A new causative heat supply for exertional heat stroke on runners in cold air

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Abstract
The dysregulation in heat balance, the main cause of exertional heat stroke, occurs not only in midsummer but also in the cold season. Possible causes of this are a reduction in convection and evaporation due to tailwinds and an acceleration of radiant heat inflow. Although the amount of radiant heat that reaches the surface can be estimated, the actual amount of heat that flows into the body cannot be specified yet. This paper made an experimental attempt at this. A device is made up of a temperature controllable heat sink and heat flow detector, which keeps the surface temperature constant and has a heat exchange coefficient comparable to that of the human body surface. The output of this device (total heat exchange) was divided into radiant heat exchange and other heat exchange using a standard radiant heat calibrator, Leslie cube. A phenomenon, in which a wet surface while the surface temperature was low absorbed larger heat than that of the dry surface, was found. And authors named this “hidden heat inflow”. As a result of multiple regression analyses, both radiant heat exchange and other heat exchanges are closely related to the surface temperature, and the maximum difference in total heat exchange during the experiment reached 200 kcal/m²/h. It has been suggested that this phenomenon may also occur on the surface of human skin. One of the causes of this “hidden heat inflow” is considered to be the decrease in evaporative cooling due to the decrease in surface temperature. However, this alone cannot explain all of the phenomena, so water vapor aggregation may also be involved. A “hidden heat inflow” as a sufficient heat source for exertional heat stroke or collapse during a marathon race on a cold day was evidenced experimentally.

Keywords Aggregation · Solar radiation · Wet skin · Thermal radiation detector · Hidden heat inflow

Introduction
Exertional heat stroke (EHS) is a medical emergency caused by excessive heat accumulation and lack of heat dissipation during physically strenuous activities, such as distance running and occupational activities. This is a major threat to athletes during summer. EHS reduces the willingness to compete and at the same time reduces awareness and impedes the performance of the competition. Young (1979) and Roberts (2000, 2006) suggested that symptoms of EHS can also develop during marathon races on cold days below ambient temperatures less than 10 °C. And Jones et al. (1985) analyzed all the symptoms experienced by participants of the Boston Marathon held in October and those of other races in the warmer season, reported that there is no significant difference between the two results. Laitano et al. (2019) reviewed the association between the onset of EHS and the magnitude of environmental heat load, and they pointed out that it was different from our conventional understanding. In the Tokyo-Hakone Ekiden (200-km sash relay) race in winter, a condition called “BRAKE” is well known among Japanese fans, and it is very similar to EHS. These facts suggest that heat stroke is a common phenomenon among long-distance runners and that other important factors besides air temperature and humidity can influence its occurrence.

The body heat balance of a runner during a sunny day is expressed by the following equation:
The metabolic heat production ($M$) of marathon runners is considered to be 400 kcal/m²/h, and there is no controversy (Costill 1972; de Freitas and Ryken 1989; Kyröläinen et al. 2000; Nielsen 1990, 1996). The solar or short-wavelength IR radiation ($R_{\text{short}}$) is estimated to be 200 kcal/m²/h in Tokyo (N36, at noon on January 1; Blazejczyk et al. 1993; Krys and Brown 1990). The physical workload ($W$) of running is 80 kcal/m²/h, the long-wavelength radiant heat dissipation ($R_{\text{long}}$) is 70 kcal/m²/h, and the inhaled air humidification and warming ($C_{\text{res}} + E_{\text{res}}$) consumes 80 kcal/m²/h. When the remaining 370 kcal/m²/h can be dissipated by sweat evaporation and convection, their heat balance will be completed. Convection ($C$) on their skin surface depends on the temperature difference between skin surface ($T_{\text{surface}}$) and ambient air ($T_{\text{ambient}}$), and the airspeed or the verosity. Evaporation from the skin surface ($E$) depends on the water vapor pressure difference between the skin surface and ambient air and airspeed. The maximum cooling capacity of ambient air, evaporation plus convection ($E + C$), can be estimated at 1000 kcal/m²/h or more while a runner running at 20 km/h in calm and windless air with 1 atm, 10 ºC, and 60% relative humidity (%RH) by the methods of Gagge and Nishi (1977), and Nishi (1981). However, if the tailwind speed is the same as the runner’s ground speed (airspeed=0), $C + E$ drops to 370 kcal/m²/h, and the cooling capacity will be lost completely (Blazejczyk et al. 1993; Krys and Brown 1990). Usual runner’s limbs move faster than the airspeed of the torso, the actual ($E + C$) is considered to be greater than this estimation, and the runner is unlikely to be placed in a negative heat balance. So how did marathon runners running in cold weather develop EHS, as Young (1979) and Roberts (2006) recorded? It must be considered that there is an unknown factor that has not been described so far in the onset of EHS by a marathon running in cold air. The principle of cooling the body by thermal sweating is well understood (Kerslake and Waddell 1958; Gagge and Nishi 1977; Nag 1984), but this principle may not be applicable to runners running in cold air.

