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ARTICLE

Efficacy of water spray for evaporative cooling in athletes with spinal cord injury

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Abstract

Study design Interventional crossover study.

Objective Spinal cord injury (SCI) disrupts afferent input to the hypothalamus and impairs efferent vaso- and sudomotor output, especially in lesions above the sympathetic chain (T1-L2). In consequence, persons with SCI under heat stress experience impairment in the ability to dissipate heat proportional to the lesion level. Thermoregulatory dysfunction places an individual at high risk of hyperthermia, which can be life threatening, especially for athletes with SCI during exercise. Current evidence on therapeutic cooling techniques in athletes with SCI is limited, but basic physiologic and research data suggest water spray (WS) might be efficacious, particularly in athletes with tetraplegia (TP), who are most impaired in thermoregulation. The aim of this study was to evaluate the effect of WS on core temperature (Tc) during exercise in athletes with SCI.

Setting Texas, USA.

Methods Eleven individuals with SCI: seven with TP, four with paraplegia (PP); and sixteen able-bodied (AB) controls underwent a wheelchair intermittent sprint exercise for 90 min under two conditions: (1) WS application every 15 min and (2) control (C), without WS. Tc was measured every 15 min and was analyzed for the effect of group (TP, PP, and AB) and time. Change in Tc (ΔTc) was also compared between groups.

Results ΔTc was significantly higher in TP vs. PP ($p < 0.0001$) and TP vs. AB ($p < 0.0001$) groups under C treatment. WS significantly attenuated ΔTc in TP ($p = 0.001$), but did not change ΔTc in PP or AB.

Conclusion WS effectively attenuated Tc elevation during exercise in athletes with TP.

Sponsorship Texas chapter of the Paralyzed Veterans of America.

Introduction

During exercise, skeletal muscles increase heat production by 30–40-fold and the energy produced is released as heat that must be rapidly dissipated to avoid hyperthermia [1]. Maintaining core temperature (Tc) during exercise within the narrow thermoneutral range of 36.7–37.5° C (rectal) [2] during metabolic heat production with exercise is accomplished through complex neural connections between the hypothalamus, cardiovascular system, and skin [3]. Warm sensitive neurons within the pre-optic area of the hypothalamus are activated by local hypothalamic temperature and afferent thermal input from the skin and deep viscera [4, 5]. When excited, these neurons initiate an efferent response to dissipate heat through mechanisms of convective and evaporative cooling through vasodilation and sweating, respectively [6]. Spinal cord injury (SCI) disrupts the transmission of efferent signaling for vasodilation and sweating. As a result, during exercise, persons with SCI experience impaired heat dissipation capacity that is proportional to the lesion level [7–10].

Evaporative cooling via sweating has been suggested to be the most efficient and primary method of heat dissipation [11, 12]. Sweat, comprised mainly of water, has a high

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specific heat that allows for augmented heat absorption through conduction and heat removal through evaporation [3, 5]. Sweating responses (SRs) in persons with tetraplegia (TP) consist of forehead sweating [10, 11, 13, 14] or complete anhidrosis [7, 15]. Meanwhile, persons with high (above T6) paraplegia (PP) demonstrate decreased SR compared to AB persons [7, 10, 15, 16], whereas persons with low PP (T7 and below) have SR comparable to that of AB persons [17, 18].

Clearly, impaired heat dissipation increases the risk of potentially unsafe Tc elevation during heat stress conditions, which is documented in SCI literature [11, 19, 20]. It follows that identification of an effective cooling strategy would increase safety during exercise, especially for those with TP, who often exhibit no sweating whatsoever [19]. Although ice vests provide whole body cooling before/pre-cooling (PRE) and during exercise [21, 22], they can be cumbersome to don and impractical; as they interfere with upper body movements required for wheelchair propulsion and ball handling. Anecdotally, water spray (WS), which mimics sweat and thus evaporative cooling, is commonly observed to be a cooling intervention of choice during paralympic competitions of persons with SCI, and is practical to use [23, 24]. WS has not demonstrated a cooling benefit in one small study of persons with PP [23] but provides synergistic cooling in TP athletes pre-cooled with an ice vest [23, 24]. Thus, WS alone might cool Tc during exercise, especially in TP, but has not been studied as an isolated cooling intervention in groups of persons with TP and PP in the same exercise protocol to date.

