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An investigation of thermophysiological responses of human while using four personal cooling strategies during heatwaves

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ABSTRACT

This study aimed to examine how human body thermophysiologically responds to four commonly used cooling strategies (i.e., electric fan cooling [AirFC], evaporative cooling clothing [EvapCC], hybrid cooling, i.e., evaporative cooling clothing combined with electric fan cooling [EvapCC & AirFC] and liquid cooling clothing [LiqCC]) during heatwaves. An adaptive 'Newton' manikin was used to predict human physiological responses while using these four cooling systems. Four heatwave conditions were selected, i.e., 36 °C, 33% RH (hot-dry, denoted as HD1), 36 °C, 67% RH (hot-humid, denoted as HH1), 40 °C, 27% RH (extremely hot-dry, denoted as HD2) and 40 °C, 54% RH (extremely hot-humid, denoted as HH2). A metabolic rate of 2.5 METs was used to mimic moderate work while sitting at either home or outdoors. AirFC was only found to bring cooling benefits in HD1 and HH1. EvapCC was effective in both HD1 and HD2. LiqCC showed similar cooling benefits compared to EvapCC in HD1 and HD2, and also displayed cooling benefits in HH1. EvapCC & AirFC was discovered to be most effective cooling strategy in the four studied conditions. Concerning their practical applications, EvapCC & AirFC was recommended to inactive populations while staying indoors during different heatwave conditions, and EvapCC and LiqCC were more suitable for active populations while working/exercising in hot-dry conditions and hot-humid conditions, respectively.

1. Introduction

Heatwaves are likely to increase in both intensity and frequency. Heatwaves have claimed over millions of deaths worldwide during the past few decades (Li et al., 2015; Kenney et al., 2014; Lancet, 2015; Salim et al., 2015; Murari et al., 2015). Heatwave-associated high morbidity and mortality were partly attributed to the elicited body heat strain in extreme environments (Amengual et al., 2014). When the air temperature is higher than the body temperature, sweat evaporation becomes the main avenue for the human body to dissipate heat to surrounding environments (Jay et al., 2015). In extremely hot environments, the human body could receive conductive, convective and radiative heat from the environment (Cheung and McLellan, 1998). Thus, the body thermal balance would be easily disrupted in such conditions with elevated body thermo-physiological loading (Kenny and Jay, 2013). When the core temperature reaching 40 °C, cellular damage occurs rapidly, initiating a cascade of events that may lead to organ failure and possible fatality (Bowler, 1981).

In recent years, scientists have increasingly moved their research attention away from a focus on macro-environment cooling (i.e., using air-conditioning) to personal micro-environment cooling (e.g., using personal cooling clothing) (Tham and Pantelic, 2010). Generally speaking, personal cooling strategies (PCSs) are energy saving, flexible and user-friendly. Electric fan is a direct cooling strategy, and proved to be effective below some temperature limits (Ravanelli et al., 2015). Nevertheless, non-portable electric fans have a limited application to active people (Saunders et al., 2005). Portable personal cooling clothing (PCC) may thus serve as an alternative measure to mitigate body heat strain in the general population during heatwaves (Gao et al., 2012; Chan et al., 2015).

PCC utilizes cooling sources incorporated into clothing to supply cooling effect to the human body and thereby promote body heat dissipation (Gao et al., 2010a). Various types of PCC have been developed during past few decades. They could generally be divided into five categories based on the type of cooling sources: cooling clothing equipped with phase change materials (PCMs) (Gao et al., 2010a; Lu et al., 2015; Song and Wang, 2016; House et al., 2013; Kenny et al., 2011), evaporative cooling clothing (EvapCC) (Rothmaier et al., 2008), liquid cooling clothing (LiqCC) (Guo et al., 2015; Bartkowiak et al., 2015; Kaufman et al., 2001), air cooling clothing (AirFC)

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(Mclellan et al., 1998; Barwood et al., 2009 ; Yang et al., 2012; Chinevere et al., 2008; Hadid et al., 2008) and hybrid cooling clothing incorporated with multiple cooling sources (Cheuvront et al., 2008). PCMs (e.g., frozen gels and ice packs) absorb body heat during phase change. The cooling effect of PCMs mainly relies on the melting temperature and heat fusion, as well as the mass and body coverage area. AirFC utilizes circulated natural or cold air to enhance evaporative or/and convective heat exchange. AirFC may be engineered by either sewing arrayed fine hoses or embedding small air ventilation fans into clothing. LiqCC utilizes the positive temperature gradient between the human skin and the liquid to promote heat dissipation through conduction/convection (Caldwell et al., 2012; Kim et al., 2011). LiqCC is normally developed by incorporating a network of fine tubes into clothing and placed in close contact with the human skin. The refrigerating system pumps cooling liquid (such as water) to the tubing system, and the coolant is circulated in tubing loops to take away excessive body heat by conduction. Hybrid cooling combines multiple cooling sources (e.g., liquid and air cooling sources) to provide cooling so as to dissipate body heat (Semeniuk et al., 2005; Barwood et al., 2009; Lai et al., 2017; Song et al., 2016). EvapCC absorbs body heat by evaporating stored moisture inside clothing, which is normally light (< 1.0 kg), cheap and convenient to use.

