The Effect of Air Permeability Characteristics of Protective Garments on the Induced Physiological Strain under Exercise-Heat Stress

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Objectives: The high values of thermal resistance ($R_{ct}$) and/or vapor resistance ($R_{et}$) of chemical protective clothing (CPC) induce a considerable thermal stress. The present study compared the physiological strain induced by CPCs and evaluates the relative importance of the fabrics’ $R_{ct}$, $R_{et}$, and air permeability in determining heat strain.

Methods: Twelve young (20–30 years) healthy, heat-acclimated male subjects were exposed fully encapsulated for 3 h daily to an exercise-heat stress (35°C and 30% relative humidity, walking on a motor-driven treadmill at a pace of 5 km h$^{-1}$ and a 4% inclination, in a work–rest cycle of 45 min work and 15 min rest). Two bipack CPCs (PC1 and PC2) were tested and the results were compared with those attained by two control suits—a standard cotton military BDU (CO1) and an impermeable material suit (CO2).

Results: The physiological burden imposed by the two bilayer garments was within the boundaries set by the control conditions. Overall, PC2 induced a lower strain, which was closer to CO1, whereas PC1 was closer to CO2. Air permeability of the PC2 cloth was almost three times higher than that of PC1, enabling a better heat dissipation and consequently a lower physiological strain. Furthermore, air permeability characteristic of the fabrics, which is associated with its construction and weave, significantly correlated with the physiological strain, whereas the correlation with $R_{ct}$, $R_{et}$, and weight was poor.

Conclusions: The results emphasize the importance of air permeability in reducing the physiological strain induced by CPCs.

Keywords: heat strain; heat stress; protective garments; thermal resistance; water vapor resistance

INTRODUCTION

Body temperature is the net result of the balance between heat gain and heat loss. As far as the equilibrium between heat gain and heat dissipation is maintained, body temperature will be controlled within the physiological limits. Once the rate of heat gain exceeds the rate of heat loss, body temperature will rise resulting in pathological processes that consequently might develop to heat stroke (Epstein and Roberts, 2011). To a great extent, the biophysical properties of clothing—thermal and vapor resistance—limit the ability to readily dissipate heat at a rate of its accumulation and thus limit the tolerance to heat stress (Goldman, 2001).
Chemical protective clothing (CPC) is designed to protect individuals from hazardous chemical agents. The materials used to provide this protection should either be impermeable to the hazardous agents or should incorporate an active layer that will absorb or disintegrate these agents. Current CPCs are, in most cases, manufactured either from an impermeable material or from a bilayer (bipack) cloth, in which the inner layer contains the absorbing active material and the outer shell has the capacity of physical stiffness and flame retardation. The structure of a CPC cloth induces a significant thermal stress and thereby thermal discomfort, especially because of trapped air between the cloth layers and special treatments of the fabrics, which result in a high value of thermal resistance (insulation) and/or a low value of water vapor permeability index ($i_m$)—high vapor resistance (Havenith, 1999). It is noteworthy that although heat and vapor resistances of CPC materials have been reduced by over 50% over the past decades, it has been claimed that this did not result in a major improvement in terms of heat strain for the wearer (Havenith et al., 2011).

In an attempt to alleviate the thermal strain derived from encapsulation in a CPC, two major strategies have been implemented and tested over the last four decades: (i) reducing the thermal resistance of the protective garment by manipulating its structure and design and (ii) using auxiliary cooling devices. Although the latter has been proven to be very effective in alleviating heat strain (Shapiro et al., 1982; Epstein et al., 1986), the added weight-bearing burden is a drawback of those systems (Epstein et al., 1986). Thus, manufacturing a CPC that is characterized by a low insulation and high water vapor permeability without negating its protective properties is a prerequisite for the user and a challenge for CPC developers.

Prior to marketing of a CPC, it must be evaluated to ensure that the added thermal strain is minimally greater than the current standards for the same level of thermal load. Comprehensive evaluation of CPCs begins with a biophysical assessment of the materials using a guarded hot plate to determine the thermal characteristics (static thermal resistance and water vapor permeability). Since thermal properties change once the materials have been constructed into a garment (Holmer, 2006), thermal characteristics are then evaluated on a thermal manikin wearing the CPC. Although these two levels of evaluation provide essential biophysical data, only human testing in controlled laboratory conditions appropriate for the conditions under which the CPC would be used if marketed can provide the necessary data on the physiological burden it imposes (O’Brien et al., 2011). In view of the above, the present study was designed to compare the physiological strain induced by CPCs and to evaluate the relative importance of the fabrics’ thermal resistance, water vapor resistance, and air permeability in determining heat strain vis-à-vis an impermeable suit and a cotton fabric clothing ensemble.

