Thermal balance of spinal cord injured divers during cold water diving: A case control study

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Abstract
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Introduction: This study compared the thermal balance of spinal cord injured (SCI) divers and able-bodied (AB) divers during recreational cold-water dives.
Methods: Ten divers (5 AB, 5 SCI) in matched pairs dived in a shallow lake (temperature 6°C) for 30 to 36 min wearing 5 mm 'Long John' neoprene wetsuits. A gastrointestinal temperature radio pill recorded gastro-intestinal temperature (T_{gi}) prior to, immediately after and at 5, 10, 15, 30, 60, 120 min post-dive. Subjective ratings of temperature perception were recorded concomitantly using a visual analogue scale (VAS).
Results: No difference between SCI and AB divers in T_{gi} before the dive was observed (*P* = 0.85). After the dive, SCI divers cooled significantly more than AB at all measured time intervals (*P* < 0.001). Post dive, the mean maximum fall in T_{gi} during the recovery phase in SCI divers was 0.85°C (SD 0.20) and in the AB group was 0.48°C (0.48). In addition, there was greater individual variation in SCI divers compared to AB divers. There were no statistically significant differences in temperature perception between the groups either before or at any time after the dives.
Conclusions: In contrast to AB divers, divers with SCI were unable to maintain T_{gi} during short shallow dives in 6°C water and their temperatures fell further post-dive. The reduction in T_{gi} was not reflected in the subjective ratings of temperature perception by the SCI divers. The study was too small to assess how the level of spinal injury influenced thermal balance.

Introduction

The annual incidence of traumatic spinal cord injury (SCI) in developed countries is estimated at 15 to 40 cases per million people.[1] The American Disabilities Act of 1990 and the British Disability Discrimination Act of 1995 have formed the basis for greater integration of SCI individuals into society. Today, individuals with spinal cord injury participate in sports and some even compete in high-level organised events such as the Summer and Winter Paralympic Games.[2] Recreational scuba diving is becoming a popular sport among SCI individuals. According to a survey of scuba diving for disabled divers, over 50% of British dive clubs had been involved in the training of disabled divers between 1998 and 2000.[3] Specialised training for SCI recreational divers is now available worldwide through national or regional associations for handicapped divers, as well as dive education organisations.[4]

SCI divers participate in both warm- and cold-water diving. One of the main issues for divers is thermal protection since the ratio of heat conductivity of water to air is approximately 24:1.[5] Although SCI individuals participate in winter paralympic sports (alpine skiing, ice sledge hockey, Nordic skiing, wheelchair curling, biathlon), the heat loss during these activities conducted in cold air is substantially less than that experienced during immersion in cold water.

Autonomic and behavioural responses are involved in the maintenance of deep body temperature in humans within a narrow range despite large variations in ambient conditions and activity level. Central foci initiate appropriate effector mechanisms in response to thermal afferent information from skin and core regions. Injury to the spinal cord abolishes thermal afferent information from regions innervated by nerves emerging from the spinal cord below the injury. Thus, although hypothalamic and cortical regions involved in autonomic and behavioural temperature regulation are not affected, their actions are limited to the regions above the spinal cord lesion. Consequently, the ability of SCI individuals to regulate body temperature and to sense cold is impaired.[6,7] The severity of impairment is directly related to the injury level and completeness of the lesion. Deep or central temperature receptors sensitive to cold can initiate shivering above the level of the SCI.[6] Individuals with SCI show lower core temperature after cold exposure in comparison to able-bodied controls.[8,9] Central temperature mechanisms remain unaffected.[10]

