Journal of Thermal Biology 69 (2017) 311–318

Contents lists available at ScienceDirect

Journal of Thermal Biology

journal homepage: www.elsevier.com/locate/jtherbio

Comparison of heat strain recovery in different anti-heat stress clothing ensembles after work to exhaustion

Yijie Zhao[a], Wen Yi[b,*], Albert P.C. Chan[a], Daniel W.M. Chan[a]

[a] Department of Building and Real Estate, Hong Kong Polytechnic University, Hong Kong, China
[b] School of Engineering and Advanced Technology, Massey University, Auckland, New Zealand

ARTICLE INFO

Keywords:
Anti-heat stress clothing ensembles
Physiological and perceptual strain
Rate of recovery

ABSTRACT

A hot environment combined with physically demanding tasks can subject workers to a higher risk of heat stress. A series of regulations and guidelines have been proposed to design appropriate anti-heat stress work uniform to reduce body heat strain. The present study aimed to examine heat strain recovery in different anti-heat stress clothing ensembles after work to exhaustion in the heat. 10 healthy males performed intermittent treadmill running/walking to exhaustion, followed by 30 min passive recovery sitting in a climatic chamber, which simulated the hot and humid outdoor environment (34 °C temperature, 60% relative humidity, 0.3 m/s air velocity, and 450 W/m^2 solar radiation). The participants took part in five wear trials in counter-balanced order, including Sportswear, CIC Uniform, NEW Uniform, ICEBANK Cooling Vest, and NEW Cooling Vest, which have different levels of cooling capacity. Core temperature, skin temperature, heart rate, sweat loss, ratings of perceived exertion, and thermal sensations were measured throughout the entire heat exposure period. Physiological heat strain indices, including the physiological strain index (PhSI) and the perceptual strain index (PeSI), were used as a yardstick to quantify and compare the rate of recovery. Significantly lower physiological strain was observed in the newly developed NEW Uniform and NEW Cooling Vest groups compared with the commonly worn CIC Uniform group during recovery. At the end of the recovery period, participants in NEW Cooling Vest achieved the highest recovery (42.18% in PhSI and 81.08% in PeSI), followed by ICEBANK Cooling Vest, Sportswear, NEW Uniform, and CIC Uniform. The cooling capacity of anti-heat stress clothing ensembles and the recovery time significantly affect the rate of recovery in PhSI and PeSI, which may benefit the industry by formulating the appropriate work–rest schedule by considering the clothing effect.

1. Introduction

Physical labor in a hot and humid environment poses a high risk of heat stress on industrial workers, which can lead to increasing health and safety hazards. Heat stress-induced physiological and mental fatigue impairs work productivity. Workers become distracted from tasks or even ignore safety procedures because of intensive confusion, irritability and emotional stress caused by increased cardiovascular and thermoregulatory strain (Chan and Yi, 2016).

Administrative and engineering controls have been proposed to alleviate heat stress, including reasonable work arrangements (i.e., scheduling intermittent recovery/rest periods in between bouts of work), heat acclimatization program, rehydration, provision of ventilation, shelters, air-conditioning and heat-relief clothing. Intermittent recovery/rest, as an administrative control, has been used in many construction sites. Recovery helps restore the physiological and psychological states of the body, potentially allowing individuals to return to their pre-fatigue condition (Versey et al., 2013). Evidence from a number of industrial settings indicated that taking frequent short rest breaks is effective against fatigue, and good for work performance (Tucker, 2003). Workers can benefit from rest breaks, as evidenced by improved discomfort ratings and production rate (Dababneh et al., 2001; Morioka et al., 2006). Moreover, the injuries and accident risks following rest breaks were effectively reduced (Tucker et al., 2003). Simulations have been conducted to examine the optimal recovery after a period of continuous work, which balanced productivity demands with occupational health and safety concerns (Carnahan et al., 2000; Chan et al., 2012b, 2012c; Yi and Chan, 2014).

Construction work is difficult because of heat exposure, such as tasks on the floor/roof that expose workers to direct sunlight and practices in a confined place with poor ventilation. During the recovery period, the body core temperature of workers cannot return/decrease to a satisfactory value or may even continue to increase under such a hot environment if no cooling intervention is implemented (Barr et al.,

* Corresponding author at: School of Engineering and Advanced Technology, Massey University, Auckland, New Zealand.
E-mail address: yiwen96@163.com (W. Yi).

http://dx.doi.org/10.1016/j.jtherbio.2017.09.004
Received 2 April 2017; Received in revised form 13 September 2017; Accepted 13 September 2017
Available online 15 September 2017

Table 1
Anti-heat stress clothing ensembles and associated thermal properties.

Condition	Description	Cooling power (W/m^2)	R_{et} ($Pa\ m^2/W$)	I_t ($°C\ m^2/W$)
Sportswear (Chan et al., 2016b)	A commercially available unified sportswear (a T-shirt and a pair of shorts)	105.54	15.56	0.14
ICEBANK Cooling Vest (Chan et al., 2016b)	Commercially available cooling vest (a two-layer cooling vest incorporating three ice gel packs and a pair of ventilation fans), the ICEBANK Cooling Vest was worn over the sportswear during the test	124.76	13.93	0.12
CIC Uniform (Chan et al., 2016a)	CIC construction uniform (a polo T-shirt and a pair of long trousers)	94.25	18.33	0.17
NEW Uniform (Chan et al., 2016a)	The newly developed construction uniform (a polo T-shirt and a pair of long trousers)	100.95	16.96	0. 16
NEW Cooling Vest (Yi et al., 2017b)	The newly developed cooling vest (a two-layer cooling vest incorporating eight PCM packs and a pair of ventilation fans), the NEW Cooling Vest was worn over the newly developed uniform during the test	130.91	12.53	0.11

