can cause hyponatremia, especially in children (287).

Electrolyte disorders have been considered a major factor in drowning mortality previously.

Current studies suggest that this only occurs in exceptional circumstances.

Neurophysiology

The cerebral physiological response to drowning is poorly understood but is most likely an interaction between hypoxemia, submersion liquid temperature, aspiration, and cold shock. Most information pertaining to cerebral physiological responses to drowning is derived from experimental models simulating CA, which may not be directly relevant. Cardiogenic VF causes abrupt cessation of oxygenated cerebral blood flow (CBF). Asphyxia, in contrast, causes progressive cerebral hypoxia that precedes CA. Antecedent hypoxemia aggravates injury associated with asphyxial CA. In canines, a shorter interval of normothermic asphyxia-induced CA causes more severe injury than an even longer interval of VF CA (271).

A critical event in drowning is loss of consciousness (LOC). This is often attributed to asphyxia following submersion, loss of pulmonary oxygen uptake, brain energy failure, and deterioration of brain function. Hypoxemia in normothermic healthy humans causes an initial cerebral vasodilatory response to preserve oxygen delivery (3). Progressive hypoxemia leads to a depletion of high-energy phosphates and loss of electrocortical activity consistent with LOC (171). The duration of this state defines the severity of injury and reversibility of neurological dysfunction.

The CBF response to sudden cold-water immersion may be adverse. Healthy humans suddenly immersed in 0°C fresh water were monitored with transcranial Doppler (156). In untrained subjects, CBF rapidly decreased by ~50% from normal, followed by loss of sensorium necessary for self-rescue. Immersion also causes hyperventilation at a magnitude consistent with the known depressant effects of hypocapnia on CBF and mental status (122). Respiratory cold-shock responses, alone, may be sufficient to precipitate LOC, later complicated by submersion and asphyxia. Trained suppression of hyperventilation or habituation to cold prevents the CBF decrease and need for rescue (157). Hence, conscious suppression of hyperventilation in cold water may be beneficial in prolonging duration to LOC so as to aid in brain cooling before submersion.

The brain's tolerance to energy deprivation is closely associated with brain temperature (170). Brain cooling before asphyxial CA is important to submersion outcome (46, 86, 246). In the rat, deep hypothermia induced by submersion during an otherwise lethal asphyxial insult is profoundly protective, but only if core temperature decreases rapidly (283). Brain cooling in humans depends on several factors. Surface cooling of the head alone

has little effect (168). At the same time, in oxygenated humans, submersion of the head with the rest of the body accelerates the rate of core cooling by 56% (212). Circulatory function is necessary to rapidly decrease brain temperature. After LOC from asphyxia, hypothermia, or cold shock, ventricular contractions may or may not persist to provide additional brain cooling (143).

Deep hypothermic CA, employed for some surgical procedures, may offer insight into neuroprotective physiology in drowning. Brain cooling is dependent on blood flow, perfusate temperature, and cooling duration (150). Use of pH-stat control of carbon dioxide tension accelerates cooling by allowing cerebral vasodilation (128), but no opportunity for this exists in drowning. Hence, progressive brain cooling would be expected to decrease CBF proportionate to increased blood carbon dioxide solubility and a coupled decrease in cerebral metabolic rate (54, 204). The balance between these factors and water temperature likely defines the speed and depth of brain cooling during immersion and tolerance of hypoxemia.

Pulmonary aspiration may aid brain survival due to cooling of blood flowing past aspirated cold water (289). Lightly anesthetized, spontaneously breathing dogs were submerged in 4°C water with an open airway allowing aspiration (51). In controls with endotracheal tube protected airways, aspiration was prevented. Carotid blood temperature in those dogs with an open airway decreased to 29°C within 2 min, followed by a decrease in respiratory rate. Carotid blood temperature in controls decreased to only 36°C. Delivery of 29°C blood to the brain is sufficient to suppress consciousness (74) but also elevates cellular tolerance to anoxia. Trauma or use of drugs before submersion may affect any of these mechanisms.

Regardless of cause, a sustained decrease in oxygen delivery causes brain energy metabolism failure, inhibited protein synthesis (201), ATP depletion (171), loss of synaptic neurotransmission (204), oxidative stress (281), ionic gradient deterioration (20), and initiation of intracellular cascades leading to apoptosis, autophagy, or necrosis of neurons and glia (214). Little information is available to distinguish neuropathological responses induced by asphyxial vs. cardiogenic CA. Most data are derived from simulated VF arrest models where vulnerability of brain cell types to deprivation is selective. Hippocampal CA1 pyramidal neurons and cerebellar Purkinje cells are particularly sensitive (125, 209). More severe insults produce wider morphological and functional damage (248).

Many drowning victims survive, sometimes for decades, with permanent brain damage (31, 192,

224, 272, 276). Among the physiological mechanisms activated during drowning, the neurophysiological responses are vital, and their improved understanding is essential to advance intervention success (270).

Future Research

Awareness has been growing that drowning constitutes a neglected epidemic (28, 164). Because 90% of drownings occur in low- and middle-income countries (138), preventative community measures are likely to have the greatest impact (139, 216).

In this review, 14 different physiological mechanisms of drowning have been described. Each of them may play a role in drowning. A decrease in fatal and nonfatal drownings may also be achieved by a better understanding of drowning physiology.

Studies that will result in a better understanding of the mechanisms of hot water immersion, cold shock, cold-induced physical incapacitation, and fear of drowning may contribute to prevention of drowning where these mechanisms play a role. A better understanding of the physiological mechanisms of deep tissue cooling, water aspiration, hypoxic cardiac arrest, and neurophysiology may contribute to better treatment options and outcome. Better knowledge of the physiology of drowning is also crucial in forensic pathology for: interpretation of events leading to death by drowning; assessment of medical liabilities in fatal incidents; and analysis of postmortem findings. Research on breath-holding, diving response, upper airway reflexes, and autonomic conflict in drowning settings can be used as models for physiology studies. Based on these assumptions, research directives are suggested.

Research That May Help to Prevent Drowning

Hot water immersion. A large case-control study in different age groups, especially the elderly with preexisting cardiac disease, would determine whether there is an actual excess mortality during hot water bathing and its accompanying risk factors. Focused postmortem investigations can better define cause of death. Studies in human volunteers are required to define the cardiovascular effects of hot water immersion and ambient temperature.

Cold shock. A more detailed understanding of the neurophysiological pathways associated with cold shock is needed, including the relationship between surface area exposed to cold water and the magnitude of the cold-shock response. Some methods of mitigating the dangers associated with cold shock are known, but others, such as pharma-

ological interventions, remain to be investigated. The cold-shock response has undergone little study in children or the elderly. Current knowledge is largely derived from 18- to 39-yr-old subjects studied in the laboratory.

Superficial tissue cooling. The cellular and biomolecular physiology of impaired neuromuscular function during cooling requires investigation. Physical incapacitation is a major threat associated with immersion in cold water and a common precursor to drowning.

Fear of drowning. The lay community indicates this is a phenomenon that has not been appreciated by the medical and scientific community. The physiological and psychological substrates need further study, which may decrease drowning in experienced and inexperienced swimmers.

Research That May Help to Improve Treatment and Outcome of Drowning

Deep tissue cooling. Rewarming methodologies and devices need systematic appraisal of physiological and clinical efficacy in profoundly hypothermic victims.

Aspiration of water. Data from forensic and clinical studies on the frequency, severity, and clinical consequences of aspiration during and after drowning are conflicting and require more investigation. Understanding of the role of aspiration of water may be important in decision making such as: 1) When should a drowning victim be allowed to return home from the beach or the emergency department? 2) Which drowning victims may or may not benefit from extracorporeal membrane oxygenation? Studies should define the contribution of respiratory failure to drowning mortality.

Hypoxic cardiac arrest. Cardiac arrest after drowning is different from cardiogenic cardiac arrest. Immediate post-rescue data are needed to understand heart function between the moments of submersion and the onset of cardiac arrest. This information will inform whether resuscitation after drowning requires different skills or different application of skills. More knowledge is required pertaining to the effects of cardiac compressions on a hypoxic, hypothermic, and acidotic, but still working, heart.

Neurophysiology. Case reports have indicated excellent neurological outcomes from drowning (66, 93, 116, 143, 225, 253, 277). It is now evident that long-term, often disabling, cognitive deficits remain (253, 276). Comprehensive investigation into the nature of persistent cognitive deficits in drowning survivors may serve to inform study of mechanisms of injury and interventions specifically relevant to this population.

Most molecular and cellular biology associated with CNS injury in drowning has been extrapolated

from cardiogenic CA or experimental acute disruption of global CBF. CA preceded by anoxia differs markedly from abrupt flow cessation in both severity and recovery (271). Thus CNS research specific to drowning is necessary.

