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Efficiency of three cooling methods for hyperthermic military personnel linked to water availability

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ABSTRACT

Purpose: Three feasible cooling methods for treatment of hyperthermic individuals in the military, that differed considerably in water volume needed (none to ~80 L), were evaluated.

Methods: Ten male soldiers were cooled following exercise-induced hyperthermia (rectal temperature (T_{re}) ~39.5 °C) using ventilation by fanning (1.7 m s^{-1}), ventilation by fanning (1.7 m s^{-1}) while wearing a wet t-shirt (250 mL–27 °C water) and tarp assisted cooling with oscillations (80 L of 27.2 ± 0.5 °C water; TACO).

Results: Cooling rates were higher using TACO (0.116 ± 0.032 °C min^{-1}) compared to ventilation (0.065 ± 0.011 °C min^{-1}, $P<0.001$) and ventilation in combination with a wet t-shirt (0.074 ± 0.020 °C min^{-1}, $P=0.002$). Time to cool (TTC) to T_{re}=38.2 °C for TACO was shorter (14 ± 4 min) compared to ventilation only (20 ± 5 min; $P=0.018$), but not to ventilation while wearing a wet t-shirt (18 ± 6 min; $P=0.090$).

Conclusions: TACO may be an acceptable, efficient and feasible cooling method in case of exertional heat stroke. However, in case of limited water availability, transportat should be prioritized, and cooling of any form should be implemented while waiting for and during transport.

1. Introduction

Military personnel often perform in challenging environmental conditions whilst wearing highly insulating protective clothing and carrying heavy equipment. It therefore comes to no surprise that the prevalence of exertional heat stroke (EHS) is high in this profession (CheMuhamed et al., 2016). EHS is characterized by an exercise-induced body core temperature (T_c) that exceeds 40–40.5 °C along with potential dysfunction of the central nervous system and tissue damage (Hadad et al., 2004; Demartini et al., 2015; Binkley et al., 2002; Casa et al., 2012; American College of Sports et al., 2007). Common symptoms of EHS are altered alertness, headache, coma, and seizures (Hadad et al., 2004; Demartini et al., 2015; Binkley et al., 2002; Casa et al., 2012; American College of Sports et al., 2007; Butts et al., 2017a; Gaudio and Grissom, 2016; Alzeer and Wissler, 2018; Casa et al., 2007) with many cases being fatal (Rav-Acha et al., 2004; Heled et al., 2004; Bouchama and Knochel, 2002; Hunt et al., 2016).

In the unfortunate event that EHS occurs, cold water immersion is considered to be the gold standard treatment (Hadad et al., 2004; Demartini et al., 2015; Casa et al., 2007), as it results in a fast drop in T_c. The longer time spent with a T_c above 40 °C, the higher the required cooling rate for a higher chance of survival (McDermott et al., 2009). The four-to-five times greater cooling capacity of water compared to air (Tipton and Wooler, 2016), and the large body surface area covered by water, yields relatively high cooling rates (~0.2 °C min^{-1} (Butts et al., 2017b; Butts et al., 2016)) using this technique. Effective cooling strategies typically include moving large volumes of cold water across the skin surface (Power et al., 2015); a large temperature gradient between the skin and water determines how much heat will be transferred. However, the use of cold-water immersion is not feasible in most military operational settings due to the limited (or none) availability of large volumes of cold water. The present study therefore attempts to combine established guidelines regarding treatment of EHS with practical and feasible cooling methods in military operational settings.

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When cooling a person with severe EHS using cold water immersion, it is beneficial to fully immerse the person (until the neck) in 5–10 °C water. Obviously, access to a bath, to large volumes of water and water of a certain temperature may not always be feasible in a military setting. Recently, the relatively simple and economical tarp-assisted cooling with oscillations (TACO) technique has been introduced for pre-hospital care in the military (Adams, 2019; Hosokawa et al., 2017; Luhring et al., 2016). This method requires a tarp that is sized for the person and at least three people to hold the tarp and make the water oscillate. Previous research into the effectiveness of the TACO reported a cooling rate of 0.14 °C min^{-1} using 151 L of ~2 °C water and a cooling rate of 0.17 °C min^{-1} using 136 L–9 °C water respectively (Hosokawa et al., 2017; Luhring et al., 2016). Ideal cooling rates for EHS treatment (from a maximum T_c of 42.2 °C) are ≥0.155 °C min^{-1}. With such cooling rates (≥0.155 °C min^{-1}) T_c can be returned to safe levels within 20 min, limiting physiological damage as much as possible (Butts et al., 2016, 2017b). TACO seems an ideal on-site alternative for cold water immersion in military operational settings. However, it is rather unlikely to have access to large volumes of icy water in remote military operations, remote athletic events or labor situations (i.e., firefighting). More likely, large volumes of water will be available but stored at temperatures closer to the environmental conditions. In relation to this, Taylor and colleagues (Taylor et al., 2008) recently found that cooling down an individual from an esophageal temperature of 39.5 °C to 37.5 °C took only 45 s longer (2.91 min) using temperate (26 °C) water immersion compared to cold-water (14 °C) immersion (2.16 min). The relatively small, but statistically significant, differences in cooling rates may be explained by the large temperature gradient between environment and skin using cold-water immersion. Some heat gain during cold-water immersion may be caused by cold-induced thermogenesis (i.e., due to shivering) and some heat storage due to cold-induced vasoconstriction responses. Employing immersion in water with a moderate termperature, the temperature gradient between skin and water is small but heat gain is probably limited. Temperate water immersion seems to have potential in terms of cooling rate and satisfying practical issues in the field. Yet the effectiveness of the TACO using water around environmental temperature has not been established.

