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The actual insulation of multilayer clothing

by Wouter A Lotens[1]

LOTENS WA. The actual insulation of multilayer clothing. *Scand J Work Environ Health* 1989;15(suppl 1):66—75. The effect of geometric factors on insulation was calculated mathematically for standing humans. It was found that internal radiative heat transfer in an ensemble was significant for insulation, that intrinsic clothing insulation is a useful concept only for indoor climates, and that shape plays a minor role. The literature agrees closely on insulation and clothing surface area figures, and the latter are compatible with model predictions. Finally, it was shown that wind, body motion, the effects of posture, and the fit of garments are predictable. Sitting provides more insulation than standing for light clothing, but the reverse is true for heavy clothing. Insulation is decreased by about 20 % by cycling and by about 40 % by walking, and a reasonable estimate can be made of the effect of wind and wind and motion together. The effect of air motion on vapor permeability is stronger than the effect on heat transfer.

Key terms: activity, clothing, fit, insulation, manikin, model, posture, subjects, vapor permeation, wind.

Clothing is usually regarded as a single homogeneous layer, covered with an air layer. However, this is too much of a simplification for general considerations on actual clothing insulation. First, in reality, the number of layers varies over the body. The trunk is usually covered with more layers than the extremities, so that insulation is not uniform over the body, particularly for the head and hands, which are often uncovered. Second, the various fabric layers encapsulate the human body, the outermost layers having less effective insulation due to their increased surface area. The ensemble contains more air than fabric and will show radiative heat transfer, in particular for loosely fitting clothing. Third, the enclosed amount of air changes with the posture of the wearer, since clothing is tightly stretched over specific body areas when a person sits but is freely hanging during standing. The enclosed air may also change during motion of the wearer (pumping) and due to wind penetration through the fabric or through apertures (ventilation). There is also an interaction between the fit of the clothing and these air exchange effects.

In the present report these effects have been addressed in detail, and literature data have been compiled to show that there is more consistency in respect to these effects than has been generally recognized. Thus the available data banks of clothing insulation values, such as provided by McCullough et al (1), may be extrapolated to clothing insulation in a wider range of environments and activities. The effects of interaction between heat and moisture transfer (absorption, condensation), which are very significant for actual insulation as well, are beyond the scope of this paper however.

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From fabric to clothing

The various layers of clothing are draped in a special way. Underwear is often tightly fitting, due to stretchability, but trousers, shirts, sweaters, dresses, etc, typically hang loosely, trapping layers of air. In a first approximation it will be assumed that these air layers are uniform over the body, although it is clear that this assumption is not realistic for the shoulder and hip areas, where the clothing layers are in close contact, and in many other areas where pleats and folds shape air chambers rather than layers. Because of the radiation component, the conductivity of the enclosed air changes with its thickness, according to the following equation:

$$\lambda_a = 0.026 + 5 \cdot \text{tha} \quad (\text{W} \cdot \text{m}^{-1} \cdot {}^\circ\text{C}^{-1}), \quad \text{(equation 1)}$$

where tha is the average thickness (m). The first term on the right represents pure conduction and the second term is radiation.

Siple & Cochran (2) used a tape measure method to determine the thickness of clothing ensembles and compared the thickness with the actual clothing insulation, determined on a heated manikin. They found a conductivity of 0.040 $\text{W} \cdot \text{m}^{-1} \cdot {}^\circ\text{C}^{-1}$, which later became Burton & Edholm's (3) famous 4-clo-per-inch rule of thumb (1 clo = 0.155 $^\circ\text{C} \cdot \text{m}^{-2} \cdot \text{W}^{-1}$). Since fabric layers per se typically have a conductivity of 0.042 $\text{W} \cdot \text{m}^{-1} \cdot {}^\circ\text{C}^{-1}$, the enclosed air in Siple & Cochran's ensembles must have also had a conductivity of about 0.04 $\text{W} \cdot \text{m}^{-2} \cdot {}^\circ\text{C}^{-1}$, a value which compares to a size of 3 to 4 mm. In view of the much larger air chambers that have been observed, this seems to be a surprisingly low conductivity. In the laboratory of my co-workers and I a variety of work ensembles has shown higher conductivities on the average (4). At locations with a tight fit (chest and back) the conductivity was 0.047 (SD 0.008) $W \cdot m^{-1} \cdot °C^{-1}$, at locations with a normal fit (buttocks, stomach) it was 0.084 (SD 0.010) $W \cdot m^{-1} \cdot °C^{-1}$, and at locations with a loose fit (calf) the value was no less than 0.143 (SD 0.015) $W \cdot m^{-1} \cdot °C^{-1}$. Therefore, in most cases, the radiation component of clothing conductivity dominates over pure conduction, in contrast to fabrics, for which conduction has the largest contribution. Apparently the effect of drape (loose or tight fit) must be considered in more detail.

Another typical difference between fabrics and clothing is that the thickness of a clothing ensemble is usually not uniform. The extremities are less insulated than the trunk. A third point is that the human shape resembles a collection of cylindrical components rather than a flat surface. The effect of the geometric factors drape, body shape, insulation distribution, and partial skin coverage on total clothing insulation can be investigated theoretically by means of a model in which a human is represented by a number of cylindrical elements.

