Proposition of heat-stroke risk assessment based on potential effective sweating possible to measure with portable equipment and its application to the Tokyo 2020 Summer Olympic marathon event

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Abstract

We developed a method to assess heat-stroke risk during exercise in the outdoor environment based on the potential effective sweating (PES). The PES indicates the minimum effective sweating required to maintain a constant body temperature when undertaking an activity in the outdoor environment. It can be calculated easily using observed meteorological data, body size, clothing, and exercise intensity. Additionally, we propose the concept of globe PES (PESg), which can be measured using portable equipment, such as a wet-bulb globe temperature (WBGT) meter. Especially, PESWBGT can be estimated by only WBGT observations. We performed a thermal-load exposure experiment with human subjects in an outdoor urban environment, and compared the three kinds of effective sweating and actual potential sweating. The calculated PES values had deviations of 33.3–42.7% from actual potential sweating. We assessed the risk of heat stroke based on the decrease in a runner’s weight using routine meteorological data observed in recent decades. Calculations were made for start times set at 30-min intervals from 05:00 to 19:00 on August 2 and 9, the dates of the marathon event in the 2020 Summer Olympics in Tokyo. When the start time was set from 9:30 to 11:00, a runner’s weight was estimated to decrease by an average of 7.37–7.40% and a maximum of 8.09–8.20% by the end of the race. A postural movement or convulsion is likely to occur if the runner did not drink water. When the start time was set to 06:00, the weight decrease was predicted to be 6.18–7.15%; the thermal load at this time was equivalent to that of a 15:00 or 15:30 start time. Thermal loads may be smaller in the early evening than in the early morning. The average wind speed is weaker in the morning than in the afternoon, thereby decreasing the effect of wind on cooling the surfaces of the human body and the road in the morning. Hence, a change in the start time to early morning may not significantly decrease the thermal load.

Key words: Heat illness, Heat island, PES, Summer Olympics, WBGT

1. Introduction

In a study of the Tokyo heat island by the Japan Meteorological Agency based on observational data, the mean summer temperature in Tokyo rose by 1.2°C between 1931 and 2017 (Japan Meteorological Agency, 2018). The 2020 Summer Olympics in Tokyo will be held from July 24 to August 9, 2020, during the hottest season in Japan. Therefore, both athletes and spectators will need to take measures to avoid heat illness.

Ministry of the Environment, 2018).

Human sensitivity to heat in the outdoor environment is affected not only by temperature but also by other weather factors, including radiation, humidity, and wind speed. Thermal comfort indices are standardized scales used to evaluate human thermal comfort, while considering homeoastasis and physiological responses (Ohashi, 2010). In Japan, the Ministry of the Environment recommends the wet-bulb globe temperature (WBGT) as an index of heat stress (Ministry of the Environment, 2019), and the Japan Sport Association has published a policy to prevent heat illness based on the WBGT (Japan Sport Association, 2013). Several studies have evaluated the risk of heat illness based on the WBGT during a marathon event for the 2020 Summer Olympics in Tokyo (Kashimura et
using a \( WBGT \) meter that also records wind speed, whereas \( PE_{S_{WBGT}} \) can be estimated from the \( WBGT \). Each validity was also evaluated through a comparison with actual effective sweating when subjects undertook exercise in the outdoor environment, same as \( PES \).

2. Materials and Methods

2.1 Thermal-load exposure of subjects in an urban area

An experiment to assess thermal-load exposure was conducted with 10 subjects, between August and October 2013–2018. The subjects were named as subjects A to J. The subjects left the laboratory and conducted exercise during a 10–105-min period at a nearby outdoor location, at which selected meteorological elements were measured. The experimental sites were located in an urbanized area of Osaka City, Japan, and included locations in a green park, alongside a river, and under a highway. All subjects were male and 21 years old. The experiments were performed under various conditions in terms of exercise type and duration, experimental site, season, and date. The body sizes of the subjects and a summary of the experimental conditions are listed in Table 1. The maximum and average heart rates during each exercise were measured using a vivosmart HR (Garmin Ltd., Olathe, KS, USA), except for those of subjects A, B, and C. For each subject, the body weight and the weight of clothes and a drink bottle were measured before and after exercise using the following method:

1. Before the experiment, the weight of each subject wearing only underwear was measured to the nearest 1 g using an electric scale GP-100KS (A&D Company, Limited, Tokyo, Japan). The measurement was performed in an air-conditioned room where sweating did not occur.

2. The weights of clothing, sweat towel, and drink bottle were also measured to the nearest 0.1 g using an electric scale ELB3000S321 (Shimadzu Corporation, Kyoto, Japan).

3. Each subject undertaking the “jump rope” and “dancing” exercises moved to the experimental site and started the exercises. Meteorological observations were taken during the exercises.

4. Each subject undertaking the moving exercises started the exercise. Mobile meteorological observations were made during the exercises.

5. The subjects returned to the laboratory immediately after exercise, wiped the sweat from their bodies, and placed their clothes and towels into a bag to be weighed. Their body weight and drink bottle weight were also measured.

Actual effective sweating was calculated as follows:

\[
E_{s_{act}} = (W_{before} - W_{after}) - (W_{before} - W_{before})\]

where \( E_{s_{act}} \) is actual effective sweating (g); \( W_{before} \) and \( W_{after} \) are the weights of the subject, their clothes, and the drink bottle before the experiment, respectively (g); and \( W_{before} \) and \( W_{after} \) are the weights of the subject, their clothes, and the drink bottle after the experiment, respectively (g). Only three subjects, H, I, and J, consumed water during the exercise; therefore, the weight of drinking water was 0 for the other subjects. Note that \( W_{before} - W_{after} \) is the weight loss due to actual sweating. We considered that actual effective sweating or actual...
sweating reflected human heat stress most accurately. The study conformed with The Protocol of Ethics concerning Research with Human Subjects of the Osaka Institute of Technology and informed consent to participate in the experiment and to publish the findings was obtained from the study participants. A list of the main abbreviations is shown in Table 2.

