Gross Partitional Thermal Balance With Protective Clothing

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INTRODUCTION

The precise quantification of thermal flux via different routes of energy exchange between man and his environment is more difficult to accomplish with the wear of individual garmentry (1). Although *static*, bench-level evaluations may be ma& with a variety of techniques to estimate the rates of heat transfer and water vapor flux across the fabric(s), when configured and worn as an ensemble the combined routes of energy transfer become much more dynamic. This phenomenon is commonly attributed to non-uniform fabric/body-surface spacing, the number and type of ensemble closures, combined with the "pumping" effect due to the kinematic action of body movement (2). Conventional heat balance equations may therefore not accomodate a number of these additional factors *(3).* Several investigators have empirically derived mathematical factors which attempt *to explain* these complicated relationships (1,3). However, laboratory observations have consistently demonstrated lower rates of heat storage than predicted during the active wear of chemical protective ensembles (4). The present analysis was therefore undertaken to further explore the specific partioning of heat flux and energy balance during the active wear of a highly impermeable protective ensemble.

METHODS

The laboratory observations were conducted in an environmental chamber at T_{wbgt} 31°C while subjects (n=9) walked on an inclined treadmill at 1.34 m/sec at a 3-6% grade which elicited approximately 40% of each subject's VO_2 max. The subjects wore a one-piece butyl rubber suit *(TAP)* clo=2.05, i_m/clo=.04, over a lightweight shirt and trousers. A protective mask and hood were also worn. Physiological responses of core temperature (T_{re}), heart rate (HR) and skin temperature at four sites (forearm, calf, chest, and thigh) were monitored continuously and recorded every five minutes while subjects exercised until reaching tolerance limits of T_{re} = 39.0, HR > 185 bpm or volitional fatigue. Microclimate snit temperature and relative humidity were also recorded. Nude and clothed, pre and post experiment body weights were used to calculate sweat production and evaporation *(EVAP).* Thus, the EVAP term would also account for respiratory water loss. Heat storage (S) was calculated as follows:

$$S = 0.83\ \text{kcal/kg/°C x (kg body wt) x } [\ 0.8\ A\ \text{Tre} + 0.2\ A\ \text{Tsk}\}$$

Heat balance was either calculated using standard equations (1.3) from physiological measures of the folowing: metabolic rate obtained during the experiment (MR), evaporative loss (EVAP), and heat storage (S) or predicted with an integrative physiological computer model *(5).* Radiative and convective (R+C) heat loss was mathematically deduced and not obtained empirically.

RESULTS

All results are. *expressed* as Kcal/30 minutes.

Trial	//	S	=	Ω (MR)	- (R+C)	- EVAP
TAP		*108*	=	*.95 (210)*	- 30	- 62
TAP (model)		203	=	.80 (210)	+35	- 0

* Estimated Values

* *Measured Values*

Ω = 1-(work efficiency)

MR = energy consumption/30 min

CONCLUSION

These results clearly identify differences between the observed heat balance *in vivo* and those predicted from the model. Differences in total heat production will result from the use of various estimated work efficiencies, i.e. values of either 5% or 20% were used for transformation of metabolic energy to physical work However, the specific efficiency value ($\Omega \approx .80$) used here in the computer model, tended to attenuate the potential difference between the two estimates of S. Partial explanations to account for some of the above discrepancies between observed and modelled values include. 1) potential failure of the model to account for the energy required to raise the temperature of the suit (S_{suit}), calculated using the specific heat and the weight of the suit as –28 kcal 2) the model represents EVAP as 0 for the TAP, while empirically determined EVAP likely overestimates EVAP due to drippage of sweat which was not accounted for. This, coupled with the fact that not all sweat is evaporated at the skin (garment sweat thru) (6), suggests the actual term is somewhere between 0 and 62 Kcal.

Depending on the amount of heat loss which can be attributed to either EVAP or S_{suit}, the remaining delta between laboratory and modelled values for heat storage might then be attributed to the removal of heat by the pumping action of the body in motion. Thus, this air mover would need to remove as much as 95 kcal over the duration of the experiment. Using measured values of external air temperature and temperature inside the suit, along with the specific heat capacity of air, this would necessarily equate to an air exchange of approximately 960 cf or 32 cfm: a maximal air mover rate that is highly unlikely. Therefore, the range of observed and modelled values (Kcal/30min) for the TAP suit might be expressed as:

S	(R+C)	EVAP	S_{suit}	S_{air} exchange
108 to 203	-30 to 35	0 to -62	0 to -28	0 to -95

Despite advances in the mathematical description of heat exchange between sedentary clothed man and the environment, there are still many important practical factors regarding the thermal properties of clothing which remain to be more precisely quantified during human performance trials (3). The preliminary analysis described above suggests the need for more definitive techniques in measuring the key variables involved in heat balance *in vivo*. Independent validation studies must then be undertaken in order to better resolve certain estimates of physiological thermal flux and energy balance between robust mathematical models of heat storage and laboratory observations.

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