

Use of thermal manikins in environmental ergonomics

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WYON DP. Use of thermal manikins in environmental ergonomics. *Scand J Work Environ Health* 1989;15(suppl 1):84–94. Thermal manikins are a fairly standard tool in environmental ergonomics. As they can provide a rapid, accurate, and reproducible simulation of the physical processes of dry heat loss to the environment, their main application is in the study of neutral or cold conditions at relatively low activity levels. Thermal manikins provide a good estimate of the total dry heat loss from the body and the distribution of heat flow over the body surface. In a standard environment, these measures can be used to describe the thermal characteristics of clothing. With standard clothing, complex thermal environments, eg, as in vehicles, can also be quantitatively compared and evaluated. Future developments include improved simulation of evaporative heat loss; improved software for simulating internal heat transfer, heat storage, and vasoconstriction; reactive programs with target total heat loss; empirical equations predicting manikin response to temperature, air velocity, etc; and standard techniques for testing diving and survival suits.

Key terms: clothing, cold stress, heat stress, HVAC, metabolism, thermal asymmetry, thermal insulation, thermal profiles, vehicles.

Three main areas of application may be identified for thermal manikins — clothing, HVAC (heating, ventilation, air conditioning), and thermal physiology. The clothing and HVAC industries exist to develop and mass-produce artifacts that compensate for the inadequacies of the human thermoregulatory system — to adjust the microclimate to humans. This topic is the concern of environmental ergonomics, and my paper describes ways in which thermal manikins can be used in these two industries.

The thermal physiology “industry” exists to investigate the function of the human thermoregulatory system. Human subjects will always be the focus of this work, by definition, whereas the focus of the clothing and HVAC industries is the product. The function of the product can often be adequately described, measured, and improved with the use of thermal manikins in bridging the gap between the simplifications of scientific theory and the complexities of the real world. The mathematical models currently in use to describe human thermoregulatory response are so oversimplified that they are valid, even in theory, only for homogeneous environments. They cannot adequately take account of such aspects of clothing as the distribution of insulation over body sections, drape, fit, pumping, internal convection, penetration by air movement or wind, compression of insulating fabric layers, moisture diffusion, phase change and wicking (capillary moisture transport) or such aspects of HVAC as air temperature gradients, radiation asymmetry,

solar radiation on some sections of the body but not on others, air speed, direction and turbulence, deflection of air currents by the body, self-convection, posture, thermal characteristics of seats, submaximum sweating, wet shoes, or wet clothing. In the future thermal manikins may be of considerable use to thermal physiology by providing accurate and reproducible assessments of these effects on heat loss from the skin surface, but the use of thermal manikins in the further development of thermal physiology theory is not the subject of this paper.

Human heat balance in theory and in practice

Human heat balance in a homogeneous thermal environment is affected by air temperature, thermal radiation temperature, air velocity, and humidity. These quantities can be measured by means of physical sensors, each reading at a specified point. Few real environments are even approximately homogeneous, and even the climate chambers used for studies of human heat balance under homogeneous conditions are defective in that vertical thermal gradients are difficult to eliminate without vigorous mixing of the air, such vigorous mixing implying high air velocities and turbulence. The most usual climate chamber alternative, displacement ventilation achieved by air supplied through a perforated ceiling, floor, or wall, establishes an approximate laminar flow with an average air velocity of $0.1\text{--}0.2\text{ m}\cdot\text{s}^{-1}$. This level of velocity allows self-convection to take place over the body surface under most conditions of exposure — the upper body losing less heat to the environment to the extent that it is surrounded by a layer of slowly rising air, warmed by the lower sections of the body and increasing in thickness with height above the floor. Thus,

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even under artificially homogeneous conditions, the body experiences a degree of inhomogeneity (asymmetry) of heat loss that is not reflected in conventional measures of the thermal environment, even if they are repeated at a number of points within the volume to be occupied by the human body.

Self-convection is greatly modified by posture. When one lies down on a suspended net, all sections lose more heat, whereas a mattress insulates contact surfaces and blocks upward airflow so that heat losses are reduced. When one is seated, the detailed design of the chair exerts a very large effect. It can cause self-convection air currents to be blocked and be responsible for insulating up to 20 % of the body surface area. Self-convection while a person is seated leads in general to reduced heat loss from the front of the body and increased heat loss from the back, as heat originating from the legs now passes in front of the body. The exact position of the arms and legs in relation to the trunk and to each other is also influential.

Clothing modifies the effects of posture, self-convection, and insulation by mattresses and seats. In view of these complexities, one is not surprised to find that thermal physiologists often choose to study the thermoregulation of naked subjects lying on a suspended net with arms and legs extended, in the center of an elaborate climate chamber. Under these circumstances, measurement of the four thermal parameters will accurately predict human heat balance. Equations based on such studies, taking account of metabolic heat production as well, have hitherto represented the insulation provided by clothing with a single number (the clo value), and they have ignored the effects of posture, seat insulation, self-convection, thermal gradients, and the spatial and temporal variation of air velocity. They thus, in effect, describe the heat balance of a 30-inch sphere (0.76 m diameter, surface area 1.8 m^2) suspended in a homogeneous environment, insulated with a uniformly thick layer over the entire surface, and rotating slowly to counteract the effects of self-convection. Environmental ergonomists should keep this underlying physical model in mind when choosing between an apparently sophisticated index requiring the input of conventional physical quantities and an apparently crude measure such as wet bulb globe temperature (WBGT), which is based on the empirically measured heat balance of a six-inch (15.24 cm) sphere and that of a thermometer in a wet sock (as recommended for hot environments both by the National Institute for Occupational Safety and Health and by current standards of the International Organization for Standardization).

Evolution of thermal manikins

Measurement of any one physical parameter of the environment is usually affected by another — thermometers purporting to measure air temperature must be aspirated and screened from thermal radiation, wet-

bulb thermometers must be protected from air velocity, anemometers must be corrected for air temperature, etc. As there is some doubt as to how the “unbiased” measurements are to be combined to predict human heat balance, it is tempting to select some thoroughly biased sensor, such as a globe thermometer, and simply assume that its uncorrected reading is affected by air temperature, air velocity, and thermal radiation in the same way as the human body.

