

Thermal Sensation and Physiological Responses in Non-uniform Bathing Thermal Environment: A Comparative Study on 25-, 52-, and 71-year-old Participants

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Abstract

A non-uniform thermal environment significantly affects human physiological responses and even harms health. Specifically, a non-uniform bathing thermal environment is particularly deadly for older adults. Although each body part's arterial blood flow changes in the bathing thermal environment, little research has been conducted on the physiological responses of participants of different ages. Herein, we conducted a series of bathing experiments on three healthy participants aged 25, 52, and 71. The aim of these experiments to elucidate and analyze the thermal sensations and physiological responses of the participants in a non-uniform bathing thermal environment (i.e., the upper body was exposed to air, whereas the lower body was immersed in hot bathwater). We found that the non-uniform thermal environment greatly influenced a variety of physiological parameters and increased the participants' heart rates and blood flow. The youngest participant (i.e., the 25-year-old) and oldest participant (i.e., the 71-year-old) had the fastest and slowest perception of thermal sensation, respectively. The physiological responses changed significantly with the perception of thermal sensation change for the three participants. Unlike the other two participants, the oldest participant had decreased blood pressure and slowly increased thermal sensation. In addition, the oldest participant in a short bathing time had minor thermal health risks than younger participants due to exhibiting the slowest thermal response. However, older adults may experience greater thermal health risks due to their relatively slow thermal response in long-time and high-temperature bathing environments.

Keywords

non-uniform thermal environment, thermal sensation, physiological response, blood pressure, blood flow.

1 Introduction

With the aging of the world population, the thermal health of older adults has attracted increasing attention [1–4]. Young and middle-aged individuals can quickly adapt to most thermal environments daily. However, physiological responses in individuals 65 years and older weaken, making coping with various thermal environments challenging, rendering them unable to perceive incoming thermal risks and even death. Van

Hoof et al. proposed “10 questions” to summarize the relevant research and existing thermal comfort problems in older people. They propose that older adults have different caloric needs than younger adults. Older adults are relatively vulnerable to thermal conditions that exceed generally accepted ranges [5]. Baquero et al.’s questionnaire showed that young adults feel warmer under the same environmental conditions and have worse tolerance than older people. The neutral temperature of older people (25.6°C) differs from that of adults (23.2°C) by 2.4°C. Older people are less sensitive to temperature changes [6]. The thermal response regarding the comfortable temperature range of older adults is much wider than that of young individuals in indoor and outdoor thermal environments [7].

Bathing is a specific non-uniform thermal environment, which is a regular practice of many people. There are generally two ways to bathe: showering and soaking in hot water. Showers generally take a standing position, and the proportion of water flow on the skin surface is constantly changing. Japanese-style bathing is generally a long soak in shoulder-length hot water in a deep bathtub. In bathing, a part of the body is soaked in hot water, whereas another is in the air environment with a lower temperature. In the cold winter, the temperature difference between water and air environments is more significant than in other seasons. In Japan, the annual mortality rates are high in bathing environments (most in winter), with more than 85% being older individuals [8–10]. Takasaki et al. [11] conducted a survey of people over the age of 65 (average age 72.3) in four Japanese cities with low (Sapporo), medium (Osaka), and high (Akita and Fukuoka) bathing mortality rates and found that an average of 86.7% of people choose bathing in the bathtub every day, 2.0% of the people choose to only take a shower, and the rest chose to take a bath after the shower occasionally. Japanese-style bathing in winter can cause serious health problems. Takahashi et al. [12] and Suzuki et al. [13] estimated that approximately 17,000 and 19,000 people died of bathing in Japan each year, respectively. Cardiovascular diseases such as “cardiopulmonary arrest” are often considered the cause of death in a bathing thermal environment [9]. Generally, the thermal physiological response, including the cardiovascular system of older adults, is significantly weaker than that of younger individuals [10–11]. Therefore, the physiological thermal response of the elderly in the bathing thermal environment and death during bathing is imminent thermal health problems for older individuals. To study the thermal health risks during bathing, the differences in thermal response between older adults (over 65 years) and young individuals must be compared and analyzed in the non-uniform bathing thermal environment.

The physiological conditions and thermoregulatory system of older adults differ from those of young individuals. The sweating rates and skin blood flow responses of older individuals during bathing are lower than those of young individuals [17]. Nevertheless, the older individuals were comfortable, whereas young individuals were uncomfortable during the later bathing period. The subjective thermal response, a factor in the context of thermal health, is mainly evaluated based on two aspects, namely, thermal sensation (TS) [18] and thermal comfort [19]. Several studies [20–23] have compared TSs between older and young adults under the changing ambient temperature in controlled trials. Although the comfortable temperature range of young and older individuals slightly differ, the sensation of ambient temperature in older individuals is

far less susceptible than that in young individuals, and older individuals have a higher threshold for ambient temperature perception [24]. Thermal sensibility decreases with age at a high probability, and the perception of warmth decreases more prominently [25]. Furthermore, the thermal sensibility of the limbs is lower than those of other body parts. These previous studies have suggested an age-related decrease in TS and that older adults require a high-temperature environment for a long time when pursuing thermal comfort. Owing to the reduced ability of older adults to perceive thermal sensations [20], when older adults are in a bad thermal environment for a long time, although the score of TS is not very hot, the thermal response of the body may have changed dramatically, which may indicate that the body is already at health risk, eventually leading to accidents. Therefore, the study of the health risk in a bathing thermal environment should consider the TS and physiological response of the cardiovascular system, especially the blood flow (the carrier of blood circulation). However, to date, no experimental study has compared TS and response considering the arterial blood flow changes at different ages under a bathing thermal environment.

The thermoregulatory system maintains the body temperature within a narrow range; it does this through physiological responses intended to balance heat production and dissipation. People of different ages have different physiological states, rates, and ranges of physiological responses. The heat dissipation ability of older adults is relatively low, and the thermal perception ability is degraded [26]. Crandall et al. [27], Holowatz et al. [28], and Sagawa et al. [29] showed that older adults may store a large amount of heat and pose health risks due to the delayed vasodilatory reflex, which may hinder the body's heat dissipation [30-31]. Older adults' health is easily compromised in high-temperature environments, and the ability to perceive thermal physiological responses (blood flow distribution and sweating) [31-33] is associated with daily activities, such as walking and bathing [34]. According to the abovementioned studies, it can be concluded that younger and older adults exhibit significant differences in the changes undergone by their blood vessels in response to a hot environment; the thermal response of blood vessels and blood flow is a significant component of the cardiovascular thermal response. The endurance of older adults in the thermal environment is significantly lower than that of younger individuals, mainly in blood flow and sweating volume. However, these physiological responses are based on studies under the typical thermal environment without considering the non-uniform bathing thermal environment.

Nagasawa et al. [35] studied the effect of bathing on the autonomic nervous system of older individuals and healthy young individuals through heart rate and blood pressure changes. Masuda et al. [36] conducted bathing experiments considering cardiovascular responses and TS with seven young participants. The results showed that cardiovascular thermal responses considering skin blood flow changes significantly under a bathing environment. Chiba et al. [37] showed that the changes in cardiac output are affected by the bathing environment, especially in older adults. Bathing significantly affected the cardiovascular system's blood pressure, skin blood flow, and cardiac output. The studies above showed that non-uniform bathing thermal environment can dramatically affect blood flow in different parts of the body; in addition, these changes are greatly age dependent. Considering the significant health-related risks associated with bathing in older adults, it is necessary to conduct age-linked studies (comparison between older and

younger adults) that aim to elucidate different changes in various parts of the body among people with different ages and analyze mechanisms underlying health risks linked to bathing. Therefore, the changes in blood flow in various body parts must be studied in older and younger adults.

In the study conducted by Liu et al. [38], a thermo-cardiovascular regulation model was developed. This model coupled the human thermoregulation (based on the Stolwijk model [39]) and cardiovascular regulation (based on the Windkessel model [40]) models to reproduce the physiological response, including mean skin temperature, rectal temperature, blood pressure, and blood flow (head, lower limbs, and heart)) of a 50-year-old participant in the bathing thermal environment. To study the other physiological responses considering the blood circulation system of different ages participants (young, middle, and old) in the bathing thermal environment, we conducted three bathing experiments on three participants (25, 52, and 71 years old) to analyze the human body's TS and physiological response under the same non-uniform bathing thermal environment in this study. Regarding physiological response, we have considered studying eleven parts of skin temperatures, mean skin temperature, core temperature (tympanic), heart rate, blood pressure, cardiac output, blood oxygen (SpO₂), and arterial blood flow (upper limbs, lower limbs, and head) changes in body parts under different environments.

