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ACTIVE HEATING/COOLING REQUIREMENTS FOR DIVERS IN WATER AT VARYING TEMPERATURES

Erik R Bardy
Department of Mechanical Engineering
Grove City College

Joseph C Mollendorf, David R Pendergast
Center for Research and Education in Special Environments
Department of Mechanical and Aerospace Engineering
Department of Physiology and Biophysics
State University of New York at Buffalo

ABSTRACT
The active heating/cooling requirements to thermally sustain a human subject submerged in 10, 20, 30 and 40 ºC water was measured using a system that circulated water through a zoned tubesuit garment. Water at 30 ºC was circulated through the garment at a flow rate of about 0.5 L/min to each of six body regions and the outlet temperatures were measured. In addition, skin and core temperature, heat flux, and oxygen consumption was measured. The subject wore either a 6.5 mm or a 3 mm foam neoprene wetsuit. Body temperatures and heat fluxes reached steady state after 30-90 minutes and the immersions lasted 2-4 hours and core and skin temperatures remained within set thermal limits. In both wetsuits there was a linear correlation between the thermal exchange of the tubesuit and water temperature. While in the 6.5 mm wetsuit -214 to 242 W of heating (-) or cooling (+) was necessary in 10 to 40 ºC water, respectively. While wearing the 3 mm wetsuit -462 to 342 W was necessary in 10 to 40 ºC water, respectively. It was therefore concluded that a subject can be kept in thermal balance and comfort in 10-40 ºC water with active heating/cooling.
KEY WORDS: Thermal Balance, diving, heat flux, temperature, immersion

NOMENCLATURE
c_p=thermal capacity of water
i=body region
$\dot{m}$ =mass flow of water
Q_{met}=metabolic heat production
Q_s=total body heat loss
Q_{ts}=total body thermal exchange rate of the tubesuit
q_{ts}=regional body thermal exchange of the tubesuit
T_{core}=deep body core temperature
T_{in}=inlet water temperature
T_{out}=outlet water temperature
$T_{av\ skin}$=total body mean skin temperature
T_w=ambient water temperature
V_{02}=oxygen consumption

INTRODUCTION
Maintaining thermal balance is of utmost importance for long duration underwater activity, whether recreational, professional or military. Current wetsuits and drysuits are not sufficient to maintain divers in thermal balance in water above or below temperatures considered to be thermal neutral (32–35 °C). Thus to maintain thermal balance would require heating and cooling systems.

An analysis from Lippitt and Nuckols [1] estimated that the active heating requirements to for a diver in 0 ºC water in a drysuit with air or helium as the breathing gas ranged from 65–930 W at pressures ranging from 0.6–1.2 MPa (60–110 msw, meters of sea water), respectively. It was suggested that the heating requirements to sustain a diver in a wetsuit at rest at atmospheric pressure in near freezing water was nearly 400 W [2]. In spite of these estimates specific heating/cooling requirements of divers for a wide range of temperatures is lacking, particularly if an active heating and cooling system is to be developed or evaluated.

One determinant of the active requirements is the amount of insulation the diver wears. Although drysuits have greater insulation, their ergonomic function is significantly less than that of wetsuits, thus most diving is done in wetsuits (made from closed cell foam neoprene). Foam neoprene has a thermal resistance of approximately 0.09-0.10 m^2K/W (5 mm thick, 262-293 kg/m^3) at atmospheric pressure [3]. However, as ambient pressure increases the thermal resistance decreases due to compression of the gas cells (50% at 0.25 MPa, 15.25 msw) [3]. Therefore, during cold water immersion at depth, total body heat loss is greater resulting in an increased need for active heating.

Current active heating systems use electrical resistance heating or circulation of warm water for tethered divers through an umbilical connected to the surface supply source. Although this may increase dive time, being attached to the umbilical limits mobility and depth. In addition the water supplied to the diver can result in an uneven application of heat and makes it difficult to measure the amount of heating or cooling.

