RESEARCH AND APPLICATION OF LIQUID COOLING GARMENT SYSTEM BASED ON HUMAN ACUPOINTS AND MERIDIANS COOLING STIMULATION IN THE HIGH TEMPERATURE ENVIRONMENT

by

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As a cooling device for cooling the human body, the cooling garment has been used in many fields. This study was guided by the theory of traditional Chinese medicine, an acupoints-meridians cooling vest (AMCV) system was designed to cold and stimulate the acupoints and meridians of the human body. Three healthy male subjects were recruited to participate in the test, with AMCV or without AMCV (CON), in a high temperature environment (37 ±1℃, 46 ±3% RH) to simulate standing on duty for 50 minutes. The results showed that the skin temperature, T_{skin}, with AMCV was lower than that with CON ($p < 0.05$). The average T_{skin} with AMCV decreased by 0.45 ℃ more than that with CON ($p < 0.05$). The average tympanic temperature, T_{ty}, with AMCV was lower than that with CON ($p < 0.05$). However, the average T_{ty} with AMCV decreased by 0.05 ℃ more than that with CON ($p < 0.05$). The heart rate with AMCV was significantly lower than that with CON ($p < 0.05$). The average thermal sensation and thermal comfort with AMCV were better than those with CON in the corresponding period ($p < 0.05$). The results indicated that AMCV could improve thermal comfort and reduce the heat strain of the human body in a high temperature environment.

Key words*: high temperature environment, acupoints and meridians stimulation, liquid cooling vest, heat strain*

Introduction

Human beings will inevitably suffer from discomfort caused by high temperature in daily production and life. Heat strain could cause physical and psychological discomforts, reduce human performance and productivity, increase incident rates, and even threaten survival [1]. Humans are warm-blooded animals, and the core temperature of the human body is maintained at around 37 °C and fluctuates within a certain range. When human is affected by the environment or metabolic activities, the body temperature regulation system will regulate the human body to a certain extent. When the ambient temperature rises above 32 °C, the heat dissipation through conduction, convection, and radiation is almost zero or negative, and sweat evaporation plays a leading role in heat dissipation [2]. Therefore, when the human body cannot rely on its thermoregulatory system for thermoregulation, external measures should be used to

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improve the TC of the human body. As a human thermal protective device, the cooling garment could just make up for this disadvantage. The cooling garment has been used in various fields, such as mining [3], construction [4], fire protection [5], aerospace [6], military [7], medical treatment [8], *etc*. During the corona virus disease 2019 epidemic, medical staff sometimes need to test and treat patients in hot environments, and the cooling garment has played a huge role in relieving the heat strain for medical staff [9].

The effectiveness of cooling garments has been verified in many previous studies. In terms of the dry-hot environment, Ren and Zhang [10] validated the effectiveness of cooling garments using a thermal manikin and recommended the evaporative cooling vest and liquid cooling vest under heatwave conditions. Butts *et al.* [11] showed that phase change cooling could attenuate the thermal, physiological and perceptual strain of subjects during thermal work, increase personnel safety and reduce the risk of occupational heat disease. Bartkowiak *et al.* [12, 13] confirmed the effectiveness of liquid cooling garments by analyzing the mean skin temperature, physical parameters, and participants' subjective assessments. In terms of the humid-hot environment, previous studies have shown that cooling garments could also improve TC and reduce the thermal strain of humans [14, 15].

At present, the design optimization of cooling garments mainly starts from the following aspects. The first is to increase the cooling area. For example, extend the length of water pipes for liquid cooling garments, increase the number of cooling packs for phase change garments, and expand the gas area for air cooling garments. The second is to optimize the distribution of cooling parts to improve the heat dissipation efficiency of the human body, such as strengthening the cooling of the head, neck, and torso [16]. The third is to use materials with better performance. For example, use better heat-conducting water pipes for liquid cooling garments [17], and use higher quality phase change materials for phase change garments. The fourth is to optimize clothing fabrics. For instance, use thermally conductive polymers and fibers [18, 19]. The fifth is to optimize the garment construction. Adopt an ergonomic design to enhance the heat dissipation between the human body and the garment [12]. However, although the design optimization of the current cooling garments enhances its heat dissipation performance to a certain extent, it also brings some disadvantages. For example, a larger cooling surface causes a higher heat loss, and the quality of the garment is also increasing.

