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Article

The non-uniform and asymmetric thermal radiation upon the human physiological responses in outdoor environment

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Abstract: Depending on human body conditions and environmental conditions, it is sometimes difficult to conduct subject experiments. In such cases, it is effective to use a thermal manikin. There are few studies that investigate the effect of the non-uniform and asymmetric outdoor thermal environment on the mean skin temperature. The purpose of this study is to clarify the influence of the non-uniform and asymmetric thermal radiation of short-wavelength solar radiation in an outdoor environment on the calculation of the mean skin temperature. The skin temperature of the front of the coronal surface, which was facing the sun and where the body received direct short-wavelength solar radiation, and the skin temperature of the rear of the coronal surface, which was in the shadow and did not receive direct short-wavelength solar radiation were respectively measured. The feet, upper arm, forearm, hand and lower leg, which are susceptible to short-wavelength solar radiation in a standing posture, had a noticeable difference in skin temperature between sites in the sun and in shade. The mean skin temperature of sites facing the sun was significantly higher than the mean skin temperature of those in the shade.

Keywords: Asymmetry; Mean skin temperature; Non-uniform; Outdoor environment; Physiological response; Skin temperature; Solar radiation

1. Introduction

To examine the heat exchange between the human body and the environment, subject experiments are effective. However, depending on human body conditions and environmental conditions, it is sometimes difficult to conduct subject experiments. In such cases, it is effective to use a thermal manikin or a numerical thermal manikin.

With these methods using thermal manikins, correspondence between heat generation and heat dissipation of the human body and of the thermal manikin is not clear. In addition, in the numerical thermal manikin, human body shape, boundary condition, various coefficient values are not clear. The thermal manikin is a heat dummy for reproducing the heat transfer characteristics of human beings. Therefore, it is possible to evaluate the thermal environment without burdening the human body. The thermal manikin has become an indispensable item to evaluate the thermal environment.

An extremely large number of laboratory experiments on subjects assume the thermal environment to be in a homogeneous and uniform steady state. However, the ordinary indoor environment is thermally non-uniform, asymmetrical and nonstationary. In addition, the physical

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thermal environmental factors fluctuate greatly in the outdoor environment, which is in an unsteady state. In evaluating the outdoor environment, the psychological reaction of the human body is made the focus, and research quantitatively dealing with the heat balance of the human body is rare. The only studies that quantitatively investigate the influence on the human body using comprehensive thermal environment evaluation indices based on the heat balance of the outdoor environment as the axis of evaluation are those by Kurazumi et al. [1-8].

The outdoor thermal environment, short-wavelength solar radiation, long-wavelength thermal radiation and the air current are non-uniform and asymmetric evaluation factors. These may contribute as a local effect on the human body, even if the heat balance in the whole human body is the same. As pointed out by Kurazumi et al. [4, 7, 8], the influence of these environmental parameters may cause variation in the response of the human body. The human body may experience discomfort due to changing environmental factors, and so this experience can be thought to induce the condition of relative comfort. Accordingly, changes with an effect that mitigates thermal function are considered to be variables for discomfort with regard to other environmental factors also. That is, the degree of conscious awareness of thermal environmental factors may have an influence.

Horikoshi et al. [9] and Kurazumi et al. [10], who conducted heterogeneous and asymmetric subject experiments in an indoor environment, demonstrate that the psychological reactions of the human body in a heterogeneous and asymmetric thermal radiation environment have directionality under the effect of local thermal radiation, and that these psychological reactions change. Kurazumi et al. [11] demonstrate that a parameter exists for the heterogeneous and asymmetric thermal environmental factors in the thermal environment evaluation index that evaluates the effect on the human body in a heterogeneous and asymmetric thermal radiation environment. They show that there is a large spread in the response of the human body due to the effect of this parameter. That is, the spread in thermal sensory perception becomes large in outdoor spaces due to the influence of environmental stimuli in addition to the psychological response to thermal action in the outdoor space.

The thermal environment evaluation index based on the heat balance of the human body in the outdoor environment uses representative values of individual thermal environment factors as evaluation values. The change factor is handled by using a moving average value, and the non-uniform factor by using a weighted average value such as mean radiant temperature. However, although the mean skin temperature of the human body is a representative value of the local environment, studies investigating the effect of short-wavelength solar radiation in the outdoor environment are rare.

The mean skin temperature, which is the representative value for skin temperature, is used to calculate the amount of heat exchange between the human body and the environment. Since skin temperature is not uniform over the whole body surface, it is assumed that it is uniform within a given site of the body surface and the mean skin temperature is considered to be the skin temperatures averaged by the area of the surfaces as a proportion of the total surface area of the body. That is, the mean skin temperature calculation formula has been devised assuming that the skin temperature is almost uniform on the body surface.

Studies on the method for calculating the mean skin temperature deal with the physiological mean skin temperature and thermal conduction mean skin temperature. There are various measurement points and measurement sites for skin temperature, and considering the relationship between the human body and the surrounding environment, it is necessary to determine the sites judged to be affected by the surrounding environment and the distribution of skin temperature. The more skin temperature measurement scores corresponding to the skin temperature distribution are used, the smaller the skin temperature distribution within the body surface section becomes. Therefore, each representative skin temperature approximates the most probable value as the representative section value, and the accuracy of the mean skin temperature calculation is improved. However, it is difficult and impractical to actually measure a large number of measurement points. So far, six types of mean skin temperature calculation method have been proposed as follows.

