Skin Cooling on Breath-Hold Duration and Predicted Emergency Air Supply Duration During Immersion

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PURPOSE: This study was intended to determine the effect of skin cooling on breath-hold duration and predicted emergency air supply duration during immersion.

METHODS: While wearing a helicopter transport suit with a dive mask, 12 subjects (29 ± 10 yr, 78 ± 14 kg, 177 ± 7 cm, 2 women) were studied in 8 and 20°C water. Subjects performed a maximum breath-hold, then breathed for 90 s (through a mouthpiece connected to room air) in five skin-exposure conditions. The first trial was out of water for Control (suit zipped, hood on, mask off). Four submersion conditions included exposure of the: Partial Face (hood and mask on); Face (hood on, mask off); Head (hood and mask off); and Whole Body (suit unzipped, hood and mask off).

RESULTS: Decreasing temperature and increasing skin exposure reduced breath-hold time (to as low as 10 ± 4 s), generally increased minute ventilation (up to 40 ± 15 $\mathrm{L \cdot min^{-1}}$), and decreased predicted endurance time (PET) of a 55-L helicopter underwater emergency breathing apparatus. In 8°C water, PET decreased from 2 min 39 s (Partial Face) to 1 min 11 s (Whole Body).

CONCLUSION: The most significant factor increasing breath-hold and predicted survival time was zipping up the suit. Face masks and suit hoods increased thermal comfort. Therefore, wearing the suits zipped with hoods on and, if possible, donning the dive mask prior to crashing, may increase survivability. The results have important applications for the education and preparation of helicopter occupants. Thermal protective suits and dive masks should be provided.

KEYWORDS: helicopter underwater emergency breathing apparatus, helicopter crash, cold water submersion, drowning, cold shock response.

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Oil platform workers are required to fly across cold water in order to work on ocean-based oil platforms in the northern hemisphere.[4] Helicopters are the primary means of flying to these platforms. Occasionally, helicopters experience an emergency landing, ditching, or outright crash into water.[5,7,19] Helicopter ditchings or water accidents often result in fatalities. Taber and McCabe reviewed a total of 511 helicopter crashes between 1971 to 2005.[19] These accidents involved 1643 crew and passengers, and the fatality rate was 34%. In a recent review, Brooks and McDonald reported that fatality rates for helicopter crashes in water were 25% during the day, with the risk tripling at night.[5] Any factors that could improve survivability would be of great value to the industry.

Occupants of a crashed helicopter experience several challenges to survival. First, injury on impact may cause death, or incapacitation leading to death due to drowning. Second, since helicopters are inherently stable upside down (due to the location of the engine on top of the passenger compartment), they often roll into an inverted position, resulting in spatial disorientation and total submersion of the occupants (necessitating breath-holding in order to escape). Third, for most of North

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America and Europe, ocean waters are cold ($< 10°C$) for much of the year.[8]

Given these challenges, several factors contribute to the high fatality rates of helicopter crashes. First, many crashes occur from a low altitude.[5] As a result, occupants have little or no time to prepare for landing or subsequent survival actions. Before they realize it, they have impacted the water and are submerged, often upside down. Second, many helicopter occupants lack knowledge of, or training in, the correct procedure for underwater escape following a crash. The correct action sequence is to remain in the seat restraints, forcefully open the window and jettison it, hold onto the windowsill, then unfasten the seat restraints, and exit through the window. Brooks and MacDonald showed that many helicopter occupants are not informed of what to do in the event of a helicopter ditching.[5] Hence, many occupants remain trapped in an inverted helicopter cabin and drown.

The final significant factor is limited breath-hold time under water. If a helicopter is inverted after a crash, breath-holding is required to escape successfully. Normally breath-hold time is limited, but it is reduced significantly in cold water by the cold shock response.[7,9,24] The cold shock response includes an inspiratory gasp (the gasp reflex), hyperventilation, tachycardia, and an increased blood pressure and minute ventilation ($\dot{V}_E$).[7,9,24] It is evoked immediately during cold water submersion and lasts up to 1 min. The cold shock response depends on water temperature, rate of skin cooling, and amount of skin exposed.[11,16] Therefore, limited breath-hold ability is a significant risk for occupants of helicopter landings in cold water, especially if they are not wearing thermal protection.

Given that breath-hold reduction by cold water decreases underwater survival time, underwater emergency breathing systems have been developed to help solve this problem.[20,21] These systems can extend survival time considerably by providing an air source for breathing while submerged. This air source can be either uncompressed (e.g., rebreathing one's own expired air from a bag) or compressed (e.g., from a tank); this latter option provides the advantage of increased breathing time, but also presents the risk of air embolism. One example of a compressed air breathing system is the Helicopter Underwater Emergency Breathing Apparatus (HUEBA). The air supply in this apparatus is limited (~40–55 L) and the length of time it lasts (defined as endurance time) is inversely related to the rate of minute ventilation. Minute ventilation depends on factors such as physical exertion (increase in oxygen consumption), psychological factors (panic, excitement),[1] and the cold shock response itself.[15] Endurance time can be improved with proper training in the deployment and efficient use of the device.

