COMPARISON OF DIFFERENT TRACER GAS DILUTION METHODS FOR THE DETERMINATION OF CLOTHING VENTILATION

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INTRODUCTION

Clothing vapour resistance (CVR) is an important parameter when evaluating the impact of the ambient workplace climate on the worker. It determines the worker's ability to lose heat (sweat evaporation) to the environment and thereby to control his or her body temperature. This impact can be in terms of stress (heat or cold) or comfort. These evaluations are used for the classification of existing workplaces, as well as for the design of new workplaces (for example building climate control systems) and thus affect the issue of health and efficiency in the workplace. As determination of CVR is currently quite complex, very time consuming and costly, alternative methods need to be developed. Deduction of CVR from clothing microclimate ventilation measurements is such an alternative (1). Two methods for the measurement of clothing ventilation have been developed: one by Lotens and Havenith (2) in the Netherlands and one by Crockford et al (3,4), which was further developed in Loughborough for the UK Ministry of Defence by Bouskill (5). Both methods for measuring clothing ventilation are currently in use in different laboratories, however without ever being directly compared. For this paper, it was chosen to start with a practical comparison of these methods to each other and a validation of both.

METHODS

The two methods for the determination of clothing ventilation were:

Crockford method

The ventilation of the skin micro-environment ($\dot{V}_T$) was determined from separate measurements of the micro-environment volume and the air exchange rate, as originally described by Birnbaum & Crockford(4) and further developed by Bouskill et al (5):

Micro-environment ventilation ($\dot{V}_T$) = Micro-environment volume · Air exchange rate (l.min^{-1})

Micro-environment volume was measured using a light-weight, flexible, 1-piece, air-impermeable oversuit, sealed at the neck, which enclosed the whole body area including the hands and feet, over the test ensemble. Air was evacuated from the oversuit until it lay just on top of the test ensemble and thus changed the clothing micro-environment pressure, as measured on a pressure sensor attached to a perforated tubing system on the skin. Micro-environment volume was the air volume evacuated from this point until the ambient to clothing micro-environment pressure difference was -30 cm H_2O. Triplicate measurements were made and the mean value calculated. Between measurements the oversuit was opened and the clothing readjusted to original drape. Micro-environment volumes were measured at ambient temperature, pressure, dry (ATPD).

With the air-impermeable oversuit removed, air exchange rate next to the body surface was measured by gas dilution. Oxygen concentration in the micro-environment was measured continuously using a sampling harness covering the whole body except hands, feet and head. Nitrogen was flushed throughout the micro-environment, using a distribution harness, until the oxygen concentration next to the skin surface reached 10%. The shape of the Oxygen concentration curve after the Nitrogen supply was closed was used to calculate the air exchange rate according to the model:

$$p(t) = p_{air} - p_1 \cdot e^{-r \cdot t}$$

where:

r	is the rate of air exchange (min^{-1})
p(t)	is the concentration of oxygen in the clothing microenvironment (%)
p_1	is such that $p_{air}-p_1$ is the initial concentration of oxygen in the clothing microenvironment at t=0 (%)
p_{air}	is the concentration of oxygen in the surrounding air (%)

Observed oxygen return curves showed a good fit with the single exponential model used.

Lotens and Havenith method

In 1988, Lotens and Havenith and later Havenith et al (1,2) modified the original Crockford method. With this method, diluted Argon is injected at the skin at numerous locations distributed over the body (except head, hands, feet). At similar locations, gas samples of the clothing microclimate air are taken. Both injected and sampled gasses are analysed for their Argon concentration using a mass spectrometer. The dilution factor of the gas in the clothing microclimate at the skin is a measure of clothing microclimate ventilation, and can be used to calculate clothing vapour resistance (1,2).

In order to study the behaviour of both methods, various measurements were performed. In order to test repeatability, test were repeated a number of times in different conditions (including 3 wind speeds, 3 movement speeds and for 4 levels of clothing air permeability) to look at the variation. Next, day to day repeatability was studied by redoing the test on consecutive days. Then the validity of the data was determined using a tubing system that introduced a forced ventilation under the clothing. The measured ventilation values should reflect this forced ventilation level. Finally, data were obtained for four different suits, varying in air permeability, in order to study the system's sensitivity to changes in air and/or movement speed.

RESULTS

Repeatability within session: The repeatability within a session was calculated as the coefficient of variation (standard deviation divided by mean, in %) over a large number of conditions, including 3 wind speeds, 3 movement speeds and for 4 levels of clothing air permeability. The results are:

Table 1, coefficient of variation (SD/mean, in %) values of repeated measurements of ventilation and volume.

	Coefficient of variation (%)	Range (%)
Crockford volume measurement	18.8	3.5-29.0
Crockford ventilation	5.0	1.4-15.5
Lotens & Havenith ventilation	6.6	1.5-17.9

Repeatability between days: The repeatability between days was calculated as the coefficient of variation (standard deviation divided by mean, in %) between measurements on 4 consecutive days. This was done for 2 wind speeds (0.7 and 4 $m.s^{-1}$).