Studies proposing a mean skin temperature calculation method based on the total surface area weighting of the body surface section divide the distribution of the skin temperature expressed on the body surface in a certain range and make a weighted average of the section representative skin temperatures according to the ratio of the section body surface area to the total body surface area [12-29]. The characteristics of the research vary according to the number of sections and the selection of the representative skin temperature of the section. However, the skin temperature of body surfaces in mutual contact and body surfaces in contact with the floor surface are not considered. That is, the body is assumed to be spread such that there is no contact between body surfaces and to be standing in a state as if it were floating in air. Depending on the method of selecting the body surface section and representative skin temperature, these studies can find it difficult to cope with the local skin temperature distribution.

Studies that propose a mean skin temperature calculation method based on the convective heat transfer area weighting of the body surface section of the human body [30, 31] divide the distribution of the skin temperature expressed on the body surface by a certain range, and make a weighted average of the section representative skin temperatures by the ratio of the heat section transfer area to the total convective heat transfer area. Kurazumi et al. [30] shows a mean skin temperature calculation formula for the postures of standing position and chair seated position. Kurazumi et al. [31] shows a mean skin temperature calculation formula for standing, chair seated, seiza seated, cross-legged seated, sideways seated, both-knees-erect seated, leg-out seated, lateral and supine positions. Kurazumi et al. [30] investigates the method of calculating the mean skin temperature by the total surface area weighting of the human body surface section in a uniform thermal environment where the air temperature and wall temperature are equal, and examines the difference with the mean skin temperature given by the mean skin temperature calculation method based on the convective heat transfer area weighting. In a living environment where various postures are assumed, it is necessary to distinguish the mean skin temperature calculation method according to the posture. By considering the convective heat transfer area, the study clarifies that the influence of the skin temperature of a limb can be expressed in terms of the mean skin temperature in both the standing and chair seated positions. This calculation method focuses on the heat transfer area based on heat transfer theory and may be considered to cope with a non-uniform environment.

Studies that propose a mean skin temperature calculation method based on the total surface area weighting of the human body surface section and the conductive heat transfer area weighting between the body and the floor etc. [32-38] divide the distribution of the skin temperature expressed on the body surface by a certain range, and make a weighted average of the section representative skin temperatures by the ratio of the section body surface area to the total body surface area. This calculation method deals with the local skin temperature distribution by contact heat conduction. Mean skin temperature calculation formulas are given for standing, chair seated, seiza seated, cross-legged seated, sideways seated, both-knees-erect seated, leg-out seated, and lateral positions in Kurazumi et al. [37, 38]. This calculation method focuses on the heat transfer area based on heat transfer theory and may again be considered to cope with a non-uniform environment.

Further research by Kurazumi et al. [39] developed the above concept of a weighting coefficient for the heat transfer area. A mean skin temperature calculation method is proposed by a weighting of the convective heat transfer area, the radiative heat transfer area, and the conductive heat transfer area of the human body surface section. They show a mean skin temperature calculation formula for standing, chair seated, seiza seated, cross-legged seated, sideways seated, both-knees-erect seated, leg-out seated, lateral and supine positions. This calculation method focuses on the heat transfer area based on heat transfer theory and may also be considered to cope with a non-uniform environment.

In studies proposing a mean skin temperature calculation method based on the total surface area weighting of the human body surface section and the local convective heat transfer coefficient for the section [40-44], this was obtained from an equation for the body heat balance between the human body and the surrounding environment. The local convective heat transfer coefficient of each body surface section is found from a cylindrical model or thermal manikin. In deriving the body heat balance equation, it is assumed that the entire surface of the body is involved in heat exchanges through convection, radiation, and evaporation. However, even in a relatively open standing posture, there is some contact between body surfaces, and these surfaces are not involved in heat exchange with the environment surrounding the body. Especially in a seated or decubitus position etc., where there is a lot of contact between the body surface and the floor, the discrepancy with the actual situation is significant.

One study [45] that proposes a mean skin temperature calculation method based on the total surface area weighting and the skin temperature sensation of the surface section of the human body, suggests that temperature sensation is related to the expression of skin temperature. In this study, a perspiration ratio is used for temperature sensation. Representative perspiration amounts and representative skin temperatures for each body surface section of the body in a supine position exposed to a high temperature environment of 30 °C or more were measured, and the ratio of the difference in the perspiration amount of each section and the thigh with respect to the difference between the mean skin temperature calculated by the skin temperature and body surface area weighting for each section is regarded as the skin temperature sensation coefficient. The ratio of the skin temperature sensation coefficient of each section to the skin temperature sensory coefficient of the thigh is used as the weighting for calculating the mean skin temperature. Since the amount of perspiration of the human body in a high air temperature environment is the basis of calculation, the high air temperature environment is considered to be the applicable range. Therefore, caution is necessary when this method is used under conditions significantly different from the assumed thermal environment.

A study proposing a mean skin temperature calculation method based on the total surface area weighting of the body surface section and the local convective heat transfer coefficient and the skin temperature sensation for that section of the human body [46] combined the local convective heat transfer coefficient for the human body obtained from an equation for body heat balance with the weighting coefficient of Nadel et al. [45]. Since this research has research application limits that are a factor in deriving the weighting coefficient, attention is necessary when using the method with postures where the contact surface of the body surface is large or in other than a high air temperature environment.

The mean skin temperature calculation formula must be selected according to the application, such as whether the calculated mean skin temperature is used as a monitor of physiological response or applied to the body heat balance equation for the human body. In indoor environments and shady outdoor environments, there is little influence of short-wavelength solar radiation, so a strikingly non-uniform and asymmetric environment is not formed. In an outdoor environment, however, some parts of the body have shaded sites and sites facing the sun, and a remarkable difference in skin temperature is considered to occur under the influence of the short-wavelength solar radiation.

The thermal manikin body is divided into several sections from the head to the lower limb, so there is a possibility that the thermal manikin can estimate the heat exchange between the non-uniform and asymmetric thermal environment and the human body. If we know the heat transfer characteristics and the sensational and physiological temperature of the thermal environment for each divided part, we can evaluate the influence of the thermal environment on the human body in detail.

