Rebreather Unit to Prolong Underwater Survival Time

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INTRODUCTION: This study investigated whether the timing of activation affects the utility of an emergency underwater rebreather unit (RBU) when submerged in cold water.

METHOD: On two successive occasions, 16 male UK Royal Marines were submerged in stirred water at 12.2°C for up to 78 s. The subjects were lowered (taking 18 s) into the water in a seated position and were instructed to take a large breath in, activate the unit, breath-hold for as long as possible, exhale into the unit, and breathe normally to and from the unit for the remainder of submersion. On one occasion the subjects were instructed to activate the RBU when the water reached chest height (Condition-1) and, on the other, prior to the feet entering the water (Condition-2). Measurements were made of the duration of breath-hold, rebreathing and submersion, exhaled oxygen and carbon dioxide concentrations, skin temperature, and heart rate.

RESULTS: In 16 of the 32 submersions, the breath-hold was released before the subject became fully submerged and in 8 submersions the subject requested early withdrawal from the water. Mean (SD) breath-hold duration was 14.0 (13.8) s and the duration of rebreathing was 45.9 (21.9) s. The duration of breath-hold once completely submerged was longer in Condition-1 (9.1 s) than Condition-2 (4.1 s).

CONCLUSIONS: The study indicates the RBU should be activated just before the mouth becomes submerged rather than before entering the water, and that the RBU will prolong underwater stay time, thereby increasing survival prospects.

KEYWORDS: emergency underwater breathing apparatus, rebreathing, amphibious vehicle.

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The crew and passengers of the UK military Viking amphibious vehicle are provided with a military rebreather unit (RBU) to extend underwater survival time and allow escape from the vehicle should it begin to sink during maneuvers in water. The Viking is an armored, tracked, all-terrain vehicle, and can move through water at 5 kph and is used for river crossing and deployment from landing craft. The troop-carrying version can carry four people in the front cab and eight fully equipped troops in the rear unit. Escape from the front and rear cabs involves climbing out through a hatch in the cab roof and the hatches are kept open when the Viking is moving in water. Although an uncomplicated escape may only take 30-40 s (authors' unpublished observations), should sinking or rolling over occur, the time taken to escape will be longer, particularly for the last man exiting the rear cab.

The RBU is an air-tight 6.5-L bag (made from plasticized nylon) connected to a mouthpiece by rubber tubing. Upon submersion the user holds his breath (as they would if not provided with the device) and when unable to hold their breath any longer they breathe out into the bag and then rebreathe their expired air. The RBU is similar to the Air Pocket rebreather device supplied to helicopter passengers;[16] however, unlike helicopter passengers, the Royal Marine (RM) crew and passengers do not wear dry suits and hence are not overtly protected against the effects of the cold shock response when suddenly immersed in cold water.[20] This is likely to reduce their breath-hold time on immersion, as subjects immersed in water at 5°C were found to hold their breath for a mean of 19.1 s when wearing an immersion dry suit, but only 9.5 s when wearing a cotton coverall.[20] The cold shock response is initiated by the rapid reduction in skin temperature[7] and, in addition to the reduction in breath-hold time,

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uncontrollable breathing and hyperventilation, peripheral vasoconstriction, increased heart rate, and increased blood pressure are characteristics of the response.[15] As with emergency breathing systems for helicopter escape, it is the shortfall between the time needed to escape from the vehicle and breath-hold time in cold water that creates the rationale for providing an emergency underwater breathing apparatus.[3] However, whether the effects of the cold shock response would compromise the user's capability to use the RBU effectively in this user group is unclear and requires investigation.

The subjects in the current study were RM who had completed formal training with the RBU. In addition, the study also investigated whether activating the RBU before entering the water was beneficial compared to activating the RBU just before the mouth and nose became submerged. The advantage of activating the RBU before entering the water is that the users would be able to initiate and maintain the breath-hold and inhale sufficient air to subsequently rebreathe, whereas if they waited until immersed they might not be able to take an adequate inhalation of air due to the cold shock response and hence would not be able to use the RBU effectively. However, the duration of the RBU is limited as the oxygen in the bag becomes depleted and the carbon dioxide concentration in the RBU increases. Trials conducted in air, in which subjects breath-held and rebreathed continuously for as long as possible (or until the oxygen saturation of peripheral capillary blood fell to 90%) demonstrated that durations of the RBU ranged from 110 s to 206 s, depending upon the subject.[8] Hence, activating and using the RBU before entering the water would reduce the time that the user could continue to use the RBU effectively once underwater.