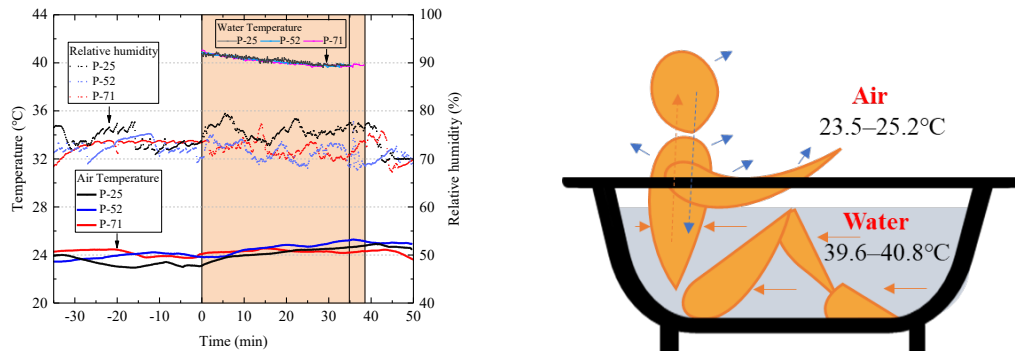
2 Methods

2.1 Experiment design

These experiments were conducted in the spring, specifically on May 13, 2022 (the average outdoor daytime temperature was 20–22 °C). We investigated the TS and change in the physiological responses of each participant in bathing thermal environment. Additionally, we characterized changes in the blood flow of the upper and lower limbs and compared them. The change trend and degree of thermal response at different ages were compared simultaneously. Finally, we also analyzed the relationship between TS and corresponding physiological responses considering the age. The experiments were conducted in the building thermal environment laboratory of the Katsura campus of Kyoto University. The experimental environment comprised three rooms: preparation, dressing, and bathroom (the layout of the experiment room is shown in Fig. 2(c)). Fig. 1(a) shows the three participants' air temperature, humidity, and bathwater temperature. In the preparation room, the air temperature is set to a constant value of 23 °C to simulate the neutral environment of the typical living room. The dressing room and bathroom environment were monitored without temperature control (23.5–25.2 °C). The hot bathwater temperature was set at 40.5 °C; however, the bathwater temperature decreased slightly with bathing time (in line with normal home bathing conditions). In the experiment, the participants were in a non-uniform thermal environment when bathing, that is, the upper body (head, chest, back, and upper limbs) was exposed to air (23.5–25.2 °C), and the lower body (waist, abdomen, and lower limbs) was immersed in bathwater (39.6–40.8°C), with a temperature difference of about 17 °C (Fig. 1(b))

Because three experiments were conducted on the same day in May, there was no significant difference in the average temperature and humidity throughout the whole experiment of the preparation room, dressing room, and bathroom (Fig. 1(a)). However, the humidity varied a lot between them. Additionally, in some instances, the RH of P-25 was 10% higher than that for P-52. Specifically, the RHs of P-25, P-52, and P-71, throughout the experiment, were 74.1 %, 72.6 %, and 72.9 %, respectively. The RH of P-25 was slightly higher than that of the other participants. However, the differences in RH were most pronounced during bathing. The humidity in the bathroom was 75.2 %, 71.2 %, and 72.0 % for P-25, P-52, and P-71, respectively. Specifically, the RH of P-25 is 4.0 % higher than that of P-52. Even though P-25's RH was sometimes higher than that of the other two participants, the average RH of all participants were not markedly different.

Three participants had almost the same experimental environments, including air temperature and humidity, bathwater temperature in the bath, and experimental process.



(a) Experiment results of humidity, air, and bathwater temperatures (b) Schematic of experiment

Fig. 1. Experiment results of humidity, air, and bathwater temperature

2.2 Experiment protocol

This study consisted of three independent 85 min experiments. Three experiments were conducted sequentially, but the thermal environments and processes were almost identical.

Before the experiment, the participants stayed in the preparation room for 30 min, changed clothes, and sat down to rest and stabilize their bodies. During this period, the researchers explained to the participants the TS evaluation criteria and physiological response measurement content (heart rate (HR), SpO₂, blood pressure (BP), blood flow (BF), and body weight) and ensured them about the safety of the thermal environment. Simultaneously, they were asked to report basic information, such as name, sex, age, and disease history. The researchers helped them to wear temperature sensors on 11 body parts (i.e., forehead, hand, upper arm, chest, back, abdomen, waist, right thigh [front, back], right lower leg [front, back], right foot, and cochlea) to continuously measure skin temperature and core temperature (tympanic) at 10 s intervals.

The instruments started measuring the skin and core temperatures at the commencement of the experiment. First, each participant (dressed in a cotton and linen jacket and baggy shorts) sat in the preparation room for 30 min to acclimate to the neutral temperature environment and maintain a stable state. The participant's TSs and physiological responses were recorded and measured in a stabilized state. Second, the participants took off the jacket and moved to the dressing room, and then were asked about TSs, and physiological responses were measured before moving to the bathroom. Third, in the bathroom, the participants entered the bathtub. The bath time of the P-25 and P-52 participants was 35 min, and that of P-71 was 38 min owing to a longer time necessary to measure BF. Finally, the participants exited the bathtub, moved to the dressing room, dried their bodies, measured the physiological response for 10 min after the bath, and finished the experiment.

2.3 Participant information

To ensure all participants were experimented with the same climate, indoor and outdoor temperature, and humidity levels, we conducted our experiments on the same day. In addition, we took into account the health and safety of all participants, with a particular focus on older adults. Therefore, we carefully selected three participants from different age groups (young, middle-aged, and senior) for this study. Furthermore, since this is a preliminary stage study, the number of participants was small. Therefore, six similar preparatory experiments (young people and middle-aged people) were done before this experiment to extract features of thermophysiological responses. Among the participants of these preparatory experiments, the 25-year-old (two times) and 52-year-old (two times) men are the P-25 and P-52 in this study. The preparatory experiments are equivalent to repeating the measurement of the participants in the experiments of this study. By comparing the results of the preparatory experiments and the experiments of this study, it can be seen that the change trend and range of physiological responses of the same participants are similar (physiological responses are not exactly the same due to different thermal environments), ensuring the reproducibility of the thermophysiological response results of this experiment. The participants had no primary diseases, no smoking habits, and light-to-no alcohol habits, although they did not drink on the day of the experiment or the day prior. Table 1 shows the detailed data of the three participants.

Participants were advised to rest the day before the experiment. Furthermore, participants were asked not to eat food or drugs for one and a half hours before the experiment and report any discomfort during the experiment to prevent injury.

Table 1. Detailed data of the participants.

Experiment Time	Age	Height (cm)	Weight (kg)	Gender
9: 28 to 10: 53	71	165.0	56.4	male
11: 40 to 13: 05	52	172.0	69.0	male
14: 50 to 16: 15	25	165.0	54.5	male

2.4 Measurements

Fig. 2(a) shows the placement of temperature and humidity sensors. The air temperature, hot bathwater temperature, surface temperature and relative humidity were monitored and recorded. During the experiment, the participants' ambient temperature and humidity (50 cm horizontally, away from the participant's trunk). The air temperature, relative humidity, skin temperature and core temperature were automatically measured with a data recorder every 10 s. The participants were asked about TS every 5 min, and HR, BP, SpO₂, and BF were measured every 10 min. Participants' body weight before and after bathing was measured in the dressing room. Table 2 provides a detailed description of the instruments used in this study. The TS is a subjective response to being cold or warm. The participants rated their TS level from ASHRAE scale 55 [41] on a 7-point scale, hot (+3), warm (+2), slightly warm (+1), neutral (0), slightly cool (−1), cool (−2), and cold (−3).

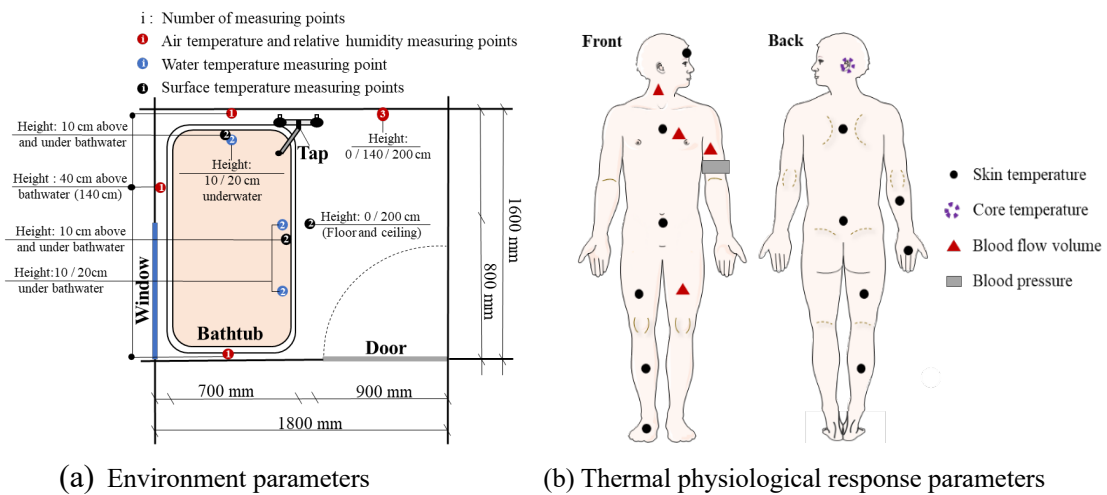


Fig. 2. Measuring points of the environmental parameters, thermal physiological response parameters, and layout of the experiment rooms

Fig. 2(b) shows the measuring points of thermal physiological response parameters. Table 3 shows the schedule of the bathing experiment and the measured parameters. Core temperature was measured by placing the device at the opening of the left ear of the participants. Before measuring the HR and BP, the BP cuff was wrapped around the left upper arm of the participant, with its lower edge 2.5 cm higher than the cubital fossa. A pulse oximeter was installed on the participant's left index finger to detect SpO₂.