As hypothermia is one of the risks in diving,[11] suitable thermal protection is part of the personal protective equipment of any diver. While in tropical waters neoprene rubber suits are the primary choice, drysuits are usually recommended for cold-water diving. However, in drysuit diving, gas must be delivered and released from the suit to maintain a constant volume during diving and to minimise the squeeze on descent or uncontrolled ascent due to excessive air. In general, drysuit diving requires specific training to control buoyancy. SCI divers need to use their arms to prevent uncontrolled rapid ascent and at the same time operate the suit and buoyancy compensator inflation and exhaust valves. The compensating air is usually taken from the breathing cylinder, decreasing diving time. Most dry suits have baggy trousers to allow passage of the feet to the boots. A large volume of air can be trapped in the legs, leading to body inversion. This can occur much faster in SCI divers who may have difficulty maintaining horizontal trim.[12] All the above might explain why SCI divers usually only use neoprene rubber wetsuits. The drawback of a wetsuit in contrast to a drysuit is that it does not offer the same level of thermal protection.

Several studies have investigated the issue of hyperthermia in SCI individuals during fever[13] and during activities conducted in warm air environments,[14,15] but there is only anecdotal information regarding the risk of cold injury among SCI individuals conducting activities in cold environments. During activities in cold air, the risk of local freezing and non-freezing cold injury to regions below the lesion and of hypothermia is most likely higher among SCI compared to able-bodied individuals. In contrast to activities conducted in air, where exposure time is essentially unlimited, during diving the exposure to the high heat loss environment is limited by the capacity of the breathing air supply.

In cold water diving the main problem is hypothermia.[16] Therefore, SCI divers would benefit from recommendations regarding planning such dives. The present study was conducted to compare gastrointestinal temperature as a valid surrogate marker of core temperature following a shallow dive in cold water in SCI and non-SCI divers. We hypothesised that SCI divers exposed to the same environmental conditions would demonstrate a larger reduction in core temperature than their able-bodied dive partners.

Methods

The study was approved by the National Committee for Medical Ethics at the Ministry of Health of the Republic of Slovenia. Written informed consent was obtained and it was made clear to all the participants that they could terminate the dive at any point. All volunteers were familiar with the methods and the diving protocol.

STUDY POPULATION

Five SCI and five able-bodied (AB) divers participated. All were experienced divers (between 100 and 300 logged diving hours), with previous experience in cold-water diving. All SCI divers were at least five years post-injury with levels of injury of T6 (two divers), T9 (one diver) and T12 (two divers), ASIA score A[17] and had no history of cardiovascular disease or diabetes. Paraplegia was the result of injuries sustained in either traffic or sports accidents, and in one case from a war injury. All five SCI divers received their diver training and certification after their spinal cord injury. Diving experience in the SCI group varied from three to 11 years and around 20 h per year of diving. Divers were matched by body mass index (BMI) and sex. Body surface area (BSA):[18]

$$BSA\ (m^2) = (height\ [cm] \times weight\ [kg]) / 3{,}600 \quad (1)$$

Lean body weight (LBW),[19] adult men:

$$LBW\ (kg) = (9{,}270 \times total\ body\ weight\ [kg]) / (6{,}680 + (216 \times BMI\ [kg{\cdot}m^{-2}])) \quad (2)$$

adult women:

$$LBW\ (kg) = (9{,}270 \times total\ body\ weight\ [kg]) / (8{,}780 + (244 \times BMI\ [kg{\cdot}m^{-2}])) \quad (3)$$

were calculated. Demographic data for all participants are summarised in Table 1.

DIVING PROTOCOL

The Adriatic Chapter of the International Association of Handicapped Divers (IAHD) organised a single recreational cold-water (6°C) dive at Gruener Lake in Tragoess, Austria, which is a shallow (maximum depth 5.4 metres' fresh water [mfw]) alpine lake at an altitude of 779 m. Appropriate altitude and fresh water considerations were included in the planning of the dives. Dives were limited to the maximum depth of the lake and a maximum of 35 min duration, and were conducted in pairs, each pair consisting of a SCI and a BMI-matched AB diver. SCI divers were instructed to start leisurely swimming after a 2 min descent and safety check and AB divers to adjust the swim pace accordingly. The pair swam for 15 min to the centre of the lake, turned around and swam back for 15 min. Table 2 lists pair-matched diving profiles.

