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PARAMETERS OF HUMAN DISCOMFORT IN WARM ENVIRONMENTS

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ABSTRACT

The relationship between thermoregulatory responses during exposure to warm and hot environments and the associated subjective perceptions, e.g., comfort, thermal sensation, etc., have been studied by numerous investigators over a considerable span of time, i.e., roughly 50 years. Skin temperature, mean body temperature, sweating, and percent of skin wettedness have been shown to have a role in comfort, thermal sensation, and perception of skin moisture. This paper reviews studies concerned with the physical and physiological parameters relative to these subjective responses and their level of magnitude, with primary emphasis on warm discomfort and skin moisture. The review indicates that, while utilizing different methodologies for quantification of skin moisture under a wide range of ambient conditions and experimental protocols, the relationship between skin wettedness and discomfort or unpleasantness is consistent and experimentally supported.

INTRODUCTION

The discomfort associated with exposure to warm and hot environments is attributed to the conscious awareness of perspiration and an elevated body temperature. The secretion of sweat onto the skin surface permits the dissipation of metabolic heat from the body by evaporation when the loss of heat by radiation and convection is insufficient to maintain thermal balance.

In cool environments, thermal and comfort sensations are best correlated with mean skin and mean body temperatures. However, in warm conditions in the resting individual and with increased metabolic levels associated with work and exercise, it was recognized that unpleasantness and thermal discomfort are associated with sweating rather than skin or body temperatures (Winslow et al., 1937, 1939; Gagge et al., 1967, 1969). At conditions cooler than neutral, skin temperature is directly related to operative temperature, air speed and clothing, but above neutrality where sweating is necessary, skin temperature rises little in relation to the severity of the environment.

Typically, skin moisture is expressed in terms of skin wettedness (w) or the fraction of the skin covered with sweat, skin relative humidity (RH_{sk}), and the moisture content (W_{sk}) of the skin or skin hydration.

The skin wettedness concept was introduced with partitional calorimetric studies on human subjects conducted by A.P. Gagge (1937). At that time a comparative analysis was made between the evaporation of sweat from the body and the evaporation from a liquid water surface, where the evaporation per unit area of a water surface (E) is proportional to the vapor pressure difference between the saturated vapor pressure at skin temperature (P_{ssk}) and the ambient (P_a) or:

$$E = he\ (P_{ssk} - P_a) \qquad (1)$$

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in which the proportionality or mass transfer coefficient (he) is dependent on air speed and surface contours. With the water surface in the contour of the human body, its evaporation rate would represent an upper limit or maximum rate of evaporation (E_{max}) for completely wet skin. The actual measured evaporation rate from the skin (E_{sk}) could then be normalized and characterized by the ratio to the maximum rate of evaporation or:

$$w = E_{sk}/E_{max} \qquad (2)$$

The ratio (w) represents the wetted area necessary to account for the observed rate of evaporation from the skin. The actual rate could then be conveniently expressed in terms of a completely wet surface or:

$$E_{sk} = w\ he\ (P_{ssk} - P_a) \qquad (3)$$

Initially, the mass transfer coefficient (he) was unknown and the experimental data were expressed only as the product (whe). This product could be determined from laboratory results as follows: $whe = E_{sk}/(P_{ssk} - P_a)$ where E_{sk} is the energy equivalent of the total rate of weight loss minus respiratory weight losses. Experimentally E_{sk} could be determined by continuous weighing with the subject sitting on a sensitive beam balance or from careful partitional calorimetery.

Experiments over a broad range of operative temperatures with the same air speed and humidity revealed that there were maximum and minimum values to the whe product. The maximum was observed to occur when the capacity for evaporative thermoregulation was exceeded and the body temperature began to rise. At this point the skin is maximally wet, i.e. presumably w=100%. Thus, assuming the skin to be 100% wet enabled the determination of the mass transfer coefficient for use in calculating the skin wettedness under other conditions. The minimum was observed in neutral and cool environments where active sweating did not occur and w represented the water vapor diffusing through the skin. The minimum value of w was found to be about 10% or less.

In subsequent experiments (Winslow et al. 1937), nude subjects indicated their sensations of pleasantness on a 1 - 5 scale: (1) very pleasant, (2) pleasant, (3) indifferent, (4) unpleasant, and (5) very unpleasant. The pleasantness sensations were related to skin temperature in cool conditions (correlation coefficient = 0.64), whereas, in warm environments skin temperature was found to be a poor indicator with relative comfort sensations relating better to sweating and skin wettedness. From the results of these studies the following relationship between pleasantness (P) and mean whole body wettedness was derived:

$$P = 2.2\ \overline{w} + 1.95 \qquad (4)$$

where P is the pleasantness values from 1 to 5, and skin wettedness ($\overline{w}$) is expressed as a decimal fraction. The correlation coefficient of this expression is 0.51. Under various warm conditions the border of the pleasant regime (P = 2.5) corresponded to a skin wettedness of 25%, while the unpleasantness border (P = 3.5) corresponded to 70%. Experiments with clothed subjects (Winslow et al. 1938) had similar results with the upper limit of the pleasantness border occurring with about 20% skin wettedness. Later measurements with a four-point comfort scale: (1) comfortable, (2) slightly uncomfortable, (3) uncomfortable, and (4) very uncomfortable, instead of the pleasantness scale, produced the same general results (Gagge et al. 1967).