This study evaluated the effect of WS on Tc in able-bodied (AB) and persons with SCI during wheelchair basketball or rugby. We hypothesized that WS would have no impact on Tc in AB persons with intact thermoregulatory control but attenuate the rise in Tc in persons with TP and PP during exercise.

Methods

Participants

Inclusion criteria was as follows: (1) at least 90 min per week of participation in wheelchair basketball or rugby (SCI participants) or aerobic exercise (AB participants) and (2) should have completed 1 year post SCI (SCI participants). Exclusion criteria was as follows: (1) inability to propel a wheelchair for 90 min; (2) history of heat-related illness (did not want to predispose to recurrent risk); and (3)

Table 1 Demographic data by group with means and standard deviations

Group	TP ($n = 7$)	PP ($n = 4$)	AB ($n = 16$)
Age (years)	$35.6 \pm 4.0^*$	27.25 ± 6.6	27.5 ± 2.6
BMI (kg/m^2)	27.0 ± 5.5	24.5 ± 2.8	25.3 ± 1.2
Levels of injury	C5, C6, C7	T4, T7, T12, L1	n/a
AIS grade A/B	5/2	2/2	n/a

$^*p < 0.01$ vs. PP and AB groups

acute medical illness. SCI participants were recruited from local wheelchair rugby and basketball teams, whereas AB participants were recruited from the local physical therapy school. Twenty-seven athletes participated: 11 with SCI (TP = 7; PP = 4) and 16 AB (Table 1).

We certify that all applicable institutional and governmental regulations concerning the ethical use of human volunteers were followed during the course of this research. The local university institutional review board approved the protocol, and all subjects provided written informed consent.

Tc measurement method

A Food and Drug Administration-approved ingestible thermometer pill/sensor (CORTEMP, HQ Inc., Palmetto, FL) was swallowed 6–8 h before practice, to ensure post pylorus passage [25]. This method is an accurate and valid approach to measure Tc [26–28].

Setting

Protocol and data collection occurred in a climate-controlled indoor gymnasium (19–22° C with 55–60% relative humidity).

Exercise protocol

Participants rested in the gymnasium for 20 min prior to measurement of baseline Tc (time = 0 min). After baseline Tc, participants engaged in a 15-min warm up of continuous wheelchair propulsion and short sprint drills. Afterward, TP athletes began a wheelchair rugby match while PP athletes began a wheelchair basketball match with rules outlined by the International Federations of Wheelchair Rugby and Basketball, respectively. The exercise pattern of both sports consists of intermittent sprints on standard basketball size court, for 60–90 min. AB athletes played wheelchair

basketball, so the muscles utilized for exercise were similar to those of SCI athletes. The upper torso was bare to maximize skin surface area available for evaporative cooling. All participants were allowed to drink water (~15° C) ad libitum.

In C condition, no cooling intervention was utilized throughout the exercise. In WS condition, after baseline Tc measurement, at 15 min intervals, WS (~15° C, tap water) was held ~15 cm from the skin surface and sprayed by the research team for up to 1 min to the following skin surface areas: head and face, anterior and posterior arms (including axilla), anterior and posterior torso, and anterior and posterior lower extremities (excluding areas covered by shorts and shoes). This equated to ~60–80% total body surface area (TBSA), as the length of shorts and socks varied. A commercially available 1 L professional lawn care spray bottle was used as it is observed to be utilized by SCI athletes at rugby and basketball competitions, and easy for persons with TP with impaired hand function to grasp.

SCI athletes completed C and WS protocols on two separate days 1 week apart. Meanwhile, AB athletes completed C and WS protocols on the same day separated by 120 min. At least 60 min lapse is required for Tc to return to baseline post exercise, so 120 min was sufficient to minimize any carryover of elevated Tc [29]. The AB group was counterbalanced where a half ($n = 8$) exercised under C conditions, and a half ($n = 8$) under WS conditions in the morning and then both groups switched conditions in the afternoon. Every 15 min, Tc was collected twice, with the average of two consecutive Tc measurements recorded.

