Evaluation of heatstroke risk at Sapporo in the Tokyo 2020 Summer Olympic marathon event compared with Tokyo

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Abstract

We compared the difference of heatstroke risk of marathon runners in the Summer Olympics on the basis of the percentage of weight decrease due to sweating using potential effective sweating, between Tokyo and Sapporo. For the women’s marathon, the difference in the rate of decrease in body weight was 0.42% when the start time was 11:00, with 7.51% loss for Tokyo and 7.09% for Sapporo. Nevertheless, when the start time was 7:00, as planned, the difference decreased to 0.28%, with a 6.94% loss for Tokyo and 6.66% for Sapporo. The estimated thermal load on runners when starting the race at 7:00 on August 8 in Sapporo was equivalent to starting at 5:30 or at 16:00 on August 2 in Tokyo. For the men’s marathon, the start time with the maximum rate of decrease in weight was 10:00, with a 6.91% loss for Sapporo and 7.42% for Tokyo. If the race started at 7:00, the rate of decrease in body weight was 6.50% for Sapporo and 7.00% for Tokyo, a 0.50% difference. However, as a result of the analysis based on the relation between wet bulb globe temperature and M-IE (equivalent to the thermal load to the human body by net radiation and sensible heat exchange), severe weather conditions might place a large thermal load on runners, even if the race venue is changed to Sapporo.

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

1. Introduction

We developed a method to evaluate heatstroke risk due to outdoor exercise on the basis of potential effective sweating (PES) values, and assessed its validity through a comparison with actual effective sweating when subjects undertook exercise in the outdoor environment. We also evaluated the heatstroke risk of marathon runners in the Summer Olympics in Tokyo on the basis of the percentage of weight decrease due to sweating using PES (Takayama et al., 2020). PES indicates the minimum effective sweating necessary to maintain a constant body temperature when undertaking activity in the outdoor environment. PES is based on a human heat balance model; therefore, a theoretical background is clear. We can easily calculate from routinely observed weather data and the subject’s body data (e.g., height, weight, clothing, and intensity of exercise).

The 2020 Summer Olympics in Tokyo will be held from July 24, 2020 to August 09, 2020, during the hottest season in Japan. Therefore, both athletes and spectators will need to take measures to avoid heatstroke*. The ability to exercise begins to decrease when the rate of decrease in body weight due to dehydration 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). In October 2019, the International Olympic Committee strongly recommended changing the venue from Tokyo to Sapporo for marathon and walking race with excessive thermal load. The Tokyo Organizing Committee of the Olympic and Paralympic Games decided that women’s and men’s marathons are going to be held on August 8 and 9, respectively, in Sapporo city, and start time of both is at 7:00. In this report, we compared the difference of heatstroke risk of marathon runners in the Summer Olympics on the basis of the percentage of weight decrease due to sweating using PES, between Tokyo and Sapporo.

2. Materials and Methods

2.1 Potential effective sweating

The PES (g) indicates the minimum effective sweating required to maintain a constant body temperature when a human undertakes outdoor activity and is calculated as follows:

\[ PES = \sum \frac{t_{\text{last}}}{t_s} \times E_s \times A_{\text{body}} \]  

where \( E_s \) is the evaporation rate of sweat on a human body (mm s\(^{-1}\)); \( t_s \) and \( t_{\text{last}} \) are the first and last steps of exercise, respectively; \( t_{\text{last}} \) is a time step of exercise (60 s); \( A_{\text{body}} \) is the body area of runner (m\(^2\)). The heat balance of a human can be determined as follows:

\[ R_{\text{abs}} - L_{\text{ir}} + M - IE - H - G - Q = 0 \]  

where \( R_{\text{abs}} \) is the total radiation flux absorbed by the human body surface; \( L_{\text{ir}} \) is the longwave infra-red radiation emitted
from the body surface; \( IE_i \) is the latent heat transfer per unit area of body surface; \( M \) is the rate of metabolic heat generation per unit area; \( H \) is the rate of heat loss by sensible heat transfer; \( G \) 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 (unit: \( \text{W m}^{-2} \)). In this study, we assumed that \( Q = G = 0 \) and latent heat transfer occurs only by effective sweating, while ignoring vapor from respiration; therefore, \( I \) is the latent heat of evaporation (2501 J g\(^{-1}\)). The value of \( E_i \) (W m\(^{-2}\)) was calculated as follows (Campbell and Norman, 1998):

\[
E_i = \frac{1}{T} \left( M - \frac{C_p (g_{lu} + g_a) (T_s - T_a)}{1 + \left( \frac{g_{lu} + g_a}{g_{lu}} \right) T_u} \right)
\]

