Int J Biometeorol (2014) 58:1919–1925
DOI 10.1007/s00484-014-0794-8

ORIGINAL PAPER

Fan-precooling effect on heat strain while wearing protective clothing

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Received: 28 May 2013 / Revised: 7 January 2014 / Accepted: 12 January 2014 / Published online: 28 January 2014

Abstract This study compared heat strain during walking while wearing impermeable protective suits between fan-precooling and nonprecooling conditions. Six males engaged in 60 min of walking at a moderate speed (~2.5 km/h) in a hot environment (37 °C, 40 % relative humidity). Fanning using a fan (4.5 m/s) and spraying water over the body before wearing the suits produced significantly lower rectal temperature before the walking (37.3±0.1 °C vs. 37.0±0.1 °C, P<0.05). In addition, whilst walking, rectal temperature was significantly lower in the precooling condition (maximum difference: 0.4 °C at 15 min of walking; 38.0±0.1 °C vs. 37.8±0.1 °C at the end of walking, P<0.05). Although skin temperature decreased during fanning, no difference was observed during walking. Heart rate was lower in the precooling condition during the early stages of walking. Thermal and fatigue perceptions whilst walking did not differ between the conditions. Body weight loss was significantly lower in the precooling condition. These results may indicate that fan precooling attenuates exertional heat strain while wearing impermeable protective clothing. The fan-cooling method is practical, convenient, and yields lower heat strain during prolonged moderate exertion.

Keywords Precooling · Protective clothing · Core temperature · Heat strain

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Introduction

Protective clothing designed for workers who are exposed to hazardous materials must defend against various agents (primary purpose), as well as provide a microenvironment that optimizes the physiological status of the wearer (secondary purpose). However, the elevation in the rate of the production of metabolic heat during working, combined with high ambient temperatures and humidity, can lead to progressive increases in body heat content. Because heat dissipation is inhibited by the restrictive clothing (Kraning and Gonzalez 1991), prolonged working may lead to heat illness and eventually death.

Precooling (i.e., removal of heat from the body immediately prior to exercise) is a popular strategy for improving exercise performance in hot conditions. This is based on a number of evidence that reducing the initial core temperature of the individual allows for greater heat storage capacity during exercise, which in turn prolongs the onset of hyperthermia-induced fatigue (Jones et al. 2012; Wegmann et al. 2012; Ross et al. 2013). Immersion in water (González-Alonso et al. 1999) and the application of iced garments to the skin (Arngrïmsson et al. 2004) are the strategies most commonly used to precool in sports activities. However, the supply of a large volume of water and ice in all occupational settings is not always possible, or practical.

Evaporative cooling using a fan and spraying water over the body has been shown to be effective in reducing core temperature (Mitchell et al. 2003). In that study, the effect of decreased core temperature persisted throughout an exhaustive running test performed in hot conditions. Although the precooled individuals wore only running shorts and maintained a lower skin temperature, it has never been proved that the same effects can be achieved while wearing restrictive clothing. Moreover, the precooled individuals exhibited a reduced time to exhaustion and reported heaviness in the legs

(Mitchell et al. 2003). In addition, they perceived increased thermal sensation and discomfort during a warm-up exercise performed after the precooling. Because wearing restrictive clothing would warm the precooled skin, those perceptual changes may disappear.

The purpose of the present study was to evaluate the effect of fan and water spraying precooling on thermal strain while wearing protective clothing in a hot environment. Because fanning-induced reduction in core temperature has been observed after the end of the fanning (Mitchell et al. 2003), we investigated how the effect of the precooling persists in a prolonged exercise test and whether thermal and fatigue perceptions were modulated by the precooling.

Methods

Participants Six healthy men volunteered for the present study. The general characteristics of the subjects were: age, 41.3±4.8 years; height, 171.5±5.5 cm; and body mass, 59.6±6.9 kg (mean ± SD). The participants were informed of the experimental procedures and potential risks and provided a signed consent form. All experimental procedures were approved by the Human Research Ethics Committee of the National Institute of Occupational Safety and Health. The study was conducted in accordance with the guidelines of the Helsinki Declaration.

