The Thermal Manikin; a Useful and Effective Device for Evaluating Human Thermal Environments

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Abstract

Thermal manikin is a device, which simulates not only body shape but also human heat production and release. The device contributes to evaluate human heat transfer, thermal resistance of clothing, and protective tools for human safety with a high representativity. According to a study using the thermal manikin, for example, convective heat transfer from the human body has been found to be different in individual body location. The convective heat transfer coefficients in extremities are so larger than those in trunk and head that it is reasonable to put gloves on hands, e.g., to effectively protect the extremities from heat loss in a cold. In natural convection system, it has been experimentally confirmed through the thermal manikin that the convective heat transfer coefficient decreases with decrease in ambient pressure. Therefore, during exposure to a low ambient pressure, even if in a cold, temperature drop in skin surface can be suppressed because of the depressed sympathetic nerve activity and of the decrease in the convective heat transfer coefficient. A baby thermal manikin aged 0.5 year-old has been originally developed with aiming for infant's safety and thermal comfort. There is a significant difference in convective heat transfer in the whole body between infant and adult because of difference in height; the coefficient is larger in infant than in adult. The baby thermal manikin has been employed for measuring the thermal resistance of clothings for infant. An estimation equation by means of the total weight of the clothing for infant has been derived to obtain the thermal resistance, because a high correlation has been confirmed between them.

Keywords: Thermal manikin, Heat transfer, Body shape, Clothing, Infant

Introduction

Thermal manikin is one of a useful device for evaluating human thermal environments because it simulates precisely human heat production and release as well as body shape. So, it is as if a reliable partner for researchers in this field. In addition, the thermal manikin can provide us with benefits of high reproducibility, convenient use, time-saving and so on. However, equipped facilities with the thermal manikin are still not many in the world even though its scientific usability is widely recognized nowadays.

It is, therefore, very fortunate for our laboratory that, a thermal manikin named Eva as shown in Fig. 1 was installed at Kyushu University in 2001. Many research works were carried out extensively by

Fig. 1 Left: Thermal manikin named Eva, which can simulate not only body shape and posture but also human heat production and release. Right: Subjective experiment of the thermal responses and comfort, in which mostly naked male subject is stayed in a cold climate chamber with Eva.

employing it for evaluating heat transfer from human body or human thermal comfort in various environments (e.g., Fukazawa et al., 2009b and 2009c) and in vehicles (e.g., Yamashita et al., 2005) as well.

A large number of research works have been successfully made in our laboratory with voluntary participation of many young, elderly, female, and male subjects with the aim of improving human's health, safe, and comfortable life. On the other hand, we have been strongly interested in the studies on heat transfer from the body or on the thermal comfort of "infant" to assure his/her health and safety. This is because infant's behavioral thermoregulation fully depends not upon themselves but upon their parents and caregivers. It is, however, hard to make examinations with participation of an infant due to ethical restrictions. Therefore, our laboratory has been challenging to develop a baby thermal manikin, which enables us to evaluate infant's thermal environments.

The challenge began in 1998. And in 2005, a baby thermal manikin was completed, as shown in Fig. 2, owing to collaborative efforts of our laboratory members, foreign colleagues, and a Japanese company. The originally developed thermal manikin highly promotes our research works especially in evaluating thermal environments for infant. As evidence, one of our research works using the baby thermal manikin received a prize in the 11th International Conference on Environmental Ergonomics in 2005. This indicates the obtained findings through the works using the baby thermal manikin were recognized to be considerably effective for designing infant's safety and health in life. In the present paper, our findings obtained through research works using the thermal manikin of Eva and the baby one are introduced.

Fig. 2 Left: Originally-developed baby thermal manikin, which simulates shape of 0.5 year-old Japanese infant as well as heat production and release, and Prof. Dr. I Holmér (Lund University, Sweden), a key-person of the developing team. Many researchers and technicians have engaged in the achievement through several years. Right: One of pilot types of the baby thermal manikin made by our laboratory members, Mr. Nonaka and Mr. Nomura, both of who were graduate students at Kyushu University.

