# INVESTIGATION ON PERFORMANCE OF THREE PERSONAL COOLING SYSTEMS IN MITIGATING HEAT STRAIN BY MEANS OF THERMAL MANIKIN

by

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*The objective of current study was to examine the effectiveness of three cooling strategies (i. e., electric air fan, evaporative cooling vest, and liquid cooling vest) in mitigating body heat strain in heat wave conditions by means of a Newton-type thermal manikin. A human thermoregulatory model was used to simulate human physiological responses while using the three cooling strategies. Two environmental conditions were selected to simulate heatwave conditions, i. e., 36 °C, 33% relative humidity (hot-dry), 40 °C, 27% relative humidity (extremely hot-dry). A metabolic rate of 1.2 MET was selected to simulate resting person or person doing light housework. It was found that the electric air fan had cooling benefit in both environments. In addition, the evaporative cooling vest and liquid cooling vest showed similar effectiveness in mitigating body heat strain in both hot-dry or extremely hot-dry environments. Thus the evaporative cooling vest and liquid cooling vest were recommended under heatwave conditions.*

Key words: *personal cooling, thermal manikin, heat strain, heat wave, heat stress*

## Introduction

During the last few decades, severe heatwaves (*i. e.*, periods of extremely high ambient temperatures) have been more frequent across countries [1], and heat-related illnesses caused by heat waves have been evidenced by the increased mortality, hospital admissions, and emergency room visits world widely [2, 3]. The heat-related illnesses are due to the accumulation of body heat strain in such environments [4]. When the ambient temperature is higher than the body temperature in such heatwave conditions (as the ambient temperature was normally higher than 35 °C in such conditions), heat transfers from the ambient to human body via conduction, convection, and radiation [5]. Perspiration evaporation is the only avenue for human body to dissipate heat and is the only physiological defense against heat stress [6, 7]. Body thermal balance would be disrupted in such conditions, initiating a series of events that may lead to work accident or even fatality [8]. Therefore, it is important to seek effective cooling strategies to manage body heat strain in such hazard heat wave environments.

During the last few decades, there has been a shift in attention from focusing on macrocooling (*i. e.*, cooling the entire environment using fan or air-conditioner) to micro-co-

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oling (*i. e.*, personal cooling strategies, PCS, cooling the micro-environment around human body) [9]. Generally, the PCS are more energy saving and environmentally friendly, more flexible (*e. g.*, they are more feasible in areas without air conditioning) [9, 10]. Recently, many techniques and technologies have been introduced in the personal cooling systems to reduce human heat strain, and all the PCS available could be classified into the following categories according to their cooling mechanism: liquid/gas cooling garment (LCG) [11, 12], evaporative cooling garments (ECG) [13], phase change material (PCM) garments [14, 15], and air ventilation cooling systems (VCS) [16, 17]. The LCG are usually composed by clothing and a network of fine tubes connected to a refrigerated coolant tank. The coolant could be fluid, gas, or non-toxic aqueous solutions. The coolant circulates through the tubes and utilizing the positive temperature gradient between the human body and clothing to remove heat away from the body via conduction and convection [11, 12]. The cooling effect of ECG is obtained by the large latent heat of moisture evaporation, and the substantial latent heat of water evaporation promises the effectiveness of ECG with a small amount of water [11]. The PCM relies on the PCM (such as frozen gels and ice packs) placed closely to the body to absorb body heat during phase change [11-17]. The cooling effect of the PCM greatly depends on PCM melting temperature and latent heat, as well as their mass and the body coverage area [17]. The VCS obtains their cooling effect by promoting moisture evaporation, as well as the promoted convective heat transfer [7].

In this study, the effectiveness in mitigating heat strain of two PCS (*i. e.*, ECG and LCG) was investigated under heat wave conditions. In addition, a macro-environment cooling strategy (*i. e.*, FAN) was also investigated for comparison. Besides the investigation of the three cooling strategies (*i. e.*, FAN, ECG, and LCG), the effects of ambient temperatures and relative humidity (RH) on the cooling performance of these strategies was also discussed. It is hypothesized that the finding of this study could provide customers with useful guidelines to make the most suitable choice to combat heat stress under heat wave conditions.