The largest impediment to this is availability of a reliable, highly characterized preclinical CNS-specific drowning recovery model. Emphasis on developing a model is paramount, as is defining confounding influences of requisite anesthetics. Drowning-specific models will allow increased understanding of CNS effects of and interactions among cold shock, autonomic conflict, aspiration and swallowing, temperature, electrolytes, and anoxia. Such understanding will allow investigation into improved CNS resuscitation techniques for drowning. Transfer of knowledge gained from the large body of research already focused on treatment of cardiac arrest, traumatic brain injury, and stroke may then be evaluated specifically in the context of drowning to define relevance and potential for clinical advance. Efficacious therapeutic and preventive concepts will emerge only when the basic injury mechanisms are better understood and preclinical therapeutic efficacy is rigorously characterized (280).

Studies That May Help the Forensic Investigations of Drowning

Aspiration and swallowing of the drowning media. Quantitative postmortem studies on the penetration of water-borne exogenous substances (such as planktonic elements, pollutants, electrolytes) in the lung, circulation, and internal organs of victims of drowning can assist the postmortem diagnosis of drowning. Moreover they may provide more accurate estimates of the volume of drowning liquid being aspirated and/or swallowed during the drowning process. First, diagnostic values of the substance concentrations found in victims with verified fatal drowning vs. non-drowning deaths should be defined to discriminate antemortem from agonal penetration or, even, ante- or postmortem contamination. Then, such values can be assessed in a range of drowning situations characterized by factors that may affect the duration of the drowning process; for instance, an acute cardiac event, alcohol or other drug intoxication, or preexisting disease. Assessment of the original concentration of such substances in the drowning media, at the site of drowning, is a prerequisite for such studies.

Postmortem changes of serum electrolyte concentrations in the organism resulting from penetration of the drowning liquid should be further assessed as a function of the duration of the drowning process and the tonicity of the drowning media. A major challenge for future studies re-

mains the discrimination between actual antemortem changes and those occurring postmortem as a result of the decomposition process and the prolonged contact of the body with the water. Research on cellular and molecular changes and markers associated with drowning should focus on those occurring during the short time frame of the drowning process. Control groups of non-drowned individuals who died on dry land and were subsequently disposed in water are vital for such studies.

Comprehensive postmortem investigations, including molecular testing and toxicology tested against controls, should clarify the actual role and pathophysiological mechanisms of preexisting diseases or acute conditions (e.g., arrhythmogenic gene mutations, cardiac disease, alcohol and drug intoxication) for drowning in different settings.

Physiology Studies

Breath-holding. The physiology of breath-holding is well understood. From a drowning perspective, what is less understood is what happens at the break of breath-hold in a submerged individual. How much water enters the stomach, and how much enters the lung? What volumes and conditions are required to produce incapacitation or laryngeal spasm? The answer to these questions is of importance but necessitates (ethically problematic) experimental studies.

Diving response. When detectable substrates of the vagal response can be identified, such markers of parasympathetic activity may be clinically relevant.

Upper airway reflexes. Further studies in this field may help to better understand when and why laryngospasm may or may not occur during drowning and whether the upper airway reflexes affect drowning mortality and morbidity.

Autonomic conflict. It has been relatively straightforward to produce arrhythmias and dysrhythmias in healthy, young humans following breath-holding submersions in cold water. It has proved more difficult to model this in other settings. Thus, although autonomic conflict may produce arrhythmias, as yet, it has not yet been possible to determine what turns these benign arrhythmias into more dangerous waveforms. A model of autonomic conflict will allow precursors that cause the descent from benign to fatal arrhythmias to be identified.

Conclusion

Immersion and submersion, the two entities of drowning, interact with basic physiological factors: temperature and oxygen. Little is known about these mechanisms when they occur under the extreme and lethal circumstances that result in

drowning. Few studies reveal how these mechanisms interact, whether directly or indirectly, and how they are influenced by autonomous protective (diving response, breath-holding, acute hypothermia) and life-threatening (cold shock, autonomic conflict, aspiration) responses.

The theories to explain how drowning happens via these mechanisms have been taken for granted for several decades. A critical appraisal, based on current understanding and knowledge, suggests that little is definitively known about the pathophysiological events associated with drowning. Such knowledge is not just of academic interest; it can guide in preventative measures, assist in the clinical treatment of drowning fatalities, and aid in forensic studies. Increased appreciation of the prevalence of drowning-related death should foster major research efforts specific to this population. ■

No conflicts of interest, financial or otherwise, are declared by the author(s). The intellectual conflict of interest is that Joost Bierens is the honorary consultant to the Maatschappij tot Redding van Drenkelingen, the Society to Rescue People from Drowning, established in 1767, which aims to reduce drowning fatalities.

Author contributions: J.J.L.M.B. conception and design of research; J.J.L.M.B., M.J.T., P.L., and D.W. drafted manuscript; J.J.L.M.B., M.J.T., P.L., and D.W. edited and revised manuscript; J.J.L.M.B., M.J.T., P.L., and D.W. approved final version of manuscript; M.J.T. prepared figures.

References

1. Abe H, Ritsuko R, Oginosawa Y. Reflex syncope during a hot bath as a specific cause of drowning in Japan. *J Arrhythmia* 29: 37–38, 2013.
2. Aihara H, Aihara M. Medical and sociological study of death during bathing (Online). <http://www.medline.ru/public/sudm/a2/art3-2-1.phtml> [September 20, 2015].
3. Ainslie PN, Shaw AD, Smith KJ, Willie CK, Ikeda K, Graham J, Macleod DB. Stability of cerebral metabolism and substrate availability in humans during hypoxia and hyperoxia. *Clin Sci (Lond)* 126: 661–670, 2014.
4. Alboni P, Alboni M, Gianfranchi L. Diving bradycardia: a mechanism of defence against hypoxic damage. *J Cardiovasc Med (Hagerstown)* 12: 422–427, 2011.
5. Alexander L. *The Treatment of Shock From Prolonged Exposure to Cold, Especially in Water*. London, UK: Combined Intelligence Objectives Sub-committee A. P. O. 413 C105, Item No. 24, HMSO, 1945.
7. Allison TG, Reger WE. Comparison of responses of men to immersion in circulating water at 40.0 and 41.5 degrees C. *Aviat Space Environ Med* 69: 845–850, 1998.
8. Ambalavanar R, Tanaka Y, Selbie WS, Ludlow CL. Neuronal activation in the medulla oblongata during selective elicitation of the laryngeal adductor response. *J Neurophysiol* 92: 2920–2932, 2004.
9. Andersson J, Schagatay E. Effects of lung volume and involuntary breathing movements on the human diving response. *Eur J Appl Physiol Occup Physiol* 77: 19–24, 1998.
10. Andersson JP, Liner MH, Fredsted A, Schagatay EK. Cardiovascular and respiratory responses to apneas with and without face immersion in exercising humans. *J Appl Physiol* 96: 1005–1010, 2004.

