Prediction of Age-Related Physiological Response in Bathing Thermal Environment Using Thermo-Cardiovascular Regulation Model

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Contents

Chapter 1　Introduction*

1.1 Research Background

Bathing is a traditional Japanese action to relax the body and has many merits for the body, such as warming the body, recovering from fatigue, rejuvenating, and enhancing sleep. However, bathing in winter also can cause serious health problems. It has been reported that many accident deaths happened during bathing [1-1]. Takahashi et al. [1-2] and Suzuki et al. [1-3] estimated that approximately 17,000 and 19,000 people died of bathing in Japan each year, respectively. Therefore, if no effective measures are taken, it is estimated that the number of deaths in bathing will reach 27,000 per year [1-4]. Annual mortality rates are high in bathing environments (most in winter), with more than 85% being older individuals [1-5]. It is worth noting that Japan's estimated number of people aged 65 or older stood at a record high of 36.4 million (accounting for 29.1%) in 2021, an increase of 220,000 from a year before. By 2030, one in every three people will be 65 or older, and one in five people 75-plus years old [1-6]. With the aging of the world population, the thermal health of older adults has attracted increasing attention [1–7]. 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.

Under such a social background, bathing accidents increase yearly, and bathing accidents are a visible thermal health risk for everyone. When considering the thermal environment of bathing from the viewpoint of health bathing, there are still points to be improved. Especially the winter, which is when bathing accidents occur frequently. Since the body temperature and other physiological parameters are affected by the thermal environment during bathing, the human body in the high-temperature environment, the low-temperature environment, and the transfer between high and low-temperature environments will have corresponding physiological and subjective thermal responses.

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These physiological and subjective thermal responses are the early warnings of the occurrence of bathing accidents. So, it is necessary to design the thermal environment for a healthier and more comfortable bath based on physiological and subjective thermal responses. However, the physiological responses are difficult to perceive, and the physiological and the subjective thermal responses do not always correspond. In other words, people can avoid bathing accidents in time if they perceive health risks through subjective thermal responses. However, many people, especially older adults, cannot subjectively feel the changes in their physiological responses. It is difficult to accurately judge their physical health level from the subjective thermal response; when they feel uncomfortable subjectively, it is already difficult to be saved.

In recent years, the issue of thermal comfort and health risks has attracted increasing attention [1-8,9]. Estimating the physiological responses of humans in transient and non-uniform environments is essential for the quantitative evaluation of the environment [1-10,11]. For many individuals, especially older adults, bathing accidents often occur owing to dramatic physiological response changes, sometimes even resulting in death. High blood pressure in the cold environment of a dressing room before bathing and subsequent low blood pressure during and after a hot bath can lead to the sudden onset of cardiovascular disease [1-12,13]. In addition, during bathing, the blood flow volume increases, and the blood flow ratio increases in some parts of the body, but the blood supply to the brain or vital organs is insufficient; consequently, loss of consciousness and drowning could occur. These explanations highlight the importance of understanding blood pressure and blood flow responses for designing a safe, healthy bathing environment.

Establishing a method for designing a thermal environment suitable for healthy bathing is essential. Therefore, it is necessary to understand the physiological responses (skin temperature, core temperature, heart rate, blood pressure, and blood flow) and subjective responses (thermal sensation and comfort) of people of different ages in the bathing thermal environment by experimental study. Nevertheless, because of the associated high health risks, the critical bathing situation with high health risks cannot be conducted through experiments. Hence, simulating and predicting bathing thermal physiological responses using a human model is essential.

1.2 Previous research

This section reviews the experimental and modeling studies on the thermal environment during bathing, the physiological responses such as body temperature, blood pressure, and blood flow, and the subjective responses of thermal sensation and comfort.

1.2.1 Subjective and physiological response in bathing thermal environment

Bathing is a specific non-uniform thermal environment, which is a regular practice of many people. Takasaki et al. [1-14] 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. They found that an average of 86.7% of people choose bathing in the bathtub daily, 2.0% prefer only to take a shower, and the rest choose to take a bath after the shower occasionally. 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.

Several experiments examining physiological responses during bathing showed that the temperature of hot water in the bath and dressing rooms influences body temperature and blood pressure [1-15,16,17]. Masuda’s research suggests that blood pressure will drop after bathing, and skin temperature drops when resting in a room of 15°C, then blood pressure rises [1-18]. Collins et al. [1-19], Tochihara et al. [1-20], and Nagasawa et al. [1-21] conducted experiments to measure the temperature, blood pressure, pulse rate, etc. of various parts of the human body during bathing. Many researchers have analyzed and studied the risks of bathing by examining the human body's physiological response during bathing. However, the past research only discussed blood pressure and heart rate and did not consider blood flow volume, an important physiological parameter of the blood circulation system.

Cardiovascular diseases such as “cardiopulmonary arrest” are often considered the cause of death in a bathing thermal environment [1-22]. Generally, the thermal physiological response, including the cardiovascular system of older adults, is significantly weaker than that of younger individuals [1-23,24]. Therefore, the physiological thermal response of the elderly in the bathing thermal environment and death during bathing are 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.

Most bathing accident research analyzes the statistics of bathing accidents, autopsies, and experiments. Because bathing experiments have certain risks, the process of bathing accident death is difficult to study through experiments, so the human model is used to carry out. It is essential to simulate and predict the human body's physiological response during bathing. By changing the environmental input conditions, we can find the healthiest bathing environment and reduce the risk of bathing, to improve the bathing environment to realize safe and comfortable bathing. Therefore, predicting physiological responses considering blood pressure and blood flow volume during bathing is essential to designing a healthy environment.

