Required clothing ventilation for different body regions in relation to local sweat rates

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Introduction

For the body to be in thermal comfort, skin temperatures have to be within the comfort range (Fanger, 1970). Skin wettedness (*w*) has been widely recognised as an additional limiting factor for thermal comfort (Havenith et al., 2002). Various sources (Goldman, 1988, Lotens, 1993, Nishi and Gagge, 1970) have suggested that thermal comfort is lost when *w* increases above 0.3, or above a value depending on metabolic rate (*M*):

$$\text{comfort requirement:} \quad w < 0.0012 \cdot M + 0.15 \tag{1}$$

with *M* in Wm^{-2} (Nishi and Gagge, 1977).
Skin wettedness *w* is defined as:

$$w = \frac{E_{sw}}{E_{max}} + 0.06 \qquad \{n.d.\} \tag{2}$$

with E_{sw} being a regulatory sweat evaporation rate, E_{max} = the maximal evaporation rate possible in the ambient climate with the present clothing and skin temperature for a totally wet skin, and 0.06 being the minimal skin wettedness (or moisture evaporation) due to diffusion through the skin. Using the saturated vapour pressure at the skin temperature ($p_{sk,s}$) to determine E_{max}, this reads:

$$E_{sk} = w \cdot \frac{\left(p_{sk,s} - p_a\right)}{R_{e,T}} \qquad \{Wm^{-2}\}$$
$$with \quad E_{sk} = E_{sw} + E_{diffusion} \tag{3}$$

The metabolic rate, together with the dry heat loss will determine the required value of E_{sk}. For a given sweat production or required sweat evaporation, the ambient vapour pressure and the clothing vapour resistance will determine the skin wettedness. Wettedness will have to increase when vapour resistance ($R_{e,T}$) or ambient vapour pressure increase.

The clothing's vapour resistance is highly affected by clothing ventilation. At higher sweat rates, diffusion of sweat through the material (static $R_{e,T}$ values) will be far too low to ascertain low skin wettedness and thereby comfort. In these cases, the main avenue of sweat evaporation and transport will be by convection through the material and openings: ventilation. In this situation, the ventilation replaces microclimate air (warm, humid) with typically cooler and dryer ambient air.

In order to calculate regional requirements for ventilation, data are needed on the regional distribution of sweat rates over the body. Such data were acquired by Inoue and Ueda (1998). These data will be used for the necessary calculations.

Regional differences in sweat production.

Total sweat production over the whole body is usually measured by weighing the subject before and after a test. When looking at regional sweat loss this technique cannot be used as the mass change of the various body segments cannot be determined separately. For the present paper, sweat capsules were used. These are small capsules that are attached to the skin. Dry air is passed through the capsule that will absorb sweat. The air is analysed in terms of temperature and humidity after leaving the capsule and from this the amount of sweat produced in the capsule is calculated. It should be considered that the method used may cause sweating to be slightly higher than normal, as the skin can be kept rather dry. One may compare the data therefore best with sweat production in a dry environment.

Sweating Data

Data were collected on a group of young males (Table 1). All subjects were Japanese.

Table 1, individual characteristics of the subjects. A_D = body surface area, MSF = mean skinfold thickness (adiposity), $\dot{V}O_{2max}$ =maximal oxygen uptake

n	Age(yr)	Height(cm)	Mass(kg)	A_D/mass($cm^2.kg^{-1}$)	MSF(mm)	$\dot{V}O_{2max}$ ($ml.kg^{-1}.min^{-1}$)
9	23±1	172±1	67±2	279±6	9±1	49±2

The subjects performed work in a climatic chamber at 28°C, 40% relative humidity. They worked at loads relative to their own fitness levels. The work rates for the different sessions were: 35, 50 and 65% $\dot{V}O_{2max}$ (maximal oxygen uptake ~ maximal work capacity). The work time was 30 minutes, which was sufficient to develop sweating at the relevant rates.

Sweat was collected at 5 sites: Forehead, Chest, Back, Thigh, Forearm. Sweat data were collected in units of $mg.cm^{-2}.min^{-1}$ with ventilated capsules. In order to derive estimates for the sweat rates for the whole body segment, data for body surface areas based on the work of Stolwijk (1970) were used. These are given in Table 2.

Table 2. Surface areas of various body segments.