11. Andersson JP, Liner MH, Runow E, Schagatay EK. Diving response and arterial oxygen saturation during apnea and exercise in breath-hold divers. *J Appl Physiol* 93: 882–886, 2002.
12. Andjus RK. Effect of hypothermia on the kidney. In: *The Physiology of Induced Hypothermia*, edited by Dripps RD. Washington, DC: National Academy of Sciences, National Research Council, 1956, p. 214–220.
13. Andrews PL, Davis CJ, Bingham S, Davidson HI, Hawthorn J, Maskell L. The abdominal visceral innervation and the emetic reflex: pathways, pharmacology, and plasticity. *Can J Physiol Pharmacol* 68: 325–345, 1990.
14. Andrews PL, Horn CC. Signals for nausea and emesis: implications for models of upper gastrointestinal diseases. *Auton Neurosci* 125: 100–115, 2006.
15. Anthony PP, Tattersfield AE. Gastric mucosal lacerations after cardiac resuscitation. *Br Heart J* 31: 72–75, 1969.
16. Arborelius M Jr, Ballidin UI, Lilja B, Lundgren CE. Hemodynamic changes in man during immersion with the head above water. *Aerospace Med* 43: 592–598, 1972.
17. Argacha JF, Xhaet O, Gujic M, De Boeck G, Dreyfuss C, Lamotte M, Adamopoulos D, van de Borne P. Facial cooling and peripheral chemoreflex mechanisms in humans. *Acta Physiol (Oxf)* 194: 161–170, 2008.
18. Aslam AF, Aslam AK, Vasavada BC, Khan IA. Hypothermia: evaluation, electrocardiographic manifestations, management. *Am J Med* 119: 297–301, 2006.
19. Associated Press. Polish toddler found in freezing cold recovering (Online). <http://www.dailymail.co.uk/wires/ap/article-2860488/Polish-boy-freezing-cold-recovering.html> [September 24, 2015].
20. Astrup J, Symon L, Branston NM, Lassen NA. Cortical evoked potential and extracellular K⁺ and H⁺ at critical levels of brain ischemia. *Stroke* 8: 51–57, 1977.
21. Babic T, Browning KN. The role of vagal neurocircuits in the regulation of nausea and vomiting. *Eur J Pharmacol* 722: 38–47, 2014.
22. Basbaum CB. Induced hypothermia in peripheral nerve: electron microscopic and electrophysiological observations. *J Neurocytol* 2: 171–187, 1973.
23. Baum D, Dillard DH, Porte D Jr. Inhibition of insulin release in infants undergoing deep hypothermic cardiovascular surgery. *N Engl J Med* 279: 1309–1314, 1968.
24. Bebek N, Gurses C, Gokyigit A, Baykan B, Ozkara C, Derwent A. Hot water epilepsy: clinical and electrophysiologic findings based on 21 cases. *Epilepsia* 42: 1180–1184, 2001.
25. Becker BE. Aquatic therapy: scientific foundations and clinical rehabilitation applications. *PMR* 1: 859–872, 2009.
26. Becker DE. Nausea, vomiting, and hiccups: a review of mechanisms and treatment. *Anesth Prog* 57: 150–156; quiz 157, 2010.
27. Bergh U, Ekblom B. Influence of muscle temperature on maximal muscle strength and power output in human skeletal muscles. *Acta Physiol Scand* 107: 33–37, 1979.
28. Bierens JJ, Knape H. The World Congress on Drowning: A move towards the future. In: *Handbook on Drowning, Prevention, Rescue, Treatment*, edited by Bierens JJ. Berlin, Germany: Springer Verlag, 2006, p. 21–37.
29. Bierens JJ, Knape JT, Gelissen HP. Drowning. *Curr Opin Crit Care* 8: 578–586, 2002.
30. Bierens JJ, Uitslager R, Swenne-van Ingen MM, van Stiphout WA, Knape JT. Accidental hypothermia: incidence, risk factors and clinical course of patients admitted to hospital. *Eur J Emerg Med* 2: 38–46, 1995.
31. Bierens JJ, Warner DS. Drowning resuscitation requires another state of mind. *Resuscitation* 84: 1467–1469, 2013.
32. Blair E. Physiologic and metabolic effects of hypothermia in man. In: *Depressed Metabolism, Proceedings of the First International Conference on Depressed Metabolism, Washington (August 1968)*, edited by Musacchia XJ, Saunders JF. New York: Elsevier, 1969.
33. Blanco Pampin J, Garcia Rivero SA, Tamayo NM, Hinojal Fonseca R. Gastric mucosa lesions in drowning: its usefulness in forensic pathology. *Leg Med* 7: 89–95, 2005.
34. Bonde-Petersen F, Schultz-Pedersen L, Dragsted N. Peripheral and central blood flow in man during cold, thermoneutral, and hot water immersion. *Aviat Space Environ Med* 63: 346–350, 1992.
35. Brauer RW, Holloway RJ, Krebs JS, Leong GF, Carroll HW. The liver in hypothermia. *Ann NY Acad Sci* 80: 395–423, 1959.
36. Brinkmann B. Tod im Wasser. In: *Handbuch Gerichtliche Medizin*, edited by Brinkmann B, Madea B. Berlin, Germany: Springer, 2004, p. 797–824.
37. Broussard DL, Altschuler SM. Central integration of swallow and airway-protective reflexes. *Am J Med* 108, Suppl 4a: 625–675, 2000.
38. Brown CM, Sanya EO, Hilz MJ. Effect of cold face stimulation on cerebral blood flow in humans. *Brain Res Bull* 61: 81–86, 2003.
39. Brown D. Deaths in triathlons may not be so mysterious; panic attacks may be to blame (Online). https://www.washingtonpost.com/national/health-science/deaths-in-triathlons-may-not-be-so-mysterious-panic-attacks-may-be-to-blame/2011/10/24/gQA70NrKnK_story.html [September 24, 2015].
40. Campero M, Serra J, Ochoa JL. C-polymodal nociceptors activated by noxious low temperature in human skin. *J Physiol* 497: 565–572, 1996.
41. Caranza R, Nandwani N, Tring JP, Thompson JP, Smith G. Upper airway reflex sensitivity following general anaesthesia for day-case surgery. *Anaesthesia* 55: 367–370, 2000.
42. Caspers C, Cleveland S, Schipke JD. Diving reflex: can the time course of heart rate reduction be quantified? *Scand J Med Sci Sports* 21: 18–31, 2011.
43. Castellani JW, Tipton MJ. Cold stress effects on exposure tolerance and exercise performance. *Compr Physiol* 6: 443–469, 2016.
44. Chiba T, Yamauchi M, Nishida N, Kaneko T, Yoshizaki K, Yoshioka N. Risk factors of sudden death in the Japanese hot bath in the senior population. *Forensic Sci Int* 149: 151–158, 2005.
45. Choate JK, Denton KM, Evans RG, Hodgson Y. Using stimulation of the diving reflex in humans to teach integrative physiology. *Adv Physiol Educ* 38: 355–365, 2014.
46. Chochinov AH, Baydock BM, Bristow GK, Giesbrecht GG. Recovery of a 62-year-old man from prolonged cold water submersion. *Ann Emerg Med* 31: 127–131, 1998.
47. Chotyanonta JS, Dinovo KM, McCulloch PF. Bilateral sectioning of the anterior ethmoidal nerves does not eliminate the diving response in voluntarily diving rats. *Physiol Rep* 1: e00141, 2013.
48. Choukroun ML, Varenne P. Adjustments in oxygen transport during head-out immersion in water at different temperatures. *J Appl Physiol* 68: 1475–1480, 1990.
49. Christie A, Aghayev E, Jackowski C, Thali MJ, Vock P. Drowning: post-mortem imaging findings by computed tomography. *Eur Radiol* 18: 283–290, 2008.
50. Clarke RS, Hellon RF, Lind AR. The duration of sustained contractions of the human forearm at different muscle temperatures. *J Physiol* 143: 454–473, 1958.
51. Conn AW, Miyasaka K, Katayama M, Fujita M, Orima H, Barker G, Bohn D. A canine study of cold water drowning in fresh versus salt water. *Crit Care Med* 23: 2029–2037, 1995.
52. Cooper KE, Ross KN. *Hypothermia in Surgical Practice*. London, UK: Cassel & Co., 1960.
53. Craig AB Jr, Dvorak M. Thermal regulation during water immersion. *J Appl Physiol* 21: 1577–1585, 1966.
54. Croughwell N, Smith LR, Quill T, Newman M, Greeley W, Kern F, Lu J, Reves JG. The effect of temperature on cerebral metabolism and blood flow in adults during cardiopulmonary bypass. *J Thorac Cardiovasc Surg* 103: 549–554, 1992.
55. Da Broi U, Moreschi C, Castellani M, Antonella B. Gastric mucosal tears and wall micro perforations after cardiopulmonary resuscitation in a drowning case. *J Forensic Leg Med* 16: 24–26, 2009.
56. Daniels SK, Foundas AL. Swallowing physiology of sequential straw drinking. *Dysphagia* 16: 176–182, 2001.
57. Datta A, Tipton M. Respiratory responses to cold water immersion: neural pathways, interactions, and clinical consequences awake and asleep. *J Appl Physiol* 100: 2057–2064, 2006.
58. de Boer J, Biewenga TJ, Kuipers HA, den Otter G. The effects of aspirated and swallowed water in drowning: sea-water and fresh-water experiments on rats and dogs. *Anesthesiology* 32: 51–59, 1970.
59. De Jesus PV, Hausmanowa-Petrusewicz I, Barchi RL. The effect of cold on nerve conduction of human slow and fast nerve fibers. *Neurology* 23: 1182–1189, 1973.
60. Deisering LF, Douglass DA. Post-laryngospasm pulmonary edema. *AANA J* 56: 246–248, 1988.
61. DiMaio DJ, DiMaio VJM. *Forensic Pathology*. Boca Raton, FL: CRC Press, 1993.
62. Douglas WW, Malcolm JL. The effect of localized cooling on conduction in cat nerves. *J Physiol* 130: 53–71, 1955.
63. Dozier TS, Brodsky MB, Michel Y, Walters BC Jr, Martin-Harris B. Coordination of swallowing and respiration in normal sequential cup swallows. *Laryngoscope* 116: 1489–1493, 2006.
64. Drinkwater E. Effects of peripheral cooling on characteristics of local muscle. *Med Sport Sci* 53: 74–88, 2008.
65. Dua K, Surapaneni SN, Kuribayashi S, Hafeezullah M, Shaker R. Pharyngeal airway protective reflexes are triggered before the maximum volume of fluid that the hypopharynx can safely hold is exceeded. *Am J Physiol Gastrointest Liver Physiol* 301: G197–G202, 2011.
66. Eich C, Brauer A, Kettler D. Recovery of a hypothermic drowned child after resuscitation with cardiopulmonary bypass followed by prolonged extracorporeal membrane oxygenation. *Resuscitation* 67: 145–148, 2005.
67. Ellis RJ. Severe hypernatremia from sea water ingestion during near-drowning in a hurricane. *West J Med* 167: 430–433, 1997.
68. Ender PT, Dolan MJ. Pneumonia associated with near-drowning. *Clin Infect Dis* 25: 896–907, 1997.
69. Ertekin C. Voluntary versus spontaneous swallowing in man. *Dysphagia* 26: 183–192, 2011.

