ABSTRACT The number of patients experiencing heat-related illnesses has gradually increased due to global warming. Owing to an aging society, 50% of patients with heat-related illnesses in Japan are elderly. Core temperature is one key parameter for health care; however, its monitoring is virtually impossible. Internet of Things (IoT) devices for healthcare have been proposed; however, the vital parameters to be monitored remain controversial. Here, we assessed the core temperature of elderly patients who were transported to hospitals by ambulance from their homes. The patients’ core temperatures were recorded by the Fire Department of Nagoya City in the summers of 2019 and 2020. The time course of the core temperature of each patient was then replicated using the integrated computational techniques through multiphysics analysis and thermoregulation under ambient condition data. According to the statistics, most elderly patients who were transported from their homes had a high core temperature. The measured core temperature in 31.4% of the patients was higher than the computed core temperature even assuming that there was no sweating. Assuming that the sweating function works well, the total amount of water loss was insufficient to have caused dehydration in a single day. These results suggest that successive heat stress during the preceding days should be considered to recreate the computed core temperature to match the measurement. These results were consistent with the previous finding that some elderly suffered from heatstroke successively over a few days. In the IoT-based monitoring system development, it would be informative for monitoring core temperature during the preceding days.

INDEX TERMS Ambulance dispatch, core temperature, elderly, heat-related illness, thermoregulation, multiphysics computation.

I. INTRODUCTION
Owing to global warming, particularly the intense heat waves [1], the number of patients experiencing heat-related illnesses has been increasing [2]–[6]. This number is mainly influenced by meteorological factors, including temperature, relative humidity, solar radiation, and wind speed [7]. Extensive studies have been conducted on the characterization of ambient conditions in different areas and countries [8], [9]. For example, the buildings surrounding an individual’s residential premises are reported to influence the air temperature in urban areas [10]–[12].

In Japan, the number of individuals transported via ambulance due to heat-related illnesses may be used as a surrogate for patients with heat-related illnesses. Additionally, ambulance transportation in Japan is free [13]. Thus,
unlike in most studies on mortality attributable to heat-related illnesses [8], [14]–[17], the data for morbidity is available. Statistics in Japan [18] show that 50% of the patients are elderly, among which > 50% suffered from heat-related illnesses in their homes [19]. Nonexternal (classical) heatstroke, which is frequent in the elderly and chronically ill patients, may gradually develop over a few days, according to one hypothesis [7], [20]–[22]. However, this hypothesis was derived statistically; thus, the detailed time course until its onset remains unknown. One reason can be the lack of measured core temperature of actual patients, which is one of the heat-related illness indexes [23]. Core temperature measured in the ambulance would be of particular importance because the first aid before and during the transportation and medical treatment in hospitals may result in core temperature lowering.

A thermoregulatory model has been used to predict heatstroke during heat exposure [24], [25]. The participants in these studies are typically healthy adults rather than elderly or individuals with chronic illnesses. Chronic illness, besides aging, is considered to impair an individual’s capacity to sweat [26]. Therefore, the computational estimation of core body temperature and sweating in the elderly for ambient heat may provide additional information on the patients. Furthermore, an individual monitoring system has been developed for this situation; however, vital parameters to measure are rather arbitrary (see Section II).

Based on the abovementioned circumstances, knowledge gaps exist on i) measured core temperature of real patients and ii) the time course of the thermoregulatory response, which is characterized by the indoor temperature of the patients’ homes. Nevertheless, these parameters are usually not obtained for actual patients since patients generally record their own data [27]. If we can compare the measured core temperature in the ambulance before the first aid and computationally replicated value, the data would be helpful to explore the mechanism and intervention of heat-related illnesses.

This study aims to elucidate the onset mechanism of heat-related illnesses for the elderly who are at a high risk of heatstroke. We then evaluated the core temperature of the elderly patients, aged > 65 years, transported from their homes due to heat-related illnesses, especially for severe patients. Specifically, the Nagoya City Fire Department has collected data on all patients’ core temperatures in the summers of 2019 and 2020. Subsequently, the time course of core temperature variation and sweating of the patients was estimated using the integrated computational techniques of multiphysics analysis and thermoregulation under ambient conditions at the corresponding time to fill out the gap of measurement.