In situations where water resources are limited, such as in most military settings, the focus of EHS treatment will often be determined by the resources available. In such situations, cold water immersion, the aforementioned TACO method, and previously reported alternatives such as ice-sheet cooling (Butts et al., 2017b) or cold water showering (Butts et al., 2016) are not feasible. For the specific case of the military, soldiers typically carry a water bottle, protective clothing and an extra clothing layer. Using these, in case of EHS one can strip the soldier from clothing, soak a t-shirt with water from one bottle, have the soldier wear the t-shirt and facilitate evaporative cooling by waving/wafting a piece of the (protective) equipment to provide additional convective cooling. Assuming some dehydration occurs during exercise, sweat production will most likely be suppressed (Sawka et al., 1985). By using the wet t-shirt, water evaporation from the t-shirt may facilitate cooling. If the military squad is also running out of water, the absolute minimum one can do in the field is to strip the soldier and then fan with a piece of equipment (Cramer et al., 2020a). To our knowledge, the cooling rates of such restricted methods have not been quantified yet.

The aim of the present study was to establish cooling rates of three feasible cooling methods for treatment of hyperthermic individuals in the military. These methodes differed considerably in volume of water: ventilation, ventilation while wearing a wet t-shirt, and the TACO method using water with a temperature close to ambient temperature. It is hypothesized that the TACO method will induce the highest cooling rate, followed by ventilation while wearing a wet t-shirt and, lastly, ventilation alone. It is further hypothesized that none of the assessed cooling methods will reach a previously recommended cooling rate of ≥0.155 °C min^{-1}.

2. Material and methods

2.1. Ethical approval

Experimental procedures were approved by the Ethics Committee of the Faculty of Behavioural and Movement Sciences of the Vrije Universiteit Amsterdam (VCWE-2020-187; amendment VCWE-2021-003). The study was conducted in accordance with the guidelines of the revised *Declaration of Helsinki* (2013). Written informed consent and a health questionnaire were obtained from all participants before participation in the study.

2.2. Participants

Ten male soldiers on active duty (age: 32 ± 8 years; height: 185 ± 5 cm; body mass: 88.2 ± 9.2 kg) participated in this study. Participants were instructed to refrain from alcohol and caffeine 24 h before the experiment and to consume 500 mL of water 0–2 h before starting the experiment. No further restrictions were placed on their diets. All participants were non-smokers, were not taking prescription medication, had no history of heat-related illnesses or cardiovascular complications and did not have any known issues with thermoregulation.

2.3. Design

Participants visited the laboratory on three occasions to walk on a treadmill (Woodway PPS Med, Weil am Rhein, Germany), until a rectal temperature (T_{re}) of 39.5 °C was reached in a climatic chamber (b-Cat, Tiel, The Netherlands) set to 30 °C and 65% relative humidity (RH). Airflow in the climatic chamber was standardized to 0.2 m s^{-1}. The selected environmental condition is reflective of a B1 environment according to NATO, which is representative of a common working environment for military personnel (The North Atlantic Treaty Organization, 2006). To ensure participant safety, exercise was terminated at T_{re} of 39.5 °C, in case of volitional fatigue or the inability to continue exercise due to an altered gait and reduced alertness as observed by the researcher. The walking speed and incline of the treadmill were self-selected. Whilst walking on the treadmill, participants wore battle dress uniform trousers or jogging trousers, a long-sleeved shirt with a mid-layer on top and a beanie. During each visit, participants were cooled down from T_{re} of ~39.5 °C to 38.2 °C via three different methods. Each cooling method started with stripping the participant down to their underwear. After that, cooling was provided using whole-body ventilation (1.7 m s^{-1}) from the front side, the same ventilation (1.7 m s^{-1}) method in combination with wearing a wet t-shirt (soaked with 250 mL of ~27 °C water), and the TACO. The 250 mL of water was sufficient to soak the t-shirt but to not let it drip (i.e., drinking water may be scarce and wasting water should be prevented in a military context) and was therefore selected from our pilot tests. The ventilation (i.e., 1.7 m s^{-1}) was based on easily reached wind speeds using a piece of soft ballistic protection, that was pre-determined during pilot tests. In the experiment, the fan was used and set to a wind speed of 1.7 m s^{-1} to simulate fanning using ballistic protection. In this way, equal wind speeds were ensured compared to hand held fanning with a piece of ballistic protection. TACO was selected because it is relatively simple and feasible to implement in the military. It is rather common that large volumes of water are being carried along in vehicles. One individual should carry the tarp and tap water should be collected from the nearest source. For the TACO method, 80 L of 27.2 ± 0.5 °C water was used. The water temperature was based on repetitive recordings of leaving tap water overnight in the B1 environment (30 °C, 65% RH), attempting to represent a military setting where a stagnated water reservoir is nearby. Four researchers each held one corner of the tarp and made sure the participant and the water oscillated for 5-min periods, with a 1-min break in between. The head of the participant was continuously above water level. To prevent a hypothermic drop, cooling was terminated once T_{re} returned to 38.2 °C (Gagnon et al., 2010). The cooling method order was balanced among participants. To prevent heat acclimation, visits were separated by at least one week and no longer than two weeks (Gill and Sleivert, 2001). To account for changes due to the circadian rhythm, each visit was scheduled at the same time of day (±1 h).

