Thermal effects of dorsal head immersion in cold water on nonshivering humans

Gordon G. Giesbrecht, Tamara L. Lockhart, Gerald K. Bristow, and Allan M. Steinman

Laboratory for Exercise and Environmental Medicine, Health, Leisure and Human Performance Research Institute, University of Manitoba, Winnipeg, Canada

Submitted 18 January 2005; accepted in final form 11 July 2005

PERSONAL FLOTATION DEVICES (PFDs) can be highly effective in prolonging the survival of victims of accidental cold-water immersion. If properly worn, a PFD can provide significant buoyancy assistance to a survivor in maintaining airway freeboard, thus reducing the likelihood of drowning. Although the amount of buoyancy is an important part of a PFD’s design, flotation posture may be equally critical. PFDs generally fit to the water. It is controversial whether cooling the dorsum of the head itself can have a substantial effect on the rate of core cooling. One hypothesis predicts a substantial heat loss through the head because of the great amount of surface blood flow in the scalp and because scalp blood vessels do not vasoconstrict in response to cold as do surface vessels in other body areas. An alternative hypothesis predicts minimal heat loss from the back of the head because immersion of the back of the head and neck would only involve 3–5% more of the BSA. As well, mathematical modeling predicts minimal conductive heat loss directly through the scalp and skull.

A few studies have addressed head cooling in animals exposed to cold water (3) and in humans exposed to cold air (6, 17), but only two human studies have included cold-water exposure of the head. Alexander (1) reported the earliest data on head cooling from studies carried out on prisoners of war in Dachau during World War II. These studies indicated that cooling the back of the head caused discomfort and significantly hastened the onset of hypothermia (1). However, these studies were grossly unethical, and the results are considered invalid and unusable because of the emaciated condition of the prisoners as well as questions regarding the protocol and accuracy of the results.

A recent study demonstrated that dorsal head immersion in 10°C water had a minimal effect on core temperature when the body was insulated (15). However, when both head and body were immersed, the body core cooling rate was 87% faster than when only the body (except for the upper chest) was immersed. Although this study addressed the specific effect of conductive heat loss through the dorsal head, core cooling would have been attenuated by shivering heat production, which is a factor that likely differed between exposure conditions. Thus the effect of head heat loss in humans in cold water requires further study.

Therefore, the purpose of this study was to isolate the specific effect of dorsal head heat loss in a protocol where either the body and/or dorsal head were exposed to cold water and where the confounding effect of shivering heat production was minimized by the use of meperidine (Demerol). This study has practical implications for conditions where shivering is absent, such as severe hypothermia, shivering fatigue during long-term cold water survival, and head trauma.

Dorsal head immersion was expected to have a minimal effect when the body was insulated but a significant effect when added to whole body cold exposure. As well, the effect of dorsal head immersion, when the body was exposed, was
expected to be greater with shivering inhibited compared with when shivering was intact (15).

METHODS

Subjects

The experimental protocol was approved by the University of Manitoba Education/Nursing Research Ethics Board. Six volunteer male subjects, each of whom provided written, informed consent, were selected for the study. These subjects were both mentally and physically healthy and had no significant medical history, and none had male-pattern baldness. They completed a medical (Physical Activity Readiness Questionnaire) questionnaire to ensure that they were free from cardiorespiratory disease and other conditions that could be exacerbated by exposure to cold water. They were studied on four separate occasions at least 24 h apart but at the same time each day to control for circadian effects. Abstinence from alcohol and tobacco for 12 h before the study was requested. They were also asked to fast for 8 h before coming to the laboratory to minimize any potential nausea caused by meperidine infusion. Compliance to these requests was confirmed before each trial.

Height, weight, age, skinfold thickness at four sites, and underwa
ter weight were determined; percent body fat was calculated based on hydrodensiometry (2). Anthropometric data for the subjects are shown in Table 1.

Instrumentation

For each trial, subjects wore a swimsuit while being instrumented in a room at an ambient temperature of 22°C. Core temperature was measured by a thermocouple in the esophagus (Tes) at the level of the cardiac atria. This site has previously been shown to provide the closest correlation to intracardiac temperature (11). Single-channel electrocardiogram and heart rate were also monitored for the duration of each trial and recorded at 30-s intervals with the metabolic information. An intravenous line was introduced into a hand vein for 

respiratory heat loss (RHL; in W) was calculated in dependence of 

Body weight were determined; percent body fat was calculated based on 

hydrodensiometry (2). BSA, body surface area. 

\[ \text{BSA} = \frac{\text{height} \times \text{weight}}{3600} \] 

Body composition was assessed by dual-energy X-ray absorptiometry (Lunar Prodigy, Madison, WI). In this method, the subject lay supine on a stretcher and was lowered with an electronically isolated hoist into the water. The order of conditions for each subject was randomly assigned to achieve a balanced design.