Previous studies have used heat flow disks to determine body heat loss, however they do not accurately reflect the actual heat loss [4, 5] and their use in warm water has been questioned. The adaptation of the total body liquid garment to a zoned garment would allow more accurate measurement of total or regional heat loss or gain to the body. If an active heating/cooling system were used this garment would have the potential to become a total and regional body calorimeter. Although not currently available, a portable active diver heating/cooling system using this liquid cooling garment could also protect the diver in warm and cold water based on appropriate cooling/heating requirements.

The purpose of this study was to evaluate the active heating/cooling requirements necessary to sustain a diver at varying ambient water temperatures (10 ºC, 20 ºC, 30 ºC and 40 ºC) with a prototype tubesuit (Med-Eng Inc, Ottawa, ON) perfused by active heating/cooling units while wearing a wetsuit. Two wetsuit thicknesses were chosen; a standard thickness of 6.5 mm and another at 3 mm, the latter to simulate a pressure of 0.25 MPa (or 15 msw) as previously determined by Bardy et al. [3]. Diver skin temperatures, heat fluxes and core temperature were used to assess the thermal status of the diver.

METHODS

The amount of active heating/cooling is determined primarily by the ambient water temperature and the insulation value of the wetsuit. One subject (age 28, 97.5 kg, 1.8 m) was tested. Total body surface area was determined according to the method described by Dubois and Dubois [6]. A total of 8 experiments were performed. The subject wore the tubesuit, perfused by an active heating/cooling system, under either a 3 mm or a 6.5 mm foam neoprene wetsuit. The wetsuits used had two layers of insulation over the upper leg and torso region, and a single layer elsewhere. The subject, for each condition, was completely immersed (0.5 meters) in a water bath set to temperatures of 10±0.05 °C, 20±0.05 °C, 30±0.05 °C and 40±0.05 °C at atmospheric pressure (all future references to ambient water temperature beyond this point are noted without standard deviations except in Table 2).

Active System Including Tubesuit

The prototype tubesuit was developed in collaboration with Med-Eng Systems Inc. (Ottawa ON) (see Figure 1). The tubesuit was composed of six body regions circulated with water from a separate heating/cooling unit. The tubing length and number of flow circuits for each body region are shown in Table 1. All tubes were made from a non-toxic medical grade vinyl compound (k_{tube}=0.125 W/m-K, d_i=0.0025 m, d_o=0.0045 m, properties from Med-Eng, Inc.). The water flow was regulated to each region of the tubesuit by varying the voltage to six separate power supplies (Elenco precision Model XP-603) connected to motor pumps (B&D, Tucson AZ). The water inlet and outlet temperatures were monitored and recorded by thermocouples (Type T, Omega) placed at the inlet and outlet of each region of the tubesuit. The water flow rate to each region was monitored and recorded by six separate turbine flow meters (McMillan Corp., Georgetown TX). The water flow rate was chosen to be 0.5 L/min for optimal heat transfer based on data provided by the manufacturer (Med-Eng Inc). A flow rate of 0.75-1.0 L/min was chosen for the hands and feet as the flow is split into two parallel paths; one to each hand and foot.

Active Heating/Cooling

The inlet water temperature was chosen to be 30 ºC. This was based on an attempt to keep skin temperatures elevated but below 32 ºC, which is the threshold for maximal body thermal resistance due to vasoconstriction [7]. The inlet water temperature was regulated by six separate constant temperature water baths (Julabo model F12, Allentown PA).

Measurement of Heating/Cooling Rate

All flow rates and inlet and outlet temperatures to each zone of the tubesuit were recorded in real time using a data acquisition system, DAQ (IO Tech, Cleveland OH). The regional and total body thermal exchange rate of the tubesuit is given by equation (1).

$$Q_{ts} = \sum_{i=1}^{6} q_{ts}^{i} = \sum_{i=1}^{6} \dot{m}^{i} c_{p} \left(T_{in}^{i} - T_{out}^{i} \right) \qquad (1)$$

The skin heat loss was directly measured using 10 heat flux sensors (Thermonetics, LaJolla Ca.) placed in different locations of the body. The body was separated into 6 regions (Head, Torso, Arms, Legs, Hands and Feet) whose surface area was calculated according to Hardy and Dubois [8].

