CONVECTIVE HEAT TRANSFER COEFFICIENT FROM BABY IS SMALLER THAN THAT FROM ADULT

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INTRODUCTION

Thermal stress becomes larger in the baby than in the adult, when they are exposed in a cold environment (Belghazi et al., 2005). This is because heat exchange in the baby is larger than in the adult due to the larger ratio of body surface area to body mass. Heat transfer form the body is also one of important factors to determine the level of the body heat exchange. Therefore, distribution of heat transfer coefficient in the adult has been well investigated through experiments using human subjects and thermal manikins in terms of effects of posture (e.g., Nishi and Gagge, 1970) or body shape (e.g., Kuklane et al., 2004). On the other hand, heat transfer property in the baby has been less discussed experimentally because of ethical matters. Therefore, in order to assess heat transfer property from the baby's body, we have developed a baby thermal manikin, which can simulate not only its shape but also heat energy production as same as baby aged in 6 months (Fukazawa et al., 2005). In this study, we aimed to obtain fundamental data about heat transfer property in the baby to contribute for thermal physiology and comfort in the baby.

METHODS

Heat transfer from the body surface was investigated employing two types of thermal manikins; one of which is shaped female adult with height of about 168 cm (hereafter, Adult) and the other one is shaped baby aged in 6 month with height of 65 cm (hereafter, Baby). The adult thermal manikin consists of 20 segments with flexible joints, while the baby one consists of 8 segments with fixed joints. In the study, both the manikins' body surfaces were coordinated into 5 locations of head, front and back torso, and upper and lower limb, because there is a difference in segmented number between the employed Adult and the Baby thermal manikins. Table 1 shows that each local surface area and its ratio to the whole body.

Table 1 Surface areas of the adult and baby thermal manikins

Location	Body surface area (m^2)		Local body area ratio (%)	
	Adult	Baby	Adult	Baby
Whole body	1.459	0.311	100.0	100.0
Head	0.106	0.058	7.3	18.7
Front torso	0.195	0.049	13.4	15.8
Back torso	0.240	0.033	16.4	10.5
Upper limb	0.326	0.056	22.3	18.1
Lower limb	0.592	0.115	40.6	36.9

The measurement was conducted in a climate chamber, whose condition was regulated at 25.0 ± 0.1 °C and 50.0 ± 0.2 %RH with an air velocity of 0.2 ± 0.1 $m \cdot s^{-1}$. Wall temperature inside of the climate chamber was also equal to the environmental one. In order to eliminate radiative heat transfer between the two manikins, the measurement using each manikin was performed in different session. A standing posture facing to the stream was employed in the study to compare the heat transfer due to body size, especially height. During the experiment, surface temperatures in all the segments were constantly maintained at 34 °C in both the Adult and the Baby. The temperatures of the surface and environment and given heat energy to the manikin were continuously recorded in a PC during the whole period of the measurement.

When wall temperature (T_r in K) is equal to the environmental one, released heat flux (q in $W \cdot m^{-2}$) from the body surface can be expressed the following equations by;

$$q = h(T_{sk} - T_e) \qquad (1)$$

$$h = h_c + h_r \qquad (2)$$

where

h: overall heat transfer coefficient ($W \cdot m^{-2}K^{-1}$)

h_r: radiative heat transfer coefficient ($W \cdot m^{-2}K^{-1}$)

h_c: convective heat transfer coefficient ($W \cdot m^{-2}K^{-1}$)

T_{sk}: surface temperature (K)

T_e: environmental temperature (K).

In the present study, T_r and T_e were kept at the same level. Thus, h can be simply calculated through Eq 1 using the obtained data. In addition, according to ASHRAE (1997), h_r can be obtained from Eq 3,

$$h_r = 4\varepsilon\sigma \frac{A_r}{A_D}\left(\frac{T_{sk} - T_e}{2}\right)^3 . \qquad (3)$$

where

ε: emissivity (-)

σ : Stefan-Boltzmann constant (5.67×10^{-8} $W \cdot m^{-2}K^{-4}$)

A_r: effective radiation area in the body (m^2)

A_D: body surface area (m^2)

In order to obtain h_r for both the standing thermal manikins, employed ratio of effective radiative body surface area (A_r/A_D) and ε in Eq 3 were 0.87 and 0.95, respectively, which were quoted from Yang et al's paper (2004).

Student's *t*-test is employed for comparison the heat transfer coefficients in the whole body and in each location between the Baby and the Adult manikins. A significance of 0.10 is used to establish a statistical difference in the study.

RESULTS AND DISCUSSION

Radiant heat transfer coefficients (h_r) in the whole body are 5.23 ± 0.00 $W \cdot m^{-2}K^{-2}$ for the Adult and 5.09 ± 0.02 $W \cdot m^{-2}K^{-2}$ for the Baby. These values are almost the same. According to the statistical analysis of *t*-test, a significant difference is, however, seen between the two manikins due to quite small standard deviation in each manikin ($p < 0.001$). The radiant heat transfer coefficient in each location is almost the same of the whole body.