METHODS

Test subjects

Twelve young (age: $25 \pm 2$ years) healthy male subjects (weight: $70 \pm 9$ kg, height: $177 \pm 7$ cm, body surface area: $1.85 \pm 0.14$ m$^2$) with no prior recorded heat illness or heat intolerance were recruited from a pool of potential test subjects that exists in our Institute. The participants were physically active university students (but not professional or elite athletes). Prior to participation in the study, they were informed of the study’s nature, its purpose, and medical risks. Their final inclusion in the study was subjected to the medical clearance by the study’s physician and after having filled out and signed an informed consent form.

The Human Use Committee of the Sheba Medical Center approved the study protocol and procedures (SCM-7394-09).

Clothing ensemble

The tests were conducted under Mission Oriented Protective Posture 4 (MOPP4) configuration (fully closed garments, gloves, and facemask). Two bipack CPCs (PC1 and PC2), which were similar in structure, with an outer layer of a fire retardant cloth and an inner layer of activated charcoal, were tested. The two clothing materials differ in their thermodynamic properties. In an attempt to eliminate differences that may emerge from different tailoring styles (coveralls versus two piece garments, extra thickness due to pockets, etc.), all four garments were tailored as coveralls, with no pockets and they were worn over shorts and a T-shirt. The garments fit the participants’ anthropometry. In order to compare the physiological strain induced by these CPCs, boundary conditions were determined by comparing the results to
those induced by standard cotton military BDU (CO1) and an impermeable material suit (CO2).

Static thermal resistance \( (R_{ct}) \) and water vapor resistance \( (R_{ct}) \) of the four materials and air permeability were measured according to ISO standards 11092 (1993) and 9237 (1995), respectively; the physical and biophysical properties of the fabrics are summarized in Table 1.

**Acclimatization process**

The study was carried out during winter time (January–February) to eliminate possible differences in heat acclimation. Prior to experimental exposures, the test subjects underwent six consecutive days of an acclimatization process. Dressed in shorts and tennis shoes, the participants were exposed daily, in a climatic chamber, to ambient conditions of 40°C and 40% relative humidity (WBGT: 32°C; heavy heat load), walking for 120 min on a motor-driven treadmill at a pace of 5 km·h\(^{-1}\) and 4% inclination (oxygen consumption: 1.3 ± 0.2 l·min\(^{-1}\); metabolic rate: 426 ± 62 W). Throughout the period of heat exposure, the subjects’ body-core temperature [rectal temperature \( (T_{re}) \)] and heart rate (HR) were monitored continuously. Fluid consumption was ad libitum.

**Experimental design**

Following the 6 days of acclimatization, each subject participated in 4 days of experimental exercise-heat stress trials, wearing the four suits in a crossover design. Participants were exposed for 3 h in a heated climatic chamber set to ambient conditions of 35°C and 30% relative humidity (WBGT: 26°C; moderate heat load) and no wind while walking for 3 h on a motor-driven treadmill at a pace of 5 km·h\(^{-1}\) and a 4% inclination (426 ± 62 W; moderate work load) in a work–rest cycle of 45 min work and 15 min rest.

For medical safety reasons, during all exposures, an experienced medical technician was attended in the climatic chamber and a trained physiologist was in the adjacent control room.

**Physiological monitoring**

**Body-core temperature.** \( T_{re} \) was measured with a rectal thermistor (YSI-401) inserted ~10 cm beyond the anal sphincter. Temperatures were displayed continuously and viewed by the attending medical staff. Data were recorded automatically by the Biopac monitoring system.

**Skin temperature.** Weighted skin temperature was calculated from measuring skin temperature at three sites (chest, arm, calf) with skin thermistors (YSI-409) according to Burton (1935). In the context of the present study, this measure was used only to roughly estimate heat loss through clothing (see Discussion), according to the model presented by Gibson (2009).