This study designed an AMCV system based on the theory of traditional Chinese medicine (TCM). Three healthy male college students were recruited to participate in tests. The results indicated that AMCV could relieve heat strain and improve the TC of humans. The AMCV can be used in low metabolic rate work areas in everyday life, such as standing guard on duty, volunteers directing traffic, and volunteers maintaining order*, etc.*

Experiments and methods

Introduction TCM theory

Acupoints are unique points in the theory of TCM, and the lines connected by specific acupoints constitute the meridians. Chinese researchers have already applied physical cooling of acupoints and meridians to treat and relieve pyrexia in clinical treatment. He [20] performed acupoints ice compress therapy and conventional western medicine ice compress treatment on two groups of fever patients, respectively. The results showed that the temperature decreasing time and body temperature of the acupoints ice compressing patients were better than those of western medicine treatment patients. Zhao [21, 22] proposed an ice moxibustion therapy. Fever could be relieved, or treated by placing a special icicle round surface on the symptomatic acupoints for stimulation. Feng and Zhang [23] reviewed infrared imaging technology and theory of meridian. It concluded that meridians could be beneficial to heat transfer. Cooling meridians might help the heat in the viscera of the human body dissipate along the meridians. This study aimed to strengthen the cooling stimulation of acupoints and meridians, thereby relieving human heat strain in hot environments. The schematic diagram of the distribution of meridians in the human torso is shown in fig. 1.

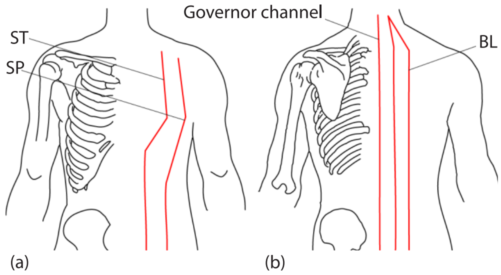

Figure 1. Schematic diagram of the distribution of meridians in the human torso; (a) shows the distribution of meridians on the front of the human body and (b) shows the distribution of meridians on the back of the human body:
ST – the stomach channel of Foot-Yangming,
SP is the spleen channel of Foot-Taiyin,
BL – the bladder channel of the Foot-Taiyang

The composition of acupoints-meridians cooling vest system

The AMCV system consisted of three components. There are the AMCV, the refrigeration system, and the temperature controller system, respectively. In addition, the refrigeration system and the temperature controller system are integrated on a backpack. The AMCV is composed of a vest sample, water pipes, metal cooling balls, and pipe connectors. The cooling vest consisted of two layers. The outer layer is an elastic and moisture-absorbing 40-count nylon-cotton Roman cloth (27% nylon, 68% rayon, 5% spandex), and the liner is the porous and ventilatory mesh (100% polyester). The vest pipe-line adopted a total-sub-total parallel connection. The main pipe-line used a PVC hose (inner diameter of Ø8 mm and outer diameter of Ø10 mm) with a total length of 75 cm. The branch pipe-line used a PVC hose (inner diameter of Ø6 mm and outer diameter of Ø8 mm) with a total length of 640 cm. There were 19 metal cooling balls (aluminum alloy 6063) distributed on the pipe-line. The *U*-shaped elbows (stainless steel) were arranged at the turn of the pipe-line to prevent excessive bending. Pipe connectors were used to connect the cooling vest and the refrigeration system. The AMCV is shown in fig. 2. The refrigeration system is composed of a refrigerator unit, a heat-dissipation unit, and a pump circulation system. The refrigerator unit provided the cold source for the vest and its critical parts were two same thermoelectric coolers (TEC), model: XH-C1206S2, Jiangsu Xinghe Electronic Technology Co., Ltd. Two waterblocks (aluminum alloy 6063) are arranged on the two sides of the TEC, respectively. The silicone grease (25 °C, thermal conductivity 13 W/mK) is settled between the TEC and the waterbolcks. The waterblock in contact with the cold side of the TEC was embedded in a shell made of acrylonitrile butadiene styrene plastic material (thermal conductivity range: 0.02-0.046 W/mK). Pure water in the waterblock was circulated and dissipated heat through a diaphragm pump and the pipe-line in the vest. The waterblock (aluminum alloy 6063) in contact with the hot side of the TEC is fixed on the shell through brackets, and the coolant (25 °C, thermal conductivity 1.1 W/mK) in the waterblock exchanges heat with the heat exchanger through the other diaphragm pump. Two axial flow fans (air-flow: 77.9 CFM) are arranged on the heat exchanger to enhance the

