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TITLE

THE EFFECT OF WAVE MOTION ON DRY SUIT INSULATION AND THE RESPONSES TO COLD WATER IMMERSION

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The Effect of Wave Motion on Dry Suit Insulation and the Responses to Cold Water Immersion

M. B. DUCHARME, M.SC., PH.D., AND C. J. BROOKS, M.B.CH.B., D.AV.MED.

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Methods: Six subjects who were each wearing a dry immersion suit system were immersed for 1 h in 16°C water in a number of different wave conditions, ranging from still water to 70 cm in height. Physiological and physical parameters were measured in order to calculate the total thermal resistance of the suit system and its components. ***Results:*** None of the physiological parameters were affected significantly by the wave conditions, except for skin heat flux, which increased with wave height from 72.0 ± 1.9 $W \cdot m^{-2}$, at 0 cm of height, to 85.5 ± 2.9 $W \cdot m^{-2}$, at 70 cm of height. Wave heights up to 70 cm decreased the insulation (including boundary layer) of the dry suit system by 14%, and the only component of the suit affected by the wave motion was the insulation of the water boundary layer, which decreased by 75%. The body sites that were most affected by wave motion were the head and the trunk, with an average 45% decrement in suit system thermal resistance at those sites at wave heights of 0 to 70 cm. No significant effect was observed at sites on the distal limbs. ***Conclusion:*** To simulate open ocean conditions in the laboratory, the standards must take the reduction of suit insulation into account.

THE CONCEPT OF AN immersion suit to protect humans in cold water is not new. There are samples of Eskimo exposure suits in the Danish National Museum that are over 100 yr old. Loss of life from shipwreck or from falling over the ship's side has, until recently, been accepted as an occupational hazard for mariners (19). In the days of impressment, the concept of issuing an item of life support equipment such as a life jacket or immersion suit to a sailor was not accepted; the equipment cost money, and it might aid the sailor to make good his escape from pressed service.

Even after accidents of the magnitude of the Titanic in 1912 and the Empress of Iceland in 1914, little thought was given to the protection of a human in cold water. At the outbreak of World War II, the causes for the loss of life from immersion in cold water were still poorly understood. More often than not the death certificates simply recorded "died from exposure" and/or "drowning." The concept of cold shock and hypothermia was ill understood. It was not until 1946, when the National Life-Saving Committee (23) reported that between 30,000 and 40,000 officers and men died in World War II from drowning and cold, that attention finally was drawn to the problem. This was further supported by McCance et al. (17), who examined these cases in more detail and published their findings in 1956.

The pioneer work on the physiology of sudden cold water immersion by Glaser and Hervey (9) and Keatinge (16) established the four phases of danger: cold shock, incapacitation, hypothermia, and post-rescue collapse. By the time of these studies, it became clear that some form of suit, preferably a dry suit, should be worn for protection following ship abandonment. Until after World War II, no standard existed for such an item. It was not until 1984 that the first standard was produced by the International Maritime Organization (14). With the development of the offshore oil industry, the Western world had started to introduce their own national standards for helicopter crew and passengers, oil rig workers, fishermen, and general maritime use (3–5). However, the majority of testing of immersion suits to date generally has been conducted in circulated water, the circulation of the water being intended to stir up the boundary layer around the suit (10).

It has been argued that this is an unrealistic test for a suit that is designed to protect a human from hypothermia in open ocean conditions, where waves of 5–8 m can be expected. In support of this argument, Steinman et al. (22) demonstrated that the core cooling rate and the decline in skin temperature of human subjects were significantly larger in rough water than in calm water. Such differences were found for loose-fitting wet suits but not for tight-fitting wet suits or for dry suits (22). In 1991, Romet et al. (20) confirmed this study by reporting a significant 29.7% reduction of wet immersion suit insulation on humans exposed to turbulent water when compared with still water. When measured on a thermal manikin, they found a reduction of 55.9%. It was found that the manikin consistently overestimated this decrement in insulation when compared with humans. In 1994, Sowood et al. (21) reported a reduction of dry immersion suit insulation, tested on a manikin, of about

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From the Defence and Civil Institute of Environmental Medicine, North York, Ontario, Canada.

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Address reprint requests to: Dr. Michel B. Ducharme, Human Protection and Performance, Defence and Civil Institute of Environmental Medicine, 1133 Sheppard Avenue West, North York, Ontario, Canada M3 M 3B9.

TABLE I. ANTHROPOMETRIC CHARACTERISTICS OF SUBJECTS.

Subject	Age (yr)	Height (cm)	Weight (kg)	A_D (m^2)	Body Fat (%)
1	23.1	178	75.2	1.92	10.6
2	22.2	179	78.5	1.97	14.4
3	25.6	179	76.0	1.94	22.3
4	21.2	183	79.9	2.01	18.3
5	25.2	178	79.5	1.97	18.4
6	32.5	179	69.6	1.87	11.4
Mean ± SE	25.0 ± 1.7	179 ± 1	76.5 ± 1.6	1.95 ± 0.02	15.9 ± 1.9

A_D, DuBois surface area (7).

30% in turbulent water (wave height of 60 cm) when compared with still water. Despite the evidence of a decrement in the insulation of a wet immersion suit in turbulent water for both manikins and humans, the effect of wave motion on the insulation of dry immersion suits has been studied only on manikins and for nonstandardized wave conditions.