**Heart rate.** Heart beats were monitored continuously and stored by a HR wristwatch (RS800, Polar, Finland). HRs were extracted from cumulative heart beats each minute.

**Physiological strain.** The Physiological Strain Index (PSI), as suggested by Moran et al. (1998), was used to compare the strain developed by the garments. The end-point strain was calculated from basal levels of HR and \( T_{re} \) and the peak values at the end of the third bout of exercise (average of the last 5 min of exercise).

**Fluid balance.** Nude body mass was measured before and after each trial on an electronic balance (±10 g). Fluid intake was ad libitum from a personal weighted flask (±10 g). If needed, the participants urinated into a calibrated cylinder (±10 ml). Sweat losses and dehydration percentage were calculated from the body mass measurements; the former, by adjusting for fluid intake and urine volume.

**Table 1. Physical and thermodynamic properties of garments under study.**

<table>
<thead>
<tr>
<th>Garment</th>
<th>Weight (g m(^{-2}))</th>
<th>Air permeability (mm ( \cdot ) sec)</th>
<th>Insulation ( R_{ct} ) (m(^2)K·W(^{-1}))</th>
<th>( \text{clo} ) (units)</th>
<th>Water vapor resistance ( R_{ct} ) (m(^2)Pa·W(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO1</td>
<td>186.0</td>
<td>96.3</td>
<td>0.11</td>
<td>0.71</td>
<td>29</td>
</tr>
<tr>
<td>CO2</td>
<td>238.5</td>
<td>0.0</td>
<td>0.21</td>
<td>1.35</td>
<td>162</td>
</tr>
<tr>
<td>PC1</td>
<td>598.7</td>
<td>23.6</td>
<td>0.31</td>
<td>2.00</td>
<td>81</td>
</tr>
<tr>
<td>PC2</td>
<td>402.8</td>
<td>68.3</td>
<td>0.21</td>
<td>1.35</td>
<td>61</td>
</tr>
</tbody>
</table>

\( 1 \text{ clo} = 0.155 \text{ m}^2\text{K}^{-1}\text{W}. \)
Statistics

The data are presented as mean values and the standard deviation of the mean. A one-factor (garment type) analysis of variance was used to evaluate any differences in physiological parameters between the CPCs. Pairwise correlations between physiological strain and the biophysical parameters were calculated using multivariate analysis (JMP statistic software, version 7). For all statistical analyses, the 0.05 level of significance was used.

RESULTS

The shaded area in Figs 1 and 2 presents the physiological boundaries set by the two control garments (CO1 and CO2); the lower limit is related to CO1 and the upper limit is related to CO2. Exposure to the specified experimental conditions resulted in a physiological strain as depicted by the change in the parameters that were monitored. During exercise, $T_{re}$ and HR rose, and during the resting period, a decrease in $T_{re}$ and HR was noted (Figs 1 and 2). As was anticipated, the physiological burden imposed by the two bilayer garments was within the boundaries set by the control conditions. However, there was a pronounced difference between PC1 and PC2. The physiological strain of PC1, as shown by the dynamics in $T_{re}$ and HR (Figs 1 and 2, respectively), was closer to those seen while wearing the impermeable suit (CO2), and PC2 showed similar physiological burden to CO1 (cotton suit).

The end point in $T_{re}$ (Fig. 3) and HR (Fig. 4) at each bout of exercise was plotted, where the shaded area depicts the boundaries conditions. A constant rise in these parameters is evident. At the end of the third bout of exercise, the average $T_{re}$ of PC1 and PC2 was 37.98 and 37.83°C, respectively. In parallel, the average HR of PC1 and PC2 was 142 and 131 bpm, respectively. The change (end point to initial values) in $T_{re}$ was 1.25 and 1.06°C and that for HR, it was 73 and 57 bpm for PC1 and PC2, respectively. Noteworthy, during the first bout of exercise, the rise in $T_{re}$ and HR paralleled and there was no significant difference between the physiological parameters, measured at the end of the first bout of exercise,
of the two tested suits or between them and the two control suits. Only at the end of the second bout of exercise, the physiological parameters parted and a significant difference ($P < 0.02$) between the two tested suits was evident. Only then, it was evident that the physiological strain induced by PC1 was similar to CO2 and that of PC2 was similar to CO1. Consequently, at the end of the experimental exposure, PSI, which combines the cardiovascular and thermoregulatory strains, was significantly higher for PC1 than for PC2 ($5.3 \pm 0.4$ and $4.7 \pm 0.1$ units, respectively) ($P < 0.02$).