Immersion Conditions

Subjects were immersed four times in 12°C water. This water temperature was used, rather than the 10°C water temperature used in our laboratory’s previous study (15), because it was found that meperidine, at the maximum dose allowed, could better inhibit shivering at the higher water temperature. For each condition, the subjects lay supine on a stretcher and were lowered with an electronically isolated hoist into the water. The order of conditions for each subject was randomly assigned to achieve a balanced design.

Body exposed, head out. The subjects wore only a bathing suit and PFD 1, which was a Type I, Safety of Life at Sea Reference Vest (model 2000, United States Coast Guard). This PFD placed the subject in a semirecumbent position with the head and upper chest out of the water. In this condition, subjects were instructed to assume a position that they felt would most likely simulate their position in a real-life situation. Most of the subjects adopted a position in which they held onto the PFD with their hands and part of their forearms out of the water; they held their legs pressed together and flexed at the knees and hips (i.e., Heat Escape Lessening Position).

Body exposed, dorsal head immersed. The subjects wore only a bathing suit and PFD 2, which was a Type V, User-Assisted Inflatable PFD (belt-pack style). This PFD placed the subject in a horizontal position with the back of the head immersed in the water to the level of the ears. The entire torso was also immersed. Subjects were given the same instructions as for PFD 1 except that the back of the head was to remain immersed in the water at all times. Most subjects assumed a similar position as with PFD 1.

Body insulated, dorsal head immersed. This condition was designed to isolate the effects of back of the head cooling. Subjects donned a 1.5-mm-thick vulcanized rubber dry suit worn over thermal underwear (top and pants), a fleece suit, and two pairs of socks. The head was not insulated. During immersion, the subjects would lie in the water horizontally with the back of the head immersed enough to include the ears. The resulting posture left ~40% of their anterior body above the water.

Body insulated, dorsal head out. The subjects donned the same insulated dry suit and adopted the same immersion posture as described above. However, a dry suit hood was worn over a fleece hood, which was added for head insulation. Subjects were lightly supported on a stretcher, which was tilted to ensure that the head was completely

### Table 1. Descriptive data for six subjects

<table>
<thead>
<tr>
<th>Subject No.</th>
<th>Age, yr</th>
<th>Height, cm</th>
<th>Weight, kg</th>
<th>BSA, m²</th>
<th>Sum of 4 Skinfolds, mm</th>
<th>Body Fat, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>22</td>
<td>177</td>
<td>68.8</td>
<td>1.83</td>
<td>69.9</td>
<td>15.0</td>
</tr>
<tr>
<td>2</td>
<td>22</td>
<td>180</td>
<td>69.5</td>
<td>1.91</td>
<td>63.4</td>
<td>21.7</td>
</tr>
<tr>
<td>3</td>
<td>33</td>
<td>184</td>
<td>89.0</td>
<td>2.08</td>
<td>65.6</td>
<td>22.5</td>
</tr>
<tr>
<td>4</td>
<td>22</td>
<td>189</td>
<td>87.0</td>
<td>2.13</td>
<td>77.0</td>
<td>18.9</td>
</tr>
<tr>
<td>5</td>
<td>27</td>
<td>189</td>
<td>91.7</td>
<td>2.20</td>
<td>61.3</td>
<td>23.8</td>
</tr>
<tr>
<td>6</td>
<td>25</td>
<td>183</td>
<td>68.5</td>
<td>1.88</td>
<td>38.1</td>
<td>15.8</td>
</tr>
<tr>
<td>Mean</td>
<td>27.0</td>
<td>184.5</td>
<td>79.1</td>
<td>2.01</td>
<td>62.6</td>
<td>19.6</td>
</tr>
<tr>
<td>SD</td>
<td>5.0</td>
<td>4.7</td>
<td>1.1</td>
<td>0.2</td>
<td>13.2</td>
<td>3.6</td>
</tr>
</tbody>
</table>

Four skinfolds are from biceps, triceps, subscapularis, and suprailiac crest. Body fat was estimated by hydrodensiometry (2). BSA, body surface area.