The main artery for the head is the common carotid artery. The subclavian artery is the main artery supplying the blood to the upper limb. The superficial femoral is the branch artery that supplies the blood to the lower limb. The BF was measured at four locations: the common carotid artery, the subclavian artery, the superficial femoral artery, and the aorta, representing the BF of the head, upper limb, lower limb, and cardiac output, respectively. The BP at each test point was measured twice, and the average of the two values was calculated. Two experts from an equipment company measured the BF.

Table 2. Instrument information.

Measurement	Instrument	Range	Accuracy
Air temperature	Onset HOBO temp/RH logger UX100-011A	−20–70 °C	±0.21 °C
Relative humidity		RH 1%–95%	±RH 2.5%
Skin temperature	Graphtec Midi logger gl840 T-type Thermocouple	−100–400 °C	±0.1%
Core temperature	N543 High precision 8CH data logger (NT logger) with thermistor probe -ITP101-27	20–50 °C	±0.1 °C
Blood pressure	OMRON Automatic Sphygmomanometer HEM-7200	0–299 mmHg	±3 mmHg
Heart rate		40–180 bpm	±5%
Blood flow	Ultrasound imaging equipment (Viamo™ c100, CANON)		±6%
SpO ₂	OMRON P300 Intelli IT	90%–100%	±2%
Weight	Mettler Toledo 1d1	0.2–150 kg	±0.015%

Table 3. Schedule of the bathing experiment and measured parameters.

Preparation Room (30 min) ↓	3 times: BF (head, heart, arm, thigh)	6 times: BP (left wrist), SpO ₂ (index finger of left hand), and thermal sensation	
Dressing room (5 min) ↓	1 time: BF (head, heart, arm, thigh)	2 times: BP, SpO ₂ , and thermal sensation	Weight
Bathroom (35 min/38 min) ↓	3 times: BF (head, heart, arm, thigh)	8 times: BP (left wrist), SpO ₂ (index finger of left hand), and thermal sensation	
Dressing room (10 min)	1 time: BF (head, heart, arm, thigh)	2 times: BP (left wrist), SpO ₂ (index finger of left hand), and thermal sensation	Weight

3 Results

3.1 Thermal sensation

Fig. 3 shows the changes in TS of the three participants during the bathing experiments. The ambient air temperature and humidity in the preparation room were 23.5–25.2 °C and 69%–79.4%. The TS of P-25 increased rapidly during bathing, to +2 at 12 min and +3 at 18 min. In addition, 10 min after bathing, the TS decreased to 0. For P-52, the TS increased to +2 after 9 min and +3 after 18 min during bathing. After bathing, at around 7 min, the TS decreased to +2 and 0 after 13 min. The TS of P-71 increased to +2 after 34 min of bathing and did not increase to +3 during the whole bathing. P-71 had a lower and slower TS than the other two participants. In other words, P-71 did not feel hot like the other two participants in the bathing environment.

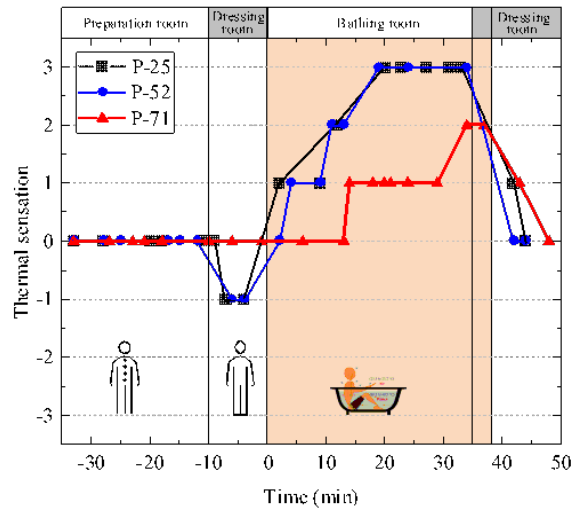
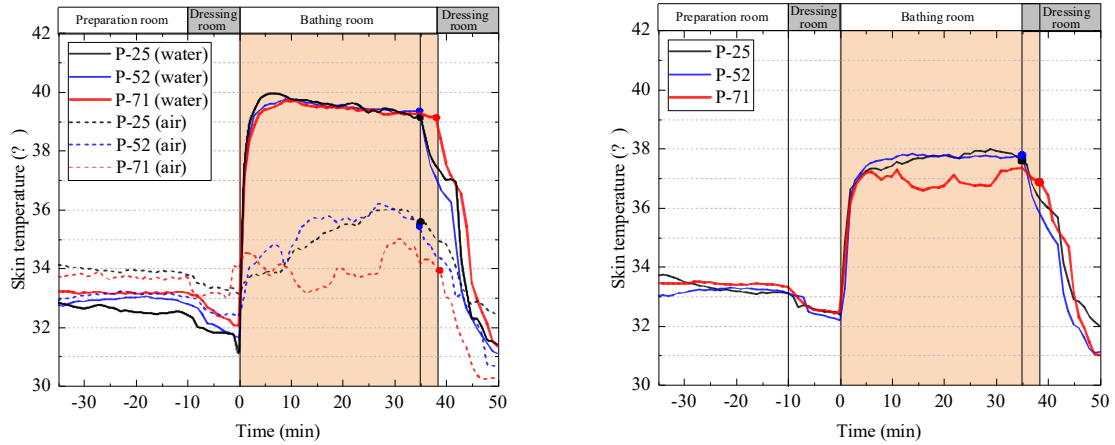


Fig. 3. Thermal sensation experiment results of the 25-, 52-, and 71-year-old-participants.

3.2 Mean skin temperature

Fig. 4 shows the experimental results of the mean skin temperatures. The mean skin temperatures (T_{mean}) were affected by the ambient temperatures (Fig. 1(a) and 4). During the bathing, a portion of the body is in an air environment and a portion is in a hot water environment. In order to better analyze the changes in skin temperature affected by the environment during bathing, Fig. 4(a) shows the mean skin temperature changes in the air and water parts during the whole experimental process. Fig. 4(a) shows that the mean skin temperature in the air environment of P-71 was significantly lower than that of the other two younger participants, P-25 and P-52 showed similar changes in the bathing room. Fig. 4(b) shows that the T_{mean} s of the skin in the air environment and the whole-body surface of P-71 were 1.85 °C and 1.16 °C lower than those of P-25 and P-52, respectively. It can be seen that the lower T_{mean} (whole body) of P-71 is mainly due to the body portion (in the air environment) with the lower skin temperature.



(a) T_{mean} of parts of the skin parts in the bathwater and air, respectively. (b) T_{mean} of the whole-body surface.

Fig. 4. Experimental results of mean skin temperature.

3.3 Core temperature

Fig. 5 shows the experimental results of core temperature (tympanic). In the preparation room before moving to the dressing room, the linen jacket was removed, and the upper body was naked in the dressing room. The tympanic temperature of P-25, P-52, and P-71 decreased by 0.05 (37.04–36.99), 0.12 (36.19–36.07), and 0.73 (36.16–35.43) °C, respectively. The temperature change in P-71 was the most obvious. While bathing in the bathtub, the tympanic temperature of P-25 and P-52 decreased in the first 5 min because although the skin touched the hot water, the lower temperature blood affected by the previous colder air thermal environment flowed into the body's core with blood circulation. It is worth noting that, P-71's tympanic temperature did not decrease significantly in the first 5 minutes of bathing. The tympanic temperature of P-71 decreased significantly when he was in the dressing room and immediately increased significantly from the beginning of the bathing, which was most obviously affected by environmental conditions. During this period, the core temperature of P-25 decreased the most and the fastest. After that, during bathing, the tympanic temperature of P-25, P-52, and P-71 increased by 1.07 (37.02–38.09), 0.97 (36.08–37.05), and 1.1 (35.57–36.67) °C in the first 35 min, respectively.

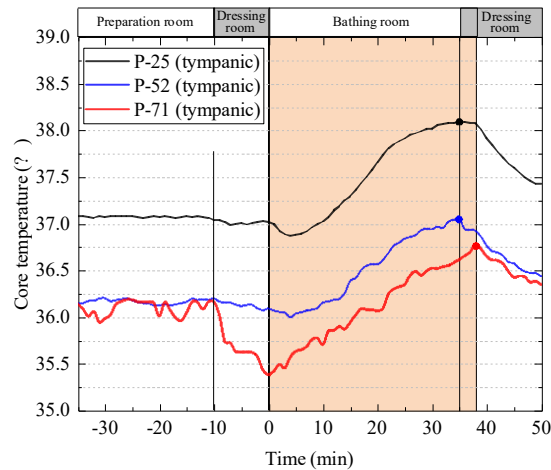


Fig. 5. Experimental results of core temperature (tympanic).

3.4 Blood pressure and pulse pressure

Fig. 6(a) shows the experimental results of BP. Most healthy adults have a regular blood pressure when their systolic and diastolic pressures are less than 120 and 80, respectively. Therefore, a systolic and diastolic pressures of 120 and 80 mmHg or higher, respectively, are considered as being characteristic of high blood pressure [42]. Low BP, or hypotension, is BP below 90/60 mmHg in healthy adults [43]. Compared to the BP results during bathing, the three participants were in a uniform thermal environment before bathing; their BP was changed in a healthy range. The hot bathwater decreased BP because of vasodilation. The diastolic BP of P-25 in the uniform thermal environment (before bathing) and non-uniform thermal environment (during bathing) fluctuated around 60 mmHg. The systolic BP of P-52 fluctuated between 108 and 122 mmHg in the non-uniform bathing thermal environment, and the diastolic BP decreased by 14 mmHg (75 to 61 mmHg). The diastolic BP of P-71 decreased by 17 mmHg (67 to 50 mmHg) during 30 min bathing.