The heat flux sensors were attached to the body using double-faced surgical tape (Stomaseal, 3M, St. Paul, MN) and then covered with single sided tape (3M transpores). This arrangement of heat flux sensors corresponded to a placement determined by Ferretti et al. [9] to best estimate the total body heat exchange. Regional heat losses were calculated as a sum of all the measuring points within that region. The measured total body heat loss was calculated as the sum of all the regional heat losses. All heat flux measurements on one side of the body were assumed to be equal to the other side as validated by Layton et al. [10].

Calibration constants for the heat flux transducers (to convert from voltage to W/cm^2) were determined by using a thermal conductivity meter [3, 11]. The total heat flux was calculated using Fourier's Law ($q=k*\Delta T/L$, k=thermal conductivity, $\Delta T=T_{hot}-T_{cold}$, L=sample thickness, q=heat flux). The calibration constants for each heat flux transducer were calculated as a ratio of the heat flux calculated from measurements of the thermal meter to the recorded voltage of each heat flux transducer.

Local skin temperatures were measured by using 17 thermocouples (Type T, Omega) placed at strategic locations. Twelve of the thermocouples were positioned according to Mitchell and Wyndham [12] (see Figure 2). Five additional thermocouples were positioned on the upper arm, 2nd finger (pointer), 5th finger (pinky), 1st toe (big toe) and 5th toe (pinky toe). 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 [13]. All data (skin heat flux and temperature) were recorded in real time by using a data acquisition system, DAQ (IO Tech, Cleveland OH).

Core temperature (T_{core}) was monitored using a wireless core body temperature monitoring system (pill sensor and reader/recording device, HT150002, HQ Inc., Palmetto, FL) swallowed 30-60 minutes prior to submersion. Metabolic heat production (Q_{met}) was estimated from measurements of oxygen consumption by collecting the expired gas in a Douglas bag. The volume and constituent gas content of the air in the bag was measured by using a gasometer (J H Emerrson, Cambridge Mass) and mass spectrometry (MGA 1100). The metabolic heat loss was then calculated from the following formula as described by Choi et al. [14].

$$Q_{met} = 5.61 * V_{0_2} - 0.08 * (5.61 * V_{0_2}) \qquad (2)$$

where 5.61 is the oxygen to energy conversion factor in W-h/Liter and 0.08 accounts for the respiratory heat loss (8%).

Experimental Procedure

The subject was fitted with thermocouples and heat flux sensors in the locations described in Figure 2. The subject then donned the tubesuit and either a 3 mm or 6.5 mm foam neoprene wetsuit. The subject also donned foam neoprene diving gloves, boots and a hood (3 mm or 5 mm thick depending in the corresponding wetsuit thickness). Before being immersed in the water, the flow rate of water through the tubesuit was set to 0.5 L/min for the torso, arms, legs and head, and 0.75-1.0 L/min for the hands and feet at a temperature of 30 ºC. The subject then entered the water (set to either 10 ºC, 20 ºC, 30 ºC or 40 ºC) and rested in the prone position supported by a harness while breathing on Self Contained Underwater Breathing Apparatus (SCUBA).

Core temperature readings were automatically recorded every minute by a receiver placed on the subjects back. In addition core temperature readings were manually taken every five minutes during the course of the experiment. To estimate the metabolic heat production, oxygen consumption was measured for an interval of two minutes after the first five minutes of immersion and then at the end of the experiment. It was assumed that the latter measurement of oxygen consumption would be representative of a steady state value [15].

Each experiment was terminated after 30 minutes of steady state readings were achieved based on core temperature and regional skin temperature. Steady state was defined as no more than a 0.1 ºC change in core temperature during a 20 minute period along with less than a 1% change in regional skin temperature and approximately 5% change in total body heat flux. The total time of submersion ranged from 2-4 hours.