This study experimentally explores how the negative heat exchange balance that causes EHS occurs, using the runner in cold weather as a computational model.

**Materials and methods**

**Surface heat-exchange detector (SHED)**

The skin surface temperature of a human at rest or during training is the most important factor governing heat exchange with the external environment. All modes of heat exchange, conduction, convection, and radiation were calculated using the skin-surface temperature as an essential factor. A SHED, shown in Fig. 1, panel 1A, is a temperature-variable heat sink coupled with a heat flux meter. It was assembled with a Peltier’s cooler (40×40 mm²; type SL-2F, Nippon Blower Co., Ltd., Tokyo, Japan) and a heat flux meter (42×20 mm²; type MF-180, EKO Instruments, Tokyo, Japan), similar to that described by one of the authors of this paper in his earlier work (Tagami 2011). A flux flow meter was mounted on the surface of the Peltier cooler with a positive output when heat flowed into the SHED. Because the surface of the heat flow meter was not hydrophilic, it could not retain water. Therefore, an approach was devised to increase its water retention capacity by covering the surface of the heat flow

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**Fig. 1 A** A schematic diagram of a surface heat exchange detector (SHED). **B** SHED calibrator (Leslie cube). This Leslie cube consisted of a stainless-steel water bath, attaching a circular cone with a 200 mm long, 75 mm diameter opening, and painted the inside in matte black. The size of the cone hole-opening matched the SHED detector.
meter with a layer of commercially available tissue paper. By spraying distilled water onto a 3×3 cm paper, the effect of the saturated paper on heat flow into the SHED could be investigated and shown as verification data.

The SHED analog output (mV) was scanned every 30 s, digitized, and stored in a data logger (CR800, Campbell Scientific, Ink, Logan, Utah). The stored data were downloaded to a personal computer via the RS232C interface and further processed using Microsoft Excel. The output values (mV) were converted to heat flow rate (W) by multiplying by the sensor-specific calibration value. The heat flow rate (W) was then divided by the unit conversion constant (1.163) to convert W/m² to kcal/m²/h. Spectrophotometry of layers of commercial tissue paper was performed at the Shimane Prefectural Industrial Technology Center using a UV–VIS-NIR spectrophotometer (V-670, JASCO Corporation, Tokyo). The results showed that wet tissue paper promoted light spectrophotometry of layers of the SHED at 30 and 35 °C, was measured in a climate room conditions (ambient temperature, black-globe temperature, wind velocity, and %RH) were measured and recorded every 10 s using a data logger (LR8402, Hioki, Tokyo). These instruments were placed in a multi-plate radiation shield (41003-2, Young Company, Michigan) with evaporative heat dissipation is included in convective heat dissipation.

Experiment 1: Effect of surface wetness and temperature on heat exchanges or its flow rate onto the SHED surface

The T\text{water} of the Leslie cube installed in a room (8 m L×6 m W×3.5 m H) at 25 °C was fixed at 50 °C in experiment 1, and the outputs of the \(Q_\text{wet}\) and \(Q_\text{dry}\) were continuously recorded. The experiment was repeated with the \(T_\text{surface}\) of the SHED varying from 20 °C, 25 °C, 30 °C, 35 °C, to 40 °C. The \(Q_\text{wet}\) and \(Q_\text{dry}\) obtained were further classified into \(R\) and \(C\) using the method described in the calibration.

Room conditions (\(T_\text{ambient}\) and %RH) were recorded every 30 s during this experiment. Environmental data were logged into a logger (TM-188D, Mother tool Co., Ueda, Nagano Pref. Japan) for further theoretical convection estimation.

Experiment 2: Effect of water on lamp-radiated heat flow onto the SHED surface

The lamp-radiated \(Q\) in the SHED was determined directly using a heat flux meter. The wet, white paper absorbed 0–3% less heat than the wet, black-stained tissue paper at surface temperatures of 20 °C, 25 °C, and 30 °C with 880-kcal/m²/h lamp radiation. Thus, the wetness and paper color had little effect on the emissivity of the SHED surface, presumably because of its thickness or higher transparency.

While the \(T_\text{surface}\) was regulated to varying temperatures (15, 20, 25, 30, and 35 °C), it was irradiated with a reflector lamp (RF110V, 180 W, Panasonic, Osaka) in a room maintained the \(T_\text{ambient}\) at 12.2 ± 1.4, 17.3 ± 0.9, 21.1 ± 1.7, 27.1 ± 1.4, and 30.6 ± 1.7 °C. The differences in heat flux induced by water (\(\Delta Q1\)) and induced by radiation (\(\Delta Q2\)) were subjected to multiple regression analyses for the SHED surface temperature and ambient temperature. The experiments were conducted in an isolated room in which the ambient temperature changed naturally without air conditioning. The exterior surfaces of the walls did not come in direct contact with ambient air. Measurements were performed at midnight to minimize the effects of diurnal temperature changes on ambient temperature. %RH was not shown in Table 2; however, \(\Delta Q1\) fully reflected the influence of %RH.