Studies conducted on exercising subjects reached similar conclusions again indicating that the sweating response is a more important determinant for comfort than skin temperature (Gagge et al. 1969). Furthermore, it was found that subjects were not as sensitive to skin wettedness during exercise and that the comfortable or acceptable skin wettedness increased with increasing metabolic rates. At high metabolic rates the uncomfortable condition corresponded to skin wettedness values above 65%. In a study of five men exercising at 3 mets in 15 different combinations of temperatures and humidity, Gonzalez et al. (1978) found that discomfort (DISC) measured on the 4 part scale was related to skin wettedness as follows:

$$DISC = 2.4\ \overline{w} - .10 \qquad (5)$$

which is a regression through the means at each climatic condition (R=0.69). With T_{sk} included in the regression the correlation through the means improves (R=0.97); resulting in the following equation:

$$DISC = 0.97\ \overline{w} + 0.216\ T_{sk} - 6.79 \qquad (6)$$

Gonzalez et al (1973) also studied the physiological and subjective responses of 10 sedentary men during slowly changing ambient conditions. Skin wettedness was evaluated from w = E_{sk}/E_{max} in which the evaporation rate (E_{sk}) from the skin was determined from continuous measurement of weight loss with a Potter platform balance and E_{max} was determined analytically from measuring the following parameters.

$$E_{max} = he\ F_{pcl}\ ((P_{ssk}) - P_a) \qquad (7)$$

where he = 2.2 hc and the permeability efficiency factor of the clothing F_{pcl} = 1/(1 + 0.43 hc Icl), in which I_{cl} is the thermal insulation level of clothing in clo units, and hc is the convective heat transfer coefficient. The subjective responses in this study were indicated as magnitude estimates. From these reported thermal comfort estimates it was found that cold discomfort related linearly with mean body temperature weighted as 0.2 T_{sk} + 0.8 T_{es} (esophageal temperature at the heart level) while warm discomfort again related linearly to skin wettedness up to the evaporation failure limit ($\overline{w}$ = 0.8) above which discomfort increased with an accelerating function. This work also confirmed that comfort and thermal sensation are separate variables in warm environments with the discomfort level rising less than thermal sensation during initial exposure.

Gagge et al. (1973), in adding discomfort predictions (DISC) to the two-node model of human temperature regulation, applied the results of the Gonzalez study to develop the expression:

$$DISC = 5(\overline{w} - .06) \qquad (8)$$

where 0.06 represents the effective moisture level of the skin surface from diffusion. The magnitude estimate values of DISC relate to the ASHRAE comfort scale and skin wettedness as follows:

Comfort Scale	Comfortable	Slightly Uncomfortable	Uncomfortable	Very Uncomfortable	Intolerable
DISC	0.0 to 0.3	1.3	2.7	3.9	4.7
$\overline{w}$	0.06 to 0.12	0.2	0.6	0.8	1.0

Converting the magnitude estimate scale of DISC to the ASHRAE comfort scale of 0 (comfortable), 1 (slightly uncomfortable), 2 (uncomfortable), 3 (very uncomfortable), and 4 (intolerable), the relationship becomes:

$$DISC = 3.71\ \overline{w} + 0.086. \qquad (9)$$

This regression indicates that a skin wettedness of 25% corresponds to comfort judgment of slightly uncomfortable.

Studies of prolonged (six hours) steady-state sweating reveal that the salt concentration on the evaporating surface progressively increases from an initial concentration of 0.1% NaCl to values approaching saturation, i.e., 26%. This decreases the effective vapor pressure of the water on the skin, causing the wettedness to increase due to the reduction in evaporation rate per unit area (Berglund et al. 1973). The rate of increase in skin wettedness measured on six sedentary men exposed to ambient conditions of 95F, 105F, and 115F (35°C, 40.5°C, and 46°C) at 50%, 25% and 20% RH respectively were 4.5%, 3.8% and 5.8%/hour. The whole body wettedness values were the area weighted means of local skin wettedness measured with an iodine starch staining technique. Based on the above discomfort-wettedness relationship, i.e., DISC = 3.71 w + 0.086, discomfort in the 115F (46°C) environment increased at the rate of 0.22 ASHRAE comfort units per hour, e.g., a sedentary person who felt slightly uncomfortable at the beginning would, at the end of a four-hour exposure, have increased the level of discomfort to uncomfortable due to an increase in skin wettedness resulting from the salt accumulation on the skin.

The critical upper limit of skin wettedness for sedentary unclothed persons beyond which dripping begins was found to be about 0.75 in still air and to decrease with increasing air speed (Berglund et al. 1977). The decrease in the upper limit skin wettedness is due to increasing nonuniformity of evaporation with higher air speeds. The upper limit reached by increasing the humidity in small steps, in an environment where air temperature equaled skin temperature, revealed that skin temperature, discomfort and heart rate increased sharply at wettednesses above the critical value, similar to what Gonzalez (1973) had observed. Oohori (1984) analyzed the clothed subject data and determined that the critical skin wettedness under clothing decreased less with increasing air speed as compared with that observed on unclothed subjects.

SKIN WETTEDNESS UNDER CLOTHING

In the previous studies, skin wettedness was determined through the relation $w = E_{sk}/E_{max}$, where E_{sk} was determined from the rate of weight loss corrected for respiratory evaporative weight loss and E_{max} was determined experimentally, as in the early methods of Winslow and Gagge, or analytically from measured parameters, as in the studies by Gonzalez and Berglund. More recently a miniature humidity sensor was designed by Graichen (1982) with which measurements of local dew point temperatures between the skin and the clothing can be made. This resistance-type dew point sensor permits simultaneous dew point measurements about 4 mm above the skin surface at various locations on the body surface. The local skin wettedness is evaluated from the definition, $w = E_{sk}/E_{max}$, and Buettner's (1935) expression for skin evaporation:

$$E_{sk} = he\ (P_{sk} - P_a) \qquad (10)$$

where P_{sk} is the measured vapor pressure just above the skin surface and P_a is the ambient vapor pressure. Maximum evaporation occurs when the surface is completely covered with water and the surface pressure equals the saturation pressure of water at the skin temperature, i.e., $P_{sk} = P_{ssk}$ expressed as:

$$E_{max} = he\ (P_{ssk} - P_a). \qquad (11)$$

Substituting into the definition equation as suggested by Kerslake (1972), skin wettedness becomes:

$$w = (P_{sk} - P_a)/(P_{ssk} - P_a). \qquad (12)$$

Humidity measurements made under clothing indicate that the dew point gradient in the space between skin and clothing is small (Berglund et al. 1985) and therefore, the vapor pressure derived from the dew point measured close to the skin is a good representation of P_{sk}.