2009; Bennett et al., 1995; Bishop et al., 1991; Kim et al., 2011b). Cooling interventions, including fanning, ventilation, air-conditioning, cooling garments, and hand and/or forearm immersion, have been widely used in civilian and military sectors. Anti-heat stress clothing ensemble, viewed as a portable and personal cooling intervention, can be appropriate and practical to use in construction workplaces, including elevated platform, limited space, uneven ground, and lack of electricity. Previous studies reported that the use of cooling suits (in the form of ice vest, air ventilation garment, and liquid cooling garment [LCG]) during the recovery period could significantly reduce body temperatures and extend the subsequent work duration (Amorim et al., 2010; Barwood et al., 2009; Bennett et al., 1995; Cadarette et al., 2003; House et al., 2013; Kim et al., 2011a, 2011b). Although many studies have evaluated cooling clothing in a work–rest protocol (i.e., time and duration of intermittent recovery between bouts of work was predetermined), work on the degree of recovery achieved during rest was less examined or quantified. Chan et al. (2012b, 2012c) examined the recovery from heat strain by using the heat strain index (i.e., physiological strain index [PhSI]) as a yardstick to calculate the rate of recovery over recovery time. Nevertheless, only one summer clothing scenario (i.e., a short-sleeved cotton shirt and a pair of long trousers) was involved in their experiments. Anti-heat stress clothing ensembles, particularly for the active cooling garments, can create a cooler microclimate between the body surface and the clothing compared with ambient environment, thereby reducing heat strain and potentially accelerating recovery. Consequently, whether different anti-heat stress clothing ensembles can influence the rate of recovery from heat strain besides recovery time remains to be determined.

Heat strain indices have been developed to examine the degree of heat strain imposed on an individual (Gallagher Jr et al., 2012). Empirical indices are constructed based on objective and subjective strain measurements (Epstein and Moran, 2006). Moran et al. (1998b) developed the PhSI, which incorporates thermoregulatory (i.e., body core temperature) and cardiovascular (i.e., heart rate) strain measurements, to quantify the physiological strain that individuals experience during work in the heat. The PhSI can be used anytime, including the recovery/rest periods, whenever certain parameters (i.e., core temperature and heart rate) are recorded. This index is able to rate and compare the heat strain between different combinations of climate and clothing quantitatively. Under field conditions, direct measures of core temperature and heart rate will be impractical and inconvenient because of the intrusive measurement and expenses (Rowlinson and Jia, 2014). By analogy of the equation of Moran et al. (1998b), the perceptual strain index (PeSI) was developed by Tikuisis et al. (2002), which combines the ratings of perceived exertion (RPE) and thermal sensation (TS), could be a feasible and alternative approach to assess the level of heat strain. The validity and applicability of this index to differentiate the level of strain under a range of heat exposures have been verified in the controlled environmental chamber and field study (Chan and Yang, 2016; Hostler et al., 2009; Petruzzello et al., 2009; Tikuisis et al., 2002; Wright et al., 2013; Yang and Chan, 2015). The PhSI and PeSI are able to depict the combined strain represented by the thermoregulatory and cardiovascular systems. The two indices will be included in this study to examine heat strain recovery from the objective and subjective perspectives comprehensively. The comparison between PhSI and PeSI will provide reference for field studies, in which objective physiological measurements/data are unavailable and only PeSI is obtained.

Anti-heat stress clothing ensembles, such as sportswear (consists of a T-shirt and a pair of shorts), construction uniform (consists of a polo T-shirt and a pair of long trousers), and cooling vest, have been introduced to for hot summer days. Our previous have studies focused on product testing, in which paired comparison was conducted between the newly developed anti-heat stress clothing ensemble and the control condition (Chan et al., 2016b; Yi et al., 2017a, 2017c). By contrast, the present study concentrated on comparing the rate of heat strain recovery after a period of exercise by using anti-heat stress clothing with different cooling power. The objective of this study was twofold: (1) to examine the effectiveness of anti-heat stress clothing ensembles in alleviating heat strain and accelerating recovery after a period of work to exhaustion and (2) to compare the rate of recovery in PhSI and PeSI over time with different anti-heat stress clothing ensembles.

2. Material and methods

2.1. Anti-heat stress clothing ensemble

Commercially available anti-heat stress clothing ensemble, including Sportswear, CIC Uniform, and ICEBANK Cooling Vest, and newly developed anti-heat stress clothing ensemble, including NEW Uniform and NEW Cooling Vest, were evaluated in the present study (Table 1). The Sportswear, CIC Uniform, and ICEBANK Cooling Vest were commercially available clothing ensembles, whereas the NEW Uniform and NEW Cooling Vest were tailor-made anti-heat stress clothing ensembles for the construction industry in our research project (Chan et al., 2016a; Yi et al., 2017b). ICEBANK Cooling Vest and NEW Cooling Vest were viewed as active cooling clothing, which utilizes cooling sources (e.g., cooling packs and ventilation fans) to increase conductive, convective and evaporative cooling, whereas Sportswear, CIC Uniform, and NEW Uniform were viewed as passive cooling clothing, which relies on natural air movement between the body surface and the clothing to facilitate evaporative heat dissipation (Selkirk et al., 2004). A total of 0.42 kg ice gel (at a melting temperature of 0 °C, in 3 packs) with a covering area of 297 cm^2 was included in the ICEBANK Cooling Vest; a total of 0.64 kg phase change material (PCM) (at a melting temperature of 28 °C, in 8 packs) with a covering area of 722 cm^2 was included in the NEW Cooling Vest (Yi et al., 2017b). The ventilation unit (a pair of fans and a piece of battery) of the ICEBANK Cooling Vest could provide a constant air flow of 12 L/s for up to 4 h,