(3)

\[
g_{lu} = \left( g_{lu} + g_a (u) \right) \left( \frac{1}{g_{lu}} \right)^{-1}
\]

(4)

where \( C_p \) is the specific heat at a constant pressure (29.3 J mol\(^{-1}\) K\(^{-1}\)) ; \( g_{lu} \) and \( g_a \) are the conductance of heat by the boundary layer, radiation, human body, tissue (2.8 mol m\(^{-2}\) s\(^{-1}\)), skin, and clothing, respectively (mol m\(^{-2}\) s\(^{-1}\)); \( u \) is the wind speed (m s\(^{-1}\)); \( T_s \) is the human core temperature (37.5°C); and \( T_a \) is the operative temperature (°C), 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. \( g_{lu} \) and \( g_a \) were calculated as follows:

\[
g_{lu} = 1.4 \times 10.135 \sqrt{\frac{d}{T_u}}
\]

(5)

\[
g_a = \frac{4 \alpha_c \sigma T_a^3}{C_p}
\]

(6)

\[
g_a (u) = g_a (0) (1 + cu)
\]

(7)

where \( d \) is the characteristic length of the human body (0.17 m); \( \alpha_c \) 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); \( g_{lu} (0) \) is the conductance of heat by the 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\(^{-1}\)). The value of \( g_{lu} \) was determined as 0.86 with the assumption wearing a white T shirt and short pants; although, we did not consider the effect of clothing color. The \( E_i \) value was calculated based on meteorological data per minute during exercise, and we calculated \( E_i \) by accumulating the values of \( E_i \) from the start to finish of exercise in equation (1). The term \( T_s \) in equation (3) can be calculated as follows:

\[
T_s = T_a + \frac{R_{abs} - \alpha_c \sigma T_a^4}{C_p (g_{lu} + g_a)} = 273.15
\]

(8)

\[
R_{abs} = \alpha_l (F_d S_d + F_s S_s) + \alpha_t (F_d L_d + F_s L_s)
\]

(9)

where \( \alpha_l \) is the absorptivity of solar radiation (0.92); \( S_d \) and \( S_s \) are the global solar radiation and reflectance of solar radiation (W m\(^{-2}\)), respectively, and their view factors are \( F_d \) and \( F_s \); and \( L_d \) and \( L_s \) are downward atmospheric and upward ground longwave radiation (W m\(^{-2}\)), respectively, and their view factors are \( F_d \) and \( F_s \). A solar elevation angle is 23.61° and 69.21° at 7:00 and 12:00, respectively, in Tokyo (35.69°N), and 24.83° and 61.74° in Sapporo, on August 9. A view factor for the direct solar radiation can be changing in the range of 0.06 to 0.34 by runner’s direction or time (Takayama et al., 2008). Nevertheless, our proposed \( PES \) can be calculated easily from routinely observed meteorological data, body size, clothing, and exercise intensity based on the human body heat balance model; moreover, it can be measured in outdoor condition by using portable equipment with a black sphere. Hence, the human body was assumed to be spherical in this study; therefore, we set \( F_d = F_s = F_a = 0.5 \).

### 2.2 Evaluation of the heatstroke risk for marathon runners in the 2020 Summer Olympics based on \( PES \)

We evaluated the risk of heatstroke in the marathon on the basis of the decrease in body weight due to sweating using \( PES \).

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

(10)

where \( WDR \) is the percentage of weight decreasing (%); \( m \) is the weight of runner (kg). We simulated the \( PES \) of runners on the basis of routine meteorological data observed from 2010 to 2019 on August 2, 8, and 9, and October 21, for start times set every 30 min from 05:00 to 19:00. The men’s marathon started at 13:00 on October 21 in the 1964 Summer Olympics in Tokyo. The body size of a runner was assumed to be 175 cm (height) and 55 kg (weight) for males, and 157 cm and 45 kg for females, and their \( A_{body} \) could be estimated to be respectively 1.65 and 1.40 m\(^2\). We determined the runner’s \( METs \) value on the basis of the \( METs \) table (Nakae et al., 2012). \( METs \) is defined as the ratio of the active metabolic rate during exercise to the resting metabolic rate (58 W m\(^{-2}\)). It was assumed that \( METs = 17 \) and \( t_{finish} - t_0 = 140 \) min in this study. \( M \) was calculated with the following equation (Formulaulation committee for required amount and guideline of exercise, 2006):