Representative body surface division of the human body and of the thermal manikin body are head, trunk, upper arm, forearm, hand, thigh, lower leg, and foot. The head and trunk may be further subdivided. Although, it is possible to study the asymmetric difference between the left and right thermal radiation stimuli received from the thermal environment targeted at the limbs, it is difficult to consider other non-uniform and asymmetric thermal environments and other body surface section to be examined.

In indoor environments and outdoor environments, there is strong influence of short-wavelength solar radiation, so a strikingly non-uniform and asymmetric environment is formed. However, there are few studies that investigate the effect of the non-uniform and asymmetric outdoor thermal environment on the mean skin temperature of the human body. Therefore, the present study aimed to clarify the influence of the non-uniform and asymmetric thermal radiation of short-wavelength solar radiation in an outdoor environment on the calculation of the mean skin temperature of the human body and on the classification of the body surface section.

2. Experiment design

2.1. Experimental process and measurement items

Experiments were conducted in Bangkok, Thailand at 13° 44′ 20″ north latitude during the dry season. For the measurements, the experiment site was selected with consideration for the condition that short-wavelength solar radiation should not be shielded during the exposure time. Weather environment elements in outdoor spaces are in a heterogeneous and unsteady state. Focusing on the influence of short-wavelength solar radiation, the experiment site chosen for the present study was a place where fluctuations of other weather environmental factors were minimized. A measurement location surrounded by buildings was selected such that the subjects were in an enclosed space and the fluctuation of airflow was mitigated. The building and the ground surface were a concrete material with high heat capacity, so the influence of long-wavelength thermal radiation was strong, but the exposure time frame of 13:00–14:30, where the solar altitude is high and fluctuation of the surface temperature decreases, was selected.

The thermal environment of outdoor spaces can be harsh to the extent that there are cases of death by heat stroke. Accordingly, extended periods in hot outdoor spaces under short-wavelength solar radiation must be avoided. Unlike an indoor space, it is difficult to consider spending extended periods in an outdoor thermal environment that can become uncomfortable due to behavioral thermoregulation by means of environmental refuge behavior. Therefore, the actual measurement of the human body response and the thermal environment was carried out in consideration of the time the subject spent maintaining the standing posture. Naturally, it can be conjectured that the human body response will differ the longer the exposure time of the subjects, but the experimental period was determined with consideration for the safety of the subjects.

Subjects remained upright and at rest in an outdoor shady space for about 60 minutes including the time spent attaching sensors, then moved on foot to the selected site. They were then exposed to the thermal environment in a standing posture for 15 minutes, positioned such that the front of the coronal plane directly faced the direction of the solar azimuth in a place where short-wavelength solar radiation was not obstructed.

The thermal environment parameters measured were: air temperature, humidity, air velocity, globe temperature, and short-wavelength solar heat quantity. Temperature, humidity, air velocity and globe temperature were measured by a portable PMV meter (Kyoto Electronics Manufacturing: AM-101, air temperature: 0 to 50.0 °C ±0.5 °C, globe temperature: 0 to 50.0 °C ±0.5 °C, mean radiant temperature: 0 to 50.0 °C, relative humidity: 0 to 100% RH ±3% RH, air velocity: 0 to 1 m/s ±0.1 m/s; 1 to 5 m/s ±0.5 m/s) at a height of 90 cm above the ground. Concerning the short-wavelength radiant heat quantity from the visible region to the near-infrared region, amounts of downward and upward solar radiation were measured by a pyranometer (PREDE: PCM-01NL, sensitivity: 7 $mV/W/m^{-2}$, wavelength range: 305 nm to 2800 nm).

The skin temperature of the human body was measured by a thermistor thermometer (Nikkiso THERM N542R data logger, measuring range: -50 to 230 °C, resolution: 0.01 °C, and a Nikkiso THERM body surface temperature probe: ITP8391). The temperature of skin open to airflow was measured at the eight positions of the head, upper arm, forearm, hand, trunk, thigh, lower leg, and foot. The skin temperature of the front of the coronal surface, which was facing the sun and where the body receives short-wavelength solar radiation, and the skin temperature of the rear of the coronal surface, which was in the shadow and did not receive short-wavelength solar radiation, were measured. The subjects were wearing T-shirts and shorts, such that the skin temperature measurement sites were exposed to the surrounding environment. The T-shirts were turned up to expose the upper arm, abdomen and lumbar area. In order to prevent burns due to heat conduction from the ground surface, posture was maintained on sandals with a sole thickness of about 1.0 cm.

2.2. Subjects

The subjects were four healthy young males and females. The subjects were age 21.0 ± 0.7 years, height 167.7 ± 5.8 cm, body weight 56.7 ± 7.5 kg, body surface area 1.6 ± 0.1 m^2, and BMI 20.1 ± 2.6,

Table 1. Physical characteristics of subjects.

Subject	Sex	Age	Height (cm)	Weight (kg)	B-area (m^2)	Rohrer Index	Native place
1	Male	21	165.3	65.0	1.71	23.79	Bangkok
2	Male	22	177.6	60.0	1.74	19.02	Bangkok
3	Female	20	163.0	44.7	1.47	16.82	Bangkok
4	Female	21	165.0	57.0	1.62	20.94	Bangkok

B-area is the calculated body surface area by Kurazumi's formula [48].
$S=100.315\ W^{0.383}\ H^{0.693} \times 10^{-4}$ (Kurazumi et al., 1994)
S: Body surface area [m^2], W: Weight [kg], H: Height [cm]
BMI is Body Mass Index.
Native place is life region from birth to 2.5 years old time.

and they were not considered to have a unique physique. In addition, the subject's height and weight are not significantly different from the average of Thai statistical data [47] (Jordan et al., 2012). In calculation of the body surface area of the human body, we used a calculation formula of Kurazumi et al. [48]. Table 1 shows the subjects' characteristics.