All divers used two-piece 5-mm neoprene wetsuits, comprising 'Long John' trousers and long-sleeved jackets. The overlapping 'Long Johns' and jacket provided a 10-mm insulative layer of neoprene for the torso. The SCI divers used tailored suits (Kanoko® superstretch/ Pile® thermic inside, zipper to face, ELIOS, Italy), the AB divers used their own 5 mm thick neoprene wet suits, which were not standardised for the study. The dive profiles (depth and duration) and water temperature were recorded with dive computers worn by each diver (D-series, Suunto, Finland). The divers entered the water from the shore. The first post-

Table 1
Demographic data for spinal cord injured (SCI) and able bodied (AB) divers; BMI = body mass index; BSA = body surface area; LBW = lean body weight

Divers	Sex	Age	Height (cm)	Weight (kg)	BMI ($kg \cdot m^{-2}$)	BSA[17] (m^2)	BSA/weight ($m^2 \cdot kg^{-1}$)	LBW[18] (kg)	Injury level
SCI1	M	45	172	68	23.0	1.80	0.025	55	T9
SCI2	M	39	170	80	27.7	1.94	0.024	60	T6
SCI3	M	44	188	85	24.0	2.11	0.025	67	T12
SCI4	W	41	158	52	20.8	1.51	0.030	41	T6
SCI5	M	40	185	88	25.7	2.13	0.024	68	T12
AB1	M	23	180	76	23.5	1.95	0.026	61	/
AB2	M	51	180	89	27.5	2.11	0.024	67	/
AB3	M	60	175	76	24.8	1.92	0.025	59	/
AB4	W	35	168	60	21.3	1.67	0.028	47	/
AB5	M	48	173	78	26.1	1.94	0.025	60	/

Table 2
Pair-matched diving profiles for SCI and AB divers

Diver pair	Max. depth (m)	Average depth (m)	Duration (min)
SCI1	4	2.1	35
AB1	4.5	2.8	36
SCI2	5.3	2.8	36
AB2	5.4	3.3	35
SCI3	4.1	2.3	33
AB3	4.6	2.8	33
SCI4	5	2.9	30
AB4	5.2	3	30
SCI5	4.2	2.5	33
AB5	4.5	2.7	32
Mean (SD)	4.6 (0.51)	2.7 (0.34)	33.3 (2.2)

dive gastrointestinal temperature (T_{gi}) measurements were performed immediately after the divers reached the shore. Non-divers helped the SCI and AB divers with the diving equipment. SCI divers had help with the wheelchair transfer and were pushed from the shore to the observational terrace (50 m distant). All divers changed into dry clothes (long trousers, T-shirt, fleece jacket, Windstopper jacket, cap) and shoes after the dive and covered themselves with a provided fleece blanket. Both groups remained seated outdoors at a table for 120 min, chatting. Weather was partly cloudy, air temperature 17°C with light wind (1 $m \cdot s^{-1}$).

DEEP BODY TEMPERATURE ASSESSMENT

T_{gi} was used as a marker of core temperature using an ingestible radio pill (CorTemp® Temperature Sensor 262K15VSOHCO38075, HQInc, Palmetto, USA), which relayed the temperature information to an external receiver/recorder (CorTemp® Data Recorder 262K w/HR HT 130042, HQInc, Palmetto, USA). These pills contain temperature recording and radio frequency emitting electronic circuits, powered by a small battery. Because there are no data about the pressure resistance of the capsules, a laboratory pressure test was performed at Seabear Diving Technology, Graz, Austria. Capsules were tested 24 hours before the dive whilst recording at approximately 1 mPa in a pressure chamber filled with water. No mechanical deformities of pills or erroneous temperature measurements were detected.