Since the cold shock response decreases breath-hold time and increases minute ventilation, any factors that attenuate this response (e.g., thermal insulation) would favor a longer endurance time for a HUEBA. Thermal protective clothing, such as a helicopter transport suit, minimizes the fall in skin temperature, attenuates the cold shock response, increases breath-hold time, and decreases minute ventilation.[14,23]

Currently, there are several models of hooded helicopter transport suits that provide high insulation to the body and head. A dive mask can also be worn on the arm during flight so it can be quickly and easily donned prior to an imminent crash. Thus, it is possible to have full body and head insulation except for the lips and chin. One limitation of these suits is that they can be very hot during flight,[13] presenting not only discomfort, but also the risk of heat-related illness if worn for extended periods. Occupants often "cheat" by leaving the hood off or even unzipping the suit in order to cool the body. Unfortunately, any crash scenario with limited preparation time would prevent doing the zipper up and donning the mask before impact. This would result in more rapid skin cooling after the crash and likely decrease breath-hold ability and, thus, the chance of survival.

The purpose of the study was to test the hypothesis that more skin exposure and colder water temperature would decrease breath-hold time, increase subsequent minute ventilation, and decrease predicted endurance time of a compressed air source (e.g., HUEBA). Documentation of this phenomenon could help tailor evidence-based guidance to inform the end users and improve their survival prospects.

METHODS

Subjects

The study protocol was approved in advance by the Education, Nursing, Research Ethics Board at the University of Manitoba. Each subject provided written informed consent before participating. Participating were 12 healthy subjects (2 women). Subjects were 29 ± 10 yr old, weighed 78 ± 14 kg, and were 177 ± 7 cm tall. All subjects were competent swimmers, only one had experience with HUEBA use in a helicopter dunker, and none worked in an industry involving helicopter travel over water. During familiarization trials they all became competent at underwater breathing through a mouthpiece. Sample size was calculated according to similar data comparing breath-hold times with varying skin insulation in cold water.[25] To achieve 95% power ($\alpha = 0.05$, 1-tailed test; $\beta = 0.05$), the sample size required to detect a statistically significant difference (mean ± SD) of 3 ± 3 s was 11. In total, 12 subjects were recruited for the study.

Equipment and Materials

Subjects were fitted with a helicopter transport suit (Survitec Group, Birkenhead, UK) (see **Fig. 1**) and a dive mask. The dry suit has an inner and outer layer with an inflatable collar that remained deflated throughout the study. The two suit layers zip together at the wrists, ankles, and neck to form one functional unit; therefore, when the main suit zipper is undone, the entire suit floods with water, wetting the skin and clothing. From the neck down the suit is waterproof; the outer layer includes attached boots and the wrist and neck openings include watertight seals. Subjects wore regular socks, pants, and a shirt as well as two sets of gloves; a knit glove was covered by a rubber glove that did not provide a waterproof seal for the hand.

