TITLE

A MODEL OF EVAPORATION FROM THE SKIN WHILE WEARING PROTECTIVE CLOTHING

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ORIGINAL ARTICLE

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A model of evaporation from the skin while wearing protective clothing

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Abstract A simple model was developed to describe the transport of water vapour from subjects working in hot environments while wearing chemical-protective clothing. The goal of the modelling was to obtain a better estimate of evaporative cooling of the subjects, as it was hypothesised that calculations of evaporative heat loss based on changes in dressed weight over-estimate the actual benefit experienced by the subjects. The model employed measured values of vapour pressure within the clothing ensemble to estimate the skin vapour pressure. The resistance of the clothing ensemble to water vapour transport was calculated from measurements of the physical properties of the materials in conjunction with estimates of the resistance of air layers between the clothing layers. The model predicts mean evaporation rates from the skin that are approximately 60% of those calculated from measured changes in dressed weight. Error analysis failed to account for the magnitude of this difference and possible explanations for the difference are advanced. A brief examination of the effect of wicking suggests that some of the difference results from a reduction of the resistance of the garment to water vapour due to wicking of liquid sweat through fabric layers.

Key words Water vapour transport · Evaporation · Protective clothing · Heat strain · Heat storage · Human performance

Introduction

Industrial and military personnel are occasionally required to operate in environments that present a percutaneous chemical hazard and, in these situations, they don specialised clothing to reduce their risk. Wearing this clothing can present its own hazard, particularly when working in hot or humid environments, as it increases the thermal stress experienced by the individual. Personnel managers are interested in the typical length of time for which people can work whilst dressed in these protective garments without incurring undue thermal strain: accurate determination of body heat storage is an important factor in predicting such tolerance times. Central to this determination is the calculation of evaporative heat transfer through the protective clothing, since evaporation may be the only available mechanism by which the body can regulate temperature in hot climates. Numerous human studies have been conducted to better understand the physiological response to work in hot environments (McLellan et al. 1992, 1993) and the results have led to speculation that traditional approaches for assessing the evaporative heat transfer may over-estimate the actual heat loss (McLellan et al. 1996). Such an error would lead to an inaccurate assessment of a subject's physiological state that would over-estimate tolerance times in the field and could increase the likelihood of incurring heat-stress casualties.

The similarity between heat and vapour transport has long been recognised, in terms of both pure diffusion and convection (Özisik 1977; Gebhart et al. 1988). In physiological investigations, determining the vapour transport from the skin to the environment is more difficult than measuring the transport of heat along the same path. The functional similarity between experimentally observed thermal conductivity and mass diffusivity in fluids has led to the derivation of relationships from which the vapour-transport coefficient can be estimated from the coefficient of convective heat transport (Rohsenow and Choi 1961). This is a significant step in simplifying the prediction of evaporation in a practicable calculation of heat storage.

One important variable in vapour-transport analysis that typically has not been measured in physiological investigations is the skin vapour pressure. Accurate measurement of ambient vapour pressure is well established (Ruskin 1965; ASHRAE 1972) however, few physiological investigations regularly employ humidity sensors to

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determine the vapour pressure at the skin or vapour pressure gradients within clothing. This may be due in part to a somewhat greater complexity of the use of such devices, although a number of investigations have successfully employed them (Gonzalez and Cena 1985; Kakitsuba et al. 1988; Nielson and Endrusick 1992). These sensors have been used to measure vapour pressure in bench-top studies of dynamic moisture movement through idealised clothing ensembles to examine comfort issues and transient moisture transport through them (Hong et al. 1988).

A recent human study (McLellan et al. 1996) employed humidity sensors mounted within clothing in an attempt to estimate skin vapour pressure during work in hot environments while the subject was wearing protective clothing. The measured vapour pressures from that study were used in an analytical model to calculate skin vapour pressure and to predict evaporation rate at the skin. The model and its results are the topic of this report.

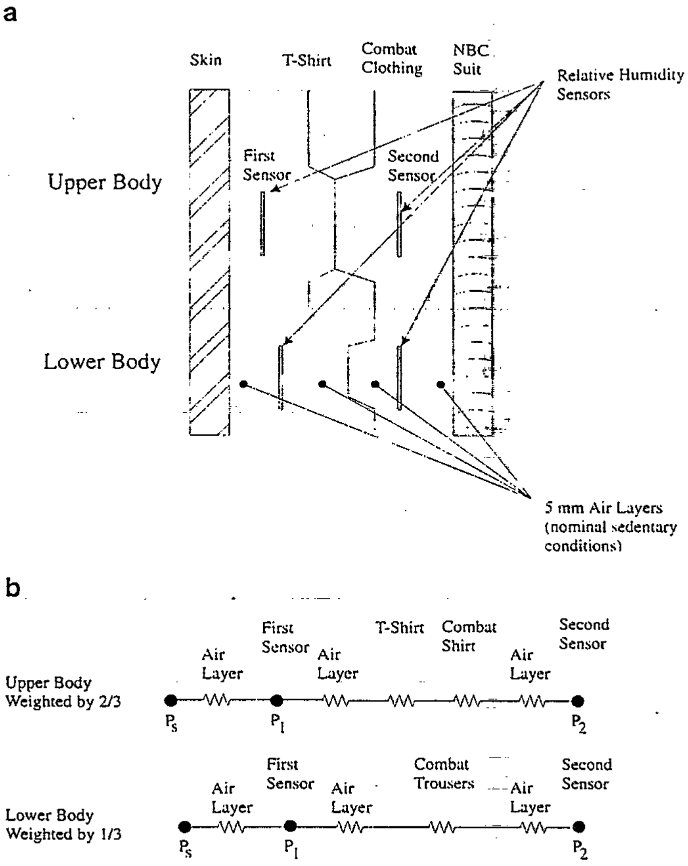


Fig. 1 **a** Schematic representation of the placement of the humidity sensors mounted in the clothing and the **b** electrical analogy model used to predict the skin vapour pressure

Methods

The vapour transport model is a transient, one-dimensional analysis of diffusion and convection, but it does not attempt to model the conjugate heat and mass transport problem. An analogy with resistive electric circuits is used to describe the vapour flow. Figure 1 shows the physical and model geometries that were used to compute the skin vapour pressure. For the purposes of this initial investigation, vapour capacitance of the clothing was not considered so that the transient nature of the problem is assumed to be due to time-varying vapour pressure at the kin. Details of the model follow a description of the experimental procedure.

