THE RELATIONSHIP BETWEEN VENTILATION INDEX AND THERMAL INSULATION

L.M. Bouskill[1], K. Kuklane[2], I. Holmer[2], K.C. Parsons[1] and W.R. Withey[3]

[1]Department of Human Sciences, Loughborough University, UK
[2]National Institute for Working Life, Solna, Sweden
[3]Centre for Human Sciences, DERA, Farnborough, UK

INTRODUCTION

Body movements result in a "bellows" effect which "pumps" the microenvironment air around and through clothing layers (1). Increased external air movement (wind) also increases air exchange, even in clothing constructed from relatively air-impermeable fabric (2). This exchange can decrease clothing thermal insulation and water vapour resistance, which influences the heat balance of the wearer.

These effects are seldom taken into account when defining the clothing needed for safe work in hot or cold conditions, even though measurements using articulated, thermal manikins have shown that movement and wind cause reductions of 50% in thermal insulation (3) and 88% in evaporative resistance (4). Consequently, the choice of clothing based on measurements of intrinsic insulation and intrinsic evaporative resistance alone may lead to under-protection in the cold and over-protection in the heat.

To overcome this limitation, ISO TR 11079 *(5)* calculates a resultant insulation and ISO 9920 *(6)* gives an empirical correction to account for the effects of body movement. However, this approach is limited because there are no data relating the change of thermal insulation to the amount of air exchanged between the clothing and the external environment.

The Ventilation Index (VI) is a sensitive and repeatable method of quantifying the air exchange characteristics of clothing. In this experiment, an articulated, thermal manikii was used to quantify the relationship between VI and thermal insulation in 2 clothing ensembles.

MATERIALS AND METHODS

Clothing ensembles. A GoreTex (GT), 1-layer ensemble and a woven, 3-layer ensemble (IREQ) were investigated. The GT ensemble comprised a jacket, which was elasticated at the waist, had a full length zipper protected by a popper-fastened wind baffle, and elasticated, cotton, knitted wrist-cuffs, and trousers with an elasticated waist and popper fasteners at the ankles. The 3 layers of the IREQ ensemble were as follows: base layer (next to skin)—short cotton underpants; knee-length cotton socks; man-made fiber long-legged underpants and man-made fiber shirt, middle layer, 'fleece' trousers and jacket; and outer layer-cotton dungarees and jacket, wool scarf, man-made fibre gloves and balaclava helmet.

Measurement **of** thermal insulation. The 'TORE' heated, articulated manikin was used to measure clothing total insulation (I_T) using the method given in CEN prENV342 **(7).** Thermal insulation of the boundary air layer **(I_a)** was measured using the nude manikin. Effective insulation (I_{cle}) was calculated as the difference between I_T and I_a. Repeatability between **runs** was high, with the difference between double determinations less **than** 5%. Environmental conditions were: ta = tr = 10°C **(1** SD = 0.1°C) and P_aH_2O = **0.73** kPa.

Measurement **of** Ventilation Index. Immediately after each measurement of I_T, VI **of** the clothing layer next to the skin was determined from separate measurements of microenvironment volume and air exchange rate **(8):**

Ventilation Index = Microenvironment Volume x Air Exchange Rate
(Liters per min) ***(Liters)*** ***(per min)***

Microenvironment volume was measured with the **manikin** wearing **an** *air-*tight oversuit over the test ensemble. Air was evacuated fiom the oversuit until it 'collapsed' onto' the test ensemble. Microenvironment volume was the air volume evacuated fiom this point until oversuit pressure was -30 cm WG. With the oversuit removed, air exchange rate in the clothing was measured by gas dilution. Oxygen concentration in the microenvironment was measured continuously. Nitrogen was flushed **through** until the oxygen concentration reached 10%; the time taken for it to return to 18% was used to calculate the air exchange rate.

VI and **I_{cle}** measurements were made in a total of 6 conditions: at **2** wind speeds-'still air' (i.e., **no** forced convection) with Va less than 0.2 $m \cdot sec^{-1}$, and **Va** = 1 **$m \cdot sec^{-1}$;** with the manikin stationary or walking at a speed of **0.37** $m \cdot sec^{-1}$ or 0.8 $m \cdot sec^{-1}$ (step length of 645mm [heel to heel] and step rate of **23** or **48** per minute, respectively).

