Exercising divers' thermal protection as a function of water temperature

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ABSTRACT

Physiological adjustments and passive thermal insulation are not sufficient to protect divers in the cold and warm waters experienced by sport, professional and military divers. In a previous study of resting subjects, divers were protected by actively heated/cooled water that perfused a six-zone (head, torso, arms, hands, legs and feet) tube suit. Subsequently a self-contained diver thermal protection system (DTPS) was developed and used in this study to test male divers ($n = 8$) wearing a 6-mm foam neoprene wetsuit in water temperatures (T_W) of 10°C-39°C at 4 feet in depth. The DTPS is a scuba backpack containing five thermoelectric devices that heat/cool water to 30°C, six pumps that circulate the water through a six-zone tube suit via two manifolds, and an electronic controller. Skin temperatures (T_S, $n = 17$) and core temperature (T_C, capsule) were measured. The DTPS and each zone of the tube suit were also instrumented.

Divers were tested with the DTPS operational (protected) and turned off (unprotected) for 90 minutes. In the unprotected condition, T_S decreased and approached T_W, while T_C trended to decrease over the exposure time. Mean T_S as a function of T_W was $T_S = 0.44\, T_W + 21.23°C$ while unprotected, but $T_S = 0.19\, T_W + 27.1°C$ when the diver was protected. The average total heating/cooling power required to protect the diver was 166±78W, 86±95W, 9±75W, 72±45W, 135±73W, 279±87W and 336±95W at 10, 15, 20, 25, 30, 35 and 39°C water temperatures, respectively. This power requirement was nominally split 4%, 22%, 22%, 14%, 25% and 13% for head, torso, arms, hands, legs and feet, respectively. While unprotected, divers T_S and T_C did not remain within acceptable limits in T_W below 25°C or above 30°C. When using the DTPS, however, they did remain within acceptable limits, and the divers reported they were comfortable.

INTRODUCTION

Tolerable submersion time (thermal balance and comfort) in water is related to ambient temperature (T_A) and time with a U-shaped curve [1,2]. Divers can stay indefinitely in water of thermal neutral temperature (T_N). However, colder or warmer ambient T_A (T_W) temperatures limit exposure time, exercise capacity, function [1,3,4,5] and cognitive performance [5,6]. Thus, temperatures below 25-30°C (T_{CR}) or above 32-35°C, where most diving takes place, limit diver performance.

Acceptable thermal limits have been established to maintain diver performance and are $T_C \pm 1.0°C$, and finger temperatures above 18°C and below 35°C [7,8]. Physiological adjustments and passive thermal insulation are not sufficient to protect divers exposed for longer times in the cold and warm waters experienced by sport, professional and military divers [7].

An active thermal protection system (DTPS) is required to thermally protect divers in both cold and warm waters.

Active protection

Hot-water suits are used by divers in cold water; they work by providing surface-heated sea water at 37-40ºC via an umbilical to the diver's suit [9]. Although this system is used often, it has many problems. Many previous studies have used the principle of flowing water over the human body with an automatically controlled heating/cooling extraction as a calorimeter and using the flow and temperature difference to calculate heat balance (flow calorimetry) [10,11]. However, these systems had not, until recently, been used in immersion, nor did they evaluate regional heat exchange. Additionally, they were not used to heat/cool subjects in cold and hot climates.

Early studies attempted to provide thermal protection in cold air to hands/fingers by heating the torso to a high level (40ºC), but these efforts failed to demonstrate protection [12]. More recent in-air studies have demonstrated that by heating the torso to about 40ºC, the hands remain vasodilated, thermally protected and functional [13,14,15,16,17]. In water, where there is high thermal conductivity compared to air, heating the torso with electrically resistive pads not only failed to protect the hands but resulted in faster and greater reductions in T_C [9]. This study [9] also failed to demonstrate a benefit for cognitive function during torso heating compared to lack of torso heating. However, the subjects noted that they felt more comfortable thermally when heated.

The uncoupling of thermal comfort and thermal balance is risky, as it may result in unrecognized hypothermia. This has been shown with divers in wetsuits who, due to high T_S, stated they felt comfortable while they were losing body heat [18,19,20].