This study was undertaken to determine whether RM subjects dressed in combat clothing could remain submerged in cold water for up to 78 s by holding their breath and using a rebreather unit. The effect of activating the RBU before water entry, compared to once immersed to chest level, was also investigated. The tested hypothesis was that RM subjects would be able to breath-hold and then use the RBU successfully and remain submerged in cold water for 78 s, regardless of when the RBU was activated.

METHODS

Subjects

Taking part in the study were 16 RM who volunteered and had completed formal RM Viking training, including in-water training with the RBU. Informed consent was gained in accordance with the Declaration of Helsinki[22] and the protocol was approved by the Ministry of Defense (Navy) Personnel Research and Ethics Committee. All subjects were men as the RM is exclusively men and the RBU is issued to the RM. The mean (SD) age, height, body mass, and percentage body fat of subjects were 24.1 (3.3) yr, 1.78 (5.9) cm, 83.7 (9.3) kg, and 15.0 (3.7)%, respectively.

Procedure

The subjects undertook two conditions according to a counterbalanced design: Condition-1—subjects took a deep breath and activated the RBU when the water level was at chest height; Condition-2—subjects took a deep breath and activated the RBU before the feet entered the water. The subjects wore RM combat clothing consisting of a long-sleeved shirt, trousers, socks, boots and field jacket, and enhanced combat body armor with breast and back plates and webbing (mass of 14 kg). Over this they wore a manually operated, uninflated military lifejacket with the RBU attached. Each subject was reminded how to use the RBU and allowed to practice activating it and using the system in air until confident with the procedure. Subjects undertook the trial one at a time and were lowered into stirred water at 12.2°C at a controlled rate [$0.1\ m \cdot s^{-1}$ ($0.3\ ft \cdot s^{-1}$)] seated in a chair with the lap belt fastened. The subject was lowered until the chair was resting on the water tank floor [at a depth of 1.6 m (5.2 ft)]; it took 18 s for the subject to become fully submerged. Subjects entered the water with the RBU mouthpiece in place and the noseclip on. The subject was instructed to take a large breath as the water reached chest height (Condition-1) or before the feet entered the water (Condition-2), activate the unit by releasing the red knob, breath-hold for as long as possible, exhale into the unit, and then breathe to and from the unit for the remainder of the submersion.

The subject remained submerged to a maximum of 78 s, (i.e., 60 s completely submerged). The chair was raised from the water and once the subject's head was above the water, he was instructed to close the RBU after the next exhalation by pushing the red knob back into position and then take out the mouthpiece. Subjects wanting to come out of the water before the end of the submersion indicated this by pointing upwards and the chair was raised out of the water. A safety swimmer (wearing a dry suit) stood in the pool beside the subjects throughout the submersions. Subjects were rewarmed in a bath or shower (as they preferred) and then donned dry combat clothing and undertook the second submersion. There was a minimum of 30 min between each subject's two submersions. Breath-hold time in air was measured after the subject had rewarmed following the second submersion; the subjects were instructed to take a slightly larger breath than normal and hold their breath for as long as possible.

Equipment

Body mass was measured using scales (Satorius AG isi20, Goettingen, Germany) and height was measured using a stadiometer (The Leicester Height Measure, Seca Ltd, Birmingham, UK). Percentage body fat was determined from the sum of skinfold thickness measured at four sites using calipers (John Bull, Harpenden, UK).[5] Water temperature was measured with thermistors placed in the water [at depths of 1.2, 0.8, and 0.4 m (3.9, 2.6, and 1.3 ft) and within 1.0 m (3.3 ft) of the submerged subject] and recorded on a Grants data logger (1200 Series, Cambridge, UK).