Segment	Male (m^2)	Female (m^2)	% of total body area
Head	0.133	0.113	6.7
Trunk	0.680	0.628	36.0
Arms	0.254	0.221	13.1
Hands	0.095	0.078	4.8
Legs	0.597	0.590	32.8
Feet	0.130	0.110	6.6
Total	1.888	1.740	100

The values for the males were used to calculate segment sweat rates. For the head it was assumed that 50% of the surface contributed to sweating:

$$segment\ sweat\ production = surface\ area \cdot capsule\ value \cdot fraction\ available \quad (4)$$

The segmental sweat productions for the segments are presented in Fig. 1.The summated segmental sweat rates (estimated total sweat production excluding hands and feet) are given in Fig. 2.

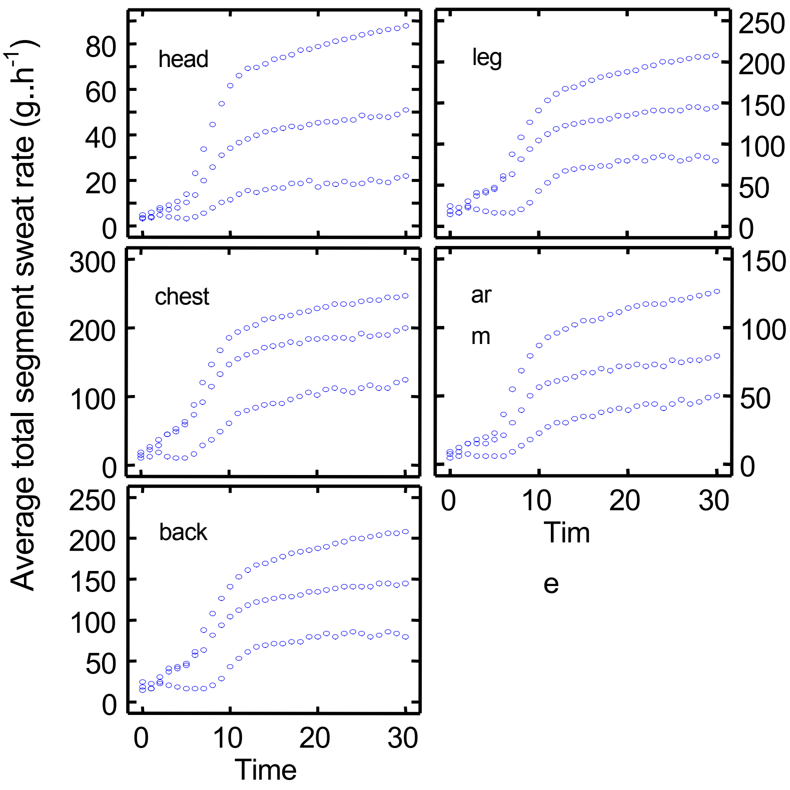

Fig. 1, average total segmental sweat rates in $g.h^{-1}$ for older and younger subjects. Bottom curve in each panel: 35%, middle 50% and top 65% $\dot{V}O_{2max}$

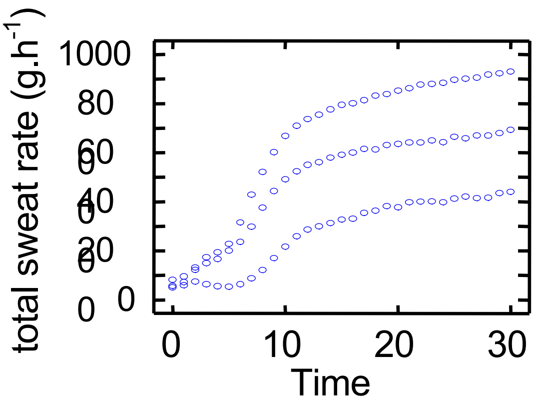

Fig. 2, summated segmental sweat rates (total body excl. hands and feet) in $g.h^{-1}$.

These data can be recalculated to obtain the relative contributions of each segment to total sweat rate (Table 3).

Table 3. Average segmental sweat rates as percentage of sweat production over all measured segments (feet, hands and pelvis excluded).