70. Ertekin C, Aydogdu I. Neurophysiology of swallowing. *Clin Neurophysiol* 114: 2226–2244, 2003.
71. Fagerlund LW. *Om Drunknoingsvätskas Inträngande I Tarmarna*. Helsingfors, Finland: J. C. Frenckell & Son, 1888.
72. Ferigno M, Lundgren CE. Breath hold diving. In: *Bennett & Elliott's Physiology and Medicine of Diving*, edited by Brubakk A, Neuman T. Philadelphia: Saunders, 2003, p. 153–180.
73. Ferris EB, Engel GL, Stevens CD, Webb Voluntary Breathholding J. Iii. The relation of the maximum time of breathholding to the oxygen and carbon dioxide tensions of arterial blood, with a note on its clinical and physiological significance. *J Clin Invest* 25: 734–743, 1946.
74. Fischbeck KH, Simon RP. Neurological manifestations of accidental hypothermia. *Ann Neurol* 10: 384–387, 1981.
75. Fleming PR, Muir FH. Electrocardiographic changes in induced hypothermia in man. *Br Heart J* 19: 59–66, 1957.
76. Forler J, Carsin A, Arlaud K, Bosdure E, Viard L, Paut O, Camboulives J, Dubus JC. [Respiratory complications of accidental drownings in children]. *Arch Pediatr* 17: 14–18, 2010.
77. Foster GE, Sheel AW. The human diving response, its function, and its control. *Scand J Med Sci Sports* 15: 3–12, 2005.
78. Fowler WS. Breaking point of breath-holding. *J Appl Physiol* 6: 539–545, 1954.
79. Fruehan Accidental hypothermia AE. Report of eight cases of subnormal body temperature due to exposure. *Arch Intern Med* 106: 218–229, 1960.
80. Fuller RH. The clinical pathology of human near-drowning. *Proc R Soc Med* 56: 33–38, 1963.
81. Gabrielsen A, Johansen LB, Norsk P. Central cardiovascular pressures during graded water immersion in humans. *J Appl Physiol* 75: 581–585, 1993.
82. Gale EA, Bennett T, Green JH, MacDonald IA. Hypoglycaemia, hypothermia and shivering in man. *Clin Sci (Lond)* 61: 463–469, 1981.
83. Garbella E, Catapano G, Pratali L, Pingitore A. Pulmonary edema in healthy subjects in extreme conditions. *Pulm Med* 2011: 275857, 2011.
84. Ghishan FK, Kiela PR. Small intestinal ion transport. *Curr Opin Gastroenterol* 28: 130–134, 2012.
85. Giammona ST, Modell JH. Drowning by total immersion. Effects on pulmonary surfactant of distilled water, isotonic saline, and sea water. *Am J Dis Child* 114: 612–616, 1967.
86. Gilbert M, Busund R, Skagseth A, Nilsen PA, Solbo JP. Resuscitation from accidental hypothermia of 13.7°C with circulatory arrest. *Lancet* 355: 375–376, 2000.
87. Goksoer E, Rosengren L, Wennergren G. Bradycardic response during submersion in infant swimming. *Acta Paediatr* 91: 307–312, 2002.
88. Golden FC, Tipton MJ. *Essentials of Sea Survival*. Champaign, IL: Human Kinetics, 2002.
89. Golden FS. Proceedings: recognition and treatment of immersion hypothermia. *Proc R Soc Med* 66: 1058–1061, 1973.
90. Golden FS, Tipton MJ, Scott RC. Immersion, near-drowning and drowning. *Br J Anaesth* 79: 214–225, 1997.
91. Gooden BA. Why some people do not drown. Hypothermia versus the diving response. *Med J Aust* 157: 629–632, 1992.
92. Gregorakos L, Markou N, Psalida V, Kanakaki M, Alexopoulou A, Sotiriou E, Damianos A, Myrianthefs P. Near-drowning: clinical course of lung injury in adults. *Lung* 187: 93–97, 2009.
93. Guenther U, Varelmann D, Putensen C, Wrigge H. Extended therapeutic hypothermia for several days during extracorporeal membrane-oxygenation after drowning and cardiac arrest. Two cases of survival with no neurological sequelae. *Resuscitation* 80: 379–381, 2009.
94. Haight JS, Keatinge WR. Failure of thermoregulation in the cold during hypoglycaemia induced by exercise and ethanol. *J Physiol* 229: 87–97, 1973.
95. Hansel J, Solleder I, Gfroerer W, Muth CM, Paulat K, Simon P, Heitkamp HC, Niess A, Tetzlaff K. Hypoxia and cardiac arrhythmias in breath-hold divers during voluntary immersed breath-holds. *Eur J Appl Physiol* 105: 673–678, 2009.
96. Hayasaka S, Shibata Y, Goto Y, Noda T, Ojima T. Bathing in a bathtub and health status: a cross-sectional study. *Complement Ther Clin Pract* 16: 219–221, 2010.
97. Hayashi N, Ishihara M, Tanaka A, Osumi T, Yoshida T. Face immersion increases vagal activity as assessed by heart rate variability. *Eur J Appl Physiol Occup Physiol* 76: 394–399, 1997.
98. Hayward JS, Eckerson JD. Physiological responses and survival time prediction for humans in ice-water. *Aviat Space Environ Med* 55: 206–211, 1984.
99. Heek C, Tirpitz D, Schipke JD. Tauchreflex beim Menschen: Factum oder Fiction? In: *Tauch- und Überdruckmedizin*, edited by Tirpitz D, Schipke JD, Laak E. Heidelberg, Germany: Kurt Haefner Verlag, 2000.
100. Henderson AR. Induced hypothermia is not “artificial hibernation”. *JAMA* 198: 1074–1078, 1966.
101. Hendey NI. The diagnostic value of diatoms in cases of drowning. *Med Sci Law* 13: 23–34, 1973.
102. Heusser K, Dzamonja G, Tank J, Palada I, Valic Z, Bakovic D, Obad A, Ivancev V, Breskovic T, Diedrich A, Joyner MJ, Luft FC, Jordan J, Dujic Z. Cardiovascular regulation during apnea in elite divers. *Hypertension* 53: 719–724, 2009.
103. Hicks CE, McCord MC, Blount SG Jr. Electrocardiographic changes during hypothermia and circulatory occlusion. *Circulation* 13: 21–28, 1956.
104. Hill L, Flack M. The effect of excess of carbon dioxide and of want of oxygen upon the respiration and the circulation. *J Physiol* 37: 77–111, 1908.
105. Hochachka PW, Buck LT, Doll CJ, Land SC. Unifying theory of hypoxia tolerance: molecular/metabolic defense and rescue mechanisms for surviving oxygen lack. *Proc Natl Acad Sci USA* 93: 9493–9498, 1996.
106. Hochachka PW, Gunga HC, Kirsch K. Our ancestral physiological phenotype: an adaptation for hypoxia tolerance and for endurance performance? *Proc Natl Acad Sci USA* 95: 1915–1920, 1998.
107. Hockaday TDR, Fell RH. Accidental hypothermia with an appendix on blood gas and acid-base measurements. *Br J Hosp Med* 2: 1083–1093, 1969.
108. Hoff BH. Multisystem failure: a review with special reference to drowning. *Crit Care Med* 7: 310–320, 1979.
109. Hori S, Suzuki M, Ueno K, Sato Y, Kurihara T. [Accidents during bathing]. *Nihon Rinsho* 71: 1047–1052, 2013.
110. Hornby PJ. Central neurocircuitry associated with emesis. *Am J Med* 111, Suppl 8A: 106S–112S, 2001.
111. Hubert G, Liet JM, Barriere F, Joram N. [Severe hypernatremia due to sea water ingestion in a child]. *Arch Pediatr* 22: 39–42, 2015.
112. Hume DE, Bell CC Jr. The secretion of epinephrine nor-epinephrine, and corticosteroid in the adrenal venous blood of the human. *Surg Forum* 9: 6–12, 1958.
113. Hume DM, Egdahl RH. Effect of hypothermia and of cold exposure on adrenal cortical and medullary secretion. *Ann NY Acad Sci* 80: 435–444, 1959.
114. Irwin CC, Irwin RL, Ryan TD, Drayer J. The legacy of fear: is fear impacting fatal and non-fatal drowning of African American children? *J Black Stud* 42: 561–576, 2011.
115. Jean A. Brain stem control of swallowing: neuronal network and cellular mechanisms. *Physiol Rev* 81: 929–969, 2001.
116. Joffe AR, Kolski H, Duff J, deCaen AR. A 10-month-old infant with reversible findings of brain death. *Pediatr Neurol* 41: 378–382, 2009.
117. Kanda K, Ohnaka T, Tochihara Y, Tsuzuki K, Shodai Y, Nakamura K. Effects of the thermal conditions of the dressing room and bathroom on physiological responses during bathing. *Appl Human Sci* 15: 19–24, 1996.
118. Kataoka Y, Yoshida F. The change of hemodynamics and heart rate variability on bathing by the gap of water temperature. *Biomed Pharmacother* 59, Suppl 1: S92–S99, 2005.
119. Keatinge WR. The effects of subcutaneous fat and of previous exposure to cold on the body temperature, peripheral blood flow and metabolic rate of men in cold water. *J Physiol* 153: 166–178, 1960.
120. Keatinge WR, Coleshaw SR, Cotter F, Mattock M, Murphy M, Chelliah R. Increases in platelet and red cell counts, blood viscosity, and arterial pressure during mild surface cooling: factors in mortality from coronary and cerebral thrombosis in winter. *Br Med J Clin Res Ed* 289: 1405–1408, 1984.
121. Keatinge WR, Evans M. The respiratory and cardiovascular response to immersion in cold and warm water. *Q J Exp Physiol Cogn Med Sci* 46: 83–94, 1961.
122. Kety SS, Schmidt CF. The effects of active and passive hyperventilation on cerebral blood flow, cerebral oxygen consumption, cardiac output, and blood pressure of normal young men. *J Clin Invest* 25: 107–119, 1946.
123. Kijima M, Isono S, Nishino T. Coordination of swallowing and phases of respiration during added respiratory loads in awake subjects. *Am J Respir Crit Care Med* 159: 1898–1902, 1999.
124. Kijima M, Isono S, Nishino T. Modulation of swallowing reflex by lung volume changes. *Am J Respir Crit Care Med* 162: 1855–1858, 2000.
125. Kirino T, Sano K. Selective vulnerability in the gerbil hippocampus following transient ischemia. *Acta Neuropathol (Berl)* 62: 201–208, 1984.
126. Kjeld T, Pott FC, Secher NH. Facial immersion in cold water enhances cerebral blood velocity during breath-hold exercise in humans. *J Appl Physiol* 106: 1243–1248, 2009.
127. Klahn MS, Perlman AL. Temporal and durational patterns associating respiration and swallowing. *Dysphagia* 14: 131–138, 1999.
128. Kurth CD, O'Rourke MM, O'Hara IB, Uher B. Brain cooling efficiency with pH-stat and alpha-stat cardiopulmonary bypass in newborn pigs. *Circulation* 96: 358–363, 1997.
129. Lang IM. Brain stem control of the phases of swallowing. *Dysphagia* 24: 333–348, 2009.

