Evaluating the thermal protection provided by a 2–3 mm wet suit during fin diving in shallow water with a temperature of 16–20°C

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Abstract
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Introduction: The purpose of the study was to evaluate the thermal protection provided by a 2–3 mm surfing wet suit during at least two hours of fin diving in shallow water with a temperature of 16–20°C. We examined the effect of wearing the suit while diving in cold water on cognitive performance, muscle strength, and hand motor function.
Methods: Subjects were six male well-trained rebreather divers, 19–23 years old, acclimatised to cold. They attended the laboratory on three separate occasions, when we conducted the experiment at one of three temperatures, 16, 18, and 20°C. Core temperature (gastrointestinal system), skin temperature, oxygen consumption, and cold perception were evaluated during the test. Before and immediately after the dives, subjects performed a series of cognitive, manual dexterity, and muscle strength tests.
Results: Core temperature decreased by 0.35–0.81°C over the two hours at all three water temperatures. No subject reached a core temperature below 35°C. The decrease in upper body skin temperature during the two hour dive ranged between 5.97 and 8.41°C ($P < 0.05$). Two hours diving in 16–20°C water resulted in a significant increase in the time taken to perform the task of unlinking and reassembling four shackles (~30% longer, $P < 0.05$). No effect was found on the cognitive or muscle strength tests.
Conclusions: A 2–3 mm wet suit provides adequate thermal protection in trained and cold-acclimatised young males engaged in active diving in shallow water with a temperature of 16°C and above.

Introduction

Thermal protection of combat divers is critical for their safety, as well as for their physical and mental function. However, a conflict always arises between the need for optimal thermal protection by a thicker diving suit and the need for optimal motor performance both in and out of the water, which of necessity implies a thinner suit. The traditional requirement for diving in water with a temperature of 18–29°C is a 5.5 mm wet suit made of neoprene, a synthetic rubber containing small gas bubbles. On the basis of presently available scientific knowledge, a diver may rest assured that a 5.5 mm neoprene suit will be sufficient for an active or passive dive lasting more than three hours at a shallow depth.[1]

For a number of years, sportswear manufacturers have been promoting thin (2–3 mm) neoprene wetsuits for a variety of water sports, such as surfing, swimming, and even diving. The high flexibility of these thinner suits may allow the diver better movement both in and out of the water,[2] which is of the greatest importance for combat divers. However, less is known about the thermal protection they provide.

Without optimal thermal protection, the diver may reach a level of thermal stress that can affect both mental and physical function.[3,4] A decrease in core temperature, even if not considered hypothermic, has been shown to affect different functional abilities that may become critical for combat divers. This may involve muscle,[3] cognitive[4] or motor function. Motor function, as well as muscle strength, may also be affected by a mild decrease in skin or core temperature.[5,6] In addition, reduced thermal protection in combat divers will lead to an increase in metabolic rate, which may in turn result in elevated CO_2 levels in the blood and thus expose them to an increased risk of central nervous system oxygen toxicity.[7]

To date, there has been little or no investigation of the thermal protection afforded by a 2–3 mm wetsuit and the concomitant effects on muscle strength, motor function or cognitive performance, with or without changes in core temperature, when diving in water to depths of less than 10 m. The purpose of the present study was therefore to evaluate the thermal protection of a 2–3 mm surfing wetsuit during at least 2 h of fin diving in shallow water with a temperature of 16–20°C. Adequate protection was defined as maintenance of core temperature at ≥ 35°C under the stated conditions. We also evaluated the effect of these conditions on cognitive performance, muscle strength, and hand motor function while wearing the suit.

Materials and methods

SUBJECTS

Subjects were six well-trained male rebreather divers, 22 (SD 1) years old, with no history of smoking. The number of subjects required for the study was determined using a formula for sample size calculation, based on the differences we hypothesised would be found on exposure to 16°C (see statistical analysis), and the expected homogeneity of the study population. All subjects were engaged in water activities in the Mediterranean Sea throughout the year and were therefore acclimatised to cold. All gave their written, informed consent to participate in the study, which was approved by the Israel Defense Forces Medical Corps Committee for Human Experimentation.

PREPARATION

Banjo type Telethermometer YSI 400A surface thermistors (YSI Inc., Yellow Springs OH, USA) were validated against a mercury thermometer, and differences between the two were noted for future readings. Upper body skin temperatures were measured, on the forearm and the chest. Due to the technical limitations of the available equipment, we measured upper body (arm and chest) skin temperature only. It was demonstrated in the past that arm skin temperature is slightly higher than calf temperature both at baseline and during a dive, and that the trend of the change was similar.[4] We assume that the two measurements we performed were to a large degree representative of the general change in skin temperature.

For core temperature measurement, we used a CorTemp™ ingestible core body temperature sensor which transmits core body temperature from the gastrointestinal system (HQ Inc. Wireless Sensing Systems & Design, Palmetto FL, USA). Each of the temperature sensors was validated against a mercury thermometer over the expected range for core temperatures between 35–39°C. Differences between the ingestible sensor and mercury thermometer readings were noted for future corrections.

We used a SwimEx Deepwater aquatic therapy pool – SX170T swimming flume (SwimEx® Systems, Warren RI, USA) which had undergone modification to allow deeper front water flow, thus making it more a simulator of underwater diving than just surface swimming.

