The effect of pre-cooling on cooling efficiency and exercise performance

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Chapter 3

How to measure thermal effects of personal cooling-systems: human, thermal manikin and human simulator study

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Abstract

Thermal effects, such as cooling power and thermophysiological responses initiated upon application of a personal cooling-system can be assessed with: i) humans, ii) thermal manikin and iii) thermophysiological human simulator. In order to compare these methods, a cooling-shirt (mild cooling) and an ice-vest (strong cooling) were measured using humans and a thermal manikin. In all conditions, cooling was provided for 45 min, while resting at the room temperature of 24.6 - 25.0 °C and the relative humidity of 22 - 24%. Subsequently, the thermophysiological human simulator was used at the same conditions to provide data on thermophysiological responses such as skin and rectal temperatures. The cooling power determined using the thermal manikin was two times higher for the cooling-shirt and 1.5 times higher for the ice-vest compared to the cooling power determined using human participants. For the thermophysiological human simulator, the cooling power of the cooling-shirt was similar to that obtained using human participants. However, it was two times lower for the ice-vest when using the thermophysiological human simulator. The thermophysiological human simulator is shown to be a useful tool to predict thermophysiological responses, especially upon application of mild cooling intensity. However, the thermophysiological human simulator needs to be further improved for strong cooling intensities in heterogeneous conditions.

3.1 Introduction

Personal cooling-systems were primarily developed to reduce or avoid heat strain in hostile aerospace and industrial environments (Nunneley, 1970). In the last decade, personal cooling-systems have also become increasingly used in sports. Their application prior to or during exercise is shown to reduce heat strain, thus helping to improve exercise performance (Marino, 2002).

The amount of heat extracted by a personal cooling-system (cooling power) is generally determined using either humans or a thermal manikin. In humans, the cooling power is dependent on the metabolic rate, the body composition and the acclimatisation (Cao *et al.,* 2005). For this reason, the use of thermal manikins is increasing, as they provide a reproducible evaluation of cooling power. However, thermal manikins also have limitations, such as the absence of vasoconstrictor response initiated in human skin when cooled. The heat transfer between the human body and the cooling-system depends on the temperature gradient between the skin and the inner surface of the cooling garment. Thus, the initiation of the skin vasoconstriction and thereby decreased skin temperature can lessen the heat transfer (Cheuvront *et al.,* 2003). The cooling power measured using the thermal manikin with the constant surface temperature, is characteristic only for this particular surface temperature. Thus, the cooling power measured with the thermal manikin is likely to be higher than the cooling power measured in humans for the same cooling-system.

Furthermore, thermal manikins are not able to simulate realistic thermophysiological responses, such as change in body core and skin temperatures. To overcome this deficiency a thermal manikin should be controlled by a model of human thermal physiology (thermophysiological human simulator). Forerunners of such systems have been already developed for testing clothing and sleeping systems (Psikuta *et al.,* 2008) and/or for evaluation of the comfort in vehicles (Farrington *et al.,* 2004). However, such systems often do not perform satisfactorily in validation trials (Psikuta, 2009; Rugh *et al.,* 2004) or are subjected to technical limitations, such as use of only mild and medium transient environmental conditions (Psikuta, 2009). The use of such a device to characterize personal cooling-systems has not been reported yet.

The aim of the present study was: i) to compare the cooling power of personal cooling-systems determined using human participants to a cooling power determined using a thermal manikin and thermophysiological human simulator ii) to compare the body core and skin temperatures measured in human participants with the ones predicted using the thermophysiological human simulator upon application of personal cooling-systems. For this purpose, two cooling-systems commonly applied in sports i) cooling-shirt and ii) an ice-vest, were used.

3.2 Methods

The two cooling-systems used in the present study were as follows: i) an evaporative cooling-shirt (Unico, Alpnachstad, Switzerland) and ii) an ice-vest (Arctic Heat, Burleigh Heads, Australia). The cooling-shirt consisted of a double-membrane system sealed to each other on all edges. The membranes are waterproof, but water vapour permeable and they enclose a hydrophilic fabric, which acts as a water reservoir and distributor. The water is inserted through inlets prepared in the outer membrane and it evaporates providing cooling to the shirt and the underlying skin (Kocjan & Rothmaier, 2007). The cooling-shirt was custom-made for each participant and the thermal manikin. We used equal amounts of water for the trials with the human participants and the thermal manikin. The ice-vest contained pockets distributed over its front and backside that are filled with the hydrophilic material. This vest was activated by water immersion and subsequent storage in a conventional freezer for at least 6 h. Adequate ice-vest sizes (small or medium) were provided for the participants and the thermal manikin.