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

(11)

Air temperature, relative humidity, and wind speed every 10 min and total global solar radiation every 1 h were respectively observed at the Tokyo and the Sapporo Automated Meteorological Data Acquisition System (AMeDAS) station. Downward atmospheric longwave radiation every 1 h was observed at Tsukuba (Tateno) and Sapporo stations. These values were used as the meteorological elements to calculate \( PES \) by interpolating every 1 min. Wind vectors should be considered in the trajectory of the athlete along the course and in terms of the general wind to evaluate the \( PES \) of a marathon runner. In this study, however, it is difficult to estimate the wind conditions on the marathon course in an urban area with a complex surface. Thus, we used only the wind speed data at the AMeDAS Tokyo and Sapporo stations with height correction to apply to equation (5) and (7), for the \( PES \) calculation. The height of the anemometer at the AMeDAS Tokyo station is 35.3 m and at the AMeDAS Sapporo station is 59.5 m above the ground surface, respectively. We corrected the observed wind speed \( U_{obs} \) at \( z_{obs} \) to the wind speed \( u \) at the reference height \( z = 1.2 \) m using equations (5), (7), and (25).
u = U_{obw} \frac{\ln(z/z_0)}{\ln(z_{obw}/z_0)} \tag{12}

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

$L_n = e_{\text{rad}} \sigma T_i^4 \tag{13}$

where $e_{\text{rad}}$ is the emissivity of infra-red (0.93). Road surface temperature $T_i$ (K) was calculated following Kondo (1992):

$T_i = T_s + \frac{Q - \sigma T_i^4 + l_p c_p U [q_{sat}(T_s) - q_a]}{4 \sigma T_i^4 + c_p c_f U + l_p c_f U A} \tag{14}$

$Q = R - G \tag{15}$

$R = (1 - \text{ref}) S_i + L_d \tag{16}$

$G = G_i \cos \left(60 \cdot \cot \phi + \frac{\pi}{4} \right) \tag{17}$

$A_i = \frac{R_i \cos \phi + B_i \cos(\alpha - \phi)}{\mu - \gamma} \tag{18}$

$\phi = \arctan \left(\frac{\gamma R_i \cos \phi + B_i [\gamma \cos(\alpha - \gamma) \sin \phi]}{1 - \gamma R_i \cos \phi + B_i [\gamma \cos(\alpha - \gamma) \sin \phi]} \right) \tag{19}$

$\gamma = \left(\sin c_p \beta \lambda \right)^2 \cos \left(\frac{\pi}{4} \right) \tag{20}$

$= 4 \sigma T_i^4 + c_p c_f U \tag{21}$

$\mu = 4 \sigma T_i^4 + c_p c_f U + l_p c_f U A \tag{22}$

where $R_i$ is the input radiation flux; $G$ is the ground heat transfer flux (W m$^{-2}$); albedo is $\alpha = 0.15$, and the efficiency of evaporation is $\beta = 0$ with the assumption of a dry road surface; $c_p$ is the bulk coefficient of sensible heat transfer; and $c_p$ are the specific heat, the density, and the thermal conductivity of an asphalt road, respectively. We set $c_p = 0.0094$, $c_p = 1.22 \times 10^5$ J m$^{-3}$ K$^{-1}$, and $\lambda = 0.91$ W m$^{-1}$ K$^{-1}$ on the basis of the experimental results of Kinouchi and Kobayashi (1999). Nonetheless, they set an anemometer at a height of 0.65 m in their experiment to calculate the bulk coefficient. Hence, we corrected the observed wind speed $U_{obw}$ at $z_{obw}$ to the wind speed “$U$” at the reference height $z = 0.65$ m using equation (12); $q_{sat}(T_s)$ and $q_a$ is the saturation specific humidity for air temperature and the specific humidity, respectively; $A$ 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 $T_r$ and $T_s$, respectively; $\omega$ is the angular velocity of the daily cycle (7.27221 $\times 10^{-3}$ radians); $t$ 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; $B_1$ is half of the diurnal range of temperature; $\phi$ and $\alpha$ are the phase differences for $T_r$ and $T_s$, respectively (radians); $\omega$ was calculated as the difference in the times at which the maximum values of $R_i$ and $T_s$ were observed; and the subscripts “$M” indicate a daily average.