Experimental protocols The volunteers performed one accommodation trial and two experimental trials on three consecutive days, the second and third in a balanced order. The experimental trials consisted of two conditions: a pre-exercise fan-cooling trial (FAN) and a nonprecooling control trial (CON). The volunteers refrained from consuming any beverages containing caffeine or alcohol from the night before the day of the experiment. They ate a light breakfast 3 h before the experiment and reported to the laboratory. After drinking 200 ml of water and completely voiding, each volunteer entered an environmental chamber set at an ambient temperature of 28 °C with 40 % relative humidity (RH). They wore only undershorts at the time. This situation is within the neutral range of autonomic thermoregulation and thermal comfort (Fanger 1970; Gagge et al. 1967; Hardy and Stolwijk 1966). No water was provided until the end of the experiment. During a 30-min rest period, rectal and skin thermistor probes were attached, and baseline measurements were obtained in a seated position. After the 30-min baseline period, participants continued to rest for 30 min with (FAN) or without (CON) fanning (precooling period). In FAN, the volunteers sat with their anterior surface closest (within 0.5 m) to two fans (one on top of another, 1.3-m height). The diameter of each fan was 0.45 m, and the airspeed was approximately 4.5 m/s. In addition, the water within a heat chamber was sprayed continuously from a handheld sprayer over the volunteers' entire body (head to feet). The spraying was frequently conducted before the water on the skin's surface dried up. After 30 min of fanning and spraying, the water was wiped off from the skin, and then the volunteers put on a round-necked T-shirt with long sleeves, long underwear, cotton gloves, rubber gloves, socks, work shoes, high-density polyethylene coveralls (Tyvek®, DuPont, Wilmington, USA), a full-face gas mask, and a helmet. Their shoes and gloves were also covered with impermeable polyethylene covers that were taped outside the ankle and wrist of the suit to ensure that no gaps would be present. The volunteers finished putting on their clothes and gear within 10 min and rested for 5 min.

The volunteers moved to a heat chamber (37 °C ambient temperature, 40 % RH) and remained seated for 5 min. After rating their perceptions, they performed a shuttle walk (back and forth along a distance of 7 m in 10 s) for 30 min. Following a 10 min break, they walked again for 30 min. During the break, the volunteers remained seated in the heat chamber. In addition, they stopped walking for 30 s every 10 min, to rate their perceptions in a standing position. These protocols and settings were chosen as patrol work in a hazardous area in summer in Japan. The workers put on protective clothing in a preparatory room, which controls 28 °C or less, and move outside at the highest temperature of 37 °C.

Measurements Rectal temperatures (T_{rec}) were measured continuously at intervals of 1 min using a thermistor probe (701 J, Nikkiso-thermo, Tokyo, Japan) self-inserted 10 cm beyond the rectal sphincter. Skin temperatures were also continuously monitored using thermistor probes (LT-ST08-00, Gram Corporation, Saitama, Japan) placed on the chest and lateral sides of the thigh and finger. Heart rate (HR) was recorded using an HR monitor (Polar RS800CX, Polar Electro, Kempele, Finland) (HR was not recorded during the precooling). The ratings of thermal sensation were based on categorical scales that ranged from −4 to 4 (nine-point scale: −4 "very cold," −3 "cold," −2 "cool," −1 "slightly cool," 0 "neutral," 1 "slightly warm," 2 "warm," 3 "hot," and 4 "very hot"). Regarding thermal pleasantness, values ranged from −3 to 0 (four-point scale: −3 "very unpleasant," −2 "unpleasant," −1 "slightly unpleasant," and 0 "neutral"). Ratings of physical and psychological fatigue were based on values that ranged from 0 to 4 (0 "not fatigued," 1 "slightly fatigued," 2 "fatigued," 3 "very fatigued," and 4 "extremely fatigued"). Body weight measurements were obtained with subjects wearing undershorts before and after the experiment.

Statistics A two-way analysis of variance (ANOVA) with repeated measures (using trial and time as main effects) was performed. If a significant F value was observed, Fisher's least significant difference (LSD) post hoc test was performed to verify the difference at a specific time point. The null hypothesis was rejected at $P<0.05$. All analyses were carried out using the StatView 5.0 software (SAS Institute, Cary, NC). Values were expressed as means ± SEM.