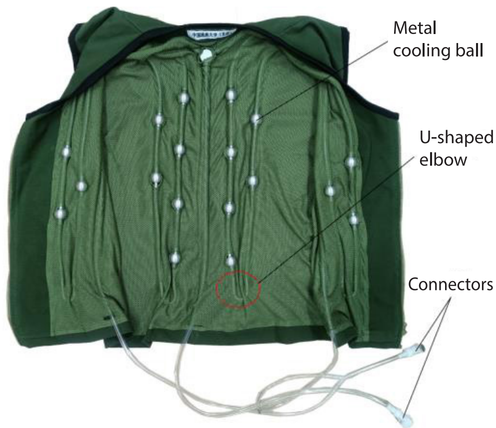

Figure 2. Anterior opening aspect of the AMCV

heat dissipation. The temperature controller system was used to control the outlet temperature and outlet flow. The weight of the AMCV is 0.85 kg, and the weight of the backpack is 3.67 kg. The rated cooling power of the refrigeration system is 110 W, and the flow rate of the vest is 1.2 Lpm.

Human body thermal balance analysis

The heat storage of the body can be written:

$$Q_s = \left(Q_m - W\right) - \left(Q_{conv} + Q_{cond} + Q_r + Q_{eva} + Q_{res}\right) \tag{1}$$

where Q_s is the heat storage of the body, Q_m – the metabolic heat production, W – the mechanical work power, Q_{conv} – the heat loss due to convection, Q_{cond} – the heat loss due to conduction, Q_r – the heat loss due to radiation, Q_{eva} – the heat loss due to sweat evaporation, and Q_{res} – the heat loss due to respiration.

Since the proportion of human effective mechanical work is small [24], it can be ignored. In most instances, the heat loss due to respiration is less than 5%, and the heat loss due to conduction is less than 1% [25], so these heat losses can be ignored. When the human body is cooled by AMCV, the amount of sweating will be reduced, so ignoring the heat loss caused by sweating. In this study, the ambient temperature is 37 °C, it is higher than the skin temperature of the human body. Therefore, the body actually gains heat from the external environment. But with the cooling of AMCV, the body could reduce heat by water pipe, Q_w. To simplify the heat transfer model, several assumptions are made:
– The temperature of the skin equals the temperature of the clothes.
– The surface of the skin and the clothes is treated as a plane.
– The heat transfer of all objects is even.

Hence, the heat storage can be simplified:

$$Q_s = (Q_m + Q_{conv} + Q_r) - Q_w \tag{2}$$

The heat loss due to convection can be expressed:

$$Q_{conv} = h_c f_{cl} (T_a - T_{cl}) A_{cl} \tag{3}$$

where h_c is the convective heat transfer coefficient, f_{cl} – the clothing area factor, T_{cl} – the temperature of the garment, T_a – the temperature of the environment, and A_{cl} – the effective cooling area.

Because the wind speed of the ambient environment is less than 0.1 m/s, there is natural-convection between the human body and the environment. The natural-convection heat transfer coefficient h_c can be expressed [26]:

$$h_c = 2.38 \left| T_{cl} - T_a \right|^{0.25} \tag{4}$$

where the ratio of the subject's clothed to unclothed surface areas, f_{cl}, is given [26]:

$$f_{cl} = 1 + 1.97 I_{cl} \tag{5}$$

where I_{cl} is the basic heat exchange resistance of garment.

The heat loss due to radiation can be expressed:

$$Q_r = h_r f_{cl} (T_r - T_{cl}) A_{cl} \tag{6}$$

where h_r can be expressed [26]:

$$h_r = 5.67\cdot 10^{-8}\varepsilon f_{\text{eff}} \frac{(T_{\text{cl}}+273)^4 - (T_r+273)^4}{|T_{\text{cl}} - T_r|} \tag{7}$$

where ε is the emissivity of the outer surface of the cooling garment, f_{eff} – the effective radiation area factor of the cooling garment, and T_r – the radiant temperature of the environment.

