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original research

Cold-Water Immersion Cooling Rates in Football Linemen and Cross-Country Runners With Exercise-Induced Hyperthermia

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Context: Ideal and acceptable cooling rates in hyperthermic athletes have been established in average-sized participants. Football linemen (FBs) have a small body surface area (BSA)-to-mass ratio compared with smaller athletes, which hinders heat dissipation.

Objective: To determine cooling rates using cold-water immersion in hyperthermic FBs and cross-country runners (CCs).

Design: Cohort study.

Setting: Controlled university laboratory.

Patients or Other Participants: Nine FBs (age = 21.7 ± 1.7 years, height = 188.7 ± 4 cm, mass = 128.1 ± 18 kg, body fat = 28.9% ± 7.1%, lean body mass [LBM] = 86.9 ± 19 kg, BSA = 2.54 ± 0.13 m^2, BSA/mass = 201 ± 21.3 cm^2/kg, and BSA/LBM = 276.4 ± 19.7 cm^2/kg) and 7 CCs (age = 20 ± 1.8 years, height = 176 ± 4.1 cm, mass = 68.7 ± 6.5 kg, body fat = 10.2% ± 1.6%, LBM = 61.7 ± 5.3 kg, BSA = 1.84 ± 0.1 m^2, BSA/mass = 268.3 ± 11.7 cm^2/kg, and BSA/LBM = 298.4 ± 11.7 cm^2/kg).

Intervention(s): Participants ingested an intestinal sensor, exercised in a climatic chamber (39°C, 40% relative humidity) until either target core temperature (T_{gi}) was 39.5°C or volitional exhaustion was reached, and were immediately immersed in a 10°C circulated bath until T_{gi} declined to 37.5°C. A general linear model repeated-measures analysis of variance and independent *t* tests were calculated, with $P < .05$.

Main Outcome Measure(s): Physical characteristics, maximal T_{gi}, time to reach 37.5°C, and cooling rate.

Results: Physical characteristics were different between groups. No differences existed in environmental measures or maximal T_{gi} (FBs = 39.12°C ± 0.39°C, CCs = 39.38°C ± 0.19°C; $P = .12$). Cooling times required to reach 37.5°C (FBs = 11.4 ± 4 minutes, CCs = 7.7 ± 0.06 minutes; $P < .002$) and therefore cooling rates (FBs = 0.156°C·min^{-1} ± 0.06°C·min^{-1}, CCs = .255°C·min^{-1} ± 0.05°C·min^{-1}; $P < .002$) were different. Strong correlations were found between cooling rate and body mass ($r = -0.76$, $P < .001$), total BSA ($r = -0.74$, $P < .001$), BSA/mass ($r = 0.73$, $P < .001$), LBM/mass ($r = 0.72$, $P < .002$), and LBM ($r = -0.72$, $P < .002$).

Conclusions: With cold-water immersion, the cooling rate in CCs (0.255°C·min^{-1}) was greater than in FBs (0.156°C·min^{-1}); however, both were considered ideal (≥0.155°C·min^{-1}). Athletic trainers should realize that it likely takes considerably longer to cool large hyperthermic American-football players (>11 minutes) than smaller, leaner athletes (7.7 minutes). Cooling rates varied widely from 0.332°C·min^{-1} in a small runner to only 0.101°C·min^{-1} in a lineman, supporting the use of rectal temperature for monitoring during cooling.

Key Words: exertional heat stroke, athletes, body surface area, heat dissipation

Key Points

- Cooling rates using cold-water immersion varied considerably depending on body size.
- After exercise, hyperthermic American-football players took longer to cool than male cross-country runners.
- Average cooling rates using cold-water (10°C) immersion were ideal in both football players and endurance runners.

When athletes exercise intensely, especially in warm or hot and humid conditions, exertional heat illness and, more specifically, exertional heat stroke (EHS) can be significant problems for them and for the clinicians treating them.[1] Characterized by a core temperature of 40°C to 42°C and central nervous system (CNS) dysfunction, EHS ultimately leads to multiple organ system failure unless the diagnosis is made quickly and appropriate treatment is initiated promptly.[2] Exertional heat stroke reportedly occurs primarily in young male athletes, military personnel, and workers performing manual labor in the heat.[3,4] Strenuous exercise under environmentally stressful conditions can cause metabolic heat production to exceed dissipation, driving core temperature to a critical level.[3] Although potentially life-threatening core temperatures can range from 40°C to 42°C, it should be noted that 1 measured "critical temperature" should not be used to confirm the diagnosis of EHS; CNS dysfunction and potential multisystem failure can occur at various core temperatures.[2,5] Many athletes who were being monitored using intestinal temperature sensors during field research experienced core temperatures of 40°C and even 42°C without CNS symptoms,[6–8] indicating that a core temperature at this level in and of itself is not diagnostic of EHS.