2.4. Measurements

To confirm hydration, urine specific gravity (USG) was measured with a handheld refractometer (PAL-S, Atago, Bellevue, USA; USG≤1.020) (Kenefick and Cheuvront, 2012). Despite the hydration guidelines, two participants had an USG>1.020 on two occasions and another two participants on one occasion. These participants were requested to drink 5 mL kg^{-1} body mass of water before commencing with the experiment. A rectal temperature (T_{re}) thermometer (Coviden Mon-a-Therm 400 Tm 3.0 mm, Medtronic, USA) was self-inserted 10 cm past the anal sphincter. Participants also wore a heart rate (HR) monitor (Polar Vantage M, Kemele, Finland). Skin temperature (T_{sk}) sensors (i-Button DS 1922L, Maxim Integrated, USA) were attached to eight skin locations according to ISO 9886 (ISO9886, 2004), using a 5 × 5 cm adhesive tape (Fixomull stretch, BSN Medical, Almere). Subsequently, a weighted mean T_{sk} was calculated using the following equation (1) (ISO9886, 2004; Kenefick and Cheuvront, 2012):

$$Mean\ T_{sk}(^{\circ}C) = 0.07\ T_{forehead} + 0.175\ T_{scapula} + 0.175\ T_{chest} + 0.07\ T_{upper\ arm} + 0.07\ T_{forearm} + 0.05\ T_{hand} + 0.19\ T_{thigh} + 0.2\ T_{calf}\ (^{\circ}C) \quad \text{(Eq. 1)}$$

Perceptual responses were assessed at 5-min intervals during the experiment. Thermal sensation (TS) was rated using a scale with intermediary values ranging from +10 (extremely hot) to −10 (extremely cold) with 0 indicating thermal neutrality (American Society of Heating, Refrigerating and Air-Conditioning Engineers, 2009). Thermal comfort (TC) was rated on a 7-point Likert scale with intermediary values (0 - comfortable, 2 - slightly uncomfortable, 4 - uncomfortable, 6 - very uncomfortable) (Gagge et al., 1967). Participants were allowed to drink ad libitum. Cooling rates for each method were calculated using equation (2). Cooling time represents the time to reach T_{re}=38.2 °C.

$$Cooling\ rate\ (^{\circ}C{\cdot}min^{-1}) = (T_{re-pre}(^{\circ}C) - T_{re\ -\ post}\ (^{\circ}C))\ /\ cooling\ time\ (min) \quad \text{(Eq. 2)}$$

2.5. Statistics

All data were synced and formatted using Python (PyCharm Community Edition, 2020 3.3). T_{re}, HR and T_{sk} data were converted into 1-min averages. Statistical analyses were performed using IBM SPSS Statistics 26.0. Effects were considered significant if P<0.05. Histograms and quantile-quantile (Q-Q)-plots were used to check if the data were normally distributed. HR, T_{re}, mean T_{sk}, TS and TC were assessed using a mixed effect model with cooling method and time (pre- and post-cooling) as fixed effects and participant as random effect. Cooling rates, time to cool (TTC; time to T_{re}=38.2 °C), initial T_{re} and walking durations were assessed using a mixed effect model, with cooling method as fixed effect and random participant effects. To assess the relationship between cooling rate and body surface area (BSA)-to-mass ratio, simple linear regression and Pearson rank correlation coefficients were conducted for the TACO method.

3. Results

3.1. HR, T_{re} and mean T_{sk}

To reach a T_{re} of 39.5 °C, participants walked on the treadmill for 93 ± 21 min before ventilation, 93 ± 20 min before ventilation with a wet t-shirt, and 90 ± 30 min before TACO (P=0.946). There were significant main effects of time on HR, T_{re} and mean T_{sk} (all P<0.001) with post-cooling values being lower compared to pre-cooling values. The main effects of cooling method and interaction effect of time *x* cooling method on HR and T_{re} were non-significant (HR: P=0.373 and P=0.988, T_{re}: P=0.055 and P=0.197 respectively; Fig. 1). There was a significant main effect of cooling method on mean T_{sk} (P<0.001), indicating that mean T_{sk} was lower using TACO compared to ventilation and ventilation in combination with wearing a wet t-shirt. The interaction effect of time *x* cooling on mean T_{sk} was also significant (P<0.001). Post-hoc testing revealed that the decrease in mean T_{sk} over time was greater using TACO compared to ventilation (P<0.001) and ventilation in combination with wearing a wet t-shirt (P<0.001). The mean T_{sk} decrease was not different between ventilation and ventilation while wearing a wet t-shirt (P=0.869). After cooling with the TACO method, the water temperature increased to 29.1 ± 0.4 °C. Calculations based on a 1.9 °C temperature increase of 80 L in 14 min show that ~650 W of heat was transferred to the water (Morrissey and Liou, 1984; Cramer and Jay, 2016; Snellen, 1966).

3.2. Cooling rate and time to cool

Initial T_{re} did not differ between cooling methods (ventilation: 39.45 ± 0.20 °C, ventilation in combination with wearing a wet t-shirt: 39.45 ± 0.22 °C, and TACO: 39.63 ± 0.20 °C; P=0.109). On average, cooling rates were 0.065 ± 0.011 °C min^{-1}, 0.074 ± 0.020 °C min^{-1}, and 0.116 ± 0.032 °C min^{-1} for ventilation, ventilation whilst wearing a wet t-shirt, and TACO respectively (Fig. 2). The corresponding TTC were 20 ± 5 min, 18 ± 6 min, and 14 ± 4 min (Fig. 2). There were significant main effects of cooling method on cooling rate (P<0.001) and TTC (P=0.016). Post-hoc testing revealed that the TACO led to higher cooling rates compared to ventilation (P<0.001) and ventilation while wearing a wet t-shirt (P=0.002), whilst the cooling rate between the latter two did not differ (P=1.000; Fig. 2). Secondly, post-hoc testing revealed that TTC was shorter using the TACO compared to ventilation (P=0.018), but not compared to ventilation while wearing a wet t-shirt (P=0.090). The difference between ventilation and ventilation while wearing a wet t-shirt on TTC was non-significant (P=1.000; Fig. 2).

3.2. Subjective responses

There was a significant main effect of time on TS and TC (P<0.001 and P<0.001; Fig. 3) with post-cooling showing lower values (i.e., less warm and more comfortable) compared to pre-cooling. The main effects of cooling (TS: P=0.234 and TC: P=0.895) and interaction effects of time *x* cooling method (TS: P=0.442 and TC: P=0.708) on TS and TC were non-significant (Fig. 3).