The objective of the present study was, first, to investigate the effect of controlled wave conditions typically observed in the North Sea on dry immersion suit insulation when tested on humans and, second, to define which components and parts of the dry immersion suit system were most affected by the wave motion.

METHODS

Subjects: Healthy male subjects (n=6) volunteered for the study. The anthropometric characteristics of the subjects are presented in **Table I.** The percentage of body fat was estimated from the summation of five skinfold thicknesses (sternum, subscapular, anterior thigh, posterior calf, lateral forearm), was measured by a Harpenden skinfold caliper (British Indicators, Ltd., St. Albans, England), and was calculated using the relationship developed by Katch et al. (15). The health status of all subjects was assessed by a physician. The subjects were fully informed of the procedures and possible risks of the study and of their right to withdraw from the experiment at any time without prejudice. Written informed consent was obtained from all subjects before experimentation. The protocol was approved by the Defense and Civil Institute of Environmental Medicine and the National Research Council Human Ethics Committees.

The subjects were asked to abstain from smoking and using any medication, drug, or other stimulant (including caffeine and alcohol) for at least 12 h before each experiment. All experiments were performed at the same time of the day for each subject. The tests were carried out in the Marine Wave Tank of the National Research Council's Institute for Marine Dynamics in St. Johns, Newfoundland.

Measurements: The core temperatures of the subjects were estimated by measuring the rectal temperature (T_{re}) using a 2-kΩ thermistor (model 44004; YSI, Yellow Spring, OH) inserted 15 cm into the rectum. Heart rate (HR) was measured using a three-point leads system (Multicare 304; Rigel Research Ltd; Surrey, England). Heat loss (H_{sk}) and skin temperature (T_{sk}) were measured using heat flux transducers (HFTs; Concept Engineering, Old Saybrook, CT) and 6-kΩ thermistors (model 44018; YSI), which were integrated into the heat flux transducers, respectively, at 12 sites similar to the Hardy and Dubois (13) modified 12-point system. The mean T_{sk} ($\bar{T}_{sk}$) and mean H_{sk} ($\bar{H}_{sk}$) were calculated using a 12-site modified weighting system to similar that of Hardy and Dubois (13). The measurement sites and weighting factors were as follows: forehead, 0.07; right scapula, 0.088; left upper chest, 0.088; right abdomen, 0.088; left lower back, 0.088; right anterior thigh, 0.095; left posterior thigh, 0.095; right shin, 0.065; left calf, 0.065; left shoulder, 0.046; left upper arm, 0.046; and left forearm, 0.046. The difference between the modified Hardy and Dubois (13) weighting system and ours is in the coverage of the extremities and upper limbs, and for this reason the sum of the weighting factors used in the present study equals 0.88. To compensate, $\bar{T}_{sk}$ and $\bar{H}_{sk}$ values were divided by 0.88. For our 12-site system, the extremities (feet and hands) were not used as measurement sites for the calculation of the suit system resistance because they do not contribute significantly (being vasoconstricted) to the survival of individuals immersed in cold water. Instead, two additional sites (shoulder and forearm) were added to the upper limbs, which were divided into three segments: shoulder, upper arm, and forearm. Using the Hardy and Dubois (13) weighting system allowed each part of the body to be represented by a least an anterior site (usually in contact with air) and a posterior site (usually in contact with water), except for the head, which was not represented by an anterior site. This is one weakness of that weighting system that should be considered in future similar experiments. The HFTs were recalibrated, and the heat flow values were corrected to account for the thermal insulation of the HFTs (8). All measurements of temperatures, heat flows, and HRs were performed continuously during the 1-h immersion period using a computer-controlled data acquisition system (model HP 75000, series 8; Hewlett Packard, Palo Alto, CA) and were averaged over 1-min periods.

In addition to the 12 HFTs on the skin, 12 thermistors were taped to the outer surface of each layer of the suit system, which consists of an insulative pile undergarment and an uninsulated immersion suit. This arrangement creates a system of three layers (components of the suit system) capable of measuring the insulation of the pile garment (including the air layer between the skin and the pile; R_{pile} in clo), the suit (including the air layer between the pile garment and the suit; R_{suit} in clo), and the water/air layer ($R_{water/air}$ in clo; **Fig. 1**) for every site as follows:

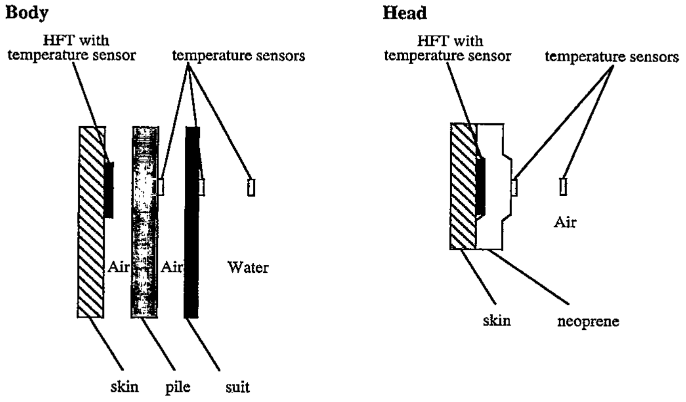

Fig. 1. Schematic representation of temperature and heat flux sensor arrangements used for subjects in the dry immersion suit system.