II. RELATED STUDIES
IEEE Xplore, PubMed, and Web of Science were systematically searched using the keywords “elderly” AND (“heatstroke” OR “heat-related illness”), and several related studies were found. In [28], an approach is proposed to detect any risky conditions inside indoor environments, and then effectively warn them to the elderly through multisensory information presentation. Takahashi et al. [29] explored whether home delivery of bottled water and broadcasting heat health warnings are effective in preventing heatstroke. These studies showed the effectiveness of the detection system and public awareness in raising awareness of the elderly.

For the search with keywords “core temperature” AND “measurement” AND (“heatstroke” OR “heat-related illness”), no measured data of core temperature of real patients for the nonexternal (classical) heatstroke were noted; most of the papers found were related to the external one, especially for athletes [30], [31]. For the search with keywords “core temperature” AND “estimation” AND (“heat stroke” OR “heat-related illness”), several related studies were found. These studies developed tracking or monitoring system of vital signals based on Internet of Things technology, including wearable sensors. In [32], an approach is proposed to estimate core temperature using wrist-worn and ambient sensors. In [33], the core temperature is estimated in real time by using the two-node model that approximates a human body as a sphere composed of skin and core layers. In [34], an eardrum ( tympanic) temperature sensor is proposed together with a sweat sensor.

Heatstroke detection systems using infrared and visible cameras have also been proposed [35], [36]. The use of face recognition techniques is being explored to detect priority hazards for young children, elderly, and chronically ill patients [35].

In summary, none of the abovementioned techniques measured the core temperature of elderly patients due to heat-related illnesses. New techniques are developed to monitor the vital signs of patients; however, they are not directly used for real patients.

Thus, the first novelty of this study lies in the measurement of core temperature rise in real patients; another is the investigation of key parameters to monitor based on the comparison of measurement and computational estimation.

III. DATA
A. METEOROGICAL DATA
The target city in this study is Nagoya City (covering an area of 326.4 km$^2$), located at 35°10’ and 136°54’, and is a major city in the Aichi Prefecture of Japan (Figure 1). The ambient temperature and relative humidity in Nagoya City are measured and provided by the Japan Meteorological Agency [37]. In Nagoya City, the ambient temperature was <28°C (thermoneutral temperature) from evening to morning, as shown in Figure 11 of the Appendix.

The meteorological data are directly utilized for the ambient exposure condition, provided that the room is in good condition. Heat load due to solar radiation is thus not considered. Depending on the type of building material used, the indoor temperature in Japanese residences is typically
a few degrees cooler than the outside temperature until after 4–5 PM [38]. The temperature within the building subsequently increases somewhat. The thermal radiation of building materials, which is warmed by ambient temperature and solar radiation, is the cause of this alteration.

Although Japan has an approximately 90% penetration rate of air conditioners [39], actual usage among the elderly is projected to be lower. According to a recent survey [40], 66% of the elderly adjust the indoor temperature by just opening the window rather than using an air conditioner (24%) and/or fan (24%). The computed core temperature may be overestimated, assuming the outdoor ambient temperature as an input parameter. Furthermore, the computation may underestimate the temperature after 5 PM. The difference in the core temperature increase was estimated to be <0.1°C when the following computational method was used.

B. INDIVIDUALS TRANSFERRED VIA AMBULANCE IN NAGOYA CITY

The population of Nagoya City is 2.32 million. The data of individuals transported via ambulance due to heat-related illnesses were collected by the Department of Emergency in Nagoya City. The data were curated during the summers of 2019 and 2020. A total of 2,513 individuals were transported via ambulance due to heat-related illnesses. We extracted the data of patients whose measured body temperature was recorded for analysis \( n = 2,316 \). These data include the date and time of the transportation, place (city block and additional information of places [apartment house, street, nursing home, road, etc.]), and core temperature when transported. Despite the high uncertainty, the axillary method (under the armpit) was used to quickly detect body temperature [41].