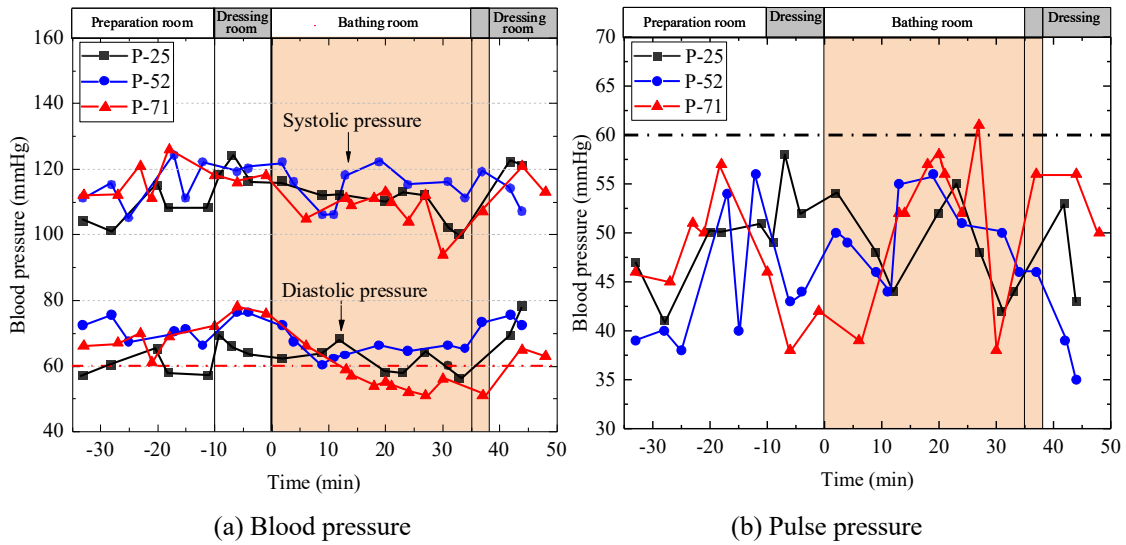


Fig. 6. Experimental results of blood pressure and pulse pressure.

Fig. 6(b) shows the changes in pulse pressure. The pulse pressure is the systolic BP minus the diastolic BP. Healthcare providers use pulse pressure to predict heart health risks, including heart attacks or strokes. Pulse pressure greater than 60 mmHg is considered a risk factor for cardiovascular disease, especially for older adults [44]. In Fig. 6(b), three participants' pulse pressure floated between 35 and 60 mmHg before bathing. During bathing, almost all the pulse pressure results of the three participants fluctuated within a range of <60 mmHg, only one point at $t = 28$, and that of P-71 was 61 mmHg.

3.5 Heart rate

Fig. 7 compares the HR of the three participants. The HR increased significantly during bathing under the non-uniform bathing thermal environment and decreased after bathing. During bathing, the HR of P-25, P-52, and P-71 increased by 1.39 times (87 to 121 bpm, from 7 to 33 min), 1.21 times (76 to 105 bpm, from 8 to 34 min), and 1.32 times (72 to 98 bpm, from 3 to 37 min), respectively. Comparing the increase in HR between the three participants during bathing, P-71 had the slowest physiological response before 33 min but showed a rapid increase after 34 min. The TS level of P-71 was 0 or 1 from 0 to 28 min but increased to 2 from 34 to 37 min (Fig. 3). The HR increased slowly from 0 to 28 mins but rapidly from 34 to 37 min. The HR trend of P-25 was reversed in P-71, which rapidly increased in the first 10 min and slowly later. Also, the HRs of P-25, P-52, and P-71 decreased slightly once in intermediate time ($15 < t < 25$).

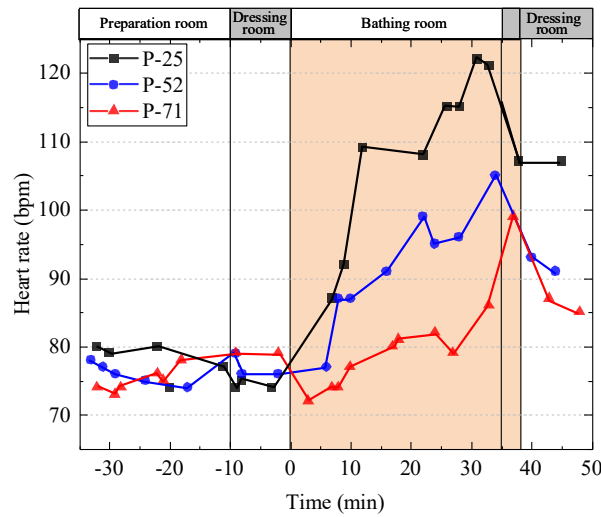


Fig. 7. Experiment results of heart rate.

3.6 Blood flow

3.6.1 Stroke volume and cardiac output

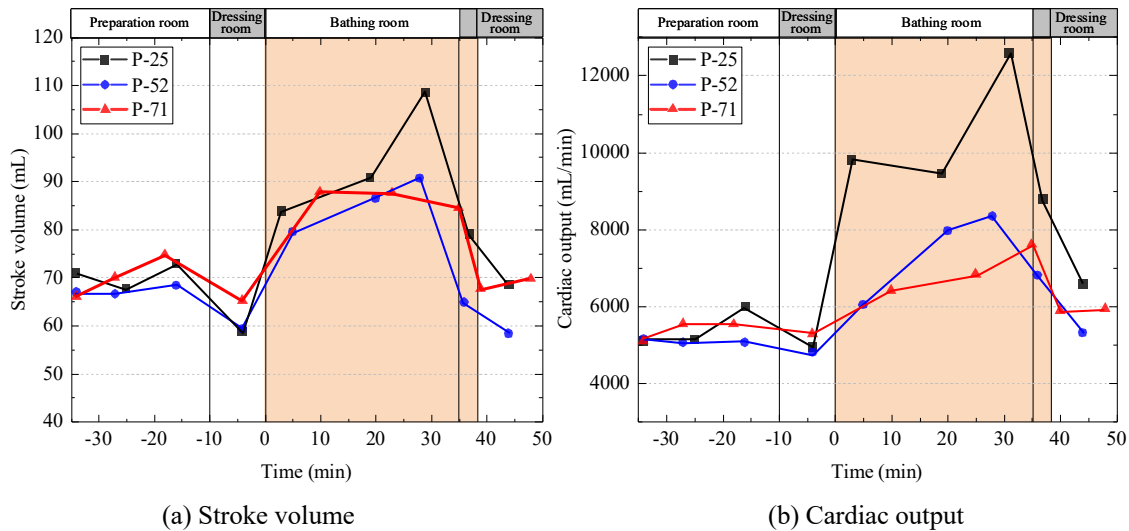


Fig. 8. Experiment results of stroke volume and cardiac output.

Stroke volume is the blood pumped from the heart during each systole [45]. Stroke volume was relatively stable before bathing for P-25, P-52, and P-71 (Fig. 8(a)). However, during bathing, P-25 showed the fastest and most significant increase, whereas P-71 showed the slightest change.

Cardiac output is the blood pumped to various body parts, especially the brain and other vital organs, by the heart per minute [46]. Cardiac output was calculated by multiplying stroke volume with HR [47]. The cardiac output of P-25, P-52, and P-71 increased by 2.3, 1.6, and 1.4 times, respectively, during bathing (Fig. 8(b)). Compared with the other two participants, the change in cardiac output of P-71 was relatively negligible. This result is congruent with the changes in HR shown in Fig. 7. After bathing, the stroke volume and cardiac outputs of all participants were restored to the pre-bathing levels, with P-71's values returning to their baseline even after prolonged 3 min bathing.

3.6.2 Blood flow to the head

The relative increase in the head BF was calculated by dividing each increased value (i.e., each data point minus the initial point) by the initial value (i.e., the first measured value at $t = -35$ min). During bathing, the head BF of P-25 initially increased ($0 < t < 20$) and then decreased, whereas that of P-52 increased and decreased in the latter half of bathing (Fig. 9). The head BF change in P-25 was significantly larger than that in P-52. P-71 showed a different trend; BF remained almost constant and then returned to a stable state faster than P-25 and P-52 after leaving the bathtub.