Exertional heat stroke is likely caused by a combination of factors that trigger a cascade of events resulting in a systemic inflammatory response.[4] Important factors such as underlying viral or bacterial illness,[9] low physical fitness,[5] high body mass,[9] sleep deprivation,[9,10] lack of acclimatization,[9] exercise intensity (metabolic rate of the athlete) unmatched by physical fitness,[9] immune deficiency responses,[11] and environmental conditions such as high ambient temperature, humidity, and radiant energy have been linked to EHS.[3,4] Other potential causes include a history of heat intolerance,[4] genetics (eg, malignant hyperthermia),[4] barriers to evaporation (clothing, equipment, or both), dietary supplements,[4] the predominance of type II muscle fibers,[12] male sex,[13] and hydration status immediately before the exercise bout (hypohydration).[10]

Although prevention is paramount, the elimination of every heat-stroke event may be difficult because the cause is still unknown; however, prompt diagnosis and proper treatment should prevent a fatal or catastrophic outcome.[5,13,14] Unfortunately, that has not been the case in American football players, given that EHS deaths have more than doubled in the last 2 decades (2005–2014 = 30 deaths and 1995–2004 = 24 deaths), as compared with the previous 2 decades (1985–1994 = 7 deaths and 1975–1984 = 17 deaths).[15]

Although our understanding of the exact cause or causes of EHS is not well established, the treatment is clearly understood.[4,16,17] Rapid cooling of the athlete with EHS or suspected EHS via full-body ice or cold-water immersion (CWI) has been shown to prevent fatal outcomes in nearly 100% of the documented cases.[16,18,19] Although this treatment for cooling hyperthermic athletes has been investigated in the laboratory and documented in the field, the population studied has primarily involved relatively small, lean individuals[16,18,20]; subsequently, the ideal ($\geq$0.155°C·min^{-1}) and acceptable (0.078°C·min^{-1} to 0.154°C·min^{-1}) cooling rates for different methods have been established in this population.[4,17] None of the studies in a systematic review[17] of cooling methods included individuals who participated in American football, the very athletes most predisposed to EHS in the United States. Large American-football players such as linemen have a large total body mass and lean body mass (LBM), which results in high amounts of heat production and storage.[7,21] They also have lower body surface area-to-mass (BSA/mass) and BSA-to-LBM (BSA/LBM) ratios compared with smaller athletes, which hinder heat dissipation by conduction and convection.[22] In addition, large linemen typically have a considerably higher percentage of body fat (many >25%) compared with lean athletes such as competitive collegiate runners.[23] Friesen et al[24] found that individuals with a high BSA/LBM (who had less lean mass but a higher body fat percentage) cooled at a faster rate than individuals of similar size (height, weight, and BSA) but with a lower BSA/LBM. The authors attributed the main difference in cooling rates between these groups to the higher residual heat load in those with greater LBM. Body fat appeared to play less of a role.[24] Clearly, physical factors (ie, total body mass, LBM, percentage of body fat, and BSA) not only contribute to heat production and storage during exercise but also play a critical role in heat dissipation during active cooling.[25,26]

Because the data used to determine acceptable or ideal cooling rates are based primarily on a relatively homogeneous population,[4] as mentioned by McDermott et al,[17] our primary aim was to answer a clinical question about the time it might take to cool a large American-football player versus a smaller, leaner individual. Therefore, the purpose of our study was 2-fold: to determine (1) whether CWI resulted in differences in the cooling rates between large American-football linemen (FBs) and relatively small, aerobically trained cross-country runners (CCs) who were hyperthermic due to exercise in the heat; and (2) whether the cooling rate using CWI (at 10°C) for FBs with exercise-induced hyperthermia reached ideal ($\geq$0.155°C·min^{-1}) or acceptable (between 0.078°C·min^{-1} and 0.154°C·min^{-1}) standards.[17]

Table 1. Participants' Physical Characteristics

Characteristic	Football Linemen (n = 9)	Cross-Country Runners (n = 7)	*P* Value
	Mean ± SD		
Age, y	21.7 ± 1.7	20 ± 1.8	
Height, cm	188.7 ± 4	176 ± 4.1	<.0001
Mass, kg	128.1 ± 18	68.7 ± 6.5	<.0001
Body fat, %	28.9 ± 7.1	10.2 ± 1.6	<.0001
LBM, kg	86.9 ± 19	61.7 ± 5.3	.004
LBM/mass, %	72.8 ± 6.6	89.9 ± 1.8	.0015
BSA, m^2	2.54 ± 0.13	1.84 ± 0.1	<.0001
BSA/mass, cm^2/kg	201 ± 21.3	268.3 ± 11.7	<.0001
BSA/LBM, cm^2/kg	276.4 ± 19.7	298.4 ± 11.7	.02

Abbreviations: BSA, body surface area; LBM, lean body mass.