$$R_{pile} = (\Delta T_1/H_{skin})/0.155$$

$$R_{suit} = (\Delta T_2/H_{pile})/0.155$$

$$R_{water/air} = (\Delta T_3/H_{suit})/0.155$$

where $\Delta T_1(°C) = T_{sk} - T_{pile}$, $\Delta T_2(°C) = T_{pile} - T_{suit}$, $\Delta T_3(°C) = T_{suit} - T_{water/air}$, H_{skin} is the heat flow in $W \cdot m^{-2}$ measured at the skin level by the HFTs, and 0.155 is the conversion factor from $m^2 \cdot K \cdot W^{-1}$ to clo (2). H_{pile} and H_{suit} are the heat flows in $W \cdot m^{-2}$ at the pile and suit surfaces estimated from a geometric projection of H_{skin}. H_{pile} was estimated by correcting the H_{skin} values by a factor proportional to the ratio as follows:

$$\text{correcting factor}_{site} = SA_{pile}/SA_{skin}$$

where SA_{pile} and SA_{skin} are the surface area (in meters squared) of the body site over the pile garment and at the skin, respectively. Since all body sites, except for the head, can be represented by a cylinder (25), the SA ratio for those sites can be simplified as follows:

$$SA_{pile}/SA_{skin} = 2\pi \cdot r_{pile} \cdot h/2\pi \cdot r_{skin} \cdot h = r_{pile}/r_{skin}$$

$$= 2\pi \cdot Circ_{pile}/2\pi \cdot Circ_{skin} = Circ_{pile}/Circ_{skin}$$

where $Circ_{pile}$ and $Circ_{skin}$ are the body site circumferences (in meters) at the sensor location over the pile garment and at the skin, respectively. For the head site, the correcting factor can be defined as follows:

$$\text{correcting factor}_{head} = 4\pi \cdot r^2_{pile}/4\pi \cdot r^2_{skin} = Circ^2_{pile}/Circ^2_{skin}$$

The same approach was used to estimate H_{suit}.

The resistance of the suit system components for the whole body (in clo) was calculated as follows:

$$R_{pilebody} = (\sum A_i/A_{body} \cdot \Delta T_{1}i)/\sum A_i/A_{body}H_i)/0.155$$

$$R_{suitbody} = (\sum A_i/A_{body} \cdot \Delta T_2 i/(\sum A_i/A_{body} \cdot H_i)/0.155$$

$$R_{water/airbody} = (\sum A_i/A_{body} \cdot \Delta T_{3}i)/(\sum A_i/A_{body} \cdot H_i)/0.155$$

where i represents the body sites from 1 – 12, A_I/A_{body} represents the ratio of the site i surface area over the body surface area and is equivalent to the weighting factor of site i used to measure $\bar{T}_{sk}$. The 12 body sites represent a resistance system in parallel. The total suit system resistance for the whole body was measured as follows:

$$R_{totalbody} = R_{pile} + R_{suit} + R_{water/air}$$

where the three components of the suit system represent a resistance system in series. To define which part of the immersion suit had its thermal resistance most affected by the wave motion, the human body was divided in four main segments: the head, which was defined by the forehead site; the trunk, which comprises the chest, subscapula, abdomen, and lower back sites; the proximal limbs, which comprise the shoulder, upper arm, and the front and back thigh sites; and the distal limbs, which comprise the forearm, shin, and calf.

The ambient temperature was continuously monitored by two 2 kΩ thermistors (model 44004; YSI): one measured the water temperature within 10 cm of the subject's feet; the other measured the air temperature 1 m above the subject. The different insulation values were calculated at steady-state during water immersion from the average temperature and average heat flow data for the last 15 min of the 1-h immersion.

Video recordings of the immersions were performed above and below water during the study to allow for a visual estimation of the surface area of the body exposed to air or to water.

Experimental procedures: Each subject was familiarized with the equipment and the procedures. All subjects experienced a 30-min immersion in water at 16°C with waves set at a height of 40 cm during the first experimental session. Thereafter, each subject was immersed once a day for nine consecutive days in water at 16°C for 1 h for a total of nine tests. The wave heights were chosen randomly and were varied between 0 and 70 cm in height (WH_0 to WH_{70}) in steps of 10 cm. The Joint Offshore North Sea Wave Project wave spectrum for irregular waves was used for the tests to represent realistic ocean wave conditions. The wave period was selected to maximize the total wave energy (18). In addition to these wave tests, a vertical immersion up to the neck was performed in calm water (V_0).

