Will prior hyperventilation reduce cerebral blood flow during escape from a submarine?

C. M. HOUSE, D. F. GRIST, and D. D. DENISON

Institute of Naval Medicine, Gosport, United Kingdom

House CM, Grist DF, Denison DD. Will prior hyperventilation reduce cerebral blood flow during escape from a submarine? Undersea Hyper Med 2001; 28(4):201-205.—This study was undertaken to determine if hyperventilation would reduce cerebral blood velocity (CBV) and thereby the risk of decompression illness (DCI) during escape from a submarine and increase the depth from which escape can be made. CBV was measured in eight subjects using Doppler ultrasound as they completed a mock submarine escape exercise. The exercise involved climbing a ladder followed by immersion in cold water—in a real escape the escapee would be exposed to increased pressure and at risk of DCI during the immersion phase. Immediately before the escape exercise the seated subjects either rested or hyperventilated at a controlled rate for 2 min. There was a third condition in which the subjects hyperventilated for 2 min and then sat and rested. The three conditions were each undertaken twice. Hyperventilation reduced mean CBV by 45%. In the first session during the first 90 s of immersion, CBV was 10% lower (P < 0.05) when the escape procedure followed hyperventilation than when following rest. In the second session CBV was similar for the two escape conditions. Following hyperventilation the restoration of CBV was more rapid during the escape condition than when the subjects rested—the reasons for this are unclear. It is concluded that, although hyperventilation effectively reduces CBV, the reduction is neither sustained during the escape procedure nor sufficiently consistent to recommend that it should be used before escape from a submarine.

decompression illness; hyperventilation; submarine escape; cerebral blood flow; Doppler ultrasonography

The depth that free ascent escape can safely be made from a submarine is limited by the physiologic risk to the escapee of developing neurological decompression illness (DCI) (White MG, Seddon F, unpublished data 1997). To make an escape from a Royal Navy submarine, the escapee wearing a specialized escape suit would climb the ladder (approximately 1.2 m in height) into the submarines escape tower. He would plug the suit into the air supply (this puts air into the suit), and the tower would then be flooded with sea water to approximately chest height and then rapidly pressurized (18–20 s). When the pressure in the tower reached that of the surrounding sea water, the upper hatch to the tower would open and the escapee would ascend to the surface at 2.8 m · s⁻¹. During an uncomplicated escape from 180 m the escapee would be exposed to raised pressure for approximately 90 s.

The tissues of the central nervous system (CNS) are at particular risk of DCI during submarine escape because of their high level of perfusion and therefore rapid uptake of nitrogen. Mathematical modeling, which combined a model of bubble dynamics with one of the body, calculated that during the compression phase of escape the tissue partial pressure of nitrogen in the gray matter, would increase from 0.8 to 3.0 bar, and during decompression rise to 8 bar (1). The model predicted that the partial pressure of nitrogen in muscle would remain at 0.8 bar throughout compression and decompression and that the volume of gas in bubbles formed in the gray matter would be 2.5 times greater than that in muscle. Experiments with goats support the calculations made by the model; as the incidents of DCI when goats are exposed to escape profiles in a hyperbaric chamber predominantly involve the CNS, whereas the DCI incidents following saturation dive profiles influence the limbs and joints (White MG, and Seddon F, unpublished data 1997). When the Pachychea sank in 1988, of the 22 submariners who successfully escaped all were diagnosed and treated for DCI; however, in that incident the pressure inside the submarine was probably raised which would have contributed to the development of DCI (2).

It has been suggested that deliberate hyperventilation before escape will reduce the risk of the submariners developing neurologic DCI during escape and could increase the depth from which escapes can be made (3). Hyperventilation reduces the arterial partial pressure of carbon dioxide, which causes vasoconstriction in central nervous blood vessels, thereby reducing cerebral perfusion. During the compression and decompression phases of the escape procedure this would theoretically reduce the uptake of nitrogen by these tissues. Although it is well established that hyperventilation reduces cerebral
blood flow (CBF) (4–6) the subsequent effects of the actions of the escape procedure upon CBF have not been evaluated. In isolation, exercise and immersion in cold water have been shown to affect arterial partial pressure of carbon dioxide and hence influence CBF (7–9); however, in all these studies changes were examined relative to normal resting levels.