METHODS

This cohort study was conducted in a controlled laboratory setting and was approved by the university's human participants institutional review board. All trials were conducted during the winter months and between 9 AM and noon to control for core temperature variations due to circadian rhythms.[27]

Participants

Given the influence of physical size on factors related to thermoregulation,[7,9,21,22,28] we anticipated a large effect size, so by using an α level of $P < .05$ and a power of 0.8, we determined that 9 participants were needed in each group. We originally recruited 10 football players and 9 male runners as volunteers, but 3 of those participants were unable to complete the protocol. Two runners had scheduling conflicts and 1 football player did not complete the cooling portion of the trial due to immediate discomfort from being submerged to his shoulders in the 10°C water. Therefore, 9 male football offensive or defensive linemen and 7 members of the men's cross-country team from the same university completed the study. The participants' physical characteristics are shown in Table 1. At the time of data collection, all athletes were engaged in their respective off-season training programs. The FBs were participating in strength training and morning workouts that included plyometrics, agility drills, and speed training, whereas the CCs participated in 45- to 60-minute endurance runs, 4 times per week. Participants were excluded if they had a history of heat-related illness, were taking a medication or supplement that might affect thermoregulation or fluid balance, or were ill at the start of the trials (ie, had an elevated baseline core temperature). All participants had undergone a medical history and physical examination performed by a physician, physician assistant, or nurse practitioner within the previous 6 months, and all were considered unacclimatized because the trials occurred during January and February in the northeastern United States.

Procedures

The participants presented to the laboratory the day before the exercise/heating and subsequent cooling trials for instructions and to sign the consent forms. They were given an ingestible core temperature sensor and instructed to ingest it 6 to 12 hours before the next morning's data collection. Ingestible sensors (CorTemp HQ, Inc, Palmetto, FL) have demonstrated temperatures (±0.1°C) that yield estimates at an acceptable level of agreement to paired samples of core body temperature using rectal thermistors.[29] The athletes were also instructed to consume water in the amount of 5.5 $mL \cdot kg^{-1}$ of body mass the evening before as well as the morning of their exercise/cooling trials in an attempt to ensure that all participants arrived at the laboratory in similar states of hydration.

Heating Protocol

The participants reported to the laboratory on the morning of their trial after eating their typical breakfast and consuming fluids as directed. A baseline core temperature (T_c) was recorded before the heating protocol began to verify that the sensor was in the intestines and was providing an accurate temperature reading and to confirm a normal resting core temperature (approximately 37°C). Each person provided a urine sample that was immediately analyzed via refractometry to ensure euhydration (urine specific gravity [USG] $\leq$1.025)[30] and was fitted with a heart-rate (HR) monitor (Polar, Lake Success, NY). The participant, dressed in shorts, socks, T-shirt, and running shoes, entered the climatic chamber and sat for 10 minutes to acclimate to the environment (ambient temperature = approximately 39°C and relative humidity = approximately 40%). He then performed a dynamic exercise protocol, alternating between riding a stationary bicycle for 10 minutes and walking/running on a treadmill with a 2% incline for 10 minutes until he reached the target T_c of 39.5°C or volitional exhaustion. *Volitional exhaustion* was defined as the inability to continue exercising at the predetermined intensity or when any signs or symptoms of heat-related stress such as dizziness or syncope occurred. The participant's HR was continuously monitored throughout the exercise bout to ensure that he exercised at an intensity that resulted in an HR of 70% to 75% of his age-predicted maximum. We were aware that the CCs were more aerobically fit and exercised on the treadmill at a slightly higher speed compared with the FBs. However, we chose this biking and treadmill protocol (which we had used previously) in an attempt to minimize the number of FBs who stopped exercise due to exhaustion before reaching the target core temperature (T_{gi}). The participants were allowed to drink water ad libitum (not quantified) during the heating trial but were neither encouraged to consume nor discouraged from consuming fluids. The fluids were cold at the beginning of the trial but were kept in the hot and humid climatic chamber and therefore warmed during the exercise bout. The T_{gi}, HR, and environmental readings were recorded every 5 minutes while the participants were inside the chamber.

Cooling Protocol

The participant exited the climatic chamber upon reaching the desired T_{gi} or volitional exhaustion and immediately walked to an adjacent locker room area (ambient temperature about 21°C) where the cooling tubs were located. He toweled himself dry and removed the HR monitor as well as his shoes, socks, and T-shirt, after which he was submerged (wearing shorts only) in a 10°C circulated cold tub to a level just above the clavicles. Each participant was submerged in the cold tub less than 3 minutes after exiting the chamber. He remained submerged until T_{gi} declined to 37.5°C, at which time he exited the cold tub. The T_{gi} was recorded just before submersion and then once every minute while the participant was in the cold tub. Special care was taken to continuously circulate the water in the tubs (using manual stirring) during the cooling protocol. In addition, we used 2 different-sized tubs (566-L tub for FBs and 378-L tub for CCs) in an attempt to match the volume of cold water to the groups' body sizes so that the percentages of water surrounding the participants were similar. When the participant reached the cooling target of 37.5°C, he exited the tub and was immediately wrapped in blankets. He walked to the laboratory, where he remained until he maintained a core temperature of $\geq$37°C for several minutes and was comfortable removing the blankets, after which he was dismissed.