Each subject was instrumented with a disposable rectal sensor, electrocardiograph leads, and 12 heat-flow transducers (incorporating temperature sensors). The subjects then donned a one-piece undergarment (model F456 pile underwear; Helly Hansen, Vancouver, BC, Canada), a pair of pile socks (model F454 pile socks; Helly Hansen), an uninsulated dry immersion suit, made of nylon/butyl laminate with neck and wrist latex/rubber seals and a back-entry waterproof zipper (Ranger dry immersion suit; Typhoon International Limited, London, UK) that was modified in the chest to accept monitoring wires (a 3-m waterproof umbilical cord was sealed to the suit to allow the sensor leads to be led from inside the suit to the data acquisition equipment), 3-mm neoprene three-finger diver's mitts, a 3-mm neoprene diver's hood with chin strap, and an inflatable twin lobe life vest with 15.4 kg of buoyancy (model M.D. 1141; Mustang Ind. Inc., Richmond, BC). An additional set of 12 thermistors was fixed on each of the 6 pile garments and immersion suits that were being used by the 6 subjects (the same suit system was used by a subject for every wave condition). The locations of the sensors on pile garments and suits were the same as for the measurement of skin temperatures, and the sensors stayed on the suit components during the duration of the experiment.

Each subject, assisted by a diver, entered the water via a platform suspended just above the water surface. Once in the water, the subject was towed out to the center of the tank using a pulley system operated from the platform. Once in position, the subject's feet were hooked with surgical tubing onto a cord fixed across the tank to ensure a constant positioning of the subjects relative to the wave propagation (facing them) and relative to the carriage over the tank where data collection was being performed. The surgical tubing ensured that subjects did not drift from the test area and that they maintained their freedom of movement.

An additional immersion test was performed in calm water (0 cm of wave height) while each subject was immersed up to the neck in a vertical posture (V_0). For this condition, additional weight was fixed to the feet of the subject to maintain the vertical position, and the amount of air inside the life vest was adjusted to maintain the subject at the proper water level.

A single wave height was tested per day with only one subject tested at any time; each subject was tested at the same time of the day and the order of wave height was the same for each of the subjects. Each immersion continued for a maximum exposure of 60 min or until: a) core temperature reached 35.0°C; b) the subject asked to be removed from the water for reasons such as, for example, nausea or dizziness; or c) the attending physician or investigator ended the exposure. Once the waves had stopped, the subject was removed from the water and was assisted onto the platform for a sitting period of 2 min.

To complement the immersion study, the insulation of the suit system also was measured in air at the same average air temperature as during the immersion tests (16.6°C). This was done for only two subjects following the same procedures as for the water immersion tests, except that each subject was free standing in air for 1 h; consequently, there was no hydrostatic pressure to expel the air from the suit. Also, the additional volume of trapped air in the suit both in the normal flotation position and in the V_0 position were measured again using the same two subjects. To achieve this, each subject was dressed with the immersion suit system, and then the umbilical cord was voided of all air and was sealed at the distal end to avoid any air leakage from the system. The subject then was immersed in water by following the same procedures as during an immersion test, and the subject adopted the normal flotation position or was immersed up to the neck. During each immersion, the volume of air expelled from the suit into the umbilical cord was measured from its length and diameter.

Statistical analysis: A one-factor (wave height) repeated-measures analysis of variance was used to compare the suit insulation at steady state during the trials and to analyze differences in skin temperature, skin heat flux, HR, and rectal temperature for the subjects' wave trials at steady state. When a significant effect was found ($p < 0.05$), a mean contrast test was used to locate significance between the means (using the Greenhouse-Geisser adjusted p value). Where applicable, data are presented as the mean ± SE. The level of statistical significance was set at $p < 0.05$, unless otherwise stated.

RESULTS

All the data presented are averages from the last 15 min of the 1-h immersion, when the thermal steady state was achieved. On average, skin and suit component temperature values decreased by $0.18 \pm 0.01°C \cdot W \cdot m^{-2}$ and heat flux values decreased by $1.98 \pm 0.15°C \cdot W \cdot m^{-2}$ over the last 15 min of the immersion, for an average decrease of only 1.5 ± 0.3% of the calculated insulation values. The measured parameters were, therefore, considered to be at the steady state after 45 min of immersion. The leakage of water into the suit was detected on only two occasions over the 54 runs. The leakages occurred through punctured umbilical cords and were not sufficient to compromise the validity of the data. The leakage was visually estimated as being no more than a few grams of water.

On average, the water temperature was 15.95 ± 0.02°C and the air temperature 16.60 ± 0.31°C during the trials, and no differences in temperature were observed between wave conditions.

Buoyancy of the human subjects: Because of the 15.4 kg of buoyancy provided by the life vest in addition to the air trapped inside the immersion suit, a significant portion of the subject's body surface area was not in contact with the water during the immersion tests. It was estimated from analysis of the video recordings performed during the tests that about 30–40% of the subjects' body surface areas were exposed to air during the water immersions. The body sites exposed to air during the tests were the forehead (almost 100% of the testing time in contact with air except for the WH_{70} condition, where occasional water splashes occurred), the chest (85 ± 5% of testing time in contact with air), the front thigh (80 ± 7% of testing time in contact with air), the forearm (79 ± 7% of testing time in contact with air), the shin (67 ± 4% of testing time in contact with air), the abdomen (51 ± 11%, of testing time in contact with air), and the shoulder (24 ± 6%, of testing time in contact with air). The proportion of time in the air for those sites varied between subjects because of differences in anthropometry between subjects and differences in suit fit and buoyancy. The upper arm site, because of its location on the inner portion of the arm facing the side of the subject's trunk, could not be seen easily by the video camera, and no firm conclusion could be reached regarding its proportion of time in air during the immersion tests.