The testing time was chosen to maintain a minimal temperature change between midnight and early morning. The room conditions (ambient temperature, black-globe temperature, wind velocity, and %RH) were measured and recorded every 10 s using a data logger (LR8402, Hioki, Tokyo) connected to a temperature/humidity meter (HN-CLN, Chino, Tokyo). These instruments were placed in a multi-plate calibration.
a pyranometer/solarimeter (Eko, Tokyo, Japan), a hot-wire anemometer (6036-A0, Nippon Kanomax, Osaka, Japan), and Bernon’s black globe with a Pt100 resistance thermometer (NR: JIS class B, Chino, Tokyo, Japan). The stored records were downloaded from a microSD and processed on a personal computer.

**Experiment 3: Effect of water on lamp-radiated heat flow in human skin**

Eight active college league players (sex, male; age, 22 ± 2; height, 178 ± 6 cm; weight, 78 ± 12 kg; sports experience, 11 ± 4 years) were included in this study. They performed on an ergometer cycle, with a load of 30–40 W and 30 min maximum duration. They underwent two measurements, before exercises and after exercises (until sweating), at temperatures of 22.0 ± 0.9 and 12.8 ± 0.9 °C. The subjects’ left lateral thighs were irradiated with a reflector lamp, resulting in an elevation of skin temperature from 30 to 40 °C. Two heat flux meters (MF180, EKO, Tokyo, Japan) bound to two thin-filmed thermocouples were fixed side by side, 5 cm apart, on the skin of the thighs using paper tape (Micropore TM, 3 M Health Care, Tokyo, Japan). The skin and the heat flux meter were covered with a layer of tissue paper similar to that used in experiment 2 and irradiated with a reflector lamp, same type as used in experiment 2, placed 35 cm away. Warm water was sprayed on or applied to one side of the flux meter covered with tissue paper. The outputs of these flux meters were thermally saturated within 1 min under experimental thermal conditions, which included the processes of water spraying and lamp irradiation. The analog output signals (in mV) were digitized using an A/D converter (NR: JIS class B, Chino, Tokyo, Japan). The values were recorded on a computer and converted to heat flow (kcal/m²/h) by dividing them by sensor-specific calibration factors. After confirming a stable flow value (A) and heat flow rate (B) with water spraying, the skin temperature of each subject (rapidly elevated by irradiation) was monitored until it stabilized. The skin-surface temperature (S) was measured at 10-s intervals using a thermocouple placed between the heat flux meter and the skin (Supplement 5). The differences in heat flux (forced heat flow by water = B’ − A’) were subjected to multiple regression analyses with the S (Table 3).

**Statistical analysis and ethical considerations**

The human skin experiment was approved by the Ethical Committee of the Faculty of Health and Sport Sciences at the University of Tsukuba (Tai25-7, 2014). The subjects were provided with sufficient information about the contents of this experiment and participated in it after agreeing to its terms and conditions. Correlation and multiple regression analyses were performed on the conductive heat flux forced by surface water and data obtained from the two experiments on instrumental and human body surfaces. The coefficients were considered significant if they contributed substantially (α = 0.05) to the predictive equation.

**Results and discussions**

The basic data measurements for SHED’s surface temperature at 30 or 35 °C, placed vertically in the air, were performed under climate chamber conditions (less than 0.1 m/s wind, 25 °C air temperature, and 40, 60, and 80% RH). The κdry and κwet values are listed in Table 1. κdry showed − 10 kcal/m²/h/°C regardless of the humidity and SHED surface temperature, κwet decreased with increasing humidity and converged at −30 kcal/m²/h/°C regardless of the surface temperature of the SHED. The κwet indicates that heat exchange on the wet surface will be more complex. ΔQ, derived Qwet minus Qdry, showed a direct correlation with Tsurface, but not with %RH. Tsurface is considered to be a

![Table 1 SHED specific κ and ΔQ measurements at 25 °C](image)

| Tambient (°C) and %RH | Tsurface (°C) | Qdry (kcal/m²/h) | κdry (kcal/m²/h/°C) | Qwet (kcal/m²/h) | κwet (kcal/m²/h/°C) | ΔQ = Qwet − Qdry (kcal/m²/h) |
|----------------------|--------------|-----------------|---------------------|-----------------|---------------------|--------------------------|
| 25, 40               | 30           | −48.5           | −9.8                | −225.9          | −44.5               | −177.4                   |
|                      | 35           | −134.7          | −14.5               | −391.9          | −39.0               | −257.2                   |
| 25, 60               | 30           | −47.4           | −10.0               | −185.2          | −36.6               | −137.8                   |
|                      | 35           | −120.1          | −12.6               | −307.2          | −30.7               | −187.1                   |
| 25, 80               | 30           | −53.4           | −10.6               | −147.4          | −29.1               | −94.0                    |
|                      | 35           | −101.1          | −10.1               | −280.4          | −28.0               | −179.3                   |
| Mean ± SD            | 30           | −49.8 ± 3.2     | −10.1 ± 0.4         | −186.2 ± 39.2   | −36.7 ± 7.7         | −136.4 ± 41.7            |
|                      | 35           | −118.6 ± 16.8   | −12.4 ± 2.2         | −326.5 ± 58.2   | −32.6 ± 5.7         | −207.9 ± 42.9            |