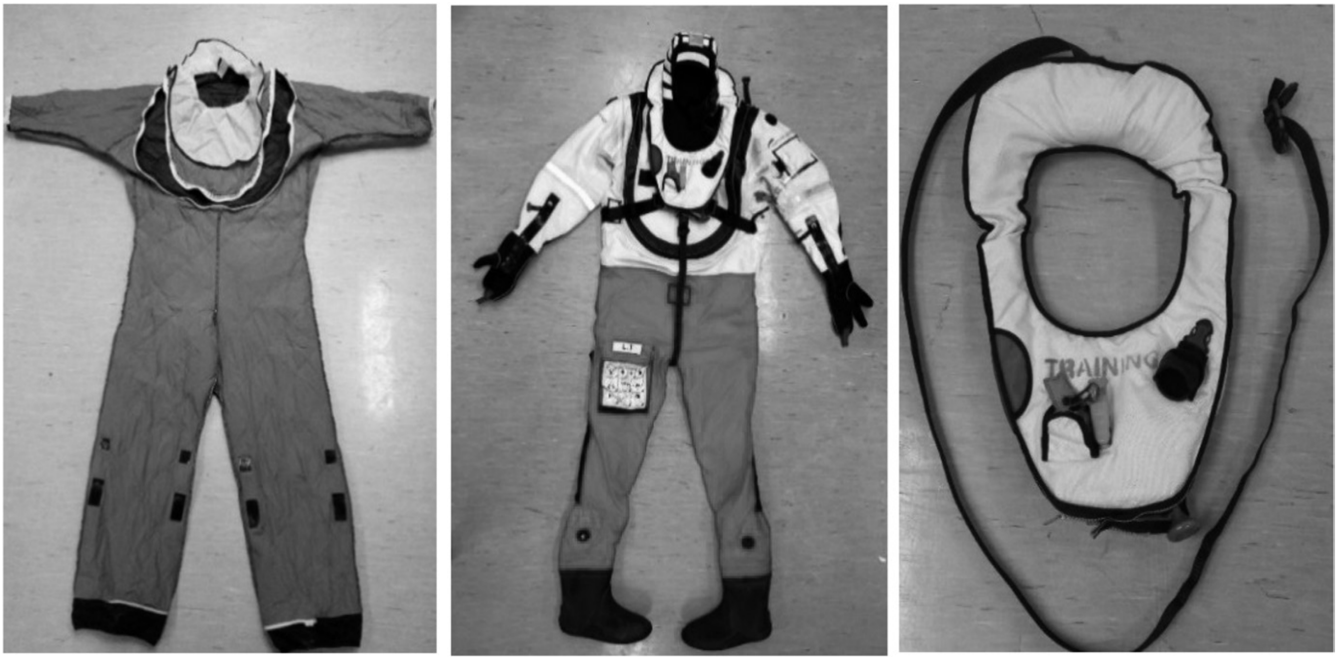

Fig. 1. The helicopter transport suit: inner layer (left), outer layer (middle), and inflatable collar (right; this was deflated throughout all trials). The two layers zip together at the wrists, ankles, and neck to form a single functional unit.

Minute ventilation was measured using a metabolic cart (Parvo Medics, East Sandy, UT, USA). Throughout each breath-hold trial, subjects breathed through a mouthpiece attached to a Hans Rudolph two-way nonrebreathable T-shaped valve which was connected via tubing to room air (inspiratory) and the metabolic cart (expiratory). This configuration allowed underwater, post breath-hold breathing. Heart rate was collected with a transmitter (Polar H7 Bluetooth) and recorded on a smartphone (Wahoo Fitness app), which was placed in a waterproof bag inside the transport suit.

In one subject, skin temperature (T_{sk}) was measured with 10 thermocouples (Concept Engineering, Old Saybrook, CT, USA) affixed to the skin at the following body segments: the head (posterior head and forehead); torso (chest, lower abdomen, upper and lower back); arms (upper arm); and legs (posterior and anterior thigh, and anterior calf). The wires from the thermocouples exited the suit via the neck; the seal was tight enough to prevent leakage during the submersions.

Sessions were conducted in a tank of either 8 or 20°C water. The water level was 1.2 m high. A platform was placed 0.4 m above the water surface for subjects to sit on between breath-hold trials. A ladder was used to climb in and out of the tank. Appropriate weights were added (on a weight belt and in a thigh pocket) to allow subjects to fully submerge without effort. A Whole Body Cold Discomfort Scale (e.g., 0 = no cold sensation to 10 = unbearably cold) was completed following each submerged breath-hold trial; responses were not limited to whole number values but could be given to a precision of 0.5).

Procedure

Familiarization session. The main purpose of this session was to familiarize the subjects with breath-holding and breathing while underwater; this was done in cool (20°C) water. After donning the suit and dive mask, they stood in the tank and were given the mouthpiece. Then they submerged their heads completely under water and breathed through the mouthpiece until they became comfortable. Next, they were given the following standard set of instructions that were used for all breath-hold trials: "Take one large breath and kneel down on the bottom of the water tank. Hold your breath as long as you can and then just breathe through the mouthpiece for 90 seconds. We will provide verbal feedback every 30 seconds while you are breathing"; the feedback provided the number of seconds left. Subjects quickly submerged themselves and kneeled on the bottom of the tank with their bodies in a vertical position from the knees up. They repeated the breath-hold/breathing trials until there was a constant breath-hold time (to eliminate any learning or practice effect). Subjects still required a familiarization exposure to 8°C water before conducting the cold-water breath-hold trials. Rather than requiring them to return for a separate session for this single purpose, this was accomplished at the beginning of the cold-water experimental session (see below).

Experimental sessions. Two experimental sessions were separated by a minimum of 48 h. Cold water sessions were conducted in 8°C water because pilot trials revealed that it would be difficult, if not impossible, to get all subjects to successfully complete four submersions in colder water, especially in the whole body exposure condition. A cool water condition in 20°C water was included to document a graded effect of skin cooling.

In each session there were five exposure conditions that varied the amount of skin contacting the water; "exposure" was defined as skin that was not being protected by either the thermal protective suit, hood or mask. The first control condition required sitting on the platform above the water with the suit zipped and hood on (no exposure, C). The remaining trials required submersion in four exposure conditions: suit zipped, hood and mask on (partial face exposed; PF); suit zipped, hood on, mask off (face exposed; F); suit zipped, hood and mask off (head exposed; H); suit unzipped, hood and mask off (whole body exposed; WB). In the cold-water condition, before the breath-hold trials were conducted, subjects practiced breathing underwater with the suit zipped up and hood on (first with the dive mask on and then with the dive mask off).

