Distribution of Evaporation Rate on Human Body Surface

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Relative humidity (R. H), vapour pressure (Psk) and evaporation rate (Esk) of the human skin surface were measured at 29 points by an evaporimeter at 25 °C, 28 °C, 31 °C, 34 °C and 37 °C of air temperature (Ta), with 35 ± 10 % R. H and the air velocity of less than 0.2 m/s. The skin temperatures and the body weight loss were also measured by thermography and electronic balance. Ten healthy female subjects aged 22-34 years, wearing brassiere and shorts, took a supine and a prone posture during experiment. Comparisons of the obtained Esk with the previous results of other studies showed that there were no definite differences among the measuring methods of Esk, while it is ascertained that the calibration of the results to some standard values such as weight loss were more important to get accurate values of Esk. Distribution patterns of Esk were almost the same in the insensible zone but they remarkably changed in the sweating zone. According to the regression analysis of Esk and Ta, 29 regions were classified into the following 9 groups which showed similar values and changes of Esk with the air temperature: 1) face, 2) front upper trunk, 3) back upper trunk, 4) front lower trunk, 5) back lower trunk, 6) arm, 7) leg, 8) hand and foot and 9) palm, sole and axilla. These results were discussed in relation to the contributing factors such as the number and the capacity of the sweat gland, the regional skin temperature and the pressure-sweat response and also in relation to the skin wettedness. (Ann. Physiol. Anthropol. 11(6): 593-609, 1992)

Key words: Regional evaporation rate, Evaporimeter, Insensible perspiration zone, Sweating zone, Sweating onset

One of the principal functions of the skin is to prevent desiccation and thus to maintain a suitable water and heat balance of the body. Water loss from the body surface by insensible and sensible perspiration plays a momentous role to control the thermoregulation by discharging body heat. Sweating is transferred from the skin surface to the outer environment through clothing, and the clothing acts as a barrier against it. Therefore, it is basically important to study the clothing comfort or clothing function from the stand point of physiological anthropology to examine the amount and the distribution of evaporation over the human body.

In relation to the distribution of sweating, there have been many reports based on physiological or

clinical interest (Ohara, 1963; Spruit, 1967; Spruit and Malten, 1969; Goodman and Wolf, 1969; Lamke, 1970; Lamke and Wedin, 1971; Tam and Darling et al., 1976; Lamke and Nilsson et al., 1977). There are, however, few reports which made investigations from a viewpoint of clothing comfort or clothing function. In particular, the measurements of perspiration conducted were not only partial but the values obtained varied largely. For example, Ohara et al. (1963) measured the perspiration rate at as many as 108 points of the body surface. But the number of the subjects he used for this purpose was only one. The method used was an unventilated capsule which depressed the natural perspiration from the skin. Spruit and Malten (1969) developed a

ventilated chamber but his work was based, *in vitro*, on the cadaverous human skin. Goodman and Wolf (1969) applied a ventilated capsule to many subjects but measurement was made on only two points. Lamke (1970)'s environmental condition adopted was only neutral temperature and Tam et al (1976)'s was set at only high and transient temperature of 30 °C–45 °C. It should also be pointed out that their ventilated chamber methods produced high values of perspiration because of the forced convection caused by the ventilation of different types of gas over the skin surface. The evaporimeter developed by Nilsson was to make up for these defects. Nilsson et al. (1977) used the evaporimeter on the 9 measuring points which he fixed by careful consideration. But his study was conducted only at 25 °C–30 °C of air temperature, that is, within the range of insensible perspiration. As mentioned above, the results obtained by these investigators did not necessarily agreed with each other. They are useful but not enough for designing comfort clothing, materials and constructions.

The present study was performed to investigate by using the Nilsson's evaporimeter how human perspiration changes with environmental condition and whether the distribution of the human perspiration would stay the same if the environmental condition changes. The human cutaneous perspiration rate on 29 points of the body of 10 female subjects were measured by evaporimeter under the environmental temperatures of 25 °C, 28 °C, 31 °C, 34 °C and 37 °C, which should have covered both insensible and sensible phases of human thermoregulation. According to our previous paper (Park and Tamura, 1992) the evaporation rate and vapor pressure on the body surface were measured and corrected by the calibration equation.

METHODS

1. Experimental conditions

All measurements were performed in a climatic chamber under different ambient temperatures at

five steps from 25 °C to 37 °C. Relative humidity was constant at $35 \pm 10\%$, and air velocity was set to less than 0.2 m/s. There was no radiative effect. The climatic chamber was controlled at these levels until the moment the experiment started to avoid the effect of the on-off change on the temperature, humidity and the air movement. These measuring conditions were determined in our previous paper (Park and Tamura, 1992).

2. Measuring methods

1) Relative humidity, vapour pressure and evaporation rate on the skin surface

The relative humidity, vapour pressure and evaporation rate on the skin surface were measured by an evaporimeter made by Servomed Co. (Sweden). The method was based on estimation of the vapor pressure gradient in the air layer immediately adjacent to the skin (Nilsson, 1977).

The measurements were conducted every 10 seconds for one minute on one measuring point. The interval from one measuring point to the next one was two minutes. The data were simultaneously recorded on a portable data collector which was connected to the computer. As with our previous paper where the measuring condition of the evaporimeter was checked, a supine or a prone position was adopted for the posture of the subject in order to place the sensors horizontally on the body surface during measurement. The order of the measurements was first from head to foot on the front and then from head to foot on the back. The observed values were corrected by the equation, $Y = 2.064 + 2.531X$ where, X is the observed values and Y is the corrected value.

2) Body weight loss

The body weight loss was measured on the electronic balance made by Sartorius (West Germany). Its sensitivity was ± 1 g. Evaporation rate for unit body surface area per unit time was estimated from the difference of body weight measured before and

Fig. 1 Measuring point

after each experiment.

3) Skin temperature

The skin temperatures were measured by thermography. The thermograms were respectively taken from four parts of the body, i. e. front upper, back upper, front lower and back lower parts of the body. The skin temperatures on the 29 regions of the body which corresponded with the measuring points of evaporation (Fig. 1) were read from the thermograms obtained.