ΔQ = − 17.527 × Tsurface + 412.61 (R² = 0.867); ΔQ = 2.037 × %RH − 191.64 (R² = 0.100)
major regulator of evaporative heat dissipation when $T_{\text{ambient}}$ is lower than the $T_{\text{surface}}$ (Table 1).

Figure 2 shows the results of calibration using the Leslie cube. Since the SHED did not touch an object, its total output ($Q$) did not include the conduction heat exchange at all and consisted solely of $R$ and $(C + E)$. A minor effect of thin paper on each slope and section was observed (data not shown). These regression equations could be used within the calibrated $Q$ range (−500 to +200 kcal/m²/h).

The environmental condition during this experiment was followed: $T_{\text{ambient}}$: 25.4 ± 0.5; %RH: 35.5 ± 3.1. Figure 3, panel 3A shows seven $Q$ values obtained by changing the surface temperature of the SHED in the order of 8.2, 13.2, 13.4, 18.4, 18.5, 28.8, and 34.5 °C. When the SHED is covered with dry paper, $Q_{\text{dry}}$ is constantly flowing onto SHED. However, when it is covered with wet paper, $Q_{\text{wet}}$ only flows into SHED when the surface temperature is below 30 °C. The two $Q$s coincide at a surface temperature of around 13.5 °C. When these data are fractioned by our calibration (Fig. 2), the $C_{\text{wet}} (=Q_{\text{wet}} - R_{\text{wet}})$ is not fully explained by the theoretical estimate of convection caused by temperature differences between the surface and the ambient air plus evaporative cooling (Fig. 3, panel 3B). This is in agreement with a geoscientific theory that states that wetlands absorb more solar radiation than dry lands (Budyko 2008). This is a simple experiment, but it shows that surface temperature has a strong influence on heat exchange and that humidity or water vapor partial pressure is the determinant. I would like to show the whole picture under the environmental conditions of a wider temperature and humidity range.

In a room with the temperature of 12 °C, a tissue paper-covered and thermally radiated SHED with surface temperatures of 15, 20, 25, 30, and 35 °C gained more heat than the dry surface with additional water and sustained these values until the water dried up (Fig. 4). The device gained heat when radiated by a lamp; however, it absorbed additional heat (−100 kcal/m²/h) when water was added to the radiated surface. Another SHED, which was not covered with paper and non-radiated (dashed line in Fig. 4), exhibited more heat loss (HL) as the surface temperature increased. Similar measurements were performed in rooms at 17, 21, 27, and 31 °C (Supplement 1–4), and the results are summarized in Table 2.

In summary of experiment 2, multiple regressions of $\Delta Q_1$ and $\Delta Q_2$ listed in Table 2 are provided. This shows that both the $T_{\text{surface}}$ and $T_{\text{ambient}}$ are important factors in determining the amount of absolute radiated heat afflux on a wet surface. The inclusion of $T_{\text{surface}}$ and $T_{\text{ambient}}$ variables explain 74% of the data fluctuation.

A multiple regression equation shows how $T_{\text{surface}}$ and $T_{\text{ambient}}$ affect the increment of heat inflow when 1000 kcal/m²/h of heat is irradiated onto a wet surface (Table 2). The value $\Delta Q_1$ increased as the surface temperature decreased, and the ambient air temperature increased. The difference between radiated and non-radiated ($\Delta Q_2$) was negatively correlated with $T_{\text{surface}}$ and $T_{\text{ambient}}$. These results suggest that the transfer of radiant heat to the human body is negatively regulated by the skin surface temperature.