This experiment was conducted to test the hypothesis that prior hyperventilation—a potent vasoconstrictor of CNS tissue—would reduce cerebral perfusion during the immersion phase of a mock submarine escape procedure. Such a reduction would theoretically reduce the uptake of nitrogen by the CNS during compression and decompression and therefore lessen the risk of DCI and increase the depth from which submarine escapes can be made. Changes in cerebral perfusion were assessed by measuring cerebral blood velocity (CBV) in the middle cerebral artery using transcranial Doppler ultrasound. CBV is representative of CBF assuming that the cross-sectional area of the insonated artery does not change; previous research suggests that this is a reasonable assumption (10–12). The technique is non-invasive and can monitor rapid changes in CBV.

METHOD

Eight males volunteered for the experiment, only male subjects were recruited, as all Royal Navy submariners are male. Their informed consent was gained in accordance with the Declaration of Helsinki, and the Ministry of Defence (Navy) Personnel Research and Ethical Committee approved the protocol. The subjects were a mean (SD) height of 179 (10) cm; mass of 80 (18) kg and were 31(6) yr old.

Experimental design: The trial was conducted in two phases; the initial phase in which the subjects practiced the hyperventilation procedure and the subsequent experimental phase.

Initial phase: The subjects practiced the hyperventilation procedure until they could perform it in a reproducible manner. The subjects were seated and breathed room air via a mouthpiece. The air was delivered at a rate of 40 liter · min⁻¹ and was supplied via a 2-liter anesthetic bag, the subjects inhaled to empty the anesthetic bag 20 times · min⁻¹ (the rate was set by a metronome). The subjects did this for 5 min. The subjects were seated and resting for 15 min before beginning hyperventilation, and they repeated the hyperventilation procedure twice more at each session. At least 20-min recovery was provided between repeats (end tidal carbon dioxide was monitored to ensure that it had returned to normal before beginning the next run). Measurements were made of heart rate, end tidal carbon dioxide, and CBV during hyperventilation and for 5 min before (control period) and 10 min after. The subjects were required to repeat the series of three hyperventilation procedures at additional sessions (on different days) until their mean CBV during the final 3 min of hyperventilation, on the three repetitions did not differ by more than 5%. The maximum number of sessions required by any subject was three. The subjects completed this phase before beginning the experimental phase.

Experimental phase: There were three experimental conditions which the subjects undertook twice:

- Two minutes hyperventilation followed by 10 min seated recovery (HYP-REST);
- Two minutes hyperventilation followed by escape procedure (HYP-ESCAPE);
- Two minutes seated rest followed by escape procedure (REST-ESCAPE).

The subjects undertook all three conditions during one experimental session, resting for 15 min before the first condition and for at least 20 min between subsequent conditions. They undertook the conditions according to a randomized Latin Square order. The subjects repeated the procedure at the same time the following day.

Clothing: The subjects wore submariners normal working clothing (cotton/polyester shirt and trousers), over which they wore the Mark 10 Submarine Escape and Immersion Equipment (SEIE). The SEIE consists of an inner liner made from spun bonded polyethylene and a single skin impermeable outer dry suit made from polyurethane-impregnated nylon (the ensemble also includes a one-man liferaft which was not used in this study). The inner and outer suits were zipped up before beginning the hyperventilation procedure; however, the hood from the dry suit was not pulled up as this would have interfered with the measurement of CBV.

The hyperventilation procedure: The subjects hyperventilated for 2 min according to the procedure described above. Upon ceasing hyperventilation they were asked to rate their symptoms of hyperventilation on a 7-point scale ranging from no symptoms [0] to severe muscle spasms in the extremities or face [7]. They were then required to immediately undertake the escape procedure (HYP-ESCAPE) or remain seated (HYP-REST).

The escape procedure: Upon ceasing hyperventilation or rest, the subjects immediately stood up and then climbed up a near vertical step ladder which had four steps and was 0.7 m in height. They then stood on a platform in a cage and plugged the hood inflation nozzle from their suit into the receptor on the cage. The subject (standing vertically) was then immersed to mid thoracic level in water at 2.1°C (SD 0.3°C) by lowering the cage
HYPERVENTILATION BEFORE SUBMARINE ESCAPE

into the water at a rate of 0.07 m·s⁻¹. The subjects were immersed for 3 min. The air temperature in the pool room was 20°C, relative humidity 50%.