The heat transfer coefficient of a cylinder of radius R_0 covered with material with a conductivity of λ_{cl} up to radius R, is given by:

$$h_{cl} = \lambda_{cl}/[R_0 \ln (R/R_0)] \quad (W \cdot m^{-2} \cdot °C^{-1}). \quad \text{(equation 2)}$$

The heat transfer coefficient of the surrounding air, normalized to the skin area, is:

$$h_a = (R/R_0)(hr + hc) \quad (W \cdot m^{-2} \cdot °C^{-1}). \quad \text{(equation 3)}$$

These two heat transfer coefficients in series result in:

$$h = [\lambda_{cl} R (hr + hc)]/[\lambda_{cl} R_0 + R_0 R (hr + hc) \ln (R/R_0)]. \quad \text{(equation 4)}$$

The values for h are finally integrated over the various cylinders to produce the total heat transfer coefficient ht.

The conversion of ht to the insulation in clo units is then achieved with:

$$I_t = 1/0.155\ ht \quad (clo). \quad \text{(equation 5)}$$

This equation gives the total insulation of clothing plus adjacent air. In experimental studies this is often the variable that is measured, although interest is focused on the clothing itself. The definition of clothing insulation per se is:

$$I_{cl} = I_t - (I_a/f_{cl}) \quad (clo), \quad \text{(equation 6)}$$

where I_{cl} is intrinsic clothing insulation (clo), f_{cl} is a surface factor (no dimension) equal to the outer surface area of the clothing over the skin surface area.

This heat transfer model was implemented in a computer program (CLOMAN2 V1.0) that allows input for clothing conductivity, the air heat transfer coefficient, and the thickness of clothing on various body parts relative to trunk insulation thickness. In figure 1 the relationship between I_{cl} and clothing thickness is shown for various distributions of insulation over the body.

Insulation is usually unevenly distributed over the body for reasons of mobility and comfort. An estimated distribution for cold weather clothing is that the thickness relative to that for the trunk is 0.7 for the arms, 0.5 for the legs, 0.3 for the feet and head, and 0.2 for the hands. If a person were to have a flat surface, the insulation would increase linearly with the thickness of the clothing and conform to the line marked "flat" in figure 1. Due to the cylindrical shape of body parts some insulation is lost, however, since the outer surface increases and can lose more heat. The result is shown by the curve "full" in the figure. Apparently the loss of insulation due to curvature is limited. Exposed skin decreases the total insulation dramatically, despite the limited skin areas involved (7 % for head, 5 % for hands, and 7 % for feet). This effect is even stronger when the air convection is high, due to wind (lowest curve). For example, the intrinsic insulation drops by 50 % when hc increases from 5 $W \cdot m^{-2} \cdot °C^{-1}$ (0.4 $m \cdot s^{-1}$, light air) to 25 $W \cdot m^{-2} \cdot °C^{-1}$ (10 $m \cdot s^{-1}$, fresh breeze).

From these considerations three important observations emerge. First, although the effect of curvature may considerably affect local insulation, particularly for the extremities, it is of minor importance for the intrinsic insulation of the ensemble. Second, intrinsic insulation is not a specific clothing constant, but depends instead on air convection. Apparently the concept of intrinsic insulation is meaningful only for a standard environment, for example, indoors. Using intrinsic insulation values to predict comfort or heat stress in another environment thus leads to errors. The problem is due to the exposed skin. If intrinsic insulation were redefined in terms of covered skin area, in contrast to total skin area, it would be largely, but not completely, independent of wind. Third, exposed skin

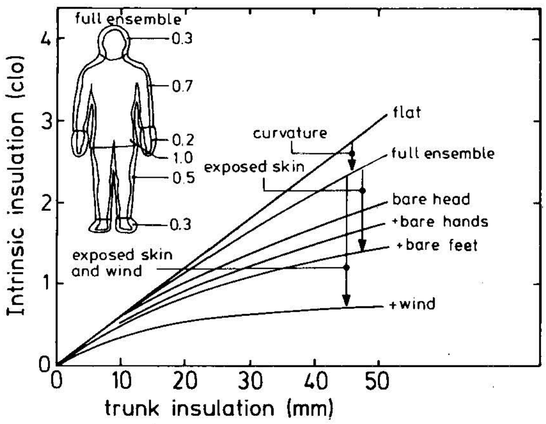

Figure 1. Intrinsic clothing insulation as a function of clothing thickness for various distributions of insulation (slightly tight-fitting clothing).

and wind together may limit the insulation of thick garments to less than 1 clo. Winter ensembles must thus have increased skin coverage. This last point has been treated in more detail later.

Figure 2 shows the total insulation (I_t) that is obtained with a certain volume of insulative material for

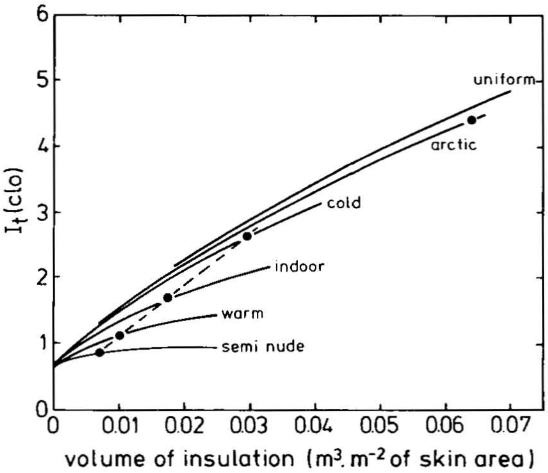

Figure 2. Total insulation (I_t) obtained with six typical distributions of insulation under still air conditions as a function of the volume of the insulative material. The broken line represents the insulation of common clothing.