The radio pill was ingested with a granola bar (Frutabela, Fructal, Slovenia) one hour before the dive. Variable gut motility among the subjects may cause the T_{gi} temperature to correspond to different regions of the gastrointestinal (GI) tract. According to normal gastric emptying (up to 2 h)[20] and small bowel transit time (up to 2 h in more than 80% population),[21] the radio pill was most likely positioned in the jejunum during measurements. The location of a GI radio pill may vary among subjects and it has been shown in one individual that the detected temperature changed with the GI location.[22] In contrast, no difference in measurements were seen when a sensor was ingested 24 h or 40 min before the first reading.[23] Since the gastrointestinal radio pill temperature system is designed for use in air, the radio receiving unit which receives and stores the amplitude

Figure 1

Individual T_{gi} before the dive (predive), immediately after the dive (pd 0) and maximal post-dive fall (maxdrop) for SCI divers (green) and AB divers (blue)

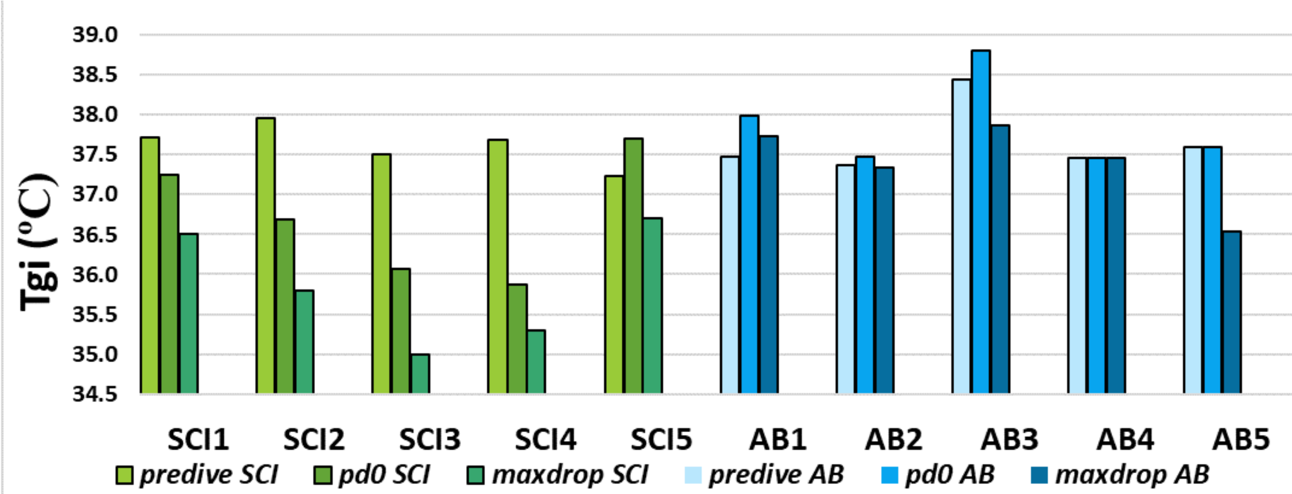


Table 3

Mean (SD) T_{gi} for SCI and AB divers pre dive, immediately post dive and at 5, 10, 15, 30, 60 and 120 min post-dive; the lowest temperature for each SCI diver is in bold; PD = post dive