Almost all documented studies have focused on cooling effects of PCCs in such specific fields as firefighting, military, and biological and chemical protection fields where the PCC is worn under protective clothing (Reffeltrath et al., 2006; Vellerand et al., 1991; Hadid et al., 2008). Few studies have been reported to investigate the effect of wearing PCC on the general public during heatwaves. The general public normally wear the PCC as a clothing outer layer. The cooling effect of the PCC worn as the outer layer might be different from that of PCC being used as the interlayer because the heat exchange between PCC and the environment is more enhanced compared to the case where PCC is worn underneath the clothing outer layer. Also, sweat evaporation is less restricted when PCC is worn as an outer layer (Teunissen et al., 2014).

The main purpose of this study was to examine human thermophysiological responses while using four different cooling strategies, i.e., EvapCC, LiqCC, AirFC, and a hybrid personal cooling clothing system based on EvapCC and AirFC (i.e., EvapCC & AirFC), during heatwaves. Besides, the effects of air temperatures and relative humidity on the cooling effectiveness of the four PCCs were discussed. The finding of this study could provide solid guidelines for the general population to select the most appropriate cooling strategy to alleviate body heat strain in various heatwave conditions.

2. Methodology

2.1. Cooling strategies

A polyester t-shirt, cotton short pants and cotton briefs (with a total thermal insulation of 0.69 clo) were used as the basic clothing ensemble and used in all tests (see Fig. 1).

2.1.1. Air fan cooling (AirFC)

A mean constant airflow of 1.0 ± 0.2 m/s was generated at the face and chest regions of the manikin by placing an electric fan (model: SF-45 MV-1V, Suiden Co. Ltd., Osaka, Japan) at the front of the manikin at a distance of 1.0 m. The airflow was measured using a hot wire anemometer (Fluke 923, Fluke Corp., Everett, WA) (see Fig. 1).

2.1.2. Evaporative cooling clothing (EvapCC)

An evaporative cooling vest (HyperkewlTM, TechNiche International, Vista, CA) comprised of a quilted nylon outer layer with HyperKewl™ polymer which was able to absorb, store and release water, a water-repellant nylon liner and an elastic trim made of cotton and polyester. The EvapCC was prepared according to the following steps before use: the clothing was soaked into the tap water (water temperature: 25 °C) for 3 min, it was then taken out from the water and squeezed to remove excess moisture. The total weight of EvapCC (with no water/ice) was 0.88 kg. The total thermal insulation of the dry vest and basic ensemble is 0.73 clo.

2.1.3. Evaporative cooling clothing + Air fan cooling (EvapCC & AirFC)

The EvapCC was used together with AirFC to enhance moisture evaporation, and the detailed descriptions of EvapCC and AirFC are the same as the above.

2.1.4. Liquid cooling clothing (LiqCC)

A liquid cooling vest incorporated with a network of fine hoses (the diameter of the hose is 0.5 cm, and the distance between each two adjacent hoses is 3.0 cm) sandwiched between two-layer polyester mesh fabrics, and was held in close contact with the body by adjusting straps at both body sides. A backpack for storing an ice pack cooling reservoir (i.e., containing a mixture of 1.5 kg ice and 1.0 kg water) was connected to the inlet and outlet tubes, and a pump and batteries were also located in the backpack. The cold water was pumped from the reservoir and circulated in the tubes. The total weight of LiqCC (including water, ice, backpack, pump and battery) is 7.0 kg. The total thermal insulation (cooling system together with the basic ensemble) of the LiqCC (excluding cooling sources, pump and battery) is 0.75 clo.

2.2. Adaptive manikin

Thermal manikins may be operated in the constant temperature, constant heating power or the comfort mode (Oliveira et al., 2008). A sweating manikin that operated in the constant temperature mode could be used to determine heat removal rate and cooling duration of personal cooling systems (ASTM-F2371, 2016). Unfortunately, the test method is proved to yield unrealistically high cooling rates for air cooling systems due to a fully saturated fabric skin surface was used during testing and also, the relative humidity in the climatic chamber was relatively low. Previous studies (Gao et al., 2010b; Richards et al., 2006) have revealed that existing operating modes were unable to simulate thermophysiological behaviour of human and the coupling of manikins with thermoregulation models was desired. Based on the main objective of this study, the adaptive manikin method was selected. An adaptive manikin is able to predict human thermophysiological responses (e.g., skin and hypothalamic temperatures, blood flow, sweating rate) while using different personal cooling strategies in various thermal environments (e.g., transient and steady conditions). In this study, a 'Newton' type adaptive manikin (Thermetrics LLC, Seattle, WA) was used. For the 'Newton' adaptive manikin, the coupling of the thermal manikin with a physiological model is based on an iterative data exchange between the manikin and the thermoregulatory model. The manikin only provides the boundary layer interface to the clothing and ambient environment, i.e., the heat transfer between the body surface and its environment is measured by the manikin rather than being predicted by the model. The heat transfer within the human body is still predicted by the thermoregulatory model. The measured real-time manikin boundary heat loss (between the body shell and environment) is applied as the feedback to the thermoregulatory model to predict the physiological responses for the next time interval (Psikuta et al., 2013). Thus, the only feedback parameter to the thermoregulatory model is the manikin surface heat flux (which is characterized by the segmental heating power of the manikin and is recorded by the ThermDAC® manikin controlling software). The skin temperature and sweating rate predicted by the 'Fiala' thermoregulatory model (Fiala et al., 1999; Burke et al., 2009) are used to control the manikin. Other physiological parameters such as the hypothalamic temperature, skin blood flow, and body heat storage are computer predictions only. Although human thermoregulatory models have been widely used to assess human and clothing performance, existing simplified clothing

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