HR: **Fig. 2** shows that, on average, HR increased significantly from 55 ± 3 bpm for the 0 cm wave condition to 61 ± 4 bpm for the 0 cm wave condition in the vertical position. Although not a significant increase when comparing within the 0 cm wave condition ($p < 0.08$), HR showed some tendency to be higher for WH_{70} (59 ± 4 bpm).

Rectal temperature (T_{re}): T_{re} decreased significantly during the hour of immersion by an average of 0.24 ± 0.02°C from 37.31 ± 0.03°C to an average of 37.07 ± 0.07°C for the last 15 min of the immersion. T_{re} was not affected by the wave conditions.

T_{sk}: The $\bar{T}_{sk}$ was not affected by the wave conditions except for the V_0 condition. $\bar{T}_{sk}$ decreased, on average, by 0.82 ± 0.26°C during the hour of immersion in water; the largest decrease in T_{sk} was observed in the distal

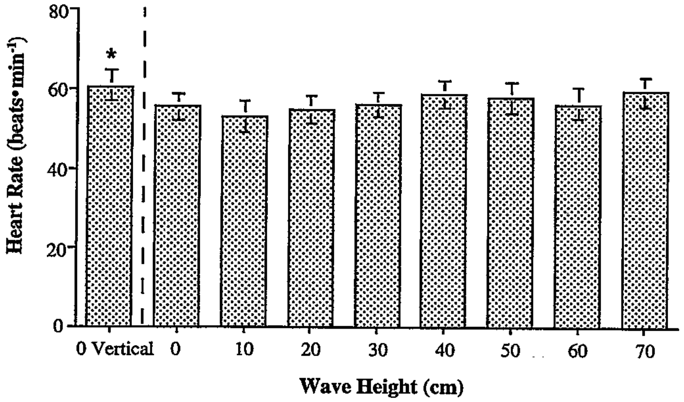

Fig. 2. Effect of wave height and vertical immersion posture on subjects' HRs during immersion in 16°C water (n = 6). Data represent the means ± SE. *significantly different ($p < 0.05$) from the 0 cm wave height condition.

limbs, particularly at the forearm site (1.35 ± 0.21°C), and the smallest decrease was for the trunk, specifically at the abdomen site (0.01 ± 0.12°C) (**Fig.** 3A).

$\bar{H}_{sk}$: Fig. 3B shows that $\bar{H}_{sk}$ was largest for the V_0 condition and was smallest for the WH_0 condition, and was, respectively, significantly higher and lower than the other wave conditions, except that $\bar{H}_{sk}$ was not different between the WH_0, WH_{10}, and WH_{20} conditions. $\bar{H}_{sk}$ also was not different between WH_{20} and WH_{50} inclusive, but these values were significantly higher than WH_0 and WH_{10}, and were lower than WH_{60} and WH_{70}. For a more detailed analysis of the wave effect on skin heat loss, the body was divided into four segments, as described in the Methods section. From WH_0 to WH_{70}, the skin heat loss (Fig. 3C) increased significantly for the head, trunk, and proximal limbs by 71.1 ± 8.0, 14.5 ± 6.8, and 9.2 ± 4.2 $W \cdot m^{-2}$, respectively, while it did not change significantly for the distal limbs (0.8 ± 6.1 $W \cdot m^{-2}$).

Insulation of the suit's components and of the suit system: In **Fig.** 4A, R_{pile} calculated for the V_0 condition was significantly lower than for the other wave conditions, and no differences were found for conditions between WH_0 and WH_{70}. R_{suit} calculated for the V_0 condition was significantly lower than for the other wave conditions, and no differences were observed for conditions between WH_0 and WH_{70} (Fig. 4B). $R_{water/air}$ was significantly higher for WH_0 and WH_{10} and significantly lower for compared with the other wave conditions (Fig. 4C). No differences were observed for conditions between WH_{20} and WH_{60} inclusive. Fig. 4D shows that R_{total} was significantly lower for V_0 compared with the other wave conditions. R_{total} did not change significantly for conditions between WH_0 and WH_{50} inclusive, except between WH_0 and WH_{30}. Values of R_{total} were not different between the WH_{60} and WH_{70} conditions, but these values were about 14% lower than R_{total} at WH_0 and WH_{10}. **Fig. 5** shows that R_{total} was most affected by the wave conditions for the head segment, for which it decreased by an average of 0.86 ± 0.06 Clo from WH_0 to WH_{70}. Comparatively, R_{total} for the trunk and proximal limb segments decreased by only 0.54 ± 0.13 Clo and 0.21 ± 0.09 Clo, respectively. No significant change was observed in R_{total} between WH_0 and WH_{70} for the distal limbs (Fig. 5).