### 2.2 Meteorological observations

The thermal environment was observed during each subject’s exercise. Meteorological elements were measured, including air temperature, relative humidity, wind speed, globe temperature, solar radiation, reflectance of solar radiation, ground infrared radiation, and downward infrared radiation. Air temperature and relative humidity (RH) were measured using a HMP155 probe (Vaisala Inc., Vantaa, Finland) installed in a ventilated tube. Wind speed was measured using an ultrasonic anemometer (Wind Sonic; Gill Instruments, Lymington, UK) and globe temperature was measured using a T-type thermocouple thermometer in a black bulb (φ 15 cm; Climatex Inc., Tokyo, Japan). These measurement data were recorded using CR-1000 (Campbell Scientific Inc., Logan, USA) or GL220A (Graphtec Corp., Tokyo, Japan) data loggers. In addition, radiation was measured using a CNR-1 radiometer (Kipp & Zonen, Delft, the Netherlands) with a data logger (Thermic Model 2300A; Eto denki Inc., Tokyo, Japan) for subjects A and B and a NR01/RA01 radiometer (Hukseflux, Delft, the Netherlands) with a CR-1000 logger for the other subjects. The measurement interval was 1 s, and a moving average was calculated every 1 min based on the 30 s before and after.

Each part of the human body can be exposed to different weather conditions due to the vertical profile of air temperature above the ground surface, and the equivalent distance of the air temperature from a human’s upper body to their head. The meteorological observation equipment used is shown in Photograph 1, together with the experimental setup for subjects A and B.

### 2.3 Potential effective sweating (PES)

Takayama et al. (2008) proposed the heat stress index (HSI) as a thermal comfort index to evaluate the heat stress received as a result of surrounding weather conditions in an urban area. The HSI is defined as a scale of temperatures that will cool a body by effective sweating and maintain the heat balance of the body. It is based on a human heat balance model for an adult male of standard body size standing for 10 min in a given thermal environment wearing summer-style clothing (e.g., a T-shirt). The practicality and validity of the HSI, $HSI$, which is a modified $HSI$,

| Subject | Height (m) | Mean weight (kg) | Action | Experiment site | n | Mean action time (min) | Clothes | Experiment period |
|---------|-----------|------------------|--------|----------------|---|-----------------------|---------|-------------------|
| A       | 1.72      | 64.364           | Walking with barrow | Urbanization area road | 23 | 16 | White T shirt and short pants | 12 days from Aug. 6 to Oct. 4, 2013. |
| B       | 1.68      | 52.167           | Work clothes with electric fan | Greening park road | 21 | 16 | Work clothes | 11 days from Aug. 17 to Sep. 8, 2014. |
| C       | 1.73      | 53.501           | Bike riding | Urbanization area road | 4  | 19 | Work clothes | 11 days from Aug. 17 to Sep. 8, 2014. |
| D       | 1.73      | 69.564           | Jump rope | Greening park area | 5  | 18 | Work clothes | 20 days from Sep. 7 to Oct. 16, 2015. |
| E       | 1.65      | 59.000           | Dancing | Greening park area | 1  | 10 | White T shirt and short pants | 16 days from Aug. 2 to Oct. 27, 2016. |
| F       | 1.85      | 75.408           | Bike riding | Urbanization area road | 1  | 23 | White T shirt and short pants | 3 days from Jul. 29 to Aug. 1, 2017. |
| G       | 1.75      | 64.897           | Bike riding | Urbanization area road | 1  | 24 | White T shirt and short pants | 3 days from Jul. 29 to Aug. 1, 2017. |
| H       | 1.72      | 60.253           | Bike riding with drinking water | Urbanization area road | 5  | 105 | White T shirt and short pants | 20 days from Jul. 27 to Oct. 8, 2018. |
| I       | 1.60      | 58.044           | Bike riding with drinking water | Urbanization area road | 5  | 68 | White T shirt and short pants | 20 days from Jul. 27 to Oct. 8, 2018. |
| J       | 1.65      | 53.161           | Bike riding with drinking water | Urbanization area road | 1  | 101 | White T shirt and short pants | 3 days from Aug. 27 to Aug. 31, 2018. |
were investigated as an index of the human thermal load from the surrounding environment by Takayama et al. (2014, 2015).
In this study, we used the potential effective sweating PES to assess human heat stress. The PES indicates the minimum effective sweating required to maintain a constant body temperature when a human undertakes outdoor activity, and is calculated as follows:

\[
PES = \sum_{t_f}^{t_{finish}} E_s \times t_{act} \times A_{body} 
\]

\[
A_{body} = 0.2 m^{0.425} h^{0.225} 
\]

where \( E_s \) is the evaporation rate of sweat on a human body (mm s\(^{-1}\)); "\( t_f \)" and "\( t_{finish} \)" are the first and last steps of the exercise, respectively; \( t_{act} \) is a time step of the exercise (=60 s); \( A_{body} \) is the body area of each subject (m\(^2\)); and \( m \) and \( h \) are the weight (kg) and height (m) of the subject, respectively. The heat balance of a human can be determined as follows:

\[
R_{abs} - L_{be} + M - lE_s - H - G - Q = 0 
\]

where \( R_{abs} \) is the total radiation flux absorbed by the human body surface; \( L_{be} \) is the longwave infrared radiation emitted from the body surface; \( M \) is the rate of metabolic heat generation per unit area (W m\(^{-2}\)); \( lE_s \) is the latent heat transfer per unit area of body surface (W m\(^{-2}\)); \( H \) is the rate of heat loss by sensible heat transfer (W m\(^{-2}\)); \( G \) is the rate of heat loss by evaporative heat transfer (W m\(^{-2}\)); and \( Q \) is the rate of heat loss by convection heat transfer (W m\(^{-2}\)).