This is a very big assumption, and, even if it were true, it does not take into consideration the influence of clothing, posture, self-convection, and the problem of how to combine readings taken at different points within the volume to be occupied by the human body if they should turn out to differ. Uncorrected physical sensors cannot be regarded as the “missing link” in the evolution of thermal manikins. There is a similar dichotomy between flat-plate instruments for measuring the properties of textiles, and thermal manikins capable of wearing finished clothing.

The use of thermal manikins, in common with many other ergonomic techniques, appears to have sprung, fully fledged, from the military ergonomics laboratories of World War II, when scientists were forced by the pressure of military necessity to cut short their development of theory and devise ways of making valid and practically useful assessments of human heat balance in complex thermal environments. Gonzales et al, in their as yet unpublished report “The Relative Applications of Predicting Effects of Environmental Clothing and Personal Equipment on Military Operations,” cited parallel developments of single-section copper manikins for assessing military clothing at, eg, the Harvard Fatigue Laboratory, the JB Pierce Laboratory, and the Quartermaster Climatic Research Laboratory (personal communication). Winslow, Herrington, and Fitzgerald were all associated with this work in the 1940s. Some of the manikins, constructed by the General Electric Company and the Bridgeport Brass Company, are apparently still in use. Their total heat loss can be measured as a function of the clothing they wear and the environment in which they are placed. Their use is limited in that they have only one posture and they do not map heat flow to the environment over the body surface. They are the precursors of modern thermal manikins that do not have these limitations. In complex thermal environments, and for clothing assessment, they are considerably more useful than the physical instrumentation that preceded them.

Many attempts have been made to increase the multifactor bias of conventional instruments through the heating of sensors to increase their sensitivity to air velocity and make their response to thermal radiation resemble that of the human body. The “eupatheoscope” mentioned by Bedford (1) was perhaps a precursor of thermal manikins — it was a large heated cylinder on legs — except that it could not wear clothing. Its very arbitrary measurements found little prac-

tical use. The "heated cigar" of the Comfy Meter[®] developed at the Danish Technical University by Lund-Madsen and now marketed commercially (Brüel & Kjaer) appears at first sight to be a contemporary example of the same principle, but the associated analogue circuitry causes the reading to correspond to the rational heat balance equation proposed by Fanger (2). Estimates of clothing insulation, metabolic rate, and humidity must be entered by hand. The Comfy Meter[®] is a hybrid — an analogue computer with a digital display, a theoretical model of human heat balance with a "multifactor biased" direct measurement of the combined effect of three out of six parameters. The shape of the heated cigar has the same angle factors as a rotating human body, and the heat balance predicted is that of the uniformly insulated, rotating 30-inch (76.2 cm) sphere of thermal physiology theory. Its use neglects the detailed effects of clothing, seats, posture, and the deflection of air currents by the body, and the problem of combining measurements made at a number of points within the volume to be occupied by the human body remains. It would be a useful "miniature manikin" in a scale model of a thermal environment, but it does not appear to have been used in this way.

Another candidate for the label of "missing link" came into operation in 1986, ie, the heated sweating cylinder used by the Finnish Textile Laboratory to study the problem of ice formation in multilayer clothing during heavy work in extreme cold (3). It cannot wear complete garments, but the effect of complete garments on the torso may be closely simulated. Sweat is produced at a controlled rate through a Goretex[®] membrane, whose temperature is independently controlled. This apparatus is useful in itself, but can be regarded as a design study for the sweating manikin "COPPELIA," which is now nearing completion.

Existing equipment

Table 1 presents data on the thermal manikin systems which, to my knowledge, are in operation in 1988. Water-filled torsos, severed limbs, assemblies of cylinders or boxes, such as ALU-MARGRETE (Danish Technical University), and early prototypes, some now in technical museums, such as HENRIK 1 (Danish Technical University), have been omitted. The approximate year when the first manikin of each series came into operation is given, along with mention as to whether each manikin can sit or stand. None of the manikins currently in operation can simulate sweating at a controlled rate that results in thermal equilibrium, although some have been used to simulate sweating, a cotton body-stocking being sprayed with distilled water before more clothing is added, and most of them could be used in this way. It can be seen that the number of sections with independent control of skin temperature is usually 16—19. Data obtained with

the only two manikins that have more sections are usually combined into 16—19 sections before presentation. Manikins built prior to 1980 are controlled manually or by simple on-off regulators or analogue control circuits. With the advent of microprocessors and microcomputers, later manikins are usually controlled digitally, the regulators then consisting of software algorithms. The proportional, integral, and differential components of the feedback loop can then more easily be optimized for each section to achieve rapid and stable control. Software calibration, on-line analysis, and more sophisticated on-line displays become feasible with digital computer control.

The main applications for which each manikin system is used are also indicated in table 1 in descending order of priority, so far as is known. Seventeen manikins are used primarily for clothing measurement, four primarily for measuring the microclimate produced by the heating, ventilating and air-conditioning of buildings, and four exclusively for measuring the microclimate of vehicles, a total of 25 in all.

It is important to note that although all the manikins articulated at the hip have been marked as capable of sitting, they do not sit very well. Their seated posture and their contact with the base and back of a seat are never satisfactory for measuring the thermal characteristics of seats. The shapes of manikins incapable of standing have been optimized for this purpose, and their contact surfaces are controlled as separate sections.

Table 1 also gives some details of three new manikin systems nearing completion — two of them capable of controlled sweating (numbers 26 and 27) and one similar to existing manikins except that it will have a female shape. All previous manikins have been intended to fit men's clothing, while invariably allowing modesty to prevail over verisimilitude.