During the transportation, the core temperature measurement was conducted several times. The average time to get travel from the fire station to a patient’s place was 6 min; however, finding a hospital afterward was case-specific. Owing to the first aid restriction of first aid during transportation, the rectal temperature cannot be measured. Some patients were cooled through first aid before the call. Although the amount of coolant used was case-specific and virtually unknown, some of them patients had an axillary temperature of 34°C–36°C, which is much lower than the normal body temperature of 36°C–37°C [42], [43]. Hereafter, measured axillary temperature is defined as core temperature without additional notification.

IV. COMPUTATIONAL METHODS

Here, we computed the body temperature changes in relation to heat exposure in the summers of 2019 and 2020 in Nagoya City and subsequently investigated the association of these data with the measured temperature of the patients transported via ambulance. The computational approach that we used was identical to that used in our previous studies [44]; thus, only the outline has been mentioned below. Previous studies have offered validations of our computational code for healthy participants [44]–[48].

A. HUMAN BODY MODELS

A human body model whose height and weight are close to the mean values for an average Japanese adult male was applied [49]. This model was developed using magnetic resonance images, and its height and weight were 1.73 m and 65 kg, respectively. The model was segmented into >50 anatomical regions or organs, such as the skin, fat, muscle, and bone. Different thermal parameters were assigned to each tissue for human thermal modeling [50]. Figure 2 presents an illustration of the anatomical body model and a definition of body parts used for the blood temperature computation (Sec. IV-B).

B. TEMPERATURE COMPUTATION

Our previous study provided a full explanation of our in-house computational code developed at the Nagoya
The human model’s thermoregulation was assumed to be similar to that of adults living in a temperate zone [46], [51], which included Nagoya City.

1) BIOHEAT EQUATION
For the bioheat transfer equation, the temperature of the human model was calculated using a finite-difference time-domain approach [52]:

\[ C(\mathbf{r}) \rho(\mathbf{r}) \frac{\partial T(\mathbf{r}, t)}{\partial t} = \nabla \cdot (K(\mathbf{r}) \nabla T(\mathbf{r}, t)) + M(\mathbf{r}, t) - B(\mathbf{r}, t) (T(\mathbf{r}, t) - T_B(m, t)) \]

where \( T \) denotes the tissue temperature at the three-dimensional position vector \( \mathbf{r} \) (voxel), \( t \) represents time, and \( T_B \) is the arterial (blood) temperature of each body part (\( m = 1, \ldots, 13 \), where \( m \) denotes the body parts defined in Figure 2b). The parameters \( C, K, M, B, \) and \( \rho \) denote the specific heat, thermal conductivity, metabolic heat generation, a term associated with blood perfusion, and the density of each tissue, respectively. A different set of thermal parameters was assigned to each tissue as previously shown [50]. The arterial temperature of each body part was changed as described in an earlier trial [46]. The arterial temperatures of the head and torso were assumed to be the same, on the basis of the high blood volume [53], and defined as the core temperature in this study.

The boundary conditions between air and tissue for Equation (1) are expressed as follows:

\[ -K(\mathbf{r}) \frac{\partial T(\mathbf{r}, t)}{\partial n} = H(\mathbf{r}, t) (T(\mathbf{r}, t) - T_a(t)) + EV(\mathbf{r}, t) \]

where \( H, T_a, \) and \( EV \) are the heat transfer coefficient, ambient temperature, and evaporative heat loss, respectively. The heat transfer coefficient includes the convective and radiative heat loss and changes over time as per the surrounding air temperature and surface skin temperature, as in an earlier study [53]. The participants were assumed to wear a half-sleeve shirt and long pants with breathable material (by multiplying \( H(\mathbf{r}, t) \) with 0.9).