The heat loss due to AMCV can be calculated by the inlet and outlet temperature of the water as well as the mass of water:

$$Q_w = mC_p(T_{\text{out}} - T_{\text{in}}) \tag{8}$$

where m is the mass of water in the pipe-line, C_p [kJkg^{-1}K^{-1}] – the heat capacity of water, $C_p = 4.2$, and T_{out} and T_{in} are the outlet and inlet temperature of the water.

Replacing the eqs. (3), (6), and (8) into eq. (2), it can be expressed:

$$Q_s = \left[Q_m + h_c f_{\text{cl}}(T_a - T_{\text{cl}})A_{\text{cl}} + h_r f_{\text{cl}}(T_r - T_{\text{cl}})A_{\text{cl}}\right] - mC_p(T_{\text{out}} - T_{\text{in}}) \tag{9}$$

when $Q_s = 0$, humam body reaches a state of thermal balance and feels comfort.

Experimental procedure

Three healthy male college students (aged 25 ±3 years, weight 71.6 ±2.7 kg) participated in the experiment. The subjects were trained before the experiment to ensure that each person was informed of the specific procedures and safety matters. During the experiment, if the subject's tympanic temperature is higher than 38 °C or the heart rate (HR) exceeds its maximum HR or the subject experiences unbearable discomfort, the experiment was stopped immediately. All subjects had adequate sleep and avoided alcohol consumption before the test.

Each subject participated in two tests (with AMCV or CON). To ensure experimental consistency and reduce the risk due to ambient temperature, each test was performed at the same time of day and the continuous heat exposure time in the hot environment was set according to GB/T4200-2008 [27]. After the test, each subject had a 24 hour physical recovery. The test was carried out at 9:00 in the morning. The subjects urinated completely and drank 200 mL of water before each experiment. All subjects wore trousers (96.3% cotton/3.7% spandex) and T-shirts (100% cotton). For the CON, subjects rested for 15 minutes before the test, and corresponding sensors were settled on the body in an environment with a temperature of 28 °C and 52% RH. After the preparation was completed, the subjects entered a climate chamber (37 ±1 °C and 46 ± 3% RH) in a standing position for 50 minutes to simulate the behavior of the guards on duty. Physiological parameters and subjective thermal sensations (TS) were monitored and recorded after subjects entered the climate chamber. For the AMCV, except for the use of the AMCV in the test, the rest of the steps and procedures were the same as those of the CON. The inlet temperature, mean ± standard deviation (SD) of the vest is shown in fig. 3.

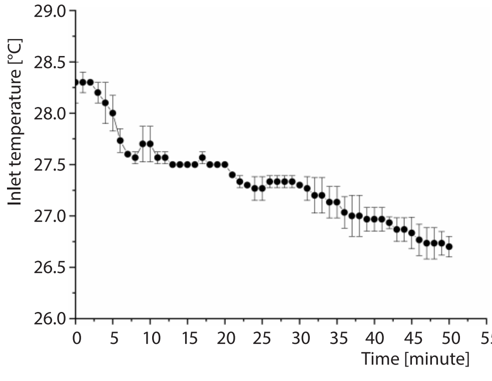

Figure 3. The inlet temperature of the vest

Measurement item

The skin temperature, T_{skin}, was measured continuously using a data logger (TYHC XSL/A-RS1P0V0) at 1 minute intervals, tab. 1. According to ISO 9886:2004 [28], the neck temperature, T_{neck}, right scapula temperature, T_{Rsca}, left hand temperature, T_{Lhand}, and right shin temperature, T_{Rshin}, were selected to calculate the T_{skin}. The T_{skin} was calculated using:

$$T_{\text{skin}} = 0.28T_{\text{neck}} + 0.28T_{\text{Rsca}} + 0.16T_{\text{Lhand}} + 0.28T_{\text{Rshin}} \tag{10}$$

The change in T_{skin} (ΔT_{skin}) was calculated by subtracting the average T_{skin} with CON from the average T_{skin} with AMCV. The tympanic temperature, T_{ty}, was measured using an infrared data logger (Yuwell, YHT101) at 1 minute intervals, tab. 1. The change in T_{ty} (ΔT_{ty}) was calculated by subtracting the average T_{ty} with CON from the average T_{ty} with AMCV. The HR was measured using a comprehensive parameter data logger (Scchengyi, XY-2 type). The HR was recorded every 1 minute. According to GB/T 18977-2003 [29], the rating of TS, via a 9-point scale ranging from very cold (–4) to very hot (+4), and TC, via a 5-point scale rating from comfortable (0) to extremely uncomfortable (4), were recorded every 5 minutes by questionnaires.