3.2.1 Human participants (HUM)

Eight healthy males aged 27 ± 4 years, of mass 72.5 ± 5.2 kg and height 181 ± 4 cm participated in the study. The participants were instructed not to consume alcohol and caffeine 24 hours before each trial, and to refrain from food 2 hours before each trial. However, they were encouraged to drink water or other non-alcoholic/non-caffeinated beverages before the trials. The Cantonal Ethics Committee of St. Gallen, Switzerland approved the study. All participants gave their informed consent in writing before participating in the study. Three, randomly applied, experimental trials were performed in a room controlled at the temperature of 24.6 ± 0.4 °C and the relative humidity of 24 ± 6%. In all experimental trials cooling or no cooling was provided for 45 min while sitting. In the two experimental trials, either the cooling-shirt or the ice-vest was used. In a third experimental trial, which served as a control condition, the participants put on a conventional sport shirt (NikeFit Dry, Nike, The Netherlands). The experimental trials were conducted at the same time of the day and at least five days apart to minimize the influence of circadian rhythms and acclimation. Rectal temperature (T_{re}), measured 10 cm beyond the anal sphincter with a rectal probe (MSR B10014, Prospective Concepts, Glattbrugg, Switzerland), was used to determine the body core temperature. The skin temperature was measured on eight body sites (forehead, right scapula, left upper chest, right arm in upper location, left arm in lower location, left hand, right anterior thigh and left calf) according to ISO 9886 (2004). Skin temperature sensors (MSR B10012, Prospective Concepts, Glattbrugg, Switzerland) were fixed on the skin using a breathable tape (Tegaderm, 3M Health Care, USA). After the instrumentation, the participants put on shorts, sport shoes, socks and depending on the experimental trial one of the cooling-systems or the sport shirt. The participants spent a similar amount of the time under above mentioned environmental conditions in order to start the trials with a similar thermal state. The weighed mean skin temperature ($\overline{T}_{sk}$) was calculated according to ISO 9886 (2004). T_{re} and $\overline{T}_{sk}$ were used to calculate the mean body temperature ($\overline{T}_{b}$) according to Webb (1993):

$$\overline{T}_{b}\ (°C) = \alpha \cdot T_{re} + (1-\alpha) \cdot \overline{T}_{sk}\ ;\ \alpha = 0.75 \qquad \text{(Eq. 3.1)}$$

The change in body heat storage (S) during experimental trials was calculated according to Burton (1935):

$$S\ (W \cdot m^{-2}) = \Delta \overline{T}_{b} \cdot m \cdot CE \cdot AD^{-1} \cdot t^{-1} \qquad \text{(Eq. 3.2)}$$

$\Delta \overline{T}_{b}$ (°C): the difference in $\overline{T}_{b}$ between the start and the end of the experimental trial

m (kg): participant's body mass

CE ($kJ \cdot kg^{-1} \cdot °C^{-1}$): heat capacity (Webb, 1993)

AD (m^2): participant's body surface area (DuBois and DuBois, 1916)

t (s): duration of the experimental trial

The cooling power ($\dot{P}_{HUM}$; $W \cdot m^{-2}$) was calculated as the difference between S obtained using the cooling-systems and S obtained in the control condition.