The blood temperature was modeled as previously described [46], with arterial and venous temperatures being independently considered [54]. Here, we defined the arterial blood temperature in the head and trunk as the core temperature.

2) THERMOREGULATORY RESPONSE MODELING
The evaporative heat loss on the skin was calculated as follows:

\[ EV(\mathbf{r}, t) = \min \{ SW(\mathbf{r}, t) \cdot 40.6/S, EV_{\text{max}}(t) \} \]

\[ EV_{\text{max}}(t) = 2.2 \cdot h_p f_{\text{pcl}}(P_S(t) - \varphi_e P_A(t)) \]

where \( SW \) and \( S \) denote the sweating rate, as defined by Equation (4), and the total surface area of the human body, respectively. The maximal evaporative heat loss \( EV_{\text{max}} \) on the body surface depends on the ambient conditions that reflect the meteorological data used in this study. The parameter \( h_p \) is the previously estimated convective heat transfer coefficient [55]. The parameters \( v \) and \( \varphi_e \) represent wind velocity and relative humidity of ambient air, respectively. The wind velocity in this study was assumed to be <0.1 m/s, which corresponds to a typical room without an air conditioner. The parameters \( P_S \) and \( P_A \) are the saturated water vapor pressures at skin temperature and at ambient air temperature, respectively, and \( f_{\text{pcl}} \) is the permeation efficiency factor of clothing and set to be 0.7 for body parts with clothing and 1 for face and upper limbs without clothes or shoes [55], [56].

The variable sweating rate (SW) is based on the following Equation (4):

\[ SW(\mathbf{r}, t) = \chi \gamma \cdot \left[ \alpha_{11} \tanh(\beta_{11}(\Delta T_S(t) - T_{S,\text{dec}}) - \beta_{10}) + \alpha_{10} \right] (\Delta T_S(t) - T_{S,\text{dec}}) + \alpha_{21} \tanh(\beta_{21}(\Delta T_H(t) - T_{H,\text{dec}}) - \beta_{20}) + \alpha_{20} \left( \Delta T_H(t) - T_{H,\text{dec}} \right) + PI \]

where \( \Delta T_H \) and \( \Delta T_S \) are the temperature increases of the hypothalamus and the skin averaged over the body, respectively. The insensible water loss \( PI \) was 0.71 g/min, based on the weight and height of the model [44], [46]. The multiplier \( \gamma(\mathbf{r}) \) denotes the dependence of the \( SW \) on the body parts [57]. The coefficients \( \alpha \) and \( \beta \) are estimated for an average \( SW \) on the basis of the measurements derived previously [58].

The parameter \( \chi \) denotes the coefficient related to the decline of sweating; \( \Delta T_{S,\text{dec}} \) and \( \Delta T_{H,\text{dec}} \) denote the threshold as per aging-related deterioration in the thermal sensitivity of the skin and hypothalamus [45], [59], [60]. To discuss the assessment of heatstroke for the elderly, the following four types of sweating were considered: (i) a healthy adult patient, (ii) a patient aged >65 years, (iii) a patient aged >75 years, and (iv) a patient without sweating (most severe case). The classification of >65 and >75 years is based on the measured data used to develop the thermoregulatory response model [61], [62]. Table 1 lists sets of the parameter in Equation (4). The blood perfusion rate via vasodilatation was changed as previously reported [44]. This response marginally influenced the core temperature variation; therefore, a comprehensive description of this modeling is not included here.

| sweating model | (i) Adult | (ii) Aged > 65 y | (iii) Aged > 75 y | (iv) Most severe case |
|----------------|-----------|-----------------|-----------------|---------------------|
| SW             | According to Eq (4) | SW = 0 |
| \( \chi \)    | 1         | 0.7 in legs, 1 in others | – |
| \( \Delta T_{S,\text{dec}} \) | 0         | 1.5         | 1.5            | – |
| \( \Delta T_{H,\text{dec}} \) | 0         | 0         | 0.4            | – |
naked condition at an ambient temperature of 30°C, when thermoregulation parameters, including blood perfusion and perspiration, as well as blood temperature, remained constant.