3. Subjects

Ten healthy female subjects from 22 to 34 years of age were used in this experiment. Table 1 shows the physical characteristics of the subjects. Each subject was dressed in only brassiere and shorts during experiment. Before the beginning of each series of measurement the subject lay on a Saran bed and was controlled to the specified conditions for at least 20 minutes. The experiments were conducted for the duration of four months from December of 1990 to March of 1991.

Table 1. Physical characteristics of subjects

Subject	Age (yr)	Height (cm)	Weight (kg)	Body surface Area (m ²)
T.M	24	164	53	1.58
M.D	23	152	41	1.35
K.B	33	164	64	1.72
S.J	28	163	63	1.66
A.M	26	156	53	1.49
O.K	22	169	79	1.82
H.N	22	166	60	1.66
K.O	22	156	53	1.51
K.K	22	151	49	1.40
U.T	22	159	49	1.47

RESULTS

The means and standard deviations (S. D) of the relative humidity, vapour pressure and the evaporation rate from 29 parts of the body surface and corresponding skin temperatures were shown in Table 2.

1. Relative humidity

The relative humidity on the regional body surface, as shown in Fig. 2, changed from about 26 % to 59 % as the temperature changed from 25 °C to

31 °C, and from 34 % to 62 %, for the change from 34 °C to 37 °C. Over all, the axilla showed the largest increase i.e., from 48 to 62 %. The palm and sole, following this, showed the change, from 43 to 50 %. The relative humidity of the other points increased gradually from 26 to 43 % for 25 °C-34 °C, except for the loin (34 °C, 46 %) and the buttock (34 °C, 55 %), and from 39 to 52 % for 37 °C, as the air temperature rose.

2. Vapour pressure

The changes of the vapour pressure on the regional body surface with ambient temperature were generally similar to those of the relative humidity (Fig. 3). Ranges of the vapour pressure were 10-25 mmHg for the ambient temperature of

25 °C-31 °C and 15-27 mmHg for 34 °C-37 °C. At 25 °C, 28 °C and 31 °C, the highest value was shown in the axilla (20-25 mmHg). The palm (16-20 mmHg) and sole (14-21 mmHg) followed this. Other regions showed much lower values varying from 10 to 17 mmHg than these three. At 34 °C and 37 °C, high values were also shown in the axilla (23-27 mmHg), sole (19-21 mmHg) and palm (19-21 mmHg). The regional differences, however, tended to become smaller than at 25-31 °C since the vapour pressure of the other regions such as the buttock (22-24 mmHg) increased greatly as the ambient temperature rose.

3. Evaporation rates from the whole body surface

The average values of the body weight loss under

Fig. 2 Distributions of relative humidity on the skin surface of the human body under five different conditions of air temperature.

Fig. 3 Distributions of vapour pressure on the skin surface of the human body under five different conditions of air temperature.

Fig. 4 Change of the body weight loss and the weighted mean evaporation rate with air temperature (● body weight loss, △ weighted evaporation rate).

each thermal condition were 23 g/m²h, 25 g/m²h, 25 g/m²h, 41 g/m²h and 56 g/m²h at the air temperatures of 25 °C, 28 °C, 31 °C, 34 °C and 37 °C respectively as shown in fig. 4. Weighted mean evaporation rates of the whole body indicated by the symbol △ in the figure were estimated by multiplying the regional evaporation rates measured with evaporimeter by the ratios of regional areas to the whole body. The mean evaporation rate increased with environmental temperature 24.6 g/m²h, 26.6 g/m²h, 27.9 g/m²h, 31.1 g/m²h and 55.7 g/m²h at each ambient temperature of 25 °C, 28 °C, 31 °C, 34 °C and 37 °C respectively. Both values, total body weight loss and estimated mean evaporation rate, agreed with each other and with the results of the previous investigation by Tamura, T. (1978). Our data in sweating range were a little lower than Tamura's, but it was common in both results that the evaporation rate from the whole body was low and almost constant below the ambient temperature of 31 °C and increased rapidly with ambient temperature above 34 °C. The former was applicable to the insensible perspiration zone of the human thermoregulation and the latter to its sweating zone.

4. Distribution of regional evaporation rate

The average values of evaporation rate for ten subjects were plotted against measuring point in Fig. 5, where the bar indicates the 95 % confidence

limit.

Fig. 5-a indicates the evaporation rate at 25 °C. The high values were shown on the palm (109 g/m²h), axilla (86 g/m²h) and sole (62 g/m²h). Observing the distribution of the evaporation rate except for these three regions, the face showed a high value (38–46 g/m²h). Among the trunk, the neck and buttock indicated 21–24 g/m²h, the abdomen showed 18 g/m²h and the other regions indicated 11–14 g/m²h. In the upper extremity, all regional evaporation rates existed between 12–14 g/m²h except the hand showing a high value of 27 g/m²h. Among the lower extremity, the foot showed a high value of 21 g/m²h, but the other regions showed a similar value of 12–14 g/m²h. Both the distributions of the evaporation rate at 28 °C and at 31 °C were similar to those at 25 °C, as shown in Fig. 5-b, and c. In order to examine the similarity of the distribution pattern of the evaporation rate under the insensible perspiration zone, the order correlations of the evaporation rate between 25–28 °C and 28–31 °C were calculated. The correlation coefficients were respectively 0.91 and 0.90. These high coefficients confirmed that the patterns of the distribution at the insensible perspiration zone were almost the same. The order correlation coefficient between 31 °C and 34 °C, on the other hand, was lower ($r=0.69$) than that and the patterns of the distribution were a little different between 31 °C and 34 °C. At 34 °C, the high values were shown on the palm (81 g/m²h), axilla (72 g/m²h), sole (76 g/m²h) and on the buttock (71 g/m²h). The values on the face were 39–50 g/m²h that was almost the same as those of the insensible zone. The trunk indicated 15–31 g/m²h except for pst.neck and lat. abdomen (34 g/m²h) and loin (46 g/m²h). The values at the back part of the trunk increased remarkably at 34 °C. The upper extremity, showed 16–21 g/m²h except the hand (35 g/m²h) and the lower extremity showed 34–42 g/m²h. The upper extremity showed a similar tendency at 31 °C. But the lower extremity except for the buttock increased remarkably at 34 °C. At 37 °C, the level of the evaporation rate of

Table 2-a. Means and standard deviations of relative humidity (R. H.), vapour pressure (P), evaporation rate (E) and skin temperature (Ts) in insensible perspiration zone.