Heat transfer from human body

General and local heat transfer from the body

Heat balance between the body and its environment should be maintained during exposure to various environments, because the internal temperature of the human body must be kept at around 37 °C. There are two types of heat transfer from human body; sensible and latent heat transfers. Sensible heat transfer consists of 3 pathways, which are conduction, convection, and radiation.

In Fig. 3, heat transfer coefficients by radiation and by convection including conduction are shown, whose data were obtained through measurement with the thermal manikin. There was no a significant difference in the radiative heat transfer coefficient between locations. On the other hand, local difference was found to be significant in the convective heat transfer coefficient. The convective heat transfer coefficients were larger in the extremities than those in the front and back trunk. That is, clothes on the extremities like gloves on hands can reduce heat loss effectively in the cold, and thus clothes on the extremities can be an effective barrier for the heat release in the cold. On the other hand, in the hot, clothes on the extremities become an unfavorable barrier because of the reduced heat release.

Combined effects of temperature and ambient pressure on heat transfer from the body

When we are exposed to warm or hot environment in which atmospheric temperature is higher than our skin surface temperature, the body sweats in order to increase evaporative heat flux. That is, in such environment, heat balance in the human depends upon the latent heat transfer. On the other hand, if a resting human is exposed to an environment whose temperature is lower than his/her skin surface one, surface temperature drop is seen due to the vasoconstriction in order to decrease sensible heat release. This is because the sensible heat flux is determined by temperature

Fig. 3 Convective and radiative heat transfer coefficients from the whole body and individual location. Data were obtained using the thermal manikin of Eva.

difference between the skin surface and the environment and also by the heat transfer coefficient. That means that, in the cold environment, heat transfer from the human body depends mainly upon the sensible heat transfer.

Figure 4 shows mean skin surface temperature during exposure to a cold regulated at 17 °C. When human was exposed to the cold environment with its pressure equivalent to the sea level (Sea level in the figure), the mean skin surface temperature largely decreased by 27.5 °C. This is because, as mentioned above, vasoconstriction took place due to the increase in activity of sympathetic nerve to diminish heat loss from the human body in the cold environment. On other hand, when human was exposed to the cold with a low atmospheric pressure, equivalent to 5,000 m of altitude (Altitude in the figure), the mean skin surface temperature did not decrease so much as at sea level.

This was because the activity of sympathetic nerve was depressed due to hypoxic exposure. It was

Fig. 4 Mean skin surface temperature during exposure to the cold environment at 1 atm (sea level) and at 0.55 atm (altitude: equivalent to an elevation of 5,000 m). The mean skin temperature showed significantly higher value in the altitude than in the sea level. **: $p < 0.01$

Fig. 5 Rectal temperature during exposure to the sea level and the altitude. No significant difference was observed between the two conditions in the rectal temperature.

Fig. 6 Dependence of the convective thermal resistance from the body surface to the environment on atmospheric pressure. Experimental data was obtained through measurements using the thermal manikin (Fukazawa et al., 2003).

interesting that no significant difference between the sea level and the altitude was seen in the rectal temperature as shown in Fig. 5, even though a significant difference was found in temperature difference between the skin surface and the environment.

Dependence of the thermal resistance by convection upon the ambient pressure was experimentally and theoretically examined by means of the thermal manikin. As seen in Fig. 6, the convective thermal resistance was found to be 0.13 m²K/W at the sea level and 0.17 m²K/W at the altitude. The convective thermal resistance increases with the increasing altitude, because the kinematic viscosity of air increases due to the decrease in its density with the elevation. This increase in the convective thermal resistance is one of the reasons why the rectal temperature at the altitude indicated almost the same value as at the sea level despite of the larger temperature difference between the skin surface and the environment.

Evaluation of thermal resistance of clothing system to estimate adaptable climate by clothing

It can be noted that clothing is one of the indispensable tools for our daily life, because in human heat balance, adaptable environment can be effectively extended by behavioral thermoregulation rather than by autonomic one. In another word, human is able to precisely adapt various environments through behavioral thermoregulation such as clothing behavior. It is, therefore, important for our life to understand thermal property of clothing by mean of a convenient device such as thermal manikin. The thermal manikin, Eva, wearing three different traditional clothings is shown in Fig. 7.