During the course of each experiment the subject was monitored to ensure the subject remained within safe thermal limits [16] (further references as "thermal limits"). In cold water, it was ensured that the core temperature did not decrease more than 1 ºC of the initial reading and that local skin temperatures remained above 20 ºC (fingers and toes>15 ºC) and in hot water the core temperature did not increase past 38.5 ºC and skin temperature did not exceed 42 ºC. If any of these criterion were violated the experiment was terminated.

Table 1: Design characteristics of the tubesuit.

		Design Rates for Each Body Region	
Body Region	Qty	Circuit Qty	Tube length per circuit (m)
Head	1	2	3.0
Torso	1	14	3.0
Arms	2	2	3.0
Legs	2	3	5.1
Hands	2	1	2.4
Feet	2	1	5.8
Total	*10*	*-*	*107*

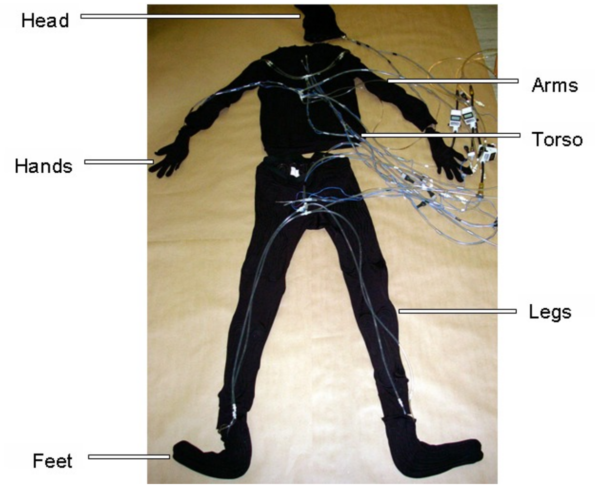

Figure 1: Tubesuit (Med-Eng, Ottawa ON) with six body regions.

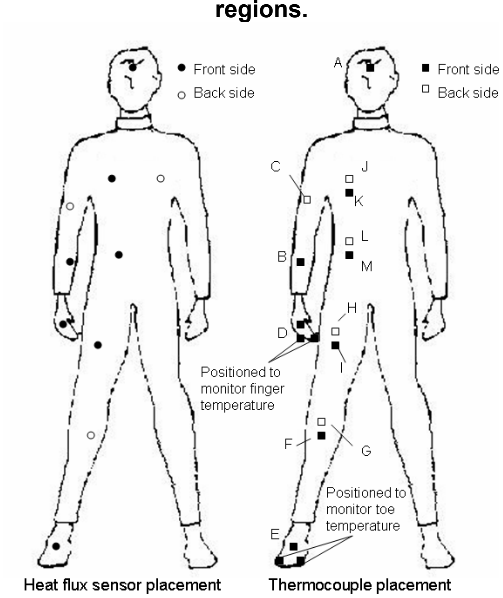

Figure 2: Heat flux sensor and thermocouple placements.

RESULTS

Core Temperature

Steady state T_{core} values and standard deviations are indicated for each immersion case in Table 2. In 10 ºC and 20 ºC water experimentally measured steady state T_{core} values were reached after approximately 120 minutes. Steady state T_{core} values for the subject in 10 ºC and 20 ºC water were 36.78±0.04 ºC and 36.91±0.02 ºC, and 37.02±0.00 ºC and 36.75±0.02 ºC in the 3 mm and 6.5 mm wetsuit, respectively. In 30 ºC water steady state T_{core} values were achieved after approximately 60 minutes reaching 36.99±0.01 ºC and 38.86±0.05 ºC in the 3 mm and 6.5 mm wetsuit, respectively. In 40 ºC steady state T_{core} readings were achieved after 20 minutes of immersion time reaching 37.34±0.00 ºC and 37.04±0.04 ºC in the 3 mm and 6.5 mm wetsuit, respectively. All core temperatures stayed within the set thermal limits [16].

