Effective Thermal Insulation of Body Segments by Summer Clothing

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SUMMARY

The aim of this study is to create a database of the effective thermal insulation provided to the body segments by various types of summer clothing (R_{clei}). In a climatic chamber with calm air conditions ($v \leq 0.15$ m/s), R_{clei} was obtained for 52 garments and 97 ensembles. In the measurements, a female thermal manikin that had twenty segments was arranged in a sitting posture. In the chamber, operative temperature was set to 27.0°C, 25.0°C, and 24.0°C for a nude manikin, a manikin clothed in a garment, and one clothed in an ensemble, respectively. R_{clei} were calculated for the nine segments—the chest, back, abdomen, buttock, upper arms, forearms, thighs, legs, and feet. The common regression for all the body segments, $R_{clei.en} = 0.784\ \Sigma R_{clei.gr}$, was proposed for estimating the R_{clei} for the ensembles ($R_{clei.en}$) from the sum of the components' R_{clei} ($\Sigma R_{clei.gr}$).

INTRODUCTION

In order to use human thermal models with multiple segments, it is essential to obtain data on the thermal insulation provided to each body segment by a type of clothing. In previous studies [1, 2, 3, 4], these data were measured for several ensembles. However, the authors were unable to find the sufficient database for estimating the thermal insulation provided by various types of clothing. The aim of this study is to create a database of the effective thermal insulation provided to body segments by various types of summer clothing (R_{clei}).

METHODS

In order to express the thermal insulation of a clothing, three kinds of insulation—total insulation (I_T), intrinsic insulation (I_{cl}), and effective insulation (I_{cle})—are used [5] [NOTE1]. For expressing the thermal characteristics of a clothing, the usage of I_{cl} is recommended [5, 6] since it is the actual thermal resistance for a temperature difference between the skin and clothing surface. However, it has the following characteristics. (1) I_{cl} for the same clothing changes depending on the airflow around the human body and the body motions. (2) At present, it is difficult to set adequate heat transfer characteristics for the clothing surfaces in each segment. Considering these characteristics and the intended application of the clothing thermal insulation data on the various body segments as an input to the human thermal models with multiple segments, the use of I_{cl} instead of I_{cle} is considered to be less advantageous. Therefore, the present authors have described the clothing thermal insulation in terms of the effective thermal insulation.

In a climatic chamber with calm air conditions ($v \leq 0.15$ m/s), the effective thermal insulation of the body segment i, denoted by (R_{clei}) [1], was measured for summer clothing garments and ensembles. $R_{cle\mathrm{i}}$ is the hypothetical thermal resistance that expresses the effect of the addition/removal of clothing. It is calculated as follows.

$$\begin{aligned} R_{cle\mathrm{i}} &= R_{dress\mathrm{i}} - R_{nude\mathrm{i}} \\ &= \frac{Q_{dress\mathrm{i}}}{Tsk_{dress\mathrm{i}} - To_{dress\mathrm{i}}} - \frac{Q_{nude\mathrm{i}}}{Tsk_{nude\mathrm{i}} - To_{nude\mathrm{i}}}, \end{aligned} \tag{1}$$

where R is the total thermal resistance [m^{2o}C/W]; Q, sensible heat loss [W/m^2]; Tsk, skin temperature [ºC]; and To, operative temperature [ºC]. The suffixes are as follows: *dress*i is the value for segment i when the body is clothed and *nude*i is the value for segment i when the body is not clothed.

With regard to the thermal insulation for the overall body, all total insulations are calculated by the global method [7] from the data on the segments. Then, the effective thermal insulation I_{cle} is calculated as follows.

$$\begin{aligned} I_{cle} &= I_T - I_a \\ &= \frac{\sum\left(Q_{dress\mathrm{i}} \cdot W_\mathrm{i}\right)}{0.155\sum\left[\left(Tsk_{dress\mathrm{i}} - To_{dress\mathrm{i}}\right)\cdot W_\mathrm{i}\right]} - \frac{\sum\left(Q_{nude\mathrm{i}} \cdot W_\mathrm{i}\right)}{0.155\sum\left[\left(Tsk_{nude\mathrm{i}} - To_{nude\mathrm{i}}\right)\cdot W_\mathrm{i}\right]}, \end{aligned} \tag{2}$$

where I_a is the total thermal insulation when the body is not clothed [clo], and W_i is the weighting coefficient for the data on segment i that is set in accordance with area ratio [N.D.].