The order of water temperatures was randomly assigned to achieve a balanced design. The order of the exposure conditions during submersion followed a modified balanced design; the PF, F, and H conditions were balanced, and the WB condition was last for every session. For each subject, this order was the same for both cool- and cold-water sessions.

In every breath-hold trial, subjects breathed normally, took one deep breath (avoiding hyperventilation), held their breath as long as possible, and then breathed through the mouthpiece for 90 s. At the beginning of each session, subjects sat on the platform with the suit zipped and hood on and performed a control breath-hold. In the remaining submersion trials, subjects stood in the tank, took one deep breath, quickly submerged themselves and kneeled on the bottom of the tank. Once they started breathing through the mouthpiece, they remained underwater for the 90-s post breath-hold period. They were then instructed to stand up, exit the water, and sit on the platform above the water for a 5-min break. During each break, subjects were shown the Whole Body Cold Discomfort Scale and asked to respond. At the end of the cold-water session, subjects were warmed in 40°C water.

Statistical Analysis

The following parameters were determined: breath-hold time (BHT), change in heart rate during each breath-hold, peak $\dot{V}_E$, mean steady-state (MSS) $\dot{V}_E$, time to steady-state (TSS) $\dot{V}_E$. Predicted endurance time (PET) for the HUEBA system in the post breath-hold period was also calculated.

Breath-hold was determined manually from the end of the large inspiration to the beginning of the next inspiration; this corresponds to the time the head could be under water. Change in heart rate was the difference from the start of breath-hold to the lowest value during the breath-hold.

Peak $\dot{V}_E$ was the highest value recorded in the post breath-hold period. Mean steady-state $\dot{V}_E$ was determined as follows: visual inspection (by the same observer) of the graph of $\dot{V}_E$ over time was used to estimate the point at which post breath-hold ventilation no longer decreased and leveled off. Data from this point to the end of the post breath-hold period (up to 90 s) was then averaged. Then, time to steady-state $\dot{V}_E$ was defined as the first point at which $\dot{V}_E$ decreased to the mean steady-state value.

Predicted endurance time included the length of breath-hold plus the time it would take to exhaust the standard air volume of 55 L in the HUEBA. The time to exhaust this air supply was calculated from the total ventilation during the period of elevated $\dot{V}_E$ added to the ventilation computed from the steady-state $\dot{V}_E$ subsequently achieved.

Skin temperature was calculated for the head, torso, arms, and legs. Since the proportional areas for each site within each body segment were similar, nonweighted means were calculated.

All statistical analyses were accomplished with the SigmaStat package within SigmaPlot 14. For heart rate in each condition, a paired *t*-test was used to compare the heart rates at the start of breath-hold with the lowest heart rates during breath-hold; this determined whether the change in heart rate during breath-hold was significant. Repeated measures two-way analysis of variance (ANOVA) (factor A, skin exposure; factor B, water temperature) then compared the change in heart rate during breath-hold and the other physiological variables. This analysis was also applied to the Whole Body Cold Discomfort Scale. Since this scale has 21 points (0–10 with increments of 0.5), results were treated as interval data, therefore justifying a parametric analysis.[12] Post hoc analyses for significant differences were accomplished using the Holm-Sidak test. Statistical significance was set at ($P < 0.05$). All data are expressed as mean ± SD.

RESULTS

During submersions there was no leakage through the main zipper and leakage was minimal, if any, through the neck and wrist seals. In one whole body exposure trial, the amount of water entering the suit was determined by adding the weight of water drained from the helicopter suit to the weight difference of the suit ensemble before and after submersion. In this trial, 13.7 L of water entered the suit.

For breath-hold time (**Fig. 2**), there was statistical significance for exposure condition [$P < 0.001$, $F = 37.5$, 4 degrees of freedom (df)], temperature ($P < 0.001$, $F = 30.3$, 1 df), and interaction ($P = 0.029$, $F = 3.0$, 4 df). In all submersion conditions, BHT was shorter in cold water by 12–19 s ($P \leq 0.003$). Submersion decreased BHT compared to control in both cold ($P < 0.001$) and warm ($P \leq 0.024$) water. Likewise, BHT was significantly lower in WB than all other conditions in cold ($P < 0.001$) and warm ($P \leq 0.007$) water. The only significant difference between the PF, F, and H conditions was between PF and H in cold water ($P = 0.26$). Partial face immersion in cold water decreased the breath-hold time from 52 ± 17 s (control) to 33 ± 14 s. Breath-hold time further decreased to 10 ± 4 s in the WB condition.

For several WB trials, heart rate data collection was interrupted when water entered the suit; therefore, all WB data were withdrawn from the analysis. Additionally, data collection failed for one or more of the PF, F, or H conditions for some subjects. Therefore, heart rate data were only analyzed for five subjects for whom complete data were available for control, PF, F, and H conditions for both water temperatures.