Statistical analyses

Initially, a two-factor ANOVA (between-subjects factor: group; within-subjects factor: condition) was performed to assess if baseline (0 min) Tc differed significantly under the C and WS conditions and between groups.

A Geisser-Greenhouse adjusted three-factor mixed ANOVA was used to evaluate main and interaction effects for time (0, 15, 30, 45, 60, 75, and 90 min), condition (C versus WS) and group (TP, PP, and AB) on Tc, followed by comparisons of means by Tukey–Kramer test and by trend analyses.

Finally, ΔTc was calculated as the difference between Tc at 90 and 0 min. Main and interaction effects for ΔTc were analyzed with a two-factor ANOVA with group as between-subjects factor and condition as within-subjects factor, followed by comparisons of means by Tukey–Kramer test. All data are reported as means with standard error of the mean. Statistical analyses were conducted using NCSS 12 Statistical Software (Kaysville, Utah, USA, ncss.com/software/ncss) and GraphPad Prism version 7.04 for Windows (GraphPad Software, La Jolla California USA, www.graphpad.com) with $p < 0.05$ being considered statistically significant.

Results

Baseline Tc

Baseline (0 min) Tc did not differ significantly under the C and WS conditions within each group; however, there was a significant main effect for the group ($p = 0.0006$). Baseline Tc was significantly lower in the TP group (36.80 ± 0.06° C) than in the PP (37.53 ± 0.05° C, $p = 0.0009$) and AB (37.27 ± 0.05° C, $p = 0.003$) groups, but did not differ between the PP and AB ($p = 0.24$).

Tc during exercise

Because the three-way ANOVA revealed a significant time × condition × group interaction ($p = 0.012$) for Tc, effects of time and condition were examined separately for each group (Fig. 1).

The TP group

In the TP group, there was a significant condition by time interaction ($p = 0.007$). Tukey–Kramer's multiple comparison tests to evaluate differences in Tc at each time point during the exercise showed that at 30 min of exercise Tc was significantly lower under C (36.81 ± 0.43° C) compared to WS (37.75 ± 0.20° C; $p = 0.01$) conditions; however, by 90 min of exercise there was a higher Tc under C (38.66 ± 0.22° C) compared to WS (37.87 ± 0.22° C; $p = 0.06$). Trend analyses showed a linear trend in the C condition ($p < 0.00001$) and a linear ($p < 0.00001$) and a quadratic ($p = 0.04$) trend for the WS revealing a plateau of Tc after 30–45 min of exercise.

The PP group

The main effects for time ($p = 0.10$), condition ($p = 0.78$), and their interaction ($p = 0.39$) were not statistically significant in PP.