Table 1. Typical thickness of insulation on the extremities of the body for typical clothing fitting six different environmental conditions; trunk insulation has been used as reference.

	Legs	Arms	Hands	Feet	Head
Body seminude	0.0	0.0	0.0	0.0	0.0
Warm environment	0.1	0.1	0.0	0.2	0.0
Indoor environment	0.5	0.7	0.0	0.3	0.0
Cold environment	0.5	0.7	0.2	0.3	0.3
Arctic environment	0.7	1.0	0.5	0.5	0.5
Uniform thickness	1.0	1.0	1.0	1.0	1.0

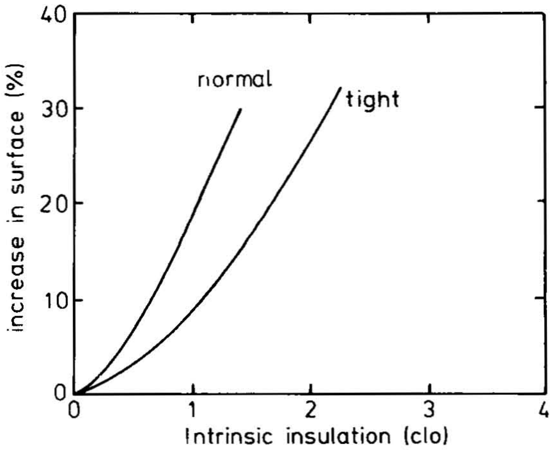

Figure 3. Calculated surface ratio f_{cl} as a function of intrinsic insulation for normal and tight fitting garments.

seminude humans, for typical ensembles for warm, indoor, cold and arctic environments, and for a uniform distribution, and table 1 presents the typical distribution on the extremities with the trunk insulation as reference. For the same amount of insulative material the highest insulation is obtained with a uniform distribution over the body. Arctic ensembles are definitely more uniform than warm weather clothing, with the head, hands, arms, and legs bare. When the approximate insulation values for the different ensembles are plotted (figure 2), the total insulation of actual clothing is linearly related to the volume of insulation material, except for very thick clothing, whose efficiency is already close to optimum. Since there is a limit to the bulk of clothing that can be tolerated, the total insulation will hardly ever exceed the value of 5 clo.

Another point of interest is the increase in the outer surface area of clothing. When the outer surface is much larger than the area of the skin, the effective insulation of the air decreases with the ratio of the two areas (introduced in equation 6) as follows:

$$f_{cl} = \text{clothing surface area}/A_D \quad \text{(no dimension)}, \qquad \text{(equation 7)}$$

where A_D is the DuBois & DuBois (5) body surface area (m^2). The air insulation is then determined as (similar to equation 3):

$$I'_a = I_a/f_{cl} = 1/[f_{cl} \cdot 0.155 \cdot (hr + hc)]. \qquad \text{(equation 8)}$$

The effect of clothing thickness on total insulation is thus counteracted by a loss of air insulation, in addition to the decreased efficiency due to curvature (figure 1). In figure 3 the calculated f_{cl} is shown as a function of the intrinsic insulation, both for normal-fitting ($\lambda_{cl} = 0.080\ W \cdot m^{-1} \cdot °C^{-1}$) and for tight-fitting ($\lambda_{cl} = 0.040\ W \cdot m^{-1} \cdot °C^{-1}$) garments. The increase in the f_{cl} factor is more or less proportional to I_{cl}:

$$f_{cl} = 1 + c \cdot I_{cl} \quad \text{(no dimension)}, \qquad \text{(equation 9)}$$

the coefficient varying from 0.08 for light, tightly fitting garments to 0.25 for warm, normally fitting garments. It will be shown later that the latter value is more realistic than the former. Consequently the higher value for λ_{cl} is more likely than the value of 0.040. This conclusion supports the already mentioned rejection of the 4-clo-per-inch rule of thumb.

Measurement of garment characteristics

Most clothing insulation measurements are done on thermal manikins. The first available manikins were those of the United States Army in 1942. Some of them are still in use, but many new devices have been designed, such as the Hohenstein equipment and the TORE manikins from Scandinavia. The first manikins were static, but the more recent ones can be motor-driven to imitate walking or cycling.

Sweating is a technological problem. The old manikins were covered with a wet cloth underneath the clothing to evoke a vapor flow, but the cloth tends to dry out before the clothing is conditioned. This was an obstruction to reliable measurement. Fully wetting a manikin is possible, but keeping the surface at a controlled wetness is difficult. A recent sweating manikin is the Finnish COPPELIA, but it is still only a prototype. Due to these problems manikins are mainly being used for heat flow measurements. The vapor resistance characteristic of clothing is usually extrapolated from flat plate results.