## Methodology

### *Cooling systems*

Three different cooling systems were investigated, fig. 1. A basic clothing ensemble (*i. e.*, CON) (included a short-sleeved polyester shirt, cotton briefs, shorts, and sandals, the thermal insulation: 0.25 clo) was selected, and was used in all experiments.

*Electric air fan* (FAN). An air fan (SF-45MV-1V, Suiden, Tokyo, Japan) was placed at the front of the manikin with a distance of 1.0 m, directly facing to the manikin. The mean generated air speed was 1.0 m/s at the chest area. The air speed was measured by an anemometer (Fluke 923, Fluke, Washington, USA).

*Evaporative cooling vest* (ECG). The evaporative cooling vest (Hyperkewl$^{TM}$, TechNiche, Vista, Cal., USA) was constructed by three layers: a nylon outer layer, water-repellant nylon liner and a middle layer of with quilted HyperKewl$^{TM}$ polymer which was able to absorb, store and release water. Prior to use, the ECG was prepared as follow: soaking it into tap water (around 23 ±2 °C) for 2 min, gently squeezing it to remove excess water (activated), and ready for use. The total weight of activated ECG was about 0.88 kg.

*Liquid cooling vest* (LCG). The liquid cooling vest used in this study incorporated with a fine tube network sandwiched between two layer polyester mesh fabrics, and the vest could be held in close contact with the body surface by adjusting straps at both body sides. A backpack, locating cooling reservoir (*i. e.*, a sealed bag filled with 1500 ml ice bottle and water) and mini pump, was connected to the inlet and outlet tubes, and a portable lithium battery was also placed in the backpack. On application, the water was driven from the reservoir and circulated in the tubes. The total weight of the activated LCG system was around 7.0 kg.