Sweat production was similar for PC1 and PC2 ($2295 \pm 643$ and $2015 \pm 469$ g/h, respectively) and also did not differ dramatically from the two control suits ($1878 \pm 373$ and $2019 \pm 428$ g/h, for CO1 and CO2, respectively). Dehydration levels were negligible.

Finally, correlating physiological strain with the biophysical parameters that are summarized in Table 1 revealed a strong negative correlation between the change in $T_{re}$ ($\Delta T_{re}$) ($r = 0.99; P < 0.02$) and, consequently, PSI ($r = 0.94; P < 0.05$) only with air permeability.

**DISCUSSION**

In the present study, the effect on the physiological strain of two bilayer CPCs, which differ in their physical and biophysical characteristics, was tested in a human study. The boundary conditions were set as a cotton fabric garment (CO1) on the more favorable side and an impermeable fabric garment (CO2) on the less favorable side. In terms of heat loss through clothing, estimated according to Gibson (2009), CO1 enabled heat loss of ~135 W $^2$m versus ~23 W $^2$m for CO2 (~83% difference). It was expected that the physiological strain induced by a bilayer CPC will lay in between the strain induced by the two control garments and the relative strain of each of the tested CPC garments will be related to its biophysical characteristics. Overall, PC2 induced a lower strain than PC1. This was evident by the lower increase in $T_{re}$ and HR and, consequently, the lower end-point PSI.

The study was conducted under controlled environmental conditions that simulate situations under which the CPC would be used if fielded and, thus, provides the necessary data.
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on the actual physiological burden they impose (Havenith, 1999; O’Brien et al., 2011). Inherently, the static values of $R_c$ and $R_e$ reported in Table 1 do not reflect effective values for two reasons: (i) the curvature of the clothing on the body will have a larger surface area than the skin and, therefore, thermal resistance of clothing will be lower because of the garment design; and (ii) the pumping effect while walking reduces significantly the effective thermal and water vapor resistance properties of the clothing ensemble (McLellan, 1996; Havenith, 1999; Holmer et al., 1999; Sawka et al., 2001; Bouskill et al., 2002; ISO 9920, 2007; O’Brien et al., 2011). Choosing the right conditions for the study is not trivial. The environmental and metabolic conditions under which our study was conducted, on the one hand, to enable the participants to endure at least 3 h of exercise-heat stress and, on the other hand, to exhibit the differences between the garments. Many studies concluded that there are no real differences between different garments, just because the conditions were too harsh to demonstrate the differences in the clothing biophysical properties on body temperature regulation (Belding and Hatch, 1955; Montain et al., 1994; Bröde et al., 2008; Caravello et al., 2008). To this end, environmental conditions in the present study were not extremely hot, but simulated correctly the operational environment. Under the study’s conditions, average skin temperature (data not shown) was approximately the same as ambient temperature, reducing the sensible heat loss, whereas work rate and work/rest cycles enabled to endure the resultant heat stress.

The weights of the two CPCs were significantly higher than those of the two control garments. This is due to the mere fact that both CPCs were bilayer garments that also contain an active material embedded in between the cloth layers, whereas the control garments were monolayers. The thickness of the clothing ensemble and hence its weight is, in most cases, a function of the number of fabric layers and each added layer to the garment and the trapped air in between the layers will tend to exert an increase in total insulation (Montain et al., 1994; Havenith, 1999). Thus, theoretically, the two tested CPCs should exhibit similar (not identical)
insulation characteristics. The static insulation value of PC1 was, however, higher than that of PC2 (in terms of clo units: 2.00 versus 1.35), and that of CO2 was similar to PC2 (clo: 1.35). Thus, not only thickness determines the insulation properties of the garment but also its structure—weave and porosity—which determine the air permeability of the fabric (Holmer, 2006; Havenith et al., 2011).