Table 2. List of main abbreviations.

| Abbreviation | Term | Constant | Unit |
|--------------|------|----------|------|
| \( A_{body} \) | Body area | | m\(^2\) |
| \( E_s \) | Evaporation rate of sweat on a human body | | mm s\(^{-1}\) |
| \( E_{es,act} \) | Actual effective sweating | | g |
| \( E_{es,g} \) | Evaporation rate of sweat on a human body based on the globe temperature | | mm s\(^{-1}\) |
| \( g_{h,b} \) | Conductance of heat by the boundary layer | \( g_{h,b} (0)=0.27 \) | mol m\(^{-2}\) s\(^{-1}\) |
| \( g_{h,b} \) | Conductance of heat by the human body | | g |
| \( g_{h,sk} \) | Conductance of heat by the skin | | g |
| \( g_{h,t} \) | Conductance of heat by the clothing | | g |
| \( H \) | Conductance of heat by the tissue | 2.8 | g |
| \( H \) | Rate of heat loss by sensible heat transfer | | W m\(^{-2}\) |
| \( I \) | Latent heat of evaporation | 2501 | J g\(^{-1}\) |
| \( L_{be} \) | Longwave infrared radiation emitted from the body surface | | W m\(^{-2}\) |
| \( L_d \) | Downward atmospheric longwave radiation | | W m\(^{-2}\) |
| \( L_u \) | Upward ground longwave radiation | | W m\(^{-2}\) |
| \( lE_s \) | Latent heat transfer per unit area of body surface | | W m\(^{-2}\) |
| \( M \) | Rate of metabolic heat generation per unit area | | W m\(^{-2}\) |
| \( PES \) | Potential effective sweating | | g |
| \( PES_{glob} \) | Globe potential effective sweating | | g |
| \( R_{abs,g} \) | Total radiation flux absorbed by the human body surface based on the heat balance of the globe thermometer | | W m\(^{-2}\) |
| \( rh \) | Relative humidity | | % |
| \( S_t \) | Global solar radiation | | W m\(^{-2}\) |
| \( S_r \) | Reflectance of solar radiation | | W m\(^{-2}\) |
| \( T_b \) | Human core temperature | | K |
| \( T_a \) | Operative temperature | 37.5 | °C |
| \( T_e \) | Globe operative temperature | | °C |
| \( T_e,g \) | Globe operative temperature | | °C |
| \( T_r \) | Road surface temperature | | °C |
| \( T_w \) | Wet bulb temperature | | °C |
| \( U_{obs} \) | Observed wind speed at \( z_{ref} \), height of AMeDAS station | | m s\(^{-1}\) |
| \( WDR \) | Percentage of weight decreasing | | % |
| \( z \) | Reference height of wind speed | | m |

Photograph 1. Appearance of subjects A and B in the experiment and the meteorological observation equipment.
body surface; $\dot{E}_s$ is the latent heat transfer per unit area of body surface; $\dot{M}$ is the rate of metabolic heat generation per unit area; $\dot{H}$ is the rate of heat loss by sensible heat transfer; $\dot{G}$ is the rate of heat loss by ground heat transfer, and $Q$ is the rate of heat storage by the human body per unit area. In this study, we assumed that $Q = G = 0$ and latent heat transfer occurs only by effective sweating, while ignoring vapor from respiration; therefore, $\dot{I}$ is the latent heat of evaporation (2501 J g$^{-1}$). The value of $\dot{E}_s$ (W m$^{-2}$) was calculated as follows (Campbell and Norman, 1998):

$$\dot{E}_s = \frac{1}{I} M \left( \frac{C_p g_{0,\text{clo}} + g_r}{g_{0,\text{clo}} + g_r} \right) (T_s - T_0)$$

$$g_{\text{clo}} = \left( \frac{g_{0,\text{clo}} + g_r(u)}{g_{0,\text{clo}} + g_r(u)} \right)^{-1}$$

where $C_p$ is the specific heat at a constant pressure ($29.3$ J mol$^{-1}$ K$^{-1}$); $g_{0,\text{clo}}$, $g_r$, $g_{\text{clo}}$, and $g_{\text{clo}}$ are the conductance of heat by the boundary layer, radiation, human body, tissue ($2.8$), skin, and clothing, respectively (mol m$^{-2}$ s$^{-1}$ K$^{-1}$); $u$ is the wind speed (m s$^{-1}$); $T_s$ is the human core temperature (C$^\circ$); and $T_0$ is the operative temperature (C$^\circ$), which is the equivalent temperature to the amount of heat that the body receives by sensible heat transfer and radiation from the surrounding outdoor environment. $g_{\text{clo}}$, $g_r$, and $g_{\text{clo}}$ were calculated as follows:

$$g_{\text{clo}} = 1.4 \times 10^{-3} \sqrt{\frac{d}{\alpha}}$$

$$g_r = \frac{4 \alpha_0 \sigma T_s^4}{C_p}$$

$$g_{\text{clo}}(u) = g_{0,\text{clo}}(0)(1 + cu)$$

where $d$ is the characteristic length of the human body (0.17 m); $\alpha_0$ is the radiation absorptivity of the human body (0.95); $\sigma$ is the Stefan–Boltzmann constant ($5.6697 \times 10^{-8}$ W m$^{-2}$ K$^{-4}$); $T_s$ is the air temperature (K); $g_{0,\text{clo}}(0)$ is the conductance of heat by skin under calm wind conditions ($0.27$ mol m$^{-2}$ s$^{-1}$ at $u = 0$ m s$^{-1}$); and $c$ is the coefficient of skin thickness (0.23 s m$^{-1}$). $g_{\text{clo}}$ was calculated as the sum of the $\text{clo}$ values for each clothing item, because the clothing of each subject was different (Gagge et al., 1941; SHASE, 2006):

$$I_{\text{clo}} = 0.708 \sum_i I_{\text{clo},i} + 0.052$$

$$g_{\text{clo}}(u) = 0.155 \times (L_{\text{clo}})^{-1} \times \frac{1}{29.3}$$

where $I_{\text{clo}}$ is the sum of the $\text{clo}$ values of a subject’s clothing and $L_{\text{clo}}$, is the $\text{clo}$ value of each clothing article according to Hanada (1992). Details of the clothing worn by each subject are shown in Table 3. In this study, we did not consider the effect of clothing color. The $\dot{I}E_s$ value was calculated based on meteorological data per minute during exercise, and we calculated $\dot{PES}$ by accumulating the values of $\dot{I}E_s$ divided by latent heat ($1 = 2501$ J g$^{-1}$) from the start to the finish of the exercise. The term $T_s$ in Equation (5) can be calculated as follows:

$$T_s = T_r + \frac{R_{\text{abs}} - \alpha_0 \sigma T_r^4}{C_p (g_{\text{clo}} + g_r)} = 273.15$$

$R_{\text{abs}}$ was calculated with Equation (13) when four elements of radiation had been observed using a net radiometer:

$$R_{\text{abs}}(T) = \alpha_0 (F_r S_r + F_s S_s) + \alpha_r (F_r L_r + F_s L_s)$$

where $\alpha_0$ is the absorptivity of solar radiation (0.92); $S_r$ and $S_s$ are the global solar radiation and reflectance of solar radiation (W m$^{-2}$), respectively, and their view factors are $F_r$ and $F_s$; and $L_r$ and $L_s$ are downward atmospheric and upward ground longwave radiation (W m$^{-2}$), respectively, and their view factors are $F_r$ and $F_s$. The human body was assumed to be spherical in this study; therefore, we set $F_r = F_s = F_r = F_s = 0.5$.