The concentrations of carbon dioxide and oxygen in the rebreather bag at the end of rebreathing and the end tidal partial pressures of carbon dioxide ($P_{ET}CO_2$) and oxygen ($P_{ET}O_2$) were measured using a mass spectrometer (Airspec QP9000, Case, Kent, UK) and recorded (PowerLab, ADInstruments, Oxford, UK). $P_{ET}CO_2$ and $P_{ET}O_2$ were measured by continuously monitoring expired gas using a capillary tube placed in the mouthpiece of the RBU, just in front of the subject's lips. The breath-by-breath respiratory traces were used to determine respiratory frequency pre-immersion, the number of breaths taken during rebreathing, and the durations of breath-holding, rebreathing, and completely submerged breath-holding. These durations and total time submerged and breath-hold time in air were also measured by observation using a hand-held stop watch (Nero Lemania, L'Orient, Switzerland).

Electrocardiogram (ECG) and heart rate were monitored and recorded using electrode pads placed on the chest and a three lead hard wire system (PowerLab, ADInstruments, Oxford, UK). Heart rate data for analysis were determined from the number of heartbeats in the 60-s pre-submersion period and every 10 s during submersion. Mean skin temperature (T_{msk}) was calculated from skin temperature measured at four sites[11] using thermistors attached to the skin using tape and recorded on a data logger (Grants Instruments, 1200 Series, Cambridge, UK).

Statistical Analysis

The normality of the data was determined using the Kolmogorov-Smirnov test.[6] The Wilcoxon signed rank test[21] or paired *t*-test were used to compare water temperature, durations of submersion, breath-holding, and rebreathing and respiratory measurements between the two conditions and to determine any effect of the order of the conditions upon the durations of submersion, breath-holding, and rebreathing. Mean skin temperature and heart rate for the two conditions were compared using a two-way analysis of variance. Significance is reported as $P < 0.05$. Statistical analysis was undertaken using SPSS v16.0.[14]

RESULTS

There was no difference in the water temperature ($z = -0.07$, $P = 0.94$) between the two conditions; mean (SD) temperature was 12.2 (0.6)°C. **Fig. 1** and **Fig. 2** show breath-hold and rebreathing durations for each subject in Condition-1 and Condition-2. Three of the subjects in Condition-1 were removed from the water before the 78-s submersion was completed; two requested to be withdrawn and the third was withdrawn as his ECG showed an abnormal rhythm. In Condition-2, six of the submersions were terminated before the subjects completed the 78-s submersion, all at the subjects' own request.

The main reason cited by the subjects for requesting withdrawal was that they felt they could not breathe. Five subjects stated that they felt they had run out of or did not have enough air, one subject stated that he could not maintain the seal on the mouthpiece, and one subject did not think that the RBU was working (the RBU was checked and found to be fully functional). The mean (SD) PO_2 and PCO_2 of the gas remaining in the RBU for these subjects were 15.3 (1.7) kPa and 5.7 (0.9) kPa, the minimum PO_2 was 11.9 kPa, and the maximum PCO_2 was 6.8 kPa.

Breath-hold and submersion duration and the duration of rebreathing did not differ for the two conditions. Mean values and statistical output are shown in **Table I**. In Condition-1, seven subjects broke their breath-hold before they were fully submerged, as did nine in Condition-2. A further one subject in Condition-1 and two subjects in Condition-2 broke the breath-hold just as they became submerged. Breath-hold duration once completely submerged was longer in Condition-1 than Condition-2. Mean (SD) (minimum to maximum) breath-hold time in air was 88 (33) (52 to 182) s.

The duration of submersion was longer ($z = -2.20$, $P = 0.03$) on the second submersion than the first: mean (SD) submersion times were 61.5 (25.6) s in Condition-1 and 71.4 (15.7) s in Condition-2. There was no effect of order on breath-hold ($z = -1.16$, $P = 0.25$), submerged breath-hold ($z = -0.15$, $P = 0.88$), or rebreathing ($z = -1.71$, $P = 0.09$) durations.