Bardy *et al.* [21] using a "proof-of-concept" active heating/cooling system combined with an instrumented six-zone liquid garment (tube suit) confirmed previous studies [1,3,4,20] that T_C achieved a steady state in 20 to 120 minutes. However, heat balance, and consequently T_S, stabilized before T_C. The Bardy study also showed that T_{CR} at rest was 25.2ºC while wearing a wetsuit, with an accompanying T_S of 32ºC, which is in agreement with a previous study that used different methods [1,3,4]. Importantly, this study showed that perfusing the tube suit with 30ºC water in resting subjects sustained T_S and T_C within the recommended thermal limits ($T_C \pm 1.0$ºC and T_S above 18ºC and less than 35ºC) [7,8] in T_W from 10-39ºC. That study [21] also showed there were regional differences in heating/cooling requirements for the various zones. In addition, they demonstrated the value of wetsuit insulation in cold as well as warm T_W.

Based on an engineering analysis and the Bardy data [21], a diver thermal protection system (DTPS) was developed, and the purpose of the present study was to test this DTPS' capability to maintain skin and core temperature within acceptable limits ($T_C \pm 1.0$ºC and T_S above 18ºC and less than 35ºC) [7,8] over a wide range of T_Ws, while they were exercising. In addition, the total and regional body heating/cooling requirements of the divers were determined. It was hypothesized that the DTPS would maintain skin and core temperatures within acceptable limits for divers free-swimming while wearing a standard wetsuit in both cold and warm water ($T_W = 10$-39ºC), and that there would be important regional differences in heating/cooling requirements.

METHODS

This study was approved by the University Institutional Review Board. The subjects documented their dive training, experience and activity, and then signed an informed consent, completed a medical survey and were given a physical exam prior to participation.

Subjects

The eight male subjects for this study were certified scuba divers, experienced (more than five years' history of diving) and actively diving (weekly). They were aged 19 to 35, 177 ± 6 cm in height, 79.43 ± 7.72 kg in weight, with a body mass index of 25 ± 2 and with an average body fat percentage of 14.9 ± 3.5% (determined by underwater densitometry).

Protocol

During the initial visit, subjects' physical characteristics were measured; they practiced donning the DTPS and breathing gear and engaged in fin swimming in the pool. The subjects were then randomly scheduled to complete two dives (protected and unprotected) in T_W of 10°C, 15°C, 20°C, 25°C, 30°C, 35°C and 39°C.

Each diver completed 14 dives, with two divers completing 16 dives. The latter number is due to technical failures that resulted in the termination of two experiments. Dives were performed in an immersion tank (12 feet by 6 feet by 8 feet) at a depth of 4 feet of water. Water temperatures were controlled to be within ±0.5°C. At least one week was allowed between dives to prevent acclimatization, and the experiments were scheduled on the same day and during the same time of day for each subject to avoid circadian rhythm effects.

Prior to the experimental protocol, each diver completed a fin-swimming test to determine maximal oxygen uptake (VO_2). Swimmers were attached to variable resistances via belt, rope and pulley system and fin-kicked to maintain a fixed position in the immersion tank. Swimmers wore a face mask and used a modified two-hose scuba mouthpiece open-circuit system to inspire from room air; expired gas was collected in "Douglas bags." Expired gas volume was determined by calibrated dry-gas meter (Harvard) and gas fractions by mass spectrometer (Perkin Elmer 1100), and standard equations were used to calculate VO_2.

From this experiment, a resistance that represented 50% of the individual subject's VO_2max was determined and used in subsequent testing. For each experiment, the diver was instrumented and then donned the tube suit next to the body, with the wetsuit over the tube suit. The foam neoprene wetsuit was a standard two-piece suit, 6 mm in thickness, with hood, finger gloves and booties. The subject entered the water and began fin-swimming against the fixed resistance that lead to a VO_2 of nominally 50-60% of VO_2max (1.5 to 2.0 L/minute). In order to achieve a thermal steady state, the experiments lasted 90 minutes, and data were collected continuously via computer throughout each experiment.

During the course of the experiment, the subject was monitored to ensure he remained within safe thermal limits [7,8]. In cold water it was ensured that the core temperature did not decrease more than 1ºC of the initial reading and that local skin temperatures remained above 20 ºC (fingers and toes > 15ºC); in hot water the core temperature (T_C) and skin temperature (T_S) did not exceed 38ºC. If any of these criteria were violated, the experiment was terminated, or the subject could voluntarily end it for any reason.