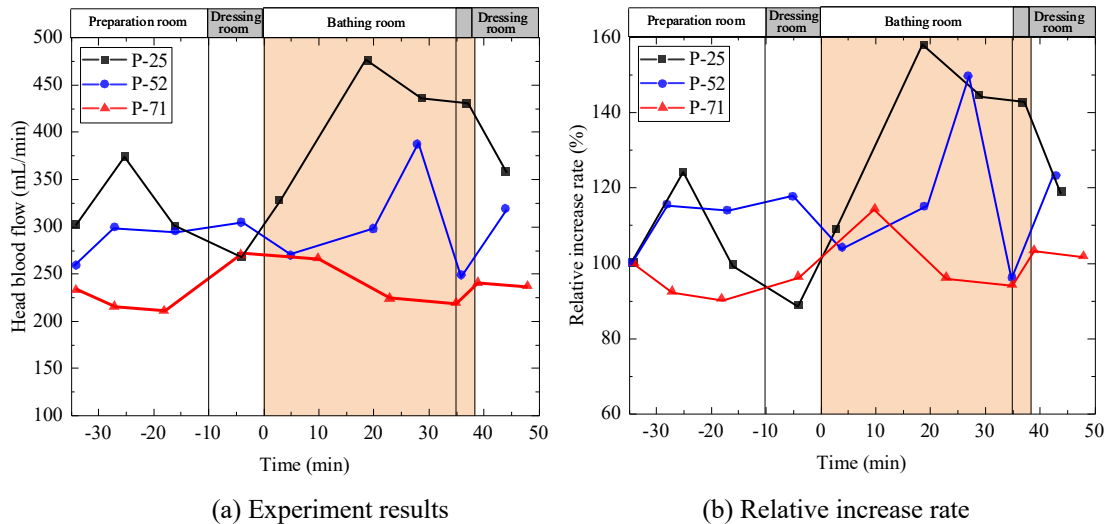


Fig. 9. Experiment results and the relative increase in the head blood flow.

3.6.3 Blood flow to the upper and lower limbs

The BF of limbs is a critical factor affecting the thermoregulatory system. The change in BF of upper and lower limbs under a bathing thermal environment can show the thermal response capacity of the body. Fig. 10 shows the experimental results of the BF of the upper and lower limbs.

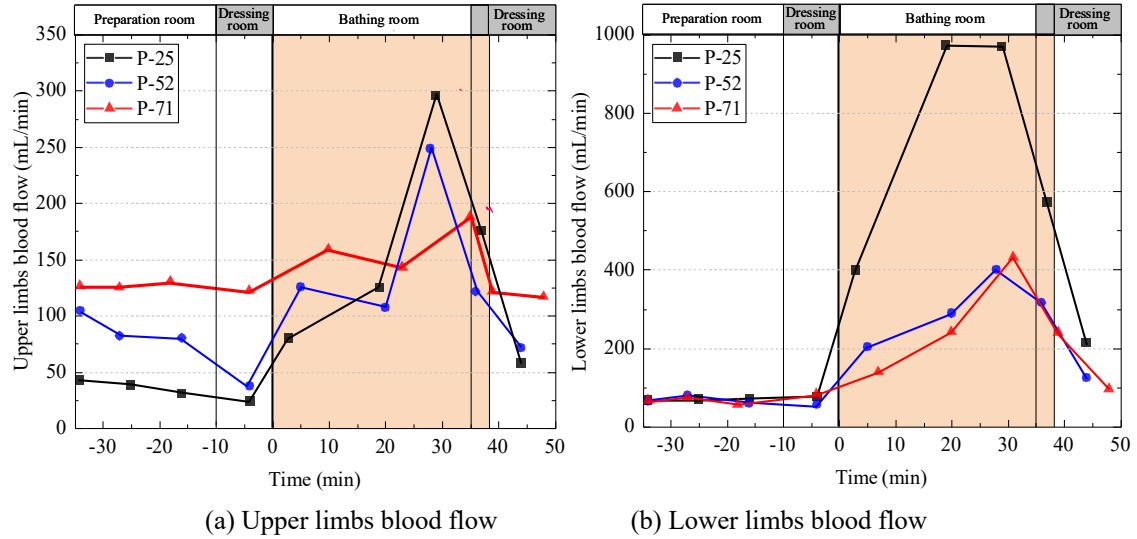


Fig. 10. Experiment results of the blood flow to the upper and lower limbs.

In the preparation room, both the upper and lower limbs were in a uniform and stable air environment, and the BF was stable in the upper and lower limbs of the three participants. During bathing, the participants were in a non-uniform thermal environment, where the upper limbs were in the air (23.5–25.2 °C) and the lower limbs in the hot bathwater (39.6–40.8 °C) (Fig. 1). The upper limbs' BF of P-25, P-52, and P-71 increased by 216 (79.6 to 295.6), 122.9 (125.3 to 248.2), and 28.8 (158.8 to 187.6) mL/min, respectively (Fig. 10(a)). The lower limbs' BF of the P-25, P-52, and P-71 increased by 892.1 (76.2 to 968.3), 344.2 (55.9 to 400.1), and 348.7 (82.4 to 431.1) mL/min, respectively (Fig. 10(b)). P-25 had substantially higher BF than the other two older participants. The increase in the BF in the lower limbs was significantly higher than that in the upper limbs. These results showed that the BF under a non-uniform bathing environment (bathwater and air) is significantly different from that under a uniform bathing environment, and it is different depending on the body part and age.

3.7 SpO₂

SpO₂ is the amount of blood oxygen [48]. The body's organs and tissues require oxygen to function, and oxygen is transported through red blood cells to other parts [49]. Most healthy adults have a normal healthy SpO₂ range of 95%–100%. If the SpO₂ decreases below this range, the human body will not receive adequate oxygen. The SpO₂ of P-25 and P-52 fluctuated between 98% and 96%, and that of P-71 fluctuated between 95% and 97% in the bathing environment (Fig. 11). Both P-25 and P-52 reported a slight difficulty in breathing at the end of the bathing. However, P-71 did not report any uncomfortable sensations in breathing during bathing. After bathing, the SpO₂ of all three participants returned to the value before bathing. Although the SpO₂ of the three participants changed during bathing, they were within the healthy range. The change in SpO₂ may not pose a thermal health risk within 35 minutes of bathing.

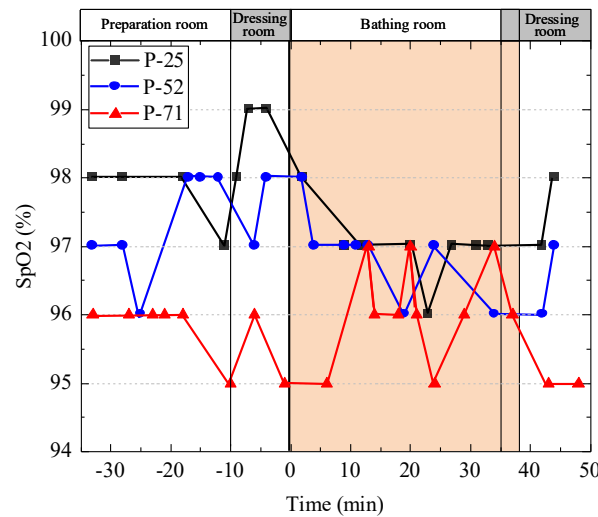


Fig. 11. Experiment results of SpO₂.

3.8 Bodyweight

Table 4 shows the body weight before and after bathing. All three participants lost weight after bathing compared to before bathing, where P-25 had the most (0.246 kg), and P-52 had the least weight loss (0.142 kg). These results indicate that a bathing thermal environment causes body water loss. Evaporative sweating is one of the main ways in which the human body dissipates heat when subjected to hot environmental conditions. In a hot environment, the loss through sweat often exceeds the fluid intake. In addition, physical health begins to deteriorate when dehydration exceeds 3% of total body water (i.e., 2% of body weight) [50]. Dehydration, if severe enough, can impair physical and mental performance, with the severity of these impairments being greater in hot environments [51]. Excessive fluid loss can cause dehydration, a common

and severe thermal health risk. Although the change in body weight in this study was small and did not cause a state of dehydration, being in a hot bathing environment for a prolonged time or at a higher temperature may cause more body fluid loss and even a health risk [52].

Table 4. Body weight before and after bathing.

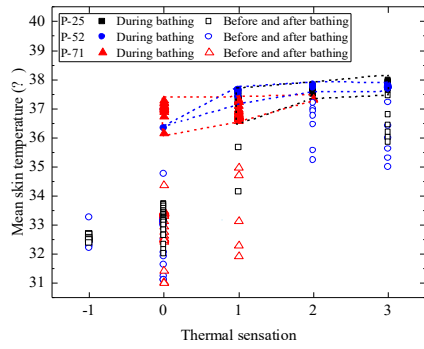
	Before bathing (naked)	After bathing (naked)	Weight change
P-25	54.356	54.11	−0.246 kg
P-52	69.037	68.895	−0.142 kg
P-71	56.378	56.206	−0.172 kg

4 Discussion

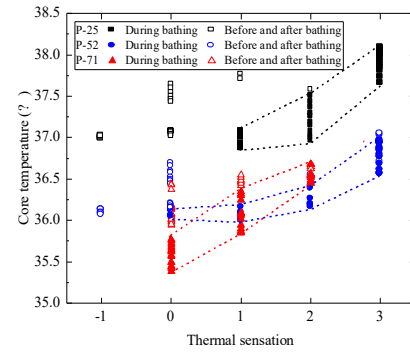
4.1 Correspondence between physiological response and TS

In daily bathing, people rely only on the subjective response (TS) to determine their thermal health risk. In this study, the older participant P-71 showed the slowest TS and did not report a hot (+3) sensation during 38 min of bathing; however, P-25 and P-52 felt hot (+3) after 20 min of bathing (Fig. 3).