Tables of insulation values have been published (1, 6—9) for a wide variety of clothing items and ensembles. In order to find the insulation of a specific ensemble that is not included in the list, one looks up the items in the ensemble in the table and uses a regression equation to find the ensemble insulation:

$$I_{cl} = a \Sigma I_{cli} + b \quad \text{(clo)}, \qquad \text{(equation 10)}$$

where I_{cli} refers to the separate items. The values for the constants a and b vary between authors. They are listed in table 2. Applying the various formulas to clothing ensembles with $\Sigma I_{cli} = 0.5$ and 1.5 clo, respectively, shows that Goldman's prediction is rather low. The other predictions agree within 15 % for the light ensembles and within 7 % for the heavier ensembles with the average formula:

$$I_{cl} = 0.75 \Sigma I_{cli} + 0.09 \quad \text{(clo)}. \qquad \text{(equation 11)}$$

In view of the theoretical considerations presented in the section "From Fabric to Clothing," regression equation 10 is peculiar. The weight factors of the separate clothing items should not be constant, but should instead depend on the other items of the ensemble and, in particular, on the uncovered skin area. The fact that, with equation 10, with uniform weights, the correlation coefficient of 0.97 is obtained (1) must be due to the fact that the heavier ensembles also have a more uniform distribution of insulation, as demonstrated in figure 2. A close look at the data of McCullough et al shows indeed that ensembles with insulation predominantly on the trunk have lower insulation values than ensembles with a better distribution.

For the calculation of I_t, not only I_{cl} must be available, but also the surface factor f_{cl}. (See equation 6.) In table 3 the literature values for f_{cl} have been compiled. When the deviating value of Fanger (14) is omitted, the various sources agree within 5 % of the value obtained with the following equation:

$$f_{cl} = 1 + 0.29 \cdot I_{cl} \quad \text{(no dimension)}. \qquad \text{(equation 12)}$$

This value compares well with the estimated value of $1 + 0.25 \cdot I_{cl}$ for normal clothing in figure 3. It should be noted that the latter estimate is based on the assumption that the clothing surface is a perfect cylinder, whereas real clothing shows folds that increase the actual surface. Mekjavic & Sullivan (16) have reported that the representation of clothing by various cylindrical elements provides a fair estimate of the actual surface. When the clothing is extremely folded, a quick estimate of the actual surface may be made with planimetric measurement of the clothing that forms the outer surface when overlaps and uncovered area are taken into account.

The use of clothing tables is not unambiguous. McCullough et al (1) showed that even trained textile students experience difficulties in identifying clothing items from those listed in the tables, the result being a standard deviation of 23 % in the intrinsic insulation. It is thus not the inaccuracy of the table, but the way the table is used that introduces error. Several other methods for determining clothing insulation have been tried, including regression on the weight, thickness, and body coverage of the clothing. The most accurate of these are the following equations given by McCullough et al (1):

$$I_{cli} = 0.0079 \cdot BSAC + 0.00131 \cdot th \cdot BSAC - 0.0745 \quad \text{(clo)} \qquad \text{(equation 13)}$$

for separate clothing items, and

$$I_{cl} = 0.676 \Sigma I_{cli} + 0.117 \quad \text{(clo)} \qquad \text{(equation 14)}$$

for the ensemble, where BSAC is body surface area covered (%), and th is thickness (mm) of the clothing items according to the American Society for Testing and Materials (17) at a pressure of 69 Pa. This method has a standard deviation of 0.09 clo. Slightly less

Table 2. Values for the constants a and b in equation 10 according to data compiled by Havenith (13).

Author	Constant	
	a	b
Sprague & Munson (9)		
Men	0.727	0.113
Women	0.770	0.050
ASHRAE (10)	0.820	0.000
Olesen & Nielsen (11)	0.730	0.170
Goldman (12)	0.690	0.000
McCullough et al (1)	0.676	0.117

Table 3. Values for the constant c in equation 9 according to data compiled by Havenith (13).

Author	Constant c
Fanger (14)	0.15
Seppanen et al (8)	0.25
McCullough & Jones (15)	0.34
McCullough & Jones (15) using data from Sprague & Munson (9)	0.29
Olesen & Nielsen (11)	0.26
McCullough et al (1)	0.31

accurate (standard deviation 0.12 clo), but less laborious is the equation (1):

$$I_{cl} = 0.255 \cdot W - 0.00874 \cdot BSAC0 - 0.00510\ BSAC1 + 0.919\ \text{(clo)}, \quad \text{(equation 15)}$$

where W is weight (kg) without shoes, BSAC0 is the uncovered body area (%), BSACl is the body area covered with one layer (%).

A basically different technique to measure the thermal characteristics of clothing is partitional calorimetry, developed in the laboratory of the JB Pierce Foundation in the late 1930s. Human subjects are used as living calorimeters in this technique with the aim of measuring the components of the heat balance equation:

$$M = Wext + Dry + Evap + Resp + Store\ \text{(W)}, \quad \text{(equation 16)}$$

where M is metabolic heat production, Wext is the external work performed, Dry is the dry heat loss due to conduction, convection and radiation, Evap is the evaporative heat loss, Resp is the respiratory dry and evaporative heat loss, and Store is the rate of heat storage in the subject. All the terms in equation 16 are measured or estimated, except for Dry, which can thus be calculated from the heat balance. The heat transfer coefficient ht and the vapor resistance, expressed as the air equivalent d, are then obtained from:

$$ht = Dry/[A_D\ (T_{sk} - T_a)]\ \ (W \cdot m^{-2} \cdot {}^{\circ}C^{-1}) \quad \text{(equation 17)}$$