Diver thermal protection system

The DTPS consists of three basic components: a tube suit, a backpack and, as used in this study, a DC electrical power source (22,23,24). The tube suit (MedEng currently Allen-Vanguard, Ottawa, Canada) was custom-built, full-body and with six zones (head, torso, arms, legs, hands and feet). The backpack is worn by the diver and designed to hold scuba tanks. The DTPS has an array of thermoelectric heating/cooling units (TECS) (5, Supercool model DL-220-24-00-00-00), pumps (6, B&D model UGP-2010-P-24) and manifolds (output to and return from the tube suit, respectively), as well as an "in-house-built" electrical control circuit. The working fluid in the suit is a small quantity (107mL) of water. The outputs of the pumps are set by the DTPS controller at an optimal flow of nominally 500mL/minute to the head, torso, arms, legs and 1.0L/minute to each of the hand and foot zones, the latter to deliver 500mL/minute to each hand and foot.

In pilot experiments (data not shown) the optimal temperature for perfusion of the tube suit for use in both hot and cold water was determined to be 30ºC. This water temperature clamped skin temperatures at a level to optimize heat exchange and prevent sweating, particularly in hot water.

The DTPS is 31.75 x 146.99 x 7.62 cm, its weight in air is 11.85kg, and it has a positive buoyancy of 0.45kg in water. It operates at a voltage of 24-32V DC, which was supplied by a ground-fault protected DC power source (Lambda, GEN3300W) in these experiments. The backpack also incorporates a ground-fault interrupter to ensure user safety in accordance with the Association of Offshore Diving Contractors [23,24]. The electrical control circuit of the DTPS is feedback-controlled and designed to maintain the supply manifold water temperature at 30°C. Polarity switching of the power to the TECS switches them from heating to cooling and their duty cycle was determined.

Measurement of heating/cooling rate

The water inlet and outlet temperatures were monitored and recorded by 24-gauge thermocouples (Omega Thermocouple Type T (Copper/Constantan) Model 5TC-TT-T-24-24, PFA Insulated with Teflon-coated tip) were placed at the inlet and outlet of each region. The thermocouples have a range of -270-350°C with 0.4% or 0.5°C limit of error. The water flow rate to each region was preset and calibrated by six separate turbine flow meters (McMillan Corp., Georgetown Texas, USA). Inlet and outlet temperatures to each zone of the tube suit were recorded in real time by a data acquisition system, DAQ (IO Tech, Cleveland Ohio, USA). The zonal and total body thermal exchange rate of the tube suit was given by

$$Q_{ts} = \sum_{i=1}^{6} q^{i}_{ts} = \sum_{i=1}^{6} \dot{m}^{i} c_p \left(T^{i}_{in} - T^{i}_{out}\right) \qquad [1]$$

where Q_{ts} (W) is the total thermal exchange rate over the entire body, q^{i}_{ts} (W) is the regional thermal exchange rate, $\dot{m}^{i}$ is the regional water mass flow rate (L min^{-1}), c_p is the specific heat of water at constant pressure (joule/gram°C), T^{i}_{in}(°C) is the regional water inlet temperature and T^{i}_{out}(°C) is the regional water outlet temperature.

Skin temperature measurements

Local skin temperatures were measured by using 17 thermocouples (24-gauge Omega Thermocouple Type T (Copper/Constantan) Model 5TC-TT-T-24-24, PFA Insulated with Teflon-coated tip) placed at strategic locations. Twelve of the thermocouples were positioned according to Mitchell and Wyndham [25]. Five additional thermocouples were positioned on the upper arm, second finger (pointer), fifth finger (pinky), first toe (great toe) and fifth toe (pinky toe). The thermocouples were attached to the body using double-faced surgical tape (Stomaseal, 3M, St. Paul, Minnesota, USA) and then covered with single-sided tape (3M Transpores). Ambient water temperature (T_W) was measured using a thermocouple immersed 30 cm away from the subject. The mean skin temperature was calculated based on a 13-point measuring system using average weighting coefficients for each region given by Hardy and Dubois [26]; equation [2], follows.

$$T_S = 0.07(A)+0.14\,\frac{(B+C)}{2}+0.05(D)+0.07(E)+0.13\,\frac{(F+G)}{2}+0.19\,\frac{(H+I)}{2}+0.35\,\frac{(J+K+L+M)}{4} \qquad [2]$$

Where:
T_S (°C) = mean skin temperature, A (°C) = head,
B (°C) = forearm, C (°C) = biceps, D (°C) = hand,
E (°C) = toe, F (°C) = front of calf, G (°C) = back of calf,
H (°C) = back of thigh, I (°C) = front of thigh,
J (°C) = scapula on back, K (°C) = pectorals on chest,
L (°C) = front abdomen, M (°C) = back of abdomen.

All data were recorded in real time by using a data acquisition system, DAQ (IO Tech, Cleveland, Ohio, USA).

