ERROR ANALYSIS OF METHODS TO DETERMINE RESULTING CLOTHING INSULATION BY PARTITIONAL CALORIMETRY

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INTRODUCTION.

Most thermal models for analysis of heat balance require a value for the resultant basic insulation of the clothing ensemble. The insulation value can be determined either by using a so called thermal manikin or by experiments on human subjects. Partitional calorimetry is a commonly used method to measure the *dry* heat transfer between the subject and the environment. However, only the total insulation value is usually obtained by this method. There are different possible approaches to the calculation of the resulting basic clothing insulation in human experiments with this method. For example, the time period selected for data analysis (i.e. metabolic steady-state, but changing body temperature or evaporation) may influence the experimental result in an unfortunate manner. Three aspects of the analysis of clothing experimental data were considered: i) which is the maximal possible range of the resulting clothing insulation value with reference to the skin evaporative heat loss, ii) how big is the difference in the resulting clothing insulation value between an analysis based on measured variables and calculated variables iii) what is the importance of the analysed time period?

METHODS.

We analysed data from a series of physiological clothing experiments performed in -10°C with different levels of clothing insulation (A-D). In A and B the subjects were at thermoneutrality, while in C and D sweating occurred. The subjects and their clothing were separately weighed before and after the experiment. The subjects were weighed at 20 minute intervals during the tests as well. The subjects walked on a treadmill at an average metabolic rate of 178 W/m^2 (speed ≈5.5 km/h). For the assessment of the range of resulting clothing insulation values we analysed data from the 60-90 minute of the experiment. The resulting basic insulation (I_{cl}) was calculated from the measured differences between the skin temperature [(T_{sk}), 13 thermistors], clothing surface temperature [(T_{cl}), infrared measurement on 12 spots] and the ambient air temperature (T_a), the heat balance equation where radiative and convective heat loss ($R+C$) were calculated from the measured variables, a calculated clothing area factor derived from the literature (f_{cl}) and the calculated radiation and convection heat transfer coefficients (h_r and h_c resp.) in the two following equations:

$$I_{cl} = \frac{T_{sk}-T_a}{R+C}\cdot\frac{T_{sk}-T_{cl}}{T_{sk}-T_a}\text{, and simplified: } I_{cl} = \frac{T_{sk}-T_{cl}}{R+C}\ (\mathrm{m^2 \cdot {}^\circ C \cdot W^{-1}}) \quad \text{(eq. 1)}$$

where the clothing surface temperature was measured and

$$I_{cl} = \frac{T_{sk}-T_a}{R+C} - \frac{1}{f_{cl}}\cdot\frac{1}{h_r+h_c}\ (\mathrm{m^2 \cdot {}^\circ C \cdot W^{-1}}) \quad \text{(eq. 2)}$$

where the heat transfer over the boundary air layer was calculated; $h_r = 3.2\ \mathrm{m^{-2} \cdot {}^\circ C^{-1} \cdot W}$ according to Fanger [1] and $h_c = 6.51 \cdot (walking\ speed)^{0.391}$ according to Nishi and Gagge [2].

For the analysis of the importance of the time period of analysis, data were analysed from two time periods of steady-state work, between the 25th and 45th minute (t_{45}) and between the 60th and 90th min (t_{90}) respectively. In addition, the skin evaporative heat loss was calculated in two ways considering the moisture absorbed in the clothing originating from perspiration.

RESULTS AND DISCUSSION.

Evaporative heat loss

The determination of evaporative heat loss (E) from dressed subjects is aggravated by absorption of moisture in the clothing. The lowest possible calculated E value (E_{low}) was based on the assumption that only moisture which evaporated from the subject and clothing system altogether (measured as mass loss corrected for metabolic and respiratory mass loss) chilled the skin of the subjects. The maximal possible E value (E_{high}) was consequently based on the assumption that all of the moisture which evaporated from the skin, including moisture absorbed in the clothing, chilled the skin of the subjects. Thus, the differences between the I_{cl} value based on E_{low} and E_{high} ranged from 0.001 up to 0.026 m^2°C*W^{-1} (see fig. 1, eq.1). The biggest difference of I_{cl} was consequently observed in the warmest clothing ensemble with the most absorbing fibres, in which the subjects perspirated. Most of the absorbed sweat was found in the third and outermost layer of the clothing ensemble which was in line with the report of measurements of subjects in arctic uniforms by Belding [3]. Most likely, the actual skin evaporative heat loss was somewhere in between the two extremes. This is also in agreement with Belding who suggested that the relative contribution to heat retention from moisture absorbed in the outer layers of a clothing ensemble was 30-50%.