Skin Temperature

The steady state mean total body mean skin temperature ($T_{av\ skin}$) for each case and standard deviation is indicated in Table 2. $T_{av\ skin}$ increased with increasing T_w. Values of $T_{av\ skin}$ in 10 ºC water was 27.1±0.0 ºC and 28.1±0.1 ºC in the 3 mm and 6.5 mm wetsuit, respectively. In 40 ºC water $T_{av\ skin}$ was 34.9±0.0 ºC and 33.7±0.0 ºC in the 3 mm and 6.5 mm wetsuit, respectively. A plot of $T_{av\ skin}$ with varying T_w is shown in Figure 4 for both the 3 mm and 6.5 mm wetsuit and it shows a strong linear correlation. Importantly $T_{av\ skin}$ and all local skin temperatures stayed within the thermal limits of 25 ºC≤$T_{av,\ skin}$≤42 ºC.

Skin Heat Loss

Steady state values and standard deviation of total body skin heat loss (Q_s) are shown for all cases in Table 2 along with the total metabolic heat production (Q_{met}). Steady state values for all cases were reached after approximately 60 minutes for the 10 ºC and 20 ºC immersion cases and after 20 minutes for the 30 ºC and 40 ºC immersion cases.

There was a difference in Q_s among the varying water temperatures. For example, Q_s of the subject in 10 ºC water was -163±6 W in both wetsuits. In 30 ºC water Q_s was -128±2 W and -129±3 W in the 3 mm and 6.5 mm wetsuit, respectively. Q_{met} decreased with increasing T_w. In 10 ºC water Q_{met} was 216 W and 138 W in the 3 mm and 6.5 mm wetsuit, respectively. It continued to decrease to 105 W and 131 W in 30 ºC water while in the 3 mm and 6.5 mm wetsuit, respectively. In 40 ºC water Q_{met} increased slightly to 112 W while in the 3 mm wetsuit and decreased to 120 W in the 6.5 mm wetsuit.

Thermal Exchange of the Tubesuit and the Effect of Insulation

The thermal exchange of the tubesuit (Q_{ts}) as a function of varying T_w in both the 3 mm and 6.5 mm wetsuit is shown in Figure 3. The negative y-axis indicates heat loss by the tubesuit and the positive y-axis indicates heat gained. Values of Q_{ts} for the tubesuit in 10 ºC water were approximately twice as high compared to 20 ºC water for the same wetsuit thickness. Similarly Q_{ts} of the tubesuit was twice as high in the 3 mm wetsuit compared to the 6.5 mm wetsuit while in the same ambient water temperature (10 ºC and 20 ºC). For example, Q_{ts} in the 3 mm wetsuit in 10 ºC water (-462±9 W) was twice as high compared to Q_{ts} in the 3 mm wetsuit in 20 ºC water (-226±6 W) and in the 6.5 mm wetsuit in 10 ºC water (-214±11 W). In 30 ºC and 40 ºC water the tubesuit experienced a heat gain. In 30 ºC water Q_{ts} was 45±5 W and 60±1 W in the 3 mm and 6.5 mm wetsuit, respectively. Q_{ts} in 40 ºC was greater than in 30 ºC water. Q_{ts} was 342±5 W and 242±5 W in the 3 mm and 6.5 mm wetsuit, respectively.

A regression analysis showed a strong linear correlation between Q_{ts} and T_w in both the 3 mm and 6.5 mm wetsuit. The point at which the regression line crosses the x-axis in Figure 3 indicates the T_w where the tubesuit would not experience any thermal exchange. This temperature was determined to be 27.7 ºC and 25.2 ºC in the 3 mm and 6.5 mm wetsuit, respectively.

A plot of $T_{av\ skin}$ with varying T_w is shown in Figure 4. As previously mentioned $T_{av\ skin}$ in both the 3 mm and 6.5 mm wetsuit shows a strong linear correlation with varying T_w. In Figure 3, it was shown that at a T_w of 28.1 ºC and 25.2 ºC, in the 3 mm and 6.5 mm wetsuit, respectively; the tubesuit would not experience any thermal exchange. According to Figure 4, $T_{av\ skin}$ at those perspective T_w values would be 31.8 ºC and 31.7 ºC in the 3 mm 6.5 mm wetsuit, respectively.