EXPERIMENTAL PROCEDURE

Subjects attended the laboratory on three separate occasions, when we conducted the experiment at one of three temperatures: 16, 18, and 20°C. One subject failed to attend for the 18°C session. On the first day, subjects were examined by the physician to authorise their participation in the study, after which they signed the consent form and swallowed the ingestible sensors. Height and weight were recorded for each subject. A Lange skinfold caliper (Cambridge Scientific Industries, Cambridge MD, USA) was used to measure skin fold thickness at four sites: two on the arm, on the triceps and biceps, and on the subscapular and supra-iliac skin.[8]

MANUAL TASKS

Manual handling of a light weight

Subjects were evaluated for manual handling of a light weight. They were asked to unlink and reassemble a chain composed of four identical European-type large bow shackles with a screw pin, each measuring 61 by 78 mm and weighing 185 g, in the shortest time possible. This requires good hand motor function, as well as the involvement of several arm muscle groups responsible for stabilising the humerus and elbow joints. The manual handling test was performed before and after each of the three two-hour dives. Before the first dive, subjects performed the task three to five times for training purposes, until the time they took was stable. On subsequent occasions, however, there was no training. Subjects were strongly encouraged to complete the task as fast as possible.

Handgrip strength

Handgrip strength was measured for both the dominant and non-dominant hand using a recording hand dynamometer (Stoelting Co., Wood Dale IL, USA). In this test, the base of the dynamometer rests on the first metacarpal (on the heel of the palm), while the handle lies along the middle of the remaining four fingers. When the subject is ready, he squeezes the dynamometer with maximum isometric effort, maintaining this for about 5 s. Subjects were strongly encouraged to give this exercise their maximum effort. Muscle strength was measured before and after each of the three 2-h dives.

COGNITIVE TASKS

A series of three pencil-and-paper cognitive tests was performed before and after each dive. These user-friendly tests evaluate cognitive performance related in part to prefrontal cortex function, such as speed of information processing, the ability to focus attention, executive function, and short-term memory. Participants were given detailed instructions for each test. The three tests are simple to perform, and are widely used in the field of cognitive and reasoning psychomotor testing.[9,10] On the first day, subjects had a practice session of 3–5 training trials until there was no further improvement in the results. Because the time interval between the three exposures was 24 hours, no further practice session was given.

Mathematics test

In this task, subjects were asked to perform addition and subtraction in a mixed arithmetic exercise using four single-digit numbers, for example: 4 - 3 + 8 - 6 = . Scores were assessed by recording the number of correct answers and the total number of errors over a 1 min period.

Number comparison test

In this test, multi-digit pairs of numbers were displayed to the subject, who had to decide whether the numbers in each pair were the same or different. For example, 41987 vs. 49671: Yes (numbers the same) or No (numbers different). Scores were assessed by recording the number of problems attempted, the number of correct answers, and the total number of errors over a 1 min period.

Number cancellation test (modified Stroop test)

The word "*red*" or "*blue*" appeared in black type at the beginning of each line, followed by 11 digits. The colour word was underlined randomly in either red or blue ink. If the colour word was underlined in the same coloured ink, the digits between 0–4 were to be cancelled; otherwise the instruction was to cancel the digits between 5–9. A digit could appear more than once in the line. For example, blue (red or blue underline) 89120172640. Scores were assessed by recording the number of problems attempted, the number of correct answers, and the total number of errors over a 1 min period.

EXPERIMENTAL PROTOCOL

Each subject wore a full-body 2–3 mm surfing suit (Psycho® series, O'Neill, Australia), individually fitted in accordance with the manufacturer's instructions. The legs were protected by swimming shoes and fins. Apart from the shoes, no additional protection, such as gloves or a hood, was used in the experiment.

The subject donned the closed-circuit oxygen underwater breathing apparatus (UBA), which consists of an oxygen cylinder, rebreathing bag, and soda-lime canister. Oxygen breathed from the bag is replenished automatically from the cylinder. The UBA was furnished with a pressure gauge for monitoring the oxygen pressure in the cylinder. Diving depth was 1–1.5 m. Subjects were instructed to propel themselves continuously through the water, with swimming speed controlled by the researcher and remaining constant throughout the exposure (~0.55 $m \cdot s^{-1}$). The divers remained connected to the diving gear at the sampling stops.

A series of measurements was taken at the beginning of the dive, at intervals of about 15 min during the dive, and at the end of the dive. Each sampling stop lasted about 1 min. Subjects were asked to pull themselves over to the edge of the swimming flume, lifting only their torso out of the water.

Measurements consisted of:
1. Completion of a cold score questionnaire shown to the diver on a board: 1 – comfortable; 2 – cool; 3 – cold; 4 – cold and shivering; 5 – very cold; 6 – request termination of the dive.
2. Recording of the oxygen pressure in the cylinder.
3. Skin temperature [arm (T_{arm}), and chest (T_{ch})].
4. Core temperature (T_{core}).

On day one, six subjects (three trials, two divers in each) dove continuously using a fin-diving technique at an average speed of ~0.55 $m \cdot s^{-1}$ in the swimming flume at a depth of 1–1.5 m for 2 h and at a water temperature of 20°C. On day two, five subjects dove on exactly the same protocol at a water temperature of 18°C. On day three, six subjects dove at a water temperature of 16°C. There was no possibility of changing the temperature of the large volume of water in the flume by more than 2°C in the 24-h interval between the experimental days. For this reason, among others, the experiment was not conducted in a randomised fashion with regard to temperature. Starting on day two, each of the divers was checked for the presence of the sensor in his stomach using the HQ receiver.

CALCULATIONS

Mean subcutaneous fat thickness was calculated as the arithmetic mean of measurements at the four sites according to a well-known formula:[11]

SKT = (Σsft – 16)/4, where SKT is subcutaneous fat thickness and sft is skin fold thickness.