Results

T_{rec} remained unchanged in the precooling period in both CON and FAN (Fig. 1). In FAN, T_{rec} decreased 10 min after the end of the fanning and remained low until 20 min after the beginning of the walking ($P<0.05$). T_{rec} was greater at 50 min after the onset of walking than it was at the baseline in FAN ($P<0.05$). In CON, T_{rec} increased significantly from 25 min after the onset of walking ($P<0.05$). T_{rec} was lower in FAN than in CON from 10 min after the end of the fanning to the end of the walking ($P<0.05$). Skin temperatures in the chest, thigh, and finger decreased during the precooling in FAN and were significantly lower than those recorded in CON ($P<0.05$; Fig. 2). Skin temperatures were greater during the walking than they were at the baseline in both trials. No significant differences in skin temperature were observed between the trials. HR was lower in FAN from 15 min after the onset of walking to the end of the half-time break ($P<0.05$; Fig. 3). Thermal sensation and physical and psychological fatigue were increased ($P<0.05$), whereas thermal pleasantness was decreased ($P<0.05$), during the walking (Fig. 4). None of the rating scores differed between the trials. Percentage reduction in body weight after the walking was greater in CON than in FAN (1.56 %±0.13 % vs. 1.22 %±0.07 %, $P<0.05$). Because no sweating was apparent during the resting phase, the reduction was mostly due to the walking in the heat chamber.

Discussion

We compared thermal strain during walking while wearing protective clothing between fan-precooling and nonprecooling conditions and found that fanning-induced reduction in rectal temperature continued during two subsequent 30 min walking periods. No significant difference was observed in skin temperature or thermal and fatigue perceptions.

The largest difference in T_{rec} between FAN and CON was approximately 0.4 °C, which is comparable to the results of a previous study that used a fan-precooling maneuver (Mitchell et al. 2003). In addition, the "afterdrop" phenomenon, which consists in the greatest decline in core temperature and appears a little later than the cooling period (Glaser 1949; Lee and Haymes 1995; Mitchell et al. 2003; Savard et al. 1985; Webb 1986), was also observed in the present study. The lowest T_{rec} was recorded 25 min after the end of the fanning (Fig. 1), while the subjects were wearing protective clothing, moving into the heat environment, and starting to walk. In the study performed by Mitchell et al. (2003), which consisted in an exhaustive run test that was performed while wearing only shorts, fanning-induced decreases in core temperature coincided with a reduction in skin temperature throughout the exercise. Wearing protective clothing after the fanning returned skin temperature to the initial value, and no difference between the trials was observed during the walking (Fig. 2). Therefore, regardless of clothing and skin temperature, the decline in core temperature induced by fanning may persist for at least 70 min after moderate exertion in hot conditions.

The afterdrop phenomenon seems to be explained by two mechanisms: the convection–circulation and conduction–

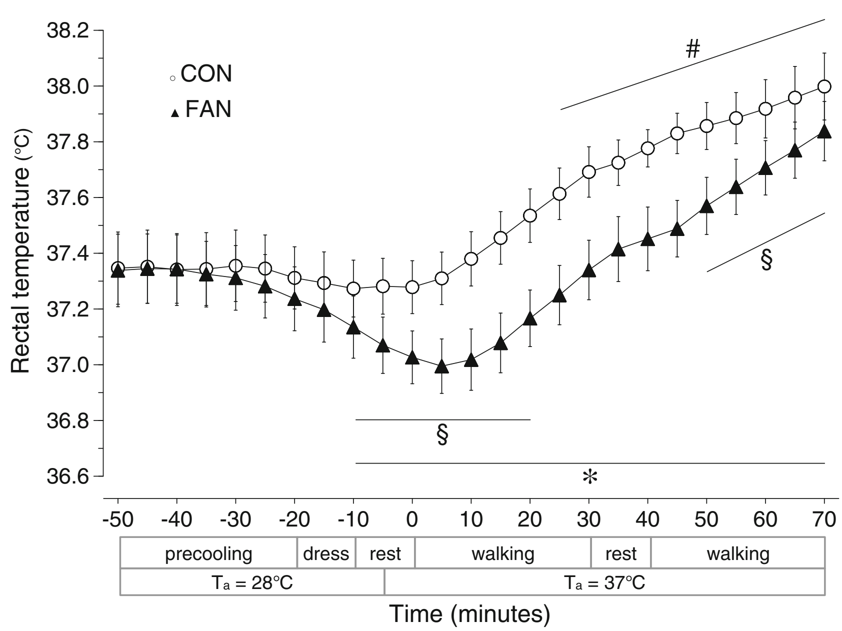

Fig. 1 Mean rectal temperature in the nonprecooling control (CON) and fan-precooling (FAN) trials. *Different ($P<0.05$) between CON and FAN; #different ($P<0.05$) from −50 min in CON; §different ($P<0.05$) from −50 min in FAN. Values are mean ± SEM (n=6). T_a, ambient temperature