In addition, if the thermal resistance of clothing system is known, adaptable climate by its clothing system can be estimated through an equation derived by Mecheel and Umbach (Tamura, 2004).

$$T_a = T_{sk} - R_f \left(q - \frac{w(p_{sk}^* - p_a)}{R_e} \right) \quad (1)$$

where,

q : heat flux released from the body surface (W/m²)

p_a : ambient water vapour pressure (mmHg)

P_{sk}^* : saturated water vapour pressure at mean skin surface temperature, T_{sk} (mmHg)

w : skin wettedness (-)

R_f : over-all thermal resistance in the clothing system (m²K/W)

R_e : over-all water vapour resistance in the clothing system (m²•mmHg/W)

T_a : ambient temperature (K)

T_{sk} : mean skin surface temperature (K)

Figure 8 shows the estimated adaptable climate range for three traditional clothings as shown in the

Fig. 7 Three types of traditional clothing for female were selected to evaluate thermal resistance using thermal manikin, Eva. Left: Kanga, traditional clothing in Kenya. Center: Merry blouse, traditional clothing of Papua New Guinea, Right: Yukata, Japanese traditional clothing for summer.

Fig. 8 Adaptable climatic thermal comfort zones in wearing the traditional clothing of Kanga (Kenya), Merry blouse (Papua New Guinea), and Yukata (Japan).

previous figure. The adaptable climate range reasonably explains the clothing which enables human to live in a climate. For example, traditional clothing of Japan, Yukata, is indeed available for the summer and that of Papua New Guinea, Merry blouse, fits to its environment of high temperature and humidity. Therefore, it can be noticed that the usage of the thermal manikin is indeed effective for evaluating or designing clothing system in terms of comfort and safety.

Evaluation of thermal environments in infant Heat transfer from infant's body differs that from adult's one

It is well known that, for human, a ratio of body surface area to its mass affects on heat exchange. The ratio of baby is remarkably so larger than that of adult that thermal stress in the baby would be significantly larger than that in the adult if they are exposed to the same environment (e.g., Belghazi et al., 2005). Since the heat transfer from the body surface substantially influences the heat exchange, the heat transfer property in the adult has been well investigated in terms of effects of its location (Ichimura et al., 1997) and posture (e.g., Nishi and Gagge, 1970) or body shape (e.g., Kuklane et al., 2004). On the other hand, the heat transfer property in the baby has been less examined. The developed baby thermal manikin has promoted the accumulation of the fundamental data on the heat transfer from the baby's body surface as mentioned below.

Figure 9 indicates radiant (h_r , (W/m²K)) and convective (h_c , (W/m²K)) heat transfer coefficients in the whole body for the baby during standing posture. The coefficients obtained from the adult thermal manikin of Eva are also plotted in the same figure. All the heat transfer coefficients were results from measurements under the same condition whose environment was constantly regulated at 25 °C and 50 %RH with an air velocity of 0.2 m/s. As seen in the Fig. 9, while the

Fig. 9 General convective (h_c) and radiant (h_r) heat transfer coefficients measured using the baby and the adult thermal manikins. Asterisk indicates significance level of t-test; *: $p < 0.05$ and ***: $p < 0.001$.

Fig. 10 Local convective heat transfer coefficients in the whole body for the baby and the adult thermal manikins. Symbols of the asterisk means significant difference of t-test analysis between the two manikins in each location. *: $p < 0.05$, **: $p < 0.01$

radiant heat transfer coefficient in the baby was found to be statistically slightly larger than that in the adult, the convective heat transfer coefficient in the baby was found to be remarkably larger than that in the adult. There was a strong tendency that local convective heat transfer coefficients for the baby indicate larger rates than those for the adult as shown in the Fig. 10. These results suggest the released heat flux from the body becomes larger in the baby than in the adult if their skin surface temperatures show the same level during exposure to the same cold environment.

