DIFFERENCES IN TOTAL EVAPORATIVE RESISTANCE DUE TO ENVIRONMENT AND ACTIVITY AS OBSERVED FOR THREE CLOTHING ENSEMBLES

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INTRODUCTION

A valuable means of understanding how clothing may affect heat stress is to quantify the resistance to dry and evaporative heat exchange. Wear tests in a controlled laboratory environment provide an opportunity to evaluate complete ensembles in a realistic situation without introducing the confounding factors of an uncontrolled environment and metabolic rate. Kenney et al. (1) proposed a wear test method that relied on progressive increases in heat stress to an inflection point where the required rate of evaporative cooling matched the maximum rate that can be supported by the combination of clothing and environment. At the inflection point, Equation 1 is true.

$$(P_{sk}-P_a) / R_{e-t} = (M - W) + (C + E)res + (T_{db}-T_{sk}) / I_t - S$$

where P_{sk} is average water vapor pressure on the skin; P_a is ambient water vapor pressure; R_{e-t} is total evaporative resistance of the clothing including air layer; M is metabolic rate; W is external work accomplished; $(C + E)_{res}$ is combined convective and evaporative heat exchange in the lungs; T_{db} is dry bulb temperature; T_{sk} is average skin temperature; I_t is total insulation of the clothing including air layer and S is rate of heat storage in the body (average over preceding 20 min).

All the terms in the equation can be measured or estimated at the inflection point except the two clothing factors: total insulation and total evaporative resistance. Following Kenney et al. (1), finding the inflection points in a warm/humid environment and a hot/dry environment provides two equations and thus permits the experimental determination of I_t and R_{e-t}. This approach assumes an independence of thermal characteristics over environmental conditions. The experimental trials reported here examine the simultaneous equation approach to estimating the thermal characteristics. It further examines the effects of environment and metabolic rate on the total evaporative resistance of three clothing ensembles.

MATERIALS AND METHODS

The thermal characteristics of 3 clothing ensembles were evaluated by progressive increases in heat stress in search of the inflection point. One ensemble was ordinary cotton work clothes (open at neck). The other 2 ensembles were limited-use coveralls with hood that were taped at the cuffs: one made from DuPont Tyvek® 1422A fabric and one made from a polypropylene (SMS) fabric.

The limited-use coveralls were examined twice during 2 studies separated by a couple of years (2).

The 3 test protocols were as follows. For the protocols in which the climate was changed, treadmill speed and grade were set to elicit a metabolic rate of

Table 1. Estimates[1] of total insulation[2] and evaporative resistance[2]

Ensemble	*Study 1* I_t	*Study 1* $R_{e\text{-}t}$	*Study 2* I_t	*Study 2* $R_{e\text{-}t}$
Cotton Work Clothes (n = 4)	0.0443 0.0274 62	0.0096 0.0049 51	-	-
SMS Polypropylene (n = 5)	0.0838 0.0269 32	0.0109 0.0031 29	0.0382 0.0400 105	0.0072 0.0053 73
Tyvek 1422A (n = 5)	0.1153 0.0811 70	0.0162 0.0058 36	0.0138 0.0212 154	0.0052 0.0100 193

[1] Determined using the method of Kenney et al. (1). Values in each block are mean, standard deviation, and coefficient of variation. Values from a second study are provided for SMS and Tyvek 1422A.

[2] I_t is in units of °C·m^2·W^{-1}; $R_{e\text{-}t}$ is in units of kPa·m^2·W^{-1}

about 160 W·m^{-2} at a zero grade (level). For *Hot, Dry Climates (HD)*, the starting dry bulb and psychrometric wet bulb temperatures were 34°C and 18°C (20% relative humidity [RH]). Once a physiological steady state was achieved, the ambient temperature was increased 1°C every 5 min while RH was maintained at 20%. For *Warm, Humid Climates (WH)*, the starting dry bulb and psychrometric wet bulb temperatures were 34°C and 18°C (20% RH). Once a steady state was achieved, the psychrometric wet bulb temperature was increased 0.7°C every 5 min until the RH reached 70%. Then, the dry bulb temperature was increased about 0.7°C every 5 min while the RH was maintained at 70%. For *Metabolic Rate, Fixed Climate (M)*, T_{db} was set at 32°C and T_{pwb} was set at 26°C (60% RH) for the experiment. Initial treadmill speed and grade were set to elicit a low metabolic rate (about 120 W·m^{-2}). Then treadmill speed was increased 0.045 m·s^{-1} every 5 min.

RESULTS

The studies were undertaken to explore the thermal characteristics of 3 clothing ensembles. Following the method of Kenney et al. (1) and accounting for heat storage, the simultaneous estimation of I_t and $R_{e\text{-}t}$ from the HD and WH protocols was undertaken. The results are presented in Table 1. For the 2 ensembles with repeated studies (SMS and Tyvek®), the mean values differed considerably, but among all the possible comparisons only the 2 Tyvek® coveralls were significantly different ($P < 0.05$) for either I_t or R_{e-t}. The coefficients of variation among subjects within a data set were between 30 and 200%, which made finding differences difficult.

When a value for I_t was assigned for each ensemble, Equation 1 can be used to estimate total evaporative resistance for each protocol. Values that were 55% of estimated intrinsic insulation plus the boundary layer of air were used to account for clothing ventilation (CV) (2). The results of this process are provided in Table 2. The CVs for R_{e-t} ranged from 7 to 36%, suggesting a greater stability in the estimation.

Using assigned values of I_t and a two-way ANOVA (5 ensembles and 2 protocols), a statistically significant difference in R_{e-t} was found across all 5 ensembles between HD and WH ($P = 0.01$) (0.0155 vs. 0.0128 $kPa \cdot m^2 \cdot w^{-1}$, respectively). On the other hand, there was no apparent difference between HD and WH for the 2 data sets that did not include the metabolic protocol (Tyvek®-1 and SMS-1). For the 3 ensembles for which the metabolic protocol employed, there was a significant difference between HD and both WH and M (two-way ANOVA, $P = 0.0001$) (0.0171 vs. 0.0118 and 0.0130).

DISCUSSION

For the estimation of clothing thermal characteristics, the technique described by Kenney et al. (1) has some variability as seen in the different results between studies and the wide variation among subjects. These differences diminish when an estimate for I_t is used. First, the selection of values for I_t was based on estimates of intrinsic insulation and the air layer from published data and was reduced by 45% for the effects of body motion and wetting of the garments (1). The values were not much different from those reported elsewhere (1). Second, the determination of R_{e-t} is not affected much by the insulation estimation (2).

The estimated value of insulation allows for greater discrimination among ensembles and exploration of the effects of protocol. Compared with the HD protocol, (1) WH had a lower R_{e-t}, which may be due to higher heat transfer from evaporation/condensation cycles within the clothing layers and (2) the elevated metabolic rate associated with the M protocol lowered R_{e-t} due to pumping factors.

CONCLUSIONS

It appeared that (1) simultaneous derivation of I_t and R_{e-t} was subject to some instability, (2) evaporative resistance was greater when a higher ambient temperature existed and (3) the increased activity associated with the metabolic trials lowered the evaporative resistance from the HD condition.

REFERENCES

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