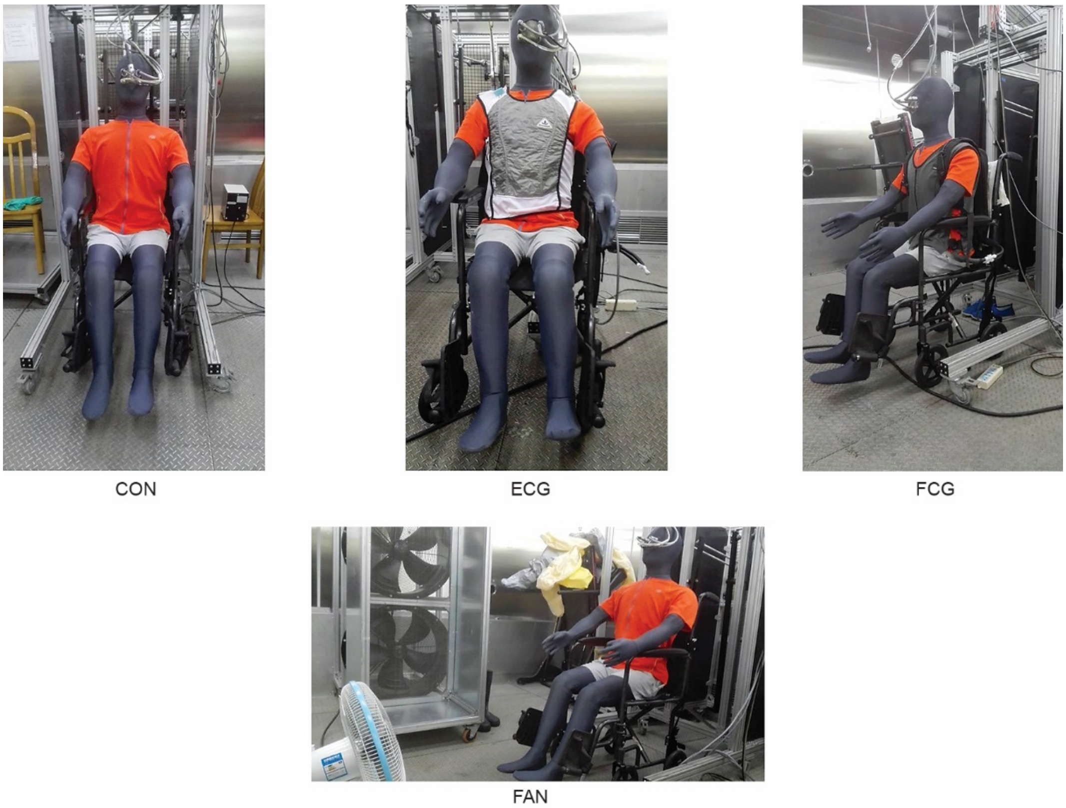


**Figure 1. Cooling systems: CON, ECG, FCG, and FAN**

### *Thermal manikin*

A 34-zone 'Newton' type thermal manikin (Thermetrics LLC, Seattle, Wash., USA) was used in this study. A thermoregulatory model control mode was selected to simulate human physiological responses in cooling system. This thermoregulatory model program was developed by ThermoAnalytics Inc. (Calumet, MI) and the model was based on the Fiala multi-segmental thermophysiological model [10]. Prior to the application of thermoregulatory model control mode, the manikin was preheated to the defined thermoneutral condition. The segmental surface temperatures of the manikin are presented in tab. 1.

### *Test conditions*

All tests were conducted in a climate chamber. Two test environmental conditions were selected: 36 ±0.5 °C and 33 ±5% RH (hot-dry environment, HD1), 40 ±0.5 °C and 27 ±5% RH (extreme hot-dry environment, HD2), respectively. A constant air velocity of 0.15 ±0.1 $ms^{-1}$ was applied in all tests. A 1.2 MET were applied to simulate the resting person or person doing light housework.

**Table 1. The manikin segmental surface temperatures under defined thermoneutral condition**

| Segments | Temperature [°C] | Segments | Temperature [°C] |
|---|---|---|---|
| Face | 35.50 | Waist | 34.49 |
| Head | 35.24 | Low back | 34.70 |
| Right upper forearm-front | 33.48 | Right pelvis front | 34.25 |
| Right upper forearm-back | 33.48 | Right pelvis back | 34.81 |
| Left upper forearm-front | 33.32 | Left pelvis front | 33.91 |
| Left upper forearm-back | 33.32 | Left pelvis back | 35.00 |
| Right upper arm-front | 33.27 | Right thigh front | 33.86 |
| Right upper arm-back | 33.27 | Right thigh back | 33.95 |
| Left upper arm-front | 33.33 | Left thigh front | 33.79 |
| Left upper arm-back | 33.33 | Left thigh back | 34.05 |
| Right hand | 34.69 | Right shin | 33.78 |
| Left hand | 34.58 | Right calf | 33.66 |
| Upper chest | 34.79 | Left shin | 34.10 |
| Shoulders | 34.85 | Left calf | 33.49 |
| Stomach | 34.48 | Right foot | 30.73 |
| Mid back | 34.70 | Left foot | 30.77 |

### *Test procedure*

The manikin was dressed with the basic clothing ensemble, and then preheated to reach the defined thermoneutral state (shown in tab. 1) at room temperature (*i. e.*, 20 ±0.5 °C). Afterwards, it was transferred into the climate chamber with the pre-set testing condition, and then applied with a cooling strategy (*i. e.*, FAN, ECG, LCG). Then, the metabolic rate of 1.2 MET was set. The testing duration was 60 min. The hypothalamic temperature, $T_{hy}$, and the mean skin temperature, $T_{sk}$, were logged with constant interval of 1 min. Each test repeated three times.