Table 1 Summary of garments (example)

Symbol	Product	Weight [g]	Material† [%]	Color
UW1	Short	79	C: 100	Blue
UW2	Panty	29	C: 100	Skin color
UW3	Brassiere	37	C: 100	Skin color
UW6	Socks (middle length)	61	C: 100	White
SU3	Camisole	98	C: 100	Light blue
SU4	Short sleeve T-shirt	185	C: 100	White
SU12	Short sleeve shirt	201	C: 60, PE: 40	Checked light blue
SU16	3/4 sleeve blouse	179	PE: 84, PU: 16	Light green
SU17	Long sleeve blouse	190	PE: 59, C: 34, PU: 7	White
SU18	Ensemble summer sweater (inner, set with SU19)	113	A: 100	Brown
SU19	Ensemble summer sweater (outer, set with SU18)	172	A: 100	Brown
SU25	One-piece dress	201	C: 95, PU: 5	Grey
SU30	Long sleeve work wear	234	PE: 60, C: 40	Grey
SD6	Trousers	449	C: 60, PE: 40	Grey
SD7	Trousers	440	C: 55, R: 40, PU: 5	Blue
SD8	Skirt	262	C: 68, PE: 28, PU: 4	Black
SD17	Working trousers	327	PE: 60, C: 40	Grey
SU26	Short sleeve T-shirt	170	C: 69, PE: 31	Grey
SD12	Short pants	187	C: 69, PE: 31	Grey
SU27	Short sleeve pajama	159	C: 100	Pink
SD14	Short pants of pajama	111	C: 100	Pink

† “C” is cotton, “PE” is polyester, “PU” is polyurethane, “A” is acrylate, and “R” is rayon.

Table 2 Summary of ensembles (example)

No.	Ensemble	Weight [g]
19	Short (UW1), socks (UW6), short pants (SD12), short sleeve T-shirt (SU26)	497
26	Short (UW1), trousers (SD6), short sleeve shirt (SU4), working wear (SU30)	947
36	Short (UW1), short sleeve pajama (SU27), short pants (SD14)	349
91	Panty (UW2), trousers (SD7), brassiere (UW3), 3/4 sleeve blouse (SU16)	685
102	Panty (UW2), socks (UW6), trousers (SD7), brassiere (UW3), camisole (SU3), 3/4 sleeve shirt (SU16), summer sweaters (SU18 and SU19)	1129
116	Panty (UW2), socks (UW6), skirt (SD8), brassiere (UW3), camisole (SU3)	487
151	Panty (UW2), socks (UW6), working trousers (SD17), brassiere (UW3), camisole (SU3), long sleeve blouse (SU17), working wear (SU30)	976
167	Panty (UW2), one piece dress (SU25)	230