Standardization

Due to the variety of applications, the widely differing budgets, and the 40 years of development represented by the systems, the 23 manikins in table 1 are not identical, and the question of measurement standardization is important. In the case of clothing measurements, McCullough & Wyon (4) obtained the same clo values with SAM and SIBMAN, once allowance was made for SAM's bald pate, and showed that skin temperature distribution was not a critical factor. A recent comparison of four manikin systems (5) confirmed this point and showed good agreement between the TORE and HENRIK series for a range of clothing insulation. However, the influence of fit was found to be very considerable. SIBMAN, which should have had clothing several sizes smaller than the other manikins, returned considerably higher clo values. Ensuring that the garments to be tested actually fit the manikin to be used is almost certainly the major prob-

lem of standardization in practice. It is for this reason that the TORE series was made to fit a standard Scandinavian clothing size from the start. Measurements of female clothing on existing (transvestite) manikin systems should therefore be treated with caution.

Principles of operation

The principle of operation of all of the manikins in table 1 is to achieve a stable dynamic equilibrium with the thermal environment and to measure the heat flow

Table 1. Existing thermal manikins.^a

Number	Completion date of original model	Name	Affiliation	Sit	Stand	Number of sections	Control ^b	Use ^c
<i>In operation in 1988</i>								
1	1945	SAM	United States Army Research Institute for Environmental Medicine, Natick, Massachusetts, United States	No	Yes	1	M	C
2	-	-	Institute for Environmental Research, Kansas State University, Manhattan, Kansas, United States	No	Yes	1	M	C
3	1964	ALMANIKIN	Royal Air Force Institute of Aviation Medicine, Farnborough, Hampshire, England	No	Yes	11	R	C
4 ^d	-	-	The Cord Group, Dartmouth, Nova Scotia, Canada	No	Yes	13	D	C
5	1972	CEPAT400	Laboratory for Environmental Physiology and Psychology, National Center for Scientific Research, Strasbourg, France	Yes	Yes	1	R	C
6	1973	HENRIK 2	Laboratory for Thermal Insulation, Danish Technical University, Lyngby, Denmark	Yes	Yes	16	A	C, H
7	-	-	Institute of Occupational Health, Helsinki, Finland	Yes	Yes	16	A	C
8	1978	CHARLIE	Hohensteiner Institute, Schloss Hohenstein, Bonnigheim, Federal Republic of Germany	Yes	Yes	16	A	C
9	-	-	Multi-tech Corporation, Natick, Massachusetts, United States	Yes	Yes	16	A	C
10	1980	SIBMAN	National Swedish Institute for Building Research, Gävle, Sweden	Yes	Yes	16	D	H, C
11	1982	VOLTMAN	National Swedish Institute for Building Research, Gävle, Sweden	Yes	No	19	D	H, S, C
12	-	-	Volvo Car Corporation, Göteborg, Sweden	Yes	No	19	D	V
13	-	-	Volvo Car Corporation, Göteborg, Sweden	Yes	No	19	D	V
14	-	-	Volvo Truck Corporation, Göteborg, Sweden	Yes	No	19	D	V
15	-	-	General Motors Corporation, Detroit, Michigan, United States	Yes	No	19	D	V
16	-	-	Hungarian Institute for Building Science, Budapest, Hungary	Yes	No	19	D	H, S, C
17	-	-	Hungarian Institute for Building Science, Budapest, Hungary	No	Yes	17	D	C, H
18	1984	TORE	National Swedish Institute for Building Research, Gävle, Sweden	Yes	Yes	18	D	C, H
19	-	-	Textile Research Institute, Göteborg, Sweden	Yes	Yes	18	D	C
20	-	-	Institute for Environmental Research, Kansas State University, Manhattan, Kansas, United States	Yes	Yes	18	D	C, H
21	-	-	TNO Institute for Perception, Soesterberg, Holland	Yes	Yes	18	D	C
22	-	-	Textile Laboratory, Technical Research Center of Finland, Tampere, Finland	Yes	Yes	18	D	C
23	1985	ASSMAN ^d	National Swedish Institute of Occupational Health, Solna, Sweden	Yes	No	36	D	C, H, V
24	1986	A LITTLE	United States Army Research Institute for Environmental Medicine, Natick, Massachusetts, United States	Yes	Yes	19	D	C
25	1987	HEATMAN	VIAC Corporation, Falun, Sweden	Yes	Yes	36	D	H
<i>Nearing completion in 1988</i>								
26	?	COPPELIA	Textile Laboratory, Technical Research Center of Finland, Tampere, Finland	Yes	Yes	18	D	C
27	?	MANNY	Battelle Corporation, Richland, Washington, United States	Yes	Yes	18?	D	C
28	?	PERNILLE	Laboratory for Thermal Insulation, Danish Technical University, Lyngby, Denmark	Yes	Yes	16	D	C

^a Several manikins are apparently in operation in Japan.

^b M = manual; R = on-off regulator; A = analogue; D = digital computer.

^c C = clothing; H = heating, etc; V = vehicles; S = seats.

^d ASSMAN is now known as AIMAN.

to or from the environment at equilibrium, skin temperature being accurately known regardless of whether or not it is controlled to preset values.

Heating

All but one of the manikins are electrically heated. The heat supplied can therefore be accurately controlled and measured in most cases to within 0.002 of the maximum rated power input to each section. The power may be dissipated internally, as in the SAM and HENRIK series, or subcutaneously, as in the VOLTMAN and TORE series. Depending on application, the power rating of each section can be up to $2000 \text{ W} \cdot \text{m}^{-2}$. Stability becomes a problem if maximum power to a section is grossly overrated. HENRIK was originally heated by means of miniature hot-air blowers in each section. When servicing these units became a problem, the system was changed. Resistive wire was evenly distributed in good thermal contact with the inside surface of each section. In TORE and VOLTMAN, heating wires are placed in grooves cast or machined into the external surface of each section. It is necessary to use Constantan resistance wire to avoid errors due to local overheating and resistance change and to use many different gauge wires. If one gauge is used throughout, small sections will have low resistance and very high power ratings per square meter. For large sections the situation will be reversed.

The manikin without electrical heating is that of the Centre d'Etudes de Physiologie Appliquée au Travail (CEPAT) described by Lebrun & Lecarpentier (6). It is heated or cooled by means of water circulating in pipes brazed to the inside surface of each copper section. The CEPAT manikin was designed to maintain a skin temperature of 35°C in a 400°C environment. It is mainly used to measure the insulation of protective clothing for extremely hot environments.