Core temperature

Core temperature (T_{CORE}) was monitored using a wireless core body temperature monitoring system (pill sensor and wireless reader/recording device, HT150002, HQInc., Palmetto, Florida, USA) swallowed 60 minutes prior to exposure to water. Core temperature readings were automatically recorded every minute by a receiver placed on the subject's back. In addition, core temperature readings were manually taken every five minutes during the course of the experiment.

Data analysis

Data are presented as mean and standard deviation (s.d.). The data for comparison of unprotected *vs.* protected was conducted by a two-way (condition vs. time) analysis of variance (ANOVA) for repeated measures. Within conditions, variables were analyzed by one-way ANOVA for repeated measures. Linear regression analysis was carried out for average skin and finger skin temperatures, as well as power requirements. Normality and constant variance were tested and power calculated. All data were analyzed using SigmaStat software, and data were plotted by Sigma Plot (Point Richmond, California, USA). The $p \leq 0.05$ was used for all analyses.

RESULTS

All eight divers completed all conditions for the 90-minute protocol when given thermal protection by the DTPS, and although thermal comfort was not quantified, all subjects said they were comfortable. No sustained shivering was noted, nor was there an increase in VO_2 during the experiments where the divers were protected. However when unprotected, the divers reported feeling very uncomfortable in the cold water, shivered in T_W below 25°C, and stopped after 60 minutes during the warmer-water exposures.

Body temperatures

The time course of changes in individual T_S measurement is not shown as the steady state data are presented (last 30 minutes of immersion). It should be noted, however, that in the unprotected state, hands, fingers, feet and toes continued to fall in temperatures as a function of immersion time approaching T_W at the end of the experiments. Also in 39°C T_W when the subjects were not protected, all T_S increased rapidly, approaching 40°C by 60 minutes, when the experiments were terminated.

Mean T_S as a function of T_W *(Figure 1, facing page)*, was $T_S = 0.44\ T_W + 21.23$ while unprotected, and significantly different while protected ($T_S = 0.19\ T_W + 27.1$). Perhaps more important in the cold water is the Ts of the finger or toe. As finger function is more critical to divers, T_S of the fingers is shown in Figure 2 *(facing page)* for the T_W 20°C and below. As can be seen *(Figure 1)* when unprotected, the diver's steady state finger T_S was linearly related to T_W ($T_S = 0.49\ T_W + 11$, $r^2 = 0.95$) and approached T_W, well below a normal functional level. When protected, divers' steady state finger T_S was linearly related to T_W ($T_S = 0.31\ T_W + 20$, $r^2 = 0.99$), and the values were above the desirable 20°C required for hand dexterity. Similar data were seen for hand, foot and toes (data not shown).

Core temperature data are shown in Figure 3 *(Page 132)* for all T_W for unprotected divers in Plate A and protected divers in Plate B. In the unprotected condition, T_C was not significantly changed as a function of time in TW of 10°C-30°C. However, in 10°C-15°C there was a trend for an increase in T_C for the initial 40 minutes, and a trend for a fall over the remainder of the exposure. In 35°C and 39°C T_W, T_C increased progressively as a function of time, resulting in termination of the experiment at about 60 minutes in 39°C T_W.

When divers were protected, the T_C was not significantly affected by submersion time (90 minutes) in all T_Ws, and the subjects reported that they were comfortable throughout the dive. The core temperatures in the unprotected condition were significantly ($p \leq 0.05$) different than when divers were protected.

FIGURE 1

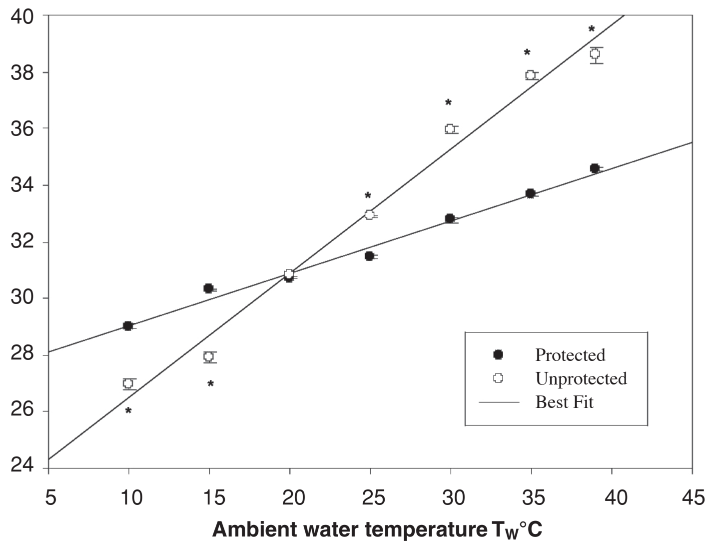


FIGURE 1 – Mean T_S ± s.d are plotted as a function of the ambient water temperature for unprotected and protected subjects. The data are the average of the last 30 minutes of submersion. The unprotected values were significantly different from the protected values (* = $p \leq 0.05$), except for T_W = 20°C.