On average, R_{total} for the sites generally above water (forehead, chest, forearm, front thigh, shin, abdomen, and shoulder sites) was 42% higher than for the sites generally under water (subscapula, lower back, back thigh, and calf sites) (**Fig. 6**). This difference essentially disappeared during the vertical posture test because all the sites were in contact with the water (in-water sites, 0.79 ± 0.10 clo; out-of-water sites, 0.86 ± 0.03 clo; see Fig. 9). For the V_0 condition, the forehead site was not used in this analysis because it stayed in contact with air. Further, as illustrated in Fig. 6, the wave conditions (the WH_0 compared with the WH_{70} condition) and the hydrostatic pressure (the WH_0 compared with the V_0

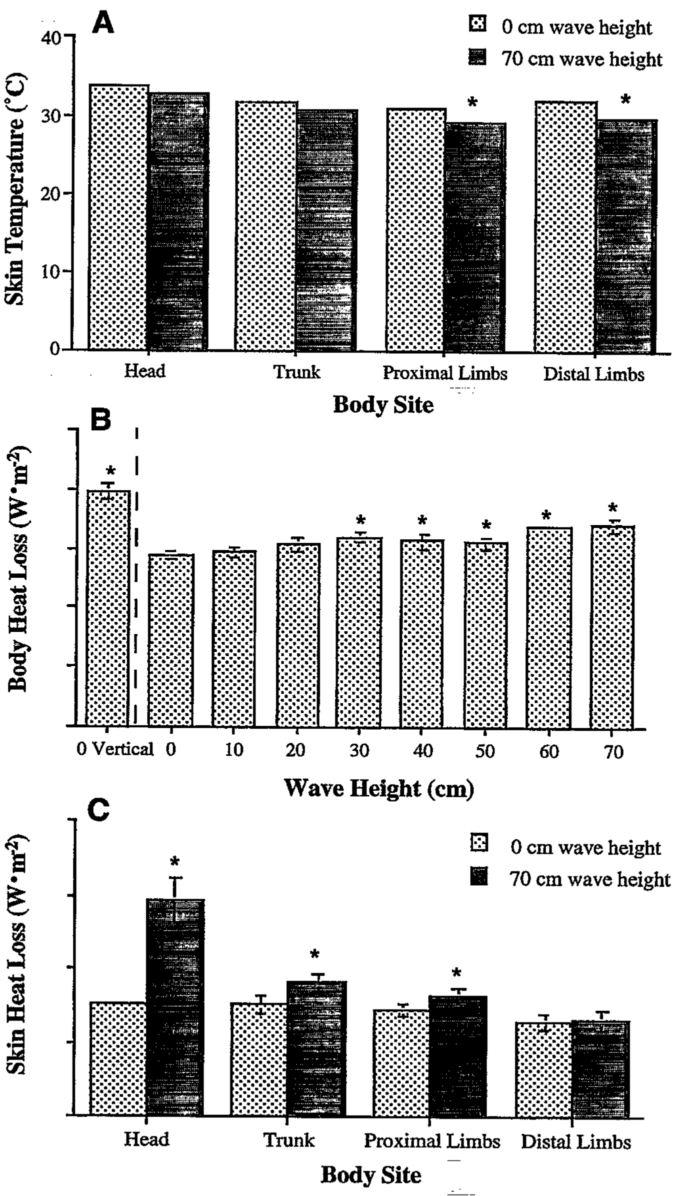

Fig. 3. Effect of wave height on: (A) skin temperature from the head (forehead site), trunk (chest, subscapula, abdomen, and lower back sites), proximal limbs (shoulder, upper arm, front thigh, and back thigh sites), and distal limbs (forearm, shin, and calf sites); (B) mean body heat flux; and (C) skin heat flux for the same sites as in (A) (n = 6). Data represent means ± SE. *significantly different ($p < 0.05$) from the 0-cm wave height condition.

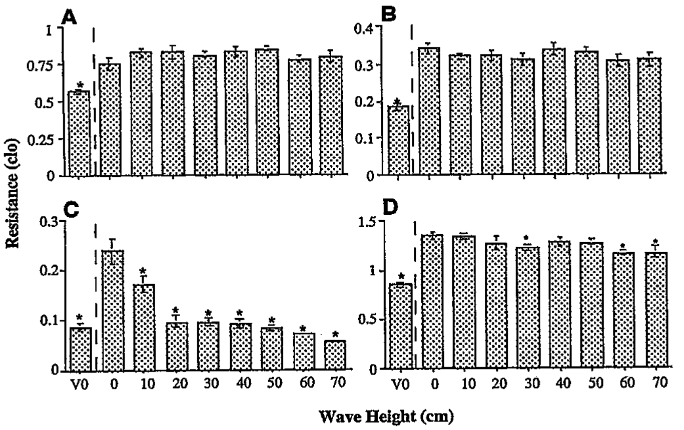

Fig. 4. Effect of wave height and vertical immersion posture on the thermal resistance of (A) the pile (R_{pile}), (B) the suit (R_{suit}), (C) the water or air ($R_{water/air}$), and (D) the total suit system (R_{total}) worn by the subjects during immersion in 16°C water ($n = 6$). Data represent means ± SE. *significantly different ($p < 0.05$) from the 0 cm wave height condition.