We validated the effectiveness of the $\dot{PES}$ through comparisons with effective sweating when subjects undertook exercise outdoors.

| Table 3. Parameters used for the clothing and the quantity of activity for each subject. $N$ is the data number used in the regression analysis between the WBGT and $\dot{M} - \dot{E}_s$. |
|---|---|---|---|---|---|---|
| Subject | Action | MEIs | $\dot{M}$ | Clothes | Detail | Weight (g) | $\text{clo}$ | $L_{\text{clo}}$ | $g_{\text{clo}}$ | $\text{WBGT}$ |
| A | Walking with barrow | 4.0 | 180 | White T shirt and short pants | Trunks | 68 | 0.05 | 0.26 | 0.86 | 22 |
| | | | | | Short | 114 | 0.12 | | | |
| | | | | | T shirt | 95 | 0.12 | | | |
| | | | | | | 163 | 22 |
| C | Bike riding | 7.5 | 300 | Work clothes | Trunks | 68 | 0.05 | 0.26 | 0.86 | 49 |
| | | | | | Long pants | 488 | 0.29 | 0.61 | 0.36 | 19 |
| | | | | | T shirt | 95 | 0.12 | | | |
| | | | | | Working | 215 | 0.33 | | | |
| | | | | | | | | | | |
| D | Jump rope | 7.5 | 300 | Black T shirt and short pants | Trunks | 68 | 0.05 | 0.26 | 0.86 | 49 |
| | | | | | Short | 114 | 0.12 | | | |
| | | | | | T shirt | 95 | 0.12 | | | |
| | | | | | | | | | | |
| E | Jump rope or Dancing | 7.5 | 300 | Black T shirt and short pants | Trunks | 68 | 0.05 | 0.26 | 0.86 | 49 |
| | | | | | Short | 114 | 0.12 | | | |
| | | | | | T shirt | 95 | 0.12 | | | |
| | | | | | | | | | | |
| F | Bike riding or Running | 7.5 | 300 | Black T shirt and short pants | Trunks | 68 | 0.05 | 0.26 | 0.86 | 49 |
| | | | | | Short | 114 | 0.12 | | | |
| | | | | | T shirt | 95 | 0.12 | | | |
| | | | | | | | | | | |
| G | Bike riding | 7.5 | 300 | Black T shirt and short pants | Trunks | 68 | 0.05 | 0.26 | 0.86 | 19 |
| | | | | | Short | 114 | 0.12 | | | |
| | | | | | T shirt | 95 | 0.12 | | | |
| | | | | | | | | | | |
| H | Bike riding with drinking | 7.5 | 300 | Black T shirt and short pants | Trunks | 68 | 0.05 | 0.26 | 0.86 | 19 |
| | | | | | Short | 114 | 0.12 | | | |
| | | | | | T shirt | 95 | 0.12 | | | |

DOI: 10.2480/agrmet.D-19-00025
2.4 Evaluation of the heat illness risk for marathon runners in the 2020 Summer Olympics in Tokyo based on PES

The men’s marathon started at 13:00 on October 21 in the 1964 Summer Olympics in Tokyo. In the 2020 Summer Olympics, the women’s and men’s marathon events will be held on August 2 and 9, respectively. The Japanese Olympic Committee has set the start time of the marathon to 06:00 to avoid heat illness*. We evaluated the risk of heat illness in the marathon based on the decrease in body weight due to sweating using PES,

\[
WDR = \frac{PES}{10 \times m}
\]  

where \(WDR\) is the percentage of weight decrease (%). We simulated the PES of runners based on routine meteorological data observed from 2009 to 2018 on August 2 and 9, and October 21, for start times set every 30 min between 05:00 and 19:00. The body size of a runner was assumed to be 175 cm (height) and 55 kg (weight) for a male, and 157 cm and 45 kg for a female, and it was assumed that metabolic equivalents (\(METs\)) = 17 and \(t_{\text{food}} = t_{\text{fuel}} = 140\) min. The air temperature, relative humidity, and wind speed vary every 10 min, as well as the total global solar radiation every 1 h, were observed at the Tokyo Automated Meteorological Data Acquisition System (AMeDAS) station. Downward atmospheric longwave radiation every 1 h was observed at Tsukuba (Tateno) station. These values were used as the meteorological elements to calculate PES by interpolating every 1 min. The wind speed is the dominant factor in the PES calculation. Wind vectors should be considered in the trajectory of the athlete and in terms of the general wind to assess the PES of a marathon runner. However, it is difficult to estimate the wind conditions on the marathon course in an urban area with a complex surface. Therefore, we used only the wind speed data at the AMeDAS Tokyo station with height correction to apply to Equations (7) and (9), for the PES calculation. The height of the anemometer at the AMeDAS Tokyo station is 35.3 m above the ground surface. We corrected the observed wind speed \(U_{\text{obs}}\) at \(z_{\text{obs}} = 35.3\) m to the wind speed \(U^*\) at the reference height \(z = 1.2\) m using Equations (7) and (9).

\[
u = U_{\text{obs}} \frac{\ln (z/z_0)}{\ln (z_{\text{obs}}/z_0)}
\]

In the equations above, \(z_0\) is the roughness length for the wind profile (= 0.01 m). Upward ground longwave radiation was calculated as follows:

\[
L_u = e_{\text{road}} \sigma T_s^4
\]

where \(e_{\text{road}}\) is the emissivity of infrared (= 0.93); the road surface temperature \(T_s(K)\) was calculated following Kondo (1992):

\[
T_s = T_e + \frac{Q - 4\sigma T_e^4 - U \rho C_f U [q_{\text{sat}}(T_e) - q_e]}{4\sigma T_e^4 + C_f \rho C_f U + U \rho C_f U \Delta}
\]

\[
Q = R^4 - G
\]

*The Tokyo Organising Committee of the Olympic and Paralympic Games is just planning that women’s and men’s marathon will be held in August 8 and August 9, respectively, in Sapporo city, and both start time will be at 7 AM. We will report the another short paper for this.