3.2.2 Thermal manikin (SAM)

Sweating agile thermal manikin (SAM), which is a multi-segmental and anatomically formed manikin with the dimensions of an adult male, was used in the present study. It is made of 22 shell parts and additional guards (face, knees, elbows and hands) and, fixed on a stainless steel skeleton with movable joints (hips, knees, shoulders and elbows). External movable-drive enables motion (Richards & Mattle, 2001). The thermal manikin was placed in a climatic chamber at the temperature of 25.0 ± 0.2 °C and the relative humidity of 22 ± 2%. Identically to the trials in HUM, the thermal manikin was dressed with shorts, sport shoes and socks. Then, depending on the trial either the cooling-system or the sport shirt was applied. The thermal manikin was operated at constant surface temperature of 34 °C that corresponded to the human mean skin temperature at the thermoneutral state. The heating power of the entire manikin ($\dot{Q}$; $W \cdot m^{-2}$) needed to maintain this temperature was registered. The cooling power ($\dot{P}_{SAM}$; $W \cdot m^{-2}$) was calculated as the difference between $\dot{Q}$ obtained using the cooling-system and $\dot{Q}$ obtained in the control condition.

3.2.3 Thermophysiological human simulator (THS)

A multi-sector thermophysiological human simulator (THS) consists of the manikin SAM controlled by the model of human thermal physiology (Fiala *et al.,* 2001; Fiala *et al.,* 1999). Thermophysiological human simulator is able to predict the overall human thermophysiological responses (Psikuta, 2009). In the simulator, the thermal manikin is set up to produce a homogeneous surface temperature and sweat rate over the entire surface of the manikin, which is physiologically changing in time. The area-weighted averages of the skin temperature and sweat rate predicted by the thermophysiological model are used as input parameters to the manikin control system. After certain interval time, the manikin measures the heat flux released to the environment for the given activity, environmental conditions and clothing worn, and provides it as a feedback for the thermophysiological model. The simulator operates by repeating the cycles of data exchange at a given interval time. The thermophysiological human simulator was placed in the climatic chamber at the temperature of 25.0 ± 0.2 °C and the relative humidity of 22 ± 2%, and dressed with the same clothing and cooling-systems. Simulated T_{re} and $\overline{T}_{sk}$ were used to calculate the change in body heat storage by using equations 3.1 and 3.2. The cooling power ($\dot{P}_{THS}$; $W \cdot m^{-2}$) was calculated as the difference between S obtained using the cooling-systems and S obtained in the control condition.

3.2.4 Statistics

We calculated the root mean square deviations (rmsd) of T_{re} and $\overline{T}_{sk}$ for each condition to evaluate the average difference between the measured value from HUM and the predicted value from THS. The fit was assessed by comparing the mean standard deviation (stdev) of the experimental data with the rmsd value (Field 2009). Specifically, when rmsd < stdev, the predicted value from THS coincided with the measured values from HUM. Thus, it was considered that the thermophysiological human simulator correctly predicted the course of T_{re} or $\overline{T}_{sk}$. Whereas, when rmsd > stdev, the predicted value from THS did not coincide with the measured values from HUM. Thus, it was considered that the thermophysiological human simulator did not correctly predict the development of T_{re} or $\overline{T}_{sk}$. Data are presented as mean ± standard deviation.

3.3 Results

3.3.1 Cooling power

The cooling power determined using SAM was about two times higher for the cooling-shirt, and about 1.5 times higher for the ice-vest, when compared to the cooling power determined with HUM (Table 3.1). The cooling power determined using THS and in

HUM was similar for the cooling-shirt. However, for the ice-vest it was about two times lower when using THS.

Table 3.1 *Cooling power provided by the cooling-shirt and the ice-vest, determined using human participants (HUM), thermal manikin (SAM) and thermophysiological human simulator (THS).*

		cooling-shirt	ice-vest
HUM	$\dot{P}_{HUM}$ (W·m^{-2})	12.0 ± 5.3	29.3 ± 8.2
SAM	$\dot{P}_{SAM}$ (W·m^{-2})	25.4 ± 1.0	43.4 ± 12.3
THS	$\dot{P}_{THS}$ (W·m^{-2})	13.2	14.3

3.3.2 Thermophysiological responses

In HUM, a decrease ($p<0.01$) in T_{re} of 0.2 ± 0.1 °C was observed for the control, whereas it remained unaltered ($p>0.05$) for the cooling-shirt (0.1 ± 0.1 °C) and for the ice-vest (0.1 ± 0.2 °C). THS predicted constant T_{re} (0.1 °C) for all conditions (Figure 3.1). As shown in Table 3.2, rmsd for predicted T_{re} was lower than the stdev of the experimentally measured T_{re}.