Oxygen consumption (\(\dot{V}O_2\)) was measured with an open-circuit from expired minute volume and inspired and mixed expired gas concentrations sampled from a mixing box (model Vmax 229, Sensormedics). \(\dot{V}O_2\) (in ml·kg\(^{-1}\)·min\(^{-1}\)) and BSA (in m\(^2\)) were used to calculate metabolic heat production (\(M\); in W) based on the equivalence of 3.5 ml·kg\(^{-1}\)·min\(^{-1}\) to 58.15 W/m\(^2\) as follows:

\[
M = \dot{V}O_2 / 3.5 \times 58.15 \times \text{BSA} \]

Respiratory heat loss (RHL; in W) was calculated in dependence of metabolism (5):

\[
RHL = 0.09M 
\]

Total energy production for the 30 min of immersion was calculated by converting the mean \(\dot{V}O_2\) during that period to kilojoules. Total energy loss was calculated as the sum of total body cutaneous heat flux and respiratory heat loss. The change in systemic heat content was determined by integrating the difference between total energy loss and production over the first 30 min of immersion. This method correlates well with direct measurements of tissue heat (13, 16).
out of the water while as much of the body was in the water as possible.

Protocol

After instrumentation, the subjects donned the required buoyancy devices and lay on the suspended stretcher. Twenty minutes of baseline measurements were then started. Ten minutes before immersion, the subjects were given 1.5 mg/kg of meperidine intravenously (diluted in 10 ml of saline) injected in five 2-ml aliquots in successive 2-min intervals. They were then lowered into the water.

Shivering heat production, as indicated by increased M and subjective evaluation, was inhibited as required with further injections of meperidine to a maximal cumulative dose of 2.5 mg/kg. Arterial oxygen saturation was monitored as an index of respiratory depression. If saturation decreased below ~95%, subjects were roused and encouraged to breathe more vigorously.

The subjects remained immersed until one of four removal criteria was met: 1) immersion time of 60 min, 2) voluntary request by a subject for removal, 3) Tes reached 34°C, or 4) termination of immersion by investigator for safety reasons. Upon removal from the cold water, subjects were placed in a 40°C stirred water bath until Tes was >36°C and they felt comfortably warm.

Data Analysis

Some subjects cooled quickly in the body-exposed conditions and reached a Tes of 34°C in as little as 30 min. Therefore, most of the analysis was done for 30 min, which was the longest time during which all subjects were immersed in all conditions.

The following calculations were then made for each condition: 1) decrease in Tes from baseline to 30 min and the end of immersion; 2) the rate of core cooling (calculated by linear regression for Tes data from 10 to 30 min of immersion); 3) cutaneous heat transfer from the head, the rest of the body, and the head and body combined (total body); 4) area-weighted mean skin temperature. Group results were calculated for each trial, and data for the four trials were compared using repeated-measures analysis of variance. Results are reported as means ± SD. P < 0.05 identified statistically significant differences. The Holm-Sidak test was used for post hoc analysis of significant differences.

RESULTS

Subjects were closely monitored for adverse affects during the serial meperidine injections. On immersion there was a transient increase in metabolism. Subsequent injections of meperidine alleviated cold discomfort as well as metabolic and visual evidence of shivering.

All subjects remained immersed for 60 min in both body-insulated conditions. In the body-exposed, head-out condition, only two subjects remained immersed for the entire 60 min because the other subjects reached the cutoff Tes of 34°C within a range of 36–48 min. In the body-exposed, dorsal head-immersion condition, all subjects exited the water before 60 min because they reached the cutoff Tes of 34°C within 30 to 57 min. Because the longest time at which all six subjects were immersed in all four conditions was 30 min, data are presented and analyzed for the first 30 min of immersion.

Core Temperature Responses

Tes decreased significantly after 15 min in all conditions (Fig. 1). After 30 min of immersion in the body-insulated conditions, Tes decreased from baseline values of 37.1 ± 0.3°C to 36.6 ± 0.2 and 36.4 ± 0.3°C in the head-out and dorsal head-immersion conditions, respectively (P < 0.01), with no difference between the two conditions. Tes was lower in the body-exposed conditions than body-insulated conditions from 15 min of immersion on (P < 0.01). After 30 min in the body-exposed conditions, Tes decreased more in the dorsal head-immersion condition (to 34.6 ± 0.6°C) than in the head-out condition (to 35.3 ± 0.6°C) (P < 0.01). The only two conditions in which all subjects were able to remain immersed for 60 min were the body-insulated conditions. After 60 min, Tes was significantly lower with dorsal head immersion (36.0 ± 0.3°C) than with the head out (36.4 ± 0.2°C) (P < 0.03).