Experimental measures: Cerebral blood velocity was measured in the left middle cerebral artery (MCA) using a transcranial ultrasonic Doppler device (Nicolet EME Companion, Wisconsin, USA) operating at 2 MHz. The ultrasonic probe was placed over the temporal window just above the zygomatic arch, the position of the probe and the depth of the signal were adjusted so that the optimum flow signal from the MCA was obtained. The probe was securely attached to the head using a Muller and Moll fixation device (Nicolet instruments, Wisconsin, USA). Mean blood velocity was continuously recorded throughout each experimental session. The calibration of the ultrasonic Doppler system was checked against known flow from a phantom blood flow generator.

Partial pressure of end-tidal carbon dioxide (PetCO₂) was measured using a mass spectrometer (Airspec QP9000, CaSe, Kent, England). The gas sample was taken just in front of the subjects lips using a capillary tube placed in the mouthpiece. The spectrometer records the maximum percentage of CO₂ in each expire, which has been converted to PetCO₂ at BTPS and reported in kilopascals (kPa).

Electrocardiograph was monitored continuously on an optically isolated diascop (Lifepulse 15, HME, Herts, UK), and heart rate was recorded at 1-min intervals on a data logger (Grants Instruments Ltd, Cambridge, UK).

Mean skin temperature was calculated from skin temperatures measured on the shin, thigh, upper arm, and chest (13), and peripheral skin temperature was measured continuously on the finger pad of the right index finger and the back of the right hand using thermistors (Grants Instruments Ltd).

All equipment was calibrated and sterilized according to the manufacturers instructions using the appropriate calibration standards and sterilizing techniques. A three-point calibration was conducted on the temperature thermistors at 1°C, 15°C, and 30°C.

Data analysis: In the experimental phase, the average blood velocity through the MCA during the 5 min before beginning each experimental condition was recorded at 30-s intervals. The CBVs for these periods were averaged and these values taken as the control CBV. Subsequent CBV readings were calculated relative to the control value.

Comparisons of CBV for the three conditions during the two sessions were made using a repeated measures analysis of variance. Normality assumptions on the residual of the model were checked and transformations of the data (logarithm) applied where necessary. To test whether CBV during the immersion phase of a mock escape exercise would be reduced by prior hyperventilation CBV data during the first 90 s of immersion in HYPI-ESCAPE and REST-ESCAPE were compared. PetCO₂ was analyzed at the corresponding times, and mean skin temperatures, heart rate, and symptom scores for hyperventilation for each condition were calculated.

RESULTS

During HYPI-ESCAPE it took the subjects an average of 18.7 s to climb to the top of the ladder whereas during REST-ESCAPE it only took 13.8 s. It took longer following hyperventilation because the mouthpiece had to be unattached from the tubing connecting it to the anesthetic bag. From the top of the ladder to being immersed took an average of 53.4 s for HYPI-ESCAPE and 56.8 s for REST-ESCAPE. None of these differences is significant (P < 0.05).

Initial analysis of the CBV data from the three conditions across the two sessions showed a significant (P < 0.05) effect of session, therefore subsequent analysis was conducted on data from the two sessions separately. Mean CBV (S.D.) during the control period for the conditions in session 1 was 55.0 (4.5) cm·s⁻¹ and during session 2 was 54.6 (4.3) cm·s⁻¹. The corresponding PetCO₂ were 5.56 (0.30) kPa and 5.56 (0.39) kPa. Table 1 shows mean (minimum and maximum) CBV (as a percent of the control level) upon completion of 2 min of hyperventilation/rest and during the first 90 s of immersion/rest for each of the sessions.