and

$$d = [(A_D\ He\ 1000\ \mathbb{D})/Evap]\ (C_{sk} - C_a)\ \ \text{(mm)}, \quad \text{(equation 18)}$$

where A_D is the DuBois body surface area (m^2), T_{sk} is the mean skin temperature, T_a is the air temperature, He is the heat of evaporation (J/g), $\mathbb{D}$ is the diffusion coefficient ($m^{-2} \cdot s^{-1}$), C_{sk} is the mean skin vapor concentration ($g \cdot m^{-3}$), C_a is the air vapor concentration ($g \cdot m^{-3}$), ht is the heat transfer coefficient ($W \cdot m^{-2} \cdot {}^{\circ}C^{-1}$), and d is the air equivalent (mm) (ie, the thickness of a still air layer that would have the same vapor resistance as the sample).

Thus during one experimental session both the heat and the vapor characteristic of the clothing can be obtained. In reality there is variation due to differences between subjects and experimental error. A good experimental design and corresponding statistical analysis is thus necessary. The heat balance technique demands more experimental skills and more effort than the manikin technique, but the results are of a higher order. The clothing parameters are obtained during realistic physiological conditions, there are few restrictions to the kind of activity of the subjects, the actual thermal strain can be observed, and the results can be interpreted in light of interindividual variability.

Olesen & Nielsen (11) concluded that partitional calorimetry is too inaccurate and too laborious to compete with manikin measurements. Although their conclusion is too bold, there is some truth in it. Lotens et al (18) modified the technique to obtain a higher accuracy at the expense of realism of the physiological condition. To increase Dry, and hence its accuracy, Evap is suppressed by wrapping the subject in plastic (figure 4). Thus ht can be determined with a relatively small error. The measurement of vapor permeation is not done by sweat diffusion, but by the diffusion of a tracer gas that is not absorbed in the clothing. This measurement can then be typically carried out in 5 min, instead of the at least 1 h needed with

Figure 4. A subject wrapped in plastic for the modified heat balance technique. The clothing still has to be donned.

actual sweat. This tracer gas technique has been developed and evaluated by Lotens & Havenith (19).

The question has been raised of whether insulation measured on a manikin and on subjects is identical. At first sight this seems to be a simple question, but there are many complications involved. The sweat production of humans causes a vapor flow which interacts with the heat flow in a complicated way. There are experimental traps that may lead to errors. Furthermore the fit of the clothing should be the same for the manikin and the subjects, and their posture should also be the same. In addition the skin temperature distribution should be the same, the subjects should be bald, and they should not breathe and move their chest. Thus, if experimenters succeed in making these conditions identical for manikins and for subjects, they would have a fair comparison, but there would hardly be a reason for different insulation values being obtained. In other words, it is not so much that manikin values are different but that they only represent one aspect of a complicated matter. More interesting is the question of whether satisfactory corrections can be given for manikin values to predict realistic heat transfer for humans. The aforementioned techniques provide useful tools in the investigation of such corrections. In the next sections the various factors involved are considered in detail.

Posture and fit

Since enclosed air layers constitute a considerable part of total insulation, it is anticipated that a change in the fit of clothing or in posture affects the insulation. During sitting the air will be driven out the thigh, buttock, and back areas, and insulation will probably decrease in comparison with insulation during standing, whereas the effective radiant surface decreases. The insulation of the adjacent air may thus increase. The chair may add insulation, but in tests usually netting chairs or stools are used that provide negligible insulation.

There are few studies to quantify the effect of fit. Lotens et al (18) did a study using repeated heat balance measurements on a lean and an obese subject with garments of a single size. The garments were thus tightly fitting for the obese subject (1.85 m, 88 kg) and loosely fitting for the lean subject (1.78 m, 61 kg). Measuring the temperature inbetween the layers gave the insulation values for the adjacent air layer, the protective outer garment, the air gap between the outer garment and the fatigues, and the fatigues. Due to the dimensions of the temperature sensors, it was inevitable that some air insulation was incorporated into the calculated insulation of the clothing layers, at the expense of the calculated insulation of the air layers. Table 4 shows that, during sitting, the total insulation was not different between the tight and loose fits, but, during standing, it was distinctly greater with the loose fit. The difference was primarily due to the fatigues that, for the lean subject, tended to fill the larger space between the body and the outer garment. A comparison of the sitting and standing posture shows a striking difference in total insulation, to which all layers except the adjacent air contributed.

With typical indoor and work ensembles the effect of posture is not so strong, but it is still clearly present. Nielsen et al (20) measured clothing insulation on men and women and concluded that I_{cl} decreased 10—20 % during sitting, while I_a increased 10—20 %. Olesen et al (7) found similar values with a movable manikin, be it that the increase in I_a was only 5 %. In figure 5 the total insulation values during sitting have been compiled as a function of insulation during standing. The net effect of changes in clothing and air insulation is rather small. For light clothing there is an increase of 10 % during sitting, but with heavy clothing there is a decrease. In particular garments with large air chambers may show a stronger decrease.

Wind and body motion

Both wind and body motion may affect insulation through the induction of air motion. When outside air

Table 4. Insulation for various layers of an ensemble for protection against chemical exposure under different conditions of fit and posture, according to data from Lotens et al (18). The area factor has been included in the insulation values.