130. Lang IM, Sarna SK, Dodds WJ. Pharyngeal, esophageal, and proximal gastric responses associated with vomiting. *Am J Physiol Gastrointest Liver Physiol* 265: G963–G972, 1993.
131. Lawler W. Bodies recovered from water: a personal approach and consideration of difficulties. *J Clin Pathol* 45: 654–659, 1992.
132. Layon AJ, Modell JH. Drowning: update 2009. *Anesthesiology* 110: 1390–1401, 2009.
133. Lemaître F, Bernier F, Petit I, Renard N, Gardette B, Joulia F. Heart rate responses during a breath-holding competition in well-trained divers. *Int J Sports Med* 26: 409–413, 2005.
134. Lemaître F, Polin D, Joulia F, Boutry A, Le Pessot D, Chollet D, Tourny-Chollet C. Physiological responses to repeated apneas in underwater hockey players and controls. *Undersea Hyperb Med* 34: 407–414, 2007.
135. Levy AD, Harcke HT, Getz JM, Mallak CT, Caruso JL, Pearse L, Frazier AA, Galvin JR. Virtual autopsy: two- and three-dimensional multidetector CT findings in drowning with autopsy comparison. *Radiology* 243: 862–868, 2007.
136. Levy-Khademi F, Brooks R, Maayan C, Tenenbaum A, Wexler ID. Dead sea water intoxication. *Pediatr Emerg Care* 28: 815–816, 2012.
137. Lindholm P, Sundblad P, Linnarsson D. Oxygen-conserving effects of apnea in exercising men. *J Appl Physiol* 87: 2122–2127, 1999.
138. Linnan M, Rahman A, Scarr J, Reinten-Reynolds T, Linnan H, Rui-Wei J, Mashreky S, Shafinaz S, Bose S, Finkelstein E, Rahman Child drowning F. *Child Drowning. Evidence for a Newly Recognised Cause of Child Mortality in Low and Middle Income Countries in Asia*. Florence, Italy: UNICEF Office of Research, 2012.
139. Linnan M, Scarr J, Giersing M. Toward a world where children do not drown. *JAMA Pediatr* 167: 110–111, 2013.
140. Lu TH, Lunetta P, Walker S. Quality of cause-of-death reporting using ICD-10 drowning codes: a descriptive study of 69 countries. *BMC Med Res Methodol* 10: 30, 2010.
141. Ludes B, Fornes Drowning P. In: *Forensic Medicine, Clinical and Pathological Aspects*, edited by Payne-James J, Busuttill A, Smock W. London, UK: Greenwich Medical Media, 2003, p. 247–257.
142. Ludlow CL. Central nervous system control of the laryngeal muscles in humans. *Respir Physiol Neurobiol* 147: 205–222, 2005.
143. Lund FK, Torgersen JG, Flaatten HK. Heart rate monitored hypothermia and drowning in a 48-year-old man. Survival without sequelae: a case report. *Cases J* 2: 6204, 2009.
144. Lund KL, Mahon RT, Tanen DA, Bakhda S. Swimming-induced pulmonary edema. *Ann Emerg Med* 41: 251–256, 2003.
145. Lundberg GD, Mattei IR, Davis CJ, Nelson DE. Hemorrhage from gastroesophageal lacerations following closed-chest cardiac massage. *JAMA* 202: 195–198, 1967.
146. Lunetta P, Miettinen A, Spilling K, Sajantila A. False-positive diatom test: a real challenge? A post-mortem study using standardized protocols. *Leg Med* 15: 229–234, 2013.
147. Lunetta P, Modell JH. Macroscopical, microscopical and laboratory findings in drowning victims: a comprehensive review. In: *Forensic Pathology Reviews*, edited by Tsokas M. Totowa, NJ: Humana Press, 2005, p. 3–77.
148. Lunetta P, Modell JH, Sajantila A. What is the incidence and significance of “dry-lungs” in bodies found in water? *Am J Forensic Med Pathol* 25: 291–301, 2004.
149. Lynch K. *Stig Severinsen sets world record double with pair of daring freedivers beneath the ice (Online)*. New York: Guinness World Records. <http://www.guinnessworldrecords.com/news/2013/10/freediver-stig-severinsen-sets-new-world-record-with-swim-250-feet-below-the-ice-on-a-single-breath-52227/> [September 25, 2015].
150. Mackensen GB, McDonagh DL, Warner DS. Perioperative hypothermia: use and therapeutic implications. *J Neurotrauma* 26: 342–358, 2009.
151. Mackie IJ. Patterns of drowning in Australia, 1992–1997. *Med J Aust* 171: 587–590, 1999.
152. MacLean D, Emslie-Smith D. *Accidental Hypothermia*. London, UK: Blackwell, 1977.
153. Maclean D, Emslie-Smith D. The J loop of the spatial vectorcardiogram in accidental hypothermia in man. *Br Heart J* 36: 621–629, 1974.
154. Manolios N, Mackie I. Drowning and near-drowning on Australian beaches patrolled by life-savers: a 10-year study, 1973–1983. *Med J Aust* 148: 165–167, –161621–170, 1988.
155. Mant AK. The post-mortem diagnosis of accidental hypothermia. *Br J Hosp Med* 2: 1095–1098, 1969.
156. Mantoni T, Belhage B, Pedersen LM, Pott FC. Reduced cerebral perfusion on sudden immersion in ice water: a possible cause of drowning. *Aviat Space Environ Med* 78: 374–376, 2007.
157. Mantoni T, Rasmussen JH, Belhage B, Pott FC. Voluntary respiratory control and cerebral blood flow velocity upon ice-water immersion. *Aviat Space Environ Med* 79: 765–768, 2008.
158. Marasakatla S, Marasakatla K. Free flow of sweat due to loss of surface tension at sweat droplets causes water-induced skin wrinkling. *Peer J PrePrints* 1: e57v4: <https://dx.doi.org/10.7287/peerj.preprints.57v4>, 2013.
159. Martin S, Cooper KE. The relationship of deep and surface skin temperatures to the ventilatory responses elicited during cold water immersion. *Can J Physiol Pharmacol* 56: 999–1004, 1978.
160. Matsuo K, Palmer JB. Anatomy and physiology of feeding and swallowing: normal and abnormal. *Phys Med Rehabil Clin N Am* 19: 691–707, vii, 2008.
161. McCulloch PF. Animal models for investigating the central control of the mammalian diving response. *Front Physiol* 3: 169, 2012.
162. McCulloch PF. Training rats to voluntarily dive underwater: investigations of the mammalian diving response. *J Vis Exp* 12: e52093, 2014.
163. McKemy DD. How cold is it? TRPM8 and TRPA1 in the molecular logic of cold sensation. *Mol Pain* 1: 16, 2005.
164. Meddings D, Hyder AA, Ozanne-Smith J, Rahman A. *Global Report on Drowning: Preventing a Leading Killer*. New York: World Health Organization, 2014.
165. Meghana A, Sathyaprabha TN, Sinha S, Satishchandra P. Cardiac autonomic dysfunction in drug naive hot water epilepsy. *Seizure* 21: 706–710, 2012.
166. Mekjavic IB, La Prairie A, Burke W, Lindborg B. Respiratory drive during sudden cold water immersion. *Respir Physiol* 70: 121–130, 1987.
167. Mekjavic IB, Tipton MJ, Gennser M, Eiken O. Motion sickness potentiates core cooling during immersion in humans. *J Physiol* 535: 619–623, 2001.
168. Mellergard P. Changes in human intracerebral temperature in response to different methods of brain cooling. *Neurosurgery* 31: 671–677; discussion 677, 1992.
169. Michael N, Sawka MN, Wenger CB, Pandolf KB. Thermoregulatory responses to acute exercise-heat stress and heat acclimation. In: *Handbook of Physiology. Environmental Physiology*. Bethesda, MD: Am. Physiol. Soc., 1996, sect. 4, vol. 1, chapt. 9, p. 157–185.
170. Michenfelder JD, Milde JH. The relationship among canine brain temperature, metabolism, and function during hypothermia. *Anesthesiology* 75: 130–136, 1991.
171. Michenfelder JD, Theye RA. Cerebral protection by thiopental during hypoxia. *Anesthesiology* 39: 510–517, 1973.
172. Miller AD, Nonaka S. Mechanisms of abdominal muscle activation during vomiting. *J Appl Physiol* 69: 21–25, 1990.
173. Miller AJ. Deglutition. *Physiol Rev* 62: 129–184, 1982.
174. Miller AJ. The neurobiology of swallowing and dysphagia. *Dev Disabil Res Rev* 14: 77–86, 2008.
175. Miwa C, Matsukawa T, Iwase S, Sugiyama Y, Mano T, Sugeno Y, Yamaguchi H, Kirsch KA. Human cardiovascular responses to a 60-min bath at 40 degrees C. *Environ Med* 38: 77–80, 1994.
176. Miyazato T, Ishikawa T, Michiue T, Maeda H. Molecular pathology of pulmonary surfactants and cytokines in drowning compared with other asphyxiation and fatal hypothermia. *Int J Legal Med* 126: 581–587, 2012.
177. Modell JH. Drowning. *N Engl J Med* 328: 253–256, 1993.
178. Modell JH, Bellefleur M, Davis JH. Drowning without aspiration: is this an appropriate diagnosis? *J Forensic Sci* 44: 1119–1123, 1999.
179. Modell JH, Davis JH. Electrolyte changes in human drowning victims. *Anesthesiology* 30: 414–420, 1969.
180. Modell JH, Moya F. Effects of volume of aspirated fluid during chlorinated fresh water drowning. *Anesthesiology* 27: 662–672, 1966.
181. Morgan WP. Anxiety and panic in recreational scuba divers. *Sports Med* 20: 398–421, 1995.
182. Morrison SF, Nakamura K. Central neural pathways for thermoregulation. *Front Biosci* 16: 74–104, 2011.
183. Murakami M, Lam SK, Inada M, Miyake T. Pathophysiology and pathogenesis of acute gastric mucosal lesions after hypothermic restraint stress in rats. *Gastroenterology* 88: 660–665, 1985.
184. Murray-Calderon P, Connolly MA. Laryngospasm and noncardiogenic pulmonary edema. *J Perianesth Nurs* 12: 89–94, 1997.
185. Nagasawa Y, Komori S, Sato M, Tsuboi Y, Umetani K, Watanabe Y, Tamura K. Effects of hot bath immersion on autonomic activity and hemodynamics: comparison of the elderly patient and the healthy young. *Jpn Circ J* 65: 587–592, 2001.
186. Naylor wg, Merrillees NCR. Cellular exchange of calcium. In: *Calcium and the Heart*, edited by Harris P, Opie L. London, UK: Academic, 1971.
187. Nisbet HI. Acid-base disturbance in hypothermia. *Int Anesthesiol Clin* 2: 829–855, 1964.
188. Nishino T. Physiological and pathophysiological implications of upper airway reflexes in humans. *Jpn J Physiol* 50: 3–14, 2000.
189. Nishino T. The swallowing reflex and its significance as an airway defensive reflex. *Front Physiol* 3: 489, 2013.
190. Nishino T, Hiraga K. Coordination of swallowing and respiration in unconscious subjects. *J Appl Physiol* 70: 988–993, 1991.