In accordance with the Helsinki Declaration [49], the details of the experiment were explained to the subjects in advance and their consent for participation in the experiment was obtained.

Experiments with subjects measuring physiological quantities as human body reactions are rarely performed using a large number of subjects. In addition, it is difficult to perform experiments assuming a statistical population. Therefore, although there are few subjects in this study, they are considered meaningful as new data.

It is rare to perform a subjective experiment that measures physiological quantities according to the response of the human body using a large number of subjects. It is difficult to perform an experiment that is hypothesized on a statistical population. Accordingly, as only a small number of subjects was used in this study, the new data are a significant addition to the literature.

3. Experimental results

The solar altitude on the experimental days was 72.98–55.81° and the solar azimuth was 211.01–247.07°. The weather during the exposure time was sunny with the sun occasionally obscured by clouds. The experiment was set up with the time of exposure to short-wavelength direct solar radiation set to 15 minutes, but weather conditions occurred in which the short-wavelength solar radiation was completely shielded. Therefore, in the following discussion, the elapsed exposure time in which all meteorological observation times were satisfied was analyzed as 13 minutes.

The temperature during the experiment was 34.2 ± 0.4 °C, relative humidity was 48.7 ± 0.9%, air velocity was 1.9 ± 0.8 m/s, globe temperature was 42.5 ± 1.4 °C, horizontal short-wavelength solar radiation was 766.5 ± 272.7 W/m^2, ground surface reflected solar radiation quantity was 86.1 ± 36.1 W/m^2. The observation area albedo was 10.7%. There was also an exposure time zone in which the temperature around the body was higher than the skin temperature.

In a normal posture, the body surfaces are in contact with each other at the armpit and inner surface of the thigh. In the standing posture, it is possible to proactively assume an open posture with respect to the air current. Also, even in a chair seated position, it is possible to be proactively open to the air current to some extent by minimizing the contact area between the human body and the chair. However, there is still some of the body surface that is not open to the air flow, such as contact between the foot and the floor surface (hereinafter "non-convective heat transfer surface").

Non-convective heat transfer surfaces exist in many ordinary postures.

A weighted average method based on the ratio of the total surface area of the body is used in the conventional mean skin temperature calculation method. However, considering the above facts, the calculation of the heat exchange quantity of the body is inaccurate in this conventional method, since non-convective heat transfer surfaces are included. In terms of heat transfer, the mean skin temperature used for accurate calculation of the quantity of convective heat exchange between the body and the environment should be the weighted average given by the area ratio of the convective heat transfer surface formed by the same skin temperature expressed on the body surface open to the air flow (hereinafter "convective heat transfer surface") with respect to the total convective heat transfer surface (hereinafter "convective heat transfer area ratio"). That is, it is necessary to use a mean skin temperature calculation method that considers the convective heat transfer area. Focusing on this point, Kurazumi et al. [30, 39] propose a mean skin temperature calculation method based on the convective heat transfer area weighting of the body surface section.

The present study assumed the perspective of applying the mean skin temperature to the evaluation of the heat balance of the body and evaluation of the thermal environment. Accordingly, to calculate the mean skin temperature, the method based on the convective heat transfer area weighting of the body surface section proposed by Kurazumi et al. [30, 39] was used.

4. Discussion

Figures 1 and 2 show examples of skin temperature change over time for the same subject exposed to the outdoor thermal environment for 13 minutes. Figure 1 shows an example of skin temperature change of the site facing the sun. A fluctuation of skin temperature considered to be influenced by cooling by perspiration and the influence of changes in air velocity and short-wavelength solar radiation was observed. Since the altitude of the sun was high and the subjects were located such that the front of the coronal plane directly faced the direction of the solar azimuth, the temperature rise is remarkable for the skin of the foot, which is a site susceptible to solar radiation in the direction normal to the short-wavelength solar radiation. The peak skin temperature was remarkably high at around 40 °C. Next, the skin temperature of the upper arm, forearm, hand and lower leg are also considered to be greatly influenced by short-wavelength solar radiation.

Figure 2 shows an example of skin temperature change of the site in the shade. Although this is for the shaded area of the site shown in Figure 1, a fluctuation of skin temperature considered to be influenced by cooling by perspiration and the influence of changes in air velocity and short-wavelength solar radiation was observed in the same way as above. However, it was not a large fluctuation compared with the skin temperature of sites facing the sun. The skin temperature of the head, upper arm and foot were extremely high, in excess of 37 °C. The amount of change in skin temperature of the same site, for which the skin temperature in the part facing the sun was remarkably high, was increased by about 0.4 °C.

Kurazumi et al. [1, 4-8] clarified the influence of reflected solar radiation on the human foot, and found that both reflected solar radiation and heat conduction from the ground surface influence the reaction of the human body. However, since the amount of change in the skin temperature of the foot in the sun and in the shade was significantly different, it is inferred that the difference in the skin temperature change is strongly influenced by short-wavelength solar