The experimental design has been reported previously (McLellan et al. 1996). Briefly, subjects walked on a treadmill at either 1 m/s on the flat (mean metabolic rate of 350 W) or at 1.3 m/s up a 3% gradient (mean metabolic rate of 512 W). The ambient temperature was 40° C and the ambient relative humidity was either 15% or 65%. Air speed in the environmental chamber was less than 0.1 m/s. The subjects wore a light cotton/polyester T-shirt, briefs, Canadian Forces (CF) combat clothing cotton/nylon), a CF Nuclear, Biological and Chemical (NBC) over-garment, a CF C4 respirator, CF NBC gloves, socks, running shoes and CF NBC over-boots. The gloves (which covered the hands and approximately one-half of the forearms), boots (which covered the feet and approximately one-half of the lower legs) and respirator (which covered the face and jaw) were impermeable to water vapour.

Skin temperatures were measured at 12 points (Vallerand et al. 1989) and averages were recorded every minute. Pairs of thermistors and humidity sensors, encased in a protective probe (Vaisala, Model Humitter 50, Woburn, Mass., USA) were attached at three sites (upper back, abdomen and upper thigh) with one of each pair located adjacent to the skin and the other located on the exterior side of the combat clothing beneath the NBC over-garment. This is shown schematically in Fig. 1a. The humidity sensors, whose electrical capacitance varied with adsorbed water vapour, were calibrated in-house according to manufacturer's specifications to a reputed accuracy of ±3%. The response time (time to reach 63% of a step change) of the humidity sensors was 6.5 s (in still air). The sensors were surrounded by a protective cage that was 1 cm in diameter. The humidity sensor itself was a flat plate, measuring approximately $4 \times 6 \times 0.2$ (thick) mm^3, located at approximately the centre of the protective cage. Average readings of the intra-clothing relative humidity and temperature at each of the six sites were recorded every 5 min.

The vapour transport was modelled as a one-dimensional flow through a resistance resulting from a series of fabric and air layers between the skin and the environment. In order to simplify the problem, vapour capacitances of the fabrics and intra-clothing air layers were not considered in this initial analysis. This simplification avoids the problem of lumping the clothing's capacitive characteristics at discrete points in the clothing; a subsequent study is planned that will attempt to incorporate vapour capacitance in the model. Wicking of liquid water through fabric layers and any subsequent evaporation in the outer clothing layers were not modelled, as little quantitative data are available that describe these phenomena and the objective was to assess evaporation at the skin. Potential effects of inter-layer wicking on the results are discussed briefly. These simplifications result in the electrical-circuit analogy shown in Fig. 1b which was used to compute the skin vapour pressure.

The humidity sensors were assumed to be perpendicular to the vapour flow with a 5-mm air space on either side due to the protective cage. The weight of the probes compressed the clothing locally, so it was assumed that air layers between fabric layers were absent near the probes. The resistance to the vapour flow between the skin and the first relative humidity sensor was assumed to be due to a 5-mm air space caused by the protective cage (R_a). The resistance between the first and second sensors on the upper body was assumed to be due to 10 mm of air caused by two protective cages ($2R_a$), plus the T-shirt and combat clothing fabrics ($2R_f$). The resistance between the first and second sensors on the lower body was assumed to be due to 10 mm of air ($2R_a$) plus the combat clothing fabric of the trousers (R_f). Since it was assumed that there was no vapour capacitance in the clothing system, the mean vapour pressure at the skin ($\bar{P}_s$) could then be calculated from the following equation:

$$\frac{\bar{P}_s - \bar{P}_1}{R_a} = \frac{(\bar{P}_1 - \bar{P}_2)}{R_{12}}, \qquad (1)$$

where $\overline{P}_1$ is the arithmetic average of the three vapour pressure measurements adjacent to the skin and, $\overline{P}_2$ is the arithmetic average of the three vapour pressure measurements on the outside of the combat clothing. The variable R_{12} is a weighted (2:1) average of the water-vapour resistance of the upper and lower portions of the body and was defined as follows:

$$R_{12} = \frac{3}{(2/(2R_a+2R_f)+1/(2R_a+R_f))}. \tag{2}$$

The weighting scheme was used to reflect the differences in the number of fabric layers on the two regions of the body. The simple average of the resistances was used because of the small number of measurement sites. An alternative method would have been to weight the resistances according to relative surface areas over which each measurement was assumed to be representative. The difference between these two approaches for the computed mean vapour resistance for the whole body was estimated to be less than 2% and thus of little significance.

As the mean skin temperature was also measured during the experimental investigation, an estimate of the mean relative humidity of the skin surface could be made. From the mean skin temperature ($\overline{T}_s$ in °C), the saturation vapour pressure ($\overline{P}_{sat}$ in pascals) was computed using the following relationship:

$$\overline{P}_{sat} = 1000 \exp\left[16.6536 - \frac{4030.183}{\overline{T}_s+235}\right]. \tag{3}$$

The mean relative humidity of the skin was then calculated by dividing the mean skin vapour pressure ($\overline{P}_s$) by the mean saturation skin vapour pressure.

The model used to calculate the evaporation rate from the skin differed only slightly from that based on Fig. 1. The vapour flow rate was computed as the difference between the skin vapour pressure derived using Eq. 1 and the ambient vapour pressure. The vapour flow rate per unit area from the skin ($\dot{m}_s$) was thus calculated from the following:

$$\dot{m}_s = (\overline{P}_s - P_a) / R_{sa}, \tag{4}$$

where:

$$R_{sa} = \frac{3}{(2/(4R_a+2R_f+R_n)+1/(4R_a+R_f+R_n))}, \tag{5}$$

and R_{sa} is a weighted resistance to water vapour between the skin and the environment. This equation is similar to Eq. 2, with the addition of resistances due to air layers between fabrics as well as inclusion of the resistance of the NBC protective garment (R_n).