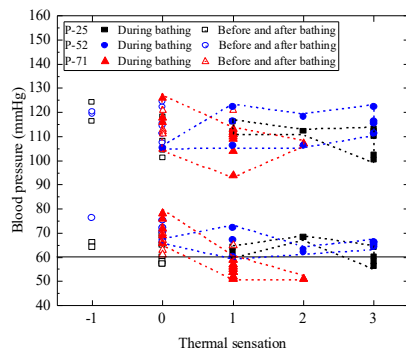
Regarding the mean skin temperature (Fig. 4), P-71 showed a significant decrease in the dressing room before bathing, whereas the TS (Fig. 3) did not change. The other two younger participants' TSs decreased from 0 to −1 with the decrease in skin temperature. During bathing, the older participant P-71 had a significantly slower and weaker TS than the other two younger participants. Fig. 12(a) shows the correspondence between mean skin temperature and TS. The temperature range of P-71 was the largest at the same TS during bathing. Although the mean skin temperature decreased after bathing, the TS did not decrease with it and delayed for a while, which may be related to the gradual decrease in the core temperature. Fig. 12(b) shows the correspondence between core temperature and TS. When the TS was 0 or 1, P-71 showed the lowest core temperature and the most significant temperature range of 0.67 °C (36.56 to 35.89 °C) compared to P-52 (0.17 °C; 35.99 to 36.16 °C) and P-25 (0.2 °C; 36.87 to 37.07 °C). The changes in P-71's core temperature is considered to be the closest with the change in TS among the three participants. In other words, when P-71 felt warm, the core temperature increased significantly. Regarding the TS change, P-25 and P-52 were more affected by the mean skin temperature, whereas P-71 was more affected by the core temperature.



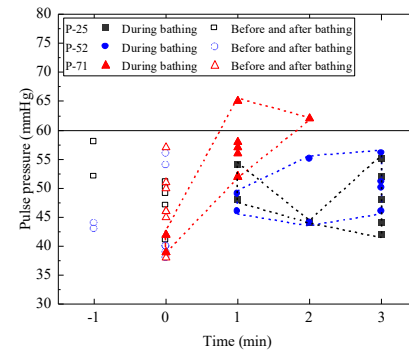
(a) Mean skin temperature



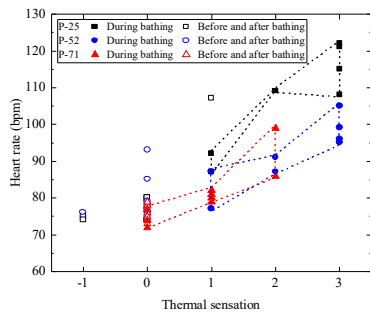
(b) Core temperature



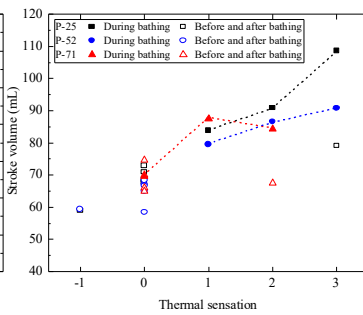
(c) Blood pressure



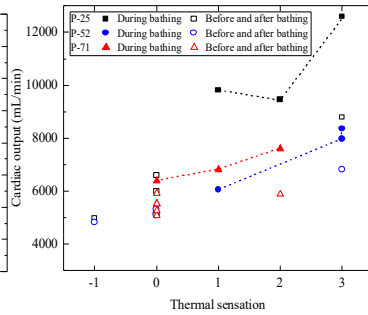
(d) Pulse pressure



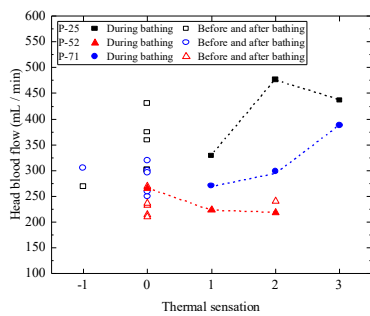
(e) Heart rate



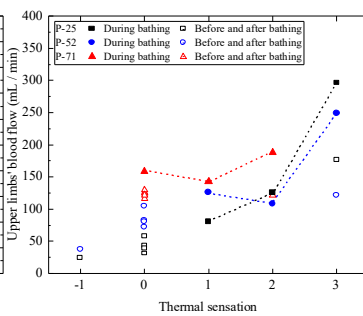
(f) Stroke volume



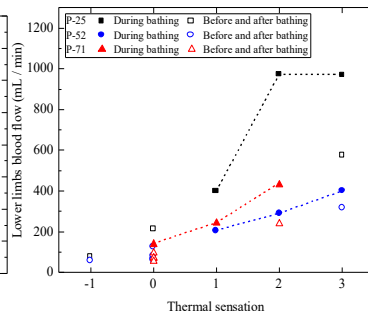
(g) Cardiac output



(h) Head blood flow



(i) Upper limbs blood flow



(j) Lower limbs blood flow

Fig. 12. Correspondence between physiological response and thermal sensation.

Regarding the BP and pulse pressure during bathing (Fig. 6), P-71 did not feel hot (+3) or any thermal discomfort (Fig. 3), but his diastolic BP decreased substantially. The pulse pressure was >60 mmHg in the later bathing period, which is also a risk indicator of cardiovascular disease. Unlike skin and core temperature, the BP and pulse pressure of P-25 and P-52 did not change obviously with TS (Fig. 12(c), (d)). Nevertheless, in P-71, the BP (especially the diastolic pressure) decreased, and the pulse pressure increased with increasing TS, which provides valuable information in predicting the physiological response during bathing for the care of older adults.

The trend in the HR change (Fig. 7) and cardiac output change (Fig. 8) was similar to that of the TS (Fig. 3). Among the three participants, P-71 had the slowest and least HR and cardiac output response, corresponding to the lowest TS. Fig. 12(e, f, g) shows the correspondence between HR, stroke volume, cardiac output, and TS. The HR, stroke volume, and cardiac output of the three participants changed significantly with TS.

The head BF of P-25 and P-52 generally increased with the TS increase (Fig. 12(h)). In contrast, the head BF of P-71 decreased slightly with increasing TS. The upper limb BF P-25 increased the largest with the TS increase, whereas P-71 had the smallest change (Fig. 12(i)). The lower limb BF of P-25 increased the most with TS, and the changing trend of P-52 and P-71 was similar; however, the TS of P-71 increased from 1 to 2, and the lower limb BF increased significantly (Fig. 12(j)).

These results show that, for the three participants, the essential physiological parameters changed with the TS change during bathing, suggesting that TS and some easily measured physiological parameters can be used for health management during bathing. Even for older adults with delayed thermal responses, the TS can still correspond to the physiological parameters. The increase in TS did not usually associate with the change in BP. Nevertheless, in the case of older adult, special attention should be paid to the relationship between the TS increase and the BP decrease.

4.2 Mechanism of heat transfer in non-uniform bathing environment

Many models created to predict thermophysiological responses under different thermal environments [53-55] consider how blood flow shapes heat transfer in the body; We can discuss the heat transfer process by blood circulation in the body of this study's results based on the Stolwijk [39] and thermo-cardiovascular regulation models [38]. Specifically, these thermal models consider the heat exchange between the central blood (heart) and each body part owing to blood flow circulation, facilitating a calculation of thermal response across various parts of the body. In the non-uniform bathing thermal environment, the lower limbs were in the hot bathwater, and the upper limbs were in the air with a lower temperature. The process of heat transfer in a human body may be modeled as follows: the lower limbs absorb heat from the hot bathwater, the blood carries the heat from the lower limbs to the whole body through blood circulation, the upper limbs absorb the heat from the blood, and then dissipate heat into the air environment.

From the overall trend of upper and lower limb BF responses and core temperatures, the relative increase in the core temperature of the three participants was consistent with the BF response. The BF of P-25 increased the most in the hot water environment (with higher temperature) and air environment (with lower temperature), absorbing and releasing most heat. The faster the BF response, the faster the core temperature increases. The BF response and core temperature increase rate of P-25 and P-52 were rapid before 20 min and gradual after 20 min; those of P-71 were the opposite, gradual first and then rapid. Although this study considered the thermophysiological responses of participants of different ages, the number of participants was small, and the environment under which the participants were studied was thermally simple (a non-uniform bathing thermal environment). Therefore, the results brought forth in this study are not generalizable across numerous contexts. However, since this study focuses on the thermophysiological response research of three participants of different ages in a similar bathing environment, these results can be used applied toward the optimization of thermo-cardiovascular regulation models intended to predict thermophysiological responses of participants based on age. Such an approach would facilitate the development of individual-specific thermo-cardiovascular regulation models. Based on this model, for P-71 comparing to P-25 and P-52, Fig. 4, shows the lower T_{mean} of upper limbs (in the air environment), and the similar T_{mean} of the lower limb (in the water environment), indicates that, for P-71, the heat transferred from the lower body (in the hot bathwater) to the upper body (in the cooler air) is less than that of the other two participants. Therefore, the lower body should have absorbed less heat from the environment at the early bathing stage ($0 < t < 20$). Compared with the other two younger participants, P-71 was less affected by the bathing thermal environment. However, at the later bathing stage ($20 < t < 35$), P-71, with a delayed thermal response, absorbed a lot of heat from the environment, similar to the other two young participants. At this stage, less BF in the upper limbs of P-71 significantly affected the lower skin temperature of the upper body, resulting in a minor temperature difference with the air environment and less heat dissipation from the upper body to the air than the other two younger participants.

When $0 < t < 5$, the temperature affected by the environment before bathing was relatively lower than that during bathing. P-25, with the fastest BF response, rapidly transported the blood with lower temperatures throughout the body, decreasing the core temperature. Contrary to the other two younger participants, P-71's core temperature increased due to the slower BF response, which prevented the lower temperature blood (air environment) from transferring to the body core. Instead, the blood temperature was more affected by the heat conductance from the hotter bath water during bathing.