In the study, the thermal manikins of the baby and the adult is treated as cylinders of 0.16 m and 0.28 m in diameter, respectively. The heat transfer from a cylinder is similar to that from a vertical flat plate, if diameter of the cylinder is exceedingly larger than thickness of the boundary air layer formed over the cylinder itself (Holman, 1997). The theoretical convective heat transfer coefficients in the whole body can be obtained for both the thermal manikins through relation between Nusselt (Nu , (-)) and Rayleigh numbers (Ra , (-)) expressed as Eqs. 3 and 4. The Ra is calculated as 2.9×10^3 for the baby and as 6.4×10^4 for the adult according to Eq. 2.

$$Ra = \frac{g\beta L^3 (T_{sk} - T_e)}{\nu^2} \cdot Pr \quad (2)$$

$$Nu = 0.59 Ra^{1/4} \quad (3)$$

$$h_c = \frac{Nu \cdot \lambda}{L} \quad (4)$$

where,

g : acceleration of gravity (m/s^2)

β : coefficient of volume expansion ($1/K$)

L : height of the thermal manikin (m)

ν : kinematic viscosity of air (m^2/s)

Pr : Prandtl number of air (-)

λ : thermal conductivity of air (W/mK)

The Nu increases with the height, L , to the power of 0.75, because the Ra increases the 3rd power of the manikin's height as seen in the Eq. 2. Therefore, the convective heat transfer coefficient increases with the increasing height to the power of -0.25. That is, convective heat transfer coefficient becomes large for the smaller one than for the taller. This is the reason why the experimented convective heat transfer coefficient showed a larger rate in the baby than that in the adult.

Figure 10 indicates local convective heat transfer coefficient of each region for the whole body. Since there is indeed the effect of height upon the convection as mentioned above, local differences in the heat transfer coefficient are found to be significant in the whole body as shown in Fig. 10.

Evaluation of thermal resistances of clothing ensembles for infant

There are significant differences in physiological thermal responses between infants/children and adults. If children are exposed to warm or hot environment, their body surface temperature goes up. An especially remarkable temperature rise can be seen in head and in trunk, due to considerable increase in their cutaneous blood flow rate (Inoue, 2004; Hirata, 2002; Tsuzuki, 1998). This is because their secreted sweat rate per a sweat gland is quite smaller than the adults. That is, their heat balance mainly depends upon the sensible heat transfer.

Behavioral thermoregulation in infant is controlled by the thermal sensation of his/her parents' or caregivers' (Araki et al., 1981) despite that there exist significant differences between infant and adult in heat transfer from the body and in physiological thermal responses as mentioned above. It has also been pointed out that clothing selected by the parents or the caregivers enhances risk of thermal stress in infant (Mitsumatsu

Fig. 11 Some of tested clothing ensembles for summer, autumn, and winter. All the tested clothing ensembles were selected based on our previous investigation (Fukazawa et al., 2009a).

et al., 1999; Yamana et al., 1987). So, thermal resistances of clothing ensembles for infant have examined to obtain helpful data for designing appropriate clothing system for infant by means of the developed baby thermal manikin.

In the examination, 30 types of clothing ensembles for infant were selected based on our previous investigation (Fukazawa et al., 2009a); 10 ensembles each were for summer, autumn, and winter, respectively as seen in Fig. 11. Their measured thermal resistances expressed in I_{cl} (clo) are shown in Fig. 12. The tested 10 clothing ensembles indicated the I_{cl} ranged from 0.25 clo to 0.46 clo in the summer and from 0.39 clo to 0.66 clo in the autumn. Remarkable difference was not found in the I_{cl} between for the summer and for the autumn. On the other hand, the clothing ensembles have the higher I_{cl} in the winter, which were rate of more than 1.5 clo.

McCullough et al. (1985) derived an equation, which enables us to obtain thermal resistance of clothing ensemble for adult without using the thermal

Fig. 12 Thermal resistances of the tested clothing ensembles for infant. Horizontal axis: Numbers are ID of the ensembles for each season. Air (left end) is the thermal resistance of boundary air layer (typical value).