Representative data for conducting this experiment on humans are shown in Supplement 5. Two heat flow meters covered with dry tissue paper were attached to human skin, and the output of the heat flow meters was stabilized while irradiating heat with a lamp (value $A'$). After that, water was sprayed on one of the meters, and approximately 3 min later, the output became stable (value $B'$). The output of the heat flow meter temporarily decreased immediately after the water was applied; however, it rapidly increased to reach a new equilibrium. No change in output was observed on the ‘dry’ heat flow meter during this period. An increment in heat flow due to sprayed water ($\Delta Q_{\text{hs}}$) is the residue from $B'$ minus $A'$. The average skin temperature ($S_1$) during “dry” heat irradiation ($A'$) and the average skin temperature ($S_2$) during “wet” heat irradiation ($B'$) were determined to be $S$ because no significant change was observed. The values of $S$, $A'$, $B'$, $\Delta Q$, and a regression equation of $\Delta Q_{\text{hs}}$ by lamp radiation and sprayed
Fig. 3  A Results of experiment 1. $Q_{\text{dry}}$, $Q_{\text{wet}}$, and $Q_{\text{wet}} - Q_{\text{dry}}$ are accordingly to SHED surface temperature; B $Q_{\text{wet}}$, $Q_{\text{wet}} - R$, and theoretical estimation of convection ($C\Delta t$, convection by the temperature difference of ambient air and SHED surface, plus evaporation (CE)) are plotted. The values ($Q_{\text{wet}} - R$) are not satisfied by the sum of predicted values of convection and evaporative ($C\Delta t$ + CE) during this experiment.

![Graph](image1)

**Fig. 4** A result of experiment 2
Table 2 Results of experiment 2. The differences of \( Q \) induced by the surface water (\( \Delta Q_1 (\text{kcal/m}^2/\text{hr}) = Q_\text{wet} - Q_\text{dry} \)), and those induced by the radiation (\( \Delta Q_2 (\text{kcal/m}^2/\text{hr}) = \Delta Q_1 L_{\text{rad}} - \Delta Q_1 L_{\text{non-rad}} \)) are listed in this table. When \( \Delta Q \) is negative, it indicates more lamp-radiated heat flow into the wet SHED surface, but when \( \Delta Q \) is positive it indicates heat flow out from the wet SHED surface. Multiple regression equations for \( \Delta Q_1 \) and \( \Delta Q_2 \) on \( T_{\text{surface}} \) and \( T_{\text{ambient}} \) are shown below this table.

| Surface temperature (\( T_{\text{ambient}} \)) | Measurement and treatment | Lamp non-radiated (\( L_{\text{non-rad}} \)) | Lamp radiated (\( L_{\text{rad}} \)) |
|---------------------------------------------|---------------------------|-------------------------------------------|-------------------------------------------|
| 12.2 ± 1.4 °C | \( Q_{\text{dry}} \) | -7.4 | 946.7 | 173.4 |
| | \( Q_{\text{wet}} \) | -80.6 | 939.1 | 176.8 |
| | \( \Delta Q_1 = Q_{\text{wet}} - Q_{\text{dry}} \) | -73.2 | 739.1 | 105.7 |
| | \( \Delta Q_2 = \Delta Q_1 L_{\text{rad}} - \Delta Q_1 L_{\text{non-rad}} \) | -474.2 | 739.1 | -20.1 |
| 17.3 ± 0.9 °C | \( Q_{\text{dry}} \) | -89.4 | 1018.2 | 28.3 |
| | \( Q_{\text{wet}} \) | -119.2 | 1032.5 | - |
| | \( \Delta Q_1 \) | -184.3 | 992.2 | - |
| | \( \Delta Q_2 \) | -343.2 | 935.9 | - |
| 21.1 ± 1.7 °C | \( Q_{\text{dry}} \) | -128.5 | 1072.2 | 718.5 |
| | \( Q_{\text{wet}} \) | -90.4 | 1052.5 | - |
| | \( \Delta Q_1 \) | -146.5 | 1040.2 | - |
| | \( \Delta Q_2 \) | -234.6 | 994.8 | - |
| 27.1 ± 1.4 °C | \( Q_{\text{dry}} \) | -64.5 | 1440.2 | 740.6 |
| | \( Q_{\text{wet}} \) | -48.4 | 1307.2 | - |
| | \( \Delta Q_1 \) | -278.8 | 1166.3 | - |
| | \( \Delta Q_2 \) | -131.6 | 1013.0 | - |
| 30.6 ± 1.7 °C | \( Q_{\text{dry}} \) | -58.7 | 1308.7 | - |
| | \( Q_{\text{wet}} \) | -110.0 | 1247.0 | - |
| | \( \Delta Q_1 \) | -82.5 | 1216.3 | - |
| | \( \Delta Q_2 \) | -50.0 | 1170.5 | - |

\( \Delta Q_1 \) indicates the difference between \( Q_{\text{wet}} \) and \( Q_{\text{dry}} \) at each ambient temperature and surface temperature; \( \Delta Q_2 \) indicates the difference in \( \Delta Q_1 \) between the lamp is on and off, of each \( T_{\text{surface}} \) condition; - no data due to \( Q_{\text{dry}} \) cannot be distinguished from \( Q_{\text{wet}} \) in these experimental conditions; multiple regression equations: \( \Delta Q_1 = -24.1 \times T_{\text{surface}} + 10.3 \times T_{\text{ambient}} + 378.7 \) (\( R^2 = 0.905, F = 0.000, P < 0.001 \)) and \( \Delta Q_2 = -10.1 \times T_{\text{surface}} + 0.1 \times T_{\text{ambient}} + 361.7 \) (\( R^2 = 0.611, F = 0.000, P < 0.001 \)).

water showed a linear function with skin temperature (\( S \)) in Table 3.