### *Statistical analysis*

All data were reported as mean ± standard deviation. A mixed model two-factor ANOVA was performed to examine whether there were significant differences between the three cooling systems (*i. e.*, ECG, FCG, FAN), and CON. If there were significant differences, paired-sample *t*-tests were conducted to determine the significant effect at different time points separated by 5 min interval. All statistical analysis was conducted by the SPSS v.20.0 (IBM Inc., Armonk, NY., USA) and the significance level, $p$, was set to 0.05.

## Results and discussion

### *Effect of FAN*

It could be observed that FAN exhibited no significantly lower $T_{sk}$ and $T_{hy}$ compared with CON in 36 °C and 33% RH (HD1), fig. 2. The curve of FAN also overlapped with that of CON in 36 °C and 33% RH condition. In contrast, FAN displayed significant higher $T_{sk}$ and $T_{hy}$ ($p < 0.05$) compared with CON in extreme hot-dry environment (*i. e.*, 40 °C and 33%

RH, HD2), fig. 3, *i. e.*, from the 20th minute and the 25th minute. to the end of the test for $T_{sk}$ and $T_{hy}$, respectively. Thus it could be concluded that the FAN could not bring cooling benefit under those two test environment. The finding was in line with the guideline provided by the U. S. Environmental Protection Agency (EPA), which suggested the air temperature limits for human using air fans was 35.6-37.2 °C [18]. In heat wave environments, the cooling benefit of FAN relied on whether the induced evaporative heat loss exceeding the promoted convective heat gain [5]. Thus the failure of the FAN in mitigating heat strain indicated that the FAN promoted more convective heat gain to the human body than the heat loss by induced evaporation under both environments.

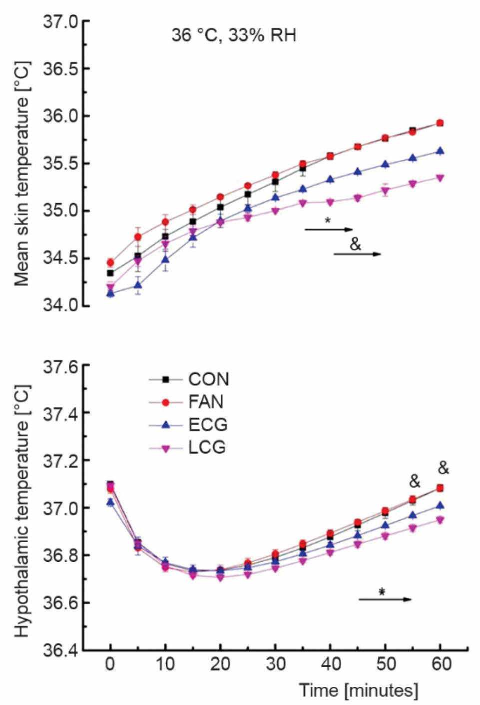


**Figure 2. Time course changes in the mean skin and hypothalamic temperatures under 36 °C and 27% RH environment**
** is the significant difference between CON and LCG,*
*& – the significant difference between CON and ECG (p < 0.05)*