Table **1.** Values of Ventilation Index (VI) and Effective Insulation (I_{cle}) measured on the two clothing ensembles

		GoreTex 1-layer clothing ensemble		**IREQ** 3-layer clothing ensemble	
		VI (*$l \cdot min^{-1}$*)	I_{cle} *(clo)*	VI (*$l \cdot min^{-1}$*)	I_{cle} *(clo)*
standing	still air	55.0	0.75	56.30	1.83
	V_a = 1 $m \cdot sec^{-1}$	6.93	0.67	58.76	1.60
walking	still air	67.7	0.54	58.11	1.61
(0.37 $m \cdot sec^{-1}$)	V_a = 1 $m \cdot sec^{-1}$	8.84	0.49	65.93	1.54
walking	still air	8.54	0.41	62.86	1.61
(0.8 $m \cdot sec^{-1}$)	V_a = 1 $m \cdot sec^{-1}$	9.55	0.41	67.51	**1.50**

RESULTS

Table 1 includes VI and I_{cle} values for the 2 clothing ensembles. Compared with the 3-layer ensemble, the 1-layer suit had an 8 to 10-fold lower VI; half the I_{cle}; and 1 complete air exchange per 5 min, rather than 1 per min. Figure 1 shows the I_{cle} and VI relationships for both ensembles, $P < 0.01$: r^2 was 0.65 for the 3-layer ensemble and 0.81 for the 1-layer suit. The effect of the highest walking speed and air speed was to increase VI by 20% in the 3-layer ensemble, and by 74% in the 1-layer suit, resulting in decreases in I_{cle} of 18% and 45% respectively.

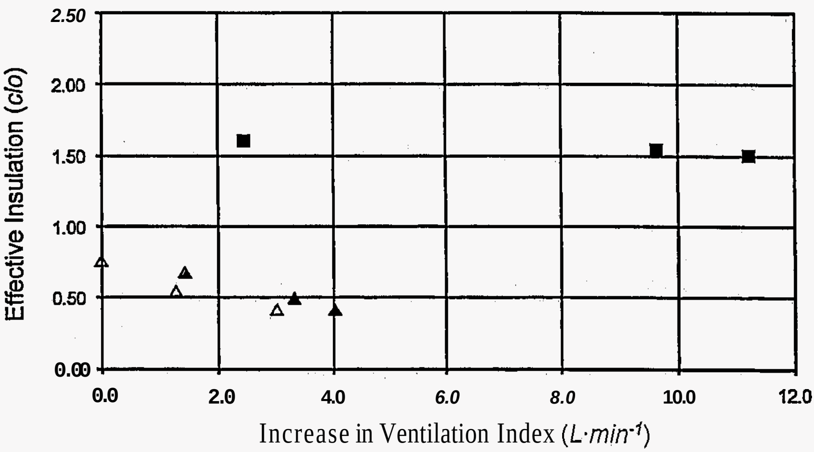

Figure 1. The influence of increasing ventilation at the skin on effective insulation of the GT (1-layer) and IREQ (3-layer) clothing ensembles. Triangular symols show the GT ensemble, square symbols show the IREQ ensemble. Open symbols show V_a = 'still air' (natural convection); closed symbols show $V_a = 1 m \cdot sec^{-1}$.

DISCUSSION

The aim of this experiment was to determine the relationship between the ventilation in 2 clothing ensembles and their thermal insulation in order to overcome reliance on indirect data that adjust intrinsic to resultant insulation. The high correlation between VI and I_{cle} shows that this approach is valid.

The ensembles were chosen because they were made from fabrics with different air permeabilities and had different designs and intrinsic insulation values. In both ensembles, an increase in VI resulted in a drop in I_{cle}. The higher VI for IREQ is a consequence of the high air-permeability of its fabrics and the larger openings at the cuffs and ankles. The relatively small increases in VI with movement and air speed suggest there is a plateau effect because of the ensemble's permeable nature. This small increase in VI resulted in only a small change in thermal insulation. In contrast, the 1-layer GT suit had a lower thermal insulation. However, its air-impermeable nature resulted in greater pumping of the microenvironment air and a relatively greater decrease in I_{cle}.

The value of this methodology is that determining the VI of clothing ensembles with different fabrics and designs is highly repeatable, even with simple equipment. Furthermore, it can be done using human subjects, carrying out activities for which the clothing has been designed. Thus it is possible to determine directly the resultant insulation of the clothing ensemble in a work situation.

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