In the closed-circuit diving system, oxygen is consumed only from the dry compressed oxygen in the cylinder, and due to rebreathing there is no loss of gas. Oxygen consumption was therefore calculated from the reduction in cylinder pressure in atmospheres absolute (atm abs), cylinder volume in litres corrected to STPD, water temperature, and the time between measurements in min:

$VO_2 = [\Delta P \times V \times 273 / (273 + T_w)] / \Delta t$, where VO_2 is oxygen consumption, ΔP is the reduction in cylinder pressure, V is cylinder volume, T_w is water temperature, and Δt is the time between measurements.

Mean upper body skin temperature was calculated as the average of chest and arm skin temperatures:
$T_{sk} = 0.5\ T_{ch} + 0.5\ T_{arm}$, where T_{sk} is mean skin temperature, T_{ch} is chest skin temperature, and T_{arm} is arm skin temperature.

Table 1
Subjects' characteristics (BSA = body surface area; BMI = body mass index)

Subject	Age (years)	Weight (kg)	Height (cm)	BSA (m^2)	BMI ($kg \cdot m^2$)	Fat (%)	Mean fat (mm)
1	23	76.5	183	1.98	22.8	12.3	6.7
2	22	70.0	177	1.86	22.3	16.6	9.4
3	22	91.5	180	2.11	28.2	21.0	13.7
4	22	70.0	180	1.89	21.6	13.5	7.5
5	21	76.0	183	1.98	22.7	13.1	7.2
6	23	72.0	176	1.88	23.2	20.8	13.5
Mean (SD)	22 (1)	76.0 (8.1)	180 (3)	1.95 (0.10)	23.6 (2.4)	16.2 (3.9)	9.7 (3.2)

Figure 1
Core temperature measured for each of the three water temperatures (16, 18, and 20°C). Values are presented as mean (SD)

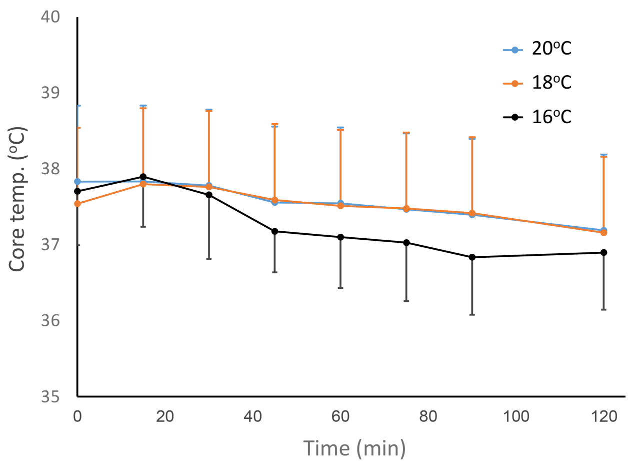
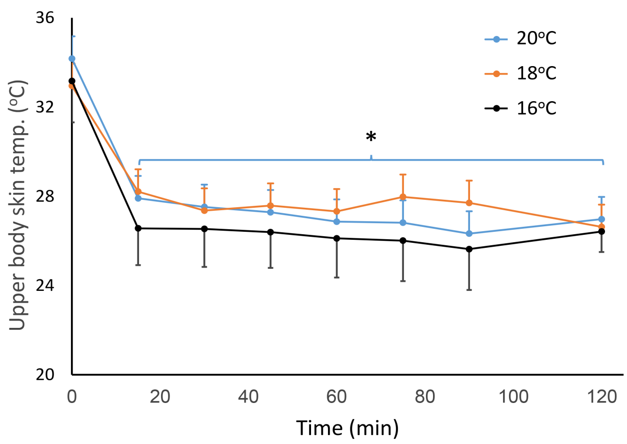


Figure 2
Upper body skin temperature measured for each of the three water temperatures (16, 18, and 20°C). Values are presented as mean (SD). * = significantly different from baseline during immersion at 16° and 20°C ($P < 0.05$)



Mean body temperature was calculated from core temperature and mean upper body skin temperature according to a well-known formula[12] as:
$T_b = 0.67\, T_{core} + 0.33\, T_{sk}$, where T_b is mean body temperature, T_{core} is core temperature, and T_{sk} is mean upper body skin temperature.

Body surface area (m^2) was calculated as:
$SA = 0.20247 \times \text{height (m)}^{0.725} \times \text{weight (kg)}^{0.425}$ according to a well-known method,[13] where SA is body surface area.

Total insulation was calculated from the total heat loss from the diver's body surface and the core-to-water temperature difference, as described in detail previously:[1]
$T_{tot} = (T_{core} - T_w) \times SA/[(0.87 \times VO_2 \times 4.83) + (0.83 \Delta T_{core} \times BM \times 0.6)]$,[14] where T_{tot} is total insulation, T_{core} is core temperature, T_w is water temperature, SA is body surface area in m^2, 0.87 (E) is the fraction of oxygen converted to heat for fin divers, VO_2 is oxygen consumption (litres × h^{-1}), ΔT_{core} is the mean core temperature over the period of time T_{core} was measured, BM is body mass (kg), 0.6 is the portion of core from the body weight. Suit insulation and body insulation were calculated by replacing the core-to-water temperature gradient in the above equation by skin-to-water and core-to-skin gradients, respectively.

STATISTICAL ANALYSIS

A test for sample size was performed using an online calculator (Statistical Solutions LLC, WI, USA), based on an expected difference of 1°C after two hours exposure and a standard difference of 0.5 between subjects. Based on these conditions, for an α of 0.05 and a power of 0.95, a sample of four subjects was found to meet the objectives of the study. Results are expressed as mean (SD). Two-way ANOVA with repeated measures (time and water temperature) was performed on core, body, and skin temperature for water temperatures of 16 and 20°C. One-way ANOVA for time was performed for a water temperature of 18°C. Values for the three water temperatures were compared with baseline, and with every measurement carried out during the experiment (at min 15, 30, 45, 60, 75, 90, 105 and 120). When ANOVA reached statistical significance, a Tukey HSD post hoc analysis was performed on the different time points for each of the water temperatures.