There were no differences in T_{msk} between the two conditions [$F_{(1,7)} = 1.72$, $P = 0.23$] or the rate of fall of T_{msk} between 0 and 30 s ($t = 0.20$, $P = 0.85$). T_{msk} varied with time [$F_{(1,9)} = 255.19$, $P < 0.01$], falling rapidly during the first 30 s of submersion from a mean (SD) pre-immersion temperature of 30.8 (2.0)°C to 24.4 (2.6)°C and then more slowly during the final 50 s of submersion to 22.0 (2.1)°C. The mean (SD) rate of fall of skin temperature (from 0 to 30 s) was 12.4 (3.4)°C · min^{-1}.

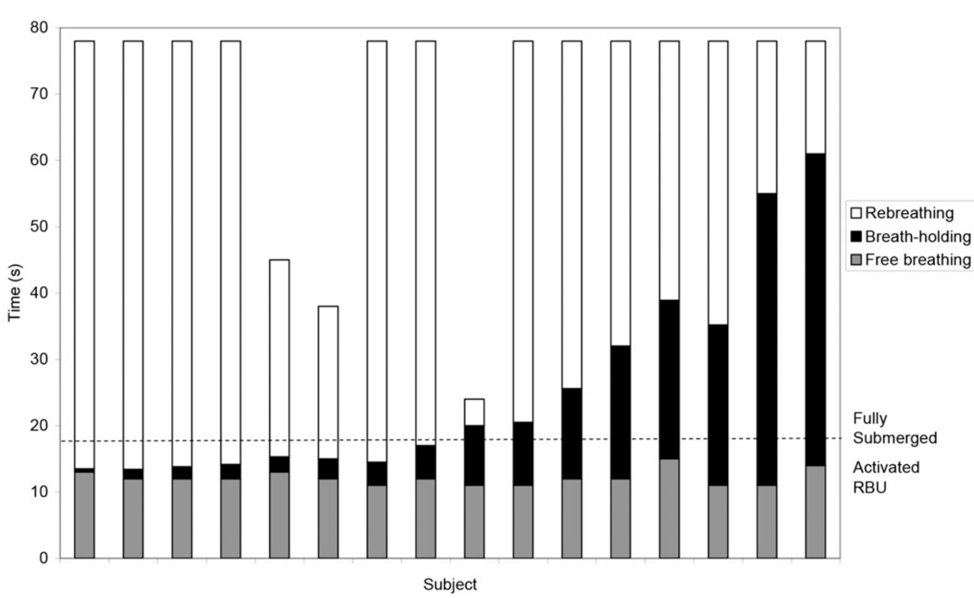

Fig. 1. Duration of breath-hold and rebreathing in Condition-1 (activate the RBU when water is at chest height).

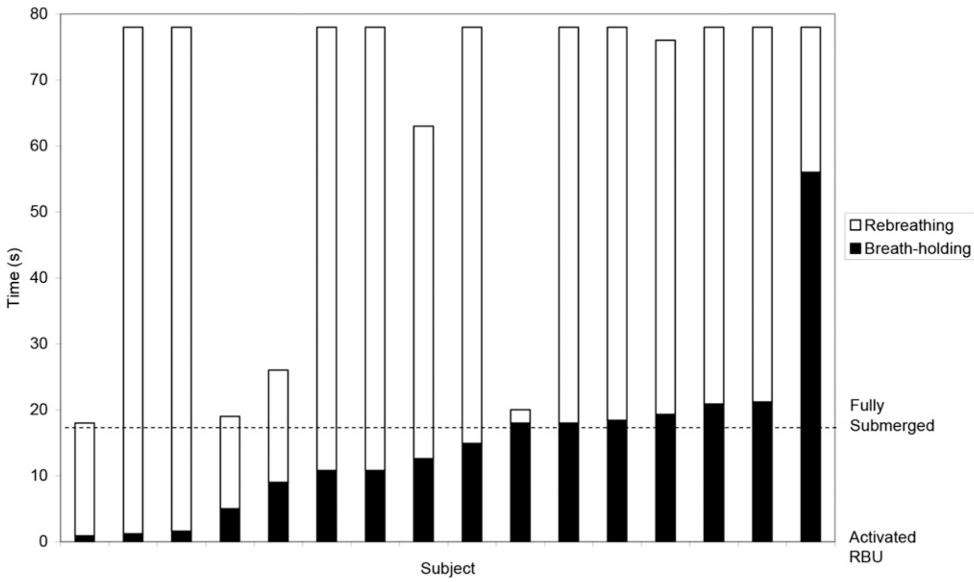

Fig. 2. Duration of breath-hold and rebreathing in Condition-2 (activate the RBU before the feet enter the water).