Table 1. The measuring equipment and its performances

Equipment (model)	Measurement parameters	Manufacturer	Measurement time interval
Data logger (XSL/A-RS1P0V0)	T_{skin}	TYHC	Once per 1 minute
Infrared data logger (YHT101)	T_{ty}	Yuwell	Once per 1 minute
Comprehensive parameter data logger (XY-2 type)	HR	Scchengyi	Once per 1 minute

Statistical analysis

All data were expressed in figs. 4(a)-4(e) as mean ± SD. All data were analyzed using a paired Student's t-test. The mean difference and 95% confidence interval are provided where applicable. For all comparisons, significance was set at $p < 0.05$.

Results

In an environment with a temperature of 37 ±1 °C and 46 ±3% RH. The T_{skin} with AMCV of the three subjects was lower than that with CON ($p < 0.05$). The ΔT_{skin} decreased by an average of 0.45 ±0.61 °C, 95% confidence interval [–0.55, –0.36], $p < 0.05$. The T_{ty} with AMCV was lower than that with CON ($p < 0.05$). The ΔT_{ty} decreased by an average of 0.05 ±0.15 °C, 95% confidence interval [–0.07, –0.03], $p < 0.05$. The HR with AMCV was lower than that with CON ($p < 0.05$). The average TS and TC with AMCV were better than those with CON in the same period ($p < 0.05$).

Discussion

In previous studies, the cooling source of liquid cooling garments was provided by compressors or ice [30, 31]. The advantage of compressor cooling is that it could provide sufficient cooling capacity. However, it has a disadvantage of heaviness. With the external load increasing, the metabolic cost is increasing while human walks [32]. In addition, the strain of