Two-way ANOVA (time and water temperature) was performed for hand motor function and cognitive tests at 16 and 20°C, while 1-way ANOVA for time was performed on the values obtained at 18°C for the comparison between pre- and post-exposure.

Figure 3
Mean body temperature measured for each of the three water temperatures (16, 18, and 20°C). Values are presented as mean (SD). * = significantly different from baseline during immersion at 16 and 20°C ($P < 0.05$)

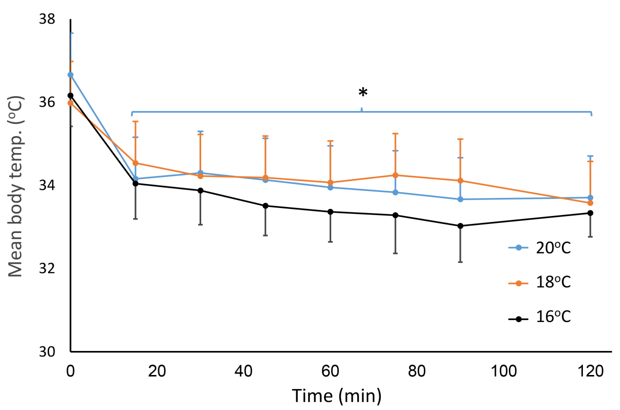


Figure 4
Cold sensation measured over the course of exposure to each of the three water temperatures (16, 18, and 20°C). Values are presented as mean (SD)

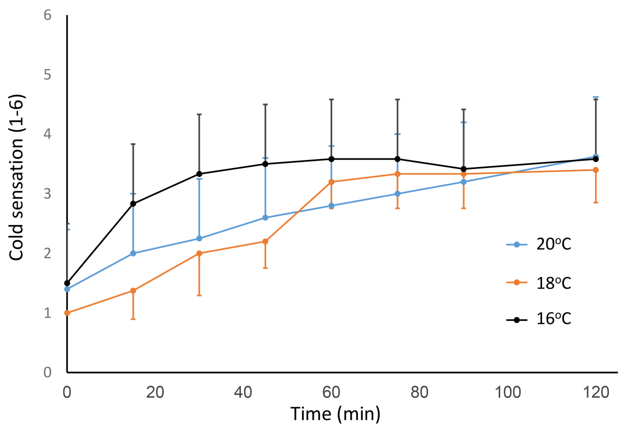
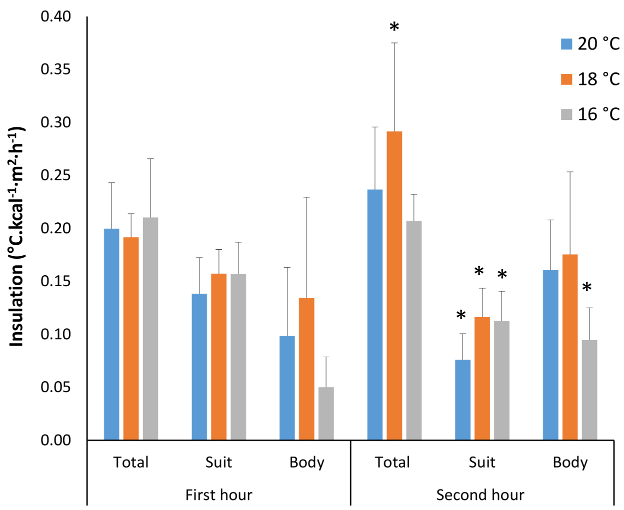


Figure 5
Total, suit, and body insulation for each of the three water temperatures (16, 18, and 20°C) during the first and second hours of cold water exposure. Values are presented as mean (SD). * = significantly different from the first hour ($P < 0.05$)



$P < 0.05$ was taken as the level of statistical significance for all analyses. A trend analysis was performed for the cognitive and motor function measurements.

Hand cold sensation was compared with baseline for each of the three water temperatures using the Friedman test for repeated measurements.

Results

MORPHOMETRIC CHARACTERISTICS

Subjects' characteristics are shown in Table 1. Subjects were young (22 (1) years of age), with a body mass index (BMI) of 23.6 (2.4) kg·m^2. Percent body fat was 16.2 (3.9)%, and the average sum of four skin folds was 38.8 (12.7) mm.

TEMPERATURE

Core temperature

The effect of water temperature on core temperature can be seen in Figure 1. Core temperature decreased over the two hours at all three water temperatures. At 20°C it had decreased by 0.29°C at 60 min, and by a further 0.35°C at 120 min. At 16°C it had dropped by 0.60°C at 60 min, and by a further 0.21°C at 120 min. Due to technical problems with the receiver on the 18°C day, we can only report a change in core temperature after 60 min in four subjects (+0.03°C), and a decrease of 0.38°C in only three subjects after 120 min. No subject reached a core temperature below 35°C. No statistical difference was found between core temperature measured at baseline and at any of the water temperatures. A comparison between the water temperatures of 16 and 20°C showed no significant difference ($P = 0.196$).