The AB group

In the AB group, the main effects for condition ($p = 0.001$) and time ($p < 0.00001$) were statistically significant, and a p-value of 0.08 was obtained for the condition × time interaction. Tukey–Kramer's test indicated significantly increased Tc under C vs. WS conditions at time points of 60 min (38.15 ± 0.12° C vs 37.80 ± 0.11° C; $p = 0.01$), 75 min (38.19 ± 0.11° C vs. 37.77 ± 0.08° C; $p = 0.0005$) and 90 min (38.19 ± 0.09° C vs 37.78 ± 0.08° C; $p = 0.007$) of exercise. Trend analyses showed a linear ($p < 0.0006$) and quadratic ($p < 0.00001$) trend under both the C and WS condition revealing an initial rise in Tc from 0 to 30 min of
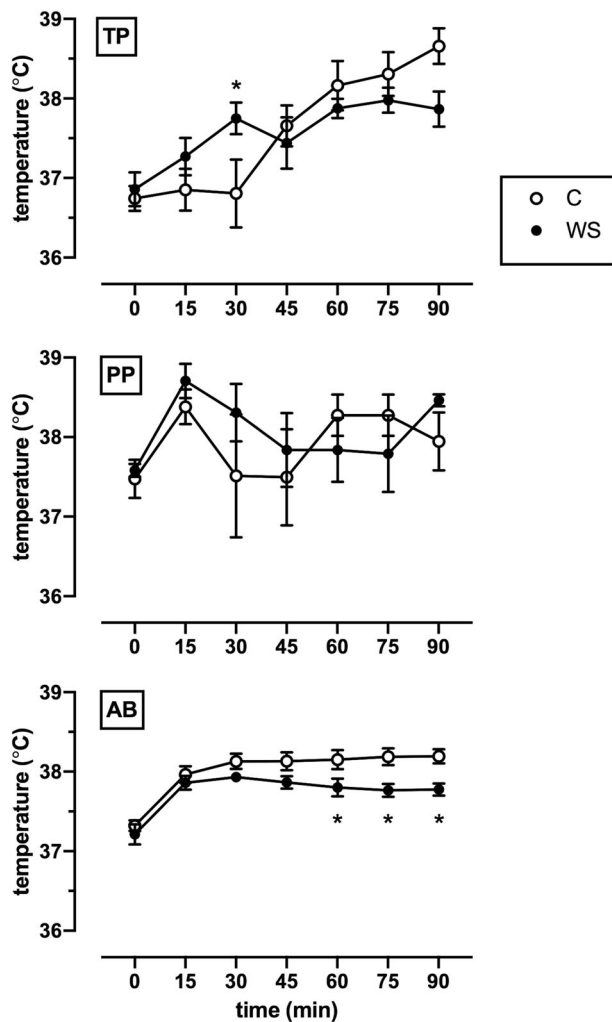
Fig. 1 Change in Tc during 90 min of wheelchair exercise in the TP (top) PP (middle) and AB (bottom) groups under C (open circles) and WS (closed squares) conditions. An asterisk (*) identifies time points at which Tc was statistically significantly different between conditions at the level of $p < 0.05$
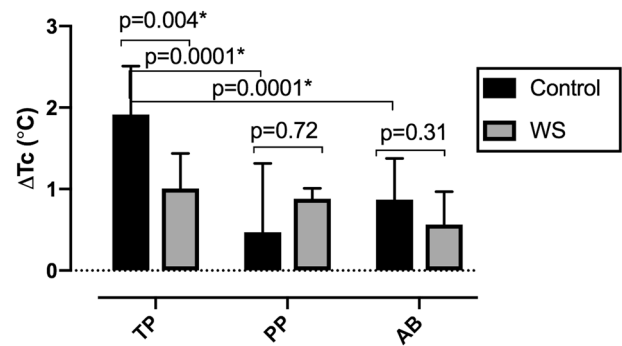

Fig. 2 Comparison of ΔTc (90–0 min) in C vs. WS condition for all participants within each group (TP, PP, and AB). An asterisk (*) identifies statistical significance at the level of $p < 0.05$. Note that while ΔTc of TP under C condition *was* significantly different than ΔTc of PP and AB under C, when the WS intervention was added, the ΔTc of the TP group was no longer significantly different from the PP or AB group

exercise followed by a plateau in C and a slight incremental decrease in Tc in the WS condition until completion of 90 min.

Change in Tc

There was a significant interaction effect ($p = 0.005$) for ΔTc between group and condition; therefore, individual means were compared using Tukey–Kramer's test. Individual data points and adjusted p-values comparing group means are shown in Fig. 2. There were no significant main effects of condition on ΔTc in either the PP or AB groups. Under C condition, ΔTc was significantly higher in TP ($1.91 \pm 0.59°$ C) than PP ($0.47 \pm 0.85°$ C; $p < 0.0001$) and AB ($0.87 \pm 0.50°$ C; $p < 0.0001$) groups. In addition, ΔTc from baseline to 90 min of exercise was significantly

increased under the C ($1.91 \pm 0.59°$ C) compared to the WS condition ($1.01 \pm 0.43°$ C; $p = 0.001$) in the TP group.

Discussion

The objective of this study was to evaluate the effect of a practical, commonly used the exogenous evaporative cooling technique on Tc during exercise in persons with TP and PP who have intrinsically impaired evaporative cooling capacity and compare its effect on Tc in AB persons with intact evaporative cooling capacity. We found that WS applied to 60–80% of the TBSA in persons with TP (and not PP) improved heat dissipation and attenuated the linear rise in Tc comparable to AB persons. The cooling efficacy of WS may explain why persons with TP in paralympic competitions commonly choose it as a cooling technique.