The visible light transmittances for dry and wet tissue paper were 70 and 85%, respectively. The reflectance of the surfaces of dry and wet tissue papers were 28 and 13%, respectively. That is, surface water on tissue paper affected both the transmission of visible light through the paper and the reflection of visible light off the paper.

The absolute value of \( \kappa_{\text{dry}} \) at SHED surface temperatures of 30 and 35 °C in a room (25 °C, 80% RH, and < 0.2 m/s air velocity) was approximately 10 kcal/m²/hr°C, which is similar to that of a thermal mannequin (Mochida 1982; Kurazumi et al. 2008). The \( \kappa_{\text{wet}} \) measured by the same method was approximately thrice the value of \( \kappa_{\text{dry}} \). It was expected to be equivalent to the sum of \( \kappa_{\text{dry}} \) and evaporative cooling rates (Nishi and Gagge 1970). However, there were some recommendations on the evaporative cooling rate (7.86 kcal/m²/hr°C) of a standing subject in a specific condition (30 °C, 60% RH, airflow 0.2 m/s) (Nag 1984); 10 kcal/m²/hr°C was obtained by applying the regression equation (Colin and Haudas 1967), and it was similar to the measured \( \kappa_{\text{wet}} \). However, in our calibration using a Leslie cube, the heat exchange of the water-covered 35 °C SHED surface had a mean \( \kappa_{\text{wet}} \) of 29.8 kcal/m²/hr°C, which was compatible with the previous measurements (28.0–44.5 kcal/m²/hr°C) in a room with an artificial climate (Table 1). Because \( \kappa_{\text{dry}} \) was close to \( h_c \) in the absence of wind, it is reasonable that \( \kappa_{\text{wet}} \) is thrice the value of \( \kappa_{\text{dry}} \) based on the Lewis relation (Gagge and Nishi 1977).

\( \kappa_{\text{dry}} \) is the sum of the convective heat transfer coefficient \( h_c \) and radiant heat transfer coefficient \( h_r \) on a dry vertical surface. When a vertical plane receives radiant heat, the temperature of the surface increases, which affects convection and conduction. Thus, a new thermal balance of the entire sensor is established. However, in the SHED, heat recovery or release is performed in a separate circuit, and the surface temperature is constantly buffered so that the output depends only on the prevailing environmental conditions. In the SHED calibration that used a Leslie cube as the radiant heat source, the \( R \) and \( C \) derived from \( Q \) minus \( R \) were positively
Table 3 Absolute differences between heat flow ($\Delta Q_{\text{hs}}$) of lamp-irradiated dry skin (A') and wet skin (B') of ten human subjects. Positive values indicate higher lamp-irradiated heat inflow, and negative values indicate loss of heat from their skin surface. Two trials in a warmer room or colder room were performed on the same day. Supplement 5 is helpful how to analyze the individual data.

| Subjects | Measurement and treatment | Trial 1 | Trial 2 | Subjects | Measurement and treatment | Trial 1 | Trial 2 |
|----------|---------------------------|--------|--------|----------|---------------------------|--------|--------|
| Sub. A   | S1: skin temp. pre-radiation (°C) | 29.5   | 29.4   | Sub. E   | S1                       | 28.5   | 27.7   |
|          | S: skin temperature (°C)     | 38.2   | 40.6   | S        | 39.0                     | 37.1   |        |
|          | $A'$ (kcal/m²/h)             | 530.3  | 466.8  | $A'$     | 357.3                     | 278.0  |        |
|          | $B'$ (kcal/m²/h)             | 96.6   | -55.3  | $B'$     | 104.9                     | 2.9    |        |
|          | $\Delta Q_{\text{hs}}$      | -433.7 | -522.2 | $\Delta Q_{\text{hs}}$ | -252.4 | -275.1 |
| Sub. B   | S1                         | 31.5   | 29.2   | Sub. F   | S1                       | 30.0   | 29.1   |
|          | S                          | 37.5   | 36.5   | S        | 39.4                     | 37.9   |        |
|          | $A'$                       | 221.7  | 331.6  | $A'$     | 400.1                     | 342.9  |        |
|          | $B'$                       | -68.2  | -128.8 | $B'$     | 109.9                     | -30.3  |        |
|          | $\Delta Q_{\text{hs}}$      | -289.9 | -460.4 | $\Delta Q_{\text{hs}}$ | -290.2 | -312.6 |
| Sub. C   | S1                         | 29.3   | 30.7   | Sub. G   | S1                       | 28.5   | 27.7   |
|          | S                          | 38.5   | 37.5   | S        | 38.4                     | 37.6   |        |
|          | $A'$                       | 507.4  | 330.1  | $A'$     | 350.5                     | 220.6  |        |
|          | $B'$                       | 80.4   | -33.6  | $B'$     | 24.6                      | -72.8  |        |
|          | $\Delta Q_{\text{hs}}$      | -427.0 | -363.7 | $\Delta Q_{\text{hs}}$ | -325.9 | -293.4 |
| Sub. D   | S1                         | 30.7   | 29.3   | Sub. H   | S1                       | 30.0   | 28.6   |
|          | S                          | 41.4   | 39.7   | S        | 39.6                     | 37.8   |        |
|          | $A'$                       | 653.4  | 637.1  | $A'$     | 601.6                     | 293.0  |        |
|          | $B'$                       | 287.2  | 215.7  | $B'$     | 221.4                     | 80.5   |        |
|          | $\Delta Q_{\text{hs}}$      | -366.2 | -421.4 | $\Delta Q_{\text{hs}}$ | -380.2 | -212.5 |