Regions	25°C						28°C						31°C									
	R.H(%)		P(mmHg)		E(g/m ² h)		Ts		R.H(%)		P(mmHg)		E(g/m ² h)		Ts		R.H(%)		P(mmHg)		E(g/m ² h)	
	MEAN	S.D	MEAN	S.D	MEAN	S.D	MEAN	S.D	MEAN	S.D	MEAN	S.D	MEAN	S.D	MEAN	S.D	MEAN	S.D	MEAN	S.D	MEAN	S.D
	Ts		Ts		Ts		Ts		Ts		Ts		Ts		Ts		Ts		Ts		Ts	
Forehead	29.25	2.74	12.27	1.06	38.24	8.49	34.90	8.49	34.90	8.49	36.19	6.85	35.62	33.82	6.99	15.92	1.66	38.56	8.27	35.91		
Cheek	31.29	2.10	12.82	0.96	46.22	5.20	34.47	5.20	34.47	5.20	48.00	9.81	35.31	35.43	7.71	16.51	1.91	46.45	6.37	35.77		
Ant. neck	26.44	2.49	10.98	0.99	20.07	5.16	34.77	5.16	34.77	5.16	19.54	5.90	35.47	31.90	7.35	14.82	2.03	24.03	3.96	35.70		
Pst. neck	27.87	4.39	11.29	1.71	24.49	16.63	34.36	16.63	34.36	16.63	23.43	14.09	35.28	32.41	7.87	15.00	2.08	26.43	8.25	35.73		
Shoulder	27.11	3.07	10.95	1.20	13.53	4.21	34.25	4.21	34.25	4.21	13.80	4.71	35.08	32.45	7.21	15.06	2.02	18.21	5.91	35.60		
Chest	27.31	2.43	10.89	0.84	12.60	4.51	34.09	4.51	34.09	4.51	15.78	4.23	35.04	31.91	7.27	14.76	1.93	15.56	3.93	35.56		
Upp. back	28.12	2.84	10.95	1.08	12.49	4.63	33.71	4.63	33.71	4.63	14.96	3.49	34.77	32.91	8.29	14.84	2.29	15.46	4.23	35.25		
Breast	27.46	2.92	10.73	0.93	11.09	3.36	33.75	3.36	33.75	3.36	12.04	1.54	34.75	31.41	7.05	14.47	1.93	13.01	3.14	35.40		
Scapula	28.89	2.66	11.01	1.01	13.22	3.24	33.18	3.24	33.18	3.24	14.49	3.92	34.48	32.87	7.61	14.87	1.98	15.67	2.68	35.15		
Axilla	47.51	16.21	19.65	6.71	85.81	63.37	34.65	63.37	34.65	63.37	24.31	9.08	107.54	84.27	34.90	58.61	19.90	25.38	8.65	99.62	78.86	35.75
Upp. abdomen	27.42	2.42	10.58	0.83	10.04	4.08	33.57	4.08	33.57	4.08	12.93	3.66	34.71	32.46	8.20	14.82	2.35	16.57	11.41	35.35		
Centerback	28.97	2.85	11.09	1.05	13.79	5.13	33.54	5.13	33.54	5.13	14.93	4.76	34.51	33.09	7.78	14.84	1.99	15.47	3.20	35.18		
Abdomen	30.35	6.39	11.51	2.14	18.47	19.17	33.25	19.17	33.25	19.17	18.24	11.75	34.38	33.16	8.50	14.82	2.34	16.64	5.71	34.98		
Lat. abdomen	27.46	2.39	10.65	0.88	10.74	3.29	33.59	3.29	33.59	3.29	14.02	5.19	34.38	32.13	7.85	14.65	2.29	15.09	6.62	35.32		
Loin	29.58	2.72	11.13	0.99	13.90	5.25	33.03	5.25	33.03	5.25	15.09	3.43	34.61	33.46	7.95	14.82	1.86	15.30	4.52	34.80		
Ant. upp. arm	27.05	2.49	10.26	1.03	11.85	3.27	33.05	3.27	33.05	3.27	13.19	2.22	34.26	31.05	7.58	13.96	1.98	14.84	2.94	34.93		
Pst. upp. arm	29.64	2.39	10.26	1.04	11.82	3.76	31.41	3.76	31.41	3.76	13.52	3.52	34.23	32.04	7.70	14.06	1.97	16.30	4.47	34.57		
Ant. forearm	27.83	2.62	10.28	0.95	12.47	4.25	32.63	4.25	32.63	4.25	13.47	3.18	33.15	31.03	7.41	13.89	1.93	13.99	2.25	34.88		
Pst. forearm	28.68	2.92	10.40	0.97	14.43	4.51	32.36	4.51	32.36	4.51	15.35	4.15	33.88	31.85	7.49	14.13	1.89	17.84	3.42	34.85		
Palm	47.66	6.14	16.20	1.74	109.15	33.62	31.17	33.62	31.17	33.62	114.70	29.32	33.87	44.38	9.67	20.01	2.05	109.87	31.40	35.12		
Hand	33.20	3.12	11.16	0.79	27.16	6.18	31.00	6.18	31.00	6.18	30.67	7.96	33.49	33.98	8.15	15.23	2.16	35.01	8.82	35.06		
Inguinalis	30.10	2.77	10.68	0.86	10.94	3.79	32.08	3.79	32.08	3.79	14.35	6.33	33.33	33.79	8.58	14.70	2.14	15.49	6.49	34.50		
Buttock	34.11	2.95	11.72	0.99	21.05	6.48	31.48	6.48	31.48	6.48	24.58	7.20	33.75	40.51	13.73	17.01	3.91	36.50	27.48	34.03		
Ant. thigh	29.35	2.73	10.53	0.96	13.85	5.06	32.24	5.06	32.24	5.06	16.94	5.27	33.26	32.94	8.12	14.39	1.93	18.40	5.56	34.54		
Pst. thigh	29.47	2.76	10.49	0.96	13.39	5.17	32.11	5.17	32.11	5.17	17.56	5.64	33.83	34.20	8.85	14.67	2.16	22.06	7.58	34.25		
Ant. leg	29.37	2.98	10.36	0.96	12.35	3.67	31.89	3.67	31.89	3.67	15.15	3.69	33.52	32.91	8.18	14.21	1.90	16.98	8.31	34.38		
Pst. leg	30.26	2.84	10.47	0.95	13.86	5.47	31.55	5.47	31.55	5.47	17.55	5.38	33.54	33.67	8.46	14.46	2.04	20.38	4.83	34.25		
Foot	38.51	4.51	10.90	1.08	20.56	6.88	28.00	6.88	28.00	6.88	22.85	6.32	31.21	36.12	8.34	14.98	1.52	27.68	11.22	33.50		
Sole	48.73	7.04	13.89	1.13	61.72	17.95	27.55	17.95	27.55	17.95	78.86	26.55	32.50	49.91	5.83	20.63	2.40	101.80	28.73	34.63		
MEAN	31.34	3.69	11.52	1.27	24.11	9.17	32.68	9.17	32.68	9.17	27.23	9.80	34.18	35.05	8.47	15.58	2.32	29.63	10.71	35.00		
Weighted Mean					24.57	7.92	32.56	7.92	32.56	7.92	26.58	7.39	34.04					27.87	6.91	34.92		
Weight Loss					23.31	4.36					24.87	3.55						24.63	8.47			