The participants reported within 1 week of their experimental trial for subsequent measurements of height, weight, and body composition. Height was measured to the nearest centimeter using a standard laboratory stadiometer. Body composition including total body mass, LBM, and percentage of body fat was measured via air displacement plethysmography. This was done using a BodPod body composition tracking system (Cosmed, Chicago, IL) that was calibrated by a Cosmed service manager 2 months before the assessments. The BSA was estimated as per Dubois and Dubois.[31]

Statistical Procedures

We applied a general linear model repeated-measures analysis of variance to the core temperature data for the first 7 minutes of cooling (when the first participant was removed from the CWI) to determine whether differences existed in absolute core temperature over time for that period. Independent *t* tests were performed to evaluate group differences in the dependent variables of actual time (minutes) to reach 37.5°C, *cooling rate* (defined as the change in T_{gi}/time), and slope of the lines representing the change in core temperature over time. Calculating the slope of the lines for cooling allowed the use of every core temperature data point for every participant over the entire time it took to cool each person to 37.5°C. Independent *t* tests were also used to evaluate group differences in all physical characteristics and pre-exercise USG as well as the environmental conditions in the climatic chamber and the water temperature in the cooling tubs. Pearson correlations were conducted to assess relationships between cooling rate

Table 2. Time of Cooling to Reach 37.5°C and Cooling Rate (°C per Min)

	Football Linemen (n = 9)	Cross-Country Runners (n = 7)	P Value
	Mean ± SD		
Baseline core temperature, °C			
Precooling	39.13 ± 0.4	39.39 ± 0.14	.12
Postcooling	37.5 ± 0.03	37.5 ± 0.1	.30
Time of cooling, min	11.4 ± 3.9	7.7 ± 1.8	.04
Cooling rate, °C/min	0.156 ± 0.06	0.255 ± 0.05	.002

($°C{\cdot}min^{-1}$) and the following factors: total body mass (kg), BSA (m^2), LBM (kg), LBM/mass (%), body fat (%), BSA/mass, and BSA/LBM (both in $cm^2{\cdot}kg^{-1}$). Statistical analyses were performed using SPSS (version 21; IBM Corp, Armonk, NY), and the level of significance was set at $P < .05$.

RESULTS

Heating Protocol Data

The climate chamber conditions did not differ between the FB and CC trials. Ambient temperature and relative humidity in the chamber were 39.7°C ± 0.7°C and 42.2% ± 13.6% for FBs and 39.3°C ± 1.2°C and 36% ± 18.7% for CCs. There were also no differences in water temperature of the circulated cold tubs (FBs = 10.3°C ± 0.47°C, CCs = 10.3°C ± 0.27°C; $P = .98$). The USG was not different between groups (FBs = 1.022 ± 0.004, CCs = 1.023 ± 0.006), indicating a similar level of hydration before the heating protocol. Mean HR did not differ between the groups during the exercise/heating trial (FBs = 145.1 ± 15 and CCs = 148.2 ± 7.8 beats/min), but the time to reach the target 39.5°C T_c was different (FBs = 73.3 ± 11 minutes, CCs = 61.3 ± 9.4 minutes; $t_{8,6} = 2.32$, $P = .036$).

Cooling Data

No differences were present between T_{gi} before ($t_{14} = -1.65$, $P = .12$) or after ($t_{14} = 1.07$, $P = .30$) cooling, as shown in Table 2. Of the 16 participants, 8 (5 FBs and 3 CCs) did not reach the T_{gi} of 39.5°C due to volitional exhaustion. The maximal core temperatures ranged from 38.95°C to 39.6°C in FBs and 39.2°C to 39.7°C in CCs. The general linear model repeated-measures analysis of variance revealed a difference in T_{gi} during cooling over time ($F_{1,6} = 111.4$, $P < .000$) and a significant interaction ($F_{1,6} = 12.8$, $P = .001$). Cooling over time as determined by the slope of each line differed between groups (FBs = –0.1661 ± 0.054, CCs = –0.2597 ± 0.057; $t_{14} = 3.14$, $P = .007$). These data depicting mean core temperature during cooling over time, as well as individual data from each participant, are shown in the Figure. The time to reach 37.5°C (Table 2) was different between the FBs (11.4 ± 3.9 minutes) and CCs (7.7 ± 1.8 minutes; $t_{14} = 2.17$, $P = .04$). More important, the cooling rate was also different for the FBs ($0.156°C{\cdot}min^{-1} \pm 0.06°C{\cdot}min^{-1}$) versus the CCs ($0.255°C{\cdot}min^{-1} \pm 0.05°C{\cdot}min^{-1}$; $t_{14} = -3.64$, $P = .002$), as indicated in Table 2.