Table 2: Steady state values of core temperature (ºC), total body skin temperature (ºC), total body heat loss (W) and metabolic heat production (W).

	T_w	T_{core}	$T_{av,\ skin}$	Q_s	Q_{met}
3 mm wetsuit	10±0.05	36.78±0.04	27.1±0.0	-163±6	216
	20±0.05	37.02±0.02	29.9±0.0	-132±4	152
	30±0.05	36.99±0.01	32.7±0.0	-128±2	105
	40±0.05	37.34±0.00	34.9±0.0	-59±1	112
6.5 mm wetsuit	10±0.05	36.91±0.00	28.6±0.1	-163±6	138
	20±0.05	36.75±0.02	31.4±0.1	-131±2	137
	30±0.05	38.86±0.05	31.4±0.1	-129±3	131
	40±0.05	37.04±0.04	33.7±0.0	-133±2	120

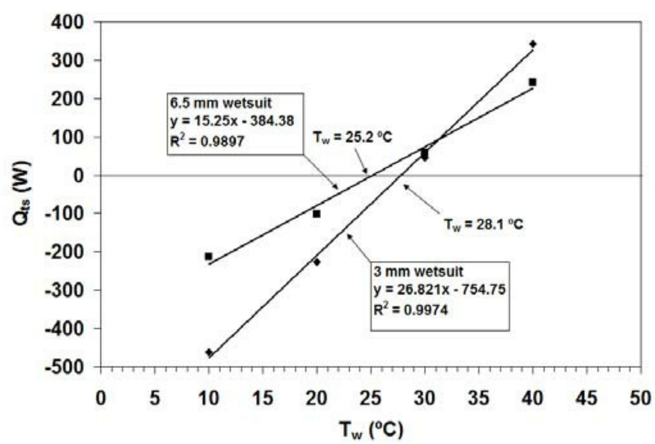

Figure 3: Total tubesuit thermal exchange as a function of varying T_w for both wetsuit thicknesses.

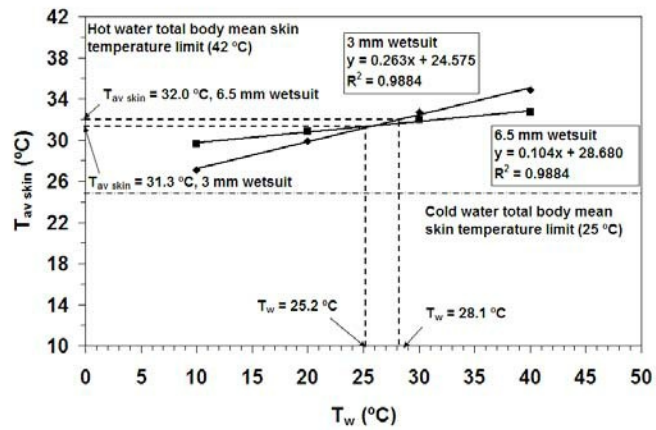

Figure 4: The total body average skin temperature as a function of varying T_w for both wetsuit thicknesses.

DISCUSSION

Core Temperature

The time course of achieving steady state in T_{core} ranged from nearly 0 minutes (40 ºC-3 mm wetsuit case) to 120 minutes (in 10 ºC and 20 ºC immersion cases). All steady state T_{core} measurements stayed within the set thermal limits. In a previous study (Ferretti et al. [9]) the total time to steady state for nude subjects in critical water temperature was approximately 60–65 minutes, which is consistent with the data for the 30 ºC immersion cases in the present study.

In 20 ºC and 30 ºC water the metabolic heat production (oxygen consumption) was greater in the 3 mm wetsuit than in the 6.5 mm wetsuit. This is consistent with the increased insulation of the 6.5 mm wetsuit compared to the 3 mm wetsuit. In addition, it was observed that the subject intermittently shivered in the 10 ºC-3 mm wetsuit case which would naturally increase Q_{met} (V_{02}). In 30 ºC and 40 ºC water the differences in Q_{met} (V_{02}) between the two wetsuits was negligible.