Fig. 13 Thermal resistance of the clothing ensemble increases with the increasing total weight itself.

manikin measurement. The estimation requires several parameters such as ratio of covered area with clothing to the whole body and thickness of the clothing. Much more simple equation has been produced to estimate thermal resistance of clothing ensemble for adult by Tamura (2004), in which required parameter is total weight of the clothing ensemble only due to a good correlation. As shown in Fig. 13, there was also a high correlation between the thermal resistance of the ensembles for infant and its total weight. The thermal resistance of the clothing ensemble increased with increase in the total weight, W (kg). Its correlation can be expressed by Eq. 5 because of a high correlation coefficient of $r = 0.94$ ($p < 0.001$). It should be remembered that its validity is confirmed by weight of 0.65 kg.

$$I_{cl} = 3.83 \cdot W \quad (5)$$

In the case of estimating thermal resistance of clothing ensemble as a function of its total weight, the coefficient for infant is 3.83, while that for adult is 0.57 referring to Tamura (2004). This large difference in the coefficient between infant and adult is because of the difference in body surface area.

Required thermal resistance of clothing ensemble for infant

Required thermal resistance of clothing ensemble for infant was calculated and presented by a solid line in Fig. 14. In the calculation, heat production was set at 68 W/m^2 as resting infant. Note that the heat production during rest is normally 1.2 times larger than the basal metabolic rate of 54 W/m^2 (Tochihara, 2007; Sato, 1992). Evaporated heat loss from infant's body surface

Fig. 14 Solid line indicates required thermal resistance of clothing ensemble for infant plotted against environmental temperature. Symbol shows estimated thermal resistance of the tested seasonal clothing ensembles. Estimation is made by Eq. 5, whose data of total weight, W , are quoted from our investigation on the clothing behavior (Fukazawa et al., 2009a).

was set 12 % of the heat production (Fukazawa et al., 2009a). For heat transfer from the body surface, heat transfer coefficient were 5.4 W/m²K by convection and 5.7 W/m²K by radiation (Fukazawa et al., 2009a). Figure 14 indicates that, when infant is in environment of 10 °C or 20 °C, he/she requires clothing ensemble of about 2 clo or 1 clo, respectively. On the other hand, when infant is in environment of around 29 °C and above, no clothing ensemble is required from view point of the thermoregulation.

The thermal resistances of the observed clothing behavior in each season (Fukazawa et al., 2009a) are also plotted against the actual environmental temperature in the Fig. 14, in which the resistance was calculated using Eq. 5. As expressed by the empty symbol, the actually worn clothing ensembles by infant indicated the thermal resistance of 0.53 clo to 0.81 clo in the summer, whose observed ambient temperature was from 25.6 °C to 32.4 °C. Accordingly, these estimated thermal resistances of the ensembles were larger than the required one. This clothing behavior must be due to prevent their body from the excessive solar radiation. In the autumn, the employed clothing ensemble indicated also larger thermal resistance to the required one as expressed by the gray symbol. In the winter, the required infant's clothing ensemble is thermal resistance of 0.8 clo to 1.8 clo corresponding to the atmospheric temperature of 12 °C to 21 °C. However, as expressed by the filled symbol, clothing ensembles worn actually by infant ranged more or less larger thermal resistance than the required one. This means that the parents or the caregivers tend to put too much ensemble on their infants.

Conclusion

In the present paper, some of our research works using the thermal manikins are introduced. It can be stressed that data obtained by measurement using the thermal manikin indeed helps us to evaluate effect of environment on the human heat transfer on a firm experimental and analytical basis to improve our daily life in terms of safety and thermal comfort, although the human subjective measurement is also still indispensable. In addition, heat transfer property of ordinal objects like clothes, chairs and beddings, can be evaluated precisely through measurements using the thermal manikin. Finally, we would emphasize that the thermal manikin is an effective device and a reliable research partner for evaluating human thermal environment.

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