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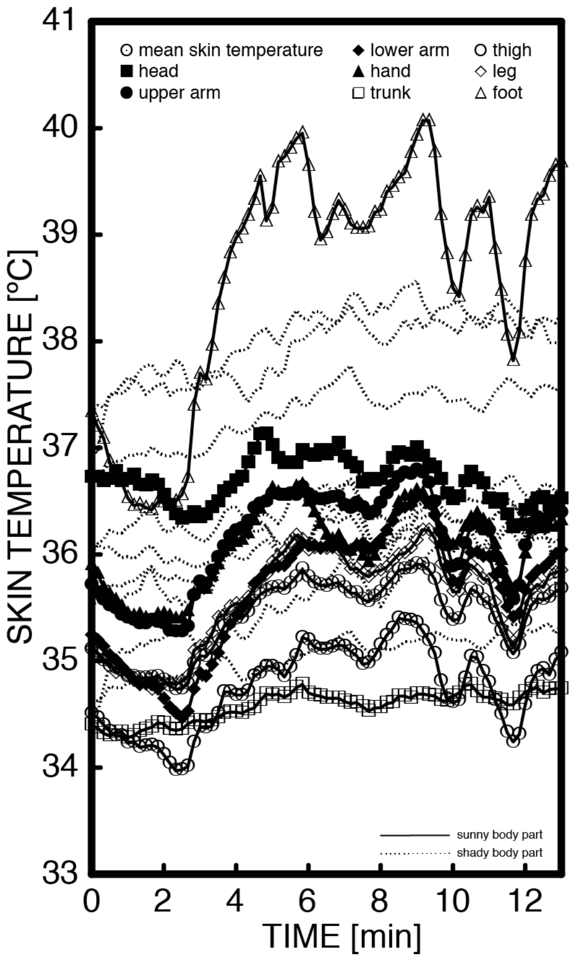

Figure 1. Changes of skin temperature exposed to the outdoor thermal environment in the sunny body part.

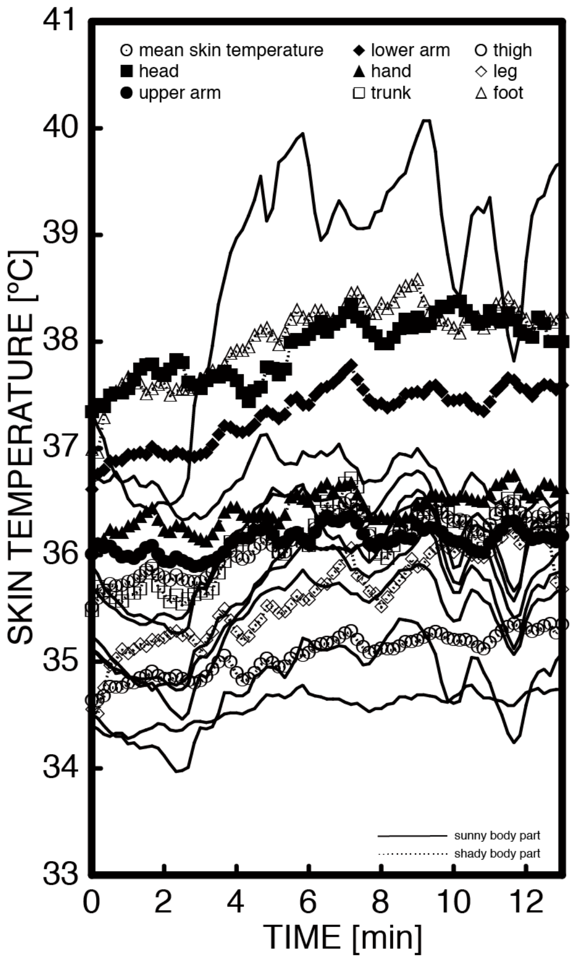

Figure 2. Changes of skin temperature exposed to the outdoor thermal environment in the shady body part.

radiation.

Figure 3 shows the change in mean skin temperature over time for skin exposed to the outdoor thermal environment for 13 minutes. Although there is a slight variation by subject, as described above, there was seen to be a fluctuation in the change in mean skin temperature that may have been influenced by cooling by perspiration, as well as fluctuations of air velocity and short-wavelength solar radiation. However, the overall fluctuation tendency tends to be such that the variation in the mean skin temperature of sites facing the sun is higher than the variation at sites in the shade, and this variation becomes larger over time. For subjects with the largest difference between the fluctuation of mean skin temperature for sites facing the sun 13 minutes after exposure and the fluctuation at sites in the shade, this was 1.4 °C. Meanwhile, this was 0.3 °C for the lowest subjects.

There are very few studies that actually measure the skin temperature of the human body in a non-uniform and asymmetric thermal environment. The research of Horikoshi et al. [50] and Kurazumi et al. [10, 11] measured the influence on human skin temperature from the perspective of a non-uniform and asymmetric thermal environment in an indoor space. The research of Maruyama and Tamura [51] measured the influence on human skin temperature from the perspective of sites covered by clothing and open to the atmosphere. These studies demonstrate that variations in skin

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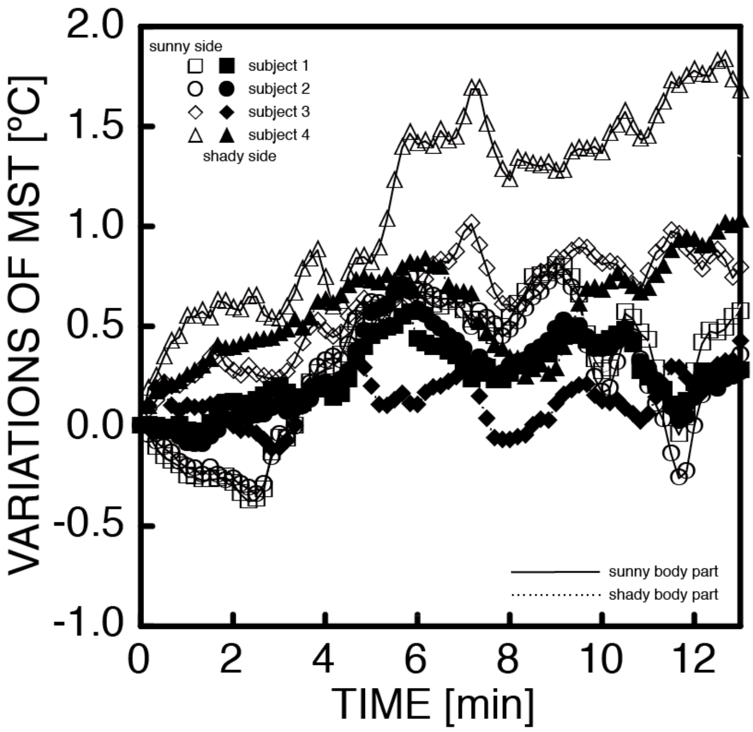

Figure 3. Changes of variation of mean skin temperature.

temperature are exhibited in a non-uniform and asymmetric thermal environment according to the influence of the local conditions.