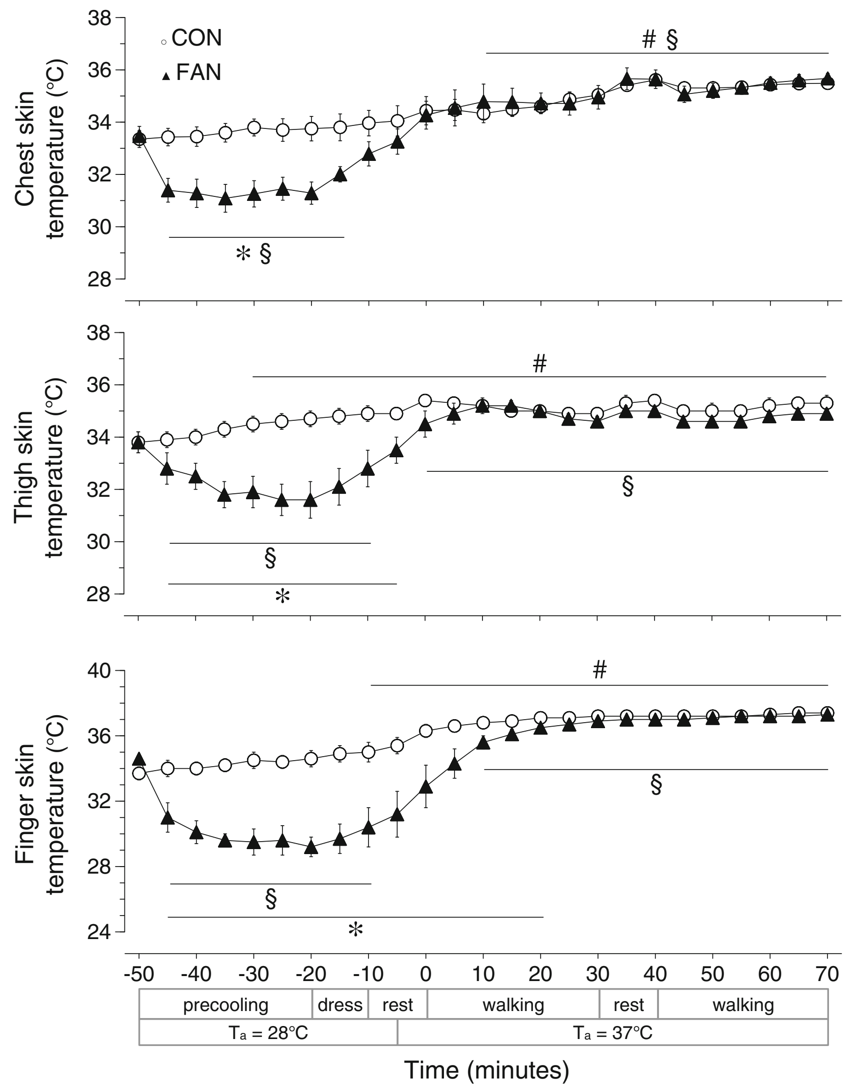

Fig. 2 Mean skin temperature on the chest, thigh, and finger in the nonprecooling control (CON) and fan-precooling (FAN) trials. *Different ($P<0.05$) between CON and FAN; #different ($P<0.05$) from −50 min in CON; §different ($p<0.05$) from −50 min in FAN. Values are means ± SEM (n=6). T_a, ambient temperature