Conducting layer

Between the heating layer, however constructed, and the outer surface, there is usually a conducting layer to ensure an even surface temperature. The SAM, the CEPAT, and the A LITTLE manikins are actually made of copper, and ALMANIKIN of aluminum, whereas most of the rest have conducting layers of electro- or thermo-deposited copper or aluminum sandwiched between layers of plastic and fiber glass.

Measurement

The HENRIK and the CEPAT manikins measure internal temperature and calculate surface (skin) temperature from a knowledge of heat flow and surface resistance, both of which are assumed to be evenly distributed over the surface of each section. Other manikins measure skin surface temperature directly by means of resistive sensors, usually nickel or cadmium wire. If these sensors are several meters long and evenly

distributed over the surface of each section, a reliable estimate of skin temperature is obtained. These sensors are vulnerable to mechanical damage and constitute the major weakness of most manikins in practical use, as they must be at or very close to the actual surface. Mechanical damage to these wires can even result from severe frost or heat exposure, eg, during transport, due to the expansion and contraction of the surface. (See the Calibration section.)

Control

The power input can be controlled through the altering of the voltage, through the use of analogue circuits or digital/analogue convertors, or through the maintenance of a constant voltage and the pulse coding of the input current. In the last case it is essential to have extremely rapid switching transistors to ensure square-wave pulses whose shape is not load dependent. Power-supply units should also have remote-sense inputs to eliminate load-dependent cable losses. Only with these precautions can accuracies of 0.002 of the maximum power rating be routinely achieved over the whole working range.

Analysis

Voltage measurement, or counting pulses over a fixed integration period, together with a knowledge of the (preferably constant) internal resistance, yields a total power input value for each section in watts. Before this input value can be converted to watts per square meter, accurate knowledge of the heated surface area of each section is required. This information is best obtained if the amount of masking tape used to cover each section completely is weighed to an accuracy of 0.01 g. If the same technique is used on a cylinder of known surface area and both procedures are repeated an adequate number of times, requisite accuracy can be achieved. It need only be done once for each manikin series, ie, if manufacturing procedures are assumed to be accurate.

Total power input for the manikin, divided by its total surface area, usually close to 1.8 m^2 (the value for an average European male), gives total heat loss in watts per square meter. The area-weighted mean skin temperature minus the environmental operative temperature, divided by the total heat loss, yields the accepted standard unit for total clothing and air insulation (in $^{\circ}\text{C} \cdot \text{m}^2 \cdot \text{W}^{-1}$). Division by 0.155 converts this value to the clo unit (7). The TORE series displays this value, and similar values for each section, as a continuously refreshed table of values. It is then possible to alter the drape and fit of a garment and to see the results immediately in these terms, or to see the effect of adding or subtracting a garment. Color changes are used to indicate whether a particular value is changing or stable; therefore removing a jacket causes an immediate color change for the affected sections. The display returns to monochrome when the values are

reliably stable. A similar visual feedback is used if any section has reached the maximum or minimum power rating, as the equilibrium is then spurious. The analysis of measurements made by earlier manikins was off-line and fairly time-consuming, and this kind of optimization and learning by instant feedback was inhibited. Similar advances in the analysis and presentation of results for microclimate optimization follow.

Calibration

Skin temperature sensors must be calibrated against reference thermometers with the manikin passively exposed (unheated) to a number of homogeneous environments at different temperatures in the range of 30–35°C. This procedure is usually carried out in a climate chamber. The VOLTMAN series has an auto-calibration facility which achieves an accuracy that is an order of magnitude better even under field conditions. The manikin is placed in an air-freight container which is well-insulated and fitted with a 24-V truck fan. The manikin process controller adjusts the speed of this fan continuously to achieve a series of very accurately controlled air temperatures in the box while maintaining very high air velocities around the manikin. The resistance of each of the 19 skin temperature sensors is read when each stable condition has been maintained for 3 h. New regression equations are calculated automatically and stored.

This completely automatic sequence takes about 12 h and can be carried out during the night in a workshop or even in a hotel room on vehicle test expeditions. This possibility eliminates measurement errors due to mechanical damage to sensors during transport or in field use. Skin temperatures must be measured and controlled to within 0.1°C to achieve sufficient accuracy in heatflow measurements. Voltages, currents, and resistances can of course be measured with standard instruments, and such measurements should be repeated at intervals.

Reference exposures

A key concept in thermal manikin measurement is that of the reference exposure under standard conditions. In clothing measurements, this procedure takes the form of a reference exposure without clothing to distinguish between the insulation of the clothing and that of the air surrounding it. In measurements of microclimates, a reference exposure is necessary before heat flow can be expressed in terms of the equivalent homogeneous temperature (EHT), ie, that temperature which, in the reference exposure, produced the same heat flow from the section in question. Thermal manikins find their main use in complex thermal environments, where the degree of thermal asymmetry must be quantified to reduce or eliminate “drafts,” ie, excessive cooling of certain body sections. While the sensation of losing 100 W · m⁻² is not familiar to most people, expressing the same value as an equivalent

homogeneous temperature of 15°C on the basis of a reference exposure makes it easier to assess. A suitable reference environment, as used by me for VOLTMAN, is one in which all surfaces approximate to air temperature, humidity is constant, thermal gradients in all three directions are very low, and air velocities are so low (<0.1 m · s⁻¹) that the self-convection of the manikin is unaffected when visualized by the use of smoke. The manikin is supported in a seated posture on a wide-mesh net seat that compresses the clothing but does not insulate the contact surfaces. A typical car seat will then reduce heat flow from contact surfaces so much that equivalent homogeneous temperatures above 30°C are obtained in a 22°C environment. Only one reference condition is strictly required, as heat flow is linearly related to the equivalent homogeneous temperature and is zero when the environment is at skin temperature. The results of the reference exposure are regression equations relating heat flow in watts per square meter to the equivalent homogeneous temperature. They are calculated, stored, and used on-line (8).