Mean Skin Temperature Responses

During the baseline period, mean skin temperature was slightly, but significantly, higher during body-insulated conditions (33.4 ± 0.7°C) than without insulation (31.7 ± 0.7°C; P < 0.01). Area-weighted mean skin temperature decreased slightly in the body-insulated conditions to 31.7 ± 1.0°C after 30 min of immersion (P < 0.001). In the body-exposed conditions, area-weighted mean skin temperature decreased more during cooling in dorsal head-immersion (to 15.9 ± 1.1°C) vs. head-out (to 17.7 ± 0.5°C) conditions (P < 0.001).
Metabolic Responses

Baseline values for \(\dot{V}O_2\) were similar for all conditions, and there were no differences between the initial 10 min of baseline and the 10 min of meperidine injections (Fig. 2). \(\dot{V}O_2\) remained at or below baseline levels throughout immersion in both body-insulated conditions. In the two body-exposed conditions, three subjects started to shiver slightly after ~20 min of immersion due to the combination of increased thermal stimulus to shiver (from decreasing core temperature) and metabolism of meperidine. Thus \(\dot{V}O_2\) did not increase during immersion in the body-exposed head-out condition and increased slightly by ~18% over baseline \((P < 0.01)\) in the body-exposed head-in condition. Values were slightly, but significantly, higher during immersion in both body-exposed conditions compared with the body-insulated conditions \((P < 0.01)\).

There were no intercondition differences in heart rate. Baseline heart rate was 74 ± 5 beats/min. After a transient increase to 109 ± 9 (body-exposed conditions) and 86 ± 5 beats/min (body-insulated conditions) during entry into the water, heart rate decreased gradually in all conditions from 70 ± 4 to 66 ± 4 beats/min from 10 to 30 min of immersion, respectively.

Total Cutaneous Heat Loss

Total body cutaneous heat loss was similar in all baseline conditions (Fig. 3). Heat loss increased markedly immediately on immersion with the effect in exposed areas gradually decreasing as skin cooled and the temperature gradient between skin and water decreased.

Heat loss and energy production during 30 min of cooling are presented in absolute terms in Fig. 4; values are for total body (including respiratory heat loss) and each main body region. Total body heat loss was ~2.8 times greater in the body-exposed conditions than the body-insulated conditions \((P < 0.01)\) with the greatest loss seen in the body-exposed, dorsal head-immersed condition \((P < 0.03)\). The only difference between body-insulated conditions was that head heat loss was greater in the head-in condition \((P < 0.01)\). Compared with the body-insulated conditions, heat loss was greater with the body exposed in all areas except the head and arms \((P < 0.003)\). Greater heat loss from the head and trunk caused higher total heat loss when dorsal head immersion was combined with body exposure \((P < 0.02)\).

\(\chi^2\) Analysis indicated that observed heat loss differed significantly from that expected (based on the assumption of
similar relative heat loss from each body region) only in the body-insulated, head-out condition (P < 0.01). In this condition, trunk loss was lower than expected and leg loss was greater than expected. There were no significant differences between observed and expected results in any of the other three conditions.

The negative energy balance during immersion was significantly higher in the body-exposed conditions (−951 and −810 kJ with head in and head out, respectively) than body-insulated conditions (−262 and −171 kJ with head in and head out, respectively) (P < 0.05).

**DISCUSSION**

This was the first ethically approved study to evaluate the isolated contribution of dorsal head and upper chest cooling on lowering of core temperature (as low as 34°C) using a human model for severe hypothermia where the complicating factor of shivering heat production was inhibited with meperidine. When the body was insulated, dorsal head immersion did not increase core cooling compared with the head-out condition. However, dorsal head immersion during whole body cooling significantly increased core cooling. After 30 min of immersion with the body exposed, T<sub>e</sub>, declined by 1.8°C in the body-exposed, head-out condition. When the dorsal head and upper chest were also immersed, T<sub>e</sub>, declined by 2.5°C. The calculated cooling rate for the dorsal head-immersed condition (5.0°C/h) was 40% greater than for the body-exposed, head-out condition (3.6°C/h).