1.2.2 Human thermoregulation model

Many studies have developed human thermoregulation models (HTMs). The Stolwijk model [1-25], one of the most well-known thermoregulation models, comprises three cylinders divided into two or more concentric layers. Stolwijk further developed a passive model [1-26] that considered the basal metabolic rate change in the muscle layer and the skin blood flow change, but the metabolic rate should be changed according to the heart rate, and the blood flow volume change of each body part was not considered. Various improved thermoregulatory models have been developed based on the Stolwijk model.

Gagge et al. [1-27] developed a two-node model by using the heat exchange equation in the passive state. However, the two-node model only applies to a uniformly heated environment; it does not consider the temperature of individual body parts or a non-uniform thermal environment. Huizenga et al. [1-28] developed the Berkeley Comfort Model to predict human physiological responses under transient and non-uniform thermal environments.

Sato et al. [1-29], Kobayashi et al. [1-30], and Takahashi et al. [1-31] developed the Joint System Thermoregulation Model (JOS) series of models, which consider shivering thermogenesis, sweating distribution, and basal metabolic rate. Furthermore, the models mentioned above did not consider the actual blood flow volume change of the cardiovascular system, a crucial carrier in the thermoregulatory system, especially in distributing the heat throughout the body in a non-uniform thermal environment.

Smith [1-32] developed a model (hereafter referred to as Smith's model) to predict temperature distribution in detail by dividing the body into 15 segments and considering the blood flow volume in each border between tissues. Sakoi et al. [1-33] and Zhu et al. [1-34,35] developed a three-dimensional HTM considering blood flow volume in detail in a non-uniform environment based on Smith's model. However, the HTM cannot accurately calculate each body part's variable blood flow volume related to the cardiovascular system unless considered and coupled with the cardiovascular regulation model (CRM).

1.2.3 Cardiovascular Regulation Model

Some cardiovascular regulation models were constructed based on the whole and realistic blood circulation system. Avolio. A.P. [1-36] developed the whole-body artery model, which divided the whole-body artery into 128 segments with realistic arterial dimensions and wall properties.

Liang et al. [1-37,38] developed a closed-loop multi-scale model of the human cardiovascular system established for application to study the hemodynamic coupled global hemodynamic changes influenced by various factors. Parati et al. [1-39] developed a CRM to analyse the blood circulation system, such as blood pressure variability, to predict blood pressure changes using spectral analysis methods.

The CRMs mentioned above are extremely complex and meticulous, which are suitable for studying cardiovascular disease treatment. One of the most famous CRMs is the Windkessel model [1-40], which is a closed-circuit model that uses compliance, representing the elasticity of blood vessels and the resistance of capillaries. The Windkessel model is a lumped model that describes the arterial system in terms of the relationship between two of the most influential physiological parameters, blood pressure, and blood flow, at the entrance of the lumps. Blood pressure and blood flow were two of the most important factors in analyzing the health risks of bathing.

1.2.4 Thermo-cardiovascular regulation model

Various coupled models combine HTMs and CRMs to predict blood pressure and blood flow volume.

Goto et al. developed an autonomic regulation model that predicts the blood pressure and blood flow rate in a uniform environment [1-41,42]. The combined model comprises two models: a thermoregulation model developed based on the Stolwijk model and an improved version of the cardiovascular model proposed by Liang et al. [1-37]. However, the combined model has hundreds of blood vessels and many uncertain parameters. Moreover, the combined model can only predict steady blood pressure and blood flow volume in a uniform thermal environment, although bathing is a transient process in a non-uniform thermal environment.

Takahashi et al. [1-43] developed a combined model by coupling a CRM with a HTM to predict blood pressure during bathing. Regardless, the simulation accuracy of blood pressure remained insufficient. Hibino et al. [1-44,45] developed a model that combined HTM and CRM to calculate blood pressure changes during bathing and sleeping, considering the degree of opening of the arteriovenous anastomoses (AVAs) [1-46]. Yoshioka et al. [1-47] developed a model that could predict blood pressure in different postures based on the model of Hibino et al. [1-44]. Nonetheless, their models do not consider blood pressure changes with postural changes and insufficiently couple the HTM and CRM.

Based on the model of Yoshioka et al., Masugi et al. [1-48] developed a model coupling the Stolwijk and Windkessel model to predict postural blood pressure changes during bathing. However, the changes in blood flow, a crucial parameter for thermal health risk, is not considered. In the cardiovascular system, blood flow volume is an essential physiological parameter closely related to the thermoregulatory system. If the body temperature is too high and the blood flow volume increases too much or too little, it will cause cardiovascular-related diseases and health risks [1-4]. Therefore, predicting changes in blood flow volume during bathing is necessary.

1.2.5 Thermal subjective and physiological response for older adults

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 [1-49]. 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) [1-50] and thermal comfort [1-51].

Several studies [1-52,53,54,55] 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 susceptive than that in young individuals, and older individuals have a higher threshold for ambient temperature perception [1-56]. Thermal sensibility decreases with age at a high probability, and the perception of warmth decreases more prominently [1-57].

Furthermore, the thermal sensibility of the limbs is lower than that 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 [1-52], 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 [1-58]. Crandall et al. [1-59], Holowatz et al. [1-60], and Sagawa et al. [1-61] 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 [1-62,63].

Older adults' health is easily compromised in high-temperature environments, and the ability to perceive thermal physiological responses (blood flow distribution and sweating) [1-64,65] is associated with daily activities, such as walking and bathing [1-66]. 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 responses of blood vessels and blood flow are significant components 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. [1-67] 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. [1-68] conducted bathing experiments considering cardiovascular responses and TS with seven young participants. The results showed that cardiovascular thermal responses considering skin blood flow change significantly under a bathing environment.