191. Nishiyama C, Iwami T, Nichol G, Kitamura T, Hirai A, Nishiuchi T, Hayashi Y, Nonogi H, Kawamura T. Association of out-of-hospital cardiac arrest with prior activity and ambient temperature. *Resuscitation* 82: 1008–1012, 2011.
192. Nitta M, Kitamura T, Iwami T, Nadkarni VM, Berg RA, Topjian AA, Okamoto Y, Nishiyama C, Nishiuchi T, Hayashi Y, Nishimoto Y, Takasu A. Out-of-hospital cardiac arrest due to drowning among children and adults from the Utstein Osaka Project. *Resuscitation* 84: 1568–1573, 2013.
193. Ohri SK, Somasundaram S, Koak Y, Macpherson A, Keogh BE, Taylor KM, Menzies IS, Bjarnason I. The effect of intestinal hypoperfusion on intestinal absorption and permeability during cardiopulmonary bypass. *Gastroenterology* 106: 318–323, 1994.
194. Orłowski JP. Drowning, near-drowning, and ice-water submersions. *Pediatr Clin North Am* 34: 75–92, 1987.
195. Orłowski JP, Szpilman Drowning D. Rescue, resuscitation, reanimation. *Pediatr Clin North Am* 48: 627–646, 2001.
196. Otis AB, Rahn H, Fenn WO. Alveolar gas changes during breath holding. *Am J Physiol* 152: 674–686, 1948.
197. Pagni CA, Courjon J. Electroencephalographic modifications induced by moderate and deep hypothermia in man. *Acta Neurochir Suppl (Wien)* 14, Suppl 13: 35–49, 1964.
198. Panneton WM. The mammalian diving response: an enigmatic reflex to preserve life? *Physiology* 28: 284–297, 2013.
199. Panneton WM, McCulloch PF, Sun W. Trigemino-autonomic connections in the muskrat: the neural substrate for the diving response. *Brain Res* 874: 48–65, 2000.
200. Parkes MJ. Breath-holding and its breakpoint. *Exp Physiol* 91: 1–15, 2006.
201. Paschen W, Proud CG, Mies G. Shut-down of translation, a global neuronal stress response: mechanisms and pathological relevance. *Curr Pharm Des* 13: 1887–1902, 2007.
202. Passias TC, Meneilly GS, Mekjavic IB. Effect of hypoglycemia on thermoregulatory responses. *J Appl Physiol* 80: 1021–1032, 1996.
203. Paton JF, Boscan P, Pickering AE, Nalivaiko E. The yin and yang of cardiac autonomic control: vago-sympathetic interactions revisited. *Brain Res Brain Res Rev* 49: 555–565, 2005.
204. Paulson O, Sharbrough F. Physiologic and pathophysiologic relationship between the electroencephalogram and the regional cerebral blood flow. *Acta Neurol Scand* 50: 194–220, 1974.
205. Paydarfar D, Gilbert RJ, Poppel CS, Nassab PF. Respiratory phase resetting and airflow changes induced by swallowing in humans. *J Physiol* 483: 273–288, 1995.
206. Pearn J. Pathophysiology of drowning. *Med J Aust* 142: 586–588, 1985.
207. Pedroso FS, Riesgo RS, Gatiboni T, Rotta NT. The diving reflex in healthy infants in the first year of life. *J Child Neurol* 27: 168–171, 2012.
208. Pendergast DR, Lundgren CE. The underwater environment: cardiopulmonary, thermal, and energetic demands. *J Appl Physiol* 106: 276–283, 2009.
209. Petito CK, Feldmann E, Pulsinelli WA, Plum F. Delayed hippocampal damage in humans following cardiorespiratory arrest. *Neurology* 37: 1281–1286, 1987.
210. Petri NM, Stipanecvic H, Sutlovic D, Gojanovic MD. Death of a scuba diver caused by vomiting and panic: a case report. *Am J Forensic Med Pathol* 32: 186–189, 2011.
211. Press E. The health hazards of saunas and spas and how to minimize them. *Am J Public Health* 81: 1034–1037, 1991.
212. Pretorius T, Cahill F, Kocay S, Giesbrecht GG. Shivering heat production and core cooling during head-in and head-out immersion in 17 degrees C water. *Aviat Space Environ Med* 79: 495–499, 2008.
213. Proulx CI, Ducharme MB, Kenny GP. Safe cooling limits from exercise-induced hyperthermia. *Eur J Appl Physiol* 96: 434–445, 2006.
214. Puyal J, Ginet V, Clarke PG. Multiple interacting cell death mechanisms in the mediation of excitotoxicity and ischemic brain damage: a challenge for neuroprotection. *Prog Neurobiol* 105: 24–48, 2013.
215. Quan L, Zhu BL, Ishikawa T, Michiue T, Zhao D, Yoshida C, Chen JH, Wang Q, Komatsu A, Azuma Y, Maeda H. Postmortem serum levels of pulmonary surfactant-associated proteins A and D with regard to the cause of death in medicolegal autopsy. *Leg Med* 11, Suppl 1: S301–S303, 2009.
216. Rahman F, Bose S, Linnan M, Rahman A, Mashreky S, Haaland B, Finkelstein E. Cost-effectiveness of an injury and drowning prevention program in Bangladesh. *Pediatrics* 130: e1621–e1628, 2012.
217. Raines S. Boy records lowest body temperature on record (Online). <http://www.abc.net.au/news/2015-02-14/boy-records-lowest-body-temperature-on-record/6096394> [September 24, 2015].
218. Reh H. *Diagnostik des Ertrinkungstodes und Bestimmung der Wasserzeit*. Düsseldorf, Germany: Mikael Triltsch Verlag, 1970.
219. Roe PF. Accidental hypothermia. *Ir J Med Sci* 454: 459–463, 1963.
220. Roosterman D, Goerge T, Schneider SW, Bunnett NW, Steinhoff M. Neuronal control of skin function: the skin as a neuroimmunoenocrine organ. *Physiol Rev* 86: 1309–1379, 2006.