Although heart rate decreased significantly during the breath-hold in all control and exposure/temperature conditions

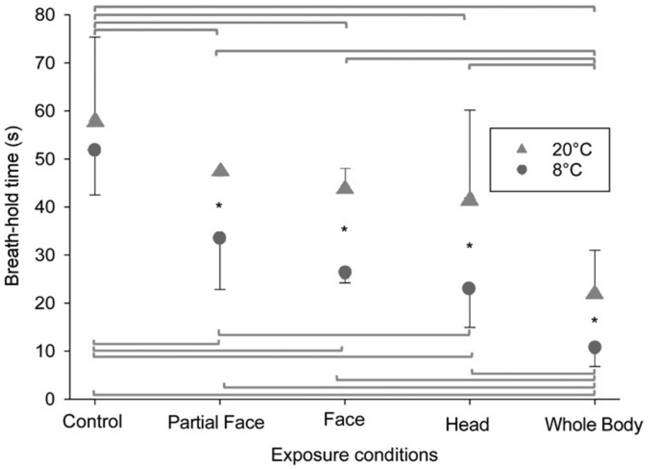

Fig. 2. Mean breath-hold time for all exposure conditions in cold (8°C) and cool (20°C) water ($N = 12$). The circles denote 8°C cold water and the triangles denote 20°C cool water. Vertical bars are the standard deviation; * indicates significant differences between water temperatures ($P < 0.05$). Horizontal brackets (top brackets correspond with the triangles and bottom brackets with the circles) indicate differences between exposure conditions within each water temperature condition ($P < 0.05$). Control: out of the water, suit zipped, and hood on; Partial Face: hood and mask on; Face: hood on and mask off; Head: hood and mask off; and Whole Body: suit unzipped, hood and mask off.

(the decrease ranged from 21 ± 15 to 32 ± 19 bpm; $P < 0.001$), there was no statistical significance for exposure condition ($P = 0.87$, $F = 0.24$, 3 df), temperature ($P = 0.82$, $F = 0.06$, 1 df), or interaction ($P = 0.42$, $F = 1.0$, 3 df).

For peak $\dot{V}_E$ (**Fig. 3**, top), there was statistical significance for exposure condition ($P < 0.001$, $F = 10.6$, 4 df), but not for temperature ($P = 0.68$, $F = 0.18$, 1 df) or interaction ($P = 0.70$, $F = 0.55$, 4 df). Peak $\dot{V}_E$ immediately post breath-hold was unaffected by water temperature but increased with increased skin exposure in both water temperatures. In cool water, peak $\dot{V}_E$ was significantly greater in WB ($79 \pm 43\ \mathrm{L \cdot min^{-1}}$) than control ($47 \pm 22\ \mathrm{L \cdot min^{-1}}$) ($P < 0.001$) and PF ($P = 0.01$). In cold water, peak $\dot{V}_E$ was significantly greater in WB ($86 \pm 43\ \mathrm{L \cdot min^{-1}}$) than control ($45 \pm 23\ \mathrm{L \cdot min^{-1}}$; $P < 0.001$) and all other exposure conditions ($P < 0.015$).

For mean steady-state $\dot{V}_E$ (Fig. 3, bottom), there was statistical significance for exposure condition ($P < 0.001$, $F = 30.3$, 4 df), temperature ($P < 0.001$, $F = 21.7$, 1 df), and interaction ($P < 0.001$, $F = 6.8$, 4 df). In cold water MSS $\dot{V}_E$ was higher in WB than all other conditions ($P < 0.001$), and higher in the H ($P < 0.01$) than the C ($P < 0.001$) and PF ($P = 0.05$) conditions. MSS $\dot{V}_E$ increased from control to WB in both cool water (14 ± 4 to $22 \pm 6\ \mathrm{L \cdot min^{-1}}$) ($P = 0.02$) and in cold water ($14 \pm 4$ to $40 \pm 16\ \mathrm{L \cdot min^{-1}}$) ($P < 0.001$).

For time to steady state $\dot{V}_E$, there was statistical significance for exposure condition ($P < 0.001$, $F = 6.8$, 4 df) and temperature ($P < 0.001$, $F = 22.8$, 1 df), but not for interaction ($P = 0.08$, $F = 2.2$, 4 df). TSS $\dot{V}_E$ was higher in 20°C water than 8°C water for the WB (53 and 30 s, respectively; $P < 0.001$) and H (34 and 20 s, respectively; $P = 0.01$) conditions. In 20°C water, TSS $\dot{V}_E$ for WB was higher than all other conditions ($P < 0.005$), which were not different from each other. There were no effects of condition on TSS $\dot{V}_E$ in 8°C water.