Previous studies with intact shivering have also reported that cooling the dorsal head only had little effect on core cooling, whereas dorsal head cooling increased core cooling significantly when the whole body was also immersed. Alexander (1) reported that core cooling, in 1–2°C water, increased from 3.8 to 9.4°C/h (250%) when the dorsal head was also immersed with the rest of the body. Similarly, in our laboratory’s previous study (15), dorsal head immersion in 10°C water increased core cooling by 87% from 1.5 to 2.8°C/h. Hayward et al. (10) reported similar relative differences when subjects were physically active in 10°C water. They demonstrated that drown proofing (which intermittently submersed the whole head) increased core cooling by 36% to 4.6°C/h, compared with 3.4°C/h while treading water with the head above water.

**Possible Mechanisms for the Results**

The contribution of head immersion to core temperature cooling was of major interest in this study. Blood flow in the face and scalp remains relatively high and constant compared with the rest of the body. Hertzman (12) found that the ratio of head blood flow to surface area is 4–10 times greater than seen in the trunk and proximal limbs. Froese (6) found little or no head skin vasoconstriction in response to cold, whether the cold stimuli came from the head alone or even during cooling of the whole body surface.

The results of the present study did not confirm the supposition of proportionately greater heat loss from the head. The measured heat loss from the head in both dorsal head-immersed conditions was only ~60 kJ (compared with 18–33 kJ in the two head-out conditions) In contrast, total body heat loss in the body-exposed configurations was ~1,100 and 1,260 kJ, respectively, for head-out and dorsal head-in conditions. Thus the head accounted for only ~3 and 5% of the total body heat loss, respectively, in the body-exposed conditions. The surface area of the head and neck is ~9% of the total BSA, and in this study only the dorsal head and neck were immersed. The results of this study thus indicate that heat losses from the head are not disproportionately increased over what would be expected from the head’s contribution to total BSA. The dorsal head and neck, representing ~5% of the total BSA, contributed a similar proportion of the increased total body heat loss in the body-exposed, head-in condition. This confirms the prediction of Xu et al. (20), who hypothesized minimal heat loss from the dorsal head on the basis of modeling and experimental findings.

Most of the immersed dorsal head was covered with hair. The skin was not shaved in any area to compare heat loss from shaved and hair-covered areas of the immersed scalp.
quent studies involving whole-head immersion in 17°C water have demonstrated that heat loss is ~28% less from hair-covered skin (234 W/m²) than on the bare forehead (323 W/m²; Giesbrecht GG, Pretorius P, and Bristow, GK, unpublished observations). A light mesh hood was used to hold the heat flux transducer snugly against the hair of the back of the head. This eliminated a layer of water between the hair and transducer, thus ensuring that heat loss from the skin, and through the hair, was channeled through the transducer. The mesh was light and provided negligible insulation.

The differences found in core cooling and heat loss between the body-exposed, dorsal head-immersed and the body-exposed, head-out conditions in this study were also affected by truncal immersion. Subjects wearing PFD 1 (body exposed, head out) not only had their upper chest out of the water but that region was also partially insulated by the PFD itself. In contrast, subjects wearing PFD 2 (body exposed, dorsal head immersed) not only had their posterior head and neck immersed but their entire trunk as well. Total body heat loss over 30 min for subjects wearing PFD 1 was ~1,100 kJ; truncal heat loss in the same period was ~374 kJ (~34% of total heat loss). For subjects wearing PFD 2, total body heat loss over 30 min was ~1,260 kJ; truncal heat loss in the same period was ~500 kJ (39% of total heat loss). Because the upper chest accounts for ~5% of total body surface area, the percent increase in truncal heat loss found in PFD 2 compared with PFD 1 approximates the percent increase in truncal surface area immersed in PFD 2 compared with PFD 1.