The resistances to vapour flow of the fabrics in the NBC suit and combat clothing fabrics were measured, while that of the T-shirt material was estimated from data on similar fabrics. Measurements were made using a water-vapour permeability apparatus (van Beest and Wittgen 1986). The NBC suit was a two-fabric ensemble: a cotton/nylon shell material (161 g/m^2, 0.4 mm thick with a Zepel-B repellent finish) with a water-vapour resistance of 9.7×10^3 m^2 Pa s/g (equivalent to 1.8 mm of still air) and a charcoal-impregnated foam (266 g/m^2, 2.25 mm thick) with a water-vapour resistance of 3.5×10^4 m^2 Pa s/g (6.3 mm of still air). The shell of the NBC suit is tailored, but not bonded, to the foam layer, resulting in an air gap between the two fabrics estimated to be equivalent to an average thickness of 2.5 mm of still air. This results in a total water-vapour resistance of 5.7×10^4 m^2 Pa s/g (10.6 mm of still air) for the NBC suit. The water-vapour resistance of the combat clothing was measured to be 5.0×10^3 Pa m^2 s/g (1 mm still air). The T-shirt material was not available for testing; however, known water-vapour resistance values of similar materials were approximately equal to that of the combat clothing material, which lead to the assumption that the T-shirt water-vapour resistance was 5.0×10^3 Pa m^2 s/g (1 mm still air). The resistances of the textiles used in these garments are generally small compared to that of the entire garment so the error associated with this assumption should be negligible. In addition to the above-mentioned garments, the subjects wore impermeable gloves, boots and a mask covering the face. It was estimated that these garments covered approximately 16% of the body surface area which effectively reduced the area participating in vapour loss to 84% of the total body surface area.

The distance that water vapour diffuses through the air layers between the fabric layers was estimated from measurements made of the thermal resistance of the clothing on a manikin, knowledge of the effect of clothing layers on thermal resistance and similarities between the mechanisms of diffusion and conduction. It has been observed that, under sedentary and calm conditions, the thermal resistance of the garments can be approximated as the sum (over all the clothing layers) of the intrinsic fabric resistance plus the thermal resistance of an effective 5-mm air gap beneath the clothing layer and an additional 5-mm air gap on the outer surface (Fourt and Hollies 1970). The air gaps are not, in general, uniform spaces between layers; they represent an empirical approximation, equivalent to the concept of a mean heat-transfer coefficient. The resistance of these air layers can be modified (Danielsson 1993) to reflect effects of body motion and wind (on the external air layer). Incorporating the effects of forced ventilation of clothing was not attempted, as it is complicated by the range of porosity of textiles, variability of fit and the effectiveness of different closure systems, although some research has been done examining this phenomenon (Jenkins and Kind 1986). The similarity between heat and vapour transport was used to extend this approach for calculating thermal resistance to estimate the equivalent water-vapour resistance of the air layers within the clothing.

In the equations of convective heat transport, the dimensionless Prandtl Number (Pr) describes the relative importance of the diffusivity of momentum (or the kinematic viscosity, ν) to the thermal diffusivity (α):

$$\mathrm{Pr} = \nu/\alpha. \tag{6}$$

In mass transport, the complementary parameter is the Schmidt Number (Sc) which describes the relative importance of the kinematic viscosity to the mass diffusivity (D):

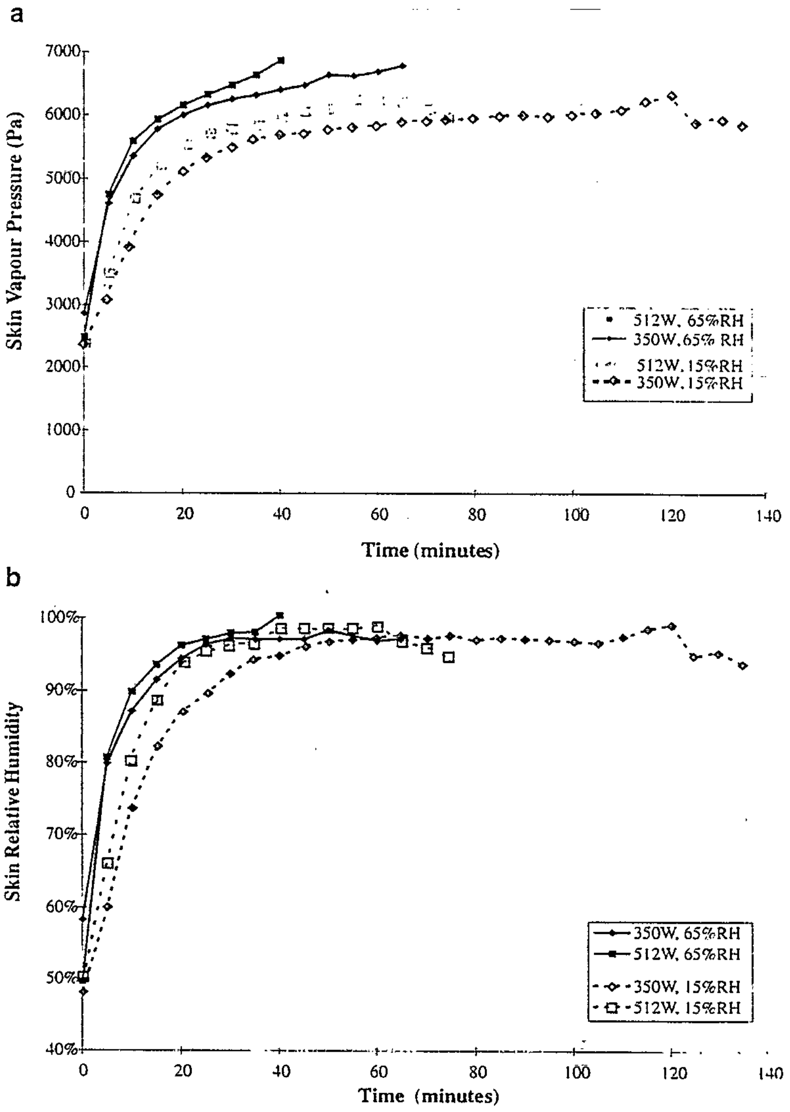
$$\mathrm{Sc} = \nu/D. \tag{7}$$

In air at 40° C, Pr is approximately equal to 0.7 while for water vapour in air, Sc is approximately 0.6. These two parameters can be used to determine the effective vapour diffusion length by dividing the effective thermal conduction length by the ratio $(\mathrm{Pr}/\mathrm{Sc})^{2/3}=1.12$ (Rapp 1970). The diffusion length beneath each clothing layer equivalent to the 5-mm thermal conduction length is then approximately 4.5 mm of still air under sedentary, calm conditions which translates into a water-vapour resistance of 2.2×10^4 Pa m^2 s/g.