221. Rosenfeld JB. Acid-base and electrolyte disturbances in hypothermia. *Am J Cardiol* 12: 678–682, 1963.
222. Sabharwal R, Johns EJ, Egginton S. The influence of acute hypothermia on renal function of anaesthetized eutheric and acclimatized rats. *Exp Physiol* 89: 455–463, 2004.
223. Sai T, Isono S, Nishino T. Effects of withdrawal of phasic lung inflation during normocapnia and hypercapnia on the swallowing reflex in humans. *J Anesth* 18: 82–88, 2004.
224. Samuel Morris Foundation (Online). <http://samuelmorrisfoundation.org.au> [September 26, 2015].
225. Samuelson H, Nekludov M, Levander M. Neuropsychological outcome following near-drowning in ice water: two adult case studies. *J Int Neuropsychol Soc* 14: 660–666, 2008.
226. Sandu N, Sadr-Eshkevari P, Schaller BJ, Trigemino G. Cardiac reflex examination. Usefulness of case reports to improve medical knowledge regarding trigemino-cardiac reflex in skull base surgery. *J Med Case Rep* 5: 149, 2011.
227. Sandu N, Spiriev T, Lemaitre F, Filis A, Schaller B, Trigemino G. Cardiac reflex examination. New molecular knowledge towards the trigemino-cardiac reflex as a cerebral oxygen-conserving reflex. *Scientific World J* 10: 811–817, 2010.
228. Satishchandra P. Hot-water epilepsy. *Epilepsia* 44, Suppl 1: 29–32, 2003.
229. Satoh F, Osawa M, Hasegawa I, Seto Y, Tsuboi A. “Dead in hot bathtub” phenomenon: accidental drowning or natural disease? *Am J Forensic Med Pathol* 34: 164–168, 2013.
230. Saukko P, Knight Immersion deaths B. Chapter 16. In: *Knight's Forensic Pathology*, edited by Saukko P, Knight B. London, UK: Arnold Publishing, 2004.
231. Schagatay E, Andersson J. Diving response and apneic time in humans. *Undersea Hyperb Med* 25: 13–19, 1998.
232. Schagatay E, Andersson JP, Nielsen B. Hematological response and diving response during apnea and apnea with face immersion. *Eur J Appl Physiol* 101: 125–132, 2007.
233. Schagatay E, Holm B. Effects of water and ambient air temperatures on human diving bradycardia. *Eur J Appl Physiol Occup Physiol* 73: 1–6, 1996.
234. Schaller B. Trigemino-cardiac reflex. A clinical phenomenon or a new physiological entity? *J Neurol* 251: 658–665, 2004.
235. Schepers RJ, Ringkamp M. Thermoreceptors and thermosensitive afferents. *Neurosci Biobehav Rev* 34: 177–184, 2010.
236. Schipke JD, Pelzer M. Effect of immersion, submersion, and scuba diving on heart rate variability. *Br J Sports Med* 35: 174–180, 2001.
237. Schmelz M. Neuronal sensitivity of the skin. *Eur J Dermatol* 21, Suppl 2: 43–47, 2011.
238. Schmid JP, Morger C, Noveanu M, Binder RK, Anderegg M, Saner H. Haemodynamic and arrhythmic effects of moderately cold (22 degrees C) water immersion and swimming in patients with stable coronary artery disease and heart failure. *Eur J Heart Fail* 11: 903–909, 2009.
239. Schulz IJ. Micropuncture studies of the sweat formation in cystic fibrosis patients. *J Clin Invest* 48: 1470–1477, 1969.
240. Selley WG, Flack FC, Ellis RE, Brooks WA. Respiratory patterns associated with swallowing: Part 1. The normal adult pattern and changes with age. *Age Ageing* 18: 168–172, 1989.
241. Senturk T, Ozbek C, Tolga D, Kazazoglu AR. J deflections on ECG in severe hypothermia and hypokalaemia: a case report. *Neth Heart J* 21: 106–108, 2013.
242. Sercarz JA, Nasri S, Gerratt BR, Fyfe ST, Berke GS. Recurrent laryngeal nerve afferents and their role in laryngospasm. *Am J Otolaryngol* 16: 49–52, 1995.
243. Shaker R, Medda BK, Ren J, Jaradeh S, Xie P, Lang IM. Pharyngoglottal closure reflex: identification and characterization in a feline model. *Am J Physiol Gastrointest Liver Physiol* 275: G521–G525, 1998.
244. Shattock MJ, Tipton MJ. ‘Autonomic conflict’: a different way to die during cold water immersion? *J Physiol* 590: 3219–3230, 2012.
245. Sidorov JJ. Intestinal absorption of water and electrolytes. *Clin Biochem* 9: 117–120, 1976.
246. Siebke H, Rod T, Breivik H, Link B. Survival after 40 minutes; submersion without cerebral sequelae. *Lancet* 1: 1275–1277, 1975.
247. Simons RW, Rea TD, Becker LJ, Eisenberg MS. The incidence and significance of emesis associated with out-of-hospital cardiac arrest. *Resuscitation* 74: 427–431, 2007.
248. Smith ML, Auer RN, Siesjo BK. The density and distribution of ischemic brain injury in the rat following 2–10 min of forebrain ischemia. *Acta Neuropathol (Berl)* 64: 319–332, 1984.
249. Spencer FC, Bahnson HT. The present role of hypothermia in cardiac surgery. *Circulation* 26: 292–300, 1962.
250. Spitz WU. Drowning. In: *Medico-Legal Investigations of Death*, edited by Spitz WU. Springfield, IL: Charles C. Thomas, 1973, p. 296–310.
251. Sramek P, Simeckova M, Jansky L, Savlikova J, Vybiral S. Human physiological responses to immersion into water of different temperatures. *Eur J Appl Physiol* 81: 436–442, 2000.