Tgi (°C)	Pre-dive	PD 0	PD 5	PD 10	PD 15	PD 30	PD 60	PD 120
SCI1	37.7	37.2	37.1	37.1	37.1	37.0	37.4	**36.5**
SCI2	38.0	36.7	36.4	36.2	36.0	36.0	**35.8**	36.7
SCI3	37.5	36.1	35.6	35.3	35.0	**35.0**	35.6	36.5
SCI4	37.7	35.9	35.9	35.6	35.4	**35.3**	35.9	36.7
SCI5	37.2	37.7	37.5	37.3	37.1	36.9	36.8	**36.7**
Mean (SD)	37.6 (0.3)	36.7 (0.8)	36.5 (0.8)	36.3 (0.9)	36.1 (0.9)	36.0 (0.9)	36.3 (0.8)	36.6 (0.1)
Tgi (°C)	**Pre-dive**	**PD 0**	**PD 5**	**PD 10**	**PD 15**	**PD 30**	**PD 60**	**PD 120**
AB1	37.5	37.9	37.8	37.7	37.7	37.8	38.0	37.9
AB2	37.4	37.5	37.4	37.4	37.4	37.4	37.4	37.3
AB3	38.4	38.8	38.5	38.6	38.4	38.6	38.0	37.8
AB4	37.4	37.5	37.4	37.5	37.6	37.6	37.7	37.5
AB5	37.6	37.6	37.4	37.3	37.3	37.4	36.9	36.5
Mean (SD)	37.7 (0.4)	37.9 (0.6)	37.7 (0.5)	37.7 (0.5)	37.7 (0.4)	37.8 (0.5)	37.6 (0.5)	37.4 (0.6)
***P*-value**	0.85	0.027	0.017	0.015	0.010	0.006	0.012	0.014

modulated signal from the pill only works in air. T_{gi} were recorded prior to, directly after and at minutes 5, 10, 15, 30, 60 and 120 after the dive. During this post-dive period, the subjects were requested not to eat or drink.

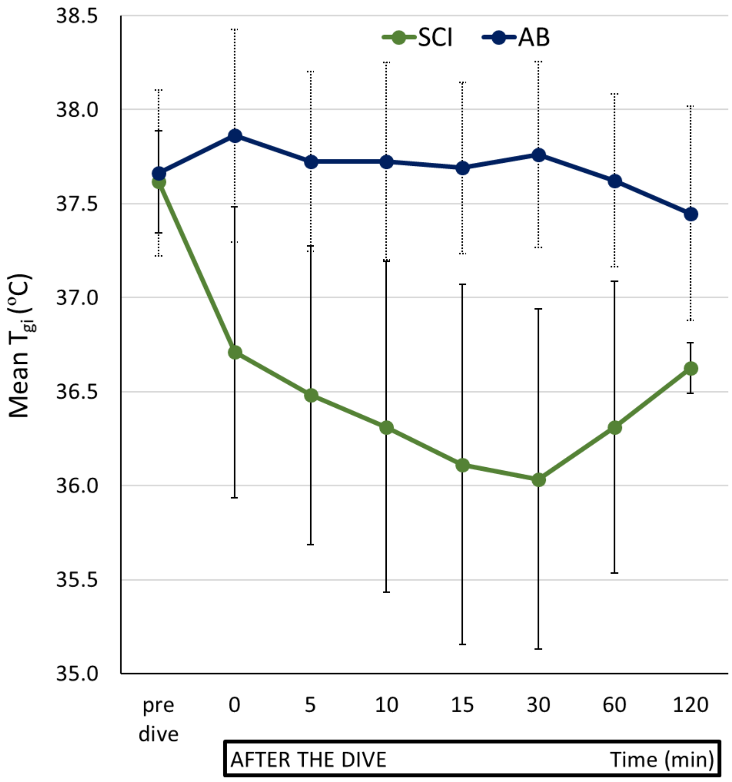
TEMPERATURE PERCEPTION

Divers were requested to provide overall ratings of temperature perception on a visual analogue scale (VAS) comprising a 10 cm horizontal line with 0 representing no perception of cold and 10 the perception of severe cold. The subjects rated their sensation of cold in parallel to the core temperature recordings pre-dive and at 0, 5, 10, 15, 30 and 60-min post-dive. In addition, it was noted if a subject was shivering.