C. COMPUTATIONAL SCENARIOS

With the sweating model defined in Table 1, the thermal analysis was conducted for heat exposure to the measured environment from April 28, 2019 to September 30, 2019 and from April 28, 2020 to August 31, 2020. The ambient temperature and humidity in Nagoya City were reported in a 1-h resolution. Thus, linear interpolation was used to determine the matching condition with a 2-s time resolution necessary for computation. Furthermore, the reported ambient temperature and humidity were substituted in Equations (2) and (3), respectively, which serve as heat load and set the permissible evaporative heat loss. The computation was performed throughout a single day, beginning in the morning and ending when the relevant patient was transported. As for the models used in the computation, the 65-year-old model (the sweating model [ii]) was used for patients who were aged 65–74 years, and the 75-year-old model (the sweating model [iii]) was used for those aged ≥75 years. Figure 3 shows the schematic explanation of exposure conditions and the relation with input data.

D. GROUPING OF ELDERLY PATIENTS BY COMPARING MEASURED AND COMPUTED CORE TEMPERATURE

We divided the elderly patients into groups according to the core temperature measured when transported because our interest here is severe cases rather than mild ones where marginal temperature increase is observed. As shown in Figure 4, we have classified them into four groups based on the core temperature with different sweating (SW in Equation (4)) (See Sec. IV.B.(2) and Table 1 for information
on sweating models). Group 1: the patients whose core temperature was <37.0°C and who were likely to be affected by cooling down for first aid. Group 2: the patients whose core temperature was ≥37.0°C and lower than computed core temperature with sweating model (ii/iii) and who can sweat within the normal range. Group 3: the patients whose core temperature was higher than computed ones with sweating model (ii/iii) and lower than the computed value with sweating model (iv) and who were expected to be unable to sweat for some reason. Group 4: the patients whose core temperature was higher than computed ones with sweating model (iv) and who cannot sweat and whose body core temperature was higher than computed ones due to environmental factors.

V. RESULTS

A. ANALISIS OF MEASURED CORE TEMPERATURE WHEN TRANSPORTED DUE TO HEAT-RELATED ILLNESSES

Table 2 shows the information of patients with heat-related illnesses analyzed here. Of these patients, 41.1% and 58.9% were transported from their homes and outside buildings, respectively. Among the patients transported from their homes, 73.8% were ≥65 years, and 55.4% of them were aged ≥75 years. Among the patients transported from outside buildings, 43.9% were ≥65 years.

The number of patients who were cooled down following first aid (<36°C) was 7.8% (181 cases), and 45% of the patients were <37.0°C (Group 1). The following discussion focuses on groups 2–4 to remove the effect of first aid as much as possible. For groups 2–4, the measured body temperature was 37.9°C ± 0.9°C, 38.5°C ± 1.2°C, and 38.4°C ± 1.0°C in patients aged ≤64, 65–74, and ≥75 years, respectively.

Figure 5 shows the age dependence of core temperature measured when the patients were transported via ambulance due to heat-related illnesses. The prevalence of heat-related illnesses rapidly increased in those aged ≥65 years. A weak positive correlation was observed between age and core temperature ($R^2 = 0.047$, $p < 0.001$ in patients transported from inside buildings and $R^2 = 0.113$, $p < 0.001$ in patients transported from outside buildings), irrespective of the place where they were transported. $P$ values of <0.05 were considered statistically significant. Additionally, a difference in core body temperature according to sex was marginal.

