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# Analysis of heat stress associated with wearing chemical protective clothing using a numerical model

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Keywords: Heat stress, chemical protective clothing, core temperature, tolerance time

*Introduction* Chemical protective clothing (CPC) is designed to effectively eliminate the interaction of hazardous chemical/biological agents with the human body. However, thermal protection and thermal comfort are two major conflicting factors for protective clothing. The intrinsic properties of high evaporative resistance greatly restrict heat dissipation mechanisms, which could create heat strain burden and reduce task efficiency as well as range-of-motion, especially when wearers are exposed to hot environments with high level of working intensity (Lee and Obendorf, 2002). It is therefore a critical need to investigate the human physiological responses and heat stress associated with CPC for reducing heat-related illness and improving task efficiency. Human trials were performed to investigate heat stress through indices such as tolerance time, heart rate, heat storage, and sweating rate. However, these previous studies dealing with heat stress in CPC focused on specific task, garment, and environment. Additionally, the obtained results from these studies were not transferable to wearers in other garments or environmental conditions (Adams et al., 1994). Thus, a mathematical model was proposed in this study to provides a systematic approach to analyze the effects of environmental conditions, clothing properties, and activity intensities on heat stress. This work offers a reasonable prediction of heat stress of CPC and can provide guidance for the design of CPC.

*Methods* A human-clothing-environment model was applied to predict the physiological responses using human/clothing/environment parameters such as metabolic rate, thermal insulation, evaporative resistance, ambient temperature, relative humidity, and wind speed. The human body was divided the into 20 segments, and each segment was comprised of four layers including core, muscle, fat, and skin layer. The central blood compartment exchanged heat with all other nodes through convection. The model was comprised of three systems: a passive system predicted heat transfer within the human body and that with its environment through evaporation, radiation, convection, and conduction; an active system simulated human thermoregulation through sweating, shivering, vasoconstriction, and vasodilation; a clothing system calculated the effect of clothing properties on heat exchange between human body and environment.
Core temperature is one of the most important physiological response parameter, and is a critical indicator of heat stress. The tolerance time was calculated by the length of time until the core temperature reaches 38.5 $^{o}$C (McLellan, 2001).
A type of CPC (level C) was selected and the clothing properties were measured by a sweating thermal manikin in climate chamber. The thermal insulation and evaporative resistance of the CPC were 0.19 $m^{2o}C/W$ and 603.47 $Pa^{o}C/W$ in static condition, and 0.15 $m^{2o}C/W$ and 364.19 $Pa^{o}C/W$ with speed of manikin movement 1.0 m/s, respectively.

*Results and discussion* The effects of ambient temperature, metabolic rate, and manikin movement on core temperatures were analyzed as displayed in Fig. 1. It was demonstrated that the core temperatures showed correlation with the ambient temperature and metabolic rate. At the ambient temperature of 30 °C, the predicted core temperatures with manikin movement of 1.0 m/s are slightly lower than those in static condition. It can be explained by the fact that the thermal insulation and evaporative resistance of CPC were changed as a result of walking movement. However, with higher ambient temperature of 40 °C, the effects of manikin movements were reduced significantly. Based on the recommended core temperature limit, the maximum exposure time was calculated (Fig. 2). It showed that the metabolic rate and ambient temperature significantly affect the tolerance time. When the metabolic rate increased from 300 $W/m^2$ (walking at 3 km/h without load) to 400 $W/m^2$ (walking at 4 km/h with load), the tolerance time reduced by 50% and 33% at the ambient temperature of 30 °C and 40 °C, respectively.

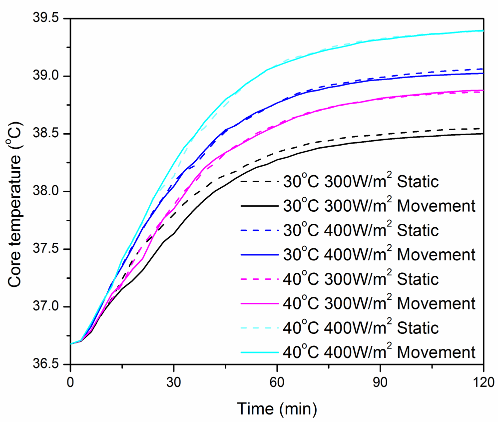


Fig 1. Simulated core temperatures in CPC

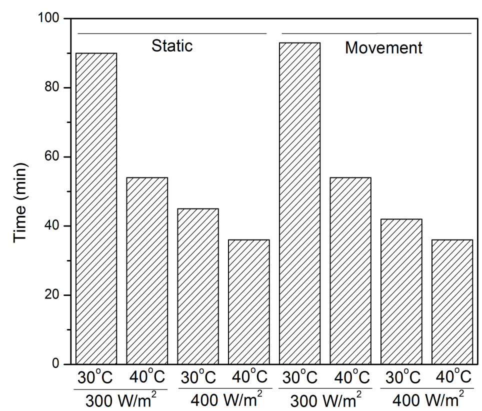


Fig 2. Simulated maximum exposure time

*Conclusion* A numerical model was applied to evaluate heat stress under different thermal environmental conditions, activity intensities, and the effect of movement status on clothing properties when wearing a typical CPC. It was concluded that the ambient temperature and metabolic rate is strongly associated with heat stress and reduced the tolerance time. Although the manikin movement greatly affected the thermal insulation and evaporative resistance of CPC, the effects of movement on heat stress can be neglected.

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