Chiba et al. [1-69] showed that the changes in cardiac output are affected by the bathing environment, especially in older adults. Bathing significantly affects the cardiovascular system's blood pressure, skin blood flow, and cardiac output. The studies above showed that a 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 of 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.

1.2.6 Optimizing model considering the age

A decline in the ability to dissipate heat during physical activity is observed in individuals as young as 40 years old [1-70]. More than 80% of the people who died in the bath environment were older adults over 65 years old [1-71], so the thermal response and thermal risk faced by older adults during bathing are necessary to be studied. The physiological conditions of older adults are different from those of younger adults, and their physiological responses to thermal environments and the degree of thermal risk they face are also different. Chapter 5 conducted three bathing experiments for participants aged 25, 52, and 71 and measured the thermophysiological responses (skin temperature, core temperature, blood flow, blood pressure, blood oxygen, urine specific gravity, and body weight) of the three participants in the bathing environment. This chapter optimizes the thermal-cardiovascular system model considering the age factor and reproduces the results of the thermal response during the bathing of different age three participants.

Differences in thermal sensation and thermoregulation between old and young are caused by differences in physiological parameters (aging) [1-72,73,74]. Stevens et al. [1-75] found that the human body is more sensitive to cold than to warm stimuli. With age, the body's thermal sensation decreases, and the thermal sensation of the extremities decreases most significantly compared to other parts of the body, especially the feet. Tsuzuki et al. [1-76] conducted a comparative experiment on thermal comfort between elderly and young people at different temperatures and the same humidity. The experimental results showed that the metabolic rate of the elderly group was only 70% higher than that of the young group.

Compared to the young group, the elderly group showed a decrease in cold sensation in warm environments (summer) and a decrease in heat sensation in cold environments (winter). Hirata et al. [1-77] reported that the threshold for sweating of older adults is about 1.5 °C higher compared to the young skin threshold temperature for sweating based on the model of Nagaoka et al. [1-78] and experimental data of Dufour and Candas [1-

79]. In the blood circulation system, the distribution of blood flow and the physiological structure of blood vessels will also change with age [1-80]. Studies have shown that the skin and muscle blood flow ratio of people over 70 years old is significantly lower than that of young people [1-81]. Vascular function and arterial structure both experience age-related alterations [1-82,83]. The process of aging is frequently linked to a reduction in the flexibility of blood arteries, a medical term known as arteriosclerosis [1-84]. The decrease in elasticity can result in heightened impedance to the circulation of blood. Vascular remodeling, characterized by the thickening of vessel walls, can occur as a result of aging [1-85]. This process of thickening leads to a decrease in the internal diameter of the blood arteries, resulting in an increase in resistance to the flow of blood.

There are a number of thermal models capable of predicting thermal responses in young adults with associated thermal sensation and thermal comfort based on skin and core temperatures [1-86,87]. There is very limited research on models of human thermoregulation model that take the age factor into account. Understanding changes in their thermophysiological responses to thermoregulation is necessary to develop models that predict thermal responses in healthy older adults in heat-stressed environments, and changes in blood circulation and metabolic rate need to be considered. In previous studies, some researchers have optimized the human thermal model considering age, for example.

The human thermoregulation model for older persons developed by Novieto [1-88] is based on the Fiala model, using the thermophysical characteristics and anthropometry literature data of older adults to modify the existing human body thermoregulation model. Ma et al. [1-89] considered improvements using four parameters (height, weight, sex, and age) based on Zhou's [1-90] young people's thermoregulation model to achieve more accurate predictions of body temperature in older adults. This model considering the physiological parameters such as the basal metabolic rate, cardiac output, body fat content, and shape of the human body, and the accuracy of the predicted skin temperature can reach more than 85.9%. But it is different to accurately predict the core temperature. The physiological parameters considered are involved in the calculation in a constant form, but in daily life, physiological parameters such as metabolic rate and cardiac output will change with changes in body temperature, heart rate, and other physiological parameters. Dynamic physiological parameters should be considered in predictive models of thermophysiological responses.

The thermal model of the elderly established by Wang et al. [1-91] is also optimized based on the Fiala model. The model inputs air temperature, wind speed, CO2 concentration, illuminance, health status of the elderly, and living time in nursing homes, and the output is thermal perception vote and skin temperature. The model considers the detection results of older adults in a specific region to predict, and it is difficult to evaluate the accuracy of individualized prediction and its applicability in different regions. At the same time, the modified model did not consider the main differences in physical indicators between the elderly and young people, such as metabolic rate, sweating rate, etc.

Rida M et al. [1-92] developed an elderly bioheat modeling that considers their thermal responses of blood flow changes in warm and cold environments to predict skin and core temperatures. This model is based on the young adult model of Karaki et al. [1-93], according to the physiological differences between older and younger people (such as decreased metabolism and decreased vasoconstriction, skin blood flow, sweating value, skin fat thickness, and threshold parameters related to core or skin temperature) were developed. The model's mean skin temperature and core temperature calculation results are consistent with the relevant experimental results, with an error of less than 0.5°C. These models predict changes in skin and core temperature by adjusting physiological parameters of different ages. They are not able to predict blood circulation system parameters such as blood pressure and blood flow, especially blood flow changes in various parts of the body. Physiological parameters of the blood circulation system, such as blood pressure and blood flow, are also important thermal physiological responses. If the thermal model can accurately predict skin temperature, core temperature, and blood circulation system parameters (blood pressure and blood flow) in a thermal environment, this model is more accurate.