Figure 6 presents the relationship between the transport time and measured core temperature in patients aged >65 years, measured when they were transported via ambulance due to heat-related illnesses in 2019 and 2020, and the number of patients transported for each hour. (a) Patients transported from inside buildings and (b) those transported from outside buildings. The patients whose core body temperature was ≤37.0°C were excluded considering the potential effect of first aid before the ambulance transportation.
A. Takada et al.: Computed and Measured Core Temperature of Patients

TABLE 3. Number and percentage of patients with health-related illnesses with a varying threshold of core temperature from 37.0°C in 0.5°C increments (N = 703).

| Threshold of core temperature (°C) | Number of patients | Percentage (%) |
|-----------------------------------|--------------------|----------------|
| ≥37.0                             | 503                | 71.6           |
| ≥37.5                             | 404                | 57.5           |
| ≥38.0                             | 318                | 45.2           |
| ≥38.5                             | 228                | 32.4           |
| ≥39.0                             | 143                | 20.3           |
| ≥39.5                             | 79                 | 11.2           |
| ≥40.0                             | 52                 | 7.4            |

these patients were transported from 8 AM to 7 PM. Higher core temperature was observed between 12 noon and 3 PM in those transported from outside buildings.

B. COMPUTED CORE TEMPERATURE CONSIDERING DECLINED THERMOREGULATION DUE TO AGE

The measured core temperature was compared with the computed core temperature, assuming that each patient was exposed to outdoor ambient heat from the morning to the time when a rescue team member measured the core temperature. The patients analyzed were those in groups 2, 3, and 4 (n = 703). The body temperature of patients with heatstroke who were aged 65–74 years was computed using the sweating model (ii); for those aged ≥75 years, the core body temperature was computed using the sweating model (iii).

Figure 7 (a) shows the relationship between the average ambient temperatures of the corresponding day from 0 AM (beginning of the day) until the time when patients were transported in the computed and measured core temperatures. As shown in Figure 7 (a), in several patients, the measured body temperature was higher than the computed temperature (groups 3 and 4). Figure 7 (b) shows the same comparison if the sweating does not cool down the body temperature (the sweating model [iv]). The computed body temperature using the sweating model (iv) shows better agreement with the measured data than the other models, especially for the patients with high body temperature. The patients in Group 4 were 31.4% (221 cases), corresponding to the colored area in Figure 7 (b). The numbers of patients aged 65–74 and ≥75 years were 45 and 176, respectively.

The wet-bulb globe temperature (WBGT) [64] is frequently used as the index of risk assessment of heat-related illnesses. Figure 8 shows the cumulative probability of ambient temperature and WBGT for the patients in Group 4, and the values of the previous day were also plotted. The threshold of daily maximum ambient temperature and WBGT, which was defined as the values whose cumulative probability exceeds 20% of the patients in the group 4, was 32°C and 28°C, respectively. The threshold for the previous day was 31°C and 29°C, respectively.

C. EFFECTS OF SWEATING AS PER THRESHOLD OF BODY CORE TEMPERATURE WHEN TRANSPORTED

We set different threshold temperatures and excluded patients whose measured core temperature was lower than the threshold. Table 3 shows the number and percentage of patients with heat-related illnesses when the threshold temperature was varied from 37.0°C in 0.5°C increments. We found that 45.2% of the elderly patients who were transported from inside a building had core temperatures of >38°C.

Figure 9 reveals the absolute error for patients with a temperature greater than the threshold temperature. When the threshold core temperature was set at 38.5°C or lower, the error in the computational model without perspiration provided worse estimates than that of the original model, wherein the sweating works. However, this was the opposite for the threshold of ≥38.5°C.

Figure 10 presents the estimated total amount of sweating in the computational models of healthy participants from morning to the time when they were transported, assuming the patients with a core temperature of >38.5°C, excluding insensible water loss. The average amount of sweating was estimated to be 222 ± 257 g. Assuming a 60-kg body weight, all patients had <2% dehydration (1,200 g), and 89% of the patients (203 cases) had <1% dehydration. If we assumed the declined perspiration function, the total amount of sweating was case-specific because sweating is nonlinear.

VI. DISCUSSION

Here, we analyzed the core temperature of the elderly (aged >65 years) who were transported via ambulance from...
their homes due to heat-related illnesses by comparing the measured and computed core temperatures.