3.3. Body surface area-to-mass ratio

The BSA-to-mass ratio of our participants was 242 ± 11 $cm^2\ kg^{-1}$. Previous research also suggested that the BSA-to-mass ratio affects the

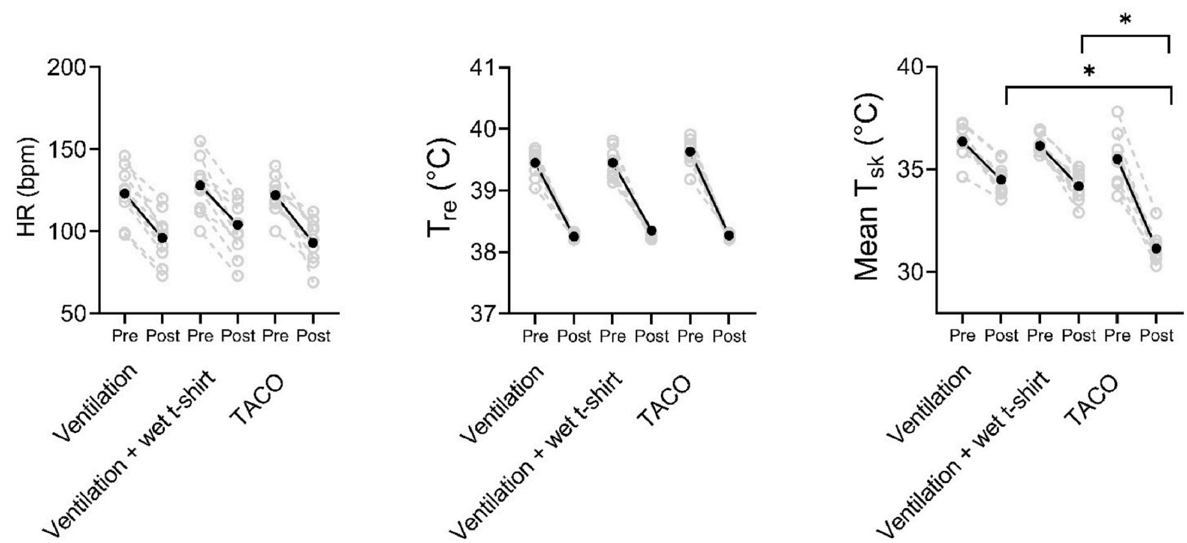

Fig. 1. The effect of three different cooling methods (ventilation, ventilation + wet t-shirt and tarp assisted cooling with oscillations; TACO) on pre- and post-cooling heart rate (HR), rectal temperature (T_{re}), and mean skin temperature (mean T_{sk}). Grey dots and lines represent individual data points. Black dots and lines represent the group average. * Denotes a significant ($P<0.05$) interaction effect of time *x* cooling method ($n=10$).

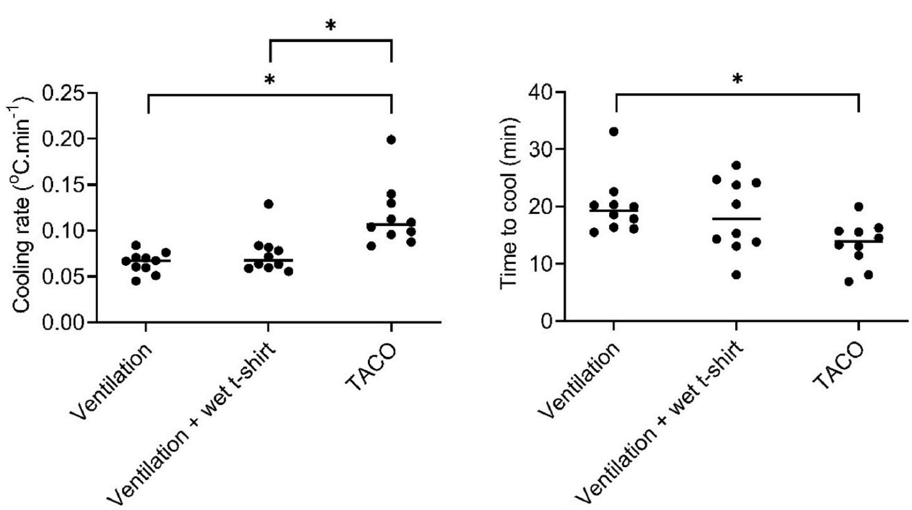

Fig. 2. The effect of three different cooling methods (ventilation, ventilation + wet t-shirt and tarp assisted cooling with oscillations; TACO) on cooling rate and time to cool (TTC). Horizontal lines represent group averages. Black dots represent individual data points. * Denotes a significant ($P<0.05$) effect of cooling method ($n=10$).

cooling rate of cold water immersion in hyperthermic individuals (Nye et al., 2016; Friesen et al., 2014). For the TACO method this was, however, not the case in the present study ($P=0.191$, $R^2=0.20$; Fig. 4).

4. Discussion

The gold standard for EHS treatment is cold water immersion. However, in the military, due to the limited (or none) availability of large volumes of cold water, this method is not always feasible. The aim of the present study was to combine established guidelines regarding treatment of EHS with practical and feasible cooling methods in military operational settings. Therefore, cooling rates of three feasible cooling methods for military field work, that differed considerably in water volume needed, were established: ventilation, ventilation while wearing a wet t-shirt and TACO using environmental temperature water (~27 °C).