Table 1 shows examples of the garments that were studied. Table 2 shows examples of the ensembles that were studied. For the measurements, a female thermal manikin that had twenty segments was arranged in the sitting posture. The manikin had an electrical heating source that was located just below its surface. The *Tsk* of each segment was maintained such that it conformed to the typical skin temperature distribution of human subjects who are in a thermally neutral state in a uniform environment [8]. The average *Tsk* for the overall body was 33.8°C. In the chamber, *To* was set to 27.0°C, 25.0°C, and 24.0°C for a nude manikin, a manikin clothed in a garment, and one clothed in an ensemble, respectively. The relative humidity was within 40 ± 20%. The data in the steady state were used for calculating $R_{cle\mathrm{i}}$ and I_{cle} in Eqs. (1) and (2). In these conditions, the measured Q from the overall body ranged from almost 30 to 70 W/m^2. I_a was 0.81 clo (= 0.13 m^{2o}C/W). $R_{cle\mathrm{i}}$ values were calculated for nine segments—the chest, back, abdomen, buttock, upper arms, forearms, thighs, legs, and feet. Measurements were carried out two or three times for each type of clothing. Two or three data sets were then obtained for each type of clothing. From these data sets, two that satisfied the condition of the difference in their $R_{cle\mathrm{i}}$ values being less than 0.031 m^{2o}C/W (= 0.2 clo) were selected. The average of these two selected data sets was then obtained as the final output of the measurements.

RESULTS AND DISCUSSIONS

Tables 3 and 4 show the examples of the obtained results. The $R_{cle\mathrm{i}}$ values for 52 garments and 97 ensembles were obtained through the selection of the data sets. In this selection, the rejections were mainly attributed to the large difference in $R_{cle\mathrm{i}}$ in the abdomen and thighs. We consider the reasons for the large differences in these segments to be as follows. In the sitting posture, there was a strong curvature along these two segments on the front side of the body. Since the clothing on these segments was located inside this curvature, the thickness of the air layer inside the clothing was largely influenced by the magnitude of the curvature. Therefore, a slight difference in the posture resulted in a large difference in $R_{cle\mathrm{i}}$. In addition, since many garments overlapped on these segments, the errors in the manner of dressing appeared were more apparent in these segments compared with the others. Even in the selected data, with regard to some ensembles in which the legs were covered only by pantyhose, $R_{cle\mathrm{i}}$ in the legs took negative values (≥ –0.005 m^{2o}C/W). We consider that the level of accuracy in the measurements was insufficient for detecting the effect of the addition/removal of the pantyhose.

Table 3 R_{clei} and I_{cle} values for garments (example)

Symbol	Chest	Back	Abdomen	Buttock	Upper arms	Fore-arms	Thighs	Legs	Feet	Overall
	R_{clei} [m²°C/W]									I_{cle} [clo]
UW1	0	0	0.113	0.065	0	0	0.021	0	0	0.06
UW2	0	0	0.030	0.042	0	0	0	0	0	0.03
UW3	0.042	0.014	0	0	0	0	0	0	0	0.03
UW6	0	0	0	0	0	0	0	0.021	0.031	0.04
SU3	0.068	0.048	0.064	0.028	0	0	0	0	0	0.09
SU4	0.113	0.121	0.123	0.059	0.076	0	0	0	0	0.19
SU12	0.134	0.137	0.106	0.068	0.144	0	0.028	0	0	0.24
SU16	0.117	0.132	0.088	0.053	0.086	0.040	0.002	0	0	0.18
SU17	0.116	0.124	0.105	0.059	0.075	0.085	0.001	0	0	0.21
SU18	0.086	0.091	0.088	0.030	0	0	0	0	0	0.08
SU19	0.074	0.103	0.046	0.036	0.068	0.023	0	0	0	0.14
SU25	0.099	0.028	0.119	0.058	0	0	0.066	0	0	0.15
SU30	0.156	0.132	0.090	0.053	0.130	0.073	0.011	0	0	0.24
SD6	0	0	0.143	0.092	0	0	0.043	0.084	0	0.12
SD7	0	0	0.121	0.055	0	0	0.032	0.050	0	0.09
SD8	0	0	0.110	0.064	0	0	0.075	0.020	0	0.10
SD17	0	0	0.129	0.077	0	0	0.061	0.079	0	0.13
SU26	0.113	0.118	0.120	0.046	0.075	0	0	0	0	0.14
SD12	0	0	0.143	0.047	0	0	0.037	0	0	0.06
SU27	0.133	0.131	0.110	0.055	0.104	0	0.004	0	0	0.18
SD14	0	0	0.118	0.059	0	0	0.045	0	0	0.07