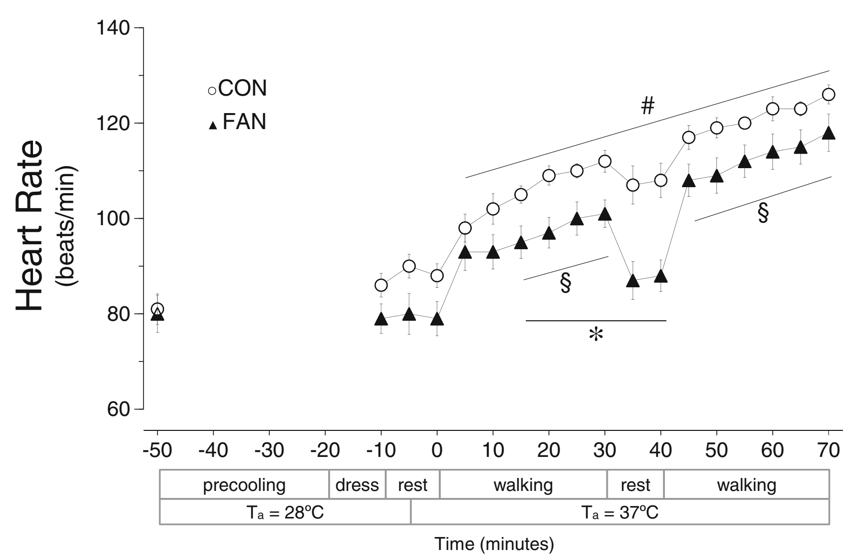

Fig. 3 Mean heart rate in the nonprecooling control (CON) and fan-precooling (FAN) trials. *Different ($P<0.05$) between CON and FAN; #different ($P<0.05$) from −50 min in CON; §different ($P<0.05$) from −50 min in FAN. Values are means ± SEM. T_a, ambient temperature (n=6)

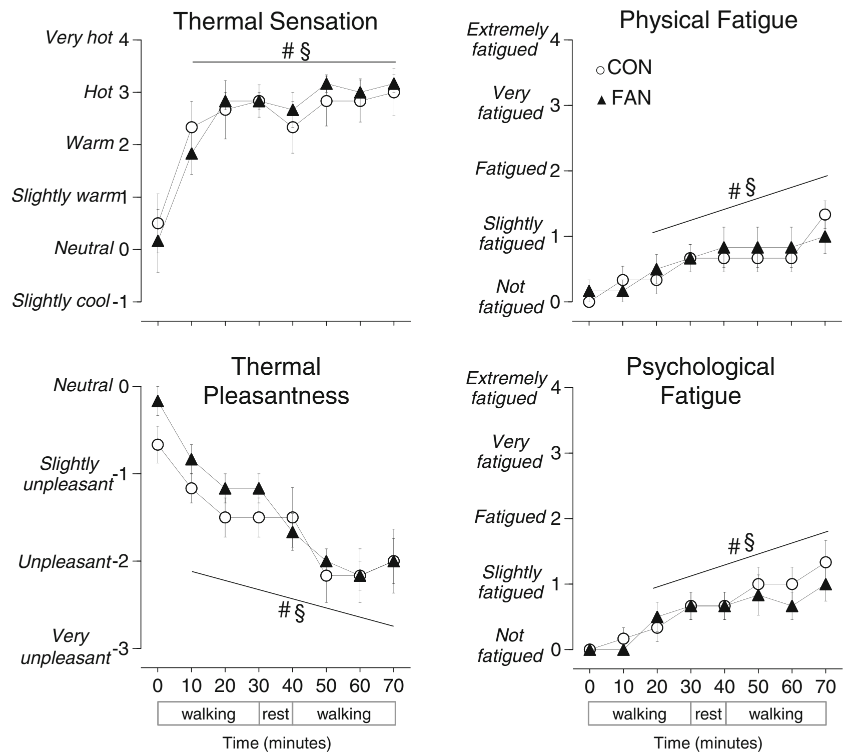

Fig. 4 Mean rating scores of thermal sensation and pleasantness and physical and psychological fatigue during walking in the nonprecooling control (CON) and fan-precooling (FAN) trials. #Different ($P<0.05$) from 0 min in CON; §different ($P<0.05$) from 0 min in FAN. Values are means ± SEM ($n=6$)

temperature gradient theories (Giesbrecht and Bristow 1992; Mittleman and Mekjavić 1988; Webb 1986). In the first theory, after the cooling procedures, enhanced surface circulation assists in transferring cooler blood from peripheral regions to the core, causing a reduction in core temperature. The second theory is based on the physical conduction of cold between the surface and core tissues. The relationship between the cooler superficial and warmer deep regions during cooling starts to reverse when the cooling stops and rewarming begins. In the present study, it remains unclear how each mechanism contributes to the afterdrop observed and how long the phenomenon lasts. The differences in T_{rec} between the trials were beginning to lessen during the second walking period. Although we could not evaluate the responses without walking after fanning, the deceased T_{rec} may begin to recover to the baseline from 1 h later.