Segment	Sweat rate % of total
Head	7
Chest	27
Back	22
Arms	12
Legs	32

Ventilation Data

The maximal amount of vapour transport by ventilation can be calculated as:

$$
\begin{aligned}
&\textit{moisture transport} = \\
&\quad \textit{ventilation volume} \cdot \{[\textit{concentration microclimate air}] - [\textit{concentration ambient air}]\}
\end{aligned}
\tag{5}
$$

$$
\textit{units}: \frac{\textit{grams}}{\textit{houre}} = \frac{m^3}{\textit{houre}} \cdot \left\{ \frac{g}{m^3} \right\}
$$

This is based on the assumption that the microclimate air is well mixed with the ventilation air, and when the moisture transport is to be interpreted as sweat loss, one also needs to assume that the microclimate has the same concentration as the saturated skin surface. In terms of ventilation efficiency, these are best-case scenarios. At very high ventilation rates one can expect that the air that is replaced will not be ideally mixed, not saturated and lower in temperature.

With these assumptions, one calculates the maximal possible moisture transport for a given amount of ventilation. Or, in a reverse reasoning: This calculation gives the minimal amount of ventilation needed to get rid of a certain amount of produced sweat.

$$
\textit{required ventilation} = \frac{\textit{sweat rate}}{[\textit{concentration microclimate air}] - [\textit{concentration ambient air}]} \tag{6}
$$

For a given sweat rate, the required ventilation will depend on skin temperature (defining saturated vapour pressure), but even more important will be the vapour pressure of the ventilation air (the ambient air). The latter can be calculated from ambient temperature and relative humidity. An example is given in Fig. 3.

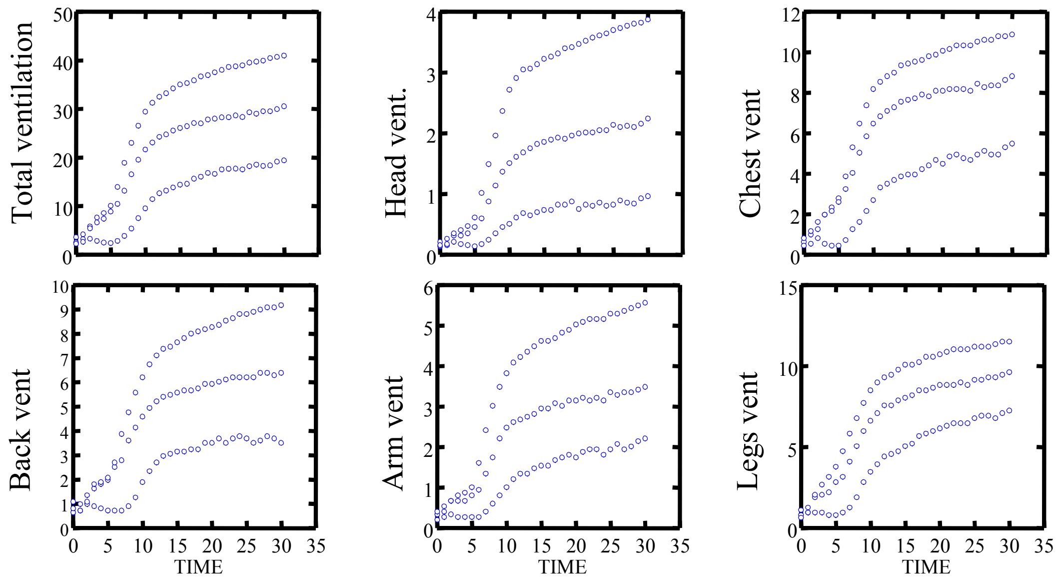

Fig. 3, required ventilation rates ($m^3.h^{-1}$) for removal of all sweat produced in a 15ºC 50%rh environment. Bottom curve in each panel: 35%, middle 50% and top 65% $\dot{V}_{O_{2max}}$

When we re-plot these results for a range of climates, the required ventilation rate can be presented in relation to the ambient vapour concentration. This produces curvi-linear relations as shown in Fig. 4.

For a specific sweat production, the required ventilation is lowest at low temperatures with its low vapour pressures. When the ambient vapour pressure approaches the skin vapour pressure (27 g.m^{-3}), the required ventilation rate will increase to infinity.