$\Delta Q_{\text{hs}} = -27.864S + 710.85\ (R^2 = 0.226)$

correlated to $Q$. The value of $Q$ minus $R$ fluctuates greatly when the surface is wet, so convective heat exchange is considered to account for most of the fluctuation. The surface of human skin is rich in blood vessels and acts as a buffer against heat invasion from the external environment. Skin temperature during exercise is even more strongly buffered by increased blood flow and sweating. Therefore, because the SHED output maintains a constant surface temperature, it closely represents the amount of heat exchanged between the human skin surface and the external environment.

The following important points were obtained by analyzing the amount of heat exchange ($Q_{\text{dry}}$ or $Q_{\text{wet}}$) in experiment 1 conducted at 25 °C. [1] $Q_{\text{dry}}$ cannot dissipate heat when $T_{\text{surface}}$ is ≤ 40 °C, and $Q_{\text{wet}}$ can dissipate heat when $T_{\text{surface}}$ is < 28 °C. [2] The $Q_{\text{dry}}$ and $Q_{\text{wet}}$ attained equivalence when $T_{\text{surface}}$ was < 22 °C, and our theoretical estimation of $C^\prime$ (sum of evaporation and convection caused by the temperature difference between the SHED surface and ambient air) cannot exceed $C$ which was obtained from experiment 1 (dashed line in Panel 3B). That is, at an ambient temperature of 25 °C, $Q_{\text{dry}}$ and $Q_{\text{wet}}$ with a surface temperature of 13.5 °C or less always match regardless of the dry/wet state of the surface. It is presumed that one of the causes of [2] is that the value, $Q$ minus $R$, increases owing to the aggregation of water vapor on the SHED. In the case of this experiment, it was shown that $Q_{\text{wet}}$ does not promote cooling but instead promotes heat absorption. Moreover, it works remarkably when $T_{\text{surface}}$ is between 20 and 30 °C. Geoscientific studies have already shown that moist soil absorbs 10% more sunlight than dry soil (Budyko 2008), and the results of our experiment support this. We believe that this is evidence of a similar phenomenon that occurs in relation to sweating human skin. During cold days, runners and outdoor workers absorb more solar heat than previously predicted when their skin surface is wet. The authors referred to this phenomenon as the hidden heat inflow (HHI), whereby greater heat flows into wet skin surfaces than dry ones when radiant heat is applied.

The results of experiment 2 were significant. They showed a significant difference between the wet and dry surfaces of the heat inflow (Fig. 4). In this experiment, fluctuations in airflow, room temperature, and humidity were minimized, so the surface temperature was the only factor invoking the heat inflow or HHI. It was confirmed that vaporization cooling was restored when the surface temperature of the SHED was 25 °C or higher, and below that, the HHI was expressed. The experiment also showed that $\Delta Q$, the difference between $Q_{\text{wet}}$ and $Q_{\text{dry}}$, decreased with increasing $T_{\text{ambient}}$ (Table 2).

The bulb used as the heat source in this study is a high-temperature and point-radiant source; $Q$ is not calibrated
by Stefan–Boltzmann’s equation, but the fluctuation of $Q$ can be read.

The results of the three experiments are summarized in Fig. 5. This shows that $\Delta Q$ is inversely proportional to the $T_{\text{surface}}$ or skin temperature. It also shows that when the surface temperature of the SHED is below 25 °C, the surface must be lost its water evaporation, or occurring condensation of water vapor in the ambient air. This phenomenon is also expected to occur on the skin running in cold air (Maron et al. 1977). These results explain the cause of the EHS that occurred during the marathon race held on a cold day and suggests that Roberts’ case report is by no means a misdiagnosis (Roberts 2000).