Table 2-b. Relative humidity (R. H), vapour pressure (P), evaporation rate (E) and skin temperature (Ts) in sweating zone.

Regions	34°C										37°C									
	R. H(%)		P(mmHg)		E(g/m ² h)		Ts		R. H(%)		P(mmHg)		E(g/m ² h)		Ts		R. H(%)		P(mmHg)	
	MEAN	S.D	MEAN	S.D	MEAN	S.D	MEAN	S.D	MEAN	S.D	MEAN	S.D	MEAN	S.D	MEAN	S.D	MEAN	S.D	MEAN	S.D
Forehead	37.07	4.39	16.62	2.10	39.07	8.22	36.15	40.31	5.70	18.28	2.81	41.89	9.95	36.27						
Cheek	38.78	4.99	17.47	2.33	50.22	11.68	36.23	42.87	7.16	19.39	3.22	57.89	17.03	36.28						
Ant. neck	34.84	5.21	15.20	2.22	20.25	10.04	35.75	39.32	6.50	17.31	2.88	27.30	11.33	35.83						
Pst. neck	37.31	4.28	16.27	1.80	34.42	18.85	35.78	42.63	8.73	18.82	3.84	46.59	23.43	35.89						
Shoulder	35.41	5.21	15.47	2.27	15.88	7.26	35.70	41.32	10.69	18.32	4.60	28.29	20.69	35.95						
Chest	35.79	3.97	15.52	1.85	16.38	5.35	35.63	43.01	10.84	18.67	4.91	31.61	21.76	35.59						
Upp. back	41.77	7.04	17.39	2.29	31.21	18.98	35.05	48.78	13.64	20.63	5.61	47.35	28.54	35.16						
Breast	35.54	5.18	15.49	2.26	16.07	8.62	35.66	43.39	12.77	19.29	5.97	36.08	31.91	35.90						
Scapula	39.67	5.90	16.72	2.19	25.64	13.88	35.21	49.25	13.63	20.97	5.87	51.61	31.25	35.26						
Axillae	51.21	5.89	23.02	3.12	71.52	24.19	35.45	61.52	14.18	26.89	6.06	100.49	56.72	35.38						
Upp. abdomen	35.66	4.96	15.33	2.19	15.19	6.22	35.44	43.69	10.66	18.85	4.72	38.00	28.17	35.39						
Centerback	40.65	6.44	16.89	2.21	27.06	15.98	34.97	50.44	10.74	21.05	4.26	57.30	29.04	34.87						
Abdomen	39.89	5.75	16.99	2.54	30.26	13.67	35.19	45.94	13.32	19.74	5.74	42.99	31.17	35.36						
Lat. abdomen	40.81	8.93	17.35	3.88	33.61	25.25	35.40	45.01	11.47	19.55	5.02	43.86	26.64	35.55						
Loin	46.61	11.41	19.16	4.41	46.07	34.72	34.65	51.52	12.56	21.51	5.28	57.28	25.30	34.87						
Ant. upp. arm	34.24	4.72	14.71	2.03	15.99	7.60	35.36	39.05	7.66	17.21	3.43	28.58	21.92	35.81						
Pst. upp. arm	34.85	4.85	15.00	2.09	20.47	6.19	35.41	38.93	7.18	17.06	3.08	27.78	7.70	35.77						
Ant. forearm	34.43	4.87	14.70	2.04	16.27	9.37	35.25	40.65	8.33	17.76	3.76	39.25	24.05	35.67						
Pst. forearm	34.81	4.59	15.02	1.99	21.21	7.52	35.37	37.44	7.80	17.68	3.37	37.31	13.80	35.62						
Palm	43.02	3.59	18.83	1.77	81.00	11.61	35.55	46.22	5.83	20.91	2.76	95.37	23.62	36.25						
Hand	39.79	5.64	17.07	2.41	53.31	26.03	35.32	44.58	8.06	19.11	3.21	66.37	19.41	35.41						
Inguinalis	40.20	6.08	16.91	2.55	29.53	23.10	35.00	47.92	10.50	20.27	4.36	51.11	22.62	35.09						
Buttock	54.76	11.38	21.52	3.78	71.49	31.23	33.93	60.13	9.52	23.85	3.79	91.89	27.44	33.85						
Ant. thigh	38.86	6.23	16.24	2.48	33.97	22.01	34.89	48.13	8.19	20.21	3.55	68.69	23.94	34.91						
Pst. thigh	41.58	8.16	16.83	2.89	41.80	22.85	34.39	49.42	8.46	20.05	3.32	69.55	22.58	34.34						
Ant. leg	40.40	8.04	16.61	3.14	41.10	23.51	34.60	49.34	8.85	20.32	3.71	74.43	29.59	34.59						
Pst. leg	40.54	7.96	16.55	3.03	40.35	25.77	34.46	47.41	7.20	19.32	2.77	62.66	23.69	34.41						
Foot	39.52	7.21	16.68	3.20	42.07	22.56	34.78	45.16	7.10	19.68	3.26	66.08	19.41	35.54						
Sole	44.20	5.83	19.34	2.50	76.06	21.70	35.67	46.88	3.94	20.71	1.78	68.23	21.55	35.75						
MEAN	39.73	6.16	16.93	2.54	36.47	16.69	35.25	45.87	9.35	19.77	4.03	53.65	23.94	35.40						
Weighted Mean					36.10	11.09	35.16					55.67	10.36	35.29						
Weight Loss					42.26	8.71						56.36	9.38							