### 2.3 Wet bulb globe temperature

The wet bulb globe temperature $WBGT$ (°C) (Yaglou and Minard, 1957) is an index of sensitivity that describes how a human feels in the surrounding thermal environment. International standards use the $WBGT$ index to specify workplace heat stress risks (Bruno and Tord, 2012). It is defined by the following equation in outdoor environments:

$WBGT = 0.7 T_s + 0.2 T_u + 0.1 T_r \tag{24}$

where $T_s$ is the globe temperature and $T_u$ is the wet bulb temperature (°C). The water vapor pressure, $e_v$ (hPa), is calculated based on $T_s$ (°C) and relative humidity ($rh$) observed at AMeDAS stations using the Tetens equation as the first step in calculating $T_s$. And in the next step, $T_u$ is determined as a convergent calculation value to $e_v$ value in the Sprung equation. $T_s$ is calculated using the following empirical formula (Tonouchi et al., 2006):

$T_s = T_r + 0.0175 S_i - 0.208 \mu \tag{25}$

We estimated $WBGT$ during the race on the basis of the AMeDAS data for 2010–2019. M-IEd, derived by equation (2) is equivalent to the thermal load on the human body due to the 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 examined the relationship between $WBGT$ and M-IEd.

### 3. Results and Discussion

#### 3.1 The risk of heatstroke for marathon runners in the 2020 Summer Olympics

da. August 2 in Tokyo versus August 8 in Sapporo for the women’s marathon

The average percentage of weight decreasing for the women’s marathon calculated from 2010 to 2019 data for August 2 and October 21 in Tokyo and August 8 in Sapporo is shown in Figure 1. The error bar is the standard deviation over the decade studied. Only the men’s marathon was held on October

![Fig. 1](https://example.com/fig1.png)

**Fig. 1.** The percentage of weight decreasing WDR (%) for women’s marathon runners calculated from the meteorological data from 2010 to 2019. The error bar is the standard deviation over the decade studied.
21 in Tokyo in the 1964 Summer Olympics. Figure 2 shows the respective time series of the means of the meteorological elements from 04:30 to 22:00 on August 2, August 9, and October 21 in Tokyo and August 8 and 9 in Sapporo calculated from the data for 2010–2019. Time series of the mean of \( T_s, T_a, T_e, \text{WBGT}, \) and \( u \), and \( S_t, L_u, \) and \( R_{abs} \) are respectively shown in Figs. 2a and 2b. We compared WDR the women’s marathon in Tokyo on August 2 and October 21 and Sapporo on August 8. The race start time with the most severe thermal load was 11:00 and 10:30, respectively, in Tokyo on August 2 and Sapporo on August 8. The slightly earlier time in Sapporo might be due to the difference in the time of sunrise. The difference in WDR was 0.42%, with runner’s rate of body weight losses of 7.51% for Tokyo and 7.09% for Sapporo, given that the start time was 11:00. However, the difference decreased to 0.28%, with losses of 6.94% for Tokyo and 6.66% for Sapporo, when the start time was 7:00, as planned. The thermal load of runners starting the race at 7:00 on August 8 in Sapporo was estimated to be equivalent to that when starting at 5:30 or 16:00 on August 2 in Tokyo. As we reported, 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 or on road surfaces may be limited due to calm conditions during the morning. The thermal load would not be decreased more than we expected by starting early in the morning. As shown in Figure 2a, the wind speed tended to decrease during the morning in both Sapporo and Tokyo. In this analysis of the women’s marathon, WDR was the smallest, 6.13%, when the race was held in Sapporo with starting at 18:00. Under these conditions, the volume of dehydration was 365 mL less than if the start time was at 7:00 in Tokyo. In this analysis, we did not consider runners’ thermal fatigue and assumed that the metabolic heat generation rate was constant regardless of weather conditions. Consequently, this result represents differences only in the heat load that runners receive from the surrounding environment. As in the 1964 Tokyo Olympics, the estimated WDR was 6.23% if the race started at 13:00 on October 21 in Tokyo. This is equivalent to the thermal loads when starting after 16:30 (6.25%) or at 5:00 (6.29%) for August 8 in Sapporo.

b. Tokyo versus Sapporo on August 9 for the men’s marathon

The average percentage of weight decreasing for the men’s marathon calculated from data for 2010–2019 for August 9 in Tokyo and Sapporo is shown in Figure 3. The time series of the means of meteorological elements from 04:30 to 22:00 on August 9 at Tokyo and Sapporo, respectively, calculated from the data for 2010–2019, are shown in Figures 2a and 2b. The start time with the maximum decrease in weight was at 10:00, at 6.91% for Sapporo and 7.42% for Tokyo. If the race started at
7:00, the rate of decrease in body weight was 6.50% for Sapporo and 7.00% for Tokyo, a 0.50% difference. The estimated thermal loads if runners started the race at 7:00 on August 9 in Sapporo were equivalent to that if they started at 5:00 or 16:30 in Tokyo. To realize a thermal load equivalent to the level seen when starting at 13:00 October 21 in Tokyo, the race should start in Sapporo after 16:30 on August 9.