The air permeability characteristic of the fabrics, which is associated with its construction and weave, significantly correlated with the physiological strain, whereas the correlation with $R_{\text{et}}$, $R_{\text{ct}}$, and weight was poor. Air permeability of PC2 was almost 70 times higher than the air permeability of CO2, although both garment materials had similar insulation properties, and air permeability of the PC2 cloth is almost three times higher than that of PC1. This is consistent with earlier studies that emphasized that the higher is the air permeability, the higher is heat loss through clothing (Holmer, 2006; Havenith et al., 2011). Indeed, a first-degree estimate of heat loss through clothing [based on Gibson’s (2009) model] was higher by ~25% for PC2 than PC1 (~64 W m$^{-2}$ versus ~49 W m$^{-2}$, respectively). In this respect, Havenith et al. (2011) concluded that ‘the effect of increasing air permeability may be stronger than improvements through the reduction of material thickness’.

The change in $T_{re}$ and HR during the first bout of exercise was similar for all four clothing ensembles, indicating a similar heat dissipation rate. Only during the next 2h of exposure, the differences between the two tested CPCs were evident. This is in accord with the dynamics in the physiological strain reported in many of the publications on CPCs (Montain et al., 1994; Caravello et al., 2008; O’Brien et al., 2011). Under the conditions of this study, where skin temperature was close to ambient temperature, the sensible heat exchange with the surrounding was negligible and the metabolic heat production consisted of the major part of accumulated heat that had to be dissipated ($E_{\text{req}}$) (Havenith, 1999). Therefore, a change in thermal resistance will not make much of a difference in regard to $E_{\text{req}}$. In contrast, a decrease in $R_{\text{et}}$ will affect favorably the maximal capacity of sweat evaporation,
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$E_{\text{max}}$ and consequently the reduction in the ratio $E_{\text{req}}/E_{\text{max}}$, indicating a lower heat strain (Levine et al., 2001). According to this analysis, during the earlier stage of exposure, humidity is built up inside the clothing (microenvironment) and $E_{\text{max}}$ is, thus, similar in all trials. At the later stages, the increased conductivity of wet clothing results in a decrease in clothing insulation, enabling increase in heat loss (Kakitsuba et al., 1988; Kenney et al., 1993; Lotens and Havenith, 1995; Chen et al., 2003). The increase in evaporative heat loss from the surface or within the clothing, possibly combined with condensation in outer layers, much dependent on the garments' air permeability (Lotens et al., 1995). Consequently, water vapor resistance and, therefore, the documented differences in the physiological strain of the various garments are time dependent. The importance of porosity in evaporative heat loss is further corroborated by the observation of Kakitsuba and colleagues (1988), who noted that evaporative heat loss is decayed exponentially as moister is being built up within the clothing. Thus, real differences between the suits will be evident only over a longer period of time, as in the case of the present study.

The results emphasize the importance of air permeability in reducing the physiological strain induced by CPCs. However, one should note that the study is limited in two aspects of its design. First, it was conducted under only one condition of exercise-heat stress, chosen to be endured for 3 h wearing a bipack PC. Hence, the findings cannot be extrapolated for other conditions (higher heat stress or work rates). Second, though it was shown that PC2 is an advantageous material over that of PC1, the practical perspective of the results should further be explored. Under the conditions of the study, during the second and third bout of exercise, the rate of change in $T_{re}$ and HR for PC1 and PC2 was rising almost linearly (Figs 3 and 4). Thus, under the conditions of the present study—45/15 min work–rest cycles and moderate/heavy heat load—a rough estimate is that wearing a bilayer CPC, similar in biophysical properties as tested in the present study, can be endured for at least 6 h before reaching physiological safety limit of $T_{re} = 38.5^\circ$C.

CONCLUSIONS

Clothing affects the level of heat stress to varying degrees. While convective and radiative heat exchange plays a minor role in hot environment, evaporative resistance is the most important factor in maintaining thermal balance. It seems that air permeability characteristic of clothing material is the major determinant in this respect since it enables better cooling. It can, thus, be concluded from the present data that for clothing material with similar static thermal resistance, the higher the air permeability value is, the lower is the physiological strain, which is in accord with the conclusion made by Havenith et al. (2011).

ETHICAL STANDARDS

We certify that all applicable institutional and governmental regulations concerning the ethical use of human volunteers were followed during the course of this research. The Human Use Committee of the Sheba Medical Center approved the study protocol and procedures (SCM-7394-09).

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

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REFERENCES