Documentation

There are no accepted conventions for depicting the asymmetry of a clothing ensemble. Clo values are usually quoted only in terms of the effect on whole-body heat balance. TORE provides an on-line table of sectional clo values, as has already been described, which may be output on paper. For microclimate assessment, my co-authors and I have proposed a standard form of presentation in terms of an “EHT profile” (9). It has already been used for the thermal environment of the driver’s seat of city buses (10), in offices with displacement ventilation (11), in comparisons of the on-off and proportional-integral regulation of air-conditioning (12), and on a routine basis for vehicle work by the Volvo and General Motors companies (restricted-circulation internal reports). Figure 1 shows an example of such a diagram. The body sections are listed in order from head to foot, in left-right sequence where applicable, those in contact with the seat being shown separately. Vertical asymmetry is apparent in the general slope of the profile, while lateral asymmetry gives rise to a “saw-tooth” profile.

Assessment

Total dry heat loss in watts per square meter may be compared with target values derived from physiological measurements of metabolic heat production and evaporative heat loss. For sedentary activities such as office work or driving, it is my experience that a discrepancy of only 5 W · m⁻² in either direction from thermoneutrality gives rise to a definite feeling of whole-body discomfort after 15–20 min. Physiological measurements of total dry heat loss are usually quoted to the nearest 10 W · m⁻², due to inaccuracies of measurement, the assumptions involved in oxygen

uptake analysis, and the uncertainty as to how much extra effort is required for mask breathing during such measurements. Thermal manikin measurement of whole-body heat loss in a given thermal environment, however complex, can be made with an accuracy that is an order of magnitude better, and, when combined with human subjective assessment of thermoneutrality, it may actually be the most accurate and reliable way of assessing metabolic rate in such circumstances. A value of $47.2 \text{ W} \cdot \text{m}^{-2}$ was found for 72 subjects performing office work (11); it corresponds very closely to 1 MET ($58 \text{ W} \cdot \text{m}^{-2}$) with 80 % dry heat loss.

Sectional dry heat loss, recalculated as the equivalent homogeneous temperature, must also be assigned a target value and an acceptable range. These values may differ for different body sections. For vehicle drivers and passengers, my co-workers and I (9) have proposed (i) ideal profiles (IP) that differ considerably between winter and summer, (ii) acceptable ranges, ie, vehicle comfort regions (VCR), that differ for drivers and passengers, and (iii) the use of a "figure of merit," ie, the standard deviation of the equivalent homogeneous temperature from the relevant ideal profile (SDIP). The recommended values are based on five years of experience with VOLTMAN in vehicle research and development and on a direct experimen-

tal comparison of manikin and human response in the vehicle environment. Figure 2 is an example of an EHT profile diagram in which the vehicle comfort region appears as a "piste," and the ideal profile as a slalom track down it. The designer of the thermal environment of the vehicle attempts to avoid going "off-piste" under specified critical operating conditions, and his adherence to the ideal profile is quantified as the standard deviation from the ideal profile. These diagrams, available on-line or directly after a wind-tunnel or field trial, greatly facilitate the development of empirical solutions to vehicle climate deficiencies. They make a quantitative comparison of competing designs or vehicles possible in terms of environmental ergonomics rather than in terms of physical and engineering quantities. Figures 3—5 are further examples of the use of this method of documentation.

If these methods of depicting and assessing thermal asymmetry were applied also to clothing, two fields of research and development, at present the preserve of very different specialists, would be brought together. Environmental ergonomists must, in practice, regard protective clothing and environmental modification as alternative and sometimes complementary solutions to human heat balance problems. The thermal insulation measurements provided at present by clothing spe-

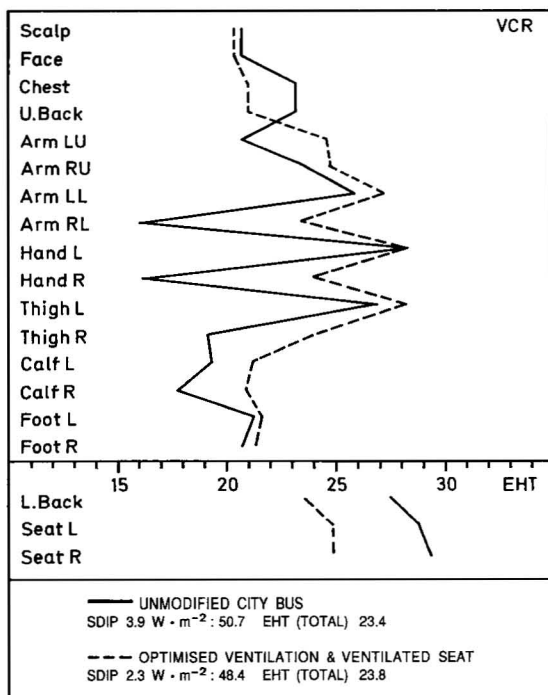


Figure 1. Profile diagram for a bus driver in full sun — effect of optimized ventilation and ventilated seat. (VOLTMAN = name of manikin used, U = upper, LU = left upper, RU = right upper, LL = left lower, RL = right lower, L = left, R = right, L Back = lower back, EHT = equivalent homogeneous temperature, SDIP = standard deviation from ideal profile)