McDermott and colleagues (McDermott et al., 2009) identified three categories of cooling efficiency based on cooling rates and the time required to return T_c from 42.2 °C to safe values (38.89 °C). Category A is a cooling rate ≥0.155 °C min^{-1} and approximately 20 min of cooling. Category B with cooling rates of 0.155 0.078 °C min^{-1} and less than 40 min of cooling. Category C with a cooling rate lower than 0.078 °C min^{-1} and more than 40 min of cooling (McDermott et al., 2009). To limit physiological damage using any cooling method, category A, B and C were considered 'ideal', 'acceptable' and 'unacceptable' cooling rates for treating EHS, respectively. In the present study, ventilation and ventilation while wearing a wet t-shirt fit into category C or unacceptable (0.065 ± 0.011 °C min^{-1} and 0.074 ± 0.020 °C min^{-1}). Whilst the TACO (0.116 ± 0.032 °C min^{-1}) method belongs to category B or acceptable. These categories differ considerably in the corresponding TTC from a T_c of 42.2 °C to safe levels (B: ≤40 min, C: >40 min of cooling). Even though this study was not conducted with EHS patients, we indeed observed a shorter TTC using TACO (14 ± 4 min) compared to ventilation only (20 ± 5 min) and ventilation while wearing a wet t-shirt (18 ± 6 min) to return to safe T_c levels. Relying on the McDermott categories, the TACO variant applied in the present study (80 L of

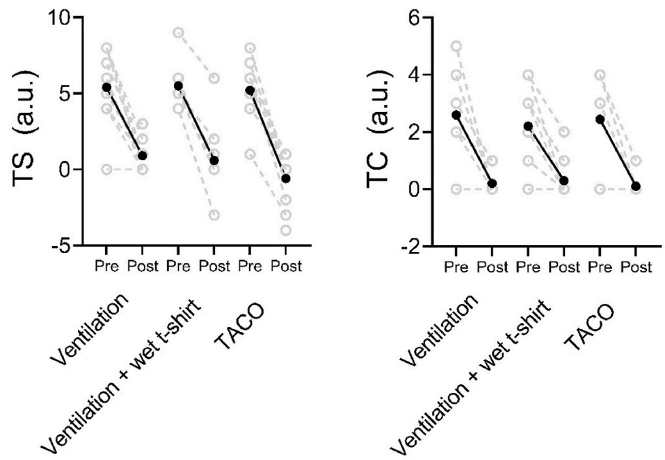

Fig. 3. The effect of three different cooling methods (ventilation, ventilation + wet t-shirt and tarp assisted cooling with oscillations; TACO) on pre- and post-cooling subjective responses: thermal sensation (TS) and thermal comfort (TC). Grey dots and lines represent individual data points. Black dots and lines represent the group average. * Denotes a significant ($P<0.05$) interaction effect of time *x* cooling method ($n=10$).

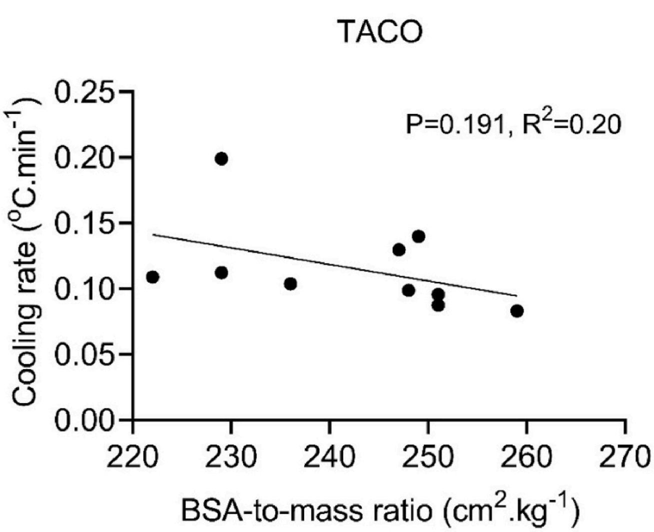

Fig. 4. The relationship between the body surface area (BSA)-to-mass ratio and the cooling rate during tarp assisted cooling with oscillations (TACO; 80 L of ~27 °C water; $n=10$).

~27 °C water) would be acceptable in the field whilst ventilation in combination with a wet t-shirt and ventilation alone would be considered unacceptable. When no other options are available, cooling with TACO should be preferred above no cooling or ventilated cooling. However, transportat to a hospital becomes crucial if large volumes (>80 L) of water are not available. Whilst waiting for, and during transport, ventilation (potentially in combination with wearing a wet t-shirt) could be performed as some cooling is preferred over no cooling at all (Ravanelli et al., 2017; Cramer et al., 2020b; Morris et al., 2019, 2021).

The physiological variable that was affected most by the cooling methods used here was mean T_{sk}. This makes sense, as the skin surface is the area where the cooling is applied. Mean T_{sk} decreased more during TACO compared to the other two methods that involved less water. The conductive and convective heat loss using TACO considerably exceeded the conductive and evaporative heat loss provided by the wet t-shirt. The lower mean T_{sk} is most likely due to the four-to-five times greater cooling capacity of water compared to air (Tipton and Wooler, 2016). Even though in our second method (ventilation in combination with a wet t-shirt) we also used water, this was only 250 mL (compared to 80 L using TACO) and the water was not oscillating, which provided less cooling (Power et al., 2015). Lower mean T_{sk} causes a greater temperature gradient from the core to the skin, facilitating convective and radiant heat loss. In the end, this probably caused the larger cooling rates and faster TTC of TACO compared to the other methods.

Previous research into the effectiveness of TACO reported a cooling rate of 0.14 °C min^{-1} using 151 L of ~2 °C water and a cooling rate of 0.17 °C min^{-1} using 136 L of ~9 °C water respectively (Hosokawa et al., 2017; Luhring et al., 2016). In the present study, a cooling rate of 0.116 ± 0.03 °C min^{-1} was observed using 80 L of ~27 °C water. Considering the large difference in water volume and water temperature with previous research, we consider the difference in observed cooling rate to be relatively small. Meanwhile, it is more likely for restricted situation such as the military to have access to relatively warm water, compared to icy water, as was investigated extensively before. Yet the ideal cooling rate for EHS treatment is ≥0.155 °C min^{-1} (Butts et al., 2016, 2017b), which was not met in the present study. Due to ethical safety limits, this study was not conducted with EHS patients (T_c that exceeds 40–40.5 °C (Hadad et al., 2004; Demartini et al., 2015; Binkley et al., 2002; Casa et al., 2012; American College of Sports et al., 2007)). It is suggested that higher initial T_{re} values correspond to higher initial cooling rates because of the larger thermal gradient (Proulx et al., 2003; Richards and Richards, 1984). The cooling rate of the TACO in actual EHS patients could therefore be higher than reported here. It should also be noted that in the military setting, EHS treatment is focused on the most one can do. Hence, it is important to quantify cooling rates of methods that require limited resources. Furthermore, military personnel should be instructed on how long a person should be cooled using different techniques in different environmental conditions, or that potentially transport to a hospital should be prioritized.

