INTRODUCTION

Evaporation of moisture, usually sweat, is essential for the maintenance of heat balance under most conditions when personal protective clothing is worn. Evaporation provides cooling where otherwise body heat losses would not be able to match metabolic heat generation (7). The energy equivalent of evaporating water or sweat from the skin is deemed only to be dependent on the temperature at which it takes place (5) (with skin temperature ranging typically from 30-36°C), but otherwise not influenced by factors such as clothing. When moisture evaporates from the skin in a person wearing clothing and travels towards the environment, it may be sorbed and subsequently desorbed by textile fibers (3), it may condensate in outer layers if these are colder than the skin (12, 8, 4) and subsequently evaporate again, it may be ventilated from the clothing microclimate through openings in the clothing or may finally diffuse through the outer clothing layer. Each of the phase changes mentioned will cause heat to be released or absorbed (8).

Most thermophysiological and clothing-related research on exchanges of heat and mass between humans and their thermal environment is based on heat balance analysis (6). This analyses the various avenues for heat generation and heat transfer: Metabolic rate (M), Radiation (R), Convection (C), Conduction (K), Evaporation (EVAP), Respiratory heat losses (RESP) and finally Heat Storage (S) in the body. Most of these parameters can be determined directly, whereas DRY heat loss (R+C+K) is normally calculated as the balance of all other heat gains and losses (DRY=M-EVAP-RESP-S). The latter is often done in clothing research, where the DRY value is used to calculate the thermal insulation of the clothing, and EVAP to calculate the clothing vapor resistance. It should be noted that any errors made in the determination of one of the heat balance parameters will end up cumulated in the value for DRY. Only when DRY can be measured directly, can this be avoided.

The method used to determine EVAP is to weigh the change of the (clothed) person’s mass per unit of time, corrected for respiratory moisture loss and metabolic mass losses. From the weight loss per unit of time, it is possible to calculate the equivalent heat loss, which is the energy required for evaporation of that quantity of moisture. The value commonly used is 2430 Joules per gram of moisture evaporated. Hence evaporative heat loss is determined as

\[ EVAP(W) = \frac{mass\ loss}{time} \cdot \text{heat of evaporation} = \frac{mass\ loss(g)}{time(s)} \cdot 2430(J \cdot g^{-1}) \]  

(1)
As mentioned above the mass loss is taken by either continuously weighing the nude or clothed person, or, due to technical difficulties of weighing an active person continuously, by weighing the person before and after a test and from the weight difference calculate the mean mass loss per unit of test time.

All such calculations assume that the evaporative efficiency, i.e. the heat actually lost by evaporation of a certain mass of water is equal to the evaporative heat loss potential (mass loss (in g) * 2430 J/g). It has been questioned whether this is the case when (protective) clothing is worn, especially when this clothing hampers the evaporation of sweat and where sorption and desorption or condensation or evaporation within the clothing takes place. As shown by Havenith et al. (8) and Broede et al. (2) the heat for evaporation is not always fully taken from the body, and cooling efficiency of sweat was shown to be dependent of vapor resistance of clothing and interacted with temperature. In their study, they generated the ‘sweat’ at the skin. Some of this may have wicked into the base layer or even further, which may have contributed to the findings. The present study was designed in an attempt to specifically look into the effect of moisture wicking away from the skin before evaporating. The hypothesis is that when the locus of evaporation is further from the skin, the evaporative cooling efficiency (i.e. the heat actually taken from the body) will be reduced.

For this purpose an experiment was performed where moisture was introduced at different distances (layers) from the skin, and the cooling efficiency was measured. The most extreme case being spraying the clothing from the outside (avoiding dripping) which is also relevant to cooling off of workers wearing encapsulating protective clothing. As such an investigation is not possible on human subjects with sufficient precision, a thermal manikin was used.

METHODS

In order to discriminate between and determine all heat exchanges, measurements were made using a thermal manikin (‘Newton’) (8). This manikin has 32 independent zones in which heat input or temperature can be controlled and measured. With a dry skin, the skin temperature of the manikin controlled at 34ºC, and a fixed environmental temperature the measured heat loss can be used to calculate dry heat resistance of the clothing worn. This measurement is described extensively in ISO15831:2004 and ASTM F1291-05 (11, 1). All heat resistances were calculated using the ‘parallel method’ as described in the standards (10). To allow measurements with wet skin, the manikin was covered with a cotton stretch ‘skin’, which was wetted and acted as a ‘sweating skin layer’. Alternatively, moisture was introduced in different layers, further away from the skin to look at the evaporation as if all the moisture had wicked to this location. Tests were performed with the following configurations:

1: nude manikin, wet skin,
2: manikin with wet skin under a cotton, polyester or polypropylene base layer and a permeable/semipermeable/impermeable outer layer of similar thickness and heat resistance (8),
3: permeable/semipermeable/impermeable outer layer as 2, but now with moisture (600g) introduced in cotton base layer instead of at skin,
4: moisture introduced at outer surface of Permeable and Impermeable outer garment. This was done with a: no base layer; b: 1 base layer; c: 2 base layers, which changed the distance of the evaporation locus in relation to the skin.
Apart from heat losses, also the weight change of the clothed, wet manikin was determined by continuous weighing of the whole setup. The whole manikin setup was placed on an accurate balance (Sartorius 150, with a resolution of 1 g; absolute accuracy to ±10g). This setup enabled the amount of water evaporated from the clothing system and thus the real evaporative heat loss and real evaporative heat resistance to be determined (8).