Upper body skin temperature

The effect of water temperature on upper body skin temperature is presented in Figure 2. Upper body skin temperature dropped by ~6°C during the first 15 min of all three exposures, after which the changes were very small. When subjects dove in 16, 18 and 20°C water, the decrease in upper body skin temperature during the first hour was 6.0, 5.8 and 7.3°C, with a subsequent increase during the second hour of 0.3, 0.1 and 0.1°C, respectively. There was no statistically significant difference between upper body skin temperature measurements for water temperatures of 16 and 20°C ($P = 0.231$). All of the upper body skin temperature measurements performed at 16°C were significantly lower than baseline ($P < 0.05$). There was no statistically significant difference between any of the measurements and baseline for exposure to 18°C ($P > 0.075$). For the upper body skin

Table 2
Motor function before and after the dive (values are presented as mean (SD))

Temp.	Pre-dive time (s)	Post-dive time (s)	Delta (%)	F-value	P-value
20°C	44.0 (4.4)	57.8 (4.7)	33 (20)	27.618	0.001
18°C	43.8 (2.5)	56.2 (4.6)	28 (4)	22.474	0.003
16°C	42.5 (3.4)	58.3 (4.8)	38 (14)	43.515	0.001

Table 3
Handgrip strength for right and left hands before and after the dive (values are presented as mean (SD); RH = right hand; LH = left hand; MH = mean hand)

Water temperature	Pre-dive			Post-dive			*P*-value
	RH strength (kg)	LH strength (kg)	MH strength (kg)	RH strength (kg)	LH strength (kg)	MH strength (kg)	
20°C	45.4 (6.0)	43.7 (7.2)	44.6 (6.3)	45.4 (5.2)	47.2 (5.9)	46.3 (5.1)	0.61
18°C	48.5 (8.0)	49.5 (8.6)	49.0 (8.2)	46.1 (6.8)	45.0 (5.2)	45.6 (5.7)	0.52
16°C	46.1 (3.0)	47.3 (6.0)	46.7 (3.9)	45.6 (4.6)	44.0 (5.4)	44.8 (4.8)	0.48

Table 4
Summary of cognitive test results (values are presented as mean (SD))

Test	Score based on:	Water temperature					
		20°C		18°C		16°C	
		Pre-dive	Post-dive	Pre-dive	Post-dive	Pre-dive	Post-dive
Number cancellation	Problems attempted	13.5 (2.4)	12.7 (2.3)	15.2 (2.3)	14.4 (1.1)	15.7 (3.8)	14.8 (2.0)
	Correct answers	12.7 (1.9)	12.3 (2.1)	13.4 (1.9)	13.0 (1.6)	14.8 (3.8)	13.7 (2.5)
	Errors	0.8 (1.0)	0.3 (0.5)	1.8 (0.8)	1.4 (1.1)	0.8 (0.8)	1.2 (0.8)
Mathematics	Correct answers	14.8 (4.5)	14.8 (4.6)	16.2 (4.1)	15.4 (6.9)	16.3 (6.8)	15.8 (5.2)
	Errors	0.7 (0.8)	0.7 (0.8)	1.4 (1.1)	0.6 (0.5)	1.2 (0.8)	0.8 (0.4)
Number comparison	Problems attempted	18.5 (6.4)	17.7 (6.2)	20.6 (6.8)	18.6 (6.5)	20.5 (6.6)	18.2 (6.9)
	Correct answers	18.3 (6.5)	17.5 (6.2)	20.0 (6.7)	18.0 (6.2)	20.2 (6.4)	17.5 (7.2)
	Errors	0.2 (0.4)	0.2 (0.4)	0.6 (0.9)	0.6 (0.9)	0.3 (0.5)	0.7 (0.8)

temperature measurements performed at 20°C, statistically significant lower skin temperatures were found at min 15, 30, 45, 60, and 90 compared with baseline ($P < 0.05$).

Mean body temperature

The effect of water temperature on mean body temperature is presented in Figure 3. When subjects dove in 16, 18 and 20°C water, the decrease in mean body temperature during the first hour was 2.5, 1.9 and 2.6°C, with a further decrease of 0.3, 0.5 and 0.4°C during the second hour, respectively. There was no statistically significant difference between the measurements for water temperatures of 16 and 20°C at any given time. A statistically significant difference from baseline was found for measurements performed at 20°C ($P < 0.05$) and 16°C ($P < 0.005$), but not at 18°C.

Cold sensation

The effect of water temperature on cold sensation relative to time is presented in Figure 4. During immersion at 18 and 20°C, cold sensation intensity was significantly different from baseline from min 60 until the end of the exposure, whereas at 16°C this was the case from min 30 ($P < 0.05$).

Insulation

Total body and suit insulation was calculated for the first and second hour of immersion. Total insulation ranged from 0.21 to 0.24°C·kcal^{-1}·m^2·h^{-1} in the first hour and from 0.22 to 0.33°C·kcal^{-1}·m^2·h^{-1} in the second hour. Body insulation ranged from 0.11 to 0.14°C·kcal^{-1}·m^2·h^{-1} in the first hour and from 0.14 to 0.20°C·kcal^{-1}·m^2·h^{-1} in the second hour. Suit insulation ranged from 0.10 to 0.11°C·kcal^{-1}·m^2·h^{-1} in the first hour and from 0.08 to 0.13°C·kcal^{-1}·m^{2}·h^{-1} in the second hour (Figure 5).

MANUAL TASKS

Manual handling of a light weight

A summary of the measurements of manual handling before and after the two hours of water activity is presented in Table 2. Two hours of diving at 16–20°C resulted in a significant increase in the time taken to perform the task of unlinking and reassembling the four shackles. The time taken to complete the task for all three water temperatures increased by ~30%. For 16°C the increase was 15.8 s (38 [14]%), for 18°C it was 12.4 s (28 [4]%), and for 20°C 13.7 s (33 [20]%).

Handgrip strength

The results of the handgrip strength measurements are summarised in Table 3. There was a small insignificant decrease in handgrip strength of 1.87 (4.36) kg for 16°C, and a small non-significant increase of 1.73 (4.55) kg ($P = 0.214$) for 20°C. There was no statistically significant difference between handgrip strength at 16 and 20°C. No significant difference in handgrip strength was found at 18°C.