3.2 The relationship between WBGT and the thermal environment surrounding the runners

The relationship between WBGT and M-IE, every 10 min from 5:00 to 21:00 is illustrated in Figure 4. The mean and maximum values of WBGT and M-IE, respectively, for 2010–2019 are plotted in Figures 4a and 4b. M-IE, is equivalent to the thermal load on a human body due to net radiation and sensible heat exchange. A negative M-IE value indicates that the body is receiving a heat load from the surrounding environment. The rate of heatstroke starts to increase when WBGT exceeds about 25°C, and it increases rapidly at levels ≥28°C (Ministry of the Environment, 2019). In this analysis, the WBGT values at which M-IE, became 0 were 28.9°C and 26.2°C for the average and maximum, respectively, based on linear regression. This result supports our previous report (Takayama et al., 2020). The heat load received from the surrounding environment increases gradually when WBGT exceeds these values, although cooling by sensible heat transfer and radiation from the body surface occurs when the WBGT is below these values. A runner’s body must emit the metabolic heat and the received sensible heat via latent heat exchange with effective sweating. These results are consistent with the concept of a WBGT risk level, which has been demonstrated empirically for human activity. The respective time series of the means for 2010–2019 of the WBGT and M-IE, from 05:00 to 21:00 for women’s and men’s marathons are respectively shown in Figures 5a and 5b. The
data in Figures 5a and 5b indicate that the time period in which $M\text{-}IE$, would become negative is from 7:59 to 14:51 and from 8:03 to 14:51, with a peak value of $-43$ W m$^{-2}$ and $-42$ W m$^{-2}$ at 11:20, respectively, given that the races were held on August 2 for women and August 9 for men in Tokyo. On the other hand, for Sapporo, $M\text{-}IE$, would become negative between 9:46 and 13:10 on August 8, although most values were positive on August 9. The peak value of $M\text{-}IE$, was $-19$ W m$^{-2}$ at 11:30 on August 8 for the women’s marathon in Sapporo, which is about half the value for Tokyo. In the data in Figure 4b, however, the negative maximum values of $M\text{-}IE$, were $-138$ and $-127$ W m$^{-2}$ in Tokyo and Sapporo, respectively, and the severe thermal condition in which the $M\text{-}IE$, values become negative could be continued during from 6:22 to 16:05 in Tokyo and from 8:15 to 14:53 in Sapporo, given that the race will be held in August. Consequently, we should consider severe weather, which might place a large thermal load on the runners, even if the venue is changed to Sapporo.

4. Conclusion

For the proposed dates of the marathon events in the 2020 Summer Olympics, we projected the rate of decrease in runners’ body weight as WDR using meteorological data observed in the last decade and by setting start times every 30 min from 05:00 to 19:00. In comparison, for the women’s marathon in Tokyo and Sapporo, the difference in the rate of decrease in body weight was 0.42% when the start time was at 11:00, with a 7.51% loss for Tokyo and 7.09% for Sapporo. However, the difference decreased to 0.28%, with a 6.94% loss for Tokyo and 6.66% for Sapporo, when the start time was at 7:00, as planned. The estimated thermal load on runners when starting the race at 7:00 on August 8 in Sapporo was equivalent to that when starting at 5:30 or at 16:00 on August 2 in Tokyo. For the men’s marathon, the start time with the maximum rate of decrease in weight was at 10:00, with a 6.91% loss for Sapporo and 7.42% for Tokyo. If the race started at 7:00, the rate of decrease in body weight was 6.50% for Sapporo and 7.00% for Tokyo, a 0.50% difference.

The value of $M\text{-}IE$, which is associated with WBGT, is equivalent to the thermal load on a human body due to net radiation and sensible heat exchange. The $M\text{-}IE$, was negative during 6:22 to 16:05 in Tokyo and during 8:15 to 14:53 in Sapporo under the most severe thermal condition in the last decade, and respective peaks reached $-138$ and $-127$ W m$^{-2}$. Therefore, severe weather conditions might place a large thermal load on runners, even if the race venue is changed to Sapporo.

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