Using multiple sensors, measurements were made under five clothing ensembles at six locations on the body surface: chest, back, upper arm, forearm, thigh and calf. The five clothing ensembles, which were worn open at the neck, wrist and ankles, were (1) short-sleeved sport shirt and Bermuda shorts, (2) long sleeved shirt and trousers, (3) short sleeved shirt, trousers and sport jacket, (4) semipermeable foul-weather suit, and (5) impermeable plastic foul-weather suit.

Except for the foul-weather suits, the clothing was primarily cotton blended with polyester. The measurements were made on five male subjects, approximately 71" (180 cm) in height with body weights ranging from 140 to 183 lb (64 to 83 kg).

The studies were conducted in a climatic chamber with the subjects sitting on a sensitive recording balance (Potter) in a 95F (35°C) environment. The ambient dew point was initially held around 46F (8°C) for about 45 minutes with the rate of weight loss and regional dew point measurements under the clothing recorded throughout this exposure period. Skin temperatures at the location of the humidity sensors were also recorded. In addition, the subjects periodically indicated their subjective feelings of thermal sensation, comfort, and sense of skin wettedness. Measurements were then repeated at steady state conditions with ambient dew points of approximately 61F, 72F, and 82F (16°C, 22°C, and 28°C).

The skin wettedness measurements are described in detail elsewhere (Berglund and Cunningham 1984). The average regional skin wettedness for all subjects expressed by linear regression lines for the long-sleeved shirt and trousers ensemble and the semipermeable coverall are given in Figures 1 and 2. The local wettedness under the semipermeable garment was significantly higher under all exposure conditions when compared with the values obtained with woven fabric clothing.

The average skin wettedness under clothing ($\overline{w}_{uc}$) can be estimated from the area weighted average of the local skin wettedness values:

$$\overline{w}_{uc} = 0.432\ (w_{chest} + w_{back})/2 + 0.173\ (w_{ua} + w_{fa})/2 + 0.235\ w_{thigh} + 0.16\ w_{calf} \qquad (13)$$

The regression lines of the mean skin wettedness under clothing for each clothing ensemble are shown in Figure 3. The $\overline{w}_{uc}$ for the short-sleeved shirt and Bermuda shorts are very similar to those with the long-sleeved shirt and trousers as would be expected, since the vapor from the skin was flowing to ambient through only one layer of cloth with both ensembles. The w_{uc} for the sport jacket ensemble was slightly higher while the average wettedness under the semipermeable and impermeable suits was much higher.

In these studies the average skin wettedness was also determined in the traditional way from total evaporative weight loss measurements over time, and the results are compared in Figure 4 with those determined by the local vapor pressure method for woven clothing. The average wettedness was calculated from the evaporative weight loss using the following equation:

$$\overline{w} = m L / (Ad\ he\ F_{pcl}\ (P_{ssk} - P_a)) \qquad (14)$$

where m is total rate of weight loss minus respiratory losses, L is the latent heat of evaporation, and Ad is the DuBois surface area.

The evaporative conductance (he) and the permeability efficiency factor (F_{pcl}) of the clothing were determined from:

$$he = 2.2\ hc \qquad W/m^2\ Torr \qquad (15)$$

$$F_{pcl} = 1/(1 + 0.143\ hc\ I_{cl}) \qquad (16)$$

where hc is the convective heat transfer coefficient (0.46 Btu/ft^{2}hr F, 2.6 W/m^{2}K) and Icl is the insulation value of the clothing i.e., clo value. The clo values were estimated to be 0.41 for the Bermuda outfit, 0.56 for the long-sleeved shirt and trousers, and 0.87 for the sport jacket ensemble. The reasonably good agreement that exists between the mean skin wettedness values determined by the two methods enables the comparison of subjective responses where the skin wettedness was determined with one method or the other.

The comfort judgments made by the subjects while wearing different ensembles and exposed to various humidity conditions are plotted against the measured average skin wettedness under clothing in Figure 5. The regression equation relating comfort to skin wettedness is:

$$DISC = 4.13\ \overline{w}_{uc} + 0.13 \qquad (17)$$

The correlation coefficient of 0.61 is similar to that reported by Winslow et al. (1937). The correlation can be improved (R=0.68) by the inclusion of mean skin temperature:

$$DISC = 4.3\ \overline{w}_{uc} + 0.53\ T_{skuc} - 20.8. \qquad (18)$$

In addition to comfort judgements, the subjects indicated their perception of skin wettedness (PSW) during the experiments on a scale of 0 (dry), 1 (slightly damp), 2 (damp), 3 (very damp), 4 (wet), 5 (very wet), and 6 (soaking wet). The results and regression line are given in Figure 6, where it is seen that the subjects demonstrated an ability to detect the level of skin moisture, i.e., R=0.60. The regression equation is:

$$PSW = 6.36\ \overline{w}_{uc} + 0.34 \qquad (19)$$

The relationship between a subject's thermal sensation and mean skin temperature is, however, less defined.