Previous research also suggested that the BSA-to-mass ratio affects the cooling rate in hyperthermic individuals. Individuals with a relatively large BSA-to-mass ratio have more area covered by water (or air) and therefore have a greater amount of heat loss (Nye et al., 2016; Friesen et al., 2014). As the TACO method heavily relies on conductive and convective heat loss, the impact of BSA-to-mass ratio was expected to contribute to the success of this method. However, this was not observed in the present study, which could be due to the relatively homogenous group in terms of BSA (range: 1.9–2.4 m^2) and body mass (range: 77.2–107.6 kg).

When EHS occurs, perceptual responses are irrelevant as the main goal is to cool the patient down as fast as possible. However, in the controlled situation of the present study, it was possible to obtain perceptual data. Our findings show that from the start to the end of cooling, participants reported an improvement in thermal comfort and sensation. Interestingly, there were no differences found in perceptual responses between cooling methods, despite differences in the mean T_{sk} between conditions. It should also be noted that a 'cold' sensation was not reported in the present study. The absence of feeling cold may relate to the protocol's adherence to the guidelines of stopping cooling at a T_{re} of 38.2 °C, to prevent a hypothermic drop. If an individual gets cold, it is possible that they begin to shiver (Fujimoto et al., 2019). Shivering is associated with vasoconstriction and an increased metabolic heat production. These both can have adverse effects on the cooling strategy as they impede cooling efficiency (Barcroft and Edholm, 1943; Eichler et al., 1969; Wyndham et al., 1959). In the present study, whilst a cold sensation was not reported, shivering was observed and noted by the participants during the ventilation while wearing a wet t-shirt method. This could have impeded heat loss with this cooling method.

4.1. Practical implication

The gold standard for EHS treatment is cold water immersion (Hadad et al., 2004; Demartini et al., 2015; Casa et al., 2007). In elite sports and large events, it is likely that the logistical requirements for this cooling method could be arranged at several locations nearby the event. Similarly, for military training purposes, it is recommended to set up facilities to be able to provide cold water immersion in the occurrence of EHS. In this way, soldiers can be cooled as fast as possible and physiological damage can be limited. However, for military personnel in the field, resources are often limited. In such situations, the TACO could be a convenient alternative for cold water immersion. Previous research reported cooling rates of 0.14–0.17 °C min^{-1} using large volumes of cold water (Hosokawa et al., 2017; Luhring et al., 2016). In the present study a cooling rate of 0.116 ± 0.03 °C min^{-1} was observed using 80 L of ~27 °C water using TACO. Yet an ideal cooling rate for EHS treatment is ≥0.155 °C min^{-1} (Butts et al., 2016, 2017b) which was not met in the present study. It should, however, be noted that in a military setting EHS treatment is often focused on the most one can do. Currently, the military advocate a 'cool first, transport second' strategy. The present study highlights that a more appropriate strategy should be: 'If large amounts of water (≥80 L) are available, cool first and transport second. If not, focus on transportat but whilst waiting for and during transport cooling should be applied in any form and as much as possible. Cooling should always be preferred over no cooling at all.'

TACO is recommended first, and if water is unavailable, ventilation (including a wet t-shirt if possible) should be preferred, above no cooling (Ravanelli et al., 2017; Cramer et al., 2020b; Morris et al., 2019, 2021). If the latter two are the only options available, then looking for transport should be prioritized, especially if the efficiency of the feasible cooling is unacceptable (cooling rate ≤0.078 °C min^{-1}). Whilst waiting for, and during transport, any type of cooling should be applied. Future research should elaborate on other potential modalities of efficient cooling (i.e., high cooling rate) with limited resources.

4.2. Limitations

A limitation to the present study is the lack of a control condition (i.e. no cooling at all). A control condition could have been used to establish whether (and to what magnitude) our cooling methods were more beneficial than no cooling at all. Previous research showed that the cooling rate during a passive control condition (~33 °C, 56% RH) was 0.04 ± 0.02 °C min^{-1} (Luhring et al., 2016). In the present study, cooling rates of ventilation and ventilation while wearing a wet t-shirt were 0.065 ± 0.011 °C min^{-1} and 0.074 ± 0.020 °C min^{-1}. Moreover, in the present study no direct comparison was made to the gold standard for cooling hyperthermic individuals (i.e., cold water immersion). Previous research has extensively established the cooling rate of cold water immersion with several water temperatures. Additionally, three categories of cooling efficiency (based on cooling rates) were developed. Therefore, we think the existing literature on cold water immersion is sufficient to compare to our results. Secondly, our findings only apply to the environmental conditions investigated here (30 °C, 65% RH). Considering the high reliance on evaporative cooling using ventilation only, and by adding the wet t-shirt, these methods could be more effective when the evaporative capacity is high (i.e., RH is low). For the TACO, the impact of air temperature and humidity seems small (calculations show that only ~200 W is transferred to air) but water temperature seems essential (~650 W heat is transferred to water and a larger temperature gradient would enhance heat loss considerably) (Morrissey and Liou, 1984; Cramer and Jay, 2016; Snellen, 1966).