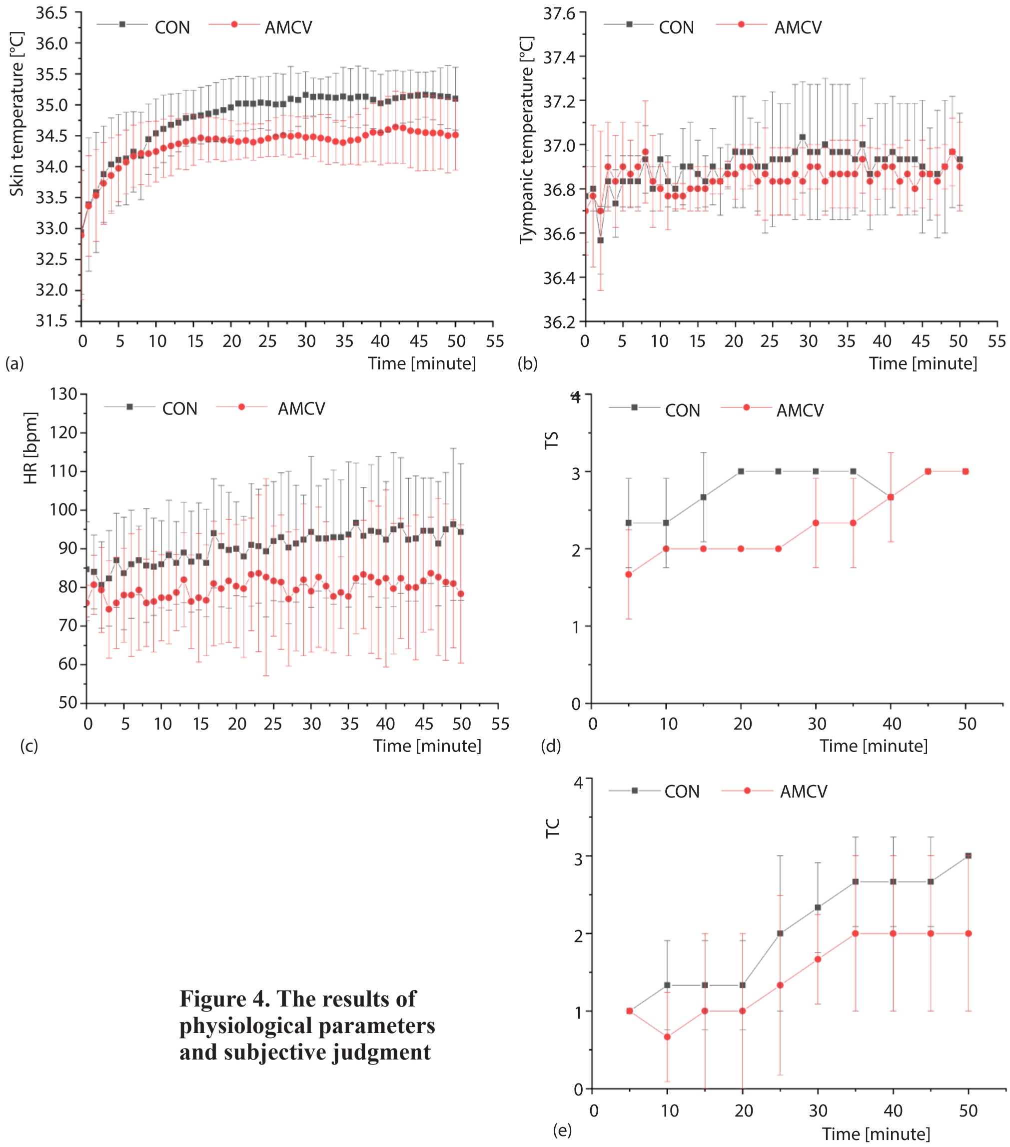

Figure 4. The results of physiological parameters and subjective judgment

the cardiovascular system tends to increase with the raising of physical load [33]. Therefore, it is necessary to reduce the weight of cooling garment equipment. The structure of ice liquid cooling garments is relatively simple, but the disadvantage is that the ice needs to be replenished regularly. It is limited especially in field operations. The TEC were used as refrigeration components in this study. There are many advantages of TEC, such as small size, no mechanical structure, and no mechanical vibration. According to the characteristics of the TEC, when the input power is constant, the greater the heat dissipation of the hot side of the TEC, the greater the cooling capacity of the cold side of the TEC. The hot side of the TEC cooled by water made the heat dissipation larger. The disadvantage of water cooling in the past is that with the increase of water temperature, the temperature difference gradually decreases, and it eventually leads to poor heat dissipation. To solve this problem, this study adopted the combination of a heat exchanger and two fans to dissipate heat for the coolant. The heat exchanger increases the heat dissipation area of the coolant, and the heat dissipation has been improved.

There are disadvantages of uneven heating and large flow resistance in the series connection of liquid cooling garment pipe-lines. The reason is that with the increase of the length, the temperature of the pipe-line in the initial section is lower than that in the final section, and the local skin may feel cold. At the same time, if the pipe-line is too long, it will also cause the problem of increased flow resistance. For this reason, a pump with a higher head is required to meet the fluid circulation of the system. Therefore, it is recommended that the garment piping is in parallel. The parallel connection could reduce the flow resistance and the load pressure of the pump. Further, the parallel connection could ensure that the temperature on both sides of the human body is the same, and the problem of uneven temperature on both sides will be improved.

In a previous study [16], the cooling efficiency could be enhanced by strengthening the cooling of the head, neck, and torso of the human body. The reason is that the body's basal metabolism and basal blood flow are mainly concentrated in the torso (basal metabolism, 74.4%, basal blood flow, 17.9%) and head (basal metabolism, 80.6%, basal blood flow, 16.6%). Therefore, strengthening the cooling of the head, neck, and torso is beneficial to body cooling [34]. Luo and Xu [35] reviewed that the temperature distribution of acupoints in the human body shows a centripetal increasing trend. The closer to the head and face, the higher the temperature value. This is echoed by cooling the head and neck to improve the cooling efficiency of the human body. Feng and Zhang [23] found the specificity of heat conduction along the channel by infrared technology. It suggested that the human meridians could be good channels for heat. By cooling meridians and acupoints, it could be beneficial for the heat in the human body to be dissipated along meridians. In addition, cooling meridians and acupoints might affect thermoreceptors and the cardiovascular system of the human body. Moreover, the cooling pipe-line is only set near the acupoints and meridians of the human body, it could reduce the length of the pipe-line, the weight of the vest, and the flow resistance of the liquid cooling pipe-line.