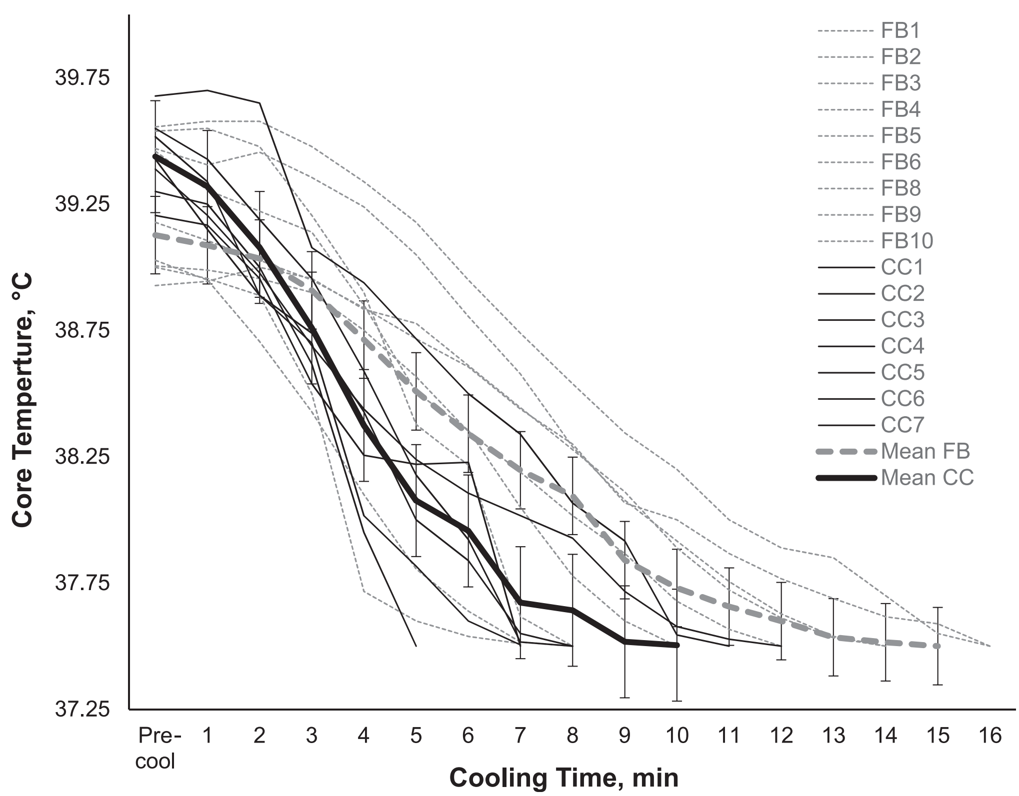

Figure. Core temperature during cooling for all 16 participants (9 football linemen [FBs] and 7 cross-country runners [CCs]) and the group means. The slope of the line for the FBs (–0.1661 ± 0.054) was different from that for the CCs (–0.2597 ± 0.057, $P = .007$).

Table 3. Correlations Between Cooling Rate and Physical Characteristics

Cooling Rate (°C/min)	*t* Value	*r* Value	*P* Value
Mass, kg	−4.39	−0.76	<.001
BSA, m^2	−4.14	−0.74	<.001
BSA/mass, cm^2/kg	4.02	0.73	<.001
LBM/mass, %	3.93	0.72	<.002
LBM, kg	−3.83	−0.72	<.002
Body fat, %	3.10	−0.64	<.008
BSA/LBM, cm^2/kg	2.05	0.48	.06

Abbreviations: BSA, body surface area; LBM, lean body mass.

Correlations

We noted significant and strong correlations between the rate of cooling and total body mass ($r = -0.76$, $P < .001$), total BSA ($r = -0.74$, $P < .001$), BSA/mass ($r = 0.73$, $P < .001$), LBM/mass ($r = 0.72$, $P < .002$), LBM ($r = -0.72$, $P < .002$), and percentage of body fat ($r = -0.64$, $P < .008$). The moderate correlation with BSA/LBM did not reach significance ($r = 0.48$, $P = .06$). These data are shown in Table 3.

DISCUSSION

This investigation has significant clinical value because no authors, to our knowledge, have investigated competitive football players (at any level) as participants in a cooling study after exercise-induced hyperthermia. Our results yielded 3 important findings: (1) it took more time to cool large FBs, which means they would need to be submerged for a longer period of time (on average >32% longer), compared with smaller athletes such as lean CCs, (2) cooling rates varied considerably, which supports the need for monitoring rectal temperature while cooling, and (3) CWI (10°C) produced an ideal cooling rate, on average, in large FBs.