Mean (SD) $P_{ET}O_2$ and $P_{ET}CO_2$ at rest, upon breaking the initial breath-hold, and the PO_2 and PCO_2 of the gas remaining in the rebreathing bag at the completion of rebreathing, and respiratory frequency and the number of breaths made during rebreathing are shown in **Table II**. There were no differences between the two conditions for these measurements. However, for the $N = 7$ subjects with complete data for both 78-s submersions, PO_2 in the rebreathing bag was lower in Condition-2. There were no differences in respiratory frequency or the number of rebreathing breaths made between the two conditions.

Heart rate varied with time [$F_{(1,13)} = 13.22$ $P < 0.01$], but was similar [$F_{(1,13)} = 0.00$ $P = 1.00$] in both conditions. Pre-immersion mean (SD) heart rate for the two conditions was 107 (25) bpm; during the first 10 s heart rate increased to 126 (21) bpm and then fell to 89 (31) bpm by 20 s when fully submerged. Heart rate continued to fall, reaching 65 (20) bpm by 50 s, but then remained stable. Bradycardia (defined as at least five consecutive R-R intervals of greater than 1.2-s intervals) was demonstrated in seven subjects. There were 14 subjects who exhibited an arrhythmia in at least 1 submersion, with arrhythmias occurring in 24 of the 32 submersions. All arrhythmias occurred after subjects had broken the initial breath-hold (although not necessarily immediately straight after breaking the breath-hold). The most common arrhythmia was ventricular ectopic beats, which were produced by 13 subjects, junctional premature (escape) beats were demonstrated by 8 subjects, sequences of bigeminy were shown by 3 subjects, instances of ventricular tachycardia by 3 subjects, and there were 2 instances of premature atrial beats in 1 subject (1 in each submersion).

DISCUSSION

This study was undertaken to determine whether RM can use an emergency RBU effectively when submerged in cold water, and whether the timing of when the RBU is activated influences utility. With only 10 of the 16 subjects successfully using the RBU and remaining submerged for the full 78 s of the experiment in both conditions, the results only partially support the hypothesis that RM subjects would be able to breath-hold and then use the RBU successfully and remain submerged in cold water for 78 s, regardless of when the RBU was activated. As five of the subjects requested to be withdrawn from the water within the first 10 s of full submersion in at least one condition, it is clear that not all RMs would be able to use the RBU effectively in cold water. Activating the RBU before the feet entered the water rather than waiting until the water reached chest height conferred no benefit, and it is recommended that the RBU should be activated when the water reaches chest height or just before the mouth becomes submerged.

Using the RBU allowed the majority of subjects to prolong submersion time beyond the breath-hold duration, which is in agreement with previous work,[17] but in contrast to other findings.[13] In the study reporting that the subjects could remain underwater for at least a further 30 s after breaking their breath-hold by rebreathing using the AirPocket, the subjects were wearing an immersion dry suit, which would protect against the effects of the cold shock response.[17] However, the subjects in the study which reported that rebreathing (using the Shell MkII rebreather unit) provided no advantage over breath-holding during submersion in water at 11°C wore only jeans, shirt, and an immersion coverall.[13] Hence, the results of the current study suggest that even without an immersion dry suit, the majority of RM can effectively use and derive benefit from a RBU in cold water.

The majority of subjects broke their breath-hold prior to full submersion and their breath-hold duration on submersion was substantially less than in air, suggesting that they were affected by the cold shock response. However, the reduction in skin temperature was quite modest (mean T_{msk} at 30 s was 24.4°C), whereas mean T_{msk} for subjects immersed (head-out) in water at 5°C wearing a

Table I. Mean (SD) (Minimum to Maximum) Breath-Hold, Submerged Breath-Hold, Submersion, and Rebreathing Durations for Conditions-1 and 2 and Statistical Output ($N = 16$).