Investigations quantifying SR during exercise and passive heat exposure in persons with SCI have consistently reported impaired sweating "proportional to lesion level". Persons with TP consistently demonstrate minimal complete anhidrosis or minimal forehead sweating [10, 11, 30]. On closer inspection, studies including only complete TP injuries [7, 13, 15] were most likely to find complete anhidrosis. The presence of forehead or other skin surface area sweating in other studies, especially those including incomplete injuries [11, 13, 31], could have been due to remaining intact pre-ganglionic sympathetic nerves, a training effect [10, 32], or some degree of autonomic dysreflexia (AD) during heat stress. Sweating from AD is primarily sympathetic adrenergic mediated [33], whereas sweating from heat stress is primarily sympathetic cholinergic mediated [34]; however, AD was never investigated as a possible explanation for sweating in the aforementioned studies. Alternatively, SR of persons with PP appears to

corelate with an area of sentient skin [7, 10, 15–17], with one author [18] citing T6 as a "cut-off level" at which persons with PP achieve equivalent SR to AB persons. In summary, when introducing an artificial sweat cooling intervention, a study design stratified by lesion level, will likely give most clinically relevant data. To our knowledge, this is the first study to test the efficacy of WS in persons with TP and PP in the same protocol.

WS in tetraplegia

At baseline, regardless of condition, Tc in the TP group was significantly lower than the PP and AB groups, which has been reported previously [35, 36]. After initiation of exercise, Tc rose linearly over time and did not plateau over the entire 90 min, demonstrating continued internal heat gain and insufficient heat dissipation under C condition. Unexpectedly, Tc was significantly cooler at 30 min in the C condition as opposed to the WS condition; however, overall there was a linear trend over the entire 90 min in C that differed from WS that showed a quadratic trend (i.e., plateau after 30–45 min). The difference at the one time point of 30 min could have been due to the less intensive play during WS conditions vs. others; however, since intensity was not controlled, we cannot definitively make this statement. Regarding the change in temperature over time, ΔTc under C condition was significantly higher in the TP group compared to the PP and AB groups, which confirms previous findings that this group is most impaired in heat dissipation [7, 8, 11]. From a clinical perspective, Tc under C condition reached levels consistent with hyperthermia (38° C), whereas WS condition protected Tc from rising to hyperthermic levels. In contrast, under WS conditions, Tc stabilized after 30 min, suggesting increased heat dissipation with the intervention.

In the one similar lab-based study, Griggs et al. compared PRE with ice vest alone and PRE followed by WS during an intermittent sprint exercise protocol [24]. WS was applied on the face and ventral aspect of both arms and torso (~50% TBSA). When compared to PRE, the combination of PRE and WS during exercise resulted in an additive/synergistic cooling effect on Tc, which suggests when used in isolation, WS may attenuate ΔTc when used in isolation.

Our study confirmed our hypothesis. Evaporative cooling via exogenous WS applied to 60–80% of the skin surface area of persons with TP significantly attenuated ΔTc during 90 min of intermittent sprint exercise to the point that TP ΔTc was not statistically different from the PP and AB groups during WS. Effectively, WS allowed persons with TP to dissipate heat as well as persons with less impaired (i.e., PP) and fully intact (i.e., AB) thermoregulatory systems.

WS in paraplegia

Trends of temperature change over time in our small ($n-4$) group of PP athletes were not linear, and there was no statistically significant impact of WS on Tc at any time point. We suspect that this results from multiple factors including (1) the heterogeneity of levels from T4 to 12 and completeness of injury, (2) a small subject pool, and (3) one outlier. ΔTc of one PP participant (T12 incomplete) dropped Tc by 0.76° C for unclear reasons, potentially related to temperature pill not being located post pylorus and thus more affected by cold water ingestion or an adaptive sweat gland response [32].

In a similar lab-based protocol, Pritchett et al. studied WS on a PP cohort ($n = 7$, two incomplete and three lesions above T8) during arm-crank ergometry, using WS applied to head, face, neck, and forearms (~15% TBSA) [23]. Pritchett found no impact of WS on Tc. The lack of efficacy could have been multi-fold: (1) the application of WS was limited to a small skin surface area or (2) the heterogeneous group (combining incomplete and complete lesions and lesions above and below T6) of PP with varying degrees of sweating capacity may have made it more difficult to detect a significant effect on Tc [24, 37]. Despite our study being conducted in the field, our findings paralleled those of Pritchett as this study found no cooling effect of WS on a small group of persons with PP. In addition to the heterogeneity of the lesion levels and completeness, our sample size is likely underpowered to detect a statistically and clinically meaningful effect in this group that has more intact SR at baseline.