Fit	Adjacent air (clo)	Outer layer (clo)	Enclosed air (clo)	Fatigues (clo)	Total (clo)
Loose					
Sitting posture	0.55	0.41	0.21	0.43	1.60
Standing posture	0.57	0.70	0.57	0.95	2.79
Tight					
Sitting posture	0.55	0.48	0.30	0.30	1.63
Standing posture	0.42	0.72	0.49	0.50	2.13

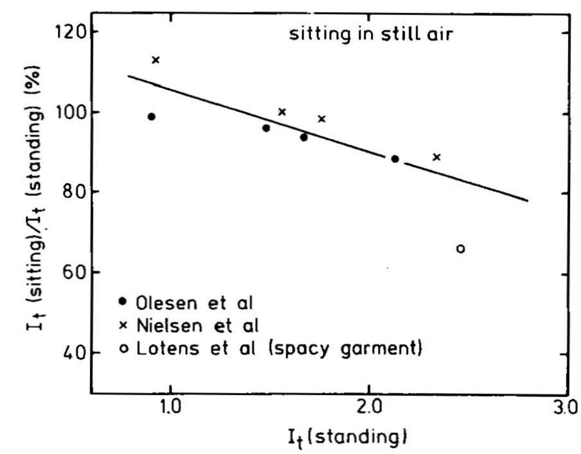

Figure 5. Total insulation during sitting, relative to standing, for various ensembles according to Olesen et al (7), Nielsen et al (20), and Lotens et al (18).

penetrates the clothing, either via closures or through the material, the effect is called ventilation. When there is no air exchange, but rather an increased circulation underneath the clothing or at the surface of the clothing, it is called convection. Usually ventilation and convection will be concomitant.

Vokac et al (21) were among the first to assess "bellows ventilation," ie, circulation underneath a garment due to rhythmic body motion during walking. This convection may decrease the insulation, but the effect is difficult to discern from outside convection. In reality the only activities that have been used to measure motion effect are those that are easily controlled in an experimental situation, ie, walking (4—5 km/h) and cycling (about 40 revolutions/min). Nielsen et al (20), who performed a direct comparison of the two activities, concluded that both I_{cl} and I_a are higher during cycling than during walking, but lower than during standing. This statement applies to conditions without wind, and the result is understandable from the fact that, during cycling, the arms and back are more static than during walking. In addition posture may have an effect, eliminating ventilation of upper body parts during cycling.

Figure 6 shows the findings of various researchers for walking and cycling. The figure proves that ventilation and convection decrease the insulation of a wide range of clothing to an equal degree, and, moreover, as for seminude subjects ($I \approx 1.0$ during standing). There may be a slight increase in the loss of insulation as clothing thickness increases, but the data are not conclusive. For many clothing ensembles the results

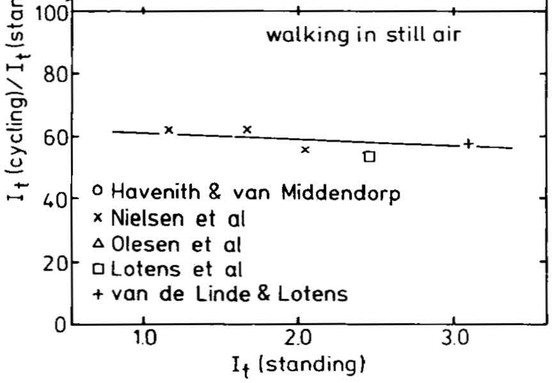

Figure 6. Total insulation during cycling and walking (lower part of figure), relative to standing, for various ensembles, according to Havenith & Van Middendorp (22), Nielsen et al (20), Olesen et al (7), Lotens et al (18), and van de Linde & Lotens (23).

could be summarized by the statement that walking decreases the total insulation by 40 % and cycling by 20 %. On the recognition that the difference between the two activities is the motion of the upper body, this statement could also be formulated as: the motion of the upper part of the body and the motion of the lower part of the body each cause a 20 % loss of insulation.

In wind the adjacent air layer is thinner and, due to the pressure, air may penetrate into the clothing. Fonseca & Breckenridge (24) used a cylindrical calorimeter to show that the insulation is predominantly lost at the windward side and that there is another, much lower peak on the lee side. The penetrating air enters the first clothing layer on the windward side, flows around the cylinder in the air gap between the layers, and leaves on the lee side. When the flow in the gap is hampered by fiber material, the second clothing layer is also penetrated on the windward side, and the net result is that the addition of fiber material actually decreases the total insulation. The data of Fonseca & Breckenridge for the total heat transfer coefficient show a linear relationship with $\sqrt{V}$ (V is wind speed), with a slope dependent on the air permeability of the windbreak layer and the air gap underneath:

$$h = d\sqrt{V} + e \quad (m^2 \cdot {}^\circ C \cdot W^{-1}). \qquad \text{(equation 19)}$$

On theoretical grounds Stuart & Denby (25) predicted a $\sqrt{V}$ dependency as well. Fonseca & Breckenridge (24) showed with their calorimeter that the insulation drops with the opening of vents and the drop is larger when the air gap between the first two clothing layers is increased. Lotens & Havenith (19) found the same phenomenon during direct measurements of ventilation on humans when they increased the air gap by means of a harness of foam strips.