where \(R^4 = (1 - ref) S_\perp + L_d\)

\[
G = G_1 \cos \left( 60 \cdot \omega t - \phi + \frac{\pi}{4} \right)
\]

\[
G_1 = A_1 \left( \frac{c_2 \rho \beta c}{\mu} \right) \frac{R^4}{\mu + \gamma}
\]

\[
\phi = \arctan \left( \frac{\gamma R^4 + \xi B_1 \left( \cos \alpha + \left( t + \gamma \right) \sin \alpha \right)}{\left( t + \gamma \right) R^4 + \xi B_1 \left( \cos \alpha - \gamma \sin \alpha \right)} \right)
\]

\[
\gamma = \left( \frac{\alpha c_2 \rho \beta c}{\mu} \right) \frac{R^4}{\pi}
\]

\[
\xi = 4 \sigma T_s^3 + C_f \rho C_f U
\]

\[
\mu = 4 \sigma T_s^3 + C_f \rho C_f U + U \rho C_f U \Delta
\]

where \(R^4\) is the input radiation flux; \(G\) is the ground heat transfer flux (W m\(^{-2}\)); and \(\text{ref} = 0.15\) and the efficiency of evaporation is \(\beta = 0\) with the assumption of a dry road surface; \(C_f\) is the bulk coefficient of sensible heat transfer; and \(c_f, \rho_f, \beta_f\) are the specific heat, density, and thermal conductivity of an asphalt road, respectively. We set \(C_f = 0.0094, c_f \rho_f = 1.22 \times 10^{6}\) J m\(^{-3}\) K\(^{-1}\), and \(\beta_f = 0.91\) W m\(^{-1}\) K\(^{-1}\), based on the experimental results of Kinouchi and Kobayashi (1999). However, they set an anemometer at a height of 0.65 m in their experiment to calculate the bulk coefficient. Therefore, we corrected the observed wind speed \(U_{\text{obs}}\) at \(z_{\text{obs}} = 35.3\) m to the wind speed \(U^*\) at the reference height \(z = 0.65\) m using Equation (15). \(q_{\text{sat}}(T_e)\) and \(q_e\) is the saturation-specific humidity for air temperature and the specific humidity, respectively. \(\Delta\) is the slope of the specific humidity for air temperature, which was calculated as the daily mean temperature; the subscript “1” represents an amplitude, and \(A_1\) and \(B_1\) are the amplitudes of \(T_e\) and \(T_s\), respectively; \(\omega\) is the angular velocity of the daily cycle (7.27221 \times 10^{-4}\) radian; \(t\) is the time in 1-min increments, in which \(t = 0\) at 04:30 (the start time) and \(t = 1439\) at 04:29 the following day; \(B_s\) is half of the diurnal range of temperature; \(\Phi\) and \(\alpha\) are the phase differences for \(T_e\) and \(T_s\), respectively (radian); \(\alpha\) was calculated as the difference in the times at which the maximum values of \(R^4\) and \(T_s\) were observed; and the subscript “M” indicates a daily average.

2.5 Measuring potential effective sweating with portable equipment (PES)

It is usually difficult to measure solar and infrared radiation using portable equipment. Therefore, we introduced a method to calculate the sum of the radiation flux absorbed by the human body surface based on the globe temperature, considering the practicality of the measurement. Globe temperature is the equivalent temperature of a non-heated spherical globe through radiation and convection. Thus, a globe thermometer enables the calculation of total radiation flux absorbed by the human body surface \(R_{\text{abs}}\) (W m\(^{-2}\)), based on the heat balance of the globe thermometer, with the following equations (Ohashi et al., 2010; Toriyama et al., 2001):

\[
R_{\text{abs}} = \rho C_f \xi U (T_e - T_s) + \rho \sigma T_s^4
\]

DOI: 10.2480/agrmet.D-19-00025
\[ C_p = 0.0156 u^{-0.82} \quad (u \leq 2.0) \]
\[ C_{Hv} = 0.019 \quad (u > 2.0) \]  
(28)

where \( \rho \) is the density of the atmosphere (1.2 kg m\(^{-3}\)); \( C_p \) is the specific heat at constant pressure (1006 J kg\(^{-1}\) K\(^{-1}\)); \( C_{Hv} \) is the bulk coefficient of sensible heat transfer; \( T_e \) is the globe temperature (K); and \( \varepsilon \) is the radiation absorptivity of a black bulb (0.95). We defined the globe operative temperature \( T_{eo}(^\circ \text{C}) \), which was distinguished from \( T_e \) as the operative temperature calculated by Equation (12), applying \( R_{amb,e} \) instead of \( R_{amb} \) and also defined the evaporation rate of sweat on a body (mm s\(^{-1}\)) and the globe potential effective sweating \( PES_g \) (g) as \( PES \) calculated using Equation (5), applying \( T_{eo} \).

\[
T_{eo} = T_e + \frac{R_{amb,e} - \alpha_t \sigma T_e^4}{C_p (g_{so} + g_r)} - 273.15
\]
(29)

\[
E_{eo} = \frac{1}{I} \left( \frac{M - C_{Hv} (g_{so} + g_r) (T_0 - T_{eo})}{1 + (g_{so} + g_r)/g_r} \right)
\]
(30)

\[
PES_g = \sum_{t_0} E_{eo} \times t_{eo} \times A_{body}
\]
(31)

where \( E_{eo} \) is the evaporation rate of sweat on a human body based on the globe temperature (mm s\(^{-1}\)). The meteorological elements required for \( PES \) calculations are only \( T_e, \rho, T_e, \) and \( u \).

### 2.6 Potential effective sweating possible to estimate from wet-bulb globe temperature (PES\(_{wbgt}\))

The \( WBGT \) (°C) (Yaglou and Minard, 1957) is an index of sensitivity that describes how a human feels in their surrounding thermal environment. It has been defined by the following equation in the outdoor environment:

\[
WBGT = 0.7T_e + 0.27T_0 + 0.11T_s
\]
(32)

where \( T_s \) is the wet-bulb temperature (°C).