In a similar study, Cunningham et al. (1985) studied the physiological and subjective responses of two men and two women to the following sequence of thermal environments:

Ta	RH (%)	Duration (min)
77F (25°C)	50	20
86F (30°C)	50	40
95F (35°C)	49	40
95F (35°C)	59	40

The test sequence was repeated with subjects wearing ensembles of 0.4, 0.6, 0.9, and 1.2 clo. Local dew point and skin temperatures were measured to determine the average skin wettedness under clothing and the mean skin temperature. The physiological responses to the heat were found to differ between the men and women studied, with the men exhibiting a greater level of skin wettedness at temperatures above neutral. The men also reported a higher level of thermal sensation and discomfort in the various environments than the women. Interestingly though, the comfort responses of the men and women relative to skin wettedness were essentially the same (Figure 7). The regression equation of discomfort to skin wettedness for men and women is:

$$DISC = 5.06\ \overline{w}_{uc} + 0.09 \qquad (20)$$

with a correlation coefficient of 0.91. The group would have reached the "intolerable" discomfort level at a skin wettedness of about 76%. Notice in this study a skin wettedness level above 25% is again considered uncomfortable. The inclusion of mean skin temperature improves the above correlation slightly (R=0.96).

$$DISC = 5.87\ \overline{w}_{uc} + 0.85\ T_{skuc} - 28.6. \qquad (21)$$

Similarly the "sense of skin wettedness" in relation to measured skin wettedness was also the same for men and women with a regression equation (R=0.74) of:

$$PSW = 6.99\ \overline{w}_{uc} + 0.21 \qquad (22)$$

Hoeppe et al. (1985) studied the effects of the vapor resistance of clothing on human response during exercise and rest. In environments that were approximately neutral for sedentary individuals (72F and 79F, 22 and 26°C) at 45% RH three fit male subjects ages 16, 29 and 38 first exercised for 35 minutes on a cycle ergometer and then rested for 60 minutes while remaining seated on the ergometer. The exercise consisted of an initial five-minute warmup phase with an increasing work load, followed by 30 minutes of exercise at a constant work load of 85 W, 50 rpm. The participants were tested in training suits made of 100% cotton, 100% polyester, a semipermeable laminate, and polyurethane coated nylon. Esophageal temperature, skin temperature, outer clothing surface temperature, dew point temperatures under the clothing next to the skin, oxygen consumption, and rate of weight loss were measured continuously. Subjective responses of thermal sensation, comfort, and perceptions of dampness were obtained every five minutes.

The insulation value of the clothing in clo units was evaluated during the resting phase from oxygen consumption, rate of weight loss, skin and outer clothing temperature measurements. The vapor permeability (i_{cl}), defined as the ratio of the dry conductive thermal resistance to the vapor resistance of the clothing, was calculated for each of the four ensembles from the following equation:

$$icl = 0.155\ clo/(2.2\ Rc) \qquad (23)$$

The vapor resistance (Rc), thermal resistance (clo), and vapor permeability (i_{cl}) of the training suits measured under steady-state conditions were:

Exercise at 5 mets

	Cotton	Polyester	Semi-permeable	Urethane on Nylon
Rc (Torr m^2/W)	0.06	0.05	0.10	0.15
		Rest		
Rc (Torr m^2/W)	0.11	0.10	0.45	0.46
clo	0.64	0.66	0.67	0.57
icl	0.42	0.48	0.11	0.08

The clothing's vapor resistance values during exercise were less than those during rest. This may be attributed to the bellowing effect of the clothing during exercise, which results in an increased mixing of the air between skin and clothing and an increased flow of ambient air through aperatures of neck, wrists, ankles, etc.

The dimensionless vapor permeability values determined at rest compare favorably with those reported by Oohori et al. (1984). The vapor permeability, icl, of a typical woven fabric is about 0.45.

During exercise the subjects' total heat production determined from oxygen consumption measurements was about 500 W or 5 mets. Figure 8 displays the mean skin wettedness under clothing throughout the course of the experiment at ambient conditions of 26°C and 45% RH with an air speed of 1.4 m/s. The clothing with high vapor resistance had higher measured skin wettedness values under all conditions, and the skin wettedness under the high vapor resistance clothing decreased more slowly following exercise. Discomfort increased consistently with skin wettedness, while the subjective feeling of dampness followed closely the measured skin wettedness.

Thermal sensations were a function of the deviation of the measured mean skin temperature (Tsk) from the predicted mean skin temperature for comfort (Tsk_c) as defined by Fanger (1972), represented by:

$$\text{Thermal Sensation} = 4.4 + 0.41\,(Tsk - Tsk_c) \qquad (24)$$

where Tsk_c (°C) = 35.7 - 0.0276 (H/A) is from Fanger (1972) and H/A is the measured internal heat production per unit surface area (W/m^2).

The comfort judgements both during and after exercise (Figure 9) are related to the measured skin wettedness by the regression equation (R = 0.81):

$$DISC = 3.6\,\overline{w}_{uc} - 0.25 \qquad (25)$$

which indicates again that in warm environments, comfort is primarily dependent upon skin wettedness. At a skin wettedness of 25%, DISC is 1.4 or a little more uncomfortable than "slightly uncomfortable" and similar to the 25% level found in previous studies. The regression equation relating perceived skin wettedness to measured skin wettedness (Figure 10) had an even higher correlation coefficient (R = 0.91):

$$\text{Sense of Wettedness} = 7.1\,\overline{w}_{uc} - 0.75 \qquad (26)$$

Thus discomfort and feelings of dampness again both increase linearly with the increased measured skin wettedness.

COMPARISONS BETWEEN STUDIES

In the comfort studies described, skin wettedness was measured with different techniques and methods by different investigators and under different conditions. Discomfort and perceived wettedness regressions as a function of mean skin wettedness from several studies are plotted in Figure 11 where it is seen that the results are in good agreement. The regression line developed by Winslow, Herrington and Gagge was the first relating comfort to skin moisture in warm environments. Their results are somewhat difficult to compare numerically to the others because they used a pleasantness scale from 1 to 5, which is dissimilar from the ASHRAE scale employed in later studies. All of the regression equation results discussed in the paper are listed in Table 1.