The Effect of Body Size and Composition on Cooling Rate

The rate of nonevaporative cooling in humans depends on the conductivity of the tissue (muscle, adipose, and skin) and the surface area through which heat can be exchanged with the environment. Therefore, the factors most responsible for causing variations in cooling rate are related to differences in body size and composition. Specifically, these factors are total body mass (mass), which includes both LBM and adipose tissue, total BSA, and BSA/mass. The ratio of BSA to LBM could also play a role.[24–26] By design and for clinical relevance, our groups differed considerably in all of these aspects. This not only makes it difficult to identify the most important factors responsible for the large dissimilarities found in cooling rates, but it also hinders the ability to compare our results with those of studies in which the physical differences between groups were not as great. In making comparisons with similar cooling studies, it should also be noted that we used ingestible (intestinal) sensors and not rectal thermistors, although both are reliable measures of core temperature and intestinal temperature is a valid measure of rectal temperature.[29,32]

Lemire et al[25] studied the effect of adiposity on cooling efficiency after exercise-induced hyperthermia using CWI (2°C) and found no difference in cooling rates between participants with similar LBM but with either a low body fat percentage (LF = 12.9%) or a high body fat percentage (HF = 22.3%). Friesen et al[24] compared cooling rates in participants who had either a high or low BSA/LBM; the high BSA/LBM group cooled at a faster rate during immersion in both cold (2°C) and temperate (26°C) water. The group with a high BSA/LBM also had more body fat (20%) compared with the low BSA/LBM group (13%), which suggests that the cooling rate was determined more by BSA/LBM than adiposity.[24] Our data differed from the findings of these studies, indicating that body fat percentage may have contributed to the difference in cooling rate between our groups, given that the correlation between these 2 factors was strong (–0.66). However, the difference in body fat percentage between the lean CCs (10.2%) and the FBs (28.9%) was considerably greater than for the LF (13%) and HF (22%) groups in the Lemire et al study[25] and the low BSA/LMB (about 13%) and high BSA/LBM (about 20%) groups in the study by Friesen et al.[24] In addition, our FB group, who cooled at a slower rate than the CC group, had a lower BSA/LBM but a higher body fat percentage, which suggests that differences in cooling cannot entirely be explained by either of these factors.

With regard to body composition, it is important to note that our groups not only differed extensively in percentage of body fat but also in percentage of LBM to mass (LBM/mass), whereas the group differences in LBM/mass were not as drastic in other studies.[24–26] We found a strong correlation between LBM/mass and cooling rate ($r = 0.72$), which was considerably different between our groups, with CCs having a notably higher LBM/mass (90%) compared with the FBs (73%). Freisen et al[24] specifically focused on cooling rates in groups divided into high or low BSA/LBM. Their high BSA/LBM group, which cooled at a faster rate, had a lower LBM/mass (78.5%) compared with their low BSA/LBM group (89%). Our CC participants, who had a higher BSA/LBM and a faster cooling rate, actually had a considerably higher LBM/mass (90%) compared with our FB players (<73%). This may indicate that the key factors in cooling could simply be BSA and total body mass as described in normothermic individuals.[33]

In a separate investigation, Lemire et al[26] compared sex differences in rectal cooling rates using CWI at 2°C after exercise-induced hyperthermia and found that the women with less body mass (64.2 ± 9.3 kg versus 73.6 ± 9.4 kg) and less lean body mass (48.4 ± 4.5 kg versus 63.4 ± 7.2 kg) cooled at a faster rate than men. The women and men were matched for BSA/mass, but the women had a higher body fat percentage (23.9% versus 13.8%). When combining the men's and women's results, Lemire et al noted the highest correlation between cooling rate and BSA/LBM ($r = 0.70$, $P < .001$). Our correlation between these factors was not strong ($r = 0.48$) and did not reach significance ($P = .06$). However, we found strong correlations between cooling rate and total body mass ($r = -0.76$), cooling rate and BSA ($r = -0.74$), and therefore, between cooling rate and BSA/mass ($r = 0.73$). As reported by Lemire et al,[26] their participants did not reflect a large range of possible values for BSA/mass, but our participants clearly did. The BSA/mass was only 170.6 cm^2·kg^{-1} in our largest FB but 281.3 cm^2·kg^{-1} in the smallest CC. Overall, our data suggest that total body mass and BSA, and the combination of the 2 (BSA/mass), showed the strongest relationships to the difference in cooling rates between the groups.

It should be noted, however, that both LBM and total body mass likely played an important role in the continued rise in T_{gi} in the FBs after they ceased exercise and exited the climatic chamber. Whereas 4 of the FBs continued to experience a rise in T_{gi} during the few minutes between the end of exercise and submersion in the cooling tub, and several still had small increases in T_{gi} even during the first minute of active cooling, only 1 CC experienced this phenomenon. This may reflect not only a lower rate of heat dissipation but continued heat production postexercise in the FBs, who had considerably higher LBM (87 kg) compared with the CCs (62 kg). The continued rise in T_{gi} in several FBs could also reflect their longer exercise time.