COGNITIVE TESTS

The results of the three cognitive tests (mathematics, number comparison, and number cancellation) are summarised in Table 4. We found no significant effect of the three temperature conditions on any of the tests. However, we noted a consistent non-significant decrease in performance on the number comparison and cancellation tests, both in the number of problems attempted and the number of correct answers. For example, in the number cancellation test we found that after two hours there was a decrease of 0.8 in the number of problems attempted for a water temperature of 20°C, a decrease of 0.8 for 18°C, and of 0.9 for 16°C. There was no significant difference between 16°C and 20°C.

Discussion

The present study was conducted on well-trained, acclimatised subjects. Its main finding is that a full-length, 2–3 mm neoprene wet suit can protect fin divers from significant thermal stress for at least the first two hours of a dive in shallow water with a temperature of 16°C and above. Suit insulation as calculated in the present study was found to be ~80% of that of a 5.5 mm suit.[1] Immersion in 16°C water induced a significant decrease in upper body skin temperature (6.8°C), mean body temperature (2.9°C), and core temperature (0.8°C), although core temperature failed to reach the critical level required for a definition of hypothermia. These temperature changes were accompanied by significant cold sensation (a score of 4–5 out of 6) and a decrease in motor function (~30%; $P < 0.05$), but with no effect on muscle strength or on any of the cognitive performance parameters measured in the study.

Core temperature increased slightly during the first 15 min of the 2 h exposure, decreased during the subsequent 60 min, and stabilised over the final 30 min (Figure 1). The initial small elevation in core temperature observed in 16 and 20°C water may be related to overheating while wearing the suit before entering the swimming flume, an observation reported in previous studies.[15,16] The decrease in core temperature, particularly from min 15 to 90 in 16°C water, took place at a rate of 0.85°C per hour. This is comparable with the previous study from our laboratory, in which a decrease in core temperature of 0.3–1.2°C was found in fin divers wearing a 5.5 mm suit in 17–18°C water.[1] The high inter-subject variability in core temperature changes observed in the present investigation was also similar to the cited study.[1] Because subjects were well controlled for metabolic rate, both by supervision of their pre-exposure food intake and of their physical activity rate during the cold exposure (a uniform, paced swimming velocity), this variability may be explained by the wide range of percent body fat (12.3–21%) and body surface area (1.86–2.11 m^2), which have been shown to influence the rate of heat loss from the body.[17] Muscle shivering, although not monitored in the present study, was evident in some of the subjects. Related in part to the subject's body fat, muscle shivering increases heat production and delays the core temperature drop, and may thus also have contributed to the inter-subject variability found in the study.

A number of investigators found a correlation between reduction in core temperature and skin fat thickness.[1,17,18] We observed a stable core temperature over the last 30 min in 16°C water, when no change was found: 36.83, 36.85, and 36.90°C at 90, 105, 120 min, respectively. Stability of core temperature represents a balance between heat production and heat loss. Our results are in agreement with the suggestion of a previous investigation,[19] that core temperature may stabilise when wearing a slightly thicker suit (4 mm), and that during exercise slimmer subjects will reach a stable core temperature when exposed to ~13°C. Core temperature stabilised in the present study at all three water temperatures. The decrease in both 18 and 20°C water was very small during the entire experiment, whereas in 16°C water core temperature dropped until about min 60, after which it stabilised (Figure 1).

Exercise increases heat production from active muscles. However, the increase in heat loss during exercise in cold water is also partially due to vasodilatation in the working muscle tissue.[14] It was found that a work intensity of > 200 kcal·m^{2}·h^{-1}, which is 4–5 multiples of the resting metabolic rate (1 MET), is more advantageous than rest for maintaining a higher core temperature in cold water.[20] The subjects in the present study consumed 1.2–1.3 L O_2·min^{-1}, which is ~4 MET, suggesting that the stabilisation of core temperature may be explained in part by the fin activity performed by the divers. The fact that our subjects had been well trained in swimming may have protected them from the muscle fatigue which could have resulted from the physical activity rate in the study. However, untrained individuals may not succeed in maintaining this level of physical activity, which can induce heat production due to work of the muscles, but also result in accelerated heat loss due to the convection of heat in the water.

Previously, it was reported that the thermal protection provided by a neoprene suit decreases with an increase in ambient pressure.[21] Based on the observations of that study, we calculated that for combat divers using a rebreather, who are usually limited to a depth of ~8 m to reduce the risk of developing central nervous system oxygen toxicity, the depth effect on the suit will be a reduction of no more than 25% in its thermal protection.

Hand motor function, as evaluated by the shackle test, decreased after two hours of fin diving at all three water temperatures (Table 2). A large body of literature exists on the correlation between the drop in skin temperature and the decrease in hand and finger dexterity.[5,6] It was found that finger dexterity decreased for a hand skin temperature of 13, but not 16°C.[5] In contrast, an earlier study found that finger skin temperature had to drop to 10–13°C for there to be a decrease in finger dexterity.[22] In addition, it was demonstrated that the performance of tasks involving significant movement of the joints is very sensitive to cooling of the fingers and the hand, similar to the task required of subjects in the present study.[23] It was even shown that cooling of the forearm on its own resulted in a decrement on a finger dexterity task. This decrease in hand motor function was explained in part by changes in neuromuscular function, as well as peripheral mechanisms in the limbs.[24,25] In the present study, forearm skin temperature was measured at 15-min intervals throughout the exposure, and the lowest temperature measured close to the end of the two hours was ~24°C (Figure 3). However, whereas the forearm skin area was covered by the suit, the fingers were unprotected, predicting a much larger decrease in skin temperature there. This may explain the ~30% increase in the time taken to complete the task after two hours immersion in cold water.