Wind direction is another important factor. The winds in the Northern Hemisphere have different velocities, but their directions are mostly westerly. The running courses in which EHS cases have been reported often include long straight ways heading east-northeast. The Hakone Ekiden in Japan is no exception. The body temperature balance of runners running under such environmental conditions tends to be negative, increasing the risk of EHS. Contrary to the well-known phenomenon of heat dissipation due to sweating on the body surface, a wet and low-temperature surface receives more heat than a dry surface when thermally radiated (Clark et al. 1977; Tanda 2016). A water-induced lowered thermal conductivity (Chen et al. 2003) and diminished sweat evaporation by the lowered skin temperature, are causative factors for this phenomenon. Thus, cooled skin surfaces add an unknown heat source for runners in cold air, causing an occasional EHS and decreased endurance. Further studies are necessary to find ways to protect outdoor athletes from radiant heat and to enable them to maintain their level of performance.

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**Declarations**

**Conflict of interest** The authors declare no competing interests.

**References**

Blazejczyk K, Nilsson H, Holmer I (1993) Solar heat load on man. Review of different methods of estimation. Int J Biometeor 37:125–132. https://doi.org/10.1007/BF01212621

Budyko MI (2008) Heat balance of the earth’s surface, 1st Russian ed. Springer Science + Business Media, New York

Blazejczyk K, Nilsson H, Holmer I (1993) Solar heat load on man. Review of different methods of estimation. Int J Biometeor 37:125–132. https://doi.org/10.1007/BF01212621

Budyko MI (2008) Heat balance of the earth’s surface, 1st Russian ed. Springer Science + Business Media, New York

Chen YS, Fan J, Zhang W (2003) Clothing thermal insulation during exercise. Int J Biometeorol 34:69–75. https://doi.org/10.1007/BF01093450

Kurazumi Y, Tsuchikawa T, Ishii J et al (2008) Radiative and convective heat transfer coefficients of the human body in natural convection. Build Environ 43:2142–21533 (Radiative and convective heat transfer coefficients of the human body in natural convection - ScienceDirect)

Kyröläinen H, Pullinen T, Candau R et al (2000) Effects of marathon running on running economy and kinematics. Eur J Appl Physiol 82:297–304. https://doi.org/10.1007/s004210000219

Laitano O, Leon LR, Roberts WO et al (2019) Controversies in exertional heat stroke diagnosis, prevention, and treatment. J Appl Physiol 127:1338–1348. https://doi.org/10.1152/japplphysiol.00452.2019

Maron MB, Wagner JA, Horvath SM (1977) Thermoregulatory responses during competitive marathon running. J Appl Physiol: Respirat Environ Exercise Physiol 42:909–914. https://doi.org/10.1152/jappl.1977.42.6.909

Mochida T (1982) Mean convective heat transfer coefficient for the human body. Jpn J Ergon 18:261–267. https://doi.org/10.5100/jje.18.261 (In Japanese with English abstract)

Nag PK (1984) Convective and evaporative heat transfer coefficients of the persons in different activities. J Human Ergol 13: 43–49. https://doi.org/10.1118/jhe1972.13.43

Nielsen B (1990) Solar heat load: heat balance during exercise in clothed subjects. Eur J Appl Physiol 60:452–456. https://doi.org/10.1007/BF01212621

Nielsen B (1996) Olympics in Atlanta: a fight against physics. Med Sci Sports Exerc. 28:665–8 (https://www.ncbi.nlm.nih.gov/pubmed/8784753)

Nishi Y (1981) Thermal heat exchange between human and environment. In: Nakayama A, editor. Thermophysiology. Rikogaku-sya; 1981. p. 33–43, Japanese.

Nishi Y, Gagge AP (1970) Direct evaluation of convective heat transfer coefficient by naphthalene sublimation. J Appl Physiol 29:830–838. https://doi.org/10.1152/jappl.1970.29.6.830

Roberts WO (2000) A 12-yr profile of medical injury and illness for the twin cities marathon. Med Sci Sports Exerc 32:1549–1555. https://doi.org/10.1097/00005768-200009000-00004

Roberts WO (2006) Exertional heat stroke during a cool weather marathon: a case study. Med Sci Sports Exerc 38:1197–1203. https://doi.org/10.1097/00005768-200611000-00010

Tagami K (2011) Japan Pat. No. 4608653, Human thermal exchange detector, 2011. http://www.jpo.jst.go.jp/PDFView.html?type=nationalPatent&id=11966&property=entryPdf (in Japanese). Accessed 21 Oct. 2020

Tanda G (2016) Skin temperature measurements by infrared thermography during running exercise. Exp Thermal Fluid Sci 71:103–113. https://doi.org/10.1016/j.expthermflusc.2015.10.006

Young KC (1979) The influence of environmental parameters on heat stress during exercise. J Appl Meteorol 18:886–897. https://doi.org/10.1175/1520-0450(1979)018<0886:TOEPO>2.0.CO;2

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