As a result of investigating the difference between the fluctuation in mean skin temperature in sites facing the sun and the fluctuations in sites in the shade, a significant difference of $p < 0.01$ ($F = 146.1$) is shown. Also, as a result of investigating the difference between the fluctuation in mean skin temperature in sites facing the sun and the fluctuations in sites in the shade and their interaction over exposure time, a significant difference of $p < 0.01$ ($F = 51.1$) is shown.

In an outdoor environment in which the local influence on the human body becomes stronger, the tendency for the variation in the skin temperature to become stronger may be more pronounced because the thermal radiation environment is more non-uniform and asymmetrical due to short-wavelength solar radiation. This suggests that, when clarifying the effect on the human body in an outdoor environment, it is necessary to take into account the non-uniformity and asymmetry of the skin temperature for sites facing the sun and in the shade. Accordingly, when evaluating the body heat balance of the human body and the thermal environment in an outdoor environment, it is essential to consider the non-uniformity and asymmetry not only of the physical elements of the environment, but also of the skin temperature, which is an element on the side of the human body.

In other words, it can be said that the thermal manikin needs to be divided not only in the head and trunk but also in the limbs into the anterior part and the posterior part of the coronal plane. we can evaluate the influence of the thermal environment on the human body in detail.

5. Conclusions

In an outdoor environment, some parts of the body have shaded sites and sites facing the sun, and a remarkable difference in skin temperature is considered to occur under the influence of short-wavelength solar radiation. When evaluating the body heat balance of the human body and the thermal environment in an outdoor environment, it is essential to consider the non-uniformity and asymmetry not only of the physical elements of the environment, but also of the skin temperature, which is an element on the side of the human body. Therefore, when applying the mean skin temperature to the body heat balance equation of the human body, it is necessary to consider the influence of short-wavelength solar radiation.

Therefore, the present study aimed to clarify the influence of the non-uniform and asymmetric thermal radiation of short-wavelength solar radiation in an outdoor environment on the calculation of the mean skin temperature of the human body and on the classification of the body surface section.

A fluctuation of skin temperature considered to be influenced by cooling through perspiration and the influence of changes in air velocity and short-wavelength solar radiation was observed. The temperature of skin when receiving short-wavelength solar radiation due to the positional relation close to the normal direction was remarkably high at about 40 °C. The feet, upper arm, forearm, hand and lower leg, which are susceptible to short-wavelength solar radiation in a standing posture, had a noticeable difference in skin temperature between sites in the sun and in shade. The mean skin temperature of sites facing the sun was significantly higher than that of those in the shade. When evaluating the body heat balance of the human body and the thermal environment in an outdoor environment, it is essential to consider the non-uniformity and asymmetry not only of the physical elements of the environment, but also of the skin temperature, which is an element on the side of the human body.

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References

1. Kurazumi, Y.; Tsuchikawa, T.; Matsubara, N.; Kondo, E.; Horikoshi, T. Evaluation of enhanced conduction-corrected modified effective temperature ETFe as the outdoor thermal environment evaluation index. Energy and Buildings 2011, 43(10), pp. 2925-2937.
2. Kurazumi, Y.; Matsubara, N.; Tsuchikawa, T.; Kondo, E.; Ishii, J.; Fukagawa, K.; Ando, Y.; Yamato, Y.; Tobita, K.; Horikoshi, T. Psychological effects of the environmental stimuli on thermal sense in outdoor spaces. Japanese Journal of Biometeorology 2011, 48(4), pp. 129-144.
3. Kurazumi, Y.; Tsuchikawa, T.; Kondo, E.; Ishii, J.; Fukagawa, K.; Yamato, Y.; Tobita, K.; Ando, Y.; Matsubara, N.; Horikoshi, T. Thermal comfort zone in outdoor environment. Journal of Human and Living Environment 2012, 19(2), pp. 115-127.
4. Kurazumi, Y.; Kondo, E.; Ishii, J.; Sakoi, T.; Fukagawa, K.; Bolashikov, Z.D.; Tsuchikawa, T.; Matsubara, N.; Horikoshi, T. Effect of the environmental stimuli upon the human body in winter outdoor thermal environment. Journal of Environmental and Public Health 2013, 2013, pp. 1-10.