the whole body increased, especially, the centerback (57 g/m²h) and ant. forearm (39 g/m²h) conspicuously rose, but the distribution pattern did not change so much as shown by the order correlation coefficient ($r=0.86$) between 34 °C and 37 °C.

Individual differences of the evaporation rate

were examined by means of variation coefficient. In the insensible zone, the axilla, pst.neck, abdomen, upper abdomen and buttock showed a high variation coefficient over 0.5. In the sweating zone, the regions located on the lower part of the body and the posterior part of the trunk showed the coeffi-

Fig. 5-a Distributions of evaporation rate on the skin surface of the human body at 25 °C of air temperature.

Fig. 5-c Distributions of evaporation rate on skin surface of the human body at 31 °C of air temperature.

Fig. 5-b Distributions of evaporation rate on skin surface of the human body at 28 °C of air temperature.

Fig. 5-d Distributions of evaporation rate on skin surface of the human body at 34 °C of air temperature.

Fig. 5-e Distributions of evaporation rate on skin surface of the human body at 37 °C of air temperature.

Table 3. Regression equations between air temperature and regional evaporation rate both for insensible perspiration zone and for sweating zone and the intersection of two regression lines.

Measuring Point	25–31°C	34–37°C	Intersection
1 Forehead	$Y=36.2+0.05X$	$Y=7.1+0.94X$	(32.8, 37.9)
2 Cheek	$Y=45.8+0.04X$	$Y=-36.7+2.56X$	(32.8, 47.1)
3 Ant. neck	$Y=2.8+0.66X$	$Y=-59.6+2.35X$	(34.7, 21.8)
4 Pst. neck	$Y=15.8+0.32X$	$Y=-103.5+4.06X$	(31.9, 26.1)
5 Shoulder	$Y=-6.7+0.78X$	$Y=-124.8+4.14X$	(34.3, 17.2)
6 Chest	$Y=0.8+0.49X$	$Y=-156.3+5.08X$	(34.3, 17.8)
7 Upperback	$Y=0.4+0.50X$	$Y=-151.7+5.38X$	(31.2, 15.9)
8 Breast	$Y=3.1+0.32X$	$Y=-210.7+6.67X$	(33.7, 13.9)
9 Scapula	$Y=3.0+0.41X$	$Y=-268.6+8.66X$	(32.9, 16.5)
10 Axilla	$Y=111.6-0.56X$		
11 Upperabdomen	$Y=-17.0+1.09X$	$Y=-243.2+7.60X$	(34.7, 20.5)
12 Centerback	$Y=6.9+0.28X$	$Y=-315.7+10.08X$	(32.9, 16.1)
13 Abdomen	$Y=26.3-0.31X$	$Y=-114.0+4.24X$	(32.6, 24.4)
14 Lat. abdomen	$Y=-7.0+0.73X$	$X=-82.6+3.42X$	(30.8, 15.3)
15 Loin	$Y=8.2+0.23X$	$Y=-80.9+3.73X$	(35.5, 15.4)
16 Ant. upperarm	$Y=-0.7+0.50X$	$Y=-126.7+4.20X$	(34.5, 16.5)
17 Pst. upperarm	$Y=-7.0+0.75X$	$X=-62.3+2.43X$	(32.8, 17.4)
18 Ant. forearm	$Y=6.2+0.25X$	$Y=-244.1+7.66X$	(33.8, 14.8)
19 Pst. forearm	$Y=-0.0+0.57X$	$Y=-161.3+5.37X$	(33.6, 19.1)
20 Palm	$Y=165.3-2.04X$		
21 Hand	$Y=-5.7+1.31X$	$Y=-94.7+4.35X$	(29.2, 32.6)
22 Inguinalis	$Y=-7.6+0.76X$	$Y=-215.1+7.19X$	(32.2, 16.8)
23 Buttock	$Y=-44.7+2.58X$	$Y=-159.7+6.80X$	(30.4, 33.6)
24 Ant. thigh	$Y=-4.8+0.76X$	$Y=-359.5+11.57X$	(32.8, 20.0)
25 Pst. thigh	$Y=-22.8+1.44X$	$Y=-272.8+9.25X$	(32.0, 23.5)
26 Ant. leg	$Y=-6.8+0.77X$	$Y=-336.6+11.11X$	(31.9, 17.9)
27 Pst. leg	$Y=-13.2+1.09X$	$Y=-212.5+7.44X$	(31.4, 21.0)
28 Foot	$Y=-9.6+1.19X$	$Y=-230.1+8.01X$	(32.4, 28.9)
29 Sole	$Y=66.0+0.34X$		
30 Whole body	$Y=11.3+0.54X$	$Y=-117.6+4.63X$	(31.5, 28.2)

cients of over 0.5 at 34 °C, while the regions located on the trunk and anterior part of the upper extremity showed high coefficients at 37 °C. These results suggest that the individual difference of the evaporation rate in the sweating zone were large, both at 34 °C and at 37 °C, on the regions where the evaporation rates were in increasing phase.