EHS patients have a T_c that exceeds 40–40.5 °C (Hadad et al., 2004; Demartini et al., 2015; Binkley et al., 2002; Casa et al., 2012; American College of Sports et al., 2007) but due to ethical safety limits, we were limited to 39.5 °C. It is suggested that higher T_c values correspond to higher initial cooling rates because of the larger thermal gradient (Proulx et al., 2003; Richards and Richards, 1984). Lastly, participants in the present study were males. Previous research found that hyperthermic females show higher cooling rates compared to males (Friesen et al., 2014; Boehm and Miller, 2019). This was mainly associated with differences in BSA-to-mass ratio and partly to T_{sk} (Burse, 1979; Yanovich et al., 2020), both of which are generally higher in females, allowing for larger surface to dissipate heat from and a greater temperature gradient between skin and air. Females have a relatively larger area to lose heat from, typically resulting in higher cooling rates. It could be that cooling rates would have been higher in females using the techniques studied here. If males show a lower cooling rate in general, at least we investigated the lower limit of what is possible using these cooling techniques (Friesen et al., 2014; Boehm and Miller, 2019).

5. Conclusions

Cooling rates for ventilation (0.065 ± 0.011 °C min^{-1}), ventilation while wearing a wet t-shirt (0.074 ± 0.020 °C min^{-1}), and TACO (0.116 ± 0.032 °C min^{-1}) were established. Considering the direct relationship between the time above a core temperature of 40 °C and the outcome of cooling, in remote settings we recommend applying TACO if this is feasible.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

Adams, W.M., 2019. An alternative method for treating exertional heat stroke: tarp-assisted cooling. Athl. Train. Sports Health Care 11, 101–102.
Alzeer, A.H., Wissler, E., 2018. Theoretical analysis of evaporative cooling of classic heat stroke patients. Int. J. Biometeorol. 62, 1567–1574.
American College of Sports, M., Armstrong, L.E., Casa, D.J., Millard-Stafford, M., Moran, D.S., Pyne, S.W., Roberts, W.O., 2007. American College of Sports Medicine position stand. Exertional heat illness during training and competition. Med. Sci. Sports Exerc. 39, 556–572.
American Society of Heating, Refrigerating and Air-Conditioning Engineers, 2009. ASHRAE handbook: Fundamentals. GA ASHRAE, Atlanta.
Barcroft, H., Edholm, O.G., 1943. The effect of temperature on blood flow and deep temperature in the human forearm. J. Physiol. 102, 5–20.
Binkley, H.M., Beckett, J., Casa, D.J., Kleiner, D.M., Plummer, P.E., 2002. National Athletic Trainers' Association position statement: exertional heat illnesses. J. Athl. Train. 37, 329.
Boehm, K.E., Miller, K.C., 2019. Does gender affect rectal temperature cooling rates? A critically appraised topic. J. Sport Rehabil. 28, 522–525.
Bouchama, A., Knochel, J.P., 2002. Heat stroke. N. Engl. J. Med. 346, 1978–1988.
Burse, R.L., 1979. Sex differences in human thermoregulatory response to heat and cold stress. Hum. Factors 21, 687–699.
Butts, C.L., McDermott, B.P., Buening, B.J., Bonacci, J.A., Ganio, M.S., Adams, J.D., Tucker, M.A., Kavouras, S.A., 2016. Physiologic and perceptual responses to cold-shower cooling after exercise-induced hyperthermia. J. Athl. Train. 51, 252–257.
Butts, C.L., Spisla, D.L., Adams, J., Smith, C.R., Paulsen, K.M., Caldwell, A.R., Ganio, M. S., McDermott, B.P., 2017a. Effectiveness of ice-sheet cooling following exertional hyperthermia. Mil. Med. 182, e1951–e1957.
Butts, C.L., Spisla, D.L., Adams, J.D., Smith, C.R., Paulsen, K.M., Caldwell, A.R., Ganio, M.S., McDermott, B.P., 2017b. Effectiveness of ice-sheet cooling following exertional hyperthermia. Mil. Med. 182, e1951–e1957.
Casa, D.J., McDermott, B.P., Lee, E.C., Yeargin, S.W., Armstrong, L.E., Maresh, C.M., 2007. Cold water immersion: the gold standard for exertional heatstroke treatment. Exerc. Sport Sci. Rev. 35, 141–149.
Casa, D.J., Armstrong, L.E., Kenny, G.P., O'Connor, F.G., Huggins, R.A., 2012. Exertional heat stroke: new concepts regarding cause and care. Curr. Sports Med. Rep. 11, 115–123.