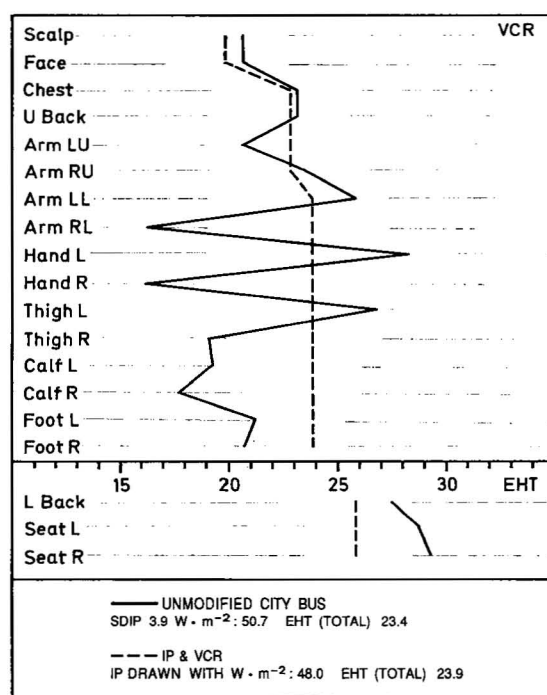


Figure 2. Profile diagram for a bus driver in full sun — unmodified city bus. (VOLTMAN = name of manikin used, VCR = vehicle comfort regions, U = upper, LU = left upper, RU = right upper, LL = left lower, RL = right lower, L = left, R = right, L Back = lower back, EHT = equivalent homogeneous temperature, SDIP = standard deviation from ideal profile, IP = ideal profile)

cialists (where each garment is assessed only in terms of its contribution to whole-body thermal insulation) are not adequate for this purpose. An insulated jacket may well have the same conventional clo value as a pair of insulated trousers. In a real situation, with drafts, cold seats, thermal gradients, and direct sunshine, they do not result in the same sensations. Clothing designers need better information on the effects of their products if they are to play their part in correcting the thermal deficiencies of problem environments.

Prediction of thermal discomfort

Total dry heat loss is probably the best available predictor of whole-body thermal discomfort, and I have found sectional dry heat loss to predict sectional thermal discomfort with correlation coefficients in excess of 0.8 (11). A linear relationship between the equivalent homogeneous temperature and the mean thermal vote (MTV) has invariably been found where the mean thermal vote is based on the 7-point Bedford scale in which -3 is assigned to "much too cold," -2 to "too cold," -1 to "comfortable but cool," 0 to "ideal," and so on, applied to sectional thermal discomfort by

asking subjects to fill in these figures on a diagram of the body divided into sections corresponding to those of the manikin. It has been found that, although there appears to be a stable sigmoidal relationship between mean thermal vote and the percentage of "too hot" and "too cold" responses in different populations providing these responses, subjects will accept a greater degree of asymmetry in a vehicle than in a building, ie, the slope of the EHT/MTV regression differs between these contexts in our data.

Physical indices of the equivalent homogeneous temperature

The equivalent homogeneous temperature is a purely physical measurement, but a complex and expensive thermal manikin system is required to obtain it. It is sometimes useful to derive empirical indices that predict sectional EHT values in a given context in terms of the relevant physical parameters. This procedure has been carried out by Wyon & Sandberg (11) for the unusual thermal environment created by displacement ventilation in offices; it has enabled engineers to compare diffusers, flow rates, etc, in terms of temperatures and air velocities, while ensuring that the EHT

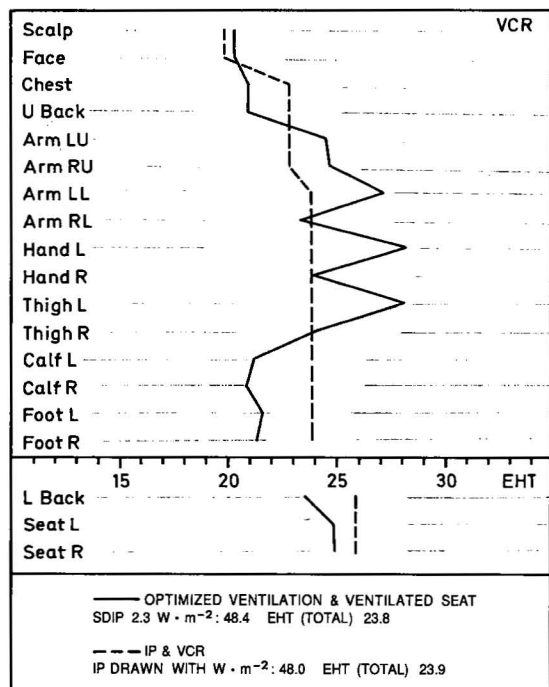


Figure 3. Profile diagram for a bus driver in full sun — optimized ventilation and ventilated seat. (VOLTMAN = name of manikin used, VCR = vehicle comfort regions, U = upper, LU = left upper, RU = right upper, LL = left lower, RL = right lower, L = left, R = right, L Back = lower back, EHT = equivalent homogeneous temperature, SDIP = standard deviation from ideal profile, IP = ideal profile)

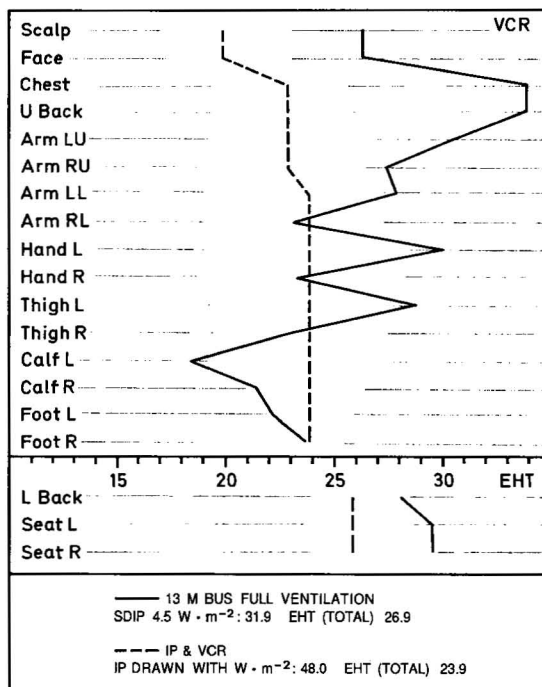


Figure 4. Profile diagram of the ideal profile (IP) and vehicle comfort regions (VCR) of the microclimate of a city bus driver's seat — example of a city bus. (VOLTMAN = name of manikin used, U = upper, LU = left upper, RU = right upper, LL = left lower, RL = right lower, L = left, R = right, L Back = lower back, EHT = equivalent homogeneous temperature, SDIP = standard deviation from ideal profile)