5. Changes of regional evaporation rate with ambient temperature

In order to find out whether the linear relationship between the sweating rate and the environmental temperature could be organized and to find out the temperature at which the regional sweating occurred, the regression analysis was performed between the regional evaporation rate and the ambient temperature. The intersection of two regression equation lines, one of which was estimated for the insensible perspiration zone and the other for the sweating zone, should correspond to the ambient

temperature where sweating occurred. As shown in Table 3, the regression equation of the weighted mean evaporation rate of the whole body to the insensible zone was $Y = 11.27 + 0.54X$ and that to the sweating zone was $Y = 117.64 + 4.63X$. The ordinates of the intersection (31.5, 28.2) meant that the critical ambient temperature at which sweating occurred was about 31.5 °C and the average evaporation rate at the critical point was 28.2 g/m²h. Compared with this change of the mean evaporation rate of the whole body, the changes of the regional evaporation rate were characterized as follows (Fig. 6).

(1) Face

Both the cheek and the forehead showed evaporation rates (35-50 g/m²h) higher than the mean value in the insensible zone and showed only a small increase in the sweating zone as was indicated by the regression coefficients of 2.56 and 0.94. The changes with the air temperature was small in these regions.

Fig. 6-a Regression lines between air temperature and the regional evaporation rate on the face both for insensible perspiration zone and for sweating zone.

Fig. 6-c Regression lines between air temperature and the regional evaporation rate on the lower trunk both for insensible perspiration zone and for sweating zone.

Fig. 6-b Regression lines between air temperature and the regional evaporation rate on the upper trunk both for insensible perspiration zone and for sweating zone.

Fig. 6-d Regression lines between air temperature and the regional evaporation rate on the upper extremity both for insensible perspiration zone and for sweating zone.

Fig. 6-e Regression lines between air temperature and the regional evaporation rate on the lower extremity both for insensible perspiration zone and for sweating zone.

Fig. 6-f Changes of the regional evaporation rate on the axilla, palm and sole with air temperature.

(2) Neck and upper part of the trunk

The evaporation rates on any region of this part were lower than the mean value in both the insensible and the sensible zones. The regions except for the neck indicated low values of 14–20 g/m²h in the insensible zone, while the neck showed a little higher value of 20–26 g/m²h that was close to the mean value. The coordinates of the intersections of regression equations showed that the onset of sweat appeared at low temperatures on the upperback (31.2 °C), pst. neck (31.9 °C), centerback (32.9 °C) and scapula (32.9 °C) and that the sweating on the other regions such as ant. neck (34.7 °C) and chest (34.3 °C) occurred at high temperature. The former four regions all belonged to the back part of the trunk and the latter to the front part of the trunk. The back regions also showed higher regression coefficients (4.1–10.1) for the sweating zone than the front regions (2.3–7.6). At 37 °C, the evaporation rate on the back regions reached to 45–60 g/m²h, while those on the front remained at 20–40 g/m²h. It was concluded from these results that the back part of the neck and trunk was not only easy to sweat but full of sweat.

(3) Lower part of the trunk

In the insensible zone, the four regions except for the buttock showed almost the same evaporation rate (10–20 g/m²h). However, the value on the buttock was twice as high as those on the other regions. At 37 °C the values of the front regions, that

is, of the abdomen, lat.abdomen and inguinalis were lower than those of the back regions such as the loin and buttock. Sweating occurred at lower temperature on the back regions (30.5 °C) than on the front regions (32–32.5 °C). These relationships between the front and the back were similar to the result of the upper part of the trunk.

(4) Upper extremity

The regions on the arm indicated an evaporation rate lower than the mean value both in the insensible and in the sweating zones. The sweat onsets were at 33–34.5 °C, higher than those of the whole body. Both results suggested that the arm was hard to sweat and the amount of sweat from the arm was not so much. On the other hand, the evaporation rate on the hand was higher in any ambient temperature than the mean value and the onset temperature of the sweating (29.2 °C) was the lowest of all regions. The hand had the characteristics of a large amount of insensible perspiration, of most easily sweating and of a large amount of sweating.

(5) Lower extremity

The evaporation rates for these regions except for the foot were lower (10–15 g/m²h) than that of the whole body. The foot showed a little higher value of 20–25 g/m²h. The characteristics of these regions were shown in the sweating zone, that is, the powerful sweating. The regression coefficients for five regions in the sweating zone ranged from 7.4 to 11.6. The values were much higher than the mean

Fig. 7 The regression line for each mean evaporation rate in nine groups.

value of 4.6; especially the coefficient of the ant. thigh of 11.6 was the largest of all 29 regions.

(6) Palm, sole and axilla

The regression equations for these three regions could not be obtained. They showed no relationship with the ambient temperature. Evaporation from these three regions must be due to the insensible perspiration that is more of mental and emotional nature and not due to the sensible perspiration by thermal sweat.

As the results of the regression analysis it was concluded that each region on the human body had different characteristics of sweating in terms of the insensible perspiration level, the onset temperature of sweating and the sweating rate. The amount of the evaporation rate in the sweating zone had some relationship with the critical temperature of sweat onset. Grouping the regions from these relationships, the regions were classified into the following nine groups: (1) face, (2) front of upper trunk, (3) back of upper trunk, (4) front of lower trunk, (5) back of lower trunk, (6) arm, (7) thigh and leg, (8) hand and foot and (9) palm, sole and axilla. Fig. 7 shows the regression equation graphs recalculated for each nine groups. Among these regions, the front upper trunk and arm, the back upper trunk and front lower trunk showed almost the same tendency.