FIGURE 2

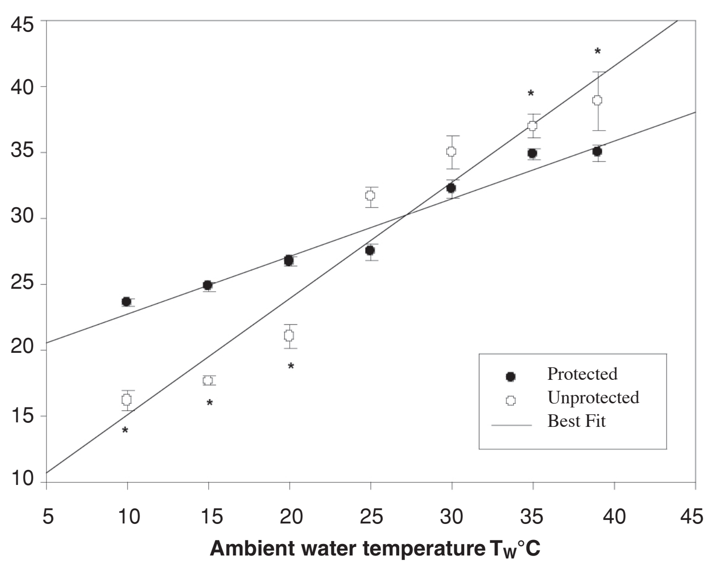


FIGURE 2 – Mean T_S ± s.d (average of the last 30 minutes of submersion) of the fingers in the unprotected and protected condition are plotted as a function of ambient water temperature. The unprotected values were significantly different from the protected values (* = $p \leq 0.05$), except for 25 and 30°C.

Thermal status

Due to the decrease in T_S it can be concluded that the divers were not thermally protected in the unprotected condition in cold water (<25°C). They were protected, however, in the protected condition. The divers were also not protected in warm water when they were unprotected, as their T_S, mean T_S and T_C rose significantly, and in fact, in T_W of 39°C, the experiment was terminated at 60 minutes. In the protected state, divers completed the warm-water experiments and were thermally protected.

Regional and total power requirements

The steady state (last 30 minutes of submersion) total heating/cool requirements calculated from Equation 1 (+ for heating and – for cooling) (power, W) *(Page 129)* to protect the divers are shown in Figure 4 *(Page 133)*. Total power was significantly (r^2 = 0.99) linearly related to T_W, with a slope of -17.2 and value of 345W at 0°C (intercept) *(see Table 1, Page 134)*. In 39°C the power requirement reached 335W. There was a large variability among the subjects, with coefficients of variation of 28% in 39°C and 46% in 10°C.

The data for steady state (last 30 minutes of submersion) heating/cool requirements for each individual zone are shown in Figure 5 *(Page 133)*. There were significant linear regressions between regional power requirements as a function of water temperature for specific zones, as shown in Table 1.

For the T_W below 20°C, the percentage of the total power was nominally 4 ± 2%, 30 ± 5%, 18 ± 3%, 11 ± 5%, 30 ± 7%, 7 ± 3% for head, torso, arm, hand, leg and foot. For T_W 35°C and above, a different pattern was observed: It was 8 ± 2%, 6 ± 1%, 27 ± 5%, 22 ± 3%, 13 ± 18%, 24 ± 8% for head, torso, arm, hand, leg and foot, respectively. However, at T_W of 20°C, while most regions were being heated (+ power), in the exercising legs there was an 18W flux to the tube suit, which met or exceeded the requirements of the other zones, thus minimizing the power from the TECs.