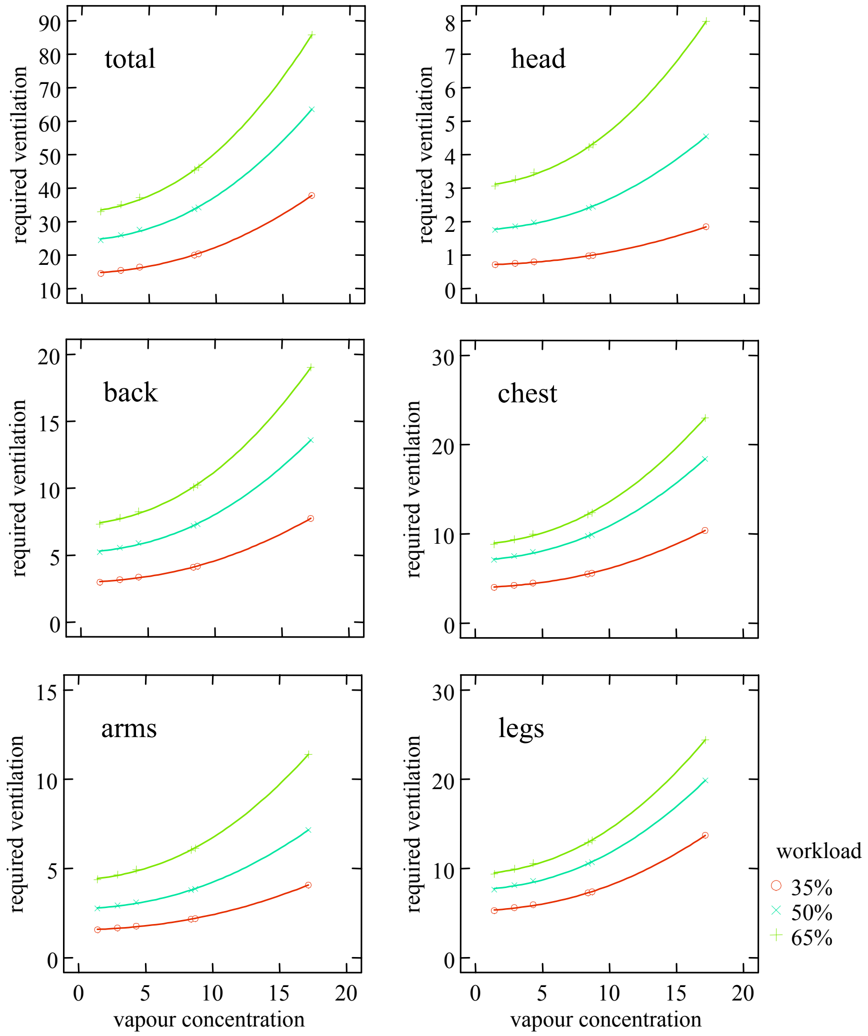

Fig. 4, required clothing ventilation (m^3.h^{-1}), total body and per segment in relation to ambient vapour concentration (in g.m^{-3}) for three workloads while cycling.

Practical examples

The data presented in this paper were based on measurements of cycling subjects. Hence, it may be debated whether they could be applied to other sports. One may expect however, that those sports involving the legs as important contributor to the power output would be close enough to the data to be used for illustration purposes.

In order to illustrate the data, the relation between required ventilation and sporting effort for some conditions is presented in table 4.

Table 4. Ventilation requirements to remove all produced sweat for different activity levels in various outdoor sports. Sweat rates are assumed equal at all temperatures. In practice, these (and the required ventilation rates) may be lower in the cold due to the increased dry heat loss.

Activity Level									
Cycling	14 km/h			19 km/h			22 km/h		
Walking/jogging	5 km/h			6.5 km/h			8 km/h		
Ski, cross country, (Excellent snow)	-			6.5 km/h			9 km/h		
Hiking uphill	5%, 3.5 km/h			9%, 3.5 km/h			15%, 3 km/h		
Mountain Climbing	-			-			18%, 5 kg load		
Required Ventilation Rates ($m^3.h^{-1}$) at 0, 15 and 25ºC (all 100% rh)									
Temperature	0	15	25	0	15	25	0	15	25
Whole body	16	21	39	26	35	64	36	47	87
Chest	4.3	5.6	10.3	7.5	9.9	18.4	9.4	12.4	23.0
Back	3.2	4.2	7.8	5.6	7.3	13.6	7.8	10.2	19.0
Legs	5.6	7.4	13.7	8.1	10.7	19.9	10.0	13.1	24.4
Arm	1.7	2.2	4.0	2.9	3.8	7.2	4.7	6.1	11.4

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