	CONDITION-1	CONDITION-2	STATISTICAL OUTPUT
Breath-hold time (s)	13.2 (14.9) (0.5 to 47.0)	14.9 (13.0) (0.9 to 56.0)	$z = -0.66$; $P = 0.51$
Breath-hold time once completely submerged (s)	9.1 (14.1) (0.0 to 44.0)	4.1 (10.1) (0.0 to 41.0)	$z = -2.09$; $P = 0.04$
Submerged time (s)	70.1 (17.5) (24.0 to 78.0)	62.6 (25.3) (18.0 to 78.0)	$z = -1.15$; $P = 0.25$
Rebreathing time (s)	44.8 (20.0) (4.0 to 64.6)	47.7 (26.4) (2.0 to 76.8)	$z = -1.40$; $P = 0.16$

Table II. Mean (SD) Respiratory Data and Statistical Output (*N* = 16, Unless Stated as *N* = 7, Which Includes the Subjects Who Completed the 78-s Submersion in Both Conditions).

	CONDITION-1	CONDITION-2	STATISTICAL OUTPUT
Resting $P_{ET}O_2$ (kPa)	16.4 (0.8)	16.1 (1.0)	t = 1.86 *P* = 0.08
Resting $P_{ET}CO_2$ (kPa)	5.2 (0.4)	5.2 (0.6)	z = -1.53 *P* = 0.13
$P_{ET}O_2$ upon breaking breath-hold (kPa)	16.8 (1.8)	16.4 (1.6)	t = 1.23 *P* = 0.23
$P_{ET}CO_2$ upon breaking breath-hold (kPa)	4.9 (1.2)	5.4 (1.0)	t = -1.41 *P* = 0.18
Po_2 in the bag following rebreathing (kPa)	10.5 (3.3)	10.6 (3.5)	t = 1.08 *P* = 0.30
Pco_2 in the bag following rebreathing (kPa)	7.0 (0.7)	6.9 (0.8)	z = -1.45 *P* = 0.15
Po_2 in the bag following rebreathing (kPa) (*N* = 7)	10.6 (1.0)	8.7 (1.1)	t = 9.59 *P* < 0.01
Pco_2 in the bag following rebreathing (kPa) (*N* = 7)	7.0 (0.4)	7.3 (0.4)	t = -1.75 *P* = 0.13
Resting respiratory frequency (number)	16.9 (3.9)	16.6 (4.3)	t = 1.86 *P* = 0.08
Rebreathing breaths (number)	6.9 (7.5)	7.1 (4.3)	z = -1.05 *P* = 0.30
Rebreathing breaths (number) (*N* = 7)	4.0 (2.9)	6.4 (4.3)	t = -1.33 *P* = 0.23

cotton overall had fallen to 18.2°C by 30 s of immersion and their mean breath-hold time was 9.5 s.[20] This suggests that submersing the head in the current study may have significantly contributed to the magnitude of the cold shock experienced by subjects and their inability to maintain their breath-hold. It is unlikely that $P_{ET}O_2$ and $P_{ET}CO_2$ were responsible for the breaking of the breath-hold, as $P_{ET}O_2$ is much higher and $P_{ET}CO_2$ is much lower than measured at break-point in studies of maximum breath-hold in air, in which $P_{ET}O_2$ and $P_{ET}CO_2$ are reported as 8.2 (0.5) kPa and 7.2 (0.3) kPa.[9] One subject reported difficulty keeping the mouthpiece in place, which may have been due to the direct effect of the cold water numbing the mouth and face.

The RBU provided a substantial benefit of increasing the time that the subjects were able to remain underwater beyond their underwater breath-hold time, in 1 case by up to 14 times. This could have been more as some subjects may have been able to continue using the RBU beyond the 78-s experimental cutoff limit. However, as has been previously shown, not all subjects can use underwater breathing devices in cold water. Of eight subjects, three could not tolerate using an emergency underwater breathing device in water at 5 and 15°C despite wearing an immersion dry suit.[17] In addition, that study and the current study may under-represent the true number of individuals who would be unable to use an emergency underwater breathing device in cold water, as the subjects for both studies volunteered and knew that the study would involve submersion in cold water.