FIGURE 3A – *unprotected*

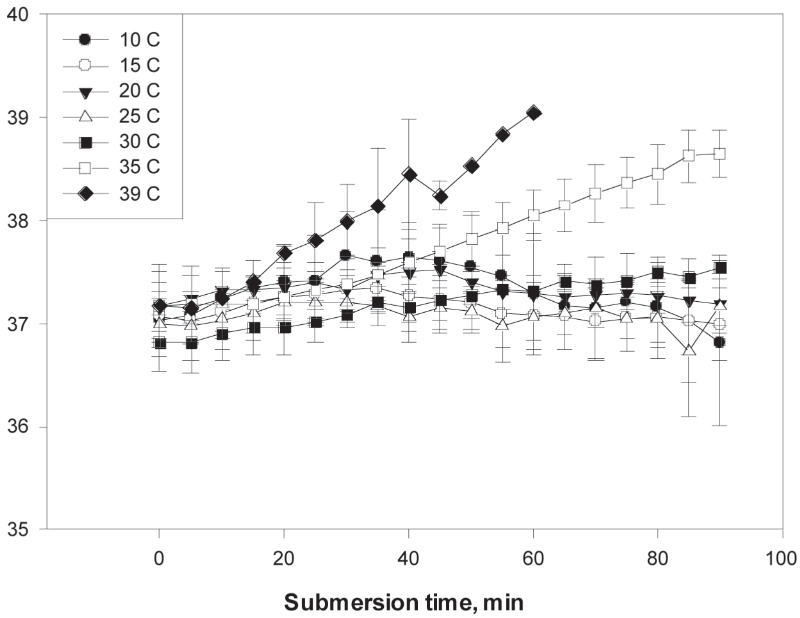
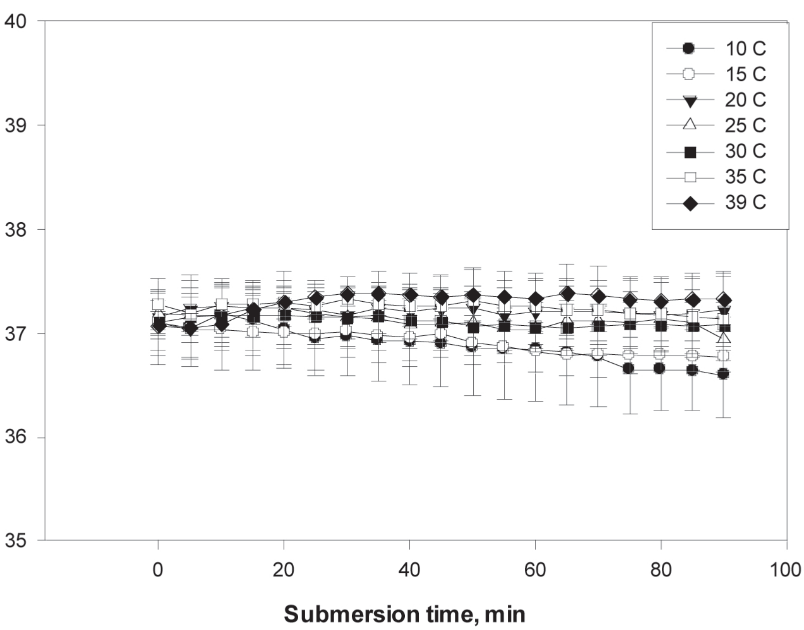


FIGURE 3 – Core temperatures for unprotected (upper plate, A) and protected (lower plate B) are plotted as a function of submersion time for the various water temperatures. The values are average (± s.d.) values of all subjects. The core temperatures were significantly different between protected and unprotected for T_W below 20°C and above 35°C ($p \leq 0.05$).

FIGURE 3B – *protected*



DISCUSSION

The primary finding of the present study was that the DTPS maintained divers' T_S and T_C within acceptable limits [7,8] during exercise in water temperatures from 10°C to 39°C. The philosophy of this system is to maintain the diver's thermal balance by minimizing heat flux to the ambient water, keeping the T_S within a range of 20°C to 35°C, and which, in turn, maintains T_C in an acceptable range (± 1°C) [7,8]. The DTPS is designed to be a backpack for scuba tanks, and if battery-powered, allows the swimmer to free-swim for a prolonged period of time.

Divers' first physiological defense against cold stress is the vasoconstriction of tissue blood flow to increase body insulation [27], which is greater the thicker the body fat layer [1,3,4,28]. In addition, the vasoconstrcition affects muscle blood flow, which adds body insulation but at the cost of reduced oxygen delivery and exercise capacity [27]. If the vasoconstriction is not sufficient to prevent a reduction in T_C, metabolism is increased to produce more heat [1,3,4]. However at T_W below T_N, the body loses heat, and T_C may decrease to a new steady state or continue to decrease if the thermal stress is too great. These physiological adjustments to cold stress compromise the diver's performance, and in fact, disable the hands and feet, whose temperatures drop most when approaching T_W due to their extreme vasoconstriction, low metabolism and large surface area for exchange of heat [29,30, 31].