When $5 < t < 20$, P-25 had a faster BF response in the lower limbs than P-52 and P-71 (Fig. 10). This BF response in the lower limbs is reflected in the core temperature increase. Fig. 13 shows the changes in the core temperature (tympanic) during bathing, as determined as follows: the end value minus the initial value of each time segment. During $5 < t < 20$ periods, the core temperature of P-25 increased more rapidly than those of P-52 and P-71.

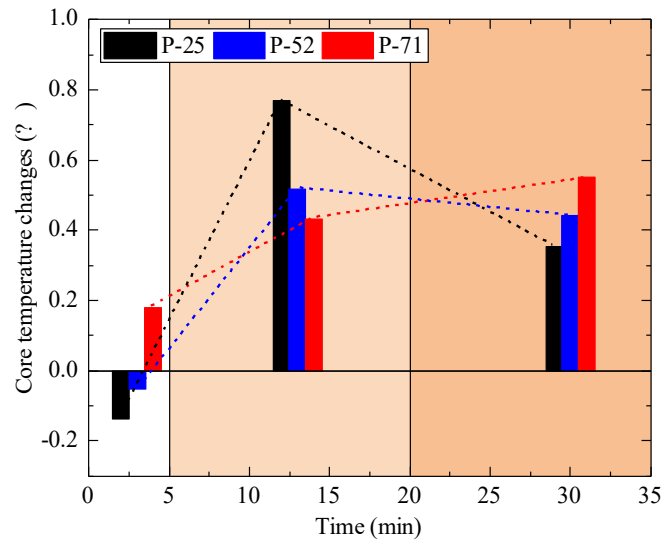


Fig. 13. Changes in the core temperature of participants during bathing.

At $20 < t < 35$, P-71 still had the slowest lower and upper limb BF response than those of P-25 and P-52 (Fig. 10). The upper limb BF did not increase with the lower limb BF with time, indicating that the BF did not timely carry the heat absorbed by the lower limb from the hot water environment to the skin of the upper limb for heat dissipation into the air. At $20 < t < 35$, the increase in the core temperature of P-25 and P-52 decreased, whereas that of P-71 was still increased and higher than that of the other two younger participants.

From the overall trend of upper and lower limb BF responses and core temperatures, the relative increase in the core temperature of the three participants was consistent with the BF response. The BF of P-25 increased the most in the hot water environment (with higher temperature) and air environment (with lower temperature), absorbing and releasing most heat. The faster the BF response, the faster the core temperature increases. The BF response and core temperature increase rate of P-25 and P-52 were rapid before 20 min and gradual after 20 min; those of P-71 were the opposite, gradual first and then rapid. Although this study considered the thermophysiological responses of participants of different ages, the number of participants was small, and the environment under which the participants were studied was thermally simple (a non-uniform bathing thermal environment). Therefore, the results brought forth in this study are not generalizable across numerous contexts. However, since this study focuses on the thermophysiological response research of three participants of different ages in a similar bathing environment, these results can be used applied toward the optimization of thermo-cardiovascular regulation models intended to predict thermophysiological responses of participants based on age. Such an approach would facilitate the development of individual-specific thermo-cardiovascular regulation models.

4.3 Which is more risky, elderly or younger?

In the early stage of bathing, due to the delayed and gradual thermal response of BF, the body of P-71 absorbed less heat than the other two participants, resulting in a slower core temperature increase. In other words, the older adult with slower BF thermal responses had a lower thermal health risk than younger individuals for a short bathing period. Because P-25 had the fastest and the largest thermal response of BF, his thermal health risk due to the high body temperature might be the largest among the three participants.

However, if the bathing duration is longer and the BF thermal response is still slow, the heat dissipation will also be less. Consequently, the core temperature may continue to rise rapidly, indicating that the thermal health risk of older adults may be higher than that of younger individuals. In addition, a higher BF with longer bathing duration will increase the risk of cardiovascular disease, especially for older adults with weakened cardiovascular systems.

When comparing the thermal responses of older and younger adults in thermal environments, the delayed and slow thermal response of older adults in a warm environment can reduce the heat absorbed by the body from the thermal environment, thus reducing the thermal health risks. However, in a cold environment, the delayed and slow thermal response may affect the ability of the body to maintain body temperature, and the body may rapidly dissipate heat, thus posing higher health risks.

5 Conclusions

In this study, we conducted three bathing experiments with three different-age participants to compare the TS and physiological response in a non-uniform bathing thermal environment. Changes in the HR, BP, pulse pressure, BF, SpO₂, and body weight were measured as physiological responses. We analyzed the relationship between TS and thermal physiological response and determined the risk to thermal health in the non-uniform bathing thermal environment based on the experimental results.

The main conclusions are summarized as follows:

- (1) In the same non-uniform bathing thermal environment, the TS of the two younger participants increased at a similar rate, substantially faster than P-71 (older adult). However, P-71 showed a more delayed and less TS during bathing.
- (2) The physiological responses changed significantly with the TS change for the three participants; P-71 also showed a more delayed and less thermal physiological response during bathing.
- (3) The correspondence between P-71's TS and BP differed from the other two younger participants. The TS increased, and BP decreased, whereas that of younger participants was relatively stable. Although P-71 did not experience any physical discomfort with the increase in TS, the diastolic BP decreased.
- (4) In short-time bathing, P-71 with delayed and slow thermal response experienced lower thermal health risks than the two younger participants.

These conclusions indicate that the non-uniform bathing thermal environment significantly affects the physiological parameters, especially BP and BF. An older individual may have a lower thermal health risk than a young individual in short-time bathing due to the delayed BF thermal response. In this study, the implication of the results is that, by reproducing the thermal physiological responses of three participants, we can optimize the thermo-cardiovascular regulation model to consider more participants under different thermal environments. This would allow for a broad-scale exploration of thermal physiological responses, thereby facilitating a fine-scale exploration of the relationship between TS and thermophysiological responses in different thermal environments. The ultimate goal is to complete the development of thermal models and design a healthy, comfortable, and safe bathing thermal environment. Furthermore, we will measure the TSs and physiological responses of additional participants (e.g., older and female) in different thermal environments, along with the statistical analysis of the obtained results.

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References

- [1] G. Fan, J. Xie, H. Yoshino, U. Yanagi, K. Hasegawa, N. Kagi, T. Goto, Q. Zhang, C. Wang, J. Liu, Indoor environmental conditions in urban and rural homes with older people during heating season: A case in cold region, China, *Energy and Buildings*, 167 (2018) 334–346.
- [2] Y. Jiao, H. Yu, Z. Wang, Q. Wei, Y. Yu, Influence of individual factors on thermal satisfaction of the elderly in free running environments, *Building and Environment*, 116 (2017) 218–227.
- [3] A. Schneider, R. Rückerl, S. Breitner, K. Wolf, A. Peters, Thermal control, weather, and aging, *Current Environmental Health Reports*, 4 (2017) 21–29.
- [4] R. Bills, V. Soebarto, T. Williamson, Thermal Experiences of Older People during Hot Conditions in Adelaide. In Zuo J, Daniel L, Soebarto V (Eds.), *Fifty Years Later: Revisiting the Role of Architectural Science in Design and Practice*, Proceedings of the 50th International Conference of the Architectural Science Association, (2016) 7–9. Adelaide, SA, Australia.
- [5] J. V. Hoof, L. Schellen, V. Soebarto, J. K. W. Wong, J. K. Kazak, Ten questions concerning thermal comfort and ageing. *Building and Environment*. 120 (2017) 123-133.
- [6] M. T. Baquero, N. Forcada, Thermal comfort of older people during summer in the continental Mediterranean climate, *Journal of Building Engineering*, 54 (2022) 104680.
- [7] Z. Wang, H. Yu, Y. Jiao, Q. Wei, X. Chu, A field study of thermal sensation and neutrality in free-