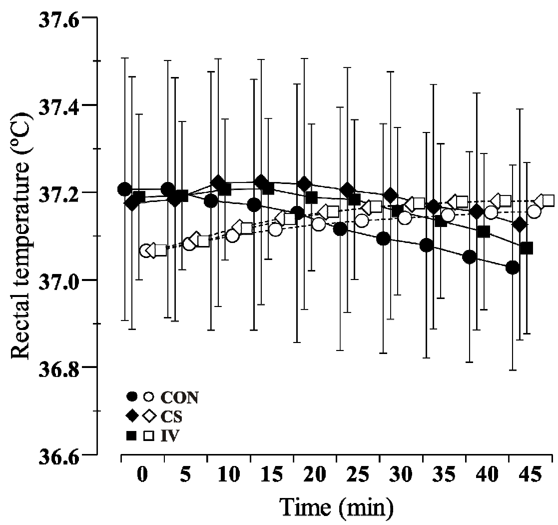

Figure 3.1 *Body core temperature for control (CON), cooling-shirt (CS) and ice-vest (IV). Full-bodied markers represent HUM and empty-bodied markers represent THS.*

Table 3.2 *Mean standard deviation (stdev) of the experimentally obtained data in human participants and root mean square deviation (rmsd) of the simulated data using THS obtained for comparison of rectal (*T_{re}*) and skin (*$\overline{T}_{sk}$*) temperatures.*

		control	**cooling-shirt**	**ice-vest**
T_{re} **(°C)**	stdev	0.3	0.3	0.2
	rmsd	0.1	0.1	0.1
$\overline{T}_{sk}$ **(°C)**	stdev	0.5	0.5	0.9
	rmsd	0.1	0.3	$1.7^{\#}$

 # denotes higher rmsd for the predicted data in THS compared to the stdev of the experimental data in HUM.

As shown in Figure 3.2, in HUM $\overline{T}_{sk}$ decreased ($p<0.001$) by 1.5 ± 0.3 °C for the cooling-shirt and by 2.7 ± 0.7 °C for the ice-vest. $\overline{T}_{sk}$ remained unaltered for the control condition (0.1 ± 0.3 °C). THS predicted $\overline{T}_{sk}$ to decrease with 0.3 °C for control, by 1.4 °C for cooling-shirt and by 1.5 °C for ice-vest. Furthermore, rmsd obtained from the predicted data of THS was lower as compared to the stdev of the experimentally obtained data in HUM for the control and the cooling-shirt. However, for the ice-vest rmsd was larger compared to the stdev of experimental data obtained with HUM (Table 3.2).

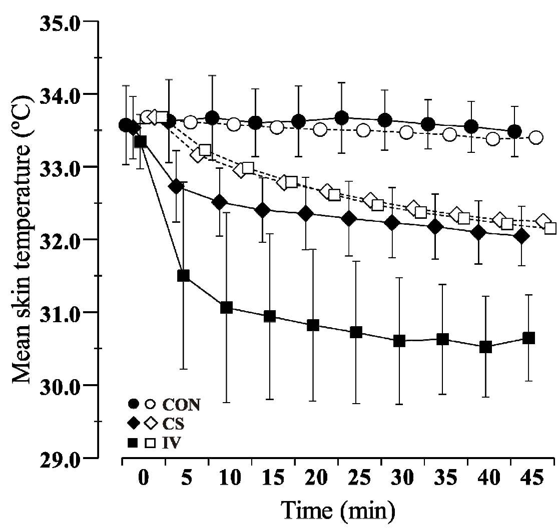

Figure 3.2 *Body core temperature for control (CON), cooling-shirt (CS) and ice-vest (IV). Full-bodied markers represent HUM and empty-bodied markers represent THS.*

3.4 Discussion

The results of the present study show that the cooling power determined with the thermal manikin is not comparable to the measurement with human participants. However, this disagreement is partly reduced when using the thermophysiological human simulator. The thermophysiological human simulator successfully predicted T_{re} and $\overline{T}_{sk}$ upon the application of the mild intensity of cooling and T_{re}, but not $\overline{T}_{sk}$ upon the application of the strong intensity of cooling.