Since the subjects were walking, mixing of the air layers in the clothing was promoted, reducing resistance to both heat and moisture transfer from the above resting values. Danielsson (1993) observed that the convective heat-transfer coefficient (the inverse of the convective thermal resistance) between clothing layers varied approximately linearly from 5.25 W/(m^{2}K) when standing to 11 W/(m^{2}K) when walking at a speed of 2 m/s (no external wind, all closures fastened). Based on this information, the vapour resistance of the air layers was decreased by 35% and 42%, respectively, for the 1 and 1.3 m/s walking speeds. The predicted vapour resistance for each internal air layer was thus reduced to 1.4×10^4 Pa m^{2}s/g for the slower walk and to 1.3×10^4 Pa m^{2}s/g for the faster walk. Danielsson (1993) also found that walking reduced the thermal resistance of the outer boundary layer and so the water-vapour resistance attributed to the outer air layer was reduced from 2.2×10^4 Pa m^{2}s/g when still to 1.5×10^4 and 1.3×10^4 Pa m^{2}s/g when walking at 1 and 1.3 m/s respectively. It was assumed that walking did not promote forced ventilation through the fabrics and that the secured closures on the NBC garments precluded significant air exchange through the garment openings. Implementing these effects resulted in vapour-flow resistances for the clothing ensemble of 1.17×10^5 Pa m^{2}s/g and 1.11×10^5 Pa m^{2}s/g when walking at 1 and 1.3 m/s respectively.

Since the skin vapour pressure varied with time, the vapour flow rate given by Eq. 4 was used as an estimate of the instantaneous vapour flow rate. The water that evaporated from the skin and reached the environment during the course of an experiment

Fig. 2 Variation of the skin vapour pressure (**a**) and relative humidity (**b**) with time during tests. Data are averages over all subjects



was calculated by numerically integrating the results from Eq. 4 using a simple rectangular quadrature.

Results and discussion

The computed mean skin vapour pressure obtained from Eq. 1, averaged over all subjects, is shown in Fig. 2a. The skin vapour pressure increases asymptotically from its initial value tending to a final equilibrium value, although in the tests of high ambient relative humidity, equilibrium was not achieved before all of the subjects withdrew from the test.

The mean skin relative humidity (averaged over all subjects) shown in Fig. 2b was calculated using the mean skin vapour pressures (Fig. 2a) and the mean saturation vapour pressure (Eq. 3) was calculated from the measured mean skin temperature. The response is similar to that of the mean skin vapour pressure, i.e. increasing rapidly from the initial level and asymptotically approaching an equilibrium value, although in this case the mean skin relative humidity to reach a level close to saturation regardless of the ambient relative humidity. The curves become more variable with continued exposure, as subjects are removed from the environmental chamber at different times. That the relative humidity of the skin did not quite reach saturation is almost certainly a limitation of the model since no "tuning" of the model to the experimental data was done and the subjects' skin was visibly wet at the end of the experiments. The greatest uncertainty in the model lies in assigning a water-vapour resistance to the interstitial and external air layers, which suggests that the water-vapour resistance was under-predicted by approximately 5%. Such an error would result in an over-prediction of the evaporation rate, although the exact errors are not readily identifiable with any certainty. This 5% error is comparable to the coefficient of variability (standard deviation divided by the mean) of the mean vapour pressures measured in the experimental investigation.

Initially, the mean skin vapour pressure and saturation level varied considerably between subjects, by as much

50% of the mean value. As the tests progressed, the uncertainty of each mean skin vapour-pressure value decreased to between 2 and 6% of the mean values. Near the end of the test, the number of participating subjects decreased and the magnitude of the standard deviation increased to between 5 and 10% of the mean value. In some tests, the last couple of measurements represent data from a single individual.

These results indicate that it may not be appropriate to assume a saturated skin condition for the computation of evaporation rate, at least not at the commencement of exercise. This is particularly true in more thermally stressful conditions, as the time to reach saturated skin conditions can take about half the duration of the test. Furthermore the initial skin vapour pressure can be less than the ambient vapour pressure, resulting in a temporary negative vapour flow from the environment to the skin.

The vapour pressures adjacent to the skin ($\bar{P}_1$) and outside the combat clothing $\bar{P}_2$ varied with time (t) subject, work rate and ambient relative humidity. In general, they tended to follow an asymptotic relationship from an initial, unsaturated value to near saturation of the general form:

$$P_i = a_1 - a_2 \exp(t/\tau). \qquad (8)$$

Equation 8 was fitted to the vapour-pressure data at the two distances through the clothing system for each subject as well as for the group under each test condition. The coefficients of Eq. 8 given in Table 1 represent the group fit. The first coefficient, a_1, is the final, equilibrium vapour pressure (in pascals) at the measurement site and its value appears to depend principally upon the ambient vapour pressure since the skin vapour pressure eventually saturates (becoming practically constant except for variation in the mean skin temperature). Examination of the results using analysis of variance (ANOVA) (between subjects and tests) indicated that the final vapour pressure at all measurement sites was statistically greater in the tests carried out under humid conditions than in those in the dry ($P<0.005$). No dependence on metabolic rate was found.

The second coefficient, a_2, is the difference between the initial vapour pressure and the final vapour pressure (in pascals) at the measurement site. ANOVA results indicated no significant dependence on either the ambient relative humidity or the metabolic rate, although any such dependence may well be determined by conditions in the environmental chamber prior to testing. Preconditioning of the clothing's vapour pressure was not part of the method in the original investigation and so the initial vapour pressures within the clothing or at the skin were not strictly controlled.

The third coefficient, τ, is the response time of the system (in minutes) which is assumed for this model to reflect the transient characteristics of the changing skin vapour pressure. In fact, however, it should also reflect the product of the water-vapour resistance and the water-vapour capacitance of the clothing system. From Table 1, it can be seen that τ decreases as the exercise level increases for any given ambient condition, consistent with the reduction of the water-vapour resistance of interstitial and external air layers of the ensemble due to exercise. ANOVA indicated a dependence of τ on metabolic rate (or possibly body movement) for changes both adjacent to the skin ($P<0.02$) and outside of the combat clothing ($P<0.06$). Analysis also indicated a strong dependence of τ on the ambient relative humidity ($P<0.01$) but no interaction was found between the metabolic rate and the ambient relative humidity.