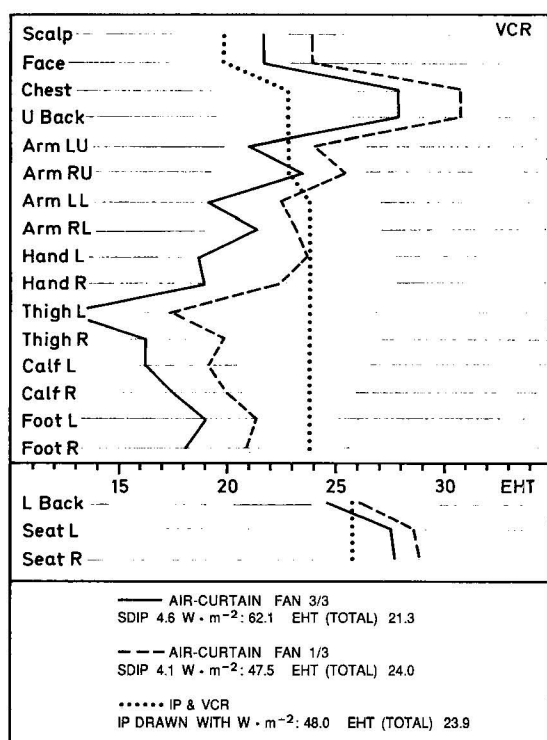


Figure 5. Profile diagram of the ideal profile (IP) and the vehicle comfort regions (VCR) of the microclimate of a city bus driver's seat — experimental air-curtain bus. (VOLTMAN = name of manikin used, U = upper, LU = left upper, RU = right upper, LL = left lower, RL = right lower, L = left, R = right, L Back = lower back, EHT = equivalent homogeneous temperature, SDIP = standard deviation from ideal profile)

values remain within comfortable limits derived in a laboratory comparison of human and manikin response. Such indices should only be applied to contexts in which the EHT profile may be expected to have a similar appearance, ie, contexts presenting the same kind of thermal asymmetry. Another example of a physical index based on thermal manikin response is total manikin heat loss predicted in terms of air temperature and wind speed (13).

Special applications

In addition to their use in assessments of clothing, HVAC solutions for buildings and vehicles, and outdoor environments, thermal manikins capable of measuring dry heat loss have been used in a number of special applications, eg, to assess humidity transients in clothing (14), to resolve conflicts between the thermal requirements of patients and staff in hospital wards (15), to quantify pumping effects in clothing (16), to assess the alleviation of solar load on vehicle occupants through the use of reflecting glass windows (Norin et al 1987, Volvo internal report), to assess electrically heated seats (Larsson et al 1988, Volvo internal report),

and to develop a ventilated seat for city bus drivers (10).

Evaporative heat loss

When total dry heat loss, as measured on a thermal manikin, is less than the metabolic rate for the activity under study, the discrepancy is an accurate estimate of the evaporative heat loss required and may be expressed as a required sweat rate in liters per hour. In situations in which there is some doubt as to whether it would be possible to achieve thermal equilibrium by sweating, it would be desirable to simulate sweating with a thermal manikin so as to be able to optimize the evaporative cooling power of the clothing, seat, and environment combined. No manikin capable of simulating sweating has yet been built (table 1), but a project to construct such a manikin is nearing completion in Finland. The COPPELIA manikin will be a TORE manikin with a Goretex[®] membrane skin and over 200 sweat glands individually controlled by a computer. Capillary material bonded onto the back of the Goretex[®] membrane spreads the distilled water released by each gland. At sweat rates below the effective maximum the "skin wettedness" will be both incomplete and somewhat unnatural. In addition, assessing the vapor diffusion resistance of the clothing barrier is dependent on measurements of air humidity in the very small volume between skin and clothing and is difficult. However, even without such measurements, the trials would provide a fairly good empirical simulation of human heat balance to verify whether a given sweat rate is possible. If quantitative assessment of the vapor diffusion resistance of an ensemble is required, it can be done by means of an iterative procedure in which sweat rate is increased and decreased to find the minimum value at which maximum total heat loss is achieved. As equilibrium must be achieved at each trial value of sweat rate, the procedure will be lengthy, and it must be repeated without clothing. Supplementary measurements of total dry heat loss with and without clothing, with zero sweat rate, when combined with the two values of maximum effective sweat rate, enable evaporative heat loss to be distinguished from dry heat loss, and the vapor diffusion resistance of the clothing to be distinguished from that of the environment. The sweating cylinder developed in Tampere has already been found useful in this way, and the COPPELIA system will make this kind of measurement possible for complete ensembles.

Future developments

Thermal manikin techniques have already developed to the stage where a great diversity of applications is possible and very likely in the near future. Total heat loss affects human performance, and therefore also safety, while sectional heat loss determines comfort,

draft sensation, and the risk of cold-related muscular injury. Thermal manikins provide the specific feedback necessary to be able to optimize a complex thermal environment rapidly and effectively with the use of protective clothing or environmental modification. Several very different solutions can be quantitatively compared, and, if they produce the same result, the most economic can be selected. Environmental controls can be adjusted to provide constant manikin response (ie, the equivalent homogeneous temperature) rather than constant air temperature, and this is an important distinction when solar radiation or high air velocities are involved.

Manikin response has been "calibrated" against human response where heat balance and discomfort sensations are concerned. However, the risk of cold-related muscular injury has not been studied as a function of sectional heat loss, as experiments designed to provoke such a response are generally regarded as unethical. An important future application of thermal manikins will be in epidemiologic studies of work situations in which people have already suffered cold-related muscular injury. Once sectional heat loss has been calibrated in this way, it will be possible to set both health and safety limits on thermal asymmetry, as well as comfort limits.