STATISTICAL ANALYSES

After test for normality (Shapiro-Wilk test) a two-way mixed ANOVA statistical model, calculated with IBM SPSS® 25.0 software, was used to assess the effect of time, group and interaction between time and group on T_{gi}. Paired sample *t*-tests were used to establish whether the mean T_{gi} recorded at specific times were different between the groups; data are presented as mean (SD). It was not possible to assess changes in T_{gi} against injury level in the SCI divers because of the small numbers. Subjective ratings of temperature perception of the SCI and AB divers were evaluated with Mann-Whitney U tests (M-WU); these data being presented as median and inter-quartile range (IQR). The alpha level of significance was set at 0.05.

Figure 2
Mean (SD) T_{gi} in five SCI (green) and five AB (blue) divers before and at different times out to 120 min post-dive after a 6°C dive



Results

All divers completed the dives according to the dive plan. There were no untoward events either during or immediately after the dives and all planned temperature measurements in all divers were documented successfully.

DEEP BODY TEMPERATURE

Individual pre-, immediate post-dive and lowest post-dive T_{gi} are shown in Figure 1. There was no difference in pre-dive T_{gi} between the groups (SCI: 37.6°C (SD 0.2); AB: 37.7°C (0.4); $P = 0.85$) but a significant difference post-dive (SCI: 36.7°C (0.77); AB: 37.9°C (0.56); $P = 0.02$). Table 3 lists all measured T_{gi}.

Post-dive, the mean maximum fall in the recovery phase in T_{gi} in SCI divers was 0.85°C (0.2) and in the AB group 0.48°C (0.48). In addition, there was greater individual variation in SCI divers (mean max difference (SD): 1.75°C (0.6)) compared to AB divers (0.75°C (0.4)) in the recovery phase. The dive did not significantly alter the deep body temperature of the AB group (before: 37.7°C (0.4); after: 37.4°C (0.6); $P = 0.47$).

ANOVA revealed that there were significant main effects on T_{gi} for time (F[7.56] = 9.789; $P < 0.001$), group (F[1.8] = 11.61; $P = 0.009$) and interaction between time and group (F[7.56] = 5.47; $P < 0.001$). Thus, there were statistically significant differences in T_{gi} between the SCI and AB divers measured post-dive. Figure 2 shows the mean T_{gi} for both groups through the measured time. In the AB group, mean T_{gi} after 120 min is only 0.3°C less than the pre-dive mean, whereas in the SCI group, it is 1.0°C lower (pre-dive: 37.6°C (0.27), 120 min post-dive: 36.6°C (0.14)).