The water vapor pressure, \( e_v \) (hPa), was calculated based on the air temperature and relative humidity using the Tetens equation (Tetens, 1930) as the first step in the \( T_e \) calculation. \( T_e \) was obtained in the next step using a convergent calculation as it approached \( e_v \) in the Sprung equation:

\[
e_v = \rho \times 6.11 \times 10^{7.5T_e / (237.3+T_e)}
\]
(33)

\[
e_v = e_{sat,e} - \left( \frac{A}{755} \right) (T_e - T_s) \rho \]
(34)

where \( e_{sat,e} \) is the saturation vapor pressure for \( T_e \) as calculated by Equation (34); \( A \) is a constant (0.50); and \( \rho \) is atmospheric pressure (1000 hPa).

Electric-type relative humidity sensors have become popular in recent years, with typical \( WBGT \) sensors measuring \( T_e, \rho, \) and \( T_e \) to calculate the \( WBGT \). The meteorological data (air temperature, humidity, and globe temperature) required to calculate the \( WBGT \) are easy to measure in the field using portable equipment, giving the \( WBGT \) a practical advantage over other indices. Given this practicality, the \( WBGT \) has been standardized as ISO-7243 (JIS Z 8504 in Japan) and has become one of the most common thermal comfort indices used worldwide. We tried to estimate \( PES \) from the observed \( WBGT \) in this study. \( M - IE \), can be calculated from Equations (4) and (5). We analyzed the relationship between the \( WBGT \) and \( M - IE \), in the experiment to determine thermal-load exposure, and attempted to evaluate \( IE \) using the \( M - IE \), value estimated from the \( WBGT \) and a subject’s \( M \).

\[
M - IE = H + L_{aw} - R_{aw} = a \cdot WBGT + b
\]
(35)

where \( a \) is the slope and \( b \) is the intercept. Here, \( M - IE \) is equivalent to the thermal load to the human body by net radiation and sensible heat exchange; hence, it is dependent on environmental factors, except for the condition of the subject’s clothing (receiving a thermal load leads to a negative value). We defined the \( PES_{wbgt} \) evaluated using the \( E_{ei,wbgt} \) estimated from the \( WBGT \), which could be distinguished from both \( PES \) and \( PES_g \).

\[
E_{ei,wbgt} = \frac{(h - a \cdot WBGT + M)}{l}
\]
(36)

\[
PES_{wbgt} = \sum_{t_0} E_{ei,wbgt} \times t_{ei} \times A_{body}
\]
(37)

where \( E_{ei,wbgt} \) is the evaporation rate of sweat on a human body based on the \( WBGT \) (mm s\(^{-1}\)) and \( PES_{wbgt} \) (g) is the wet-bulb globe temperature potential effective sweating.

### 2.7 Rate of metabolic heat generation

Determined by using the METs table, human subjects A, B, C, and marathon runners:

\[
M \text{ was calculated with Equation (38), which applies data from the METs table (Nakae et al., 2012):}
\]

\[
M = \frac{m \times METs \times 1.05}{860.04 \times A_{body}} \times 1000
\]
(38)

where \( METs \) is the subject’s \( METs \) value based on the \( METs \) table, and is the ratio of the active metabolic rate during exercise to the resting metabolic rate (38 W m\(^{-2}\)). The \( METs \) and \( M \) of each subject are shown in Table 3. Subjects A and B walked slowly and their \( METs \) values were 4.0, which is the equivalent of “pushing a stroller on foot” in the \( METs \) table. The \( METs \) of subject C was 7.5, which corresponds to “bicycling, general” in the \( METs \) table. The subject rode a bicycle mounted with meteorological observation equipment.

Calculated from measuring; Human subjects D, E, F, G, H, I, and J:

Before the experiment, each subject completed a 12-min run test from one to four times, following the Cooper method. Oxygen consumption \( VO_2 \) (L min\(^{-1}\)) during the exercise was calculated using Equations (39) and (40) (Kenneth, 1968). \( M \) was calculated from the heart rate monitored during the thermal-load exposure experiment:

\[
VO_2_{max} = m \times (0.021 \times dis - 7.23)/1000
\]
(39)

\[
VO_2 = IA \cdot VO_2_{max}
\]
(40)

where \( VO_2_{max} \) is the maximum oxygen consumption (L min\(^{-1}\)); \( dis \) is the average distance run during a 12-min trial (m); and \( IA \) is the intensity of the activity, which was calculated based on the Karvonen Formula (Karvonen et al, 1957) as follows:
where $HR$ is the maximum heart rate during exercise; $RHR$ is the resting heart rate (65 min$^{-1}$); and $MHR$ is the maximum heart rate (min$^{-1}$). The $MHR$ was calculated using the following equation (Tanaka et al., 2001), because the commonly used formula of $MHR = 220 - \text{age}$ does not have a strong basis (Robert and Roberto, 2002):

$$MHR = 207 - 0.7 \times \text{age}$$

(42)

where age is the age of the subject (i.e., 21 years). METs and energy consumption during exercise were calculated using the following equations based on $VO_2$ and resting oxygen consumption $RVO_2$ (0.0035 L kg$^{-1}$ min$^{-1}$):

$$\text{METs} = \frac{VO_2}{mRVO_2}$$

(43)

$$E = 1.05 \times \text{METs} \times m \times t_{\text{act}}$$

(44)

where $E$ is the energy consumption during exercise (kcal); the coefficient 1.05 represents the energy consumption per 1 METs of exercise per 1 h per 1 kg body weight (kcal METs$^{-1}$ kg$^{-1}$ h$^{-1}$); and $t$ is the duration of exercise (1/60 h in this study). $M$ was calculated by applying $E$ and $VO_2$, as follows (Nakayama, 2014; Weir, 1949):

$$M = 351.82 \times (0.23VCO_2 + 0.77VO_2)/A_{\text{body}}$$

(45)

$$VCO_2 = \left( \frac{E}{t_{\text{act}} - 3.94VO_2} \right) \times 1/A_{\text{body}}$$

(46)

where $VCO_2$ is the quantity of CO$_2$ generation from exercise (L min$^{-1}$).

### 3. Results and Discussion

#### 3.1 Validity of $PES$ and $PES_g$

The relationships between $PES$ with $PES_g$ and $E_{\text{act}}$ for the ten subjects in the thermal-load exposure experiment are shown in Figures 1 and 2, respectively. The root mean square error (RMSE) and bias of $PES$ and $PES_g$ for $E_{\text{act}}$ are shown in Table 4. The RMSEs of $PES$ and $PES_g$ for $E_{\text{act}}$ were 108.7 and 99.7 g, respectively, equivalent to 36.3% and 33.3% of the average actual sweating of each subject. The biases were $-22.8$ g (7.6%) and $-8.3$ g ($-2.8$%) for $PES$ and $PES_g$, respectively, which represented slight underestimations. As $PES$ indicates the minimum amount of sweating required to maintain the heat balance between a human body and the surrounding environment, such an underestimation may not be inconsistent with the actual situation.