A. MESASURED CORE TEMPERATURE OF PATIENTS

As shown in Figures 5 and 6, the core temperature of the patients transported via ambulance was higher for the elderly, and the number of patients increased in the afternoon, based on the data acquired by the Fire Department of Nagoya City; 54% of the elderly patients suffered from heat-related illnesses in their homes. The difference in core temperature according to sex was marginal. Note that the axillary method was used as a surrogate of core temperature because other methods were not feasible during the first aid for patients. Therefore, the core temperature reported here is an approximate value, which may result in uncertainty. The axillary temperature generally underestimates other core temperature (such as rectal temperature) [65]. Therefore, the actual core temperature of patients may be higher than reported. Furthermore, the core temperature in the elderly is lower than that in young adults (36.1°C–36.8°C); therefore, the computed temperature may have potentially overestimated the temperature difference from 37°C. Most patients made emergency calls in the afternoon, suggesting a long-time ambient heat exposure, especially when the ambient temperature was high. Some patients made the call in the morning, with a very high core temperature (>40°C) (corresponding to the left part of Figure 6 [a]), hypothesizing that some of them experienced high core temperature from the previous day(s), as reported in previous studies [7], [22], [66], [67]. For the patients with a core temperature of >38.5°C, 62 patients were transported in the morning when an average ambient temperature was <30°C. Among them, 41 (66%) cases were observed on the day when the daily maximum ambient temperature on the previous day exceeded 35°C.

B. COMPARISON BETWEEN MEASURED AND COMPUTED CORE TEMPERATURES AND SWEATING OF PATIENTS

We computationally replicated the time course of the computed core temperature (see also Appendix) to offer insight due to a lack of time course information in the measured values or because taking measurements was complicated. The comparison suggested obvious differences between the measured and computed core temperatures. Particularly, the measured values were notably higher than the computed values, indicating that the thermoregulatory function was
lower than that of the models for several patients. Otherwise, this may violate the thermodynamics law. To confirm this hypothesis, we computed the core temperature for the model without sweating. The computational results were in better agreement with the measurement, suggesting declined perspiration function in some patients with body temperatures of $>38.5^\circ$C. The temperature of 32.4% of the patients was above this threshold temperature.

As shown in Figure 7, half of the patients had a higher body temperature than that with the non-sweating model condition, especially in patients with a body temperature of $>38.5^\circ$C. Simulating the situation of patients with a body temperature of $>38.5^\circ$C when transported, the computed amount of sweating in 89% of those patients was <1% of their body weight (600 g, assuming a 60-kg body weight). Of note, approximately 2% of the dehydration attributable to body weight loss is an index [68]. These comparisons hypothesized that if the cause of the heat-related illnesses in some patients was attributable to dehydration, this would be caused by the accumulation of heat stress for several days rather than during a single day [7], [22], [66], [67]. Moreover, this suggested that the thermodynamics law may be violated (see the marked region in Figure 6 [b]) although cannot be replicated computationally or analytically replicated in a single day.

If the thermoregulatory response works well, the core temperature will decrease to the level of thermoneutral condition at night (see Figure 11 of the Appendix). Additionally, the countermeasure for ambient temperature adjustments, such as air conditioner and fan, would be marginal as in a survey [40]. The threshold of outdoor ambient temperature, when the patients in Group 4 were observed, is demonstrated in Figure 8. According to [69], WBGT is defined as a warning at 25$^\circ$C–28$^\circ$C, severe warning at 28$^\circ$C–31$^\circ$C, and the threat of heat-related disorder at $>31^\circ$C in daily life.

The threshold of daily maximum WBGT on the day of transportation was consistent with severe warning. Notably, WBGT and ambient temperature on the previous day were slightly higher than those on the corresponding day. These results suggested that the heat-related illnesses were caused not only by the heat of a single day but also by the accumulation of heat damage from the previous day(s).