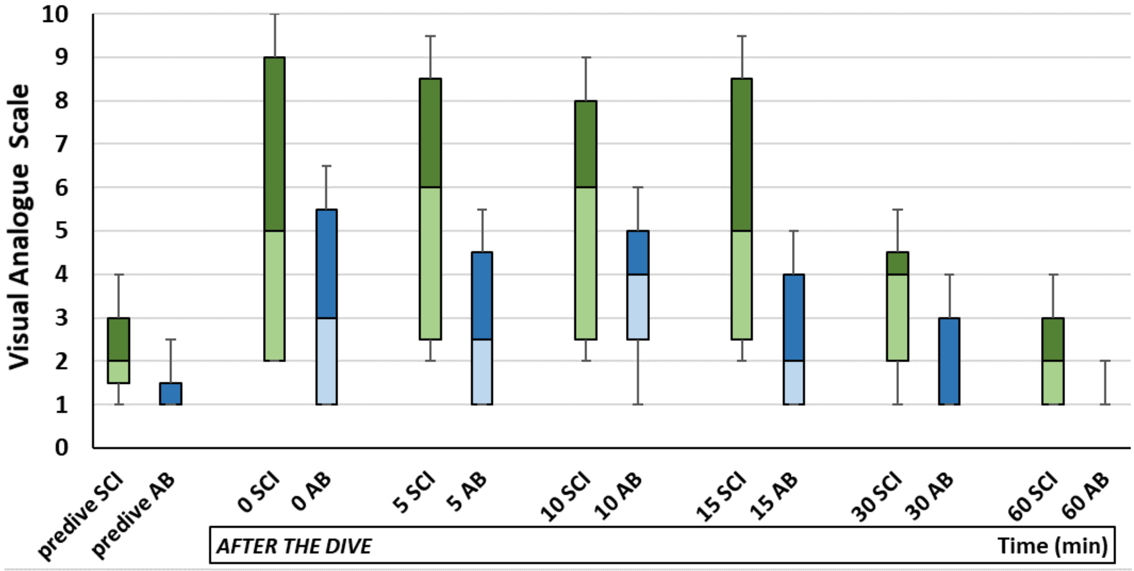
COLD SENSATION

There were no statistically significant differences in the perception of temperature between the AB and SCI divers either before, immediately after or at any time post-dive (Figure 3). SCI divers started to report increasing perceptions of cold immediately after to 15 min post-dive. Thereafter, despite a continued reduction in T_{gi}, the SCI divers did not perceive any further increases in cold perception after 15 min post-dive (Figure 3). Only SCI divers 3 and 4 (one T6 and the other T12 injury levels) exhibited shivering around the torso and sternocleidomastoid muscles lasting about 25 min post dive.

Discussion

The principal finding of the present study is that SCI divers experienced a significant but variable fall in T_{gi} during and after a 30–35-min, shallow, cold-water (6°C) dive. In contrast, AB divers exhibited uniformly only a minimal change in deep body temperature during the dive and no 'afterdrop' post dive.

Figure 3
Assessment of cold with a visual analogue scale (0 – no cold and 10 – severe cold) in five SCI divers (green) and five AB divers (blue) prior to the dive and at 0, 5, 10, 15, 30 and 60 min post-dive (median [IQR] as box and whisker plots)



Since a given dive pair, comprising an AB and SCI diver, conducted the dive together, the activity of the two divers should be similar. Before the dive, all divers were instructed to swim leisurely. However, the pattern of swimming between groups was different. For SCI divers, propulsion is provided by using the arms and non-SCI divers the legs. Core temperature falls significantly more when exercise is performed by the arms when compared with the legs in cold water.[24] The larger surface area-to-body mass ratio will also contribute to this accelerated heat loss. According to the values for surface-to-mass ratio, the ratio for arms is almost twice that for legs.[25] SCI have a higher convective coefficient[26] and, therefore, higher absolute heat flux to cold water. On the other hand, the muscle temperature depends on exercise intensity, which might be higher in the SCI group. Also, blood flow would be greater in higher intensity exercise, so a greater proportion of heat is transferred to the core. It can be postulated that the SCI group were exercising at a higher intensity than the AB divers whilst swimming side-by-side at the same pace and, therefore, had a higher metabolic rate. However, the peripheral location of the working, perfused muscles indicates that most of this heat would be lost to the cold water. It is assumed that SCI divers have greater conductive and convective heat transfer at the neoprene-water interface than AB divers.

It is also likely that there are differences in the pattern and magnitude of heat loss from different body regions. Despite the thermal insulation provided by the neoprene suit, the skin temperature during the dive most likely decreased to a level where vasoconstriction was initiated to retain heat. Whereas, for the regions above the level of the spinal cord injury the level of vasoconstriction was most likely similar to or possibly greater than that in the AB divers, regulation of perfusion of regions below the injury would be substantially impaired in the SCI divers.[27] The difference in perfusion of peripheral regions within the two diver groups using skin temperatures was not monitored in the present study. Nevertheless, the greater cooling of the core region of the SCI divers can be attributed to impairment in the regulation of peripheral perfusion and, thus, impairment of the heat retention response.