After precooling, reduced HR has been reported during the early stages of prolonged exercise tests (Lee and Haymes 1995; Olschewski and Brück 1988; Schmidt and Brück 1981), as well as significant decreases in sweat loss (Duffield and Marino 2007; Hessemer et al. 1984; Olschewski and Brück 1988; Schmidt and Brück 1981; Sleivert et al. 2001). By estimating sweat loss from changes in body weight, our findings (including HR response; Fig. 3) were consistent with those of previous studies. A decreased core temperature may delay the onset of sweating and vasodilation in the skin for heat dissipation (Kruk et al. 1990). In this regard, fan precooling (with spraying) has an advantage in heat exertion while wearing protective clothing: prevention against hypohydration and lessening of cardiovascular strain, because protective clothing wearer cannot replace fluids.

Thermal and fatigue sensations were not different between the trials during walking (Fig. 4). The thermal perception evoked by thermal stimulation can be divided into two categories, “thermal sensation” and “thermal pleasantness” (Cabanac 1979; Cabanac 1971; Hensel 1981). Thermal sensation is the thermal information that pertains to external objects or the environment and is obtained only through the warm or cold receptors in the skin (Cabanac 1979). In contrast, thermal pleasantness is affected by information from the skin and body core temperature (Cabanac 1979). The reduction in T_{rec} in FAN did not induce a difference in thermal pleasantness between the trials, before and during walking. The decrease in core temperature (0.4 °C) may not have been sufficient to induce changes in thermal pleasantness, or the elevation in skin temperature would have become dominant in the perceptual change. There were no differences in the rating scores of fatigue sensations during walking between FAN and CON. Although some studies that included mid- to high-intensity exercise showed alternation in perceived exertion after precooling (González-Alonso et al. 1999; Mitchell et al. 2003), it seems unlikely that precooling-induced physiological changes affect physical and psychological fatigue sensations during moderate exercise.

Conductive cooling, for example, water immersion and use of ice products, is a common strategy for precooling (Ross et al. 2013). Convective and evaporative cooling by using a fan and spraying may be less effective in reducing core temperature than conductive cooling but would limit excessive skin vasoconstriction. The moderate temperature of air flow and sprayed water may promote heat transference from the body's core to the skin for dissipation (Weiner and Khogali 1980). Furthermore, the mild cooling can reduce the potential risk of "cold shock" that is generally accompanied by a sympathetic overdrive, responsible for inspiratory gasp, hyperventilation, hypocapnia, tachycardia, heart rhythm troubles, and hypertension (Datta and Tipton 2006). Workers who have cardiovascular and/or pulmonary problems could be encouraged to use the fan and spraying technique. And above all, a fan and spraying are easier logistically than using ice products and certainly much easier compared to water immersion for workers and organizers.

We recognize that there are potential limitations in the design of our study. Foremost, exercise and heat exertions were low level. Future study needs to examine whether the advantages of fan precooling are effective for more intense exertion and more hyperthermic condition. Second, although the exertion level was low, we should have separated the trials by more than few days. Regardless of the differences in core temperature, no perceptual advantages were shown in the present study. Because the evaluation of perceptions was subjective, sequential experimental days may influence the volunteer's assessment. Third, the sprayed water temperature and volume varied among the subjects. Although we attempted to keep the subject's skin continually moist by warm water spraying, it was estimated that the temperature ranged from 28 to 37 °C and the volume was from 100 to 300 ml. Fourth, physiological measurements conducted in the present study were limited. Data of sweat rate, skin blood flow, whole-body skin temperature, blood pressure, and oxygen consumption during the precooling and walking would be helpful in evaluating the potential mechanism of the cooling action. In addition, some kind of physical and psychological performance tests may be needed after the walking because fan precooling was found to reduce running time to exhaustion at VO_{2max} (Mitchell et al. 2003). Finally, although we could not measure the participants' fitness level, it was suggested that fitness level influences effectiveness of precooling treatment (Schmidt and Brück 1981). In order to be able to practically use fan precooling, it needs to be assessed how specific fitness affects the response to and effectiveness of fan precooling.

In conclusion, the present study demonstrated that fan cooling before walking in a hot environment while wearing impermeable protective suits leads to reduced heat strain during walking compared with the noncooling condition. Core temperature, heart rate, and hypohydration were reduced after precooling, whereas thermal and fatigue perceptions did not differ. This technique has a practical application in occupational settings: to reduce heat strain in hot environments. Future investigation should examine the effective duration of the fanning benefits, as well as the wind-speed effect on the inhibition of heat strain, for application in a variety of occupational and industrial settings.