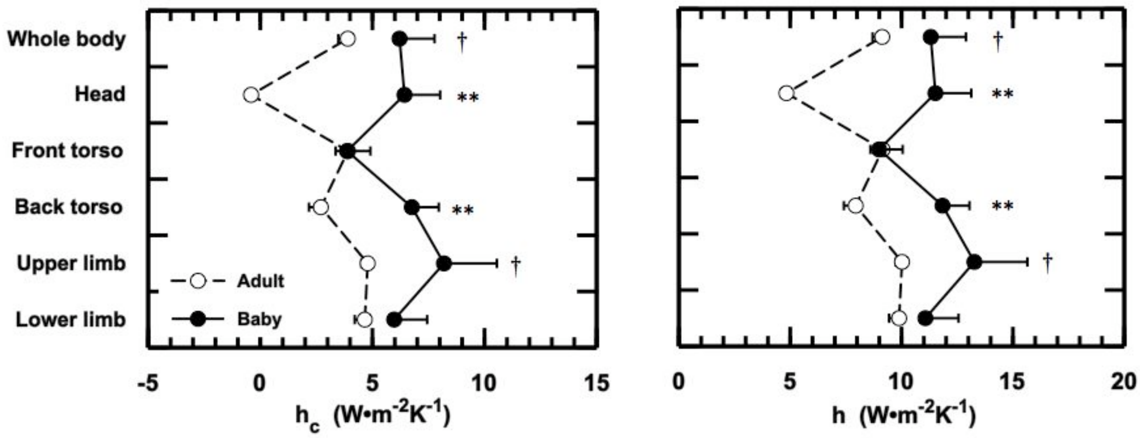

Figure 1 Convective (h_c) and over-all heat transfer coefficients (h) in the whole body and the individual location for the Baby and the Adult manikins. Symbols of ** and † indicate significant differences of *t*-test results between the manikins less than significances of 0.01 and 0.10, respectively.

Convective heat transfer coefficients (h_c) of the whole body and the individual location are shown in Figure 1 (left). The coefficient in the whole body for the Adult shows 3.9 W·m^{-2}K^{-2}, while that for the Baby indicates 6.2 W·m^{-2}K^{-2}. According to statistical analysis, there is a strong tendency to be large in h_c for the Baby compare to the Adult due to significance less than 0.10 († in Figure 1). No differences are observed between the Adult and the Baby in the local h_cs of the front torso and the lower limb. On the other hand, similar results in the h are obtained in the local h_cs of the head, the torso back, and the upper limb with high significancies ($p < 0.01$, ** in Figure 1).

Overall heat transfer coefficient in the whole body and in each location, h, can be obtained by sum of h_r and h_c as expressed as Eq 2. Therefore, same results of statistical analysis are obtained in the h of the whole body and of the individual locations as seen in Figure 1 (right).

When the Adult and the Baby manikins can be considered as cylinders, whose diameters are 0.28 m and 0.16 m, respectively. If the thickness of the boundary air layer formed on surface is small enough compared with the diameter of the manikin, the heat transfer of the whole body can be discussed using the same relations used for vertical flat plates (Holman, 1997). In that case, Rayleigh numbers (*Ra*, dimensionless) become 6.4x10^4 for the Adult and 2.9x10^3 for the Baby using the following Eq.

$$Ra = \frac{g\beta L^3\left(T_{sk} - T_e\right)}{\nu^2} \cdot Pr \qquad (4)$$

where
g: acceleration of gravity (9.8 m·s^{-2})
β: volume coefficient of expansion (K^{-1})
L: height of the manikin (m)
ν: kinematic viscosity of air (m^2·s^{-1})
Pr: Prandtl number of air (dimensionless)

Therefore, the h_c of the whole body can be expressed by the relation using Nusselt number (*Nu*, dimensionless) and the *Ra* as:

$$Nu = 0.59 Ra^{0.25} \quad (5)$$

$$h_c = \frac{Nu \cdot \lambda}{L} \quad (6)$$

where

λ : thermal conductivity of air ($W \cdot m^{-1} K^{-1}$).

Through the Eq 4, the *Ra* increases the 3rd power of the manikin's height. Therefore, the *Nu* increases with the height to the power of 0.75. Accordingly, the convective heat transfer coefficient becomes large with the height to the power of -0.25. This is the reason why the h_c in the whole body showed a larger value in the Baby compared to the one in the Adult.

In the case of the present study, the h_c of the Baby can be estimated to be 1.3 times larger than that of the Adult, because of their height difference. However, the resulted ratio through the experiment for the Baby showed 1.6 times larger than for the Adult. This difference between the theoretical and experimental values would be due to an effect of uneven body shape.

The Adult wore a wig on the head in all the measurements, while the Baby did not. That was the reason why the h_c in the head of the Adult showed remarkably smaller value than that of the Baby. Accordingly, this result reflected in the *h* in the head.

No difference was seen in the h_c in the front torso between the Adult and the Baby, even though the thickness of the boundary air layer increases with height. This was because, for the Adult, the boundary air layer separated from the body surface at the chest because of the breasts.

CONCLUSIONS

The present study showed that difference in the convective heat transfer coefficient between the Adult and the Baby. The convective heat transfer of the Adult was smaller than that of the Baby. This difference was mainly due to difference in *Ra*, because the boundary air layer over the surface of the manikin becomes thicker with increasing the height.

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