Table 4 R_{clei} and I_{cle} values for ensembles (example)

No.	Chest	Back	Abdomen	Buttock	Upper arms	Fore-arms	Thighs	Legs	Feet	Overall
	[m²°C/W]									[clo]
19	0.094	0.107	0.402	0.130	0.063	0	0.045	0.010	0.024	0.25
26	0.215	0.185	0.332	0.156	0.181	0.072	0.072	0.098	0	0.50
36	0.110	0.105	0.308	0.156	0.089	0	0.063	0	0	0.24
91	0.135	0.123	0.175	0.085	0.068	0.031	0.028	0.040	0	0.27
102	0.262	0.273	0.316	0.161	0.144	0.042	0.056	0.065	0.026	0.47
116	0.094	0.060	0.218	0.122	0	0	0.094	0.042	0.034	0.27
151	0.294	0.259	0.323	0.163	0.172	0.153	0.082	0.080	0.025	0.60
167	0.100	0.044	0.127	0.096	0	0	0.083	0	0	0.19

With regard to the value for the overall body, I_{cle} ranged from 0.02 clo to 0.24 clo for the garments and from 0.13 clo to 0.60 clo for the ensembles. Fig. 1 shows a plot of I_{cle} for ensembles ($I_{cle.en}$) against the sum of the components' I_{cle} ($\Sigma I_{cle.gr}$). The slopes of the regressions of $I_{cle.en}$ by $\Sigma I_{cle.gr}$ (indicated in Fig. 1) are slightly less than those reported by McCullough et al. ($I_{cle.en} = 0.76\Sigma I_{cle.gr} + 0.079$, $I_{cle.en} = 0.84\Sigma I_{cle.gr}$) [9]. The Difference in the posture (standing in study [9] and sitting in the present study) and difference in the clothing type (only summer clothing is used in our study) are possible explanations for this discrepancy. In order to ascertain the reasons for this discrepancy, it is necessary to measure

I_{cle} of the same clothing as used in our study in the standing posture and also to measure I_{cle} of various types of clothing.

Table 5 shows the ranges of the calculated R_{clei} for the garments and ensembles. R_{clei} was large in the trunk and was relatively small in the periphery of the limbs. Fig. 2 shows a plot of

Table 5 Ranges of calculated R_{clei}

		Chest	Back	Abdomen	Buttock	Upper arms	Forearms	Thighs	Legs	Feet
						[m^2°C/W]				
Garments	Min	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	Max	0.162	0.137	0.150	0.092	0.144	0.085	0.075	0.084	0.034
Ensembles	Min	0.082	0.042	0.127	0.075	0.000	–0.001	0.019	–0.005	0.000
	Max	0.315	0.303	0.405	0.216	0.181	0.153	0.133	0.098	0.037