The data in the present study demonstrate that when protected, but not when unprotected, thermal steady state T_S and T_C occur within 20 to 60 minutes. In the unprotected condition, neither T_S nor T_C were in a steady state in either the colder (<20°C) or warmer (>35°C) water temperatures. These data are in agreement with a previous study that

FIGURE 4

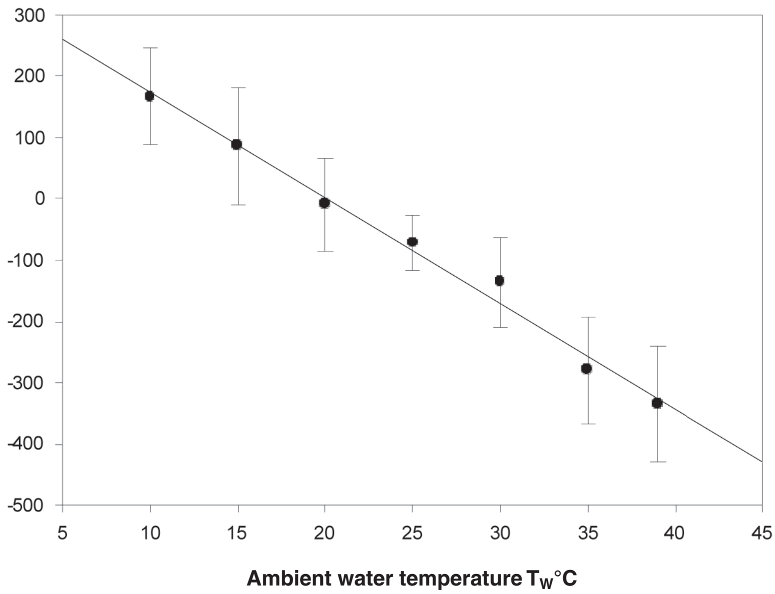


FIGURE 4 – Diver heating/cooling requirement is plotted as a function of ambient water temperature. The values are mean ± s.d. of all subjects in the protected condition. The + values represent heating and the – values cooling powers.

FIGURE 5

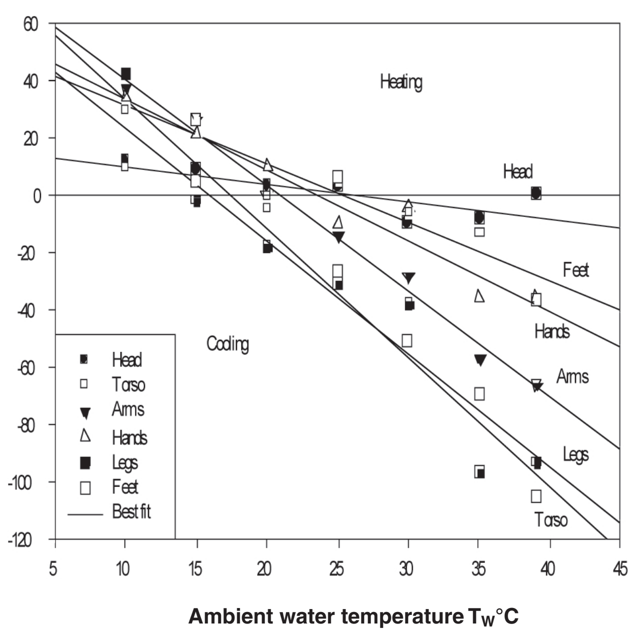


FIGURE 5 – The regional heating/cooling requirements of the diver are plotted as a function of ambient water temperature. The values are mean of all subjects.

showed T_S achieves heat balance preceding the stabilization of body temperature during cold-water immersion [20].

Although wetsuits increase insulation, their effect is transient and body cooling still results, particularly in hands and feet in cold water [18,19]. It is the case that the thicker the wetsuit the more insulation is provided [32], and thus the tolerable exposure time is longer. However, body movement may be restricted and hypothermia may still result if a diver wears a thicker wetsuit.

The DTPS used in the present study employed a six-zone tube suit to deliver water heated to 30°C, thus maintaining T_S between 25-35°C. Even the extremities were maintained above 20°C and thus were likely to be fully functional [7,8]. Previous studies have shown that there are significant temperature gradients between body segments as well as within a given segment [29,30,31]. In addition, regional differences in heat flux have been reported using heat flux disks [3], although heat flux measures have been questioned, particularly in warm water [17, 18,33].