The development of thermal manikin techniques, as opposed to their application, is likely to continue, but will be a minority preoccupation in comparison. Reference has already been made to future developments of sweat simulation and of physical indices predicting manikin response in specific circumstances. Computer programs will probably be developed to model the physiological processes of heat storage and internal heat transfer, processes that are not usually simulated at present. It may be appropriate to develop computer programs that will simulate vasoconstriction by adjusting set values for skin temperature to achieve a target total heat loss under conditions of cold. This application would take some time but would provide a good estimate of resulting hand skin temperature in situations where it would be critical for skilled performance. Off-line estimates of heat loss with different skin temperature distributions can already be made more accurately if sectional clo values have been measured empirically. These program developments do not require any hardware changes and can be implemented very easily in the TORE and VOLTMAN systems.

The thermal assessment of complex environments is incomplete without some measurement of how the microclimate at the head affects the eyes. Dry, or even sweating, heat loss from the head itself is not an adequate measure. In the future thermal manikins for vehicle assessment may be provided with some additional sensors at the eye, and the response of these sensors will be related to human criteria of the kind developed by Wyon & Wyon (17).

For the special purpose of measuring human heat balance in survival and diving suits in water, robust

and water-resistant versions of existing manikins are required, but this application does not require any new principles of measurement. As human trials are, in this case, both unpleasant and dangerous, it would appear to be an ideal field of application for thermal manikin techniques. Manikins 3 and 4 of table 1 are already used for this purpose.

Availability of thermal manikins

Thermal manikins are not yet in series production. The potential market does not seem to justify the expense and practical difficulty of setting up series production. Each manikin system listed in table 1 was the result of a research project by researchers who would much rather use the equipment than make it. Familiarity with the equipment was thereby enhanced, a considerable advantage when malfunctions must be dealt with. Thermal manikin systems are complex, vulnerable and expensive, but they are cost-effective in a very wide range of applications. Research organizations wishing to acquire their own system are recommended to assemble the team of engineers and scientists who are to use it and then to make it possible for the team to build their own. An important provision is that they should do so in close collaboration with specialists who have already built a successful thermal manikin system. Between two and four person-months of specialist time is sufficient, and two person-years is a reasonable estimate of the total work involved. This approach has already been funded as a United Nations Industrial Development Organization project for technology transfer and was carried to a successful conclusion (18).

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References

1. Bedford T. Basic principles of heating and ventilation. London: Lewis, 1964.
2. Fanger PO. Thermal comfort. New York, NY: McGraw-Hill, 1970.
3. Meinander H. Introduction of a new test method for measuring heat and moisture transmission through clothing materials and its application on winter work wear. Espoo (Finland): Technical Research Center of Finland, 1985. (Publication 24.)
4. McCullough EA, Wyon DP. Insulation characteristics of winter and summer indoor clothing. ASHRAE Trans 1983;89:614-33.

5. Wyon DP, Lund-Madsen T, Tammela E. Quantitative comparison of clothing measurements using different thermal manikins. Helsinki: Nordtest, 1987.
6. Lebrun JC, Lecarpentier D. Mannequin thermoregulé. Strasbourg: Ecole Nationale Supérieure des Artes et Industries, 1972.
7. Olesen BW. A new Nordic standard proposal for measuring the thermal characteristics of clothing. In: Seifert B, Esdorn H, Fischer M, Rüden H, Wegner J, ed. Proceedings of indoor air '87: proceedings of the 4th international conference on indoor air quality and climate; vol 3. Berlin (West): Institute for Water, Soil and Air Hygiene, 1987:481—6.
8. Wyon DP, Tennstedt JC, Larsson S. Assessment of vehicle climate using the VOLTMAN thermal manikin system. In: Wilson JR, Corlett EN, Manenica I, ed. New methods in applied ergonomics. London: Taylor and Francis, 1987:153—8.
9. Wyon DP, Larsson S, Forsgren B, Lundgren I. Standard procedures for assessing vehicle climate with a thermal manikin. In: Proceedings of the sub-zero engineering conditions conference, Rovaniemi, Finland. Detroit, MI: Society of Automotive Engineers 1989:383—94. (Paper 890049.)
10. Wyon DP, Larsson S, Eriksson LE. Förarplatsens sommarklimat i stadsbussar [The micro-climate of the driver's seat in city buses in summer]. Stockholm: Arbetsmiljöfonden, 1987. (CYAT report.)
11. Wyon DP, Sandberg M. The relationship between local thermal discomfort due to displacement ventilation and local heat flow from a thermal manikin exposed to the same conditions. Gävle (Sweden): National Swedish Institute for Building Research, 1989. (GLSM project report).
12. Wyon DP, Tennstedt JC. The effects of on-off and proportional-integral regulation of air-conditioning on human heat balance. Gävle (Sweden): National Swedish Institute for Building Research, 1989. (TA project report, Tour Andersson Technical Information Series, Västerhaninge, Sweden.)
13. Wyon DP. Wind-chill equations predicting whole-body heat loss for a range of typical civilian outdoor clothing ensembles. Scand J Work Environ Health 1989;15 (suppl 1):76—83.
14. de Dear RJ, Tanabe S, Knudsen HN, Pejtersen JH, Mackeprang J, Fanger PO. Thermal response of wool clothing during humidity transients. In: Seifert B, Esdorn H, Fischer M, Rüden H, Wegner J, ed. Proceedings of indoor air '87: proceedings of the 4th international conference on indoor air quality and climate; vol 3. Berlin (West): Institute for Water, Soil and Air Hygiene, 1987:399—403.
15. Wyon DP. Värmebalans av patienter och anställda vid olika vårdrumstemperaturer: en laboratorie studie med termisk mannekang [Heat balance of hospital patients and staff at different hospital ward room temperatures: a laboratory study with a thermal manikin]. Gävle (Sweden): Statens Institut för Byggnadsforskning, 1982. (Meddelande 26.)
16. Olesen BW, Slawinska E, Madsen TL, Fanger PO. Effect of body posture and activity on the thermal insulation of clothing: measurements by a moving thermal manikin. ASHRAE Trans 1982;88:791—805.
17. Wyon NM, Wyon DP. Measurement of acute response to draught in the eye. Acta Ophthalmol 1987;65:385—92.
18. Wyon DP, Tennstedt JC. Construction of a thermal manikin. Wien: United Nations Industrial Development Organization, 1985. (Final project report SSA/SI/HUN/82/801).