252. Steele CM, Miller AJ. Sensory input pathways and mechanisms in swallowing: a review. *Dysphagia* 25: 323–333, 2010.
- 252a.(a)Stig Severinsen: 22 minutes Guinness World Record Breath Hold [Online]. *Discovery*. <https://www.youtube.com/watch?v=AqERqQj-ozc> [September 25, 2015].
253. Suominen PK, Sutinen N, Valle S, Olkkola KT, Lonnqvist T. Neurocognitive long term follow-up study on drowned children. *Resuscitation* 85: 1059–1064, 2014.
254. Swann HG, Brucer M. The cardiorespiratory and biochemical events during rapid anoxic death; fresh water and sea water drowning. *Tex Rep Biol Med* 7: 604–618, 1949.
255. Swann HG, Brucer M, et al. Fresh water and sea water drowning; a study of the terminal cardiac and biochemical events. *Tex Rep Biol Med* 5: 423–437, 1947.
256. Swann HG, Spafford NR. Body salt and water changes during fresh and sea water drowning. *Tex Rep Biol Med* 9: 356–382, 1951.
257. Szpilman D, Bierens JJ, Handley AJ, Orlowski JP. Drowning. *N Engl J Med* 366: 2102–2110, 2012.
258. Taylor NA, Tipton MJ, Kenny GP. Considerations for the measurement of core, skin and mean body temperatures. *J Therm Biol* 46: 72–101, 2014.
259. Tei C, Horikiri Y, Park JC, Jeong JW, Chang KS, Tanaka N, Toyama Y. [Effects of hot water bath or sauna on patients with congestive heart failure: acute hemodynamic improvement by thermal vasodilation]. *J Cardiol* 24: 175–183, 1994.
260. Tipton M, Bradford C. Moving in extreme environments: open water swimming in cold and warm water. *Extrem Physiol Med* 3: 12, 2014.
261. Tipton M, Golden F. The physiology of cooling in water. In: *Drowning: Prevention, Rescue, Treatment*, edited by Bierens JJLM. Heidelberg, Germany: Springer, 2014, p. 843–848.
262. Tipton MJ. Immersion fatalities: hazardous responses and dangerous discrepancies. *J R Nav Med Serv* 81: 101–107, 1995.
263. Tipton MJ. The initial responses to cold-water immersion in man. *Clin Sci (Lond)* 77: 581–588, 1989.
264. Tipton MJ. Sudden cardiac death during open water swimming. *Br J Sports Med* 48: 1134–1135, 2014.
265. Tipton MJ, Gibbs P, Brooks C, Roiz de Sa D, Reilly TJ. ECG during helicopter underwater escape training. *Aviat Space Environ Med* 81: 399–404, 2010.
266. Tipton MJ, Golden FS. A proposed decision-making guide for the search, rescue and resuscitation of submersion (head under) victims based on expert opinion. *Resuscitation* 82: 819–824, 2011.
267. Tipton MJ, Kelleher PC, Golden FS. Supraventricular arrhythmias following breath-hold submersions in cold water. *Undersea Hyperb Med* 21: 305–313, 1994.
268. Tipton MJ, Stubbs DA, Elliott DH. Human initial responses to immersion in cold water at three temperatures and after hyperventilation. *J Appl Physiol* 70: 317–322, 1991.
269. Tokutomi T, Miyagi T, Morimoto K, Karukaya T, Shigemori M. Effect of hypothermia on serum electrolyte, inflammation, coagulation, and nutritional parameters in patients with severe traumatic brain injury. *Neurocrit Care* 1: 171–182, 2004.
270. Topjian AA, Berg RA, Bierens JJ, Branche CM, Clark RS, Friberg H, Hoedemaekers CW, Holzer M, Katz LM, Knape JT, Kochanek PM, Nadkarni V, van der Hoeven JG, Warner DS. Brain resuscitation in the drowning victim. *Neurocrit Care* 17: 441–467, 2012.
271. Vaagenes P, Safar P, Moossy J, Rao G, Diven W, Ravi C, Arfors K. Asphyxiation versus ventricular fibrillation cardiac arrest in dogs. Differences in cerebral resuscitation effects: a preliminary study. *Resuscitation* 35: 41–52, 1997.
272. Vahatalo R, Lunetta P, Olkkola KT, Suominen PK. Drowning in children: Utstein style reporting and outcome. *Acta Anaesthesiol Scand* 58: 604–610, 2014.
273. van Beeck EF, Branche CM, Szpilman D, Modell JH, Bierens JJ. A new definition of drowning: towards documentation and prevention of a global public health problem. *Bull World Health Organ* 83: 853–856, 2005.
274. van Berkel M, Bierens JJ, Lie RL, de Rooy TP, Kool LJ, van de Velde EA, Meinders AE. Pulmonary oedema, pneumonia and mortality in submersion victims; a retrospective study in 125 patients. *Intensive Care Med* 22: 101–107, 1996.
275. van der Ploeg GJ, Goslings JC, Walpoth BH, Bierens JJ. Accidental hypothermia: rewarming treatments, complications and outcomes from one university medical centre. *Resuscitation* 81: 1550–1555, 2010.
276. Vanagt WY, Wassenberg R, Bierens JJ. No gold standard for neurocognitive outcome assessment of drowned children. *Resuscitation* 85: 981–982, 2014.
277. Varon J, Marik PE. Complete neurological recovery following delayed initiation of hypothermia in a victim of warm water near-drowning. *Resuscitation* 68: 421–423, 2006.
278. Vincent MJ, Tipton MJ. The effects of cold immersion and hand protection on grip strength. *Aviat Space Environ Med* 59: 738–741, 1988.
279. Vrijsen BEL, Kotsopoulos AMM, Vandeviviere YDO, van Oers J, A, H. Negative pressure pulmonary oedema: a rare complication of anaesthesia. *Neth J Critical Care* 16: 54–56, 2012.
280. Warner DS, James ML, Laskowitz DT, Wijdkids EF. Translational research in acute central nervous system injury: lessons learned and the future. *JAMA Neurol* 71: 1311–1318, 2014.
281. Warner DS, Sheng H, Batinic-Haberle I. Oxidants, antioxidants and the ischemic brain. *J Exp Biol* 207: 3221–3231, 2004.
282. Wensel RH, Bigelow WG. The use of heparin to minimize thrombocytopenia and bleeding tendency during hypothermia. *Surgery* 45: 223–228, 1959.
283. Westin B, Miller JA Jr, Boles A. Hypothermia induced during asphyxiation: its effects on survival rate, learning and maintenance of the conditioned response in rats. *Acta Paediatr* 52: 49–60, 1963.
284. Weston CF, O'Hare JP, Evans JM, Corral RJ. Haemodynamic changes in man during immersion in water at different temperatures. *Clin Sci (Lond)* 73: 613–616, 1987.
285. Widdicombe J. Upper airway reflexes. *Curr Opin Pulm Med* 4: 376–382, 1998.
286. Wong G, Clark JE, Shattock MJ. Failure of the QT interval of the electrocardiogram to prolong during a diving response-induced bradycardia in human subjects. In: *Proceedings of The Physiological Society*. King's College London: The Physiological Society, 2009, p. PC27.
287. Wright M, de Silva P, Sinha S. Hyponatraemia in children. *BMJ* 305: 51–52, 1992.
288. Writh I, Lignitz E, Scheibe E, Schmelting A. [Interpretation of the term "hydrocution"]. *Arch Kriminol* 220: 65–76, 2007.
289. Xu X, Tikuisis P. Thermoregulatory modeling for cold stress. *Compr Physiol* 4: 1057–1081, 2014.
290. Yen LY, Jayaprakash PT. Prevalence of diatom frustules in non-vegetarian foodstuffs and its implications in interpreting identification of diatom frustules in drowning cases. *Forensic Sci Int* 170: 1–7, 2007.
291. Yoshioka N, Chiba T, Yamauchi M, Monma T, Yoshizaki K. Forensic consideration of death in the bathtub. *Leg Med* 5, Suppl 1: S375–S381, 2003.
292. Zald DH, Pardo JV. Cortical activation induced by intraoral stimulation with water in humans. *Chem Senses* 25: 267–275, 2000.