Table 1. Regression Equations of Subjective Responses

Source	Met	Clo	Equation	R
Winslow (1938)	1	0.05	$P = 2.2\,\overline{w} + 1.95$	0.51
Gonzalez (1973)	1	0.05	$DISC = 3.71\,\overline{w} + 0.086$	
Gonzalez (1978)	3	0.05	$DISC = 2.4\,\overline{w} - 0.1$	0.69
			$DISC = 0.97\,\overline{w} + 0.216\,T_{sk} - 6.8$	0.97
Berglund (1984)	1	0.4-0.9	$DISC = 4.13\,\overline{w} + 0.13$	0.61
			$DISC = 4.3\,\overline{w} + 0.593\,T_{sk} - 20.8$	0.68
Cunningham (1985)	1	0.4-1.2	$DISC = 5.06\,\overline{w} + 0.09$	0.91
			$DISC = 5.87\,\overline{w} + 0.85\,T_{sk} - 28.6$	0.97
			$DISC = 3.02\,RH_{sk} - 0.37$	0.59
Hoeppe (1985)	1&5	0.64	$DISC = 3.6\,\overline{w} + 0.25$	0.81
Berglund (1984)	1	0.4-.9	$Psw = 6.36\,\overline{w} + 0.34$	0.60
Cunningham (1985)	1	0.4-1.2	$Psw = 6.99\,\overline{w} + 0.21$	0.74
Hoeppe (1985)	1&5	0.64	$Psw = 7.1\,\overline{w} - 0.75$	0.91

SKIN RELATIVE HUMIDITY

In addition to skin wettedness, skin moisture can also be expressed as skin relative humidity (RH_{sk}), defined as the ratio of the vapor pressure of the skin surface (P_{sk}) to the saturated vapor pressure of water at skin temperature (Pssk) (Buettner 1935):

$$RH_{sk} = P_{sk}/P_{ssk}. \tag{27}$$

Skin relative humidity is related to skin wettedness as follows:

$$RH_{sk} = w + (1 - w)P_a/P_{ssk} \tag{28}$$

or

$$w = (RH_{sk} - P_a/P_{ssk})/(1 - P_a/P_{ssk}). \tag{29}$$

There are advantages to both expressions. Skin relative humidity is easier to determine, depending only on the skin vapor pressure. Skin wettedness is, however, a better direct indicator of effective evaporation and physiological strain. The total evaporation rate of a surface that is 90% wet can only increase a maximum of 10% with all other parameters remaining constant. The same evaporation assessment cannot be made as easily from knowing the surface has a 90% skin relative humidity.

As a predictor of warm discomfort, skin relative humidity is comparable to skin wettedness. For example, the comfort data from the study by Berglund and Cunningham (1984) discussed earlier are plotted against skin relative humidity in Figure 12. The regression equation is:

$$DISC = 3.02\ \overline{RH}_{sk} - 0.37 \tag{30}$$

with a correlation coefficient of 0.59 and where $\overline{RH}_{sk}$ is a decimal fraction.

MOISTURE CONTENT

Kerslake (1972) has related the skin relative humidity to the moisture content of the skin. For example, at a skin relative humidity of 90%, the moisture content (weight of hydrated skin/weight of dry skin) is 0.5. As skin absorbs water, it swells and becomes soft. Kerslake observed that hidromeiosis, i.e., occluding of sweat glands, only occurs at high levels of skin moisture, i.e., $RH_{sk} > 90\%$. Further, the friction between skin and clothing, as well as a fabric's perceived coarseness, increases with skin moisture (Gwosdow et al. 1986), which may also be related to the increasing moisture content of the skin.

CONCLUSION

Skin moisture has an impact on warm discomfort. This observation first made by Winslow, Herrington, and Gagge has been reaffirmed by numerous investigators under a wide variety of conditions. The relationships found between skin wettedness and comfort have been very consistent. The early "rule of thumb" that a sedentary person will not feel comfortable or pleasant if skin wettedness is greater than 25% has been repeatedly supported. Further, it has been demonstrated that people are sensitive perceivers of skin moisture. Thus, hot arid conditions can be comfortable even at high perspiration rates because the skin can remain dry, indicating that the evaporation potential of a situation is of great importance for warm environment occupancy. Increased air motion, humidity control, and clothing content and design that promotes ventilation of the space between skin and fabric and transport of vapor, are important parameters in decreasing skin wettedness and discomfort.

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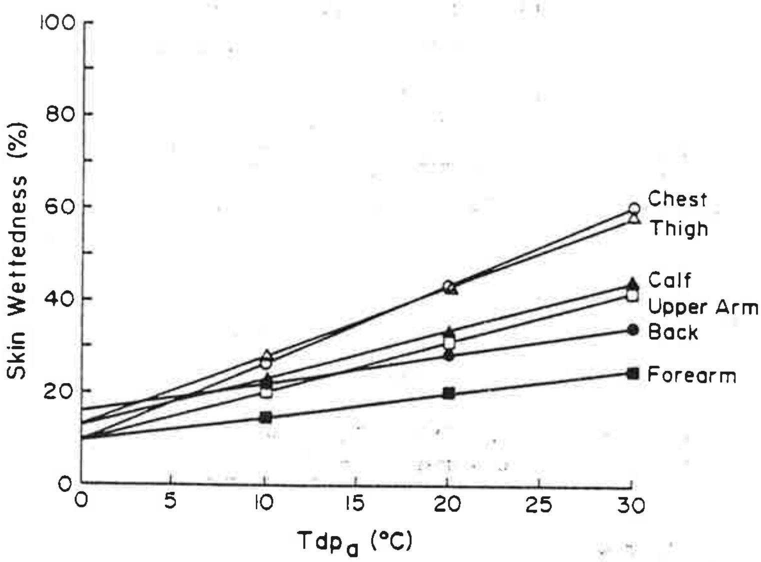