The 'afterdrop' in core temperature is a characteristic response observed during rewarming of individuals after exposure to a high heat loss environment inducing core temperature cooling.[28] The aetiology of the core temperature afterdrop is suggested to be the thermal inertia in heating the cooled peripheral regions.[29,30] The SCI group experienced greater continued cooling during the post-dive 120 min observation time. The heat production created as a by-product from exercise stopped after the dive. Divers stayed in an air environment in which further cooling via convection (light wind (1 $m \cdot s^{-1}$)) and evaporation (before changing into dry clothes) can occur. SCI divers needed longer (up to 10 min) to change and, therefore, were more exposed to heat loss. The absence of a significant T_{gi} after-drop in the AB divers suggests that they remained in or close to thermal balance during and after the dive. However, the difference in afterdrop was so prominent that longer changing time can only contribute to cooling without being a main reason for it.

COLD PERCEPTION

The perception of body temperature was similar in the two groups despite the lower T_{gi} in the SCI group. A rating of temperature perception is a result of cortical integration of thermo-afferent information. The lack of sensory information from the regions below the injury would not appear to contribute significantly to the overall perception of cold in the SCI divers. Consequently, within the framework of the dives conducted and the cold exposure experienced by the SCI divers, it would appear that their behavioral regulation of body temperature would be appropriate but is altered, which might present safety issues.

SHIVERING

Despite the decrease in core temperature in the SCI divers during the dive, shivering was observed in only two of them post dive. Shivering in humans with an intact spinal cord is initiated by thermo-afferent information from temperature sensors in the skin, as well as direct thermal stimulation (temperature of blood perfusing the region) of hypothalamic temperature neurons. Whereas, the former is probably substantially reduced in SCI, it is the latter that provides the stimulus for shivering in muscles with intact innervation.[31] Previous studies suggest that the muscles of the lower extremities are not activated during the initiation of shivering; activation of the shivering proceeds caudally starting with the mastoid and sternocleidomastoids muscles.[32,33] The impaired activation of the leg muscles in SCI divers is likely less important than the impairment of heat retention in this situation. Because both groups remained seated during the observation time, the activity level of the divers post-dive did not account for the slower rewarming in the SCI divers.

LIMITATIONS

The small number of divers is the main limitation of the study. However, it is difficult to find SCI divers with similar levels of injury who also perform cold-water dives. This is likely why there have been no previous studies of SCI vs. AB divers. All the SCI divers were classified as ASIA score A (no sensory or motor function is preserved in the sacral segments S4–S5) and had an injury at the thoracic level with the complete absence of motor function below the level of injury. The variability of the cooling pattern could be the result of the different levels of thoracic injury (T6 to T12), but the small numbers prevent any worthwhile analysis of this relationship.

Matching divers by BMI could be a possible limitation of the study. BMI does not reflect location or amount of body fat but it is internationally recognised as a marker of obesity and adiposity.[34,35] A higher BMI, whether reflecting greater body fat, increased muscle mass or simply overall size, is associated with a slower drop in core temperature during cold-water swimming.[36,37] Therefore, it was assumed that BMI matching was appropriate for the given conditions. Also, the two groups were shown to be matched for the body surface area-to-mass ratio, a factor that contributes to heat loss (Table 1).[38]

Using gastrointestinal temperature as a marker of core temperature could be a limitation because the location of the radio pills is dependent upon gastrointestinal motility. Despite that, the radio pill is widely accepted and used in field-based exercise studies as an indicator of core temperature.[39] Finally, for real-time detailed core temperature changes, continuous temperature monitoring during the dive is essential. Unfortunately, no commercial measurement system has been available until recently.

Conclusions

In a shallow dive in 6°C water, the deep body temperature of SCI divers fell significantly, whereas in AB divers it remained stable. However, the decrease in T_{gi} approached levels considered hypothermic (35°C) in only one (with a T12 injury) of the five SCI divers. The subjective perception of cold by SCI divers did not reflect the reduction in T_{gi} observed. Further studies are needed with larger numbers, various water temperatures, dive times and injury levels, preferably in controlled laboratory conditions and with in-dive monitoring.

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