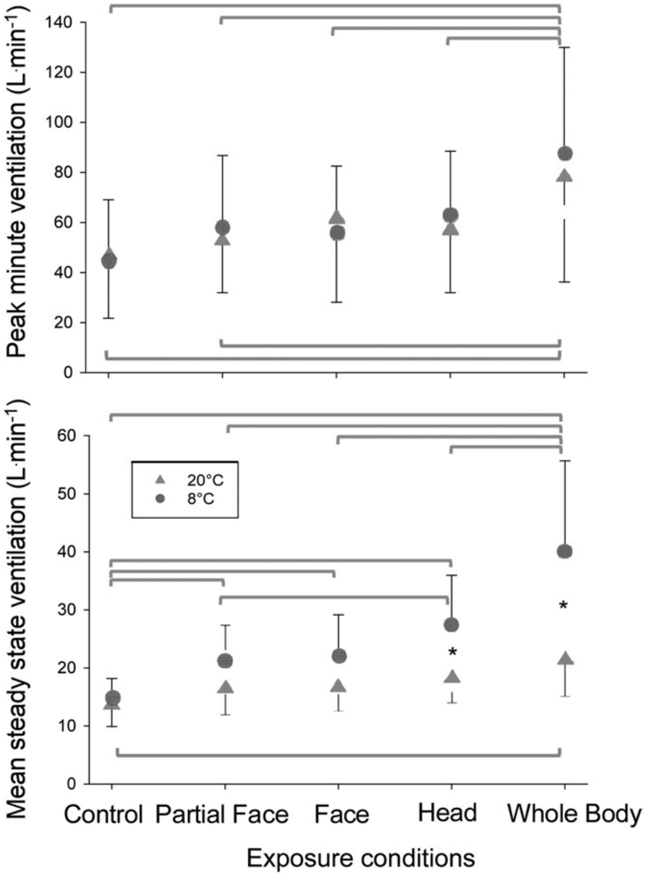

Fig. 3. Top: mean peak minute ventilation during the post breath-hold breathing period (up to 90 s) for all exposure conditions in cold (8°C) and cool (20°C) water ($N = 12$). Bottom: mean steady-state ventilation post breath-hold for all exposure conditions in cold (8°C) and cool (20°C) water ($N = 12$). The circles denote 8°C cold water and the triangles denote 20°C cool water. Vertical bars are the standard deviation; * indicates significant differences between water temperatures ($P < 0.05$). Horizontal brackets (top brackets correspond with the circles and bottom brackets with the triangles) indicate differences between exposure conditions ($P < 0.05$). Control: out of the water, suit zipped, and hood on; Partial Face: hood and mask on; Face: hood on and mask off; Head: hood and mask off; and Whole Body: suit unzipped, hood and mask off.

For predicted endurance time (**Fig. 4**), there was statistical significance for exposure condition ($P < 0.001$, $F = 35.6$, 4 df) and temperature ($P = 0.019$, $F = 7.5$, 1 df), but not interaction ($P = 0.2$, $F = 1.6$, 4 df). PET was similar in the control for both water temperatures (about 3 min 48 s). PET decreased from control in all exposure conditions in both 20°C water ($P < 0.001$) and 8°C water ($P < 0.04$). Likewise, PET was lower in WB than all other conditions in both 20°C water ($P \leq 0.01$) and 8°C water ($P < 0.001$). PET for the PF, F, and H conditions were not different from each other in any water temperature; in cold water their pooled average (2 min 29 s) was two times longer than WB (1 min 11 s) ($P < 0.02$), and in cool water their pooled average (3 min 5 s) was about 50% longer than WB (2 min 10 s) ($P < 0.02$).

Data for Whole Body Cold Discomfort (**Table I**) passed the tests for normality (Shapiro-Wilk) and equal variance

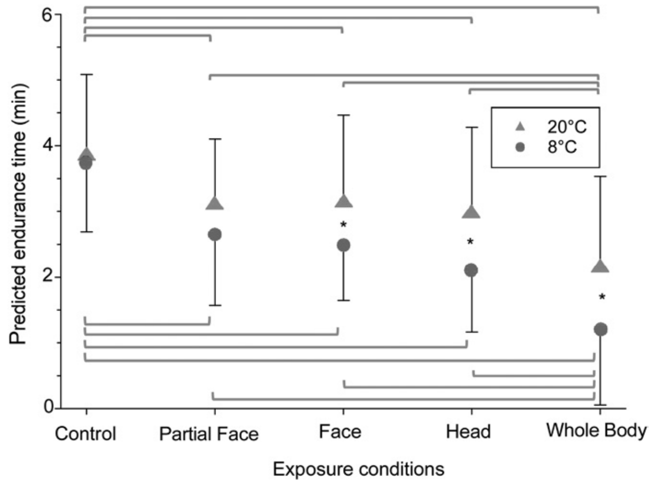

Fig. 4. Mean predicted endurance time for all exposure conditions in cold (8°C) and cool (20°C) water ($N = 12$). The circles denote 8°C cold water and the triangles denote 20°C cool water. Vertical bars are the standard deviation; * indicates significant differences between water temperatures ($P < 0.05$). Horizontal brackets (top brackets correspond with the triangles and bottom brackets with the circles) indicate differences between exposure conditions ($P < 0.05$). Control: out of the water, suit zipped, and hood on; Partial Face: hood and mask on; Face: hood on and mask off; Head: hood and mask off; and Whole Body: suit unzipped, hood and mask off.