Table 1 Coefficients of Eq. 8 for time variation of vapour pressures within the clothing at the inner and outer measurement sites. Values are means±standard deviation (*in parentheses*) obtained using average vapour pressures at the same time of the test for all subjects for each of the specified test conditions

Test	Adjacent to skin			Outside combat clothing		
	a_1 (Pa)	a_2 (Pa)	τ (min)	a_1 (Pa)	a_2 (Pa)	τ (min)
Light exercise, 15% RH	5698 (26)	3540 (81)	17.71 (0.8)	4889 (20)	3184 (42)	26.4 (0.8)
Heavy exercise 15% RH	5780 (32)	3564 (72)	12.84 (0.6)	4870 (65)	3144 (96)	19.0 (2)
Light exercise, 65% RH	6415 (60)	3585 (144)	9.89 (0.9)	5972 (69)	3534 (161)	10.0 (1)
Heavy exercise 65% RH	6409 (99)	3922 (188)	7.21 (0.8)	5858 (83)	3602 (165)	6.6 (0.7)

If the transient characteristic of the skin vapour pressure is determined solely by the skin, as assumed, then it would be expected that the response time at the two measurement sites would be identical. While a case for this could be argued in relation to the environment with a high relative humidity, the response times for the two sites in the low-humidity environment are notably different. This suggests that the clothing does play a role in determining the observed response times, implying a significant capacitance effect.

Diverging from the model assumptions for a moment, the expected changes in the water-vapour resistance due to body motion do not alone explain the variation of τ shown in Table 1, particularly between the dry and humid test conditions. This suggests that increased relative humidity plays a role in reducing either the water-vapour resistance or the capacitance of the clothing. It has been shown that the water-vapour resistance of certain materials (most notably monolithic, hydrophilic films used for water-vapour permeable, water-proof clothing) does decrease with increasing relative humidity (Dolhan et al. 1989; Osczevski and Dolhan 1989; Farnworth et al. 1990), however, none of the clothing materials of this study has demonstrated this characteristic. This suggests that the vapour capacity of the clothing may be decreasing with increasing relative humidity, although most textiles exhibit the opposite effect, having a higher regain at higher relative humidities (Morton 1962, 1993). The complex sorption characteristics of the activated charcoal

Table 2 Coefficients of Eq. 8 when fitted to the mean skin vapour pressure change. Values are the mean±standard deviation (*in parentheses*) determined from the average computed skin vapour pressure of all subjects

Test	At the skin		
	a_1 (Pa)	a_2 (Pa)	τ (min)
Light exercise, 15% RH	6039 (30)	3724 (101)	15.4 (0.8)
Heavy exercise, 15% RH	6165 (39)	3759 (96)	11.5 (0.6)
Light exercise, 65% RH	6590 (58)	3606 (138)	9.8 (0.9)
Heavy exercise, 65% RH	6623 (108)	4048 (199)	7.4 (0.9)

in the NBC clothing may result in a lower capacitance at higher relative humidities but this is speculation and the reason for the magnitude of the change in τ was not ascertained.

Table 2 shows the coefficients obtained when Eq. 8 was fitted to the mean skin vapour pressure (average of all subjects). The final skin vapour pressure (indicated by coefficient a_1) was found to be greater in the environment with the higher relative humidity compared to the lower relative humidity ($P<0.005$) but it was independent of the work rate. This seems reasonable, since walking at the two rates results in a small difference (≈5%) in the vapour resistance of the clothing ensemble. Thus, the equilibrium value of skin vapour pressure should depend only upon the ambient vapour pressure and the mean skin temperature. From Fig. 2a, however, it would appear that the metabolic rate influences the rate at which the skin vapour pressure increases, which is also reflected as a decrease in the time constant, τ, with increasing metabolic rate ($P=0.06$). The time constant for the skin vapour pressure, τ, was also found to be inversely dependent upon the ambient relative humidity ($P=0.01$). The reason for this is not clear, although it may be the result of a physiological response of an increased sweat rate due to an increase in perceived rate of heat strain. In other words, the change in skin vapour pressure is not completely described by the step response function implicit in Eq. 8.

The instantaneous mean vapour flow rate from the skin to the environment was computed for each 5-min interval using Eq. 4 and these results are shown in Fig. 3. In the low-humidity test and walking at 1 m/s, the vapour flow appears to reach an equilibrium value, while in the high-humidity test the vapour flow rate continues to increase until all subjects had been withdrawn from the test. Similar results are observed for tests while walking at 1.3 m/s.

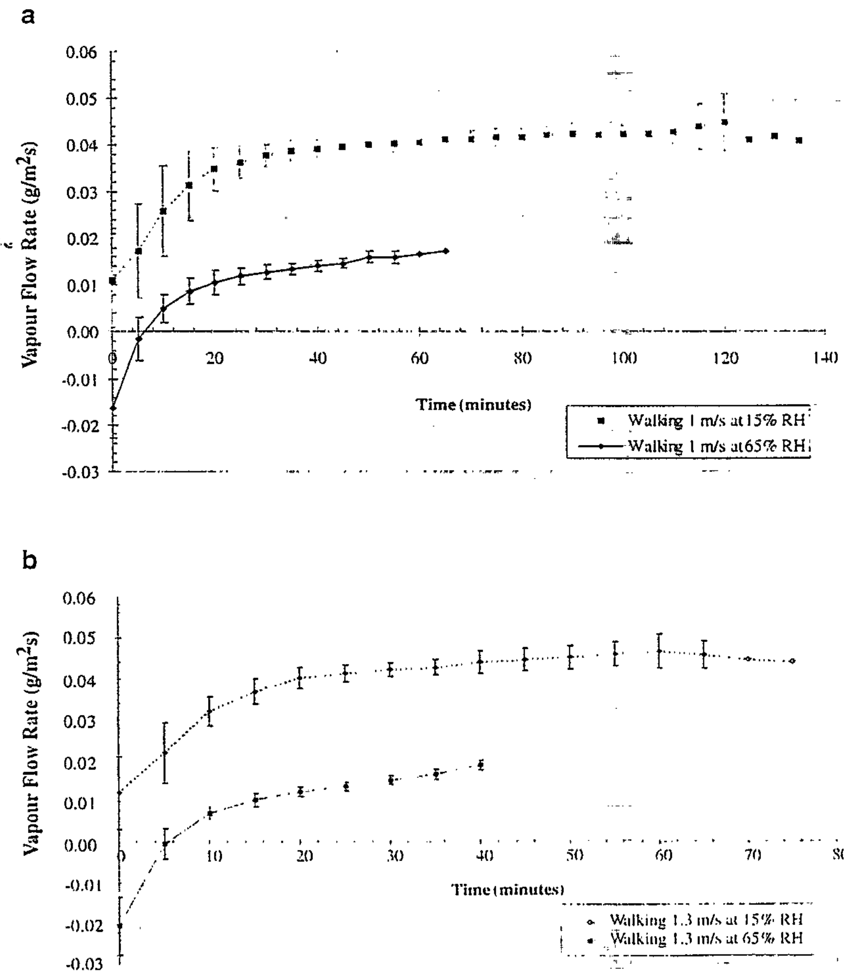


Fig. 3a, b Typical plots of the computed vapour flow rate as a function of time. Shown are results from tests with **a** light exercise (350 W) and **b** heavy exercise (500 W), at the two ambient relative humidities (average and standard deviation of all subjects measured at 5-min intervals)