Subsequently, we considered the total radiation flux absorbed by the human body surface, which was evaluated by $R_{\text{abs}}$ and $R_{\text{abs,gr}}$. Figure 3 shows the relationship between wind speed, $u$, and relative error ($R_{\text{abs,gr}} - R_{\text{abs}}$). The relative error of $R_{\text{abs,gr}}$ was within about $\pm 0.20$ when the wind speed was less than 3 m s$^{-1}$, although it often exceeded $+0.20$ under strong wind conditions. This was attributable to the overestimation of the sensible heat transfer between the surface of a globe sphere and the surrounding air by linear approximation under strong wind conditions. The relative error of $R_{\text{abs,gr}}$ tended to become larger when the subjects undertook fast movement (e.g., riding a bicycle) rather than exercises without vigorous movement (e.g., jumping over a rope or dancing). However, there were few differences in the RMSEs and biases of each evaluated value against $E_{\text{act}}$ between the $PES$ based on $R_{\text{abs}}$ and $PES$ based on $R_{\text{abs,gr}}$. $PES_g$ can be calculated with setting a subject’s body size,

$$LA = \frac{HR - RHR}{MHR - RHR}$$

(41)

| Table 4. Deviation of $PES$ and actual effective sweating. |
|-----------------|--------------------|-------------------|
| $PES$ | $PES_g$ | $PES_{\text{act}}$ |
| RMSE | (%) | 108.67 | 99.70 | 127.68 |
| Bias | (%) | -22.84 | -8.32 | -17.48 |

Fig. 1. Relationship between $PES$ and $E_{\text{act}}$ in an outdoor thermal-load exposure experiment.

Fig. 2. Relationship between $PES_g$ and $E_{\text{act}}$ in an outdoor thermal-load exposure experiment.
clothing, and METs if the meteorological elements of $T_a$, $rh$, $u$, and $T_g$ are measured in the field. Consequently, if the wind speed is measured by the $WBGT$ meter, a more effective and physical thermal index can be calculated (e.g., the potential rate of weight decrease due to sweating) to evaluate the risk of heat illness using the $WBGT$ meter in the field.

3.2 Evaluation of heat illness risk by $PES_{WBGT}$

$M - I_E$ is equivalent to the thermal load by net radiation and sensible heat exchange (see Section 2.6). A negative $M - I_E$ value indicates that the body is receiving a heat load from the surrounding environment. Figure 4 illustrates the relationship between the $WBGT$ and $M - I_E$. The coefficients of determination ($R^2$) were 0.47, following linear regression analysis, being significant at the 99% level.

A human can die due to heat illness when the $WBGT$ exceeds 21°C during exercise, and the risk of heat illness rises to the “warning” level when the $WBGT$ exceeds 25°C, according to the Japanese Society of Biometeorology (2013) and the Japan Sport Association (2013). It is recommended that no exercise should be undertaken when the $WBGT$ exceeds 31°C. The rate of heat illness occurrence starts to increase when the $WBGT$ reaches about 25°C (Ministry of the Environment, 2019). The $WBGT$ values at which $M - I_E$ became 0 were 24.7°C (Figure 4). The heat load received from the surrounding environment increases gradually when the $WBGT$ exceeds these values, although cooling by sensible heat transfer and radiation from the body surface will occur when the $WBGT$ is below these values. This indicates that the sense of heating, even without movement, will become stronger gradually when the $WBGT$ exceeds about 25°C. These results are consistent with the concept of a $WBGT$ risk level, which has been demonstrated empirically for human activity. However, the distribution of $M - I_E$ for the $WBGT$ is extremely variable. The dashed lines above and below the regression lines in Figure 4 are the maximum and minimum limits of the 95% significant prediction interval. For example, when the $WBGT$ is 21 and 25°C, the 95% significance level of the prediction interval ranges from −38.2 to 91.8 and −67.4 to 62.4 for $M - I_E$, respectively (W m$^{-2}$). It is therefore apparent that the estimation of $M - I_E$ based on regression equations using the $WBGT$ as an explanatory variable includes considerable error. Two of parameters in Equation (36) were determined as $(a, b) = (-7.32, 180.45)$ in the result of regression equations obtained in Figure 4. We calculated the $PES_{WBGT}$ using Equation (37).

Figure 5 shows the relationship between $PES_{WBGT}$ and $E_{S,act}$. The RMSE and bias of $PES_{WBGT}$ for $E_{S,act}$ are shown in Table 4. The RMSE was 127.7 g for $PES_{WBGT}$, which was equivalent to 42.7% of the average actual effective sweating. The RMSE was 127.7 g
for \( PES_{\text{WBGT}} \), which was equivalent to 42.7% of the average actual effective sweating. These values were slightly larger than when the \( PES \) or \( PES_x \) were used. The bias was \(-17.5 \, \text{g} \, (-5.8\%)\), with the same slight underestimation as for the \( PES \) or \( PES_x \).