Hyperventilation reduced mean PetCO₂ by approxi-

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<tr>
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<th>HYPI-REST</th>
<th>HYPI-ESCAPE</th>
<th>REST-ESCAPE</th>
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<tbody>
<tr>
<td>S1: end hyperventilation/rest</td>
<td>53.6 (43.5:67.2)</td>
<td>54.5 (46.8:65.9)</td>
<td>100.2 (91.0:109.4)*</td>
</tr>
<tr>
<td>S2: end hyperventilation/rest</td>
<td>54.8 (41.4:70.9)</td>
<td>55.3 (45.6:66.4)</td>
<td>99.5 (88.4:109.4)*</td>
</tr>
<tr>
<td>S1: 90 s immersion/rest</td>
<td>88.1 (72.8:114.3)</td>
<td>95.6 (78.2:120.1)</td>
<td>106.0 (92.3:124.2)*</td>
</tr>
<tr>
<td>S2: 90 s immersion/rest</td>
<td>86.3 (52.8:104.8)*</td>
<td>104.2 (78.3:128.9)</td>
<td>106.4 (89.7:121.7)</td>
</tr>
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*Significantly different (P < 0.05) from HYPI-ESCAPE.
mately 2.5 kPa and mean CBV by approximately 45%. During the first 90 s of immersion in session 1, mean CBV was 10.4% lower when the immersion followed hyperventilation than when following rest, this difference is significant ($P < 0.05$). In session 2 the mean difference was only 2.2% which is not significant. PetCO2 during the first 90 s of immersion was significantly lower ($P < 0.05$) in HYP-ESCAPE than REST-ESCAPE in session 1 but not in session 2.

The most commonly reported symptoms following hyperventilation were "mild lightheadedness or dizziness" which was a symptom score of 2, the lowest score reported was 0—no symptoms—and the highest score 5, which was "severe tingling in extremities or tingling in lips". The reductions in mean skin, hand and finger temperature were the same for the two immersion conditions. Mean heart rates were similar for the two sessions; upon immersion following hyperventilation mean heart rate was 96 beats · min⁻¹, 88 beats · min⁻¹ when the escape procedure followed rest and at the corresponding time during HYP-REST 69 beats · min⁻¹.

**DISCUSSION**

The results do not conclusively support the hypothesis that CBV during the immersion phase of a simulated submarine escape exercise would be reduced by prior hyperventilation. Although hyperventilation was successful in reducing CBV to approximately 55% of its control level, by the time the subjects were immersed in the water their mean CBV was restored to a mean of 86.3% (session 1) and 102.5% (session 2). This substantially limits the benefits of hyperventilation as a method of reducing the risks of DCI during submarine escape.

Delaying hyperventilation until inside the escape tower, although theoretically an attractive option, would not be possible in reality as the escapees need to fully don the hood on the escape suit before they escape, and there is not sufficient space inside the escape tower to do this and they may require assistance. If the escapees hyperventilated in the tower with the suit hood suit already donned they would be rebreathing their exhaled breath, which would negate the benefits of hyperventilation. In addition, a period of hyperventilation in the tower would increase the overall time needed to escape, which could compromise the survival of those waiting to escape.

Cerebral blood velocity was restored more rapidly during the escape procedure following hyperventilation than when the subjects sat and rested. In addition the restoration of CBV in HYP-ESCAPE occurred more quickly than that of PetCO2. The reason for the rapid rise in CBV during the escape procedure following hyperventilation is not certain. The favored theory is that it is due to greater stimulation from the sympathetic system in this condition, a view supported by the heart rate data. Previous researchers have shown that electrical stimulation of the sympathetic cord in the upper thoracic level during hyperventilation raised CBV in the middle cerebral artery by 32% and that this was preceded by an increase in heart rate (14).

The rapid rise in CBV during the escape exercise following hyperventilation could have occurred because of a decrease in the diameter of the MCA. With the Doppler technique used in this study it is not possible to measure the diameter of the vessel and to determine changes in blood flow it is assumed that the diameter of the artery does not change. This assumption has been supported by a number of researchers. Angiographic measurements and measurements made using the 133Xe-clearance technique have shown that the diameter of the MCA does not change during hypocapnia or hypercapnia and exercise (10,15). In addition, if changes in the diameter of the MCA were responsible for the rapid restoration of CBV during HYP-ESCAPE, we would expect a similar increase in CBV in the REST-ESCAPE condition. As this did not occur, we would suggest these findings were not due to methodologic factors.

It is suggested that the CBV results differed between the two sessions because the subjects became habituated to the cold water. Although the SEIE is a dry suit, the integral gloves are made from leather and allow water to pass through them. Previous research has shown that cold
water immersion is associated with a reduction in PetCO₂ and CBV (18) and that with repeated immersions the PetCO₂ response is attenuated (19).

It is concluded that although hyperventilation effectively reduces CBV, the reduction is not sustained during the escape procedure and therefore we would not recommend that it should be used before escape from a submarine.

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REFERENCES