(Brown-Forsythe). For these data there was statistical significance for exposure condition ($P < 0.001$, $F = 72.6$, 3 df) and temperature ($P < 0.001$, $F = 89.5$, 1 df), but not interaction ($P = 0.075$, $F = 2.5$, 3 df). Whole Body Cold Discomfort was significantly higher in cold water for all conditions ($P < 0.001$). For each water temperature, Whole Body Cold Discomfort in WB was significantly higher than all other conditions ($P < 0.001$). In 8°C water, cold discomfort also increased significantly from PF to F to H ($P < 0.02$). In 20°C water, the only other significant difference was found between PF and H ($P = 0.02$).

Skin temperatures for the four body segments (head, torso, arms, and legs) were similar during the presubmersion control period (ranging from 34.1 to 34.9°C). During all breath-hold submersions, T_{sk} decreased to similar values within each segment for the PF, F, and H conditions; therefore these results were pooled. In 8°C water the decrease in T_{sk} from control (listed here for the pooled value of PF, F, and H, and WB, respectively) was as follows: head (14.2 and 18.5°C); torso (2.4 and 19.4·°C); arms (2.8 and 16.2°C); and legs (5.1 and 19.6°C). Results in 20°C water were comparatively similar, but the decreases in T_{sk} were smaller. Therefore, submersion in the PF, F, and H conditions elicited small decreases for the torso, arms, and legs, but a large decrease for the head. WB submersion caused large decreases for all four body segments.

Table I. Whole Body Cold Discomfort.

T_{WATER}	PARTIAL FACE	FACE	HEAD	WHOLE BODY
8°C	4.7 ± 1.4	†5.7 ± 2.5	†7.3 ± 1.2	†8.9 ± 1.0
	*	*	*	*
20°C	‡0.5 ± 0.5	§1.0 ± 0.8	1.7 ± 1.1	†4.3 ± 1.6

Values (mean ± SD) for four skin exposure conditions in two water temperatures (0 = no cold sensation, to 10 = unbearably cold). T_{water}, water temperature.

*Significant effect of water temperature ($P < 0.05$); †separates values that are significantly different within each temperature condition ($P < 0.03$); ‡different between PF and H conditions ($P < 0.03$); §different between F and WB conditions ($P < 0.01$).

DISCUSSION

This study quantified the effects of water temperature and the amount of skin exposure on both breath-hold time and subsequent minute ventilation when the whole body and head are completely submerged below the water. We also predicted how these factors would affect the endurance time of a standard HUEBA system. Our hypotheses were generally confirmed. Decreasing water temperature and increasing skin exposure reduced the breath-hold time (to as low as 10 s), generally increased minute ventilation, and decreased predicted endurance time of a 55-L HUEBA system (to as short as 1 min 11 s).

Our decrease in breath-hold time is consistent with earlier studies. Hayward et al. demonstrated that decreasing water temperature from 15 to 0°C reduced breath-hold duration in uninsulated subjects during whole body and head submersion.[9] Similarly, breath-hold duration in 5°C water was reduced as different protective suits allowed increased skin cooling (e.g., drysuit, wetsuit, and cotton overalls, respectively).[25] The maximum effect of skin cooling on breath-hold was seen between the control (out of water) and cotton overalls in 5°C water (45 to 9 s, respectively). This effect was similar to our decrease from control to whole-body exposure in 8°C water (52 to 10 s, respectively). In a related study, breath-hold time during face-only immersion was also reduced as water temperature decreased from 15 to 0°C.[10] None of these studies focused on ventilation subsequent to the breath-hold.

The present increase in peak $\dot{V}_E$ with whole-body exposure in cold water supports earlier findings in 10 and 15°C head out immersions[6,16] where the magnitude of the gasp response (an indicator of respiratory drive and determined by mouth occlusion pressure at 0.1 s after onset of inspiration) was highest in whole-body exposure, followed by upper torso and arm exposure. These studies did not focus on breath-hold.

Our increase in steady-state $\dot{V}_E$ with colder water and increased skin exposure is consistent with studies in which mean $\dot{V}_E$ increases with less thermally protective clothing[14,23,25] or greater skin exposure (e.g., whole body vs. torso and/or limbs).[11,22] Decreasing water temperature from 25 to 5°C also increases mean $\dot{V}_E$.[11,24]

Following peak $\dot{V}_E$, the time to decrease to steady-state $\dot{V}_E$ was shorter in cold water and longest with WB exposure in 20°C water. Little attention has been paid to variations in the time to recover to a steady-state $\dot{V}_E$. Keatinge and Nadel observed that after maximum ventilation, there was a rapid decline to near-normal values within 20–30 s in 25°C showers.[11] Although they report that this decline was less abrupt in 0°C, no details or data were provided.