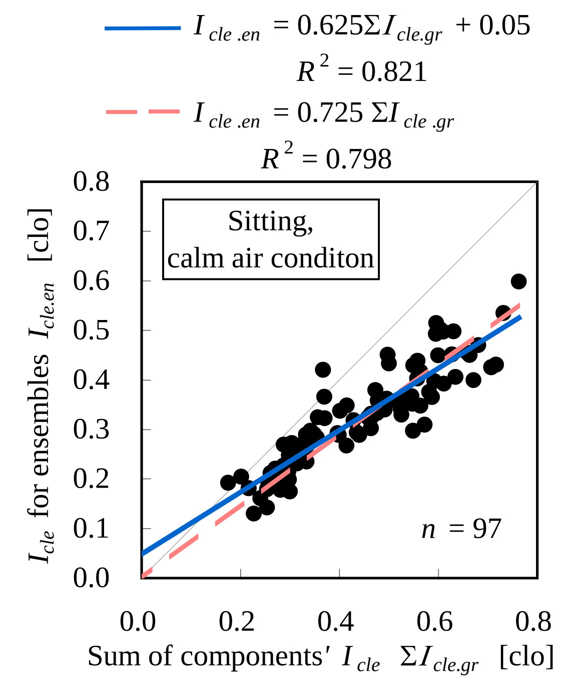

Fig. 1 $I_{cle.en}$ vs. $\Sigma I_{cle.gr}$ for the overall body

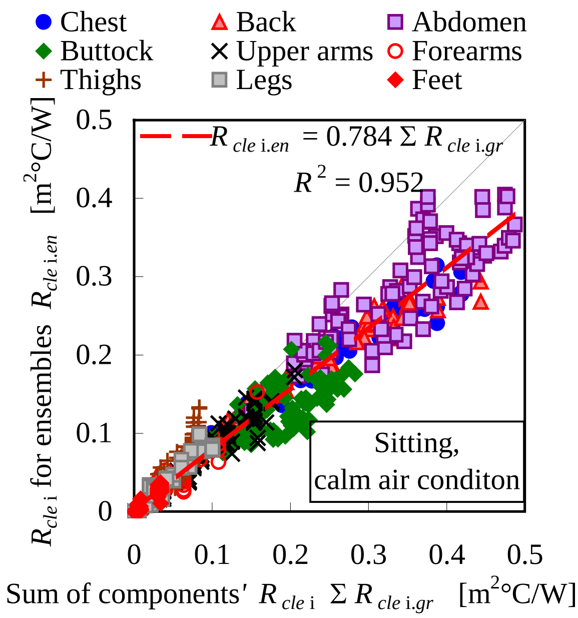

Fig. 2 $R_{clei.en}$ vs. $\Sigma R_{clei.gr}$ for nine segments

Table 6 Slope (A), intercept (B), standard deviation of error (sd) for regressions of $R_{clei.en}$ by $\Sigma R_{clei.gr}$

$R_{clei.en} = A\Sigma R_{clei.gr} + B$		Chest	Back	Abdomen	Buttock	Upper arms	Fore-arms	Thighs	Legs	Feet
$B \neq 0$	A	0.667	0.672	0.659	0.525	0.823	0.838	1.042	0.886	0.840
	B	0.0248	0.0259	0.0572	0.0309	–0.0015	–0.0007	0.0002	–0.0016	–0.0002
	sd	0.012	0.014	0.036	0.023	0.011	0.008	0.014	0.006	0.004
	A					0.763				
	B					0.0049				
	sd	0.015	0.017	0.041	0.032	0.012	0.009	0.020	0.008	0.005
$B = 0$	A	0.761	0.773	0.817	0.678	0.811	0.829	1.045	0.862	0.833
	sd	0.016	0.018	0.039	0.024	0.011	0.008	0.014	0.006	0.004
	A					0.784				
	sd	0.016	0.019	0.041	0.031	0.012	0.008	0.022	0.007	0.004

the $R_{cle\mathrm{i}}$ values for the ensembles ($R_{cle\mathrm{i}.en}$) against the sum of the components' $R_{cle\mathrm{i}}$ ($\Sigma R_{cle\mathrm{i}.gr}$) for nine segments. In each segment, $R_{cle\mathrm{i}.en}$ tends to be slightly less than $\Sigma R_{cle\mathrm{i}.gr}$. The plot exhibits an approximately similar relationship for the all segments. Table 6 shows the slope (*A*), intercept (*B*), standard deviation of error (*sd*) [9] [NOTE2] for the regressions of $R_{cle\mathrm{i}.en}$ by $\Sigma R_{cle\mathrm{i}.gr}$ for each segment and the values common to all the segments. In the individual regressions with an intercept, large *sd* values were observed for the abdomen (0.036 m^2°C/W) and buttock (0.023 m^2°C/W). Many overlaps of the garments explain the larger *sd* in these segments in comparison to the *sd* in the other segments. When an *sd* of 0.041 m^2°C/W (slightly larger *sd* than that in the abdomen of 0.036 m^2°C/W) is regarded as acceptable, the common regression ($R_{cle\mathrm{i}.en} = 0.784\Sigma R_{cle\mathrm{i}.gr}$) can be used for the nine segments.