DISCUSSION

Measuring method

The methods of measuring the perspiration rate which have been used in previous investigations were the nonventilated capsule method, ventilated capsule methods by using many types of hygrometries, as well as the open air method by evaporimeter. The values obtained by these methods were compared with our data obtained. In the insensible zone, Ohara's values (1963) measured on the abdomen and the forearm at the air temperature of 25.2-26.2 °C on one subject by nonventilated method agreed well with our values. This may suggest that the absorption property of the filter paper located inside the nonventilated capsule was enough not to depress the insensible perspiration from the skin surface. Both the Spruit's data (1969) obtained from the dead skin on the back and the Goodman's data (1969) measured on the forearm and the chest by ventilated capsule were lower than our data. Evaporation rate from the dead skin may be less than those from the living subject. Goodman compared the insensible perspiration rates under different vapor pressure of the flow gas in the capsule, and he concluded that the insensible perspiration decreased with the increase of the vapor pressure of the flow gas in the capsule. Goodman, however, did not calibrate the measured data themselves with certain standard values such as the body weight loss. That could be the reason his value is

lower than ours. Lamke et al. (1971) measured the perspiration on the back, chest, arm and leg in the neutral temperature by a ventilated capsule and compared the data with the body weight loss and confirmed the reliability of the results. His data agreed well with ours. In comparison with the data obtained by the same open air method as ours, evaporimeter, Nilsson's data showed lower value than ours in general. It would be the reason that our data were corrected by the calibration equation as mentioned in the previous paper while his data were not. It would be concluded from the results that any type of capsules disturbed the natural conditions of the skin surface by only placing it on the skin and that the calibration of the results was the most important in using any methods. In the sweating zone, our data except for the abdomen agreed with the Herzman's data (1957) measured on 2 male subjects at 33 °C. Tam et al. (1976) also obtained the data on the palm and sole in the sweating zone. But since their results were obtained under transient conditions, the data could not be compared with ours. Difference in measuring method, that is, capsule-use or not, ventilated or non-ventilated in the capsule, would affect the skin surface conditions inside the capsule and also on the evaporation rate from the skin, especially in the sweating zone. In the sweating zone, after the sweat comes out as much as completely making the body surface wet, the sweat does not act effectively in cooling the body. Under this condition sweat gland activity is suppressed in some manner by water lying on the skin (Nadel and Stolwijk, 1973). This phenomenon was called hidromeiosis. Brown and Sargent (1965) and Ogawa (1976) noted that hidromeiosis was most often associated with a wet skin, and that the suppression of sweating could be reversed by exposing the wetted skin to a dry ambient, or by removing the wetted stratum corneum and also by rapidly rehydrating the sweating individual. Brown and Sargent theorized and Berglund and Gonzales (1977) also proposed that hidromeiosis is due to a mechanical

obstruction of the dermal pore, perhaps via the hydration of the keratin. Although it was expected that the evaporation rate was affected by a measuring method adopted especially by the humidity or the air flow conditions inside a capsule, this study was not able to confirm the above. Because there have been few comparative data measured under the same condition by different methods in the sweating zone, the comparison among the data could not be done satisfactorily. This study treated the evaporation rates from the skin surface in natural condition and it is not necessarily equal to the sweat rate on the skin. The coincidence of the results with Herzman's data is presumed that his ambient temperature was not so high and the evaporation rate was the same with the sweat rate at that temperature. It could not be confirmed whether or not hidromeiosis occurred at 37 °C in this study.

Distribution of evaporation rate over human body

The evaporation on the palm, sole and axilla was extremely high among the other regions in the insensible zone. The high insensible perspiration on the palm and the sole may be due to the special construction of the epidermis as well as the mental sweating on these regions as pointed out by Kuno. The insensible perspiration on the axilla was not only high but also of large individual difference. Above all, the results were much different from the results of others. This may be explained by the fact that sweating occurs on the axilla both mentally and thermally. Another explanation could be that with the fossa of the axilla usually closed by the upper arm, sweat would be difficult to evaporate freely from the axilla. This upper arm position might also affect the evaporation on the axilla, although the subjects were told to open the axilla by keeping the upper arm in abduction position about 3 minutes before the measurement by evaporimeter.

Even except for these three regions, the rate of evaporation was different from region to region.

The skin temperature could be one of the factors to induce the difference in regional evaporation in the insensible perspiration because the skin temperature would affect the vapor pressure on the skin surface. A correlation, however, was not admitted ($r=0.1-0.2$) between the evaporation rate and the skin temperature. Skin temperature might have little relationship to the distribution of the evaporation in the insensible zone. Another factor to the difference of regional evaporation would be the number of sweat glands as suggested by Goodman et al. (1969). According to Kuno (1956), there are a large number of sweat glands on the face, palm, sole, hand and loin, which happen to correspond to the regions which showed a high rate of evaporation in this study. The correlation between the number of sweat glands and the evaporation rate at 28 °C was significantly high ($r=0.74$). Our results supported the opinion of Goodman. In the sweating zone, the regional evaporation was large in the order of back lower trunk > hand > foot = leg > face > mean > back upper trunk = front lower trunk > arm = front upper trunk. As the factor contributing to these regional differences of the evaporation rate, Kuno pointed out the number of the actual sweat gland and the capacity of the individual gland. The correlation between regional evaporation except for the axilla at 37 °C and the number of sweat glands of Kuno's was positive ($r=0.28$) and the correlation between the capacity of the sweat gland and the evaporation rate was negative ($r=-0.29$). Neither was significant. The contribution of the capacity and the number of sweat glands was denied in the range of this condition. It may be effective at higher temperatures or under exercise conditions. The second factor for the amount of regional evaporation would be the skin temperature (Nadel and Bullard et al., 1971; McCaffrey et al., 1979; Ogawa et al., 1970). A sweat rate is controlled by a central integration of core and skin temperatures with an addition of the peripheral action of local skin temperature (Nadel and Bullard et al., 1971). Nadel and Bullard (1971)