It can be seen from the above that some scholars have developed a thermal model for older adults by modifying the physiological parameters of basal metabolic rate, cardiac output, sweat factors, body weight, body surface area, and height, and predicted some physiological changes in older adults [1-94]. Novieto and Zhang [1-95] reported a biothermal model of aging by modifying the known IESD-Fiala model [1-96,97] but did not take into account the blood flow distribution, compliance, and blood flow to various parts of the body. Furthermore, thermal regulation models are typically distinguished between younger and older models. Nevertheless, the decline of the thermoregulatory system commences from the age of 40. Therefore, it is imperative to incorporate age group segmentation into the thermal response model.

1.3 Objectives

This thesis conducted experiments involving participants of various ages and analyzed the data collected to investigate the impact of the thermal environment on the human body during bathing. This research focused on examining the correlation between the human body's physiological response during bathing, the surrounding thermal environment, and the age of the participants.

This thesis aims to develop a thermo-cardiovascular regulation model to predict the physiological responses of the human body, including skin temperature, core temperature, blood pressure, and blood flow in the bathing thermal environment. The model takes into account the surrounding thermal environment and the physical activities of the human body. The objective of safe and healthy bathing is to provide a framework that comprehends the physiological parameters involved in bathing, with a particular focus on blood circulation. Furthermore, we have enhanced the model to create an individual model considering variables such as height, weight, heart rate, and age that can accurately forecast an individual's thermal physiological response in a bathing thermal environment.

1.4 Research structure

Figure 1-1 shows the structure of this paper. Chapter 2 examines the thermal physiological response of people in the thermal environment before, during, and after bathing, including thermal sensation, local skin temperature, core temperature, blood pressure, head and lower limb blood flow, and cardiac output. Chapter 3 introduces the basic theories of the thermoregulation model and cardiovascular regulation model. Chapter 4 analyzes and compares the simulation and experimental results of physiological response during bathing, including skin and core temperature, blood pressure, and blood flow volume, to verify the proposed thermo-cardiovascular regulation model. Chapter 5 conducts three bathing experiments on three participants (25, 52, and 71 years old) to analyze the different age participants' thermal sensations and physiological responses under the same non-uniform bathing thermal environment and study the relationship between subjective and physiological responses. Chapter 6 focuses on predicting the thermal physiological response in three distinct age groups: young, middle-aged, and older to optimize the individual thermo-cardiovascular regulation model considering the age-related changes in physiological factors, height, and weight.

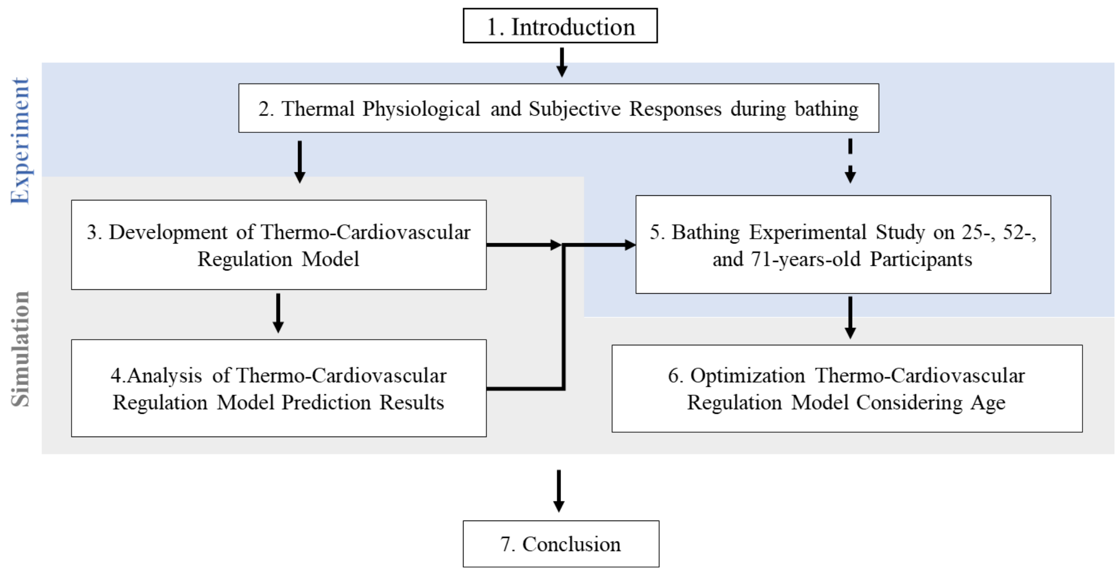

Figure 1-1 Structure of this thesis

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Chapter 2 Thermal Physiological and Subjective Responses during bathing*

2.1 Introduction

This chapter presents an overview of the bathing experiment conducted in winter (24 January 2020) with a 50-year-old man. The purpose of this experiment is to measure and analyze the participant's thermal physiological response in the bathing thermal environment, considering skin temperature, core temperature, blood pressure, and blood flow volume.

2.2 Outline of bathing experiment

2.2.1 Experimental conditions

Seven days before this experiment, we conducted a preliminary experiment to ensure the reliability of the experimental results in this chapter. We compared the preliminary and formal experimental results; the results of the two experiments are consistent with the same variation range and trend, demonstrating that the experimental results in this chapter are reasonable and credible.