Table 3 Mean±standard deviation (*in parentheses*) values of the measured and predicted evaporation rate averaged over all subjects. Measured values are changes in dressed weight over the duration of each test corrected for respiratory and metabolic mass losses. Only body surface area covered with vapour-permeable material was used in the calculation of the measured mean vapour loss. Computed values are based on the calculated vapour-pressure difference and the vapour resistance of the clothing ensemble. The difference is the computed minus the measured vapour transport rates expressed as a percentage of the measured value

Test	Measured mean vapour loss	Computed mean vapour loss	Difference	Test duration
	[g/(m^{2}s)]	[g/(m^{2}s)]	(%)	(min)
Light exercise at 65% RH	0.0156 (0.002)	0.0081 (0.002)	–47.9	56.1 (8)
Heavy exercise at 65% RH	0.0134 (0.003)	0.0083 (0.002)	–38.3	38.0 (3)
Light exercise at 15% RH	0.0593 (0.010)	0.0374 (0.002)	–37.0	115.0 (17)
Heavy exercise at 15% RH	0.0638 (0.004)	0.0382 (0.002)	–40.1	63.9 (8)

In the tests at high ambient relative humidity at both walking speeds, the vapour flow rate was initially negative, since the ambient vapour pressure initially exceeded the skin vapour pressure. This negative vapour flow should not result in a negative evaporative heat flux since the ingress of water vapour did not result in condensation but simply increased the local vapour pressure throughout the clothing without reaching saturation levels.

It is common practice to report the water-vapour resistance of materials and garments in terms of an evaporation resistance. An argument can be made that this is philosophically inappropriate, although under steady-state conditions it is of little consequence. Under transient conditions, however, this practice would suggest an initial evaporative heat flow to the body resulting from the ingress of ambient water vapour. A more physically realistic and philosophically sound practice would be to report ensemble and fabric characteristics in terms of their resistance to vapour flow or vapour-transport characteristics. Thus, a negative "evaporative heat flux" would only result if condensation occurred if the skin vapour pressure reached saturated conditions.

The calculated instantaneous rates of vapour flow were numerically integrated and a mean vapour flow rate was determined for each subject in all tests. The area used to calculate the measured mean vapour loss was 84% of the total individual surface area as the subjects wore some vapour-impermeable items of clothing. The mean vapour flow rates were averaged over all subjects in each test to obtain the group mean rates which are shown in Table 3. The computed rate of vapour loss was compared to the mean change in dressed weight (average of all subjects, corrected for both respiratory and metabolic losses) in each test.

In all cases, the model's predicted rate of vapour loss was less than the measured vapour loss rate by between 37% and 48%. A number of possibilities exist that could contribute to this difference. An obvious potential source of error is the assumption of no vapour capacitance in the clothing. Discussion of this will be left to a future investigation. Another source of error is the calculation of the ensemble vapour resistance which involves several assumptions and approximations. These approximations have been found to give reasonable agreement (Cain 1991) for computing thermal resistances compared to measurements with a thermal manikin. Under sedentary conditions with no wind, the computed thermal resistance differed from the measured values by less than 15%. Danielsson (1993) reported a similar uncertainty (approximately 20%) for heat transfer coefficients across air layers in clothing when walking. The water-vapour permeability calculated for the clothing ensemble used in the experimental investigation (9.8×10^4 m^2 s Pa/g) differs by about 5% from published values derived from measurements made on wetted manikins (10.4×10^4 m^2 s Pa/g; Gonzalez et al. 1994). These considerations imply that as much as one-half of the difference between the predicted and measured vapour loss rates may be due to uncertainties in assessing the ensemble vapour resistance in individual cases. This still leaves a significant difference between the measured and computed rates of vapour loss. It is also known that regional differences exist in sweat rates over the body (Kuno 1956; Cotter et al. 1995). In the experiments considered here, the areas of the body reported to have the highest sweat rates (face, hands and feet) are largely covered with impermeable materials, reducing their impact on the evaporation rate. The remaining areas reportedly have a similar sweat rate, ≈0.24 g/(m^{2}s), with the upper back having a somewhat greater sweat rate, 0.35 g/(m^{2}s), and the thigh having a somewhat lesser sweat rate, 0.16 g/(m^{2}s) (Cotter et al. 1995). It is possible that regional differences in the ensemble vapour resistance and the sweat rate could result in marked differences in local evaporation rates which may not be adequately represented by the three-point measurement used in the study of McLellan et al. (1996).

McLellan et al. (1996) also computed the expected evaporative heat loss using empirical relationships derived at the United States Army Research Institute of Environmental Medicine (USARIEM) with values of ensemble vapour permeability measured from USARIEM's sweating manikin. The predicted evaporation rate based on USARIEM's method (which assumes saturated skin conditions when the required evaporation rate for thermal neutrality exceeds the maximum evporation rate through the clothing) was found to be approximately 10% greater than that predicted by the model in this report. This difference between the two predicted rates of evaporative heat loss is consistent with the unsaturated skin vapour pressure calculated at the beginning of the tests. McLellan et al. (1996) speculated that some of the difference between the experimentally measured and empirically predicted sweat rates may due to some sweat being transferred between clothing layers in areas where garment drape results in close contact of clothing layers. The hypothesis is that this sweat would then evaporate from outer clothing layers at a faster rate since there would be less resistance between the evaporation point and the environment. Since the evaporation is occurring in the clothing rather than at the skin, less efficient cooling of the body results. Unfortunately, the current state of knowledge on inter-fabric transport of sweat is not sufficiently advanced to make an accurate assessment of this effect on the rate of water loss from the skin. Further complicating this tissue is the requirement for inter-layer "wicking" to occur only in areas where the fabrics are in contact with one another. Inter-layer wicking should depend on the fit and drape of the garment on each individual. The effectiveness of inter- and intra-layer wicking in promoting the movement of sweat from the skin is somewhat controversial, with little corroborated data available in the literature.