Group Comparisons of Cooling Rate

The second major purpose of this study was to determine whether immersion in 10°C water would produce an ideal cooling rate for large American-football linemen who were hyperthermic due to exercise in the heat. *Category A* (ideal cooling) is defined as a cooling rate greater than $0.155°C \cdot min^{-1}$, whereas *category B* (acceptable cooling) is defined as a cooling rate between $0.078°C \cdot min^{-1}$ and $0.155°C \cdot min^{-1}$.[17] In a controlled field study, Clements et al[20] found no difference in cooling rates ($0.16°C \pm 0.01°C \cdot min^{-1}$) between CWI (14°C) and ice-water immersion (5°C) in hyperthermic runners. Their participants' mean precooling rectal temperature (approximately 39.55°C) was similar to that of our CCs, who experienced a considerably higher cooling rate ($0.255°C \cdot min^{-1}$) compared with the FBs. Although their participants were nearly identical in size (68.5 ± 2.1 kg) and body fat percentage (11.2% ± 1.3%) to our CC group, the researchers only immersed the torso (shoulders to hips) of the runners, which could account for the slower cooling rate due to less BSA for nonevaporative heat loss. In a field study during an actual 11.5-km road race, Armstrong et al[16] reported a cooling rate of $0.20°C \cdot min^{-1}$ in hyperthermic runners with a mean precooling rectal temperature of 41.7°C who were immersed (torso and thighs) in ice water that was 1°C to 3°C. This cooling rate was slightly lower than what we found in our hyperthermic CC group; however, the runners in the Armstrong et al investigation had considerably higher precooling rectal temperatures and were not fully immersed in the water, which could account for the small differences in cooling rates between these studies.

The cooling rate of $0.255°C \cdot min^{-1}$ in our CCs who were completely immersed to their clavicles in 10°C water was expected and fell nearly midway between the cooling rates using ice-water immersion at 2°C and CWI at 20°C ($0.35°C \cdot min^{-1}$ and $0.19°C \cdot min^{-1}$, respectively) reported by Proulx et al.[34] This suggests that the colder the water used for full-body immersion, the faster the cooling rate. It is plausible that colder water (for example, ice water at 2°C) might produce a faster cooling rate for the larger football population, but this research is yet to be done.

McDermott et al[17] acknowledged that the lack of cooling information in the American-football population was a limitation in the current literature. In the systematic review, the 7 cooling studies meeting the inclusion criteria for the review included only athletes (primarily male endurance runners) who weighed between 68 and 84 kg.[16,20,34–36] Given the considerable differences we found (7.7 minutes or $-0.255°C \cdot min^{-1}$) for the small athletes already documented in the literature compared with the cooling time (11.4 minutes) and subsequent cooling rate ($0.156°C \pm 0.06°C \cdot min^{-1}$) for our FBs, this information is crucial for the practicing clinician who works with American football players. It is worth noting that the values of our National Collegiate Athletic Association Division II FBs appeared very similar in body size and, it is important to note, in the percentage of body fat (>25%) to those values reported by Noel et al[23] for Division I football players in 2003. They are also similar in body size and BSA/mass to linemen in the National Football League.[7]

A recently published study by Miller et al[37] showed that submerging hyperthermic participants to neck level in 10°C water resulted in a faster cooling rate ($0.28°C \cdot min^{-1}$) when the participants were clad in a full football uniform (football pants with knee, thigh, and tailbone pads, shoulder pads with a jersey, a helmet, and tennis shoes) in addition to what was considered the control uniform (undergarments, shorts, socks, T-shirt, and running shoes), which, when worn alone, yielded a cooling rate of $0.23°C \cdot min^{-1}$. Although the cooling rate was faster in those wearing the full football uniform, both conditions resulted in rates that were more similar to the cooling rate found in our CC group than that in our FB group. Again, this is likely due to body size because their participants (82.3 ± 12.6 kg, body fat = 13% ± 4%) were more physically matched to our CC group (68.7 kg and 10.2% body fat) than to our FB group (128 kg and about 29% body fat). Probably more important, the BSA/mass of their participants was approximately 243 $cm^2 \cdot kg^{-1}$, which was closer to our CC group (268 $cm^2 \cdot kg^{-1}$) than to our FB group (201 $cm^2 \cdot kg^{-1}$). This again points to the fact that total body mass, BSA, and, as a consequence, BSA/mass are the most critical determinants of cooling-rate differences between smaller individuals and very large athletes such as American-football players.

A survey of high school athletic trainers who have treated EHS in football players showed that only 2% actually used rectal temperatures to assess and monitor core temperature, although 68% of those surveyed who had not treated EHS said they would monitor rectal temperature.[38] This is unfortunate and does not comply with current recommendations and standards of best practice.[4] This study clearly shows that the time it takes to cool a large football lineman is considerably different than the time required to cool a smaller athlete, indicating that rectal temperature must be used to monitor changes in core temperature during cooling.[4] We found a significant and clinically relevant group difference with only a 2°C drop in core temperature (39.5°C to 37.5°C), which means the differences in cooling rates could be much larger if the cooling is begun at a higher core temperature (40°C to 42°C), as is typical with EHS. Data from this study of actual football players are timely in light of the most recent National Athletic Trainers' Association position statement on exertional heat illnesses, which states, "Although cooling rates may vary, the cooling rate for CWI will be approximately $0.2°C \cdot min^{-1}$ ($0.37°F \cdot min^{-1}$) or about 1°C every 5 minutes (or 1°F every 3 minutes) when considering the entire immersion period from postcollapse to 38.98°C (102°F)."[4] Unfortunately, until this study, there were no published data on cooling rates of CWI in football linemen. It is remarkable that the cooling rates of our 16 participants, using identical methods and water temperatures, ranged from 0.332°C·min^{-1} in a 63-kg runner to only 0.101°C·min^{-1} in a 124.5-kg lineman. Therefore, clinicians who are working with football (the one sport in a traditional setting most likely to be associated with EHS[15]) must not count on a specific cooling rate (ie, 0.20°C·min^{-1}) when using CWI at 10°C to treat a large player thought to have EHS but rather should rely on the actual measurement of rectal temperature. We suspect this would be true regardless of whether the athlete is submerged while still wearing his full football uniform or not.[37]