Skin Temperature

Steady state $T_{av\ skin}$ was reached in less than 30 minutes while in 40 ºC and in approximately 60 minutes for all other water temperatures. Steady state $T_{av\ skin}$ values decreased with decreasing T_w. In addition, in cold water $T_{av\ skin}$ was higher in the 6.5 mm wetsuit compared to the 3 mm wetsuit. In hot water $T_{av\ skin}$ was higher in the 3 mm wetsuit compared to the 6.5 mm wetsuit. The increased insulation of the 6.5 mm wetsuit provided more thermal protection thus maintaining elevated $T_{av\ skin}$ in cold water compared to the 3 mm wetsuit. In the same manner in hot water the increased thermal protection of the 6.5 mm wetsuit would result in lower $T_{av\ skin}$ values compared to the 3 mm wetsuit. It is noted though that all skin temperatures for all immersion cases stayed within the thermal limits for regional and total body mean skin temperature indicating that the tubesuit protected within this criterion.

Skin Heat Loss

The time to achieve steady state for Q_s ranged from 20 minutes in 30 ºC and 40 ºC water to approximately 60 minutes in 30 ºC and 40 ºC water, which is similar to the time to steady state for $T_{av\ skin}$. For the cold water immersion cases (10 ºC and 20 ºC) the total time to steady state for T_{core} was considerably longer (approximately 120 minutes). This is consistent with data from Tikuisis [15] who showed that heat balance, and consequently skin temperatures, stabilizes before body core temperatures. Values of Q_s varied little in comparison between all immersion cases except in the 40 ºC-3 mm wetsuit case. In 40 ºC water Q_s was more than 2x greater then in the 6.5 mm wetsuit (-133±2 W) compared the 3 mm wetsuit (-59±1 W). This difference in Q_s can be explained from the differences in insulation. With the increased insulation of the 6.5 mm wetsuit, less heat would enter the body allowing the tubesuit to remove more metabolic heat resulting in higher skin heat loss. In the 3 mm wetsuit more heat was entering from the ambient due to less thermal insulation. The tubesuit therefore was removing less metabolic heat due to being overwhelmed by heat from the ambient. Therefore the overall skin heat loss was less. In cold water since Q_s was approximately equal between the two wetsuits, this would suggest that the tubesuit was effectively providing enough heat to the body to maintain thermal balance.

In cases where Q_{met} closely matched Q_s the subject was in thermal equilibrium. All values of Q_{met} were within 25% of Q_s except in the 40 ºC-3 mm wetsuit case where Q_s was 47% less than Q_{met}. This indicates that overtime the subject would gain more heat and regional skin temperatures would continue to rise although steady state was maintained for 60 minutes. In all immersion cases all body temperatures remained within a range that would suggest thermal balance was achieved.

Thermal Exchange of the Tubesuit and the Effect of Insulation

From the data in the present study it was shown that Q_{ts}=0 at a T_w of 28.1 º C and 25.2 º C in the 3 mm and 6.5 mm wetsuit, respectively. These temperatures correspond to the critical water temperatures (T_{cw}) previously reported (Park et al. [17]) where the subjects were immersed in water to the neck in a 5 mm wetsuit. The critical water temperature was defined as the lowest water temperature the subject could tolerate for 3 hours without shivering [9, 17, 18]. It was determined that T_{cw} at atmospheric pressure (0.1 MPa) was 22-24 ºC. This increased to 26-28 ºC and 27-30 ºC at 0.2 MPa (10 msw) and 0.25 MPa (15 msw), respectively. This corresponds to a decrease in insulation of foam neoprene of approximately 42% and 53% at 0.2 MPa and 0.25 MPa, respectively according to data from Bardy et al. [3]. The resultant T_w for Q_{ts}=0 of the tubesuit in the 3 mm and 6.5 mm wetsuit correspond to the T_{cw} determined by Park et al. [17] for a subject in a 5 mm wetsuit at atmospheric pressure and at 0.25 MPa. In addition, the total body average skin temperature of the subject corresponding to zero thermal exchange between the tubesuit and the subject was 31.3 ºC and 32.0 ºC in the 3 mm and 6.5 mm wetsuit respectively (according to Figure 4). This is approximately equal to the mean skin temperature of the subjects at critical water temperature in the Park et al. [17] study which were 29-32 ºC.