In order to test the hypothesis that wicking affects the rate of evaporation and to obtain a rough estimate of its effect, a simple test was performed. Details are presented in Appendix A but, in brief, fabric samples of the combat clothing, charcoal-impregnated foam and shell fabric were mounted in the water-vapour permeability apparatus, attempting to minimise any spaces between each layer. The transport of water vapour across the fabric samples was measured for the cases when the fabrics are in direct contact with the wet surface (referred to as "On Water"), separated from the wet surface by an air gap ("Above Water") and in contact with the wet surface but isolated from liquid water by a layer of water-vapour-permeable, water-proof material to prevent wicking ("Isolated On Water"). The measured vapour-transport coefficients of the assembly of fabrics, corrected for the air and water-proof layers, under each of these three conditions are shown in Fig. 4.

When wicking is precluded, either by having an air gap or a water-proof layer between the wet surface and the sample, the water-vapour transport rate is lower than that when the fabric sample is in direct contact with the wet surface and wicking can occur. An explanation for this apparent increase in the vapour permeability of the materials, consistent with the hypothesis of McLellan et al. (1996) is that when wicking occurs liquid water is transported some distance through the fabrics before it evaporates and diffuses through the rest of the fabrics. The wicking rate must be greater than the diffusion rate of the dry fabrics, and the evaporation site in the fabric assembly will occur at a point where the remaining thickness of the fabrics results in a diffusion rate equal to the wicking rate.

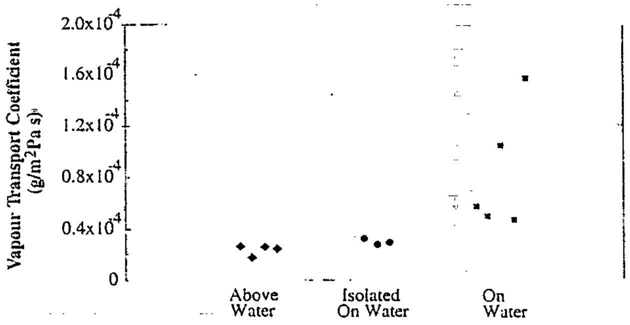


Fig. 4 Transport of water vapour across the Nuclear, Biological and Chemical and combat clothing fabric ensemble with no air gaps between fabric layers

A rough estimate of the effect of wicking on the total evaporation rate indicated that the difference between the model evaporation rate and that measured experimentally could be accounted for if as little as 10% of the body surface area was covered by clothing with a greater apparent water vapour transport coefficient due to inter-layer wicking [$\approx 5\times10^{-5}$ g/(m^2Pa s)]. This small surface area (0.15–0.20 m^2) could easily result from clothing contact with the skin on the chest, shoulders, upper back and front of the thighs.

These results do not, however, make any statement about evaporative heat transport, since the interface at which evaporation is occurring is not known. If evaporation occurs at the skin, it is estimated that more than 90% of the evaporative heat loss is from the skin while wearing the NBC clothing (Appendix A). If evaporation occurs between the charcoal-impregnated foam and the shell fabric, heat flux estimates are more tenuous, but the resulting heat flux from the skin may be reduced to as little as 56% of the total, with the remainder of the energy being supplied by the environment. The evaporative heat loss from the subject decreases continuously as the evaporation site moves out towards the outermost fabric layer.

The difference between the predicted and measured mean rates of vapour loss has significant implications for determining the evaporative heat loss. Unfortunately, differentiating between evaporation from the skin and from the clothing ensemble is difficult in human studies. A follow-up physiological investigation has been proposed in which liquid sweat on the skin is isolated from the clothing yet vapour transport is only slightly restricted, as was done in the simple experiment in Appendix A. Certain clothing materials exhibit the characteristics of being highly permeable to vapour at high relative humidity while being resistant to liquid water. If such a material was also highly elastic or if it could be tailored to be an extremely close-fitting garment worn next to the skin, it should be possible to eliminate inter-fabric wicking of sweat. After accounting for respiratory and metabolic mass losses, the resulting changes in dressed weight should be due to evaporation at the skin alone.

Conclusion

The vapour pressure at the skin and within clothing, computed from experimental data, appears to vary in a manner similar to a classic transient response of an R-C network to a step-change in boundary conditions. Since the clothing has been *assumed* to have no vapour capacitance, such a response is assumed to be a result of the transient skin vapour pressure boundary condition. The skin vapour pressure was found to be initially unsaturated but after approximately 20–40 min, depending on ambient conditions and work rate, it had become fully saturated. During tests in an environment of 65% relative humidity, the skin vapour pressure did not quite reach equilibrium before the end of the test due to the continued increase in mean skin temperature; however, it did effectively reach saturation. During an environment with a relative humidity of 15%, skin vapour pressure became effectively constant and saturated at the two work rates investigated. The skin was found to be below saturation for a significant portion of each test regardless of ambient conditions or metabolic rate and thus the computed rate of vapour transport was less than that predicted by other techniques that assume continuous skin saturation. Indeed, in the environment of high ambient relative humidity, the instantaneous vapour flow rate was found to be initially negative (from the environment to the skin) as the skin vapour pressure was lower than that of the environment.

The computed rate of vapour loss from the skin using the model developed here and measured vapour pressures in the clothing were found to be between 52% and 63% of that calculated from measurements of changes in dressed weight. At most, half of this discrepancy might be explained by uncertainty in the estimate of the resistance of the clothing to transmission of vapour; however, this still leaves a substantial difference in the vapour transmission rate determined by these two methods. If the model proves to be a better estimation of the evaporation rate from the skin compared with changes in dressed-weight calculations, this would significantly decrease the calculated heat loss from the body and result in a higher rate of heat storage.

To explain this difference, it is hypothesised that a significant amount of sweat is transferred as a liquid between fabric layers in areas where the garment's fit and drape result in close contact. This sweat subsequently evaporates from layers further out in the clothing. This process is less efficient for cooling the body, as a significant portion of the energy required to evaporate the sweat can be drawn from the environment itself. This hypothesis is supported by similarities in calculations of evaporative heat loss based on the computed vapour transport rates and USARIEM evaporative-heat-loss relationships which are based on measured evaporation rates from wetted thermal manikins. A simple experiment indicated that wicking between fabric layers of the materials used here can result in an increase in the evaporation rate by as much as two to three times that occurring if only diffusion is present. Explanation of the difference between the modelled evaporation rate and the measured evaporation rate requires that less than 10% of the clothing surface area has a higher vapour transport rate such as that found to result from inter-layer wicking. Unfortunately, the increased evaporation rate does not appear to be as efficient and may result in little or no additional heat loss from the body compared with the non-wicking case. In an attempt to resolve this question, a subsequent investigation has been proposed involving both bench-top and human testing to get a better estimate on the effect of wicking on both the evaporation rate and the efficiency of the evaporation from the perspective of body thermoregulation.