Most of the individuals (>85%) who die during bathing annually are older adults (over 65 years) [2-1], who have poorer thermoregulatory ability than individuals of other ages. Therefore, to ensure the safety and health of older participants, the physiological response and health condition of middle-aged individuals in a bathing thermal environment should be analyzed before using older adults. Meanwhile, the female body temperature is greatly affected by hormone levels and fluctuates significantly during menstruation and ovulation, while the male body temperature generally remains relatively stable. Therefore, in this chapter, a healthy, middle-aged (50 years) man was used to conduct a bathing experiment with a long duration.

*The content of this chapter has been expanded by the author based on a portion of the author's papers [6-1] submitted to Building and Environment.

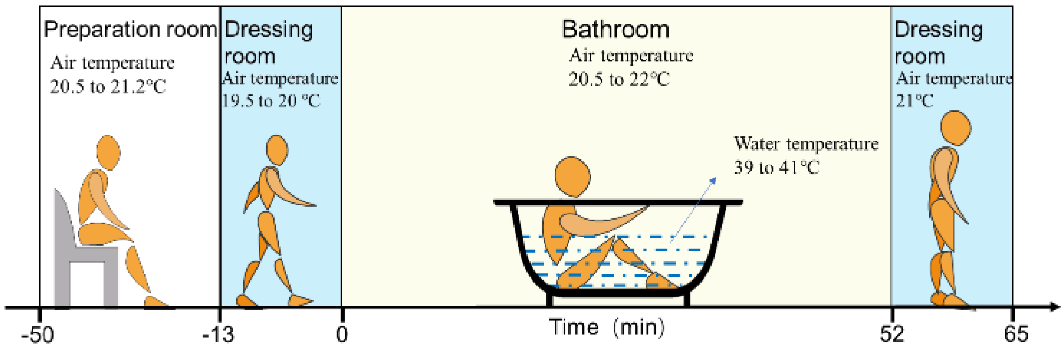
The participant had no basic diseases and no smoking or coffee-drinking habits. He did, however, occasionally drink alcohol, although he did not drink on the day of the experiment or the day prior. Table 2-1 shows the physique of the participant. Based on the Declaration of Helsinki, we explained the research content and experimental process in detail to the experimental participants, and the experimental participants agreed to conduct the experiment.

Table 2-1 Physique of the participant

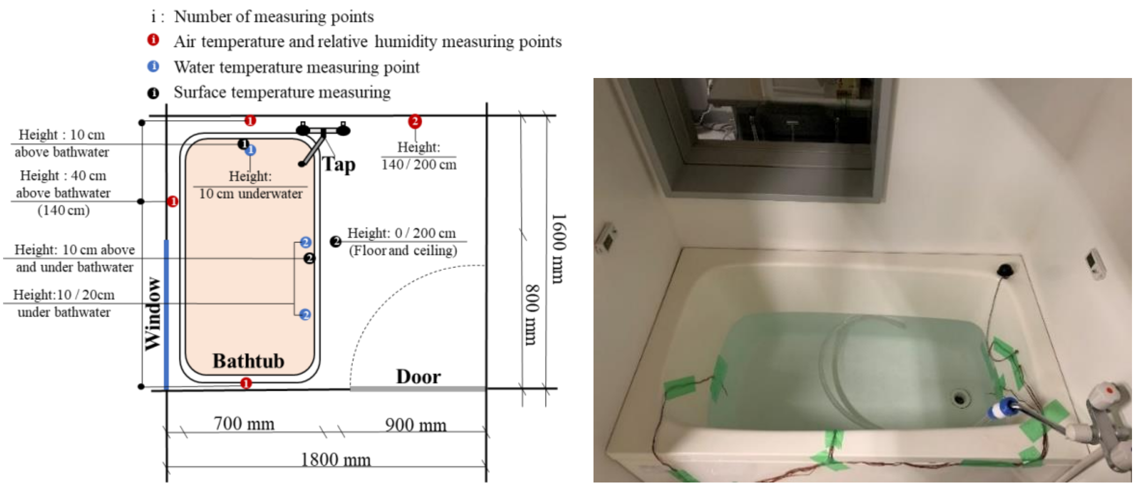
Date	2020/01/24
Age	50
Height	172 cm
Time	10:14 am ~ 12:09 am
Gender	Male
Weight	69.28 kg

2.2.2 Experimental process

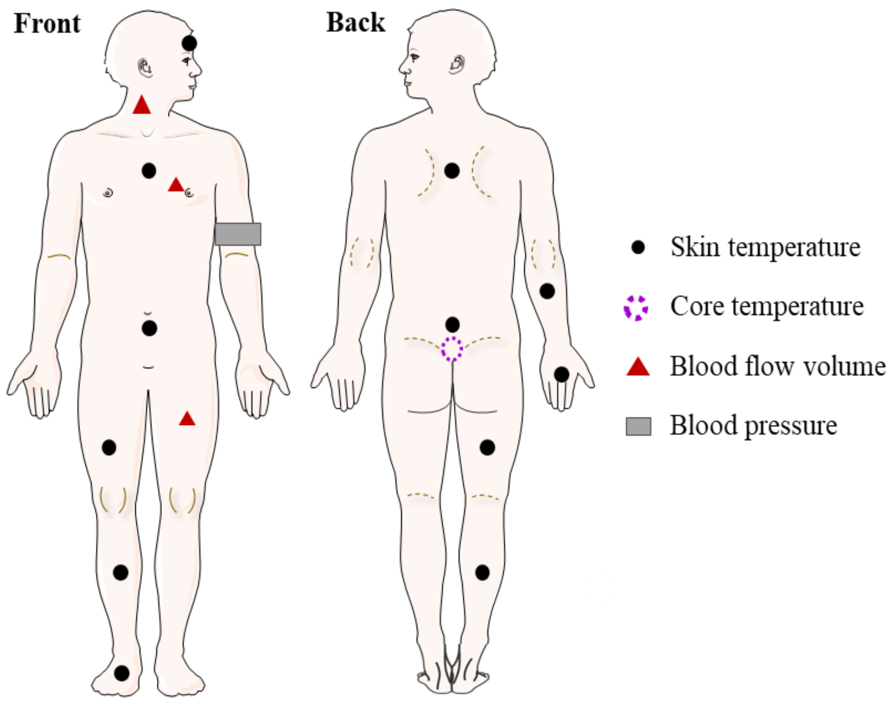
Figure 2-1 shows the experiment schedule, bathroom layout, and measuring points. In this experiment, physiological responses were measured throughout the entire bathing process, from the seated resting state in the preparation room until the exit from the bathroom. This experimental procedure was designed to measure the changes in human physiological responses to movement between a warm and cold environment and the bathing process. Before bathing, the participant (draped with blankets around the upper and lower body) sat in the preparation room (approximately 21 ℃) for 37 min to stabilize the body condition. Subsequently, the participant (dressed in shorts only) moved to the dressing room (approximately 18 ℃) where he remained for 13 min, after which he moved to the bathroom (Figure 2-1(b)) and entered the bathtub. The bathwater level was 15 cm above the participant's navel. After 50 min of bathing (bathwater temperature: 39 to 41 ℃), the participant exited the bathtub, dried off with a towel, moved to the dressing room, and finished the experiment.