Insulation had a strong affect on the Q_{ts} in cold water where approximately two times more heat was lost in the 3 mm wetsuit compared to the 6.5 mm wetsuit. This is validated by observing that although Q_s was the same in both wetsuits, $T_{av\ skin}$ was higher in the 6.5 mm wetsuit compared to the 3 mm wetsuit. Since $T_{av\ skin}$ was higher in the 6.5 mm wetsuit, the only way for Q_s to remain the same was for the insulation to be higher. In 30 ºC water the tubesuit heat gain was small since T_w was close to the set value of the water inlet temperature (30 ºC) and values of T_{cw} for a nude subject (27-33 ºC, [9]). In 40 ºC water the tubesuit heat gain was 41% greater in the 3 mm wetsuit compared to the 6.5 mm wetsuit. This heat gain was, like the heat loss, was dependant on the amount of insulation worn. The difference in heating requirements in 40 ºC water between the two wetsuits was smaller in value than the cooling requirements in 10 ºC and 20 ºC water. The 6.5 mm wetsuit has twice the thermal resistance of the 3 mm wetsuit, but the cooling requirement was 29% less in hot water (40 ºC) whereas in cold water the heating requirement was 48% (10 ºC water) and 56% (20 ºC water) less. The difference in the heating/cooling requirements to keep the diver thermally neutral arises from the direction of heat flow. In cold water (10 ºC and 20 ºC water) the tubesuit was losing heat to the ambient through the wetsuit insulation and gaining heat from the body's metabolic heat. Therefore the only direction of lost heat was to the ambient, which is controlled by the amount of wetsuit insulation. Since the insulation of a 6.5 mm wetsuit is approximately twice as high compared to the 3 mm wetsuit, the total heat lost was approximately twice as high (given the same ΔT). In hot water (30 ºC and 40 ºC water) the tubesuit is removing metabolic heat and heat gained from the ambient through the wetsuit insulation. The heat gain therefore was coming from two directions (metabolic and ambient) in which heat from one direction (the ambient) is determined by the wetsuit insulation. The value of insulation in warm water was less than it is in cold water as the insulation protects against heat gain from the water, but not from the metabolism. The higher the thermal resistance of the wetsuit, the more the diver is protected from ambient heat gain and the more the tubesuit is effective in removing waste metabolic heat. This is observed in comparing Q_s and Q_{met}. In the 6.5

mm wetsuit similar Q_{met} and Q_s values, as discussed earlier, indicate that the subject was in thermal equilibrium. That indicates that the heat gained by the tubesuit (242±5 W) was sufficient. On the other hand in the 3 mm wetsuit Q_s was 47% less than Q_{met} indicating the heat gain from the tubesuit was not sufficient in removing enough waste metabolic heat. Although there was this mismatch in Q_{met} and Q_s, the subject's core temperature was still steady.

CONCLUSIONS

The data from this study show that a subject can be kept in thermal balance and comfort while wearing a 6.5 mm foam neoprene wetsuit in water temperatures varying from 10-40 ºC while wearing a tubesuit perfused with about 0.5 L/min of water set at 30 ºC. The active heating/cooling requirements to maintain a subject within the set thermal limits while in a 6.5 mm wetsuit ranged from –214±5 W in 10 ºC water to 242±5 W in 40 ºC water. In a 3 mm wetsuit the heating requirement nearly doubled in cold water and the cooling requirements increased by 41% in hot water requiring –462±9 W in 10 ºC water to 342±5 W in 40 ºC water. This also indicates that the heating/cooling requirements for the active system have a strong dependency on wetsuit insulation in both hot and cold water. In addition, although differences in Q_{met} and Q_s may lead to future transients, steady core and skin temperatures were reached. These steady state values were maintained within the limits that would support the conclusion that the diver was in thermal balance and comfort.

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