Bartkowiak *et al.* [13] conducted a group of experiments in an environment with a temperature of 35 °C. The subjects were cooled with a cooling liquid with an inlet temperature of 19 °C. Results showed that the maximum HR of the human body reached about 105 bpm, the maximum skin temperature was close to 35 °C, and the maximum temperature of the external auditory channel was 36.6 °C. In Ashtekar *et al.* [4], the construction workers wore a cooling garment in an environment with a temperature of 39.8 °C, and the temperature of the liquid cooling suit pipe-line was 15 °C. In 90 minute trials, the human HR reached 106 ±13 bpm, the weighted skin temperature was 32 ±1.3 °C, and the oral temperature is 36.8 ±0.5 °C. Sveta *et al.* [36] implemented a series of experiments using a cooling garment in an environment with a temperature of 40 °C. Results showed that the maximum tympanic temperature reached 37.96 ±0.21 °C, the skin temperature reached 36.11 ±0.18 °C, the HR was 138 ±18 bpm, and the sweating rate was 0.44 ±0.12 L per m^2. In this study, with the cooling of AMCV, the maximum tympanic temperature reached 36.9 ±0.2 °C, the skin temperature reached 34.6 ±0.6 °C, and the HR was 96 ±19 bpm. The experimental results are different because of the different working conditions. As can be seen, a lower inlet temperature tends to better human physiological parameters. The original intention of the AMCV in this study is to relieve the heat strain of the body rather than fully meet the heat dissipation needs. According to GB/T 18048-2008 [37], the average low metabolic rate of the body is 180 W, and the average medium metabolic rate is 295 W. In these cases, if the human is to be fully thermally comfortable, the cooling power would be at least 295 W. Even if the cooling capacity required by the human body is set, the problem of local skin overcooling will be caused due to the small cooling area. On the contrary, it reduces the local TC of the human body.

Conclusion

In this study, an AMCV system based on cooling human acupoints and meridians to relieve human heat strain was proposed. The skin temperature with AMCV decreased by an average of 0.45 °C than that with CON ($p < 0.05$). The HR with AMCV was lower than that with CON ($p < 0.05$). Although the tympanic temperature with AMCV was decreased by an average of 0.05 °C than that with CON ($p < 0.05$), the TS and TC with AMCV were improved than those with CON ($p < 0.05$). The reason is that the human meridians could be good channels for heat dissipation and cooling acupoints and meridians might affect thermoreceptors and the cardiovascular system of the human body. In general, cooling the whole torso is a better choice, the proposal of this study can be used as an assistant function in whole torso cooling to further improve human comfort and TS. Meanwhile, AMCV can be also used in low metabolic rate work areas in everyday life.

Acknowledgment

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Nomenclature

A_{cl} – effective cooling area, [m^2]
C_p – heat capacity of water, [kJkg^{-1}K^{-1}]
f_{cl} – clothing area factor
f_{eff} – effective radiation area factor of the cooling garment
HR – heart rate, [bpm]
h_c – convective heat transfer coefficient, [Wm^{-2}K^{-1}]
h_r – radiation heat transfer coefficient, [Wm^{-2}K^{-1}]
m – mass of water in the pipe-line, kg
Q_{cond} – heat loss due to conduction, [W]
Q_{conv} – heat loss due to convection, [W]
Q_{eva} – heat loss due to sweat evaporation, [W]
Q_m – metabolic heat production, [W]
Q_r – heat loss due to radiation, [W]
Q_{res} – heat loss due to respiration, [W
Q_s – heat storage of the body, [W]
T_a – temperature of the environment, [°C]
T_{cl} – temperature of the garment, [°C]
T_{in} – inlet temperature of the water, [°C]
T_{out} – outlet temperature of the water, [°C]
T_r – radiant temperature of the environment
T_{skin} – skin temperature, [°C]
T_{ty} – tympanic temperature, [°C]
ΔT_{skin} – change in T_{skin}, [°C]
ΔT_{ty} – change in T_{ty}, [°C]
W – mechanical work power, [W]

Greek symbol

ε – emissivity of the outer surface of the cooling garment

Acronyms

AMCV – acupoints-meridians cooling vest
BL – bladder channel of the Foot-Taiyang
CI – confidence interval
CON – without AMCV
SP – spleen channel of Foot-Taiyin
ST – stomach channel of Foot-Yangming
TC – thermal comfort
TCM – traditional Chinese medicine
TEC – thermoelectric cooler
TS – thermal sensation

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