WS in able-bodied

The lack of difference in Tc at time = 0 min in C vs. WS conditions demonstrated that despite C and WS protocols being performed on the same day, Tc sufficiently dropped to resting levels before initiation of the subsequent protocol. After initiation of exercise, Tc rose linearly within both conditions until 30 min then plateaued, presumably from evaporative and convective heat loss via sweating and vasodilation, respectively. Furthermore, the lack of significant difference in ΔTc (Tc at 90 min−Tc at 0 min) between C and WS conditions reflects the fact that thermoregulatory responses of SR and vasodilation in AB persons are intact and adding exogenous sweat does not provide significant additional heat dissipation to impact the change in temperature over the entire 90 min protocol. However, the significant difference in Tc only at time = 60, 75, and 90 min in the WS condition was an unexpected/incidental finding. We hypothesize that the potential for dehydration after prolonged (i.e., >60 min) exercise could decrease SR in C, which was compensated for in WS, but

further studies are needed to confirm. In addition, ΔTc of the AB group was more than double that of the PP group. Potential explanations for this include, but are not limited to the AB group having increased metabolic heat generation with more muscle mass vs. decreased conditioning in wheelchair propulsion with decreased efficiency of performance (as they do not normally propel wheelchairs) vs. dehydration, as given the two conditions (C and WS) were performed on the same day.

Skin surface area considerations in SCI

Persons with >40% TBSA of denervated skin surface areas have been shown to have impaired thermoregulatory capacity during exercise compared to persons with <40% denervated skin surface area [38]. After finding no Tc cooling from WS applied to ~17% TBSA, Pritchett suggested that application over a larger surface area might be more effective [23]. Our study and that of Griggs', which did find a cooling effect on Tc, both applied WS to >50% of TBSA. In summary, evaporative cooling over a minimal threshold of 40–60% of skin surface area may be required for persons with TP and PP (especially those above T6) to dissipate heat as effectively as AB. Furthermore, it should be mentioned that the back, chest, and forehead have the highest local sweat rates [17, 39]. In conclusion, the authors recommend future WS studies cover 40% TBSA at minimum, and include the back, chest, and forehead, especially if these areas are anhidrotic.

Limitations

Limitations include small and unequal sample sizes, data collection on the same day (AB group only), and different sports played between groups. The TP group was statistically significantly older and while persons over age 60 years do have impaired thermoregulatory control, none in the TP group superseded that threshold (age range 25–40 years old) so it is very unlikely that the statistically significant difference in age has any clinically meaningful implication in the Tc responses [40]. In addition, controlling for exercise intensity is problematic within a field-based study; however, level of injury is a greater determinant of Tc increases during exercise than exercise intensity or activity profile, which is why subjects were grouped by level [24, 41]. In efforts to minimize the variability of Tc changes between conditions, each person served as their own control in the crossover design. Finally, participants wore shorts only to maximize skin surface area for evaporative cooling. While this is inconsistent with wheelchair sporting attire of shirt and shorts, this study demonstrates the maximal potential for evaporative cooling of WS.

In conclusion, this is the first study to evaluate the comparative effect of WS, as a single cooling intervention during exercise on Tc in a group of athletes with TP, PP, and AB during exercise in a gymnasium/field-based environment. WS did significantly attenuate ΔTc in athletes with TP allowing them to dissipate heat as efficiently as AB persons over 90 min of exercise. On the other hand, WS had no impact on Tc at any time point or on the change in Tc over 90 min in persons with PP. Interestingly, WS also provided additional heat dissipation to AB persons only after 60 min of exercise. The added heat dissipation provided to athletes with TP who are most thermoregulatory impaired may explain why paralympic athletes naturally choose to utilize WS in competitions. Future studies of a larger cohort of persons with complete (AIS A) TP and PP, divided into levels above and below T6, with WS applied to a minimum of 40% of TBSA (including forehead, chest, and back) are recommended to confirm these findings.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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