All results presented in this paper are calculated for the clothed area only, excluding data from the head, hands and feet. Results will be presented lumped over the different underwear types.

Table 1. Heat and Vapor transfer properties of materials used determined according to EN31092/ISO 11092. Air permeability was determined according to EN ISO 9237: 1995 (9)

<table>
<thead>
<tr>
<th>Code</th>
<th>Description</th>
<th>Air permeability l/(m²s)</th>
<th>Rct (m² K/W)</th>
<th>Ret (m² Pa/W)</th>
<th>imt</th>
</tr>
</thead>
<tbody>
<tr>
<td>Underwear</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO</td>
<td>Gnägi Cotton</td>
<td>0.024</td>
<td>4.2</td>
<td>0.34</td>
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<tr>
<td>PES</td>
<td>Helly Hansen Polyester</td>
<td>0.029</td>
<td>3.4</td>
<td>0.51</td>
<td></td>
</tr>
<tr>
<td>PP</td>
<td>Lifa Active Polypropylene</td>
<td>0.026</td>
<td>3.7</td>
<td>0.42</td>
<td></td>
</tr>
<tr>
<td>Outer layer</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PERM</td>
<td>O2 (blue inside) Inner surface: PTFE membrane Outer surface: hydrophilic</td>
<td>1.02</td>
<td>0.025</td>
<td>5.6</td>
<td>0.25</td>
</tr>
<tr>
<td>SEMI</td>
<td>O1 Inner surface: hydrophobic coating Outer surface: PTFE membrane</td>
<td>1.98</td>
<td>0.023</td>
<td>18.6</td>
<td>0.07</td>
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<tr>
<td>IMP</td>
<td>PVC</td>
<td>0.24</td>
<td>0.007</td>
<td>∞</td>
<td>-</td>
</tr>
</tbody>
</table>

Experimental conditions
The main part of the testing for this experiment was performed at 20ºC, with 40% rh (vapor pressure 1 kPa). The manikin was placed in front of three fans, mounted in a vertical line, producing a reference wind speed of 0.5 m/s. From the data obtained, ‘Apparent Evaporative Heat Loss’ is calculated as:

$$\text{Apparent Evaporative Heat Loss} = \text{Total Heat Loss Wet Manikin} - \text{Dry Heat Loss} \quad (1)$$

Then, the ‘Apparent Evaporative Cooling Efficiency’ was calculated as the Apparent Evaporative Heat Loss of the wet manikin divided by the ‘Evaporative Cooling Potential’ (weight loss * 2430 J/g/time) of the same condition (8).

$$\text{Apparent Evaporative Cooling Efficiency} = \frac{\text{Apparent wet heat loss of wet manikin}}{\text{Evaporative Cooling Potential}} \quad (2)$$
RESULTS

The results for the nude manikin and the various configurations with semipermeable clothing, as measured at 20ºC, are presented in Fig. 1. As expected the value for evaporation of the nude manikin is very close to 1, implying that here virtually all of the heat of evaporation is actually taken from the body. The same appears to be true for the clothed manikin with a wet skin in this climate. However, when the locus of evaporation is fully moved to the underwear (base layer) it is evident that the cooling efficiency is reduced substantially. I.e. only a part of the energy for evaporation is taken from the body. The rest appears to be taken from the environment. In the more extreme case of the evaporation taking place from the outer surface of the clothing, the effect gets even stronger, and if in addition more base layers are worn, pushing the evaporation locus further and further from the skin the energy taken from the body drops to 20% of the total energy required for the evaporation.

CONCLUSIONS

After showing in earlier papers (2, 8, 13, 14) that the amount of energy taken from the body for the evaporation of a given quantity of sweat is dependent on the clothing permeability and on the ambient temperature, the present experiments have clearly demonstrated that this ‘evaporative cooling efficiency’ is also dependent on the location where the evaporation takes place in terms of its distance to the skin. A dramatic fall of cooling efficiency takes place when moisture is wicked away from the skin before it evaporated. Though the wicking may also have a positive
effect when the skin is not fully wet (different from this test) by increasing the surface area of evaporation, there may be situations where it will lower the cooling power. Where both skin and clothing are wetted, no risk of dehydration is present, and a large amount of ventilation takes place in the clothing, having the extra evaporation from the fabric may also be beneficial. In encapsulated clothing however where the microenvironment may be close to become saturated, and only a small fraction of produced sweat may evaporate, it would be best if this evaporates directly from the skin and is not wicked further out.

The experiments have also demonstrated that spraying clothing from the outside with water will have a cooling efficiency of about 20 to 40% for the amount of evaporated water. In this condition, if a surplus of water is sprayed on to cool the person, additional conductive cooling will take place where this water is cooler than the person’s clothing.

REFERENCES

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