3.4.1 Cooling power

The cooling power was higher for both cooling-systems when determined using the thermal manikin and compared to the human participants. This difference can be explained by the absence of the physiological control of the manikin, in particular simulation of the vasoconstrictor response. In humans, the initiation of vasoconstrictor response, reflected in decreased skin blood-flow and thereby decreased skin temperature, is shown to negatively affect the heat transfer between the human body and the cooling-system (Cheuvront *et al.,* 2003). In the present study, and as reported elsewhere (Bogerd *et al.,* 2010), a decreased skin blood-flow ($p<0.05$) was observed for both cooling-systems at locations directly exposed to cooling (chest, back) and at the periphery (finger pad of middle finger). For the ice-vest, a decreased skin blood-flow was also observed at the upper arm. Consequently, in human participants the temperature gradient between the skin and the inner surface of the cooling-system decreased. Thus, the smaller amount of heat was extracted from human participants as compared to the thermal manikin with the constant surface temperature.

In order to calculate the change in body heat storage in human participants, a two-compartment thermometry model was used (Webb, 1993). Specifically, the change in body temperature through cooling that served to calculate the amount of heat extracted was determined from T_{re} and $\overline{T}_{sk}$ differences between the beginning and at the end of cooling. Jay *et al.* (2007) suggested that such two-compartment thermometry model underestimates changes in body heat storage during moderate-intensity steady-state exercise. In their study, under similar environmental conditions to that of the present study, changes in T_{re} (0.7 ± 0.2 °C) and $\overline{T}_{sk}$ (1.1 ± 0.6 °C) were observed. Whereas, in present study only a change in $\overline{T}_{sk}$ was observed upon cooling (1.5 ± 0.3 °C for mild cooling and 2.7 ± 0.7 °C for strong cooling). We did not observe changes in T_{re}, representing the larger component in the calculation of body temperature change (Eq. 3.1). Thus, it is unlikely that using a two-compartment thermometry model in present study would give either a major underestimation or overestimation of the change in body heat storage. Moreover, to approximate the real change in body heat storage we used equation (Eq. 3.2) derived from the conditions (cold exposure) close to that of the present study (Webb, 1993).

Compared with the thermal manikin the thermophysiological human simulator is shown to be useful tool to predict cooling power of personal cooling-systems, especially for the mild cooling intensity. The thermophysiological human simulator uses average heat flux from the entire manikin as an input value for the physiological model. Thus, the cooling, which was applied to torso in present study is treated as if spread over the whole manikin surface. For the cooling-shirt, the heat extracted from the torso was relatively small (26.0 ± 1.0 W) as compared to the heat lost from the whole simulator (40.6 ± 1.6 W). While for the ice-vest the heat extracted from torso was high (54.9 ± 18.7 W) as compared to that lost from the whole simulator (69.4 ± 19.6 W). Both cooling-systems covered, however, similar surface areas. This may be the reason for an inaccurate prediction of the $\overline{T}_{sk}$ for strong cooling intensity. Thus, it is suggested that increasing the cooling homogeneity over the body provided by the cooling-system, is likely to enable the prediction of more realistic physiological responses.

3.4.2 Thermophysiological responses

The thermophysiological human simulator successfully predicted T_{re} for both cooling-systems as evident from lower rmsd obtained from predicted data compared to the stdev obtained from experimental data. This shows that the thermophysiological human simulator can be used as a tool to predict body core temperature response upon application of personal cooling-systems used. Furthermore, the thermophysiological human simulator successfully predicted $\overline{T}_{sk}$ for mild cooling, however, not for strong cooling (Table 3.2). For mild cooling the predicted $\overline{T}_{sk}$ within the first 15 min of cold exposure (Figure 3.2) lies on the border of one standard deviation of measured $\overline{T}_{sk}$. Thus, the predicting ability of thermophysiological human simulator for $\overline{T}_{sk}$ might be limited for short duration exposures; however this needs to be further investigated. For strong cooling, the predicted $\overline{T}_{sk}$ was underestimated. It is likely that the reason for this underestimation lies in the non-homogeneity of cooling as discussed above. Nevertheless, it also has to be noted that $\overline{T}_{sk}$ measured in human participants included locations directly exposed to cooling (chest and back). Therefore, the temperature measured by the sensors might not only record the skin temperature, but might be also influenced by the temperature of the ice-vest. This would mean that the measured skin temperatures would be lower than the real values.