A number of studies have suggested that finger dexterity and task performance are more dependent on finger blood flow than on finger temperature,[5,26] implying that as long as blood flow to the fingers is sufficient for the task, the temperature will be of less consequence. In contrast, a later study demonstrated that finger dexterity can be maintained with direct heating even if finger blood flow decreases.[27] In the present study, the 2-h long exposure of subjects' hands to mildly cold water was shown to have a greater effect on manual performance than the fast cooling induced by exposure to extreme cold.[5] Although the implication of the current results, especially for combat divers, may be the need to wear gloves, this may not always be the right solution. When Korean women divers wore a wet suit, the addition of gloves failed to provide any extra protection against heat loss at 17°C, and even caused deterioration of finger motor function.[28]

Handgrip strength is important in many areas of manual activity. This test has frequently been used to evaluate the effect of intramuscular temperature on muscle strength. A number of studies showed that the immediate effect of cold application was a reduction in muscle strength,[29,30] whereas others failed to do so.[31] For example, in twelve female college students who placed their forearm in a 10°C cold bath for 30 min, handgrip strength was reduced by 6 kg (-19%) compared with baseline.[30] In contrast, in another study[31] no effect of cold exposure was found on forearm muscle strength, agreeing with the present investigation in which no consistent change was observed (Table 3). The small decrease we found in forearm skin temperature also implies that forearm muscle temperature was maintained throughout the exposure, which may explain why there was no significant drop in muscle strength.

None of the cognitive function tests showed a significant effect of the three water temperatures on simple cognitive function. A number of investigators have evaluated the effect of a decrease in core temperature on cognitive performance. Cognitive performance was not affected by a moderate reduction in core temperature (a decrease of 0.3–1°C in rectal temperature and a mean skin temperature of 26°C).[32] Different protocols used to evaluate the effect of cold exposure on cognitive performance resulted in vastly differing conclusions. Among other theories regarding the relationship between cognitive tasks and cold, it was suggested that cold may cause distraction,[33] resulting in impaired performance of different tasks, whereas it was also speculated that cold exposure may result in improved performance due to increased attention on the part of the subject.[34] The amount of training prior to cold stress may play a critical role in the measured effect of cold on certain aspects of performance.[34] However, the cognitive tests used in the present study were sufficiently simple for subjects to achieve stable performance over 2–3 trials. It would be very difficult to speculate as to the effect of training prior to cold water exposure when in the present study no significant effect was measured.

LIMITATIONS

One limitation of the present study may be its design. A counterbalanced design, which can account for any accumulated fatigue or acclimatisation to cold water, may have been more appropriate. However, because our subjects were considered to be well trained and acclimatised to cold water, this may not have had a significant effect on our findings.

A further limitation may be that the skin temperature measurements, which were performed only on the upper body (chest and arm), cannot be considered whole body skin temperature. However, it has been demonstrated that upper body skin temperature is slightly higher than leg skin temperature both at baseline and during a full body dive.[4] The change found in the study may therefore represent the actual change that would have been found in lower limb skin temperature.

Conclusions

In summary, the present study demonstrated that a 2–3 mm wet suit provided adequate thermal protection in trained and cold-acclimatised young males, engaged in active diving in shallow water with a temperature of 16°C and above. Stability of core temperature proved that a balance had been achieved between heat production and heat loss. No reduction in cognitive or hand muscle function was found, other than a decrease in hand/finger motor function.

References

1 Arieli R, Kerem D, Gonen A, Goldenberg I, Shoshani O, Daskalovic YI, et al. Thermal status of wet-suited divers using closed circuit O_2 apparatus in sea water of 17-18.5°C. Eur J Appl Physiol Occup Physiol. 1997;76:69–74. PMID: 9243172.

2 Naebe M, Robins N, Wang X, Collins P. Assessment of performance properties of wetsuits. J Sports Engineering Technol. 2013;227:255–64. doi: 10.1177/1754337113481967.

3 Bergh U, Ekblom B. Physical performance and peak aerobic power at different body temperatures. J Appl Physiol Respir Environ Exerc Physiol. 1979;46:885–9. doi: 10.1152/jappl.1979.46.5.885. PMID: 468604.

4 Davis FM, Baddeley AD, Hancock TR. Diver performance: the effect of cold. Undersea Biomed Res. 1975;2:195–213. Available from: http://archive.rubicon-foundation.org/2428. [cited 2018 November 4]. PMID: 15622739.

5 Clark RE. The limiting hand skin temperature for unaffected manual performance in the cold. J Appl Psychol. 1961;45:193–4. doi: 10.1037/h0044644.

6 Chen WL, Shih YC, Chi CF. Hand and finger dexterity as a function of skin temperature, EMG, and ambient condition. Hum Factors. 2010;52:426–40. doi: 10.1177/0018720810376514. PMID: 21077564.

7 Arieli R, Ertracht O. Latency to CNS oxygen toxicity in rats as a function of PCO_2 and PO_2. Eur J Appl Physiol Occup Physiol. 1999;80:598–603. PMID: 10541928.

8 Durnin JVGA, Rahaman MM. The assessment of the amount of fat in the human body from measurements of skinfold thickness. Br J Nutr. 1967;21:681–9. doi: 10.1079/BJN19670070. PMID: 6052883.

9 Bloch-Salisbury E, Lansing R, Shea SA. Acute changes in carbon dioxide levels alter the electroencephalogram without affecting cognitive function. Psychophysiology. 2000;37:418–26. doi: 10.1111/1469-8986.3740418. PMID: 10934900.

10 Eynan M, Tal D, Arie E, Ne'eman F, Adir Y. CO_2 detection in closed-circuit oxygen divers with and without a distracting task. Aviat Space Environ Med. 2006;77:1028–33. PMID: 17042247.