Surprisingly, there are only a few studies that evaluate clothing insulation for standing humans as a function of air motion. The effect of air motion on the insulation of the adjacent air layer is well known from both physiological measurements [$hc = 8.3\sqrt{V}$ (from reference 26)] and physical measurements [wind-chill chart (27)], but the effect on I_{cl} has not been as well investigated. In figure 7 the data have been calculated with equation 19 as rewritten for this application:

$$I_t = I_{t0.3}\,[(f\sqrt{0.3} + 1)/(f\sqrt{V} + 1)] \text{ (clo)}, \qquad \text{(equation 20)}$$

where $I_{t0.3}$ is the insulation at $V = 0.3\ m \cdot s^{-1}$. (This value was used for reference because, in most studies, there is some light air motion and natural convection); f is equal to d/e in equation 19 and has the value 1.3 for light clothing, 0.8 for medium heavy clothing, and 0.4 for heavy clothing.

It should be noted that heavy clothing will usually be more airtight than light clothing. No distinction has been made between air permeability and clothing thickness. Although there is some variance in figure 7, probably due to the difference in the windbreaking property of the clothing, there is a general decline in insulation with increasing wind speed, the decline being greater for light clothing than for heavy clothing.

Givoni & Goldman (29) published the following prediction equation:

$$I_t = I_{t\,1.0}\,V^{-p} \quad \text{(clo)}, \qquad \text{(equation 21)}$$

where $I_{t\,1.0}$ is defined at 1 m · s^{-1}. This equation was introduced to explain discrepancies between measured and predicted heat stress for low air motion and is fitted basically at 0.5 and 5 m · s^{-1} (30). The pumping coefficient p has the value of 0.25 for light clothing, 0.2 for medium heavy clothing, and 0.15 for heavy clothing.

Equations 20 and 21 provide nearly the same figures, except for high wind speed, for which equation 21 predicts insulations that are too high since there is an increasing discrepancy between light clothing and pure air.

The combined effect of body motion and wind is not a summation of the two, since there is an interaction. Wind induced by body motion should, true enough, be added to external wind, but the effect of this total wind speed is less than proportional, as figure 7 proves. Thus, in wind, the effect of body motion is reduced. Givoni & Goldman (29) expanded equation 21 to take both wind and motion of walking into account:

$$I_t = I_{t\,1.0}\,V_{eff}^{-p} \quad \text{(clo)}, \qquad \text{(equation 22)}$$

where V_{eff} is the effective wind speed,

$$V_{eff} = V + 0.004\,(M - 105) \quad (\text{m} \cdot \text{s}^{-1}), \qquad \text{(equation 23)}$$

and M is the metabolic rate. For walking in still air, with an approximate metabolic rate of 360 W, V_{eff} amounts to slightly more than 1 m · s^{-1}, which is a value too low to explain the 40 % loss of insulation found in figure 6, ie, 6 m · s^{-1} for heavy garments and 2 m · s^{-1} for light clothing would be more accurate according to figure 7. The idea behind equation 23 is probably correct, however. According to this idea, when the effect of wind and walking on the relative insulation is determined at a wind speed of 4 m · s^{-1} for the two available references, 55 % is predicted for heavy clothing rather than the measured value of 52 % (23) (10 m · s^{-1} effective wind speed), and for air only at 1.1 m · s^{-1} 51 % is predicted (3.1 m · s^{-1} effective wind speed) rather than the measured 47 % (20). Thus figure 7 could be a valuable tool for the estimation of insulation.

Lotens & Havenith (19) applied the trace gas technique to measure the ventilation of windproof rainwear and thus obtained the ventilation through the closures. The results shown in figure 8 prove that at least for the ventilation part of the heat loss, the equivalent wind velocity of walking amounts to more than 2 m · s^{-1} for the jacket and more than 6 m · s^{-1} for the trousers. These values are not inconsistent with those deduced from figure 7.

Effect of ventilation on vapor permeation

It is not an unusual practice to determine the relation between heat and vapor permeation on a flat plate and extrapolate this value (eg, i_m or equivalent) to the complete garment worn by subjects. From a theoretical point of view this procedure is not correct. The heat transfer is given by:

$$\text{Dry} = (hcd + hr)\,A_D\,(T_{sk} - T_a) \quad (\text{W} \cdot \text{m}^{-2}), \qquad \text{(equation 24)}$$

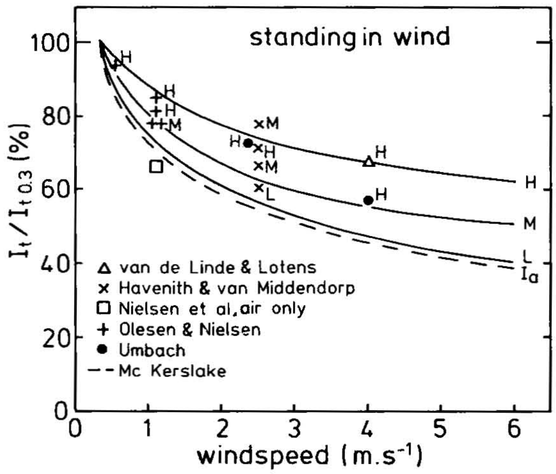

Figure 7. Total insulation during standing in the wind, relative to an air velocity of 0.3 m · s^{-1}, according to van de Linde & Lotens (23); Havenith & Van Middendorp (22); Nielsen et al (20), air only; Olesen & Nielsen (11); and Umbach (28). The solid lines are predicted with equation 20 in the text, and the broken line represents the measurements (air only) of McKerslake (26). (H = heavy clothing, M = medium weight clothing, L = light clothing).