5. Kurazumi, Y.; Ishii, J.; Kondo, E.; Fukagawa, K.; Bolashikov, Z.D.; Sakoi, T.; Tsuchikawa, T.; Matsubara, N.; Horikoshi, T. The influence of outdoor thermal environment on young Japanese female. International Journal of Biometeorology 2014, 58(5), 963-974.
6. Kurazumi, Y.; Ishii, J.; Fukagawa, K.; Aruninta, A. The influence of tropical urban climate upon the human body. International Joint Conference of SENVAR-iNTA-AVAN 2015 (SIA 2015), Johor, Malaysia, 24-26 November, 2015, pp. 105-114.
7. Kurazumi, Y.; Ishii, J.; Fukagawa, K.; Kondo, E.; Aruninta, A. Ethnic differences in thermal responses between Thai and Japanese females in tropical urban climate. American Journal of Climate Change 2016, 5(1), pp. 52-68.
8. Kurazumi, Y.; Ishii, J.; Fukagawa, K.; Kondo, E.; Nyilas, A.; Aruninta, A. Seasonal differences of psychological and physiological responses in tropical urban climate. Health 2017, 9(6), pp. 896-920.
9. Horikoshi, T.; Kurazumi, Y.; Hirayama, K.; Tsuchikawa, T.; Kobayashi, Y. Indication of the effect of asymmetric thermal radiation of the human physiological and psychological responses. Second World Congress on Heating, Ventilating, Refrigerating and Air-Conditioning-CLIMA 2000 III, Sarajevo, Yugoslavia, 27 August-1 September, 1989, pp. 188-193.
10. Kurazumi, Y.; Horikoshi, T.; Hirayama, K.; Tsuchikawa, T.; Kobayashi, Y. The influence of asymmetric and uneven thermal radiation environments upon the human body: In the case of constant operative temperature. Journal of Architecture, Planning and Environmental Engineering (Transactions of AIJ) 1993, 447, pp. 17-26.
11. Kurazumi, Y.; Saito, K.; Horikoshi, T. The influence of asymmetric thermal radiation environments upon the human body: In the case of constant operative temperature and right and left, back and forth asymmetry. Japanese Journal of Biometeorology 1994, 31(2), pp. 75-84.
12. Pfleiderer, H. Studien über den Würmehaushalt des Menschen. Zeitschrift für die Gesamte Experimentelle Medizin, 1993, 90, pp. 245-296.
13. Burton, A.C. Human calorimetry II. The average temperature of the tissues of the body. Journal of Nutrition 1935, 9(3), pp. 261-280.
14. Winslow, C.-E.A.; Herrington, L.P.; Gagge, A.P. A new method of partitional calorimetry. American Journal of Physiology 1936, 116(3), pp. 641-655.
15. Hardy, J.D.; DuBois, E.F. The technic of measuring radiation and convection. Journal of Nutrition 1938, 15(5), pp. 461-475.
16. Palmes, E.D.; Park, C.R. Thermal regulation during early acclimatization to work in a hot dry environment. Bulletin of the United States Army Medical Department Field Research Laboratory, Report 2-17-1, Fort Knox, Kentucky, 1947.
17. Research Committee on Physiological Reaction to Climatic Seasonal Change, 7th Division of Scientific Research Aid Board, Department of Education, Japan Seasonal variations of skin temperature distribution of Japanese male adults. Nisshin Igaku 1952, 39(3), pp. 121-136.
18. Kurata, M.; Funazu, Y. A practical method of evaluating mean skin temperature. The Journal of Science of Labour 1954, 30, pp. 332-337.
19. Teichner, W.H. Assessment of mean body surface temperature. Journal of Applied Physiology 1958, 12(2), pp. 169-176.
20. Iampietro, P.F.; Bass, D.E.; Buskirk, E.R. Heat exchanges of nude men in the cold: Effect of humidity, temperature and wind speed. Journal of Applied Physiology 1958, 12(3), pp. 351-356.
21. Miura, T.; Morioka, M.; Kimura, K.; Akutsu, A.; Hyodo, S.; Osawa, H.; Tihira, Y.; Okazima, T. Experimental studies on the optimum temperature of room cooling in summer in relation to the outdoor temperature. The Journal of Science of Labour 1960, 36, pp. 283-336.
22. Miura, T.; Kimura, K.; Akutsu, A.; Sato, T.; Morioka, M.; Kogi, K.; Takagi, K.; Masuda, T.; Nishibe, T. Experimental studies on the optimum temperature of room cooling for lightly clothed men in summer in relation to the outdoor temperature (Part I). The Journal of Science of Labour 1962, 38, pp. 198-214.
23. Ramanthan, N.L. A new weighting system for mean surface temperature of the human body. Journal of Applied Physiology 1964, 19(3), pp. 531-533.
24. Stolwijk, J.A.J.; Hardy, J.D. Partitional calorimetric studies of responses of man to thermal transients. Journal of Applied Physiology 1966, 21(3), pp. 967-977.
25. Mitchell, D.; Wyndham, C.H. (1969) Comparison of weighting formulas for calculating mean skin temperature. Journal of Applied Physiology 1969, 26(5), pp. 616-622.