- running aged-care homes in Shanghai, *Energy and Buildings*, 158 (2018) 1523–1532.
- [8] Y. Tochihara, A review of Japanese-style bathing: its demerits and merits, *Journal of Physiological Anthropology*, 41 (2022) 1–14.
 - [9] F. Satoh, M. Ogawa, I. Hasegawa, Y. Seto, A. Tsuboi, Death in hot bathtub phenomenon: accidental drowning? or natural disease?, *The American Journal of Forensic Medicine and Pathology*, 34 (2013) 164–8.
 - [10] H. Suzuki, W. Hijiki, T. Tanifuji, N. Abe, T. Fukunaga, Characteristics of sudden bath-related death investigated by medical examiners in Tokyo, Japan, *Journal of Epidemiology*, 25 (2015) 126–32.
 - [11] Y. Takasaki, Y. Nagai, K. Inoue, K. Inoue, M. Maki, T. Ohnaka, Y. Tochihara, Factors related to regional differences in elderly bathing habits and bathing accident mortality in winter (in Japanese), *Human and Living Environment*, 18 (2011) 99–106.
 - [12] R. Takahashi, Y. Sakamoto, K. Tsuzuki, Y. Asakawa, Actual conditions of cardiopulmonary arrest (CPA) during bathing in Japan -Analysis of 9,360 cases of emergency transport in 47 prefectures- (in Japanese), *Tokyo Metrop Geriatr Hosp Inst Gerontol*, (2014) 99–106.
 - [13] M. Suzuki, T. Shimbo, T. Ikaga, S. Hori, Sudden death phenomenon while bathing in Japan mortality data, *Circulation Journal*, 81 (2017) 1144–1149.
 - [14] Y. Ohtsuka, S. Inokuma, H. Sugimoto, Analysis of bathing related accidents in Japan -Collaboration with Japanese association for acute medicine—Collaboration with Japanese Association for Acute Medicine—, *The Journal of The Japanese Society of Balneology, Climatology and Physical Medicine*, 74 (2011) 239–45.
 - [15] Y. Inoue, N. Gerrett, T. Ichinose-Kuwabara T, Y. Umino, S. Kiuchi, T. Amano, H. Ueda, G. Havnith, N. Kondo, Sex differences in age-related changes on peripheral warm and cold innocuous thermal sensitivity, *Physiology & Behavior*, 164 (2016) 86–92.
 - [16] Y. Tochihara, N. Hashiguchi, I. Yadoguchi, Y. Kaji, S. Shoyama, Effects of room temperature on physiological and subjective responses to bathing in the elderly, *Journal of the Human-Environment System*, 15 (2012) 13–9.
 - [17] C. Miwa, H. Shimasaki, M. Mizutani, Y. Mori, K. Maeda, A. Deguchi, Effect of aging on thermoregulatory and subjective responses during a 15-minute bath at 41° C, *Journal of the Human-Environment System*, 23 (2022) 45–53.
 - [18] ISO7730: 2005 Ergonomics of the thermal environment Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria.
 - [19] S. Takada, Study on the Lower Limit of Indoor Humidity Subject Experiments on Psychological Responses, *Indoor Air*, (2020).
 - [20] L. Schellen, W. D. van Marken Lichtenbelt, M. G. Loomans, J. Toftum J, M. H. De Wit, Differences between young adults and elderly in thermal comfort, productivity, and thermal physiology in response to a moderate temperature drift and a steady-state condition, *Indoor air*, 20 (2010) 273–283.
 - [21] Y. Tochihara, T. Ohnaka, Y. Nagai, T. Tokuda, Y. Kawashima, Physiological responses and thermal sensations of the elderly in cold and hot environments, *Journal of Thermal Biology*, 18 (1993) 355–

- [22] V. Soebarto, H. Zhang, S. Schiavonet, A thermal comfort environmental chamber study of older and younger people, *Building and Environment*. 155 (2019) 1–14.
- [23] B.N. Balmain, S. Sabapathy, M. Louis, N. R. Morris, Aging and thermoregulatory control: the clinical implications of exercising under heat stress in older individuals, *BioMed Research International*, 2018 (2018) ID8306154.
- [24] K. J. Collins, A. N. Exton-Smith, C. Doré, Urban hypothermia: preferred temperature and thermal perception in old age, *British Medical Journal*, 282 (1981) 175–177.
- [25] S. Guergova, A. Dufour, Thermal sensitivity in the elderly: a review, *Ageing Research Reviews*, 10 (2011) 80–92.
- [26] M. Shibasaki, K. Okazaki, Y. Inoue, Aging and thermoregulation, *The Journal of Physical Fitness and Sports Medicine*, 2 (2013) 37–47.
- [27] C. G. Crandall, T. E. Wilson, K. C. Kregel, Mechanisms and modulators of temperature regulation, *Journal of Applied Physiology*, 109 (2010) 1219–1220.
- [28] L. A. Holowatz, W. L. Kenney, Peripheral mechanisms of thermoregulatory control of skin blood flow in aged humans, *Journal of Applied Physiology*, 109 (2010) 1538–1544.
- [29] S. Sagawa, K. Shiraki, M. K. Yousef, M. Miki, Sweating and cardiovascular responses of aged men to heat exposure, *Journal of Gerontology*, 43 (1988) M1–M8.
- [30] C. G. Armstrong, W. L. Kenney, Effects of age and acclimation on responses to passive heat exposure, *Journal of Applied Physiology*, 75 (1993) 2162–2167.
- [31] O. Inbar, N. Morris, Y. Epstein, G. Gass, Comparison of thermoregulatory responses to exercise in dry heat among prepubertal boys, young adults and older males, *Experimental Physiology*, 89 (2004) 691–700.
- [32] J. D. Armstrong, Heart rate as an indicator of activity, metabolic rate, food intake and digestion in pike, *Esox lucius*. *Journal of Fish Biology*, 29 (1986) 207–221.
- [33] W. H. Hsieh, C. H. Wang, T. H. Lu, Bathtub drowning mortality among older adults in Japan, *International Journal of Injury Control and Safety Promotion*, 26 (2019) 151–155.
- [34] D. H. Zappe, G. W. Bell, H. Swartzentruber, R. F. Wideman, W. L. Kenney, Age and regulation of fluid and electrolyte balance during repeated exercise sessions, *American Journal of Physiology-Regulatory, Integrative and Comparative Physiology*, 270 (1996) R71–R79.
- [35] Y. Nagasawa, S. Komori, M. Sato, Y. Tsuboi, K. Umetani, Y. Watanabe, K. Tamura, Effects of hot bath immersion on autonomic activity and hemodynamics comparison of the elderly patient and the healthy young, *Japanese Circulation Journal*, 65 (2001) 587–592.
- [36] Y. Masuda, S. Marui, I. Kato, M. Fujiki, M. Nakada, K. Nagashima, Thermal and cardiovascular responses and thermal sensation during hot-water bathing and the influence of room temperature, *Journal of Thermal Biology*, 82 (2019) 83–89.
- [37] T. Chiba, M. Yamauchi, N. Nishida, T. Kaneko, K. Yoshizaki, N. Yoshioka, Risk factors of sudden death in the Japanese hot bath in the senior population, *Forensic Science International*, 149 (2005)

151–158.

- [38] H. Liu, D. Ogura, S. Hokoi, C. Iba, Study on physiological response considering blood flow volume in transient and non-uniform bathing thermal environment using thermo-cardiovascular regulation model, *Building and Environment*, 228 (2023) 109820.
- [39] J. A. J. Stolwijk, A mathematical model of physiological temperature regulation in man. No. NASA-CR-1855. NASA, Jan. (1971).
- [40] N. Westerhof, J. W. Lankhaar, B. E. Westerhof, The arterial Windkessel. *Medical & Biological Engineering & Computing*, 47 (2009) 131-141.
- [41] G. S. Brager, R. De Dear, Climate, comfort, & natural ventilation: a new adaptive comfort standard for ASHRAE standard 55. In *Proceedings, Moving Thermal Comfort Standards into the 21st Century*. (2001). Windsor, UK.
- [42] M. C. Odden, P. R. Beilby, C. A. Peralta, Blood pressure in older adults: the importance of frailty. *Current hypertension reports*, 17 (2015) 1-8.
- [43] G. Manley, M. M. Knudson, D. Morabito, S. Damron, V. Erickson, L. Pitts, Hypotension, hypoxia, and head injury: frequency, duration, and consequences, *Archives of Surgery*, 136 (2001) 1118–1123.
- [44] J. D. Spence, Risk from low blood pressure in frail older adults: diastolic pressure and pulse pressure are important, *Age and Ageing*, 50 (2021) e5–e6.
- [45] J. Gonzalez-Alonso, R. Mora-Rodríguez, E. F. Coyle, Stroke volume during exercise: interaction of environment and hydration, *American Journal of Physiology-Heart and Circulatory Physiology*, 278 (2000) H321–H330.
- [46] J. L. Vincent. Understanding cardiac output. *Critical Care*, 12 (2008) 1–3.
- [47] R.M. Berne, Cardiovascular physiology, *Annual Review of Physiology*, 43 (1981) 357–358.
- [48] B. B. Hafen, S. Sharma, Oxygen Saturation. In: *Stat Pearls*. Treasure Island (FL): Stat Pearls Publishing; (2023).
- [49] K. D. McClatchey (ed)., *Clinical laboratory medicine*. Lippincott Williams & Wilkins (2002).
- [50] S. N. Cheuvront, R. W. Kenefick, S. J. Montain, M. N. Sawka, Mechanisms of aerobic performance impairment with heat stress and dehydration, *Journal of applied physiology*, 109 (2010) 1989-1995.
- [51] R. J. Maughan, S. M. Shirreffs, Dehydration and rehydration in competitive sport. *Scandinavian journal of medicine & science in sports*, 20 (2010) 40-47.
- [52] S. Iwase, Y. Kawahara, N. Nishimura, et al. A comparison of head-out mist bathing, with or without facial fanning, with head-out half-body low-water level bathing in humans—a pilot study. *International journal of biometeorology*, 58 (2014) 999-1005.
- [53] J. W. Ring, R. de Dear, Temperature transients: A model for heat diffusion through the skin, thermoreceptor response and thermal sensation, *Indoor Air*, 1 (1991) 448-456.
- [54] Y. Xie, J. Niu, H. Zhang, S. Liu, J. Liu, T. Huang, J. Li, C. M. Mak, Development of a multi-nodal thermal regulation and comfort model for the outdoor environment assessment, *Building and*

Environment, 176 (2020) 106809.

- [55] C. Huizenga, Z. Hui, E. Arens, A model of human physiology and comfort for assessing complex thermal environments, *Building and Environment*, 36 (2001) 691-699.