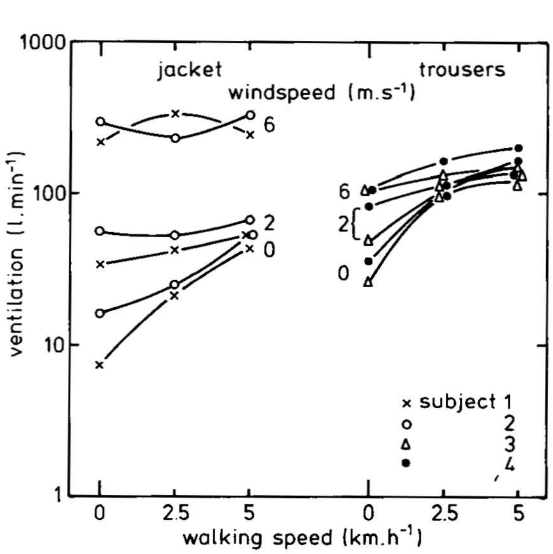

Figure 8. Ventilation of rainwear as a function of walking speed and wind speed according to Lotens & Havenith (19).

where hcd and hr are the conductive and radiative components of the clothing plus air heat transfer coefficient, respectively; hcd is almost invariably the heat transfer coefficient of still air, amounting to 0.026/th (th being the thickness of clothing + air) since fiber conductivity is only important in cases with extremely dense fabrics. The latent heat transfer is represented by:

$$\text{Evap} = \text{L hcd } A_D\, (C_{sk} - C_a) \quad (W \cdot m^{-2}). \qquad \text{(equation 25)}$$

When ventilation is induced, there is convective transfer in addition to conduction, and equations 24 and 25 must be modified:

$$\text{Dry} = (\text{hcd} + \text{hcv} + \text{hr})\, A_D \quad (T_{sk} - T_a) \qquad \text{(equation 26)}$$

and

$$\text{Evap} = \text{L } (\text{hcd} + \text{hcv})\, A_D \quad (C_{sk} - C_a), \qquad \text{(equation 27)}$$

where hcv is the convective heat transfer coefficient. (It is neglected that the value of L is not exactly the same for hcd and hcv.) The convection makes Evap obviously change faster than Dry, and there is no simple proportionality. In fact, equations 26 and 27 provide a means for estimating the component hr. In the experiments of Lotens et al (18) on standing subjects, the dry heat transfer coefficient was changed by a factor of 1.85 by the introduction of wind with a velocity of 3 $m \cdot s^{-1}$, whereas the latent heat transfer coefficient was changed by a factor of 3.75:

$$(\text{hcd} + \text{hr} + \text{hcv})/(\text{hcd} + \text{hr}) = 1.85 \qquad \text{(equation 28)}$$

and

$$(\text{hcd} + \text{hcv})/\text{hcd} = 3.75. \qquad \text{(equation 29)}$$

Substitution of equation 27 into equation 28 immediately reveals

$$\text{hr} = 2.2\ \text{hcd}.$$

Apparently, in the type of clothing used, the radiant heat transfer dominates when a person stands in still air, but it is challenged by the convection of the wind (hcv = 2.75 hcd according to equation 29). The average conductivity of the clothing is then:

$$\begin{aligned} \text{th } (\text{hr} + \text{hcd}) &= 3.2\ \text{th} \cdot \text{hcd} \\ &= 3.2 \cdot 0.026 \\ &= 0.084\ W \cdot m^{-1} \cdot {}^{\circ}C^{-1}, \end{aligned}$$

the result supporting the formerly mentioned estimate of 0.080 $W \cdot m^{-1} \cdot {}^{\circ}C^{-1}$ for normal clothing ensembles.

Concluding remarks

A simple model of a human built from various cylinders and clothed in a homogeneous layer of insulation material shows that the rule of thumb that clothing provides 4 clo of insulation per inch of thickness is an overestimation and that the concept of intrinsic insulation is not independent of the environmental conditions, in contrast to the aim. The distribution of insulation over the body and, in particular, exposed skin has a strong influence on basic insulation. The insulation table values are therefore only valid for indoor environments.

Various tables of clothing insulation do agree closely, but their use is complicated by the problems of identifying clothing items. Regression on the weight, surface coverage, and thickness of the clothing may provide greater accuracy.

The obtained ensemble insulation values are basically valid for standing humans only, but their application may be extended to real tasks by the use of correction factors for posture, fit, motion, and wind. The effect of fit can be summarized by the statement that the space under the outer garment is either filled by body tissue (tight fit) or by enclosed air (loose fit). Sitting shows a slight increase in insulation for light clothing and a slight decrease for heavy clothing in comparison to standing. Cycling causes a 20 % and walking a 40 % loss of insulation, almost regardless of the clothing. The effect of wind is linearly related to $\sqrt{V}$, with a stronger effect on light than on heavy clothing. In particular the effects of motion and wind are so strong that for many outdoor conditions the insulation is less than half the table value. Vapor transfer through clothing is more sensitive to wind than heat transfer is.

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