While clothing vapour capacitance may affect vapour loss from the body, it should not be reflected in changes in dressed weight, which is often the basis for estimating evaporative heat loss and was the central focus of this investigation. Additional work has been proposed to expand the model to include clothing vapour capacitances in order to address this issue and to predict what effect clothing vapour capacitance will have on evaporation from the body and homeostasis.

Appendix A: investigation of the effect of wicking on vapour transport

The water vapour peremeability apparatus (van Beest and Wittgen 1986) was used to provide an estimate of the effect of inter-fabric wicking on the apparent water vapour transport across several layers of fabric. The fabrics were mounted in a jig as shown in Fig. A1, after having been exposed overnight to a relative humidity of ≈100%. The fabrics were drawn tight before the clamping ring was fastened to the base to minimise sagging of the materials and to minimise any gap between fabric layers. The test specimen was then placed in the apparatus in one of two orientations: with an air gap between the fabrics and the wet surface (labelled as "Above Water") or with the fabrics directly on the wet surface ("On Water"). Additionally, a layer of water-vapour-permeable, water-proof fabric (Sympatek) was inserted in the fabric assembly directly between the combat-clothing fabric and the wet surface ("Isolated On Water"). The resulting vapour-transport coefficient was corrected for the effect of the Sympatek so that the reported value reflects only the contributions due to the combat clothing fabric and the NBC suit fabrics. The temperature was approximately 20° C.

In the tests "Above Water" and "Isolated From Water", the fabrics appeared to remain dry, both visually and to the touch. In the tests "On Water", the combat clothing fabric, which was in direct contact with the wet surface, was visibly soaked but the shell fabric of the NBC suit appeared dry. The foam material felt slightly damp. This suggests that for "Above Water" and "Isolated From Water" tests, water was evaporating from the wet surface and diffusing through the fabrics, while in

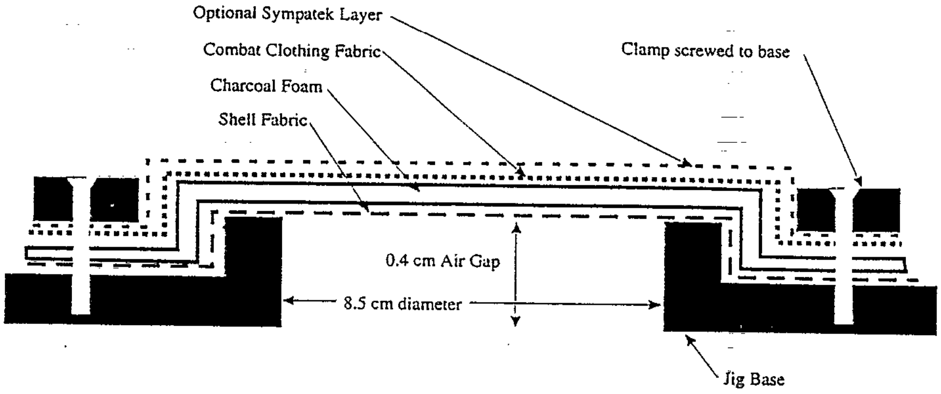


Fig. A-1 Placement of the sample fabrics in the water-vapour permeability apparatus test jig. Fabrics were tensioned to minimise air gaps between layers. The jig could be inserted in the apparatus either as shown, to provide a stand-off from the wet surface below, or inverted to provide direct contact between the fabrics and the wet surface. The Sympatek layer was used in several tests with the fabrics in contact with the wet surface to prevent wicking

the "On Water" test water was evaporating from somewhere in the fabric assembly, probably in the foam middle layer. The measured rates of vapour transport are shown in Fig. 4 of the main report.

Two notably higher water-vapour transport coefficients were measured in the tests with the fabrics in direct contact with the water ("On Water"). These values are suspected to be the result of some wicking through the apparatus jig, rather than through the sample, directly to the dry surface of the apparatus. If this suspicion is correct, these two values would over-estimate the transfer rate actually occurring through the sample.

The thermal resistances of the fabrics were measured in-house (FOX-300 Heat Flow Meter Instrument; LaserComp, Lynnfield, Mass., USA): values for combat clothing and NBC shell fabric were each found to be 0.01 m^2K/W, and that for charcoal-impregnated foam was found to be 0.06 m^2K/W. In the physiological tests, the ambient temperature was 40° C, and at the end of the tests the skin temperature was approximately 38° C. In regions of the body where the drape of the garments minimises air layers between fabric layers, the thermal resistance between the skin and the ambient air would then be the sum of the contributions due to the materials, plus that of an external air layer [approximately 0.1 m^2K/W (Danielsson 1993)], for a total resistance of 0.18 m^2K/W. This would result in a dry-heat transfer of approximately 11 W/m^2 from the ambient air to the skin.

Assuming steady state conditions, an illustrative value for the evaporation rate of 0.05 $g/(m^2s)$ results in an evaporative heat transfer of approximately 122 W/m^2 for a net heat loss of 111 W/m^2. Conversely, if the evaporation occurs at the interface between the charcoal-impregnated foam and the shell fabric, the thermal resistance between the skin and the evaporation point would be approximately 0.07 m^2K/W and the thermal resistance between the evaporation point and the environment would be approximately 0.11 m^2K/W. Using the same evaporation rate but at the new site, the heat loss from the skin would be reduced to approximately 63 W/m^2 while dry-heat transfer from the environment to the evaporation site would be approximately 59 W/m^2. This ignores any change in the thermal resistance of the fabric layers due to water in the fabrics which is a tenuous assumption if the fabrics are soaked due to perfuse sweating.

This simple analysis suggests that, in regions where the clothing drape allows wicking, the evaporative heat loss from the body can be reduced to almost half of that found when evaporation occurs at the skin. Whether this phenomenon is actually observed in practice and the magnitude of such an effect on the overall heat loss from the body will depend upon several parameters including drape, the material's wicking properties and the vapour transport characteristics of the clothing during exercise.

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