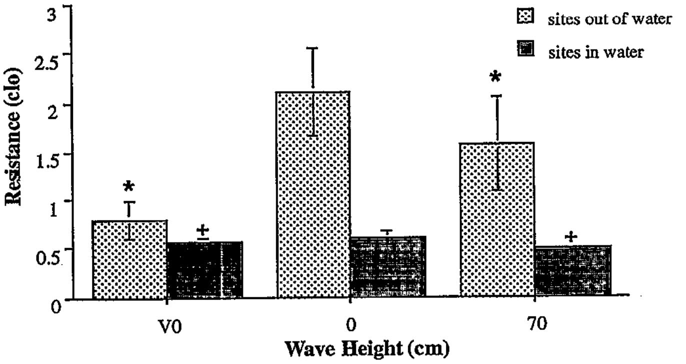

Fig. 6. Total thermal resistance (R_{total}) of the suit system worn by subjects ($R_{pile} + R_{suit} + R_{water/air}$) for the sites in water (subscapula, lower back, back thigh, and calf) and partly outside the water (forehead, chest, forearm, front thigh, shin, abdomen, and shoulder) for 0 and 70 cm wave heights and vertical immersion posture conditions (V_0) ($n = 6$). Data represent means ± SE. * significantly different ($p < 0.05$) from the 0 cm wave height condition.

condition) decreased the thermal resistance of the suit system more for the sites outside the water (wave conditions, 25.2% decrement; hydrostatic pressure, 55.4% decrement) than for the sites inside the water (wave conditions, 8.0% decrement; hydrostatic pressure, 17.9% decrement).

Insulation of the immersion suit system air: The average R_{pile} calculated during the air trial for two subjects (0.83 ± 0.11 clo) was not significantly different from the R_{pile} observed during the immersion trials (0.81 ± 0.03 clo). R_{suit} during the air trials was, on average, twice as much as the R_{suit} values calculated for the immersion trials, and R_{air} (thermal resistance of the air boundary layer) during the air trials was about 3.5 times larger than $R_{water/air}$ during the immersion trials. This results in a R_{total} value during the air trials (2.10 ± 0.03 clo) that was significantly higher than the R_{total} values obtained during the immersion trials at WH_0 and V_0.

Volume of trapped air inside the immersion suit system: During the time spent standing in air, the average total volume of trapped air measured inside the suit system for the two subjects was 25.9 ± 1.4 L (24.5 and 27.3 L), and the average volume of trapped air inside the suit during the normal flotation position was 17.5 ± 2.9 L (14.6 and 20.4 L). Thus, an average of 67.2 ± 7.5% of the total trapped air normally inside the suit system when standing in air was expelled out of the suit through the umbilical cord during the immersion tests.

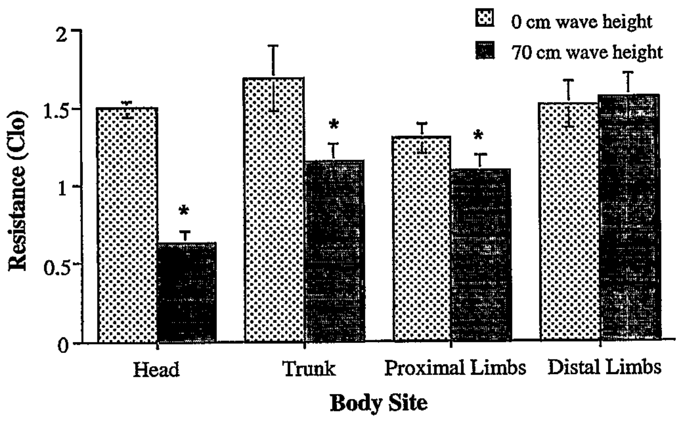

Fig. 5. Total thermal resistance (R_{total}) of the suit system for the head (forehead site), trunk (chest, subscapula, abdomen, and lower back sites), proximal limbs (shoulder, upper arm, front thigh, and back thigh sites), and distal limbs (forearm, shin, and calf sites) of the subjects for 0 and 70 cm wave conditions ($n = 6$). Data represent means ± SE. *significantly different ($p < 0.05$) from the 0 cm wave height condition.

DISCUSSION

The results confirm our hypothesis that the total thermal resistance of the dry immersion suit is decreased during wave motion compared with still water. It is decreased by 14% from still water condition to a 70-cm wave height. This, to our knowledge, is the first study reporting on the effect of standardized wave height on the thermal resistance of a dry immersion suit using human subjects. An early study by Goldman et al. (10) reported a decrease of 7% in wet suit insulation when the water was stirred with a paddle or when compressed air was introduced into the water. Other studies testing dry suits using a thermal manikin, but using the same suit system as the present study, reported a decrement in the thermal resistance of the suit of between 25 and 30% for a 60-cm wave height (21) and of 36% for a 70-cm wave height (6). Those decrements are 1.8 to 2.6 times greater than the decrement observed in the present study for humans, and the difference may be due to differences between the thermal manikin and humans in buoyancy and to trapped air in the suit. Steinman et al. (22) studied the effect of noncontrolled wave conditions on the thermal performance of antiexposure garments worn by humans, and they showed that, for dry suits, HRs were elevated in rough water compared with calm water conditions, but that there were no differences between the two conditions for rectal temperature cooling rates or declines in skin temperature. These results are in agreement with the present study in which HRs had a tendency to increase ($p < 0.08$), but rectal temperature cooling rates and skin temperatures were not affected by the wave conditions, despite a significant increase of the skin heat flux with wave height.