### 3.3 Assessment of heat illness risk for marathon runners in the 2020 Summer Olympics

**a. August 2 (women’s marathon)**

The \( PES \) for start times set every 30 min from 05:00 to 19:00 and a time series of meteorological elements from 04:30 to 22:00 on August 2, 2014, are shown in Figure 6. The average rate of body weight decrease was calculated from 2009 to 2018 for the dates of August 2 and 9, and October 21 (i.e., when the men’s marathon was held in the 1964 Summer Olympics) and are shown in Figure 7. The error bar is the standard deviation over the decade studied. The average heat load in the \( PES \) simulation was the largest in 2014. The rates of decrease in the body weight of female and male runners were 7.15% and 7.14%, respectively, when the start time was set to 06:00 under the weather conditions of August 2, 2014. The ability to exercise begins to decrease when the rate of decrease in body weight exceeds 2% (Yoshida and Takanishi, 2002). Speech disorders, respiratory distress, palpitations, and convulsion can occur when more than 5% of body weight is lost (Adolph, 1947). The rate of decrease in body weight for women was the largest for an 11:00 start, with an average of 7.37% for all years and a maximum of 8.20% in 2018. There was almost no difference between men and women. Aid stations to supply water must be placed every 5 km along the course of a marathon, in addition to the start and end (JAAF, 2019). In the simulation of the women’s marathon on August 2, 2018, the decrease in the runner’s body weight reached 2% at 34 min when the start time was 11:00. There was a high risk of dehydration before the second aid station (10 km) if runners could not drink water at the first aid station (5 km). The time required to reach 2% of body weight loss was extended to 41 min (about 12.4 km) when the start time was changed to 06:00. However, it would be difficult to supply enough water for all runners because 750 g of water loss (equivalent to one and a half 500-mL bottles) due to dehydration was predicted at 10 km. We compared the rate of decrease in body weight between morning (05:00–11:30) and afternoon (12:30–19:00) periods. The average values were 7.03% and 6.66%, respectively, that is, a 0.37% difference, which was confirmed by a \( t \)-test to be significant at the 99% significance level. \( R_{st} \) increased from early morning to noon and then decreased until the evening (Figure 6). The road surface temperature \( T_s \) and the operative temperature \( T_o \) decreased in the afternoon when the wind speed strengthened, although it increased gradually during the morning. After 15:00, these parameters decreased to the same levels as in the early morning. In a study of the relationship between the circulation of land and sea breezes and the heat island phenomenon in Tokyo, Mikami (2006) reported that typical heat islands in summer over the central urban area are limited to the early morning period, when land and sea breeze circulations become weak. The high-temperature area in the central region moves to the north by advection from the southerly sea breeze in the daytime period, while in the eastern region, where the sea breeze flows into the inland area along the river, temperatures decrease from daytime to midnight. The total radiation flux absorbed by the human body surface can be reduced by avoiding daytime exposure, whereas the effect of wind cooling on the human body and road surfaces may be limited due to the calm conditions during the morning period.

**b. August 9 (men’s marathon)**

The \( PES \) values for start times set every 30 min from 05:00 to 19:00 and a time series of meteorological elements from 04:30 to 22:00 on August 9, 2011 are shown in Figure 8. The average heat load in the \( PES \) simulation was the largest in 2011. The average \( PES \) was 3969 g (or 7.22% of body weight) for the men’s marathon held under the weather conditions of August 9, 2011. The largest rate of average decrease in body weight was 7.40% for a 10:00 start on August 9. Over all study years, the worst conditions were identified for a 9:30 start in 2017, with a rate of decrease in body weight of 8.05% and 8.09% for men and
women, respectively.

In the simulation of the men’s marathon on August 9, 2017, the rate of decrease in body weight reached 2% after 34 min when the start time was 10:30. Dehydration was highly likely before the second aid station (10 km) if the runners did not drink water at the first aid station (5 km). Even with a water supply, there was still a risk of dehydration by the second aid station (10 km). The time required to reach a 2% body weight loss was extended to 41 min when the start time was changed to 06:00, the same as the women’s marathon.

c. Comparison with the 1964 Summer Olympics in Tokyo (October 21, 1964)

In the 1964 Summer Olympics in Tokyo, only a men’s marathon was held, which was on October 21, with a start time of 13:00. The simulated rate of decrease in body weight was 6.30% for men and 6.27% for women for a marathon beginning at 13:00 on October 21 (Figure 7). The rate of decrease in body weight for men and women was 0.80% and 0.83% smaller than on August 2 and 0.81% and 0.84% smaller than on August 9, respectively. Runners in early August would have to drink at least 371–447 mL surplus water due to receiving severe thermal load from the surrounding weather conditions than they would in late October. In this analysis, we did not consider the thermal fatigue of runners and assumed that the metabolic heat generation rate was constant, regardless of weather conditions. Therefore, this result represents differences only in the heat load that runners receive from the surrounding environment.

4. Conclusion

We developed a method to assess the risk of heat stroke during outdoor exercise based on PES, which indicates the minimum effective sweating required to maintain a constant body temperature when undertaking outdoor activity and is calculated easily from routinely observed meteorological data, body size, clothing, and exercise intensity. We also proposed the use of $PES_s$, which can be calculated from air temperature, relative humidity, globe temperature, and wind speed, as well as $PES_{WBGT}$, which can be estimated from the WBGT. $PES_s$ can be measured using a WBGT meter that records the wind speed, whereas $PES_{WBGT}$ can be estimated from the WBGT measured using portable equipment. PES can be used to assess the heat illness risk of an athlete based on the rate of decrease in body weight due to dehydration. We evaluated the validity of the three kinds of PES through comparisons with actual effective sweating when subjects undertook exercise outdoors. The relative deviations of the estimated PES values were 33.3–42.7% of actual effective sweating.

For August 2 and 9, the proposed dates of the marathon events in the 2020 Summer Olympics in Tokyo, we projected the rate of decrease in body weight of runners using routine meteorological data observed in the recent decade and by setting the start times every 30 min from 05:00 to 19:00. A start time of 11:00 resulted in the largest rate of decrease in body weight on August 2. The average rate of decrease in body weight for women was 7.38%, with a maximum of 8.20% in 2018, and there was almost no difference between men and women. The largest rate of decrease in body weight was found for a 10:00 start on August 9, with an average value of 7.40% for men and maximum values of 8.05% (men) and 8.09% (women) for a 9:30 start in 2017. Runners can avoid competing under intensive sunlight if the start time of the competition is changed to the early morning. However, the cooling effect of wind on the surface of the human body and the road tended to be weaker at this time because the average wind speed is lower in the morning than in the afternoon. Hence, the decrease in thermal load following a change in the start time to early morning may still not be sufficient. The average rate of decrease in body weight exceeded 6% in both men and women at all start times on August 2 and 9; therefore, without drinking water, a runner is highly likely to experience heat illness.

Three kinds of PES were proposed in this study. PES can be determined not only from calculations based on routine observed meteorological data but also from measurements using portable equipment. Honjo et al. (2018, 2019) analyzed the spatial distribution of the WBGT and proposed the Universal Thermal Climate Index based on a detailed analysis of sunlight over a marathon course, and reported that the WBGT differed by about 1°C between exposed and shaded locations. The risk of heat illness can be assessed by considering a more detailed spatial distribution of thermal comfort elements based on reports using $PES$.

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