3.5 Conclusions

It is concluded that the heat transfer between the cooling-systems and the human participants is lower than the one measured with the thermal manikin. This must be due to the absence of vasoconstrictor response on the thermal manikin. However, lack of this response is overcome by using a thermophysiological model in conjunction with the thermal manikin. Therefore, it is suggested that a thermal manikin coupled with the model of human thermal physiology, rather than a thermal manikin alone, should be used to determine thermal effects of personal cooling-systems. However, further work is necessary in order to improve the performance of the thermophysiological human simulator for the strong cooling intensities in heterogeneous conditions.

References

Bogerd N, Perret C, Bogerd CP, Rossi MR & Daanen HAM (2010) The effect of pre-cooling intensity on cooling efficiency and exercise performance. J Sports Sci 28: 771-779

Burton AC (1935) Human Calorimetry II: The average temperature of the tissues of the body. J Nutr 9: 261-280

Cao H, Branson DH, Nam J, Peksoz S & Farr CA (2005) Development of a cooling capability test method for liquid-cooled textile system In: *Performance of protective clothing: Global needs and emerging markets* (eds) Yarborough P & Nelson C N. ASTM International, West Conshohocken, pp. 111-120

Cheuvront SN, Kolka MA, Cadarette BS, Montain SJ & Sawka MN (2003) Efficacy of intermittent, regional microclimate cooling. J Appl Physiol 94: 1841-1848

DuBois D & DuBois E F (1916) A formula to estimate the approximate surface area if height and weight be known. Arch Intern Med 17: 863-871

Farrington R, Rugh J, Bharathan D & Burke R (2004) Use of a thermal manikin to evaluate human thermoregulatory responses in transient, non-uniform, thermal environments. *International Conference On Environmental Systems*. Colorado Springs, Colorado, USA

Fiala D, Lomas KJ & Stohrer M (1999) A computer model of human thermoregulation for a wide range of environmental conditions: the passive system. J Appl Physiol 87: 1957-1972

Fiala D, Lomas KJ & Stohrer M (2001) Computer prediction of human thermoregulatory and temperature responses to a wide range of environmental conditions. Int J Biometeorol 45: 143-159

Field A (2009) Discovering statistics using SPSS. SAGE Publications Ltd, London, UK

ISO 9886 (2004) Evaluation of thermal strain by physiological measurements. International Standards Organization, Geneva, Switzerland

Jay O, Gariepy LM, Reardon FD, Webb P, Ducharme MB, Ramsay T & Kenny GP (2007) A three-compartment thermometry model for the improved estimation of changes in body heat storage. Am J Physiol Regul Integr Comp Physiol 292: 167-175

Kocjan N & Rothmaier M (2007) A new cooling garment for patients with multiple sclerosis. *The 12th International Conference on Environmental Ergonomics*. Piran, Slovenia, pp. 395-398

Marino FE (2002) Methods, advantages, and limitations of body cooling for exercise performance. Br J Sports Med 36: 89-94

Nunneley SA (1970) Water cooled garments: a review. Space Life Sci 2: 335-360

Psikuta A (2009) Development of an 'artificial human' for clothing research. Institute of Energy and Sustainable Development, De Montfort University, Leicester, UK

Psikuta A, Richards M & Fiala D (2008) Single-sector thermophysiological human simulator. Physiol Meas 29: 181-192

Richards MGM & Mattle NG (2001) Development of a sweating agile thermal manikin (SAM). *Proceedings of the 4th International Meeting on Thermal Manikins*. St. Gallen, Switzerland, pp. 23-26

Rugh JP, Farrington RB, Bharathan D, Vlahinos A, Burke R, Huizenga C & Zhang H (2004) Predicting human thermal comfort in a transient nonuniform thermal environment. Eur J Appl Physiol 92: 721-727

Webb P (1993) Heat storage and body temperature during cooling and rewarming. Eur J Appl Physiol Occup Physiol 66: 18-24