The Po_2 and Pco_2 of the gas remaining in the rebreather bag for the subjects that requested to be withdrawn from the water before completing the 78-s submersion were (with the exception of one subject in Condition-2) higher (Po_2) and lower (Pco_2) than the mean value for the subjects in this study completing the 78-s submersion, indicating that neither a low Po_2 nor a high Pco_2 were the reason for withdrawal. The alveolar Po_2 for hypoxic loss of consciousness has been reported as 4.0 to 5.1 kPa,[4] suggesting that if the subjects had been able to remain underwater, the RBU was usable. However, as the volume of gas remaining in the RBU was not measured, it is possible that when the subjects reported that they felt they could not breathe or that they had run out of air, this was because they were not able to inhale the volume of air that they wanted. This would occur if the volume of the initial breath-hold was not as large as the breaths taken during rebreathing, both of which could be caused by the effects of the cold shock response.[15]

The data in the present study suggest that activating the RBU before the feet entered the water rather than waiting until the water reached chest height confers no benefit. This conclusion is based upon the higher number of subjects requesting early withdrawal when activating the RBU before the feet entered the water (six in Condition-2 compared to two in Condition-1), breath-hold time once completely submerged was shorter when activating the RBU before the feet entered the water, and the Po_2 of the mixed expired air in the bag upon completing the submersion, which was lower in Condition-2 than Condition-1. As the skin temperature data were similar for the two conditions, it can be concluded that the differing responses were due to the timing of RBU activation.

Although the hypothesis is partially unsupported as some RM would not be able to use the RBU effectively in cold water, this largely reflects the individual variation in response, which is known to exist upon immersion in cold water.[10] It should be noted that the subjects were not performing any exercise and that no attempt was made to simulate the actions or activity required to egress a vehicle. Such activity would increase metabolic rate and possibly shorten the duration of viable submersion. In a real emergency, it is possible that the subjects would be more motivated to breath-hold and rebreathe for longer than demonstrated in this study, although these might, conversely, be negatively affected by panic.

A large number of heart rhythm abnormalities were observed in the study; similar abnormalities have been reported in studies involving breath-holding during submersion in cold water[19] and in subjects undertaking helicopter underwater escape training and breath-holding in warm water.[18] These arrhythmias are thought to be due to conflicting chronotropic inputs to the heart with a strong sympathetic drive caused by the cold shock response or anxiety and a vagally mediated parasympathetic response to apneic face immersion (also known as the "diving response").[1,2] The clinical implications of the arrhythmias are unclear as the evidence of the current and previous studies suggest that the majority have little clinical importance as they are short in duration, mainly supraventricular in origin, and produce no symptoms. However, in susceptible individuals their occurrence may be significant.

There are several possibilities that could be considered to improve the prospects for personnel attempting to escape from a sinking Viking vehicle. As there was only a modest fall in skin temperature, providing an immersion dry suit is likely to only be of limited value, whereas providing some form of thermal head protection may be more beneficial. Although an emergency short-term air supply system has been found to be easier to use, more comfortable, and subjects reported greater confidence in the device than in the Air Pocket during a mock helicopter escape exercise,[16] it is unlikely that the RBU would be replaced by a compressed gas system because of the nature of the work undertaken using the Viking vehicle. Modifications to the RBU itself, such as priming the RBU ensemble so that there is some air already in the unit prior to submersion could be considered as this would reduce the reliance on the adequacy of the volume of last inhalation before submersion for the RBU to be effective. The findings from helicopter underwater escape incidents are pertinent for escape from the Viking vehicle; notably escape training, providing breathing apparatus, and illuminating the escape exits are advocated for enhancing the chances of surviving a helicopter crash at sea.[12] Although the RM already undertake in-water training with the RBU, extending this to include training in cold water may be beneficial.

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