Acknowledgement This study was financially supported by the GOHNET research of the National Institute of Occupational Safety and Health. The authors would like to thank Dr. Yasufumi Miyake, Dr. Jun Kanda, Dr. Yoshihiro Hagiwara, and Dr. Yohjiro Kashimura (Showa University School of Medicine) for their medical assistance.

References

Arngrïmsson SA, Petitt DS, Stueck MG et al (2004) Cooling vest worn during active warm-up improves 5-km run performance in the heat. J Appl Physiol 96:1867–1874

Cabanac M (1971) Physiological role of pleasure. Science 173:1103–1107

Cabanac M (1979) Sensory pleasure. Q Rev Biol 54:1–29

Datta A, Tipton M (2006) Respiratory responses to cold water immersion: neural pathways, interactions, and clinical consequences awake and asleep. J Appl Physiol 100:2057–2064

Duffield R, Marino F (2007) Effects of pre-cooling procedures on intermittent-sprint exercise performance in warm conditions. Eur J Appl Physiol 100:727–735

Fanger PO (1970) Thermal comfort. Analysis and applications in environmental engineering. McGraw-Hill, New York

Gagge AP, Stolwijk JA, Hardy JD (1967) Comfort and thermal sensations and associated physiological responses at various ambient temperatures. Environ Res 1:1–20

Giesbrecht GG, Bristow GK (1992) A second postcooling afterdrop: more evidence for a convective mechanism. J Appl Physiol 73:1253–1258

Glaser EM (1949) The effects of cooling and of various means of warming on the skin and body temperature of men. J Physiol 109:366–379

González-Alonso J, Teller C, Andersen SL et al (1999) Influence of body temperature on the development of fatigue during prolonged exercise in the heat. J Appl Physiol 86:1032–1039

Hardy JD, Stolwijk JA (1966) Partitional calorimetric studies of man during exposures to thermal transients. J Appl Physiol 21:1799–1806

Hensel H (1981) Thermoreception and temperature regulation. Academic Press, London

Hessemer V, Langusch D, Brück LK et al (1984) Effect of slightly lowered body temperatures on endurance performance in humans. J Appl Physiol 57:1731–1737

Jones PR, Barton C, Morrissey D et al (2012) Pre-cooling for endurance exercise performance in the heat: a systematic review. BMC Med 10:166

Kraning KK, Gonzalez RR (1991) Physiological consequences of intermittent exercise during compensable and uncompensable heat stress. J Appl Physiol 71:2138–2145

Kruk B, Pekkarinen H, Harri M et al (1990) Thermoregulatory responses to exercise at low ambient temperature performed after precooling or preheating procedures. Eur J Appl Physiol 59:416–420

Lee DT, Haymes EM (1995) Exercise duration and thermoregulatory responses after whole body precooling. J Appl Physiol 79:1971–1976

Mitchell JB, McFarlin BK, Dugas JP (2003) The effect of pre-exercise cooling on high intensity running performance in the heat. Int J Sports Med 24:118–124

Mittleman KD, Mekjavić IB (1988) Effect of occluded venous return on core temperature during cold water immersion. J Appl Physiol 65: 2709–2713

Olschewski H, Brück K (1988) Thermoregulatory, cardiovascular, and muscular factors related to exercise after precooling. J Appl Physiol 64:803–811

Ross M, Abbiss C, Laursen P et al (2013) Precooling methods and their effects on athletic performance: a systematic review and practical applications. Sports Med 43:207–225

Savard GK, Cooper KE, Veale WL, Malkinson TJ (1985) Peripheral blood flow during rewarming from mild hypothermia in humans. J Appl Physiol 58:4–13

Schmidt V, Brück K (1981) Effect of a precooling maneuver on body temperature and exercise performance. J Appl Physiol 50:772–778

Sleivert GG, Cotter JD, Roberts WS, Febbraio MA (2001) The influence of whole-body vs. torso pre-cooling on physiological strain and performance of high-intensity exercise in the heat. Comp Biochem Physiol A Mol Integr Physiol 128:657–666

Webb P (1986) Afterdrop of body temperature during rewarming: an alternative explanation. J Appl Physiol 60:385–390

Wegmann M, Faude O, Poppendieck W et al (2012) Pre-cooling and sports performance: a meta-analytical review. Sports Med 42:545–564

Weiner J, Khogali M (1980) A physiological body-cooling unit for treatment of heat stroke. Lancet 315:507–509