11 Allen TH, Peng MT, Chen KP, Huang TF, Chang C, Fang HS. Prediction of total adiposity from skinfolds and the curvilinear relationship between external and internal adiposity. Metabolism. 1956;5:346–52. PMID: 13321517.

12 Tikuisis P, McCracken DH, Radomski MW. Heat debt during cold air exposure before and after cold water immersions. J Appl Physiol (1985). 1991;71:60–8. doi: 10.1152/jappl.1991.71.1.60. PMID: 1917765.

13 Du Bois D, Du Bois EF. Clinical calorimetry. Tenth paper. A formula to estimate the approximate surface area if height and weight be known. Arch Intern Med. 1916;17:863–71. doi: 10.1001/archinte.1916.00080130010002.

14 Park YS, Pendergast DR, Rennie DW. Decrease in body insulation with exercise in cool water. Undersea Biomed Res. 1984;11:159–68. Available from: http://archive.rubicon-foundation.org/2999. [cited 2018 November 4]. PMID: 6485145.

15 Holmér I, Bergh U. Metabolic and thermal response to swimming in water at varying temperatures. J Appl Physiol. 1974;37:702–5. doi: 10.1152/jappl.1974.37.5.702. PMID: 4436196.

16 Shiraki K, Sagawa S, Konda N, Park YS, Komatsu T, Hong SK. Energetics of wet-suit diving in Japanese male breath-hold divers. J Appl Physiol (1985). 1986;61:1475–80. doi: 10.1152/jappl.1986.61.4.1475. PMID: 3781961.

17 Tarlochan F, Ramesh S. Heat transfer model for predicting survival time in cold water immersion. Biomedical Engineering – Applications, Basis & Communications. 2005;17:159–66. doi: 10.4015/S1016237205000251.

18 Keatinge WR. Body fat and cooling rates in relation to age. In: Folinsbee LJ, Wagner JA, Borgia JF, Drinkwater BL, Gliner JA, Bedi JF, editors. Environmental stress: individual human adaptations. New York: Academic Press; 1978. p. 299–302.

19 Wolff AH, Coleshaw SR, Newstead CG, Keatinge WR. Heat exchanges in wet suits. J Appl Physiol (1985). 1985;58:770–7. doi: 10.1152/jappl.1985.58.3.770. PMID: 3980382.

20 Sagawa S, Shiraki K, Yousef MK, Konda N. Water temperature and intensity of exercise in maintenance of thermal equilibrium. J Appl Physiol (1985). 1988;65:2413–9. doi: 10.1152/jappl.1988.65.6.2413. PMID: 3215841.

21 Bardy E, Mollendorf J, Pendergast D. Thermal conductivity and compressive strain of foam neoprene insulation under hydrostatic pressure. J Phys D Appl Phys. 2005;38:3832–40. doi: 10.1088/0022-3727/38/20/009.

22 Gaydos HF, Dusek ER. Effects of localized hand cooling versus total body cooling on manual performance. J Appl Physiol. 1958;12:377–80. doi: 10.1152/jappl.1958.12.3.377. PMID: 13525296.

23 LeBlanc JS. Impairment of manual dexterity in the cold. J Appl Physiol. 1956;9:62–4. doi: 10.1152/jappl.1956.9.1.62. PMID: 13357416.

24 Goodman D, Hancock PA, Runnings DW, Brown SL. Temperature-induced changes in neuromuscular function: central and peripheral mechanisms. Percept Mot Skills. 1984;59:647–56. doi: 10.2466/pms.1984.59.2.647. PMID: 6096802.

25 Dhavalikar M, Narkeesh A, Gupta N. Effect of skin temperature on nerve conduction velocity and reliability of temperature correction formula in Indian females. J Exercise Sci Physiotherapy. 2009;5:24–9. Available from: http://medind.nic.in/jau/t09/i1/jaut09i1p24.pdf. [cited 2018 November 4].

26 Mills AW. Finger numbness and skin temperature. J Appl Physiol. 1956;9:447–50. doi: 10.1152/jappl.1956.9.3.447. PMID: 13376471.

27 Brajkovic D, Ducharme MB. Finger dexterity, skin temperature, and blood flow during auxiliary heating in the cold. J Appl Physiol (1985). 2003;95:758–70. doi: 10.1152/japplphysiol.00051.2003. PMID: 12730145.

28 Park YS, Kim JS, Choi JK. Increase of heat loss by wearing

gloves and boots in wet-suited subjects working in cold water. Ann Physiol Anthropol. 1992;11:393–400. doi: 10.2114/ahs1983.11.393. PMID: 1388402.
29 King PG, Mendryk S, Reid DC, Kelly R. The effect of actively increased muscle temperature on grip strength. Med Sci Sports. 1970;2:172–5. PMID: 5527261.
30 Johnson DJ, Leider FE. Influence of cold bath on maximum handgrip strength. Percept Mot Skills. 1977;44:323–6. doi: 10.2466/pms.1977.44.1.323. PMID: 840607.
31 Mecomber SA, Herman RM. Effects of local hypothermia on reflex and voluntary activity. Phys Ther. 1971;51:271–81. doi: 10.1093/ptj/51.3.271. PMID: 5544829.
32 O'Brien C, Tharion WJ, Sils IV, Castellani JW. Cognitive, psychomotor, and physical performance in cold air after cooling by exercise in cold water. Aviat Space Environ Med. 2007;78:568–73. PMID: 17571656.
33 Teichner WH. Individual thermal and behavioral factors in cold-induced vasodilatation. Psychophysiology. 1966;2:295–304. doi: 10.1111/j.1469-8986.1966tb02657.x.
34 Enander AE. Effects of thermal stress on human performance. Scand J Work Environ Health. 1989;15 Suppl 1:27–33. PMID: 2692138.

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