Figure 1. Regression lines of the regional skin wettedness under long sleeved shirt and trousers of sedentary men in a 95 F (35°C) environment as a function of ambient dew point (t_{dpa})

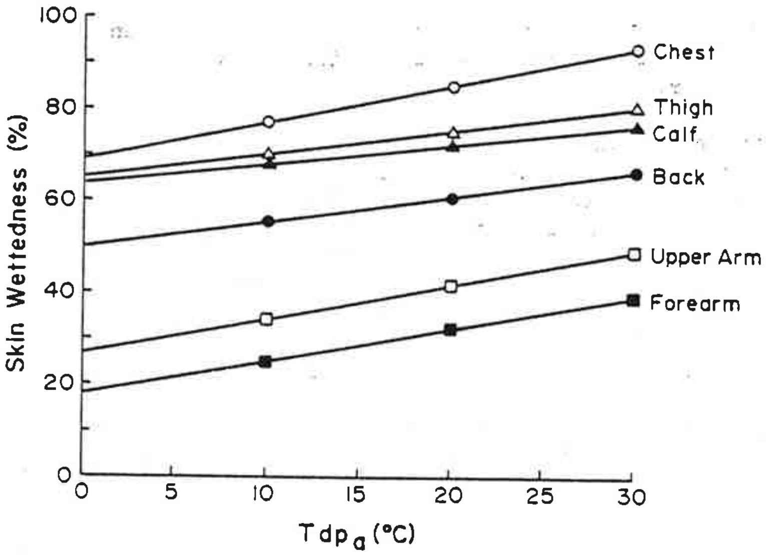

Figure 2. Regression lines of the regional skin wettedness under semipermeable coveralls of sedentary men in a 95 F (35°C) environment as a function of the ambient dew point (T_{dpa})

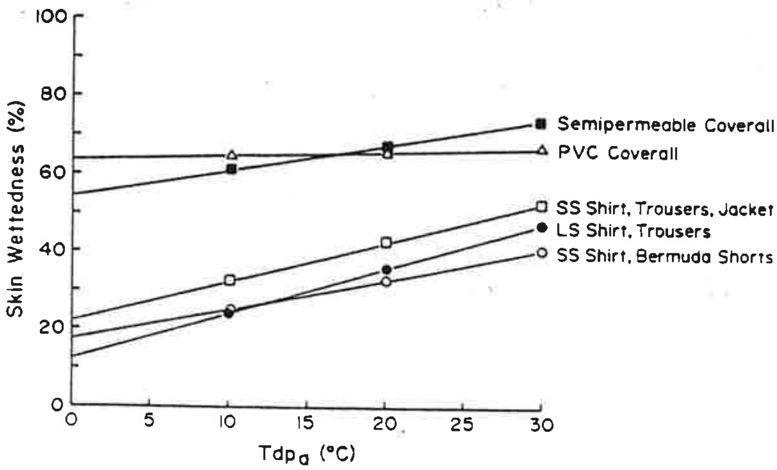

Figure 3. Regression lines of mean skin wettedness under clothing for five ensembles in a 95 F (35°C) environment

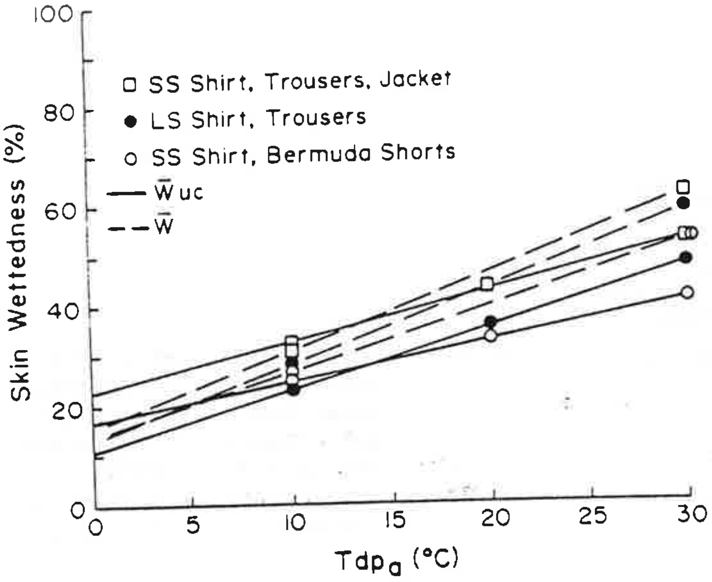

Figure 4. *Mean skin wettedness under clothing ($\bar{w}_{uc}$) and mean whole body wettedness ($\bar{w}$) for three clothing ensembles*

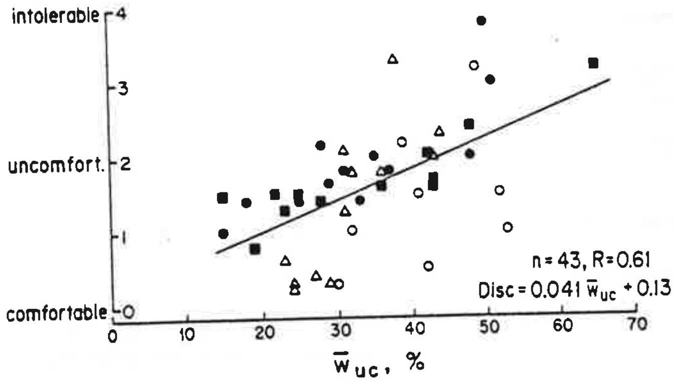

Figure 5. *Comfort responses related to skin moisture measured under woven fabrics in a 35°C environment*