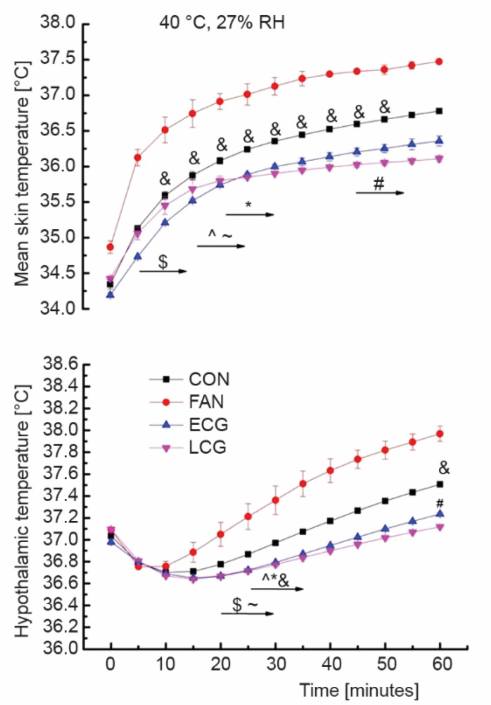


**Figure 3. Time course changes in the hypothalamic and mean skin temperatures under 40 °C and 27% RH environment**
** is the significant difference between CON and LCG,*
*& – the significant difference between CON and ECG,*
*# – the significant difference between ECG and LCG,*
*^ – the significant difference between CON and FAN,*
*$ – the significant difference between FAN and ECG,*
*~ – the significant difference between FAN and LCG (p < 0.05)*

### *Effect of ECG*

The ECG showed significantly lower ($p < 0.05$) $T_{sk}$ and $T_{hy}$ compared with CON under both HD1 and HD2 environments, from the 40th and 55th minutes to the end of the test in $T_{sk}$ and $T_{hy}$ in HD1, respectively. In HD2, significant lower $T_{sk}$ was observed from the 15th to the 50th minutes of the test, and significantly lower $T_{hy}$ from the 25th minute to the end of the test, fig. 3. Significant differences in $T_{sk}$ or $T_{hy}$ were observed between ECC and FAN, LCG in HD2, fig. 3. The ECG displayed positive effect in both environments, which indicated the heat absorbed during moisture evaporation outweighed the restriction of sweat evaporation [19]. It was also found that the ECG had longer cooling time in HD2 (*i. e.*, significant difference observed from the 25$^{th}$ minute to the end of the test) compared to HD1 (*i. e.*, significant difference observed from the 40$^{th}$ minute to the end of the test), which may be due to the higher ambient temperature and lower partial vapor pressure in HD2, and the differences in the HD2 environment promoted more moisture evaporation. However, this finding was conflict with the observation of Kaufman's study [18], who found that ECG significantly increased the skin and core temperatures. Those differences may be caused by the different testing conditions. Kaufman adopted higher exercise intensity (about 10 MET) under 37 °C and 75% RH, and also protective clothing outside the ECG [19].

### *Effect of LCG*

Significant lower $T_{sk}$ and $T_{hy}$ were observed from the 35$^{th}$ minute and the 45$^{th}$ minute to the end of the test in HD1, fig. 2, respectively, and lower $T_{sk}$ and $T_{hy}$ from the 20$^{th}$ minute and the 25$^{th}$ minute to the end of the test in HD2, fig. 3, respectively ($p < 0.05$). No significant differences in $T_{sk}$ and $T_{hy}$ were also observed between LCG and FAN, ECG in both environments ($p < 0.05$). The LCG mitigated heat strain by the heat transfer caused by the temperature gradient between the body surface and the LCG. The LCG showed better cooling benefit in HD2 (effective cooling time: from the 20$^{th}$ minute to the end of the test), fig. 3, compared with in HD1 (from the 35$^{th}$ minute to the end of the test), fig. 2. The differences in the results might be due to the different testing environments, the higher temperature in HD2 motivated the appearance of cooling effect at an earlier time point. This finding was partly in line with previous studies, which described that LCG could bring cooling effect in air temperatures between 35 °C and 48 °C [20-22].

## Conclusions

In this study, the performance of three cooling strategies (*i. e.*, using electric air fan, ECG, and LCG) in reducing heat strain was investigated in hot-dry and extremely hot-dry environments by a thermal manikin. It was found that both ECG and LCG displayed cooling benefits in dry environments, thus could be used to reduce heat strain under those environments. In contrast to show any obvious cooling effect in both environments, the electric fan even aggravated the heat strain in extreme hot-dry environment, thus it could be concluded that the fan should be prevented in heat wave conditions. It should be acknowledged that this study was focused on only thermal manikin with light exercise or low work intensity. Therefore, human trials or field wear trials should be conducted in order to make comprehensive evaluation or solid recommendation on selecting the cooling strategies in reducing the body heat strain in heat wave conditions.

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