These heterogeneities are due to differences in mass, circulation, subcutaneous fat thickness and local metabolism [34]. In addition, previous studies in air [13,14,15,17] indicated that if the torso is heated to a high level, sufficient heat can be transmitted to the body to maintain T_C as well as T_S of the fingers, in the latter case as the vasoconstriction of the finger is prevented [29,30]. However, in water heating the torso to a high temperature did not maintain T_C and T_S of the fingers [8,11], presumably due to the high heat conductivity of the water.

The total body tube suit was used in this study, as a previous study showed that heating only the torso did not prevent body cooling, and in fact resulted in a greater drop in T_C. This suggests that as heating the chest alone did not maintain T_C and T_S of the fingers [9,12] – presumably due to the high heat loss in water, that a total body system is required.

TABLE 1 – ***Results of the linear regression***

	Slope	Intercept	r^2
Total heating/cooling requirement	-17.21	345	0.99*
Head heating/cooling requirement	-0.60	16	0.65*
Torso heating/cooling requirement	-3.92	63	0.94*
Arm heating/cooling requirement	-3.68	77	0.99*
Hand heating/cooling requirement	-2.46	58	0.95*
Leg heating/cooling requirement	-4.50	78	0.93*
Foot heating/cooling requirement	-2.05	52	0.90*

* indicates significance at ≤ 0.05) of diver heating/cooling requirements as a function ambient water temperature.

In addition, there are differences in the diver heating/cooling requirements of the various zones in different T_{WS}, and in some cases, some zones are receiving heat while others are giving up heat. The total body-zone concept demonstrated in this study would appear to be required to protect both T_S and T_C.

The findings from the present study, where subjects were exercising, are similar to those of a previous study of resting divers [21] in that both studies demonstrate that divers' T_C and T_S could be maintained within the recommended limits in cold and warm water with the DTPS. In addition, the total-body-zoned tube suit used in both studies minimized body heat loss and power consumption.

In warm water, divers are exposed to heat uptake from the water, as well as their metabolically produced heat; the latter is significant during exercise. The physiological stress of hyperthermia is shown by: increased skin and cutaneous circulation; sweating and potential loss of plasma volume, which could reduce cardiac output; and the reflex vasoconstriction of blood flow to exercising muscle, which reduces exercise capacity [2]. The failure to thermoregulate is potentially severe in water temperatures above T_N. For example, at 39°C in this study, the dives were terminated at 60 minutes; the divers stated they were very uncomfortable and sometimes nauseous [35].

It has been shown that the heat taken up by the body when immersed in water can be reduced by wearing insulation, with thicker being better than thinner [21,32]. Thus, the divers in the present study wore a wetsuit, even in warm water, and with the DTPS could complete the 90 minutes of the experiment and maintain normal T_S and T_C, even during exercise. These data from the present study during exercise are in agreement with the previous study in resting subjects [21] – *i.e.*, T_S and T_C were maintained within recommended limits.

The present study also provided data for the total heating/cooling requirement to maintain divers' T_S and T_C within recommended levels [7,8]. These values were 86-166W in water from 15°C and 10°C and 278-334W in water from 35-39°C. Although we are unaware of any comparable data for warm water, previous studies have suggested divers near the surface in a wetsuit require about 400W in very cold water (5°C) [36]. The power required at 10°C from the present study suggested about 200W, but by extrapolation it would approach 400W at 0°C. Increasing insulation with a drysuit suggested that power in the range of 40-100W would be required. However, this level of heating may not protect the fingers/toes [37]. Another factor that could influence the power requirement is the depth of submersion – *i.e.*, 930W could be required at depth [37] due to the compression of the wetsuit material and subsequent loss of insulation [32, 38]. Thus, more power would be required the greater the depth.

The DTPS used in the present study was a self-contained unit. The DTPS also has no consumables: As long as electric power is provided, it will function indefinitely. Although the DTPS was supplied by electrical power by a DC generator, it has also been shown to operate from battery power (data not presented). The DTPS was automatically controlled, with no diver interface, and set to maintain a T_S of 30°C. A previous study has shown that the manual control of liquid cooling garments did not work as effectively as objective (autonomic) control [10,11]. In addition, an autonomic control of a liquid cooling suit improved comfort and decreased sweating [10,11].

CONCLUSIONS

This study demonstrated that the DTPS maintained divers' T_S and T_C within recommended limits [7,8] in 10°C-39°C water and, by extrapolation, has the capacity to protect down to 0°C. The total heating requirement was 166W at 10°C and 335W at 39°C. There were significant differences in the heating/cooling required by the different zones of the body, data that may be used in future work to minimize the power requirement to protect the diver. ■

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