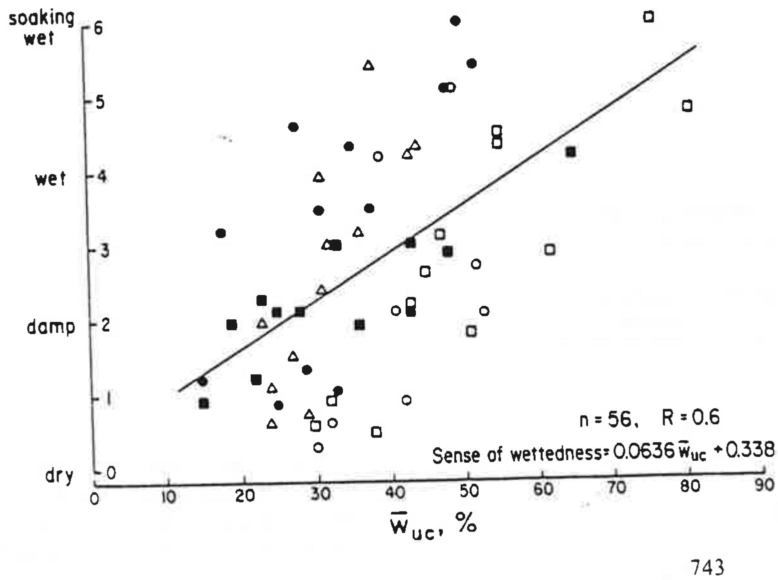

Figure 6. *Perceived skin moisture judgments compared to measured skin wettedness under clothing of sedentary men in a 95 F (35°C) environment*

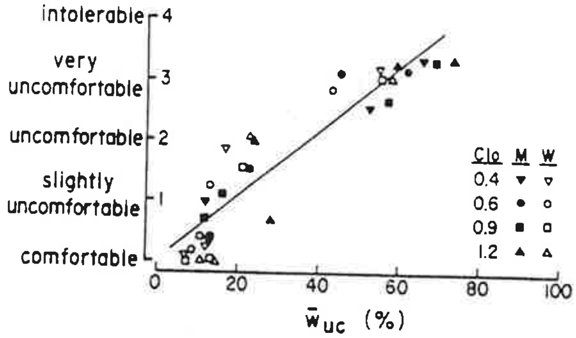

Figure 7. Comfort responses of men and women from increasingly severe climates related to their measured mean skin wettedness under clothing

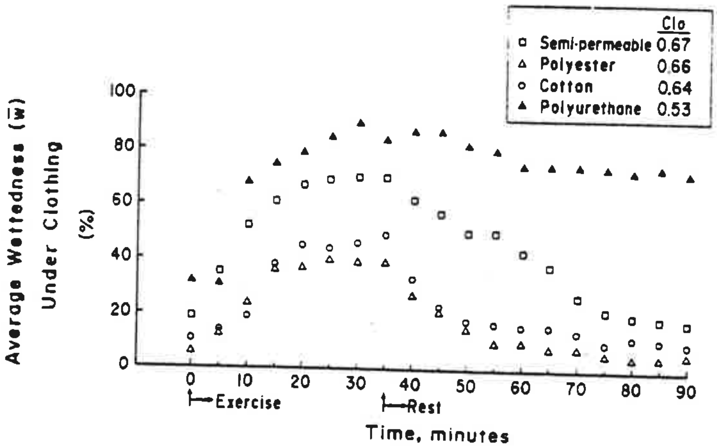

Figure 8. Mean skin wettedness under clothing during and after exercise in a 79 F (26°C) environment with 55 F (13°C) dew point and 280 fpm (1.4 m/s) air movement

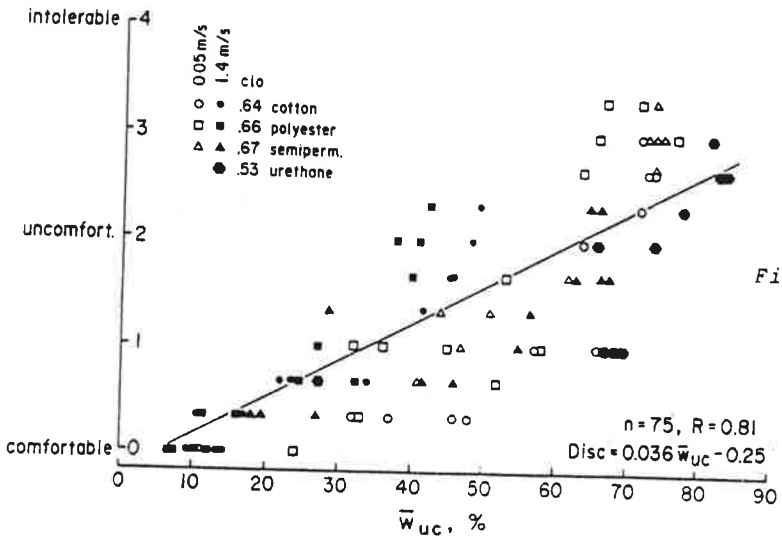

Figure 9. Comfort responses during and after exercise (5 met) related to measured mean skin wettedness under clothing