Measured and calculated dry heat transfer

The I_{cl} results from equation (2) were consistently lower than those from eq. (1) (fig.1). Thus, the calculated convective and radiative heat transfer over the boundary air layer in equation (2) seemed to be underestimated. Both equations were calculated with E_{low}. The difference between the I_{cl} value of equation 1 and equation 2 calculated with E_{low} ranged betwen 0.012 to 0.024 $m^2 °C*W^{-1}$. In the two alternative calculations equations with E_{max} the underestimation became less or negligible compared to the indirectly measured dry heat transfer (fig.1). Furthermore, the higher the insulation, the lower the influence of the boundary air layer will be. As earlier pointed out, the actual E and thus $R+C$ and I_{cl} lay in between the two extreme values.

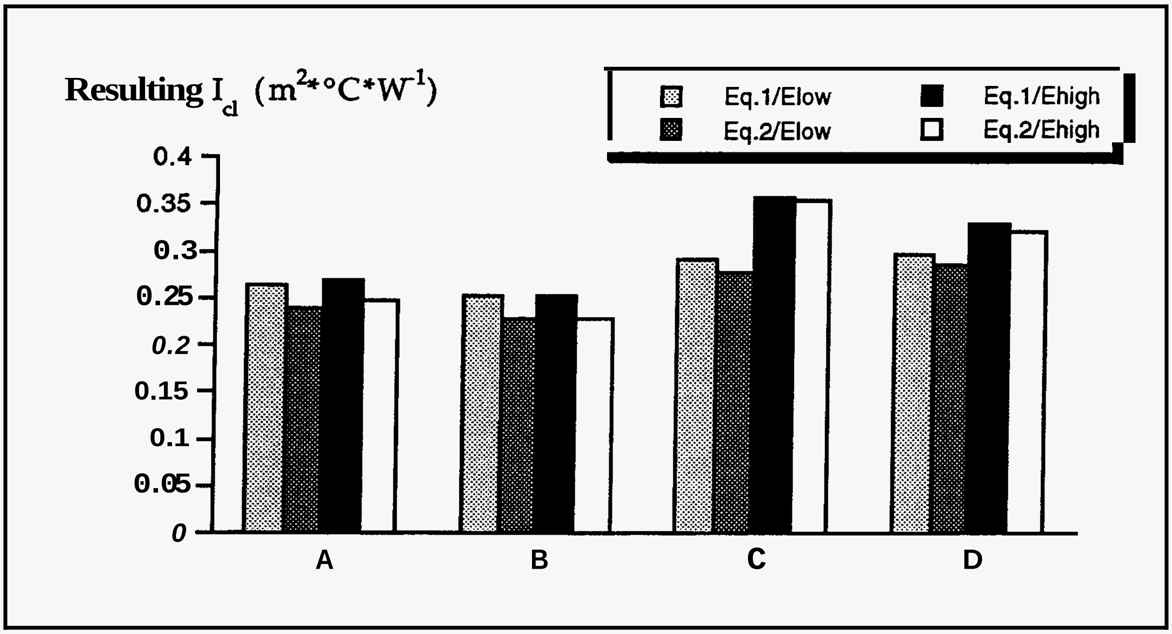

FIGURE 1. Resulting basic insulation of four clothing ensembles calculated with alternative equations.

When the above alternative calculations were taken into consideration the I_{cl} value for the individual clothing ensembles differed at most from 0.024 (the lowest insulation) up to 0.076 $m^2 °C*W^{-1}$ in the highest insulation, which was 9 to 21 % of the largest calculated I_{cl} value. The errors in the calculated variables of the heat balance were well within the errors in the I_{cl} determination.

Point of time of data analysis

Both the mean skin temperature and the rectal temperature were rather stable during the analysed time periods (t_{45} and t_{90} resp.), but the evaporation rate was changing with time. The difference between E_{45} and E_{90} was subsequently reflected in the heat balance result and the clothing insulation value. The I_{cl} value was 3 to 10 % less calculated from data in the earlier time period t_{45}.

CONCLUSIONS.

The biggest difference was found in the clothing ensembles with the highest insulation mainly because of an increasing and higher sweat perspiration in the subjects. The relative inaccuracy of the determination of resulting clothing insulation should be noticed and ought to be taken into consideration for example in thermal modeling. The precision may be improved by designing experiments so to avoid sweating, to measure clothing surface temperature and if possible also the clothing area factor.

REFERENCES.

1. Fanger P. O.1970, Thermal comfort. (Danish Technical Press, Copenhagen).

2. Nishi Y. and Gagge A. P. 1970, Direct evaluation of convective heat transfer coefficient by naphtalene sublimation, J. *Appl. Physiol.* 29: 830-838.

3. Belding H. S., Russel H.H., Darling R. C. and Folk G. E. 1947, Thermal responses and efficiency of sweating when men are dressed in arctic clothing and exposed to extreme cold, *Am.* J. *Physiol.* 149: 204-222.