pointed out that there was an inhibition of sweating corresponding to the decrease in the mean skin temperature for the lower body during lower body cooling. There was an increase in upper and lower body sweating, corresponding to the increase in the mean skin temperature of the lower body during lower body heating. After the lower body was heated, the sweat rate for the forearm increased, corresponding to the increase in the mean skin temperature of the lower body (McCaffrey et al., 1979; Werner and Heising, 1990). Ogawa (1970) also mentioned that the rate of local sweating induced by an intradermal injection of methacholine or acetylcholine was increased when the test area was heated. Furthermore, the increase of local sweating was greater with a higher initial sweat rate and with a greater rise in the skin temperature. In this study, however, a negative correlation between the evaporation rate and the skin temperature was obtained at 34 °C ($r=-0.48$) and at 37 °C ($r=-0.75$). This may relate to the evaporative latent heat. In the case of this study in which a steady state was treated and secreted sweat was able to evaporate freely through the evaporimeter under the low humidity condition, the effect of the evaporative latent heat would be greater than the effect of the skin temperature on the acceleration of the sweat secretion. Another factor contributing to the regional evaporation rate would be the pressure-sweating reflex by the skin pressure (Kuno, 1934; Takagi, 1950; Hasegawa, 1954; Nakayama, 1981; Ogawa et al., 1981; Tadaki et al., 1981; Nakayama, et al. 1987). It was demonstrated by many researchers that the rate of sweating was depressed by the skin pressure and the range of the depression relates to the pressed region. According to Nakayama et al. (1987), sweating on the thigh and leg was higher in a supine position than in the standing position, but the sweat rate on the arm did not change due to position. In our study the subjects lay in a supine or a prone position during the experiment. Our data showed that the onset of sweat

occurred at lower temperatures on the lower part of the body and the amount of evaporation on the lower body was also more than that on the upper body. In a standing position, the rate of sweating at the lower part of the body was depressed by the great pressure on the sole. In a supine or a prone posture, the pressure on the lower part of the body may be less than in a standing posture, and the depression of the sweat on the lower part of the body may be released. On the other hand, the upper part of the body was added the pressure in a supine or a prone posture and the sweat on the upper part of the body may be depressed. The sweat onset at lower temperatures and the larger evaporation rate on the lower part of the body resulted in this study might be due to those pressure-sweat response. It should be further examined how the distribution of evaporation changes between the supine posture and the standing posture.

Regional skin wettedness

The skin wettedness (w) represents the degree of wettedness of the whole body surface with sweat. The hypothesis that skin wettedness may be a major contributing factor to thermal comfort has been advanced by several investigators (Gagge et al., 1967; Berglund and Gonzales, 1977). If we interpreted w was the fraction of the wetted area to the total possible wetted area of the body, w would now be described as the percentage of the wetted skin surface. Nish and Gagge's equation (1970) for estimating w were as follows:

$$\text{Hemax} = hc \cdot 2.2 (P_s^* - P_a) \quad (\text{Kcal/m}^2\text{h}). \quad (2)$$

$$\text{He} = 0.58 \text{Esk} \quad (\text{Kcal/m}^2\text{h}) \quad (3)$$

$$w = \text{He} / \text{Hemax}. \quad (4)$$

where, Hemax: maximal evaporative heat loss from the saturated skin surface (Kcal/m²h)

hc: Convective heat transfer coefficient (Kcal/m²h°C)

2.2: Lewis' number (°C/mmHg)

P_s*: Saturated vapour pressure at the skin temperature (mmHg)

P_a: Ambient vapor pressure (mmHg)

He: Evaporative heat loss (Kcal/m²h)

Esk: Evaporation rate (g/m²h)

Usually these equations were used for the whole body. Through application of the equations to the regional data, an attempt was made to calculate the regional skin wettedness in each ambient temperature. As a result, w of the whole body were 0.076, 0.080, 0.080, 0.105 and 0.171 at 25 °C, 28 °C, 31 °C, 34 °C and 37 °C, respectively. In the insensible perspiration zone, w is known as about 0.06 (Mecheelet al., 1977). Our results (0.076 at 25 °C and 0.080 at 28 °C) nearly agreed with previous observations. The skin wettedness at 25 °C was 0.31 on the axilla, 0.27 on the palm, 0.22 on the sole and 0.10 on the cheek. The other areas indicated less than 0.1 of skin wettedness. With the air temperature rising to 31 °C, w on the buttock increased conspicuously but w at the other sites showed a little increase. At 34 °C, w remained less than 0.1 only on the front part of the trunk and the arm and w increased to the level of 0.10–0.31 at the other sites. On the other hand, the values of the axilla, palm and sole became lower. At 37 °C, the distribution of w was almost the same as at 34 °C but the level of w increased to 0.10–0.38. Here, the subjective comfort decreased with an increase of skin wettedness. The subjects still did not notice any dampness at 0.1. According to the results of the other project in our laboratory, the subjects began to feel dampness as the skin wettedness of the whole body became 0.2 or more. It is a matter for regret that the regional sensations for dampness were not examined in this study. It must be studied from now how the regional sensation for dampness is related with the regional skin wettedness.

In conclusion, the evaporimeter used in this study was useful in evaluating the regional evaporation rate in the natural condition if the calibration was performed by some standard values such as weight loss as well as the calibration according to the manufacturer's specification. The results obtained showed that the distributions of the regional evapo-

ration were common within the insensible perspiration zone, below 31 °C, and the dominant factor contributing to it was the number of regional sweat glands. The distributions of the evaporation in the sweating zone, above 31 °C were a little different from those in the insensible zone. The regional evaporation was large in the order of back lower trunk > hand > foot > leg > face > mean > back upper trunk > front lower trunk > arm > front upper trunk. These results were discussed in relation to the contributing factors such as the number and the capacity of the sweat gland and the regional skin temperature but neither were able to be ascertained because the skin temperature decreased by the evaporative latent heat. The pressure-sweat response accounted for the distribution of evaporation (lower trunk and legs > upper trunk and arms) and for the sweat onset. Further examinations on the effects of posture on the distribution of evaporation are needed in future together with the study on the effects of the regional distribution, skin wettedness of evaporation or on the comfort sensation.

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