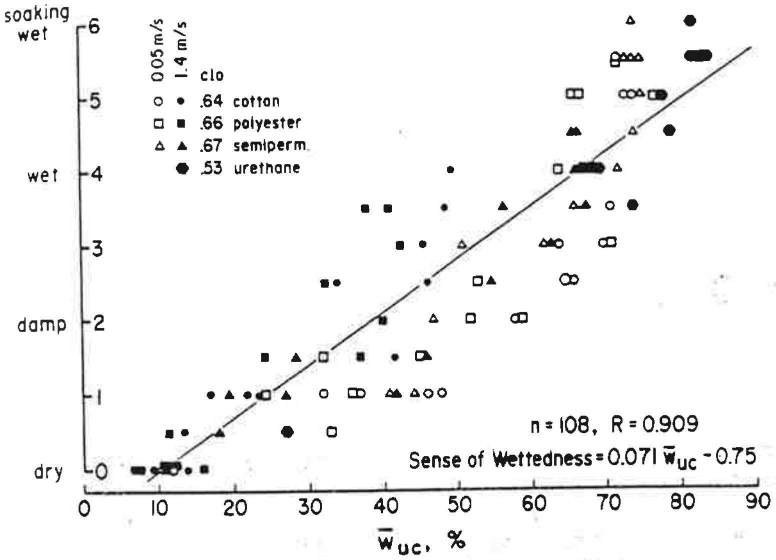

Figure 10. Perceived skin wettedness during and after exercise compared to the measured mean skin wettedness under clothing

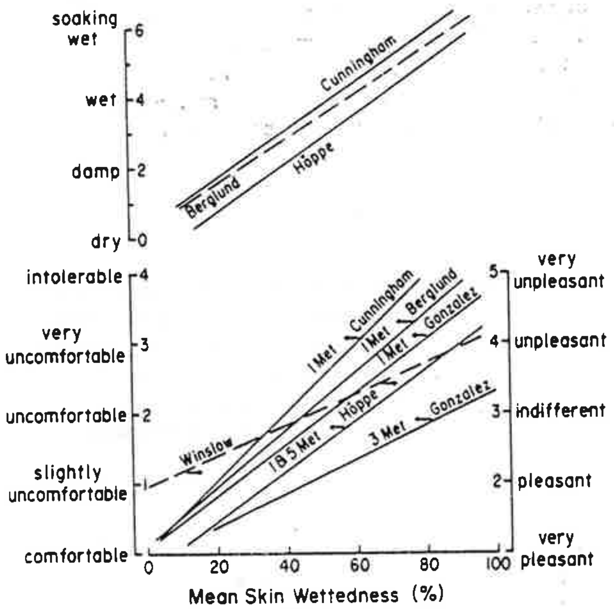

Figure 11. Comparison of comfort and perceived skin wettedness regression results

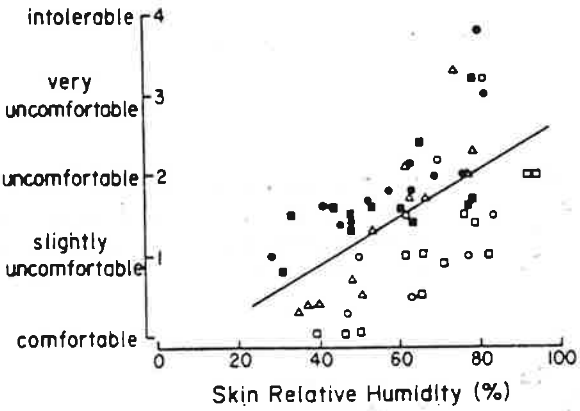

Figure 12. Relationship between comfort and skin relative humidity measured on five sedentary men in three different summer clothing ensembles in a 95 F (35°C) environment

Discussion

R. GONZALES, U.S. Army Res. Inst. Environment, Natick, MA: In response to Prof. Fanger's question, I have always wondered what the skin receptor would be that responds (or changes its responsivity) to transduce a signal for skin wettedness. This could be perhaps pressure (Pacinian) or some other one on the skin--perhaps friction produces the same (allerent) signal. One thing is clear and that is that the "gain" in DISC to wettedness does decrease with exercise (as your composite figure shows) compared to rest. Somehow the wettedness property is amplified in the sedentary state. During steady exercise, skin wettedness is, on the other hand, not as important. In response to endogenous hyperthermia with exercise, one may indeed be 100% wet. Randolph, Gagge, and I showed that mean body temperature and sweating rate were both important in discomfort estimates (Arch Sci. Physical 23). Perhaps with the fact that nude man first used clothing to adapt to a warm or hostile environment, his sedentary activity made him amplify his receptor sensitivity to skin wettedness.

L.G. BERGLUND and D. CUNNINGHAM: Thank you for your interesting comment. Figure 11 and Table 3 both show a decreased discomfort sensitivity to skin moisture with increased metabolism.

K.M. ELOVITZ, Energy Economics Inc. Foxboro, MA: How does wicking action and type of fabric (woven, knit, polyester, cotton) affect skin wettedness and sensation of comfort at equal CLO?

BERGLUND and CUNNINGHAM: Figure 8 shows little difference between skin wettedness levels measured under cotton and polyester training suits during exercise and rest. Of course, these are results of just one study, but they are somewhat surprising as cotton wicks and absorbs while polyester does neither. In general, a wicking material should feel drier as local excess liquid on the skin can be transported to areas where it can evaporate. For a given fiber, material the total wicking rate would be expected to increase with the number of fibers per unit area or volume in the fabric.

H. LEVIN, Univ. of California, Berkeley: Proportion of moisture in exhaled breath related to MET and skin wettedness effect on experimental data (weight loss) and on comfort (cooling effect)?

BERGLUND and CUNNINGHAM: When skin wettedness was determined from total body weight loss, respiratory weight losses were calculated by the methods of Fanger (1972) and subtracted from the measured rate of weight loss. The humidity ratio of expired air (Wex) can be estimated from the results of McCutchan and Taylor (see Fanger 1972):

$$Wex = 0.0277 + 0.000065 Ta + 0.2\ Wa$$

where Ta(^{o}C) and Wa are the ambient temperature and humidity. Respiratory heat loss typically is less than 10% of the total heat loss and, therefore, has only a small effect on comfort.