Other studies of wet suits have shown that leakage and flushing inside immersion suits could be responsible for a significant decrease in suit insulation between immersion in calm water and in turbulent water. Romet et al. (20) reported an average decrement in the thermal resistance of 11 wet suits of 30 and 56% for humans and manikin, respectively, from still water to turbulent water, with a 25- to 40-cm wave amplitude. This is twice the decrement observed in the present study for dry suits tested on humans, and three times the value observed on a manikin. This difference can be attributed to leakage and to flushing of water into the suits, neither of which occurred in this study. These data are supported by the study of Steinman et al. (22), which reported that wet suits allowed significantly greater rectal temperature cooling rates and larger declines in skin temperature in rough water than in calm water when compared with dry suits. Steinman et al. (22) also were able to positively correlate these changes with subjective evaluations of cold-water flushing during the immersion tests. From the studies of Hall and Polte (11), Allan et al. (1), and Tipton and Balmi (24), it is now well established that leakage of water inside a wet suit significantly decreases the effective insulation of immersion suits.

Effects of wave motion on the thermal resistance of the suit system components: At least three factors could have contributed to the reduction of the insulation provided by a dry suit during wave motion: leakage of water into the suit; compression of the suit insulation by the wave motion; and reduction of the water and air boundary layers due to water movement. The first two factors affect the insulating layers inside the suit, while the last factor affects the insulating layer of the water or air surrounding the suit. In the present study, only the last two factors could contribute to a reduction of the suit system insulation during wave motion since the suits did not leak. Sowood et al. (21) suggested that part of the decrement observed in suit thermal resistance could be attributed to the effect of the water movement over the manikin surface. The results from the present study support this assumption and our hypothesis that a major factor responsible for the decrease in suit system insulation during wave motion is the decrease of $R_{water/air}$, the insulating boundary layer surrounding the suit. In fact, our study shows that $R_{water/air}$ was the only suit system component that was significantly affected by the wave motion, and that the major portion of the $R_{water/air}$ decrement occurred at wave heights below 20 cm. R_{pile} and R_{suit} were not significantly reduced by the wave motion, as shown in Figs. 4A and B. This supports the observation of Hayes et al. (12), who reported that the deleterious effect of waves appears to be more demonstrable when the subjects are nude or wearing little clothing, probably because the reduction of the boundary layer has more impact when it is the major portion of the system insulation. These results suggest that the compression of the internal insulating layers of the suit by the wave motions was not sufficient to have an impact on the amount of air trapped inside the insulating layers of the suit during tests on human subjects.

Effects of wave motion on the thermal resistance of the different body sites: The results for humans showed that the 70-cm wave condition increased vasoconstriction (a further decrease in T_{sk} compared with the WH_0 condition) only at the limb sites (proximal and distal). This minimized the increase of the skin heat loss for the proximal limbs and abolished it for the distal limbs during wave motion (Fig. 3C). On the other hand, because of the weak vasoconstriction capacity of the skin on the head (Fig. 3A), the loss of head heat doubled from the WH_0 to the WH_{70} condition, mainly due to water splashes occurring during breaking waves at WH_{70}, while heat loss from the trunk increased by 20%. These changes were mainly responsible for the observed 58 and 32% decrements in suit thermal resistance at the head and trunk, respectively, for the WH_{70} compared with the WH_0 condition. Meanwhile, for the same wave conditions, suit thermal resistance decreased by only 16% for the proximal limbs and did not change significantly for the distal limbs. These tests suggest that to minimize body heat loss and body cooling during water immersion, further development of dry immersion suits should focus on improving the thermal protection of the head and trunk, and not of the limbs. As reported by Romet et al. (20), the results are different for wet suits, where a significant increase in heat flow was observed only at the back site, which was the site most affected by water flushing and pooling. The wave height conditions during the Romet et al. study (20) were not sufficient to cause the waves to break over the head of each subject, which could account for the absence of a significant increase in heat loss from the head.

Hall et al. (11) reported that the insulation value of an immersion suit will decrease by a factor of 2.3 when measured in water (1.45 clo; i.e., immersion up to the neck without leakage of water into the suit) compared with measurement in air (3.36 clo). They attributed this decrease to the effect of water compression (hydrostatic pressure), which reduced the trapped air in the insulation layers of the suit, and to the elimination of the boundary air layer. In the present study, we observed a decrease of R_{total} by a factor of 2.5 between the air trials and the Vo condition.

The results of the present study are limited to wave heights of up to 70 cm because of the mechanical limitations of the wave generator at the Institute for Marine Dynamics. It is expected, however, that rougher water conditions might further decrease the suit system thermal resistance by reducing the thermal resistance of the air boundary layer of the sites that were not fully immersed during the present trials (mainly, the head) and by increasing the chances for the leakage of water into the dry suit. Further studies, ideally performed in the open ocean, are required to answer those questions.

CONCLUSIONS

The present study shows that wave heights up to 70 cm will decrease dry suit system insulation by 14% when measured on human subjects. The only suit component significantly affected by the wave motion is the insulation of the water and air boundary layers surrounding the body. The body sites most affected by wave motion are the head and the torso, with a 58 and 33% decrement, respectively, in suit thermal resistance from a 0- to 70-

cm wave height. Further studies are necessary in more severe wave conditions to determine the practical limit to this reduction.

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