Using ice-water immersion or CWI (between 2°C and 10°C) as a treatment for cooling hyperthermic athletes of average size generally exceeds the category A ideal cooling rate (≥0.155°C·min^{-1}).[17] Cold-water immersion at 10°C resulted in a cooling rate of 0.255°C·min^{-1} in our CCs, which supports data from a similar laboratory study[34] in which participants who weighed 68 kg were fully immersed to their clavicles in 8°C or 2°C water, resulting in cooling rates of 0.19°C·min^{-1} and 0.35°C·min^{-1}, respectively. In our CCs, the mean time to reach 37.5°C was 7.7 minutes, and all of the athletes cooled to that target temperature by 11 minutes. Although the cooling rate was still ideal, the large FBs had a significantly slower rate (0.156°C·min^{-1}), with the mean time to reach 37.5°C being about 11 minutes. To reach the target cooling temperature of 37.5°C, several players required 14 minutes and 1 lineman required nearly 16 minutes.

Some research indicated that it is not necessary to cool hyperthermic athletes to a "normal" body temperature but more prudent to remove them from active cooling at a temperature between 38°C and 38.6°C.[39,40] Yet again, these recommendations are drawn from cooling data of average-sized individuals in whom hypothermic "afterdrop" is a concern.[40] This leads to an important limitation of our study. Unfortunately, we did not continue to record minute-by-minute data on each participant's core temperature after he exited the cold tub. However, anecdotal observations indicated that the CCs experienced a hypothermic afterdrop, whereas the FBs did not. Although only 1 of the FBs (the smallest lineman) required active rewarming after the CWI, nearly all of the CCs did, with one reaching a hypothermic level of 35.5°C.

It is crucial to note that even though exercise intensity as measured by HR was similar between the groups, it took the FBs significantly longer to reach the T_{gi} or volitional exhaustion. This may be explained by the significantly smaller LBM/mass, which was only 73% in the FBs but 90% in the CCs, and likely resulted in a lower rate of heat production at a given exercise intensity. Deren et al[21] noted a similar trend when comparing the sweat rates of large football linemen with those of small players (backs and receivers). Despite the lack of statistical significance, they reported a lower rate of heat production (as measured by metabolic heat production minus work) in the linemen (323 ± 21 W·m^2) compared with smaller backs and receivers (343 ± 31 W·m^2). They kept metabolic heat production fixed by unit surface area because they were most interested in factors related to heat dissipation, but this resulted in the linemen having significantly less (>25%) metabolic heat production per mass (6.0 versus 8.2 W·kg^{-1}) compared with the smaller players.[21] In our study, it is possible that the slightly lower mean HR in the FBs during the exercise/heating protocol, although not significant, may have also contributed to a longer exercise time period.

As with all laboratory investigations of hyperthermia, another limitation of our study was that we did not induce EHS in any of our participants. We successfully induced hyperthermia in all participants, but none exhibited signs or symptoms of EHS. Therefore, it is not known whether these cooling rates reflect what would actually occur in an athlete who was in a hypermetabolic state, as documented in those with EHS episodes.[18] Additional limitations include the fact that, although not significant, there was a 0.26°C difference between groups at precooling. We do not believe this affected our results, given that DeMartini et al[41] showed that cooling rates in mildly hyperthermic participants (38.73°C) using CWI at 14°C were comparable with those in other studies. We also did not assess skin temperature throughout the study and did not record the onset of shivering or shivering intensity, which could have assisted in the interpretation of our findings.

CONCLUSIONS

As expected, the larger FBs took considerably longer to cool (>11 minutes) than the CCs did (about 7.5 minutes), which is supported by the correlations between total body mass (r = –0.76), total BSA (r = –0.74), BSA/mass (r = 0.73), and the subsequent cooling rates of our groups. Although using CWI at 10°C resulted in a faster cooling rate in the smaller CCs (0.255°C·min^{-1}) compared with the FBs (0.156°C·min^{-1}), both rates fell into the ideal category for cooling. Cooling times for individuals exhibiting signs and symptoms of EHS should not be based on a given cooling rate (for example, ≥0.2°C·min^{-1}) but rather on monitoring rectal temperature, because the cooling times for different athlete populations can be substantially different.

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