(a) Experiment schedule



(b) Bathroom layout and measuring points of environment parameters



(c) Measuring points of thermal physiological response parameters

Figure 2-1 Experiment schedule, bathroom layout and measuring points

2.2.3 Measurement items

The preparation room had a stable thermal environment; the air conditioner was set at 21 ℃. The temperature and humidity of the dressing room and bathroom were not controlled, although the air temperature and humidity near the participant (50 cm horizontally away from the participant's trunk) were monitored and measured by the data logger at 10 s intervals. The bathwater temperature was also monitored.

The measured physiological variables were as follows: skin temperature at 12 locations (forehead, hand, arm, chest, back, abdomen, loin, thigh [front, back], calf [front, back], foot); core (rectal) temperature; heart rate; blood pressure; and blood flow volume (Figure 2-1(c)). Table 2-2 lists the details of the instruments used in this experiment. Skin and core temperatures were continuously measured during the experiment. Heart rate and blood pressure were measured every 5 min during bathing, and every 10 min before and after bathing. When measuring blood pressure, the cuff was wrapped around the participant's left arm at the height of the right atrium. The common carotid artery is the main artery supplying the head. The superficial femoral artery is the artery that mainly supplies the lower limbs. We measured the arterial blood flow volume at three locations every 10 min: the common carotid artery, the superficial femoral artery, and the aorta, representing the blood flow of the head, lower limbs, and cardiac output, respectively.

In this experiment, during bathing, the surveyor entered and exited the bathroom for measurements of blood pressure and blood flow volume and tried to make the influence of the measurement on the bathing environment negligible. Meanwhile, although many measuring points are arranged on the subject's body, the participant can also slowly move and be half submerged in hot water, so the measurement slightly influences the experimental results.

The thermal sensation is the subjective feeling of being cold or warm. In the experiment, the participant rated thermal sensation levels using the ASHRAE 55 [2-2] on a 7-point scale: hot (+3), warm (+2), slightly warm (+1), neutral (0), slightly cool (−1), cool (−2) and cold (−3).

Table 2-2 Information on instruments used in the experiment

<table>
<tr><th>Measurement</th><th>Instrument</th><th>Range</th><th>Accuracy</th><th>Interval</th></tr>
<tr><td>Air temperature</td><td rowspan="2">Onset HOBO temp/RH logger
UX00-011A</td><td>−20 °C
to 70 °C</td><td>± 0.21 °C</td><td rowspan="5">10 s</td></tr>
<tr><td>Relative humidity</td><td>1%
to 95%</td><td>± 2.5%</td></tr>
<tr><td>Skin temperature</td><td>Graphtec midi logger gl840
T-type Thermocouple</td><td>−100 °C
to 400 °C</td><td>± 0.1%</td></tr>
<tr><td>Core temperature</td><td rowspan="2">N543 High precision 8CH data logger (NT logger)
with thermistor probe</td><td rowspan="2">20 °C
to 50 °C</td><td rowspan="2">± 0.1 °C</td></tr>
<tr><td>Eardrum temperature</td></tr>
<tr><td>Blood pressure</td><td rowspan="2">OMRON automatic sphygmomanometer
HEM-7200</td><td>0 mm Hg to 299 mm Hg</td><td>± 3 mm Hg</td><td rowspan="2">5 min / 10 min</td></tr>
<tr><td>Heart rate</td><td>40 bpm to 180 bpm</td><td>± 5%</td></tr>
<tr><td>Blood flow</td><td>Ultrasound imaging equipment (Viamo™ c100, CANON)</td><td></td><td>± 6%</td><td>10 min</td></tr>
<tr><td>Skin blood flow</td><td>Laser blood flow meter (RBF-101)</td><td>0 mL/min to 100 mL/min</td><td>± 5%</td><td>10 s</td></tr>
<tr><td>Weight</td><td>Mettler Toledo 1d1</td><td>0.2 kg
to 150 kg</td><td>±0.015% kg</td><td></td></tr>
</table>