According to [70], the following two hypotheses existed for the heat-related illnesses in the elderly, also considering their habits, that is, i) the decline in thermal sensation and sweating capability and ii) overheating without using a room temperature controller in the attempt to avoid cold wind. Some elderly have been reported to have a strong aversion to the air conditioner. One reason for this aversion [70] was attributed to the fact [62] that the metabolic rate of the elderly is lower than that of young adults, resulting in the decrease of skin temperature and the increase in blood pressure due to vasocostriction caused by the cold wind. Consequently, when they noticed the increase in their body temperature, their skin temperature was significantly lower than normal.

Here, the comparison of measured and computed core temperature does not refute the hypothesis [61].

**C. LIMITATIONS**

The limitations of our study are as follows:

i) This study focused on severely ill patients and assumed that most of them are transported by ambulance. This is supported by the fact that ambulance transportation is free in Japan; therefore, most patients opt to be transported. As knowledge of first aid for heat-related illnesses has become more widespread in recent years, some patients may choose to recover at home (e.g., in China [71]). Further analysis may be needed in other countries.

ii) Considering the large intersubject variability in sweating, especially in the elderly, only the following two ages were considered for the elderly models: 65 and 75 years [45], [59], besides the no sweating model. The measured data used for these two elderly models were published in 1996 and 2007 [61], [62], respectively, when the life expectancy was lower than the present. Therefore, the decrease in sweating capacity may be smaller than that in the current population.

iii) The lack of variables of the human body model and the patient’s height and weight, which were not measured. Consequently, this single body model was applied to all patients. In the case of environmental heat stress, the core temperature caused by a single model is due to the body surface area to mass ratio. Considering the body mass index as a measure, this may result in the difference of computed temperature increase by 5%–10%, with some sex- and age-related influences [45].

iv) Another factor of uncertainty is that the indoor ambient condition of patients was assumed to be the same as the outdoor values. It is almost impossible to perform a simulation at room temperature and assess the behavior in each patient. Although there is a large variability in houses in terms of the building material, the room temperature is generally lower than the outside temperature by a few degrees in summer [38].

v) The axillary temperature was measured as core temperature owing to the short transportation time of the ambulance (several minutes on average). The data on ambulance dispatch and clinical records were not associated with each other for the restriction of personal information in Japan; therefore, further discussions for these patients are not available.

**VII. CONCLUSION**

To provide insight into the cause of severe heat-related illnesses, for the first time, this study measured the core temperature of elderly patients with heat-related illnesses in Nagoya City, Japan. The number of elderly patients (≥65 years old) was 1,302, among which the data of patients transported from their homes were extracted. The core temperature of each patient was computed using one of four types of sweating models, assuming that they spent the time at home. The measured core temperature in 31.4% of
FIGURE 11. Time course of variation in (a) ambient temperature and (b) computed core temperature in young adults aged 65 and 75 years in August 2020.

the patients was higher than the computed core temperature for a single day even when the sweating was nonexistent. Despite assuming efficient sweating, the total amount of water loss did not lead to dehydration. This may partly support a hypothesis presented in previous studies that the gradual loss of water over several days could be a potential cause of heat-related illnesses. Additionally, patients may not feel heat stress potentially owing to the reduced thermal sensation in their homes. Our results would help in understanding the onset mechanism of heat-related illnesses in the elderly.

Furthermore, these findings suggested the necessity to consider monitoring or tracking heat stress for several days rather than during a single day for the elderly in their homes, which is not considered in the current monitoring system. Future study includes the improvement of and application to the monitoring system [48].

APPENDIX

COMPUTED DIURNAL CHANGES OF CORE TEMPERATURE

Figure 11 shows the computed core temperature in young adult patients, those aged 65 years, and those aged 75 years under ambient conditions in August 2020. The following are the two factors responsible for these changes: the decline in thermal sensation and the amount of sweating [61], [62], [72], which were considered in our computation. The diurnal variation in the elderly model, especially for those aged 75 years, is wider than that in young adults. This result is attributable to the declined sweating rate. The core temperatures of the 65- and 75-year-old models were 0.2°C and 0.76°C (maximum) higher than that of the young adult model, respectively. Note that the axillary temperature computed is close to the core temperature (rectal temperature).

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