Consistent with our laboratory’s previous study (15), head cooling in the dry suit resulted in only a small drop in $T_{es}$ whereas the addition of head cooling to body cooling resulted in a large difference in $T_{es}$ decline between the two PFDs. The fact that back of the head and upper chest exposure with PFD 2 had a large affect on core cooling while isolated back of the head cooling in the dry suit condition did not may be explained by differences in the “effective perfused mass” (19) in these two conditions. In the body-insulated condition, the extremities would likely be relatively vasodilated and well perfused, because the insulated body was not significantly cold stressed and core temperature remained near normal. Any cooling effect from the back of the head would likely be dissipated throughout the larger volume of perfused body tissue, so the net cooling effect would be negligible. In the body-exposed condition, initial cooling of body and dorsal head skin, and subsequent core cooling, would cause considerable vasoconstriction, thus a smaller volume of core tissue would be perfused. Cooled blood from the scalp and upper chest would thus be distributed into a much smaller tissue volume and the net cooling effect on that core tissue would be greater. This effect of exaggerated rates of core temperature change was previously described in a warming study by Vanggaard et al. (19).

Over the first 30 min of immersion, meperidine inhibited nearly all of the subjects’ shivering heat production. There was only a small (18%) increase in mean $V_O_2$ values in the body-exposed dorsal head-in condition compared with baseline values. Because maximal shivering is normally capable of increasing $V_O_2$ by 400–500% (4), the use of meperidine in this study eliminated virtually all of the potential shivering thermogenesis.

**Practical Implications of Results**

This study has practical implications for PFD design and survival conditions where shivering is absent in immersed individuals, such as severe hypothermia, shivering fatigue during long-term cold-water survival, and head trauma. Water temperature was slightly warmer in the present study compared with our laboratory’s previous study with the same exposure conditions (12 vs. 10°C) (15). However, inhibition of shivering heat production in the present study approximately doubled the core cooling rates in the respective body-exposed conditions even though the absolute effect of dorsal head immersion was ~1.3°C/h in each study.

The high rates of core cooling found in this study (~3.6°C/h for the body-exposed, head-out condition; 5.0°C/h for the body-exposed, dorsal head-in condition) would be associated with relatively short survival times in a real-world cold-water immersion incident. Survivors who have lost the ability to generate heat through shivering (e.g., those with severe hypothermia) would rapidly cool to temperatures where loss of consciousness is probable (e.g., 30°C) and where fatal ventricular dysrhythmias become increasingly likely (e.g., 25°C).

Froese (6) postulated that enough heat can be lost through the head alone to cause core cooling (6). This supposition has gained wide acceptance in both land and sea survival literature and training manuals, wherein the head is considered a source of high heat loss. The results of this study show that victims with their body exposed are at a critical disadvantage in a cold-water survival situation when the dorsal head and upper chest are also immersed. The additional 10% of total body surface area immersed with PFD 2 (i.e., 5% from dorsal head and neck plus 5% from upper chest) increases the core cooling rate and decreases potential survival time. As demonstrated previously (15), head cooling is also associated with cognitive decrements, which would be expected to increase in severity with decreasing core temperatures.

In rough seas, waves would increase the exposed surface area of both PFDs, resulting in increased heat loss and possibly cooling rates. Thus the disadvantages described for dorsal head immersion would become even more significant in a rough-water environment. Steinman et al. (18) demonstrated significant increases in cooling rates for subjects wearing various types of PFDs and protective clothing in rough seas compared with calm seas. In an actual survival situation involving waves, the disadvantages of PFD 2 may be even more pronounced, particularly if the horizontal flotation posture resulted in a larger number of full head immersions than would occur in PFD 1. On the other hand, rough seas would also be expected to result in periodic full-chest immersions and head immersions for survivors wearing PFD 1, thus increasing the rate of heat loss over that found in these calm-water studies.

In conclusion, inhibition of shivering increased core cooling by about double the rate compared with when shivering was intact. Two different PFDs were used during cold-water immersions to either hold the head and upper chest out of the water or to allow the entire body and the dorsal head to be immersed. Increasing the immersed BSA by 10% (i.e., the dorsal head and neck, and upper chest) increased core cooling disproportionately by 39%, likely as a result of cold-induced redistribution of blood flow to a smaller perfused body core mass. Further study to determine the effect of whole head
cooling, without the positional and insulation complications of PFDs, would be valuable.

ACKNOWLEDGMENTS

The authors acknowledge the guidance and assistance Sam Wehr of the US Coast Guard’s Lifesaving and Fire Standards Division of the Marine Safety, Security and Environmental Protection Directorate.

GRANTS

This study was supported by a contract from the United States Coast Guard and grants from the Natural Science and Engineering Research Council of Canada and the Randy Chipperfield Hypothermia Research Fund.

REFERENCES