Che Muhamed, A.M., Atkins, K., Stannard, S.R., Mündel, T., Thompson, M.W., 2016. The effects of a systematic increase in relative humidity on thermoregulatory and circulatory responses during prolonged running exercise in the heat. Temperature 3, 455–464.
Cramer, M.N., Jay, O., 2016. Biophysical aspects of human thermoregulation during heat stress. Auton. Neurosci. 196, 3–13.
Cramer, M.N., Huang, M., Moralez, G., Crandall, C.G., 2020a. Keeping older individuals cool in hot and moderately humid conditions: wetted clothing with and without an electric fan. J. Appl. Physiol. 1985 (128), 604–611.
Cramer, M.N., Huang, M., Moralez, G., Crandall, C.G., 2020b. Keeping older individuals cool in hot and moderately humid conditions: wetted clothing with and without an electric fan. J. Appl. Physiol. 128, 604–611.
Demartini, J.K., Casa, D.J., Stearns, R., Belval, L., Crago, A., Davis, R., Jardine, J., 2015. Effectiveness of cold water immersion in the treatment of exertional heat stroke at the Falmouth Road Race. Med. Sci. Sports Exerc. 47, 240–245.
Eichler, A.C., McFee, A.S., Root, H.D., 1969. Heat stroke. Am. J. Surg. 118, 855–863.
Friesen, B.J., Carter, M.R., Poirier, M.P., Kenny, G.P., 2014. Water immersion in the treatment of exertional hyperthermia: physical determinants. Med. Sci. Sports Exerc. 46, 1727–1735.
Fujimoto, T., Tsuji, B., Sasaki, Y., Dobashi, K., Sengoku, Y., Fujii, N., Nishiyasu, T., 2019. Low-intensity exercise delays the shivering response to core cooling. Am. J. Physiol. Regul. Integr. Comp. Physiol. 316, R535–R542.
Gagge, A.P., Stolwijk, J., Hardy, J., 1967. Comfort and thermal sensations and associated physiological responses at various ambient temperatures. Environ. Res. 1, 1–20.
Gagnon, D., Lemire, B.B., Casa, D.J., Kenny, G.P., 2010. Cold-water immersion and the treatment of hyperthermia: using 38.6 degrees C as a safe rectal temperature cooling limit. J. Athl. Train. 45, 439–444.
Gaudio, F.G., Grissom, C.K., 2016. Cooling methods in heat stroke. J. Emerg. Med. 50, 607–616.
Gill, N., Sleivert, G., 2001. Effect of daily versus intermittent exposure on heat acclimation. Aviat Space Environ. Med. 72, 385–390.
Hadad, E., Rav-Acha, M., Heled, Y., Epstein, Y., Moran, D.S., 2004. Heat stroke. Sports Med. 34, 501–511.
Heled, Y., Rav-Acha, M., Shani, Y., Epstein, Y., Moran, D.S., 2004. The "golden hour" for heatstroke treatment. Mil. Med. 169, 184–186.
Hosokawa, Y., Adams, W.M., Belval, L.N., Vandermark, L.W., Casa, D.J., 2017. Tarp-assisted cooling as a method of whole-body cooling in hyperthermic individuals. Ann. Emerg. Med. 69, 347–352.
Hunt, A.P., Billing, D.C., Patterson, M.J., Caldwell, J.N., 2016. Heat strain during military training activities: the dilemma of balancing force protection and operational capability. Temperature (Austin) 3, 307–317.
ISO9886, 2004. Ergonomics–Evaluation of Thermal Strain by Physiological Measurements.
Kenefick, R.W., Cheuvront, S.N., 2012. Hydration for recreational sport and physical activity. Nutr. Rev. 70 (Suppl. 2), S137–S142.
Luhring, K.E., Butts, C.L., Smith, C.R., Bonacci, J.A., Ylanan, R.C., Ganio, M.S., McDermott, B.P., 2016. Cooling effectiveness of a modified cold-water immersion method after exercise-induced hyperthermia. J. Athl. Train. 51, 946–951.
McDermott, B.P., Casa, D.J., Ganio, M.S., Lopez, R.M., Yeargin, S.W., Armstrong, L.E., Maresh, C.M., 2009. Acute whole-body cooling for exercise-induced hyperthermia: a systematic review. J. Athl. Train. 44, 84–93.
Morris, N.B., English, T., Hospers, L., Capon, A., Jay, O., 2019. The effects of electric fan use under differing resting heat index conditions: a clinical trial. Ann. Intern. Med. 171, 675–677.
Morris, N.B., Chaseling, G.K., English, T., Gruss, F., Maideen, M.F.B., Capon, A., Jay, O., 2021. Electric fan use for cooling during hot weather: a biophysical modelling study. The Lancet Planet. Health 5, e368–e377.
Morrissey, S.J., Liou, Y.H., 1984. Metabolic costs of load carriage with different container sizes. Ergonomics 27, 847–853.
Nye, E.A., Edler, J.R., Eberman, L.E., Games, K.E., 2016. Optimizing cold-water immersion for exercise-induced hyperthermia: an evidence-based paper. J. Athl. Train. 51, 500–501.
Power, J., Simoes, Re A., Barwood, M., Tikuisis, P., Tipton, M., 2015. Reduction in predicted survival times in cold water due to wind and waves. Appl. Ergon. 49, 18–24.
Proulx, C.I., Ducharme, M.B., Kenny, G.P., 2003. Effect of water temperature on cooling efficiency during hyperthermia in humans. J. Appl. Physiol. 94 (1985), 1317–1323.
Rav-Acha, M., Hadad, E., Epstein, Y., Heled, Y., Moran, D.S., 2004. Fatal exertional heat stroke: a case series. Am. J. Med. Sci. 328, 84–87.
Ravanelli, N.M., Gagnon, D., Hodder, S.G., Havenith, G., Jay, O., 2017. The biophysical and physiological basis for mitigated elevations in heart rate with electric fan use in extreme heat and humidity. Int. J. Biometeorol. 61, 313–323.
Richards, R., Richards, D., 1984. Exertion-induced heat exhaustion and other medical aspects of the City-to-Surf fun runs, 1978-1984. Med. J. Aust. 141, 799–805.
Sawka, M.N., Young, A.J., Francesconi, R.P., Muza, S.R., Pandolf, K.B., 1985. Thermoregulatory and blood responses during exercise at graded hypohydration levels. J. Appl. Physiol. 1985 (59), 1394–1401.
Snellen, J.W., 1966. Mean body temperature and the control of thermal sweating. Acta Physiol. Pharmacol. Neerl. 14, 99–174.
Taylor, N., Caldwell, J.N., Van den Heuvel, A., Patterson, M.J., 2008. To cool, but not too cool: that is the question–immersion cooling for hyperthermia. Med. Sci. Sports Exerc. 40, 1962–1969.
The North Atlantic Treaty Organization, 2006. AECTP 200 - Environmental Conditions. NATO Standardization Agency.
Tipton, M., Wooler, A., 2016. The Science of Beach Lifeguarding. CRC Press.
Wyndham, C.H., Strydom, N.B., Cooke, H.M., Maritz, J.S., Morrison, J.F., Fleming, P.W., Ward, J.S., 1959. Methods of cooling subjects with hyperpyrexia. J. Appl. Physiol. 14, 771–776.
Yanovich, R., Ketko, I., Charkoudian, N., 2020. Sex differences in human thermoregulation: relevance for 2020 and beyond. Physiology 35, 177–184.