Fiala et al. [10] developed a clothing insulation model of in which the intrinsic thermal insulation of a body segment provided by the clothing ensemble ($R_{cl\mathrm{i}.en}$) is expressed by the sum of the components' intrinsic clothing thermal insulation of the body segment ($\Sigma R_{cl\mathrm{i}.gr}$). However, the definition of clothing insulation in their model is different from that used in our study; the slope of our regression (0.784) is much less than unity (used in their model). The overlap of garments compresses the air layer inside the clothing. This can explain why the slope of our regression becomes less than unity. In the previous study of Sakoi et al. [2], the relations between $R_{cl\mathrm{i}.en}$ and $\Sigma R_{cl\mathrm{i}.gr}$ were different among the body segments. However, their definition of clothing insulation was different from that in the present study and their data set was smaller. On the other hand, the variety of clothing types was large as compared with the summer clothing used in the present study. Therefore, the accuracy of our common regression may reduce significantly when the regression is applied for estimating the $R_{cle\mathrm{i}}$ provided by the types of clothing other than summer clothing.

The slope of the common regression for the nine segments becomes 0.784 and is larger than the slope of regression for the overall body ($I_{cle.en} = 0.725\Sigma I_{cle.gr}$ in Fig. 1). With the insulation for the overall body, it is reported that the effect of addition/removal of clothing garments becomes less when the clothing is worn nonuniformly [9]. The fact that the slope in the common regression for nine segments is larger than that for the overall body is explained by the same reason, i.e., the clothing distribution is more uniform for segments than it is for the overall body.

CONCLUSIONS

In a climatic chamber with calm air conditions ($v \leq 0.15$ m/s), the effective thermal insulation provided to body segments ($R_{cle\mathrm{i}}$) by summer clothing was measured. $R_{cle\mathrm{i}}$ of 52 garments and 97 ensembles was obtained for nine segments—the chest, back, abdomen, buttock, upper arms, forearms, thighs, legs, and feet. In each segment, $R_{cle\mathrm{i}}$ for the ensembles ($R_{cle\mathrm{i}.en}$) tends to be slightly less than the sum of the components' $R_{cle\mathrm{i}}$ ($\Sigma R_{cle\mathrm{i}.gr}$). Since the plot of $R_{cle\mathrm{i}.en}$ against $\Sigma R_{cle\mathrm{i}.gr}$ exhibits an approximately similar relationship for all the segments, the common regression for all the body segments, $R_{cle\mathrm{i}.en} = 0.784\Sigma R_{cle\mathrm{i}.gr}$, was proposed for estimating $R_{cle\mathrm{i}.en}$ from $\Sigma R_{cle\mathrm{i}.gr}$.

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NOTE

[1] The total thermal insulation I_T is defined as the actual thermal resistance for a temperature difference between the skin and the operative temperature of the surrounding environment. It includes the thermal resistance of air (including the effect of radiation) in addition to that of the clothing itself. Therefore, it does not express the heat transfer characteristics of the clothing itself, but that of the clothing and the environmental conditions together [5, 6]. The intrinsic thermal insulation I_{cl} is the actual thermal resistance for a temperature difference between the skin and the clothing surface. It expresses the heat transfer characteristics of the clothing itself. The effective clothing insulation I_{cle} is the hypothetical thermal resistance that expresses the effect of the addition/removal of clothing. It is defined as the difference between the total thermal insulation when the body is clothed (I_T) and the total thermal insulation when the body is not clothed (I_a). Since this hypothetical resistance I_{cle} includes the effect of the environmental conditions as well as the clothing itself, it changes with the environmental conditions [5].

[2] The standard deviation of error (*sd*) [9] is calculated as follows.

$$sd = \sqrt{\frac{\sum(\text{predicted value} - \text{measured value})^2}{\text{number of data}}}$$

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