Thermal comfort of chemical protective clothing: effect of body movement on thermal resistance

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Introduction

Chemical protective clothing (CPC) is designed to protect wearers against any potential chemical hazards they might be exposed to. To achieve that, different approaches and materials have been applied to CPC. There are one-layer high density nonwoven materials for low level protection, coated woven or nonwoven materials for high level protection, as well as active carbon based multilayer materials commonly used for military (Anna, 2003). The major issue associated with wearing CPC is the heat stress to wearers: normally the better the protection, the higher the heat stress. Restricted to material, CPC mostly has the bulky one-piece coverall design to allow the maximum flexibility of movement and adding of self-contained breathing apparatus if necessary, which adds to the physical burden of users and heat stress indirectly (Hultzapple et al., 2012). To evaluate and/or redesign CPC to reduce heat stress, its thermal property－thermal resistance (Rct) should be well informed. However, the measurement of Rct per the standard ASTM F1291 (2015) is on a standing still manikin, which doesn't represent the real situation where users are usually constantly moving. In addition, only the whole-body Rct of clothing is reported, which may neglect the variance across different local body parts. Previous studies have found that body movement can reduce clothing Rct through the change of air gap thickness under clothing, pumping effect and the creation of local ventilation during movement, and the effect varies with different clothing materials (Havenith, Heus, & Lotens, 1990; Havenith & Nilsson, 2004). Nevertheless, those conclusions are made for normal clothing, not isolation clothing like CPC. Therefore, the purpose of this study was to investigate the effect of body movement on the whole-body Rct as well as localized Rct (Rct,l) of typical CPC made from different materials. The findings of this study will enhance the understanding of CPC thermal insulation dynamics and provide insights to material selection, design improvement, and test standard revision of CPC.

Method and Analysis

Three types of commercially available CPC were selected: MG－double layer (active carbon embedded foam/woven shell), permeable and high protection; D－single layer DuPont® Tyvek®, low permeability and protection; B－single layer DuPont® Tychem®, impermeable and high protection. They were all the same size and design. Their thermal resistance was measured per standard ASTM F1291 with the manikin standing still as well as walking at a speed of 45 double steps per minute. To simulate the real wear situation of CPC, the openings at the neck, wrist, and ankle were all sealed with tape during test. Uncovered body parts like face, head, neck, hands, and feet were excluded from the calculation of Rct. The whole-body and localized thermal resistance of the surface air layer of nude manikin (Ra, Ra,l) and those of CPC (Rct, Rct,l) at 17 local body parts (symmetrical parts were analyzed for only one side) under static and dynamic conditions were analyzed using Paired sample *t*-test with a significance level of 0.05.

Results and Discussion

The results showed significant effect of body movement ($p<0.05$) on the whole-body thermal resistance: Ra reduced 24%, Rct reduced 30%—39% depending on CPC type. As shown in Figure 1, localized thermal resistance can be quite different among local body parts. It is also significantly reduced by body movement. And the amount of reduction varies a lot with different

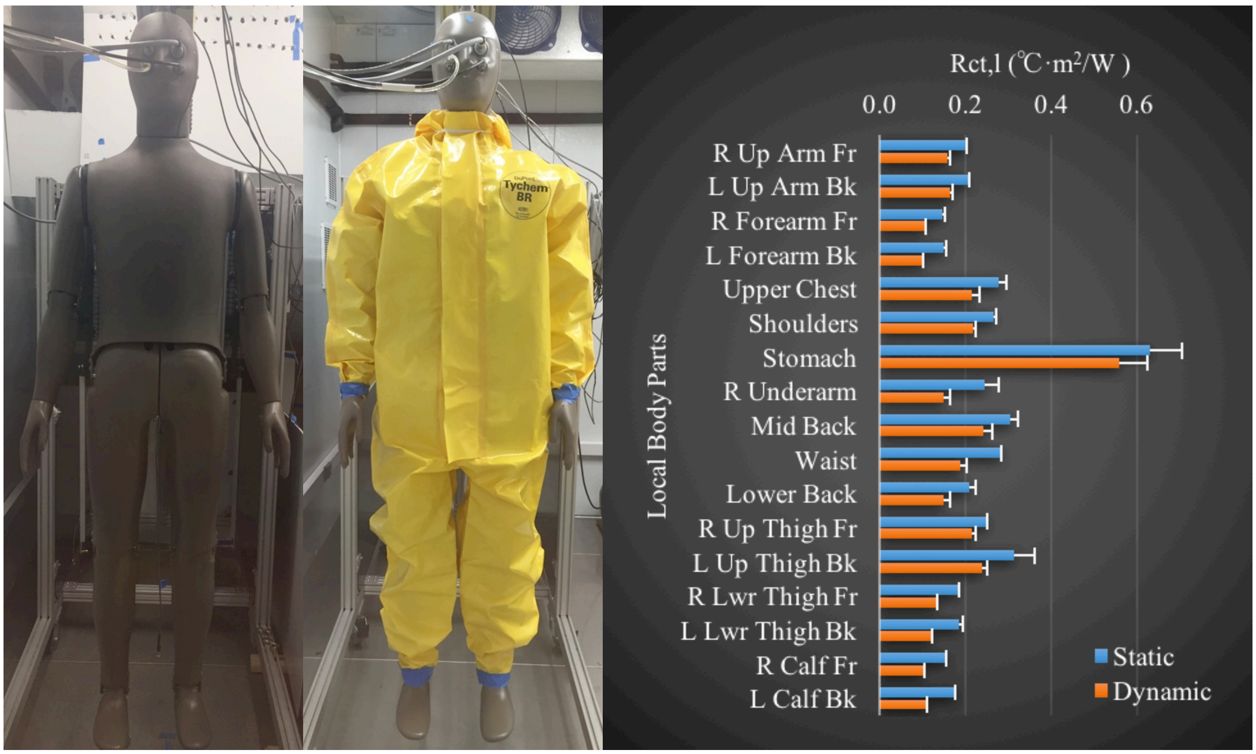

Figure 1. Nude manikin, manikin in CPC B, and localized thermal resistance of B

local body parts and CPC: Ra,l reduced 3%—46%; Rct,l reduced 13%—64% for MG, 8%—55% for D, and 11%—39% for B. This indicates a simple report of the whole-body thermal resistance does not provide full information for evaluating the thermal property of CPC. The difference in Ra,l could be contributed by 1) the uneven wind speed in the chamber, 2) the different surface area to volume ration of local body parts, and 3) local ventilation caused by arm and leg swing during body movement. While the difference in Rct,l is mostly the result of the uneven distribution of air gap over the whole body, and different local ventilation resulted from body movement. The largest air gap was found at the Stomach for all CPC, and hence the highest Rct,l. However, the materials of MG and D were limper than B. They draped better over the manikin form, and moved and misshaped more when the manikin was moving, hence larger change of air gap thickness and stronger pumping effect was manifested, which led to more reduction of Rct,l (MG: 48% and D: 64%). While B's coated material made it stiff and less likely move with body movements. Therefore, the reduction of Rct,l is much smaller (11%).

Conclusions

Body movement can significantly reduce the whole-body and localized thermal resistance of CPC by increasing local ventilation of the surface air layer, pumping effect, and changing air gap distribution under clothing. The amount of reduction may vary a lot with different CPC materials used and local body parts where CPC may fit differently. Therefore, information about localized thermal resistance and the potential interaction effect of body movement, material, and geometry design feature should always be provided and considered for better evaluation, redesign, and modeling of CPC regarding its thermal comfort.

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