Table 2, coefficient of variation (SD/mean, in %) values of different day measurements of ventilation

	Coefficient of variation (%)
Crockford	6.3
Lotens & Havenith	6.2

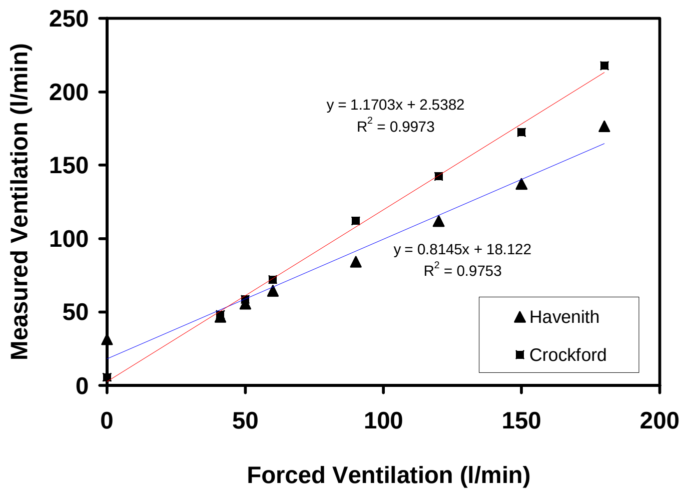

Fig 1, Validation of ventilation data by comparison with forced convection values

Validity: The results of the measurement of a forced ventilation flow for both methods, measured on a manikin are presented in Fig. 1. The forced flows ranged from 0 to 180 $l.min^{-1}$. This was the limit of the available gas meter. Further experiments, involving higher forced flows were performed using a Fleisch airflow meter. Due to technical difficulties, these measurements were not finalised by the time this paper was submitted. However these are expected to be presented at the meeting. First results indicate that for very high ventilation values (>800 $l.min^{-1}$), both methods start to diverge from the line of identity. The Crockford method starts to level off, whereas the Lotens and Havenith method's results start to increase faster than the actual forced ventilation applied.

Sensitivity: Data, comparing both methods applied to the same clothing-wind combinations are presented in Fig. 2.

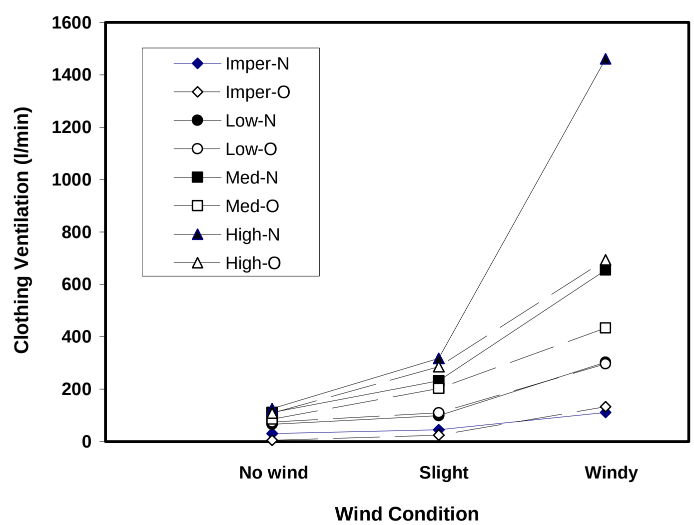

Figure 2, measurements on 4 clothing types (impermeable, low, medium and high permeability) in three wind conditions, showing the sensitivity of the methods to changing circumstances.

DISCUSSION

Repeatability: The repeatability of the individual ventilation measurements, both within one session as over consecutive days is around 4-6%, which is good, considering that typically three measurements are used to calculate an average, representative ventilation for a condition. This is also satisfactory when compared to the repeatability of clothing heat resistance measurements (6). A clear problem is present with the microclimate volume determination, required for the Crockford method. The variability here is high, which is due to problems getting a fully sealed oversuit. The topic of microclimate volume measurements is also addressed in the paper by Daanen, Hatcher & Havenith at this conference (7).

Validity: The comparison of measured ventilations with forced ventilation values is acceptable for both methods. The Lotens and Havenith method has higher values in absence of forced ventilation, but data found are comparable to natural ventilation in standing still, no wind conditions. For the Crockford method, 'no forced ventilation' measurements are actually quite low, as previously obtained data with that method typically provided higher values for this situation. Going above 40 l.min-1 forced ventilation, the Crockford method tends to overestimate, whereas the Lotens & Havenith method slightly underestimates ventilation. Both methods stay within 10 % of the forced ventilation value however. For higher ventilation, preliminary results indicate the reverse: an underestimation (levelling off) of the Crockford method and an overestimation of the Lotens & Havenith method. These effects are probably due to the characteristics of the equipment, with the Crockford method reaching the highest r value detectable by the system used, and the Lotens and Havenith method getting into problems with the tracer gas distribution of the current system.

Sensitivity: Fig. 2 shows that both methods react to the clothing air permeability and to variations in wind speed. This figure also shows signs of the problems with validity under high ventilation values. In these conditions, the data obtained by the 2 methods start to differ, with the Crockford method staying behind.

The data obtained indicate that both methods have acceptable reproducibility, validity and sensitivity for a large range of ventilation values. Problems are indicated with very low ventilation values as well as very high (>800 $l.min^{-1}$) values. The volume measurement for the Crockford method was found to be technically critical and should be replaced by a different technique as e.g. whole body scanning.

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