In the present study, breath-holding stimulated a similar decrease in heart rate in all conditions including the control (in air). This is consistent with findings by Hayward et al., who demonstrated similar decreases in heart rate during breath-holds in water temperatures ranging from 35°C (thermoneutral) to 0°C.[9]

In general, cold water exposure can elicit two opposing sets of responses. Body cooling elicits the cold shock response, which includes decreased breath-hold time, inspiratory gasp, and hyperventilation;[9] the magnitude of these responses are dependent on the amount of skin exposed, the amount of skin cooling, and rate of skin cooling.[16] Conversely, selective cooling of the face elicits the dive reflex, consisting of increased breath-hold time and decreased ventilation, heart rate, and cardiac output.[18] During combined head and body submersion, the ultimate responses will reflect the balance between these two stimuli. Since water cooling and increased skin exposure generally decreased breath-hold time and increased steady-state $\dot{V}_E$, it would seem the cold shock response predominated in these conditions in our generally inexperienced subjects.

Peak $\dot{V}_E$ following cold water breath-hold has not been well-documented with different water temperatures (e.g., 8 and 20°C). However, since this variable is a function of respiratory drive, it would be expected to be higher in colder water. This was not the case, however. Although colder water may increase respiratory drive immediately following breath-hold, it also shortened the breath-hold time, which would result in decreased arterial CO_2 compared to 20°C water. Thus, respiratory drive during whole body/head cooling may have been affected by offsetting stimuli (e.g., increased thermal drive from body surface cooling, and decreased chemical drive and thermal drive from head cooling).

Workers who are transported via helicopter to offshore oil rigs are not always trained explicitly for cold water survival. Cheung et al. demonstrated generally poor breath-hold ability in 228 offshore survival students, even during head-out immersion in 25°C water (median breath-hold time, 37 s; range, 5.4 to 120 s).[7] This would be expected to be much worse during whole body and head submersion in cold water.

Anything that increases underwater survival time in the immediate postcrash submersion period should increase the chance of escape from a helicopter that has crashed in water. Survival during submersion depends on breath-hold time and subsequent endurance time of a HUEBA (if it is available). This study has demonstrated that in cold water a helicopter transport suit can substantially increase both breath-hold time (from 10 to 33 s) and HUEBA endurance time (from about 1 to 2.5 min) through decreased minute ventilation and, thus, air consumption. The most significant factor regarding the use of the suit and mask is having the zipper done up completely with additional thermal sensation benefits provided by the hood and donning the dive mask prior to impact if possible. It must be acknowledged that long term use of this configuration in a warm helicopter potentially inflicts harmful heat stress.

Therefore, practical training for potential helicopter occupants should emphasize the proper use of the suit and mask. Occupants could also be informed that breath-hold time may be increased if they have enough time to take 1–5 deep breaths before submersion; this is long enough to increase the breath-hold time without creating a risk for hypoxic blackout.[17] Training could also include habituation or psychological training.[1,2,3]

The protocol did not follow a balanced order. Rather, a modified balanced order was followed in which the WB condition was last for all subjects. It is possible that this introduced an order or learning effect by the end of the trials. Breath-hold time could either have been lengthened by short term acclimation or shortened due to distraction and deterioration.

The protocol did not completely mimic real life situations. The mouthpiece used was not identical to that used with a HUEBA. The large bore nondemand valve was different than what the HUEBA system uses. It is not known if, or how, this may affect ventilation. The coldest water temperature (8°C) was warmer than some ocean temperatures during much of the year. Weights were used to allow complete submersion in the buoyant suits without requiring subjects to hold themselves underwater. The trials lacked other factors that would occur in a real crash such as: the element of surprise, potential inversion, and seat restraints. Disorientation is a significant factor which would tend to decrease survival time. Future cold-water studies could include inversion to increase the external validity of our results.

Subjects did not fit the demographic of many oil industry workers, who are older, less healthy, and less fit. It would, therefore, be beneficial if the study could be conducted on a group of subjects that better reflected an oil industry worker population, although this may introduce safety and ethics concerns. At the very least, a future study could determine the effect of our results on the attitudes and practices of workers who undergo training for offshore helicopter flights.

Heart rate data was incomplete for three subjects; therefore, data were only presented for five subjects. Finally, this study did not have enough men and women to allow for determination of any sex-dependent differences in the results. Future studies involving larger numbers of men and women are required to determine if any sex-dependent differences exist.

In conclusion, the results of this study confirm that proper skin coverage is required for protection against rapid skin cooling and the cold shock response. It further demonstrates the potential adverse effects of wearing a protective suit with the main zipper undone while flying over cold water. This information should be shared with helicopter occupants to convince them of the need to wear their protective equipment in full accordance with manufacturer recommendations.

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