26. Sasaki, T.; Yasumito, I.; Mizukami, M.; Inoue, T.; Ishihara, A.; Taniguchi, M. Observation of the seasonal change in metabolism of Japanese in the basic condition. The Bulletin of the Constitutional Medical Research Institute, Kumamoto University 1969, 20, pp. 72-78. (in Japanese)
27. Nadel, E.R.; Bullars, R.W.; Stolwijk, J.A.J. Importance of skin temperature in the regulation of sweating. Journal of Applied Physiology 1971, 31(1), pp. 80-87.
28. Roberts, M.F.; Wenger, C.B.; Stolwijk, J.A.J.; Nadel, E.R. Skin blood flow and sweating changes following exercise training and heat acclimation. Journal of Applied Physiology 1977, 43(1), pp. 133-137.
29. Kurazumi, Y.; Horikoshi, T.; Tsuchikawa, T.; Matsubara, N. The body surface area of Japanese. Japanese Journal of Biometeorology 1994, 31(1), pp. 5-29.
30. Kurazumi, Y.; Tuchikawa, T.; Torii, T.; Kakutani, K.; Matsubara, N.; Horikoshi, T. Weighting coefficients for calculating mean skin temperature when considering convective heat transfer areas. Journal of the Human-Environmental System 2004, 7(1), pp. 19-28
31. Kurazumi, Y.; Tsuchikawa, T.; Kakutani, K.; Yamato, Y.; Torii, T.; Matsubara, N.; Horikoshi, T. Mean skin temperature taking into account convective heat transfer areas - Calculation method of seiza sitting, cross-legged sitting, sideway sitting, both-knees-erect sitting, leg-out sitting, lateral and supine positions. Journal of Environmental Engineering (Transactions of AIJ) 2004, 585, pp. 19-26.
32. Horikoshi, T.; Dohi, M.; Tsuji, C. Experimental study on the influence of thermal conditions upon the human physiological and psychological responses in air-conditioned room. The Annals of Physiological Anthropology 1987, 6(4), pp. 255-266.
33. Sakai, K.; Choi, Y.; Umemura, S.; Horikoshi, T.; Mizutani, A. The effect of air and floor temperature on the human skin temperature, thermal sensation and heat balance. Summaries of Technical Papers of 1992 Annual Meeting of Architectural Institute of Japan Environmental Engineering 1992, 1992, pp. 999-1000.
34. Miyamoto, S.; Taniguchi, Y.; Araki, K.; Tsuchikawa, T.; Choi, Y.; Horikoshi, T. Index of thermal environment in a floor-heated room and its verification. Summaries of Technical Papers of 1994 Annual Meeting of Architectural Institute of Japan Environmental Engineering 1994, pp. 351-352.
35. Choi, Y.; Horikoshi, T.; Miyamoto, S.; Mizutani, A. Combined effect of air and heated floor temperature on man in Japanese sitting posture. Journal of Architecture, Planning and Environmental Engineering (Transactions of AIJ) 1996, 480, pp. 7-14.
36. Watanabe, S.; Horikoshi, T.; Miyoshi, Y.; Miyamoto, S.; Mizutani, A. Thermal effect of heating facility KOTATSU on the human body in Japanese style room. Journal of Architecture, Planning and Environmental Engineering (Transactions of AIJ) 1997, 497, pp. 39-45.
37. Kurazumi, Y.; Yamato, Y.; Yamamoto, S.; Matsubara, N. The new weighting coefficients of mean skin temperature calculating formulas in relation to posture. Japanese Journal of Biometeorology 1997, 34(1), pp. 101-112.
38. Kurazumi, Y.; Matsubara, N.; Furukawa, N.; Fujiwara, M.; Ue, A.; Ueki, Y.; Nagai, H.; Yamamoto, S. Japanese weighting coefficients for calculating mean skin temperature in relation to posture. Japanese Journal of Biometeorology 1998, 35(4), pp. 121-132.
39. Kurazumi, Y.; Tsuchikawa, T.; Ishii, J.; Fukagawa, K.; Yamato, Y.; Matsubara, N. Radiative and convective heat transfer coefficients of the human body in natural convection. Building and Environment 2008, 43(12), pp. 2142-2153.
40. Mochida, T.; Nishi, Y. Calculating mean skin temperature in relation to local heat transfer coefficient. Technical Papers of Annual Meeting of The Society of Heating, Air-Conditioning and Sanitary Engineers of Japan 1971, 1971, pp. 95-98. (in Japanese)
41. Mochida, T. Calculating mean skin temperature by means of engineering method. Technical Papers of the 6th Annual Meeting of Hokkaido Branch of The Society of Heating, Air-Conditioning and Sanitary Engineers of Japan 1972, 1972, pp. 5-6. (in Japanese)
42. Mochida, T. Mean skin temperature weighted with both heat transfer coefficient and skin area. Transactions of AIJ 1977, 259, pp. 67-73.
43. Ishigaki, H.; Horikoshi, T.; Mochida, T.; Uematsu, T. Experimental determination of convective heat transfer coefficient for the human body Part 5. Summaries of Technical Papers of 1991 Annual Meeting of Architectural Institute of Japan Environmental Engineering 1991, 1991, pp. 725-726.
44. Kuwabara, K.; Mochida, T.; Nagano, K.; Shimakura, K. Fundamental study of weighting factor for calculating mean skin temperature. Journal of Human and Living Environment 2001, 8(1, 2), pp. 33-40.

45. Nadel, E.R.; Mitchell, J.W.; Stolwijk, J.A.J. Differential thermal sensitivity in the human skin. Pflügers Archiv 1973, 340, pp. 71-76.
46. Mochida, T. Weighting coefficient for calculating mean skin temperature. Japanese Journal of Biometeorology 1982, 19(3), p. 55. (in Japanese)
47. Jordan, S.; Lim, L.; Seubsman, S.; Bain, C.; Sleigh, A. Secular changes and predictors of adult height for 86 105 male and female members of the Thai Cohort Study born between 1940 and 1990. Journal of Epidemiology and Community Health 2012, 66(1), pp. 75-80.
48. Kurazumi, Y.; Horikoshi, T.; Tsuchikawa, T.; Matsubara, N. The body surface area of Japanese. Japanese Journal of Biometeorology 1994, 31(1), pp. 5-29.
49. World Medical Association: WMA Declaration of Helsinki – Ethical Principles for Medical Research Involving Human Subjects. https://www.wma.net/policies-post/wma-declaration-of-helsinki-ethical-principles-for-medical-research-involving-human-subjects/ (accessed on 9 July 2018)
50. Horikoshi, T.; Tsuchikawa, T.; Kurazumi, Y.; Hirayama, K.; Kobayashi, Y. Indication of asymmetric and uneven thermal radiation environment related to thermal comfort and discomfort. Journal of Architecture, Planning and Environmental Engineering (Transactions of AIJ) 1990, 413, pp. 21-28.
51. Maruyama, Y.; Tamura, T. Responses of skin temperature to unevenly distributed and thermal sensation thermal stimuli. Japanese Journal of Biometeorology 1989, 26(3), pp. 143-154.