2.2.4 Experimental environment

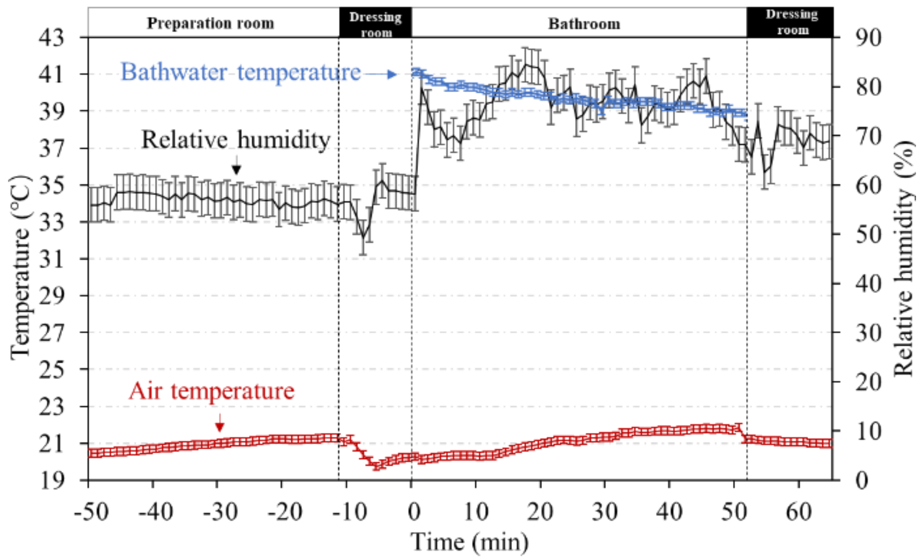


Figure 2-2 Environmental air temperature, relative humidity, and bathwater temperature during the experiment

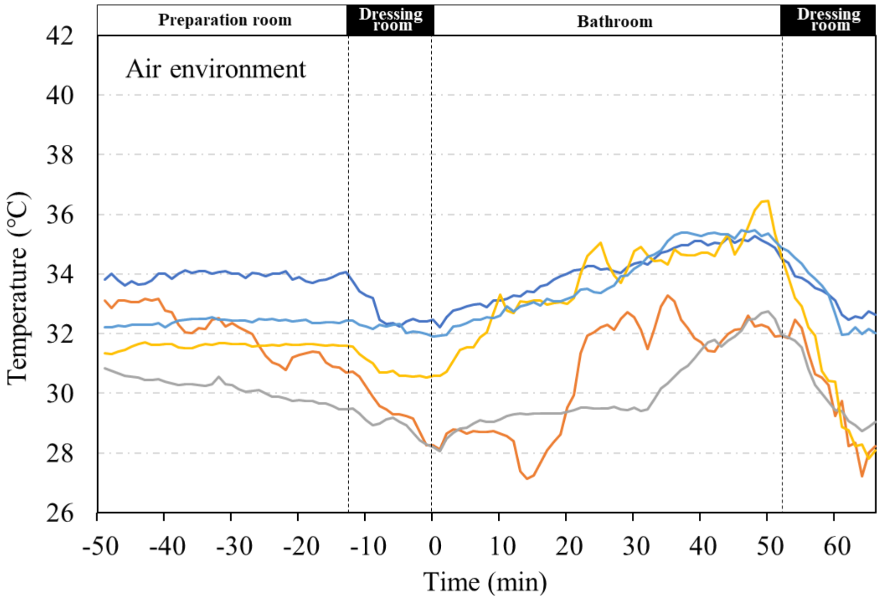
Figure 2-2 shows the air temperature, relative humidity, and bath water temperature of the participant's environment during the experiment. The temperature of the bathwater was in the range of 39 to 41 °C. The experiments were conducted using three spaces: a preparation room, a dressing room, and a bathroom. The participant moved among the three spaces. The dressing room had a cool air temperature from 19.5 to 20 °C, and the bathroom had a more significant temperature change than the other two spaces, from 20.5 to 22 °C.

The relative humidity in the preparation room was stable, but that in the bathroom fluctuated drastically and was higher (approximately 80%) than in other spaces. In this experiment, the environmental parameters, skin temperature, and core temperature were continuously measured by instruments. In addition, the surveyor entered and exited the bathroom for multiple measurements of blood pressure and blood flow volume. The action of multiple measurements had some effects on the bathing environment, but the environmental changes had corresponding thermophysiological responses of the participant during bathing.

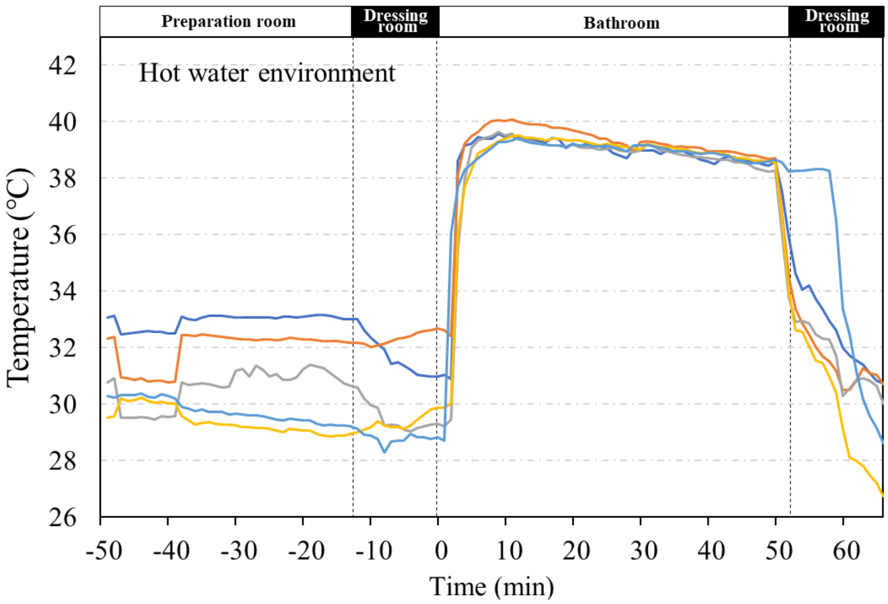
2.3 Results and analysis

2.3.1 Skin temperature

Figure 2-3 shows the measured skin temperatures. The skin temperatures of all parts were relatively stable in the preparation room and decreased in the dressing room. However, the body was in two environments: air and hot bathwater during bathing.



(a) Parts in the air environment



(a) Parts in the hot water environment

Figure 2-3 Experimental results of skin temperatures

The upper body was in an air environment, and the lower was in a hot bathwater environment. The skin temperatures of the parts in the air environment gradually increased during bathing. At the beginning of the bathing, the skin temperatures of the parts immersed in hot water increased rapidly, and the skin temperatures were almost equal to the water temperature. However, the skin temperatures of all the parts quickly decreased after bathing. Hence, the skin temperature is greatly affected by the surrounding temperature.

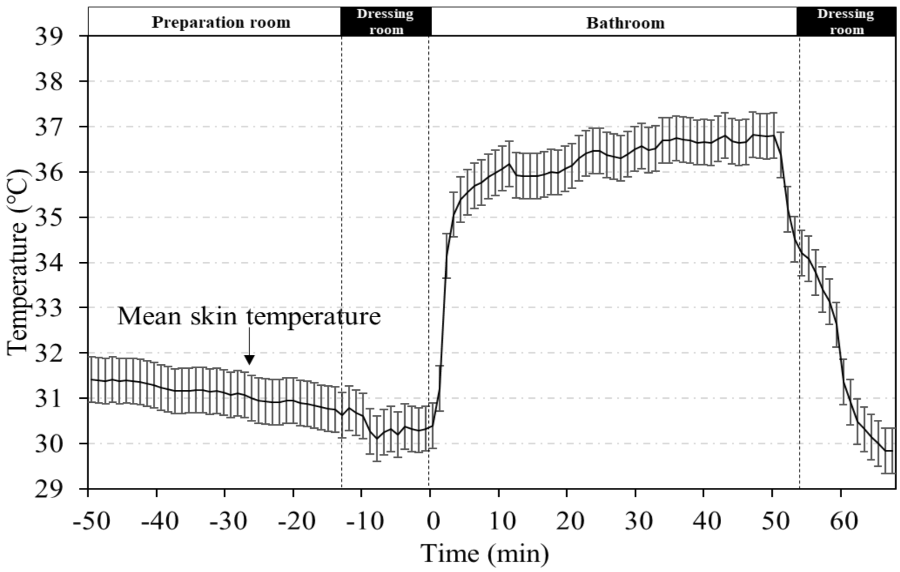


Figure 2-4 Experimental results of mean skin temperature

Figure 2-4 shows the measured mean skin temperature. The mean skin temperature (T_{skin}) was calculated using a weighted average method based on Hardy Dubois's 7-point method [2-3]. In this paper, the mean skin temperature was calculated based on Hardy Dubois's weighted 7-point method [2-4], seen as Table 2-3 and Equation (2-1).

$$T_{skin} = 0.07T_{forehead} + 0.0875\ (T_{chest} + T_{back} + T_{abdomen} + T_{loin}) + 0.14T_{arm} + 0.05T_{hand} + 0.095(T_{thigh\ front} + T_{thigh\ back}) + 0.065(T_{calf\ front} + T_{calf\ back}) + 0.07T_{foot} \qquad (2-1)$$

As shown in Figure 2-4, the T_{skin} of the participant was relatively stable in the preparation room. Then, T_{skin} decreased with the ambient temperature when the participant undressed and moved to the dressing room. During bathing, under the influence of the hot bathwater, T_{skin} increased rapidly from 30.4 to 35.4 °C and gradually increased to 36.9 °C in the bathtub. When the participant exited the bathtub, T_{skin} decreased rapidly from 36.9 to 34.5 °C and continued decreasing in the dressing room.

Table 2-3 Surface area ratio of each body part for mean skin temperature calculation

This chapter		**Hardy Dubois's 7-point method**	
Body parts	**Ratio**	**Body parts**	**Ratio**
Forehead	0.07	Forehead	0.07
Chest	0.0875	Trunk	0.35
Back	0.0875		
Abdomen	0.0875		
Loin	0.0875		
Arm	0.14	Arm	0.14
Hand	0.05	Hand	0.05
Thigh front	0.095	Thigh	0.19
Thigh back	0.095		
Calf front	0.065	Calf	0.13
Calf back	0.065		
Foot	0.07	Foot	0.07
Total	1	Total	1

2.3.2 Core temperature

Measuring temperature in the rectal is the closest way to the actual body temperature. Figure 2-5 shows the measured core temperature. The core (rectal) temperature (T_{core}) slightly decreased when the participant entered the bathtub; it increased after 10 min. It reached 37.95 °C when the participant left the bathroom, a very significant change (0.8 °C) compared with the start of bathing. In the relatively cold dressing room after bathing, T_{core} did not decrease; rather, it increased very slightly.

The human body's thermoregulatory system maintains a stable T_{core}. When the T_{amb} varied, the T_{core} changed more gently than the T_{skin}. The reason is that the skin blood with low temperature is transmitted from the skin to the core of the human body. The core temperature then rises. The skin blood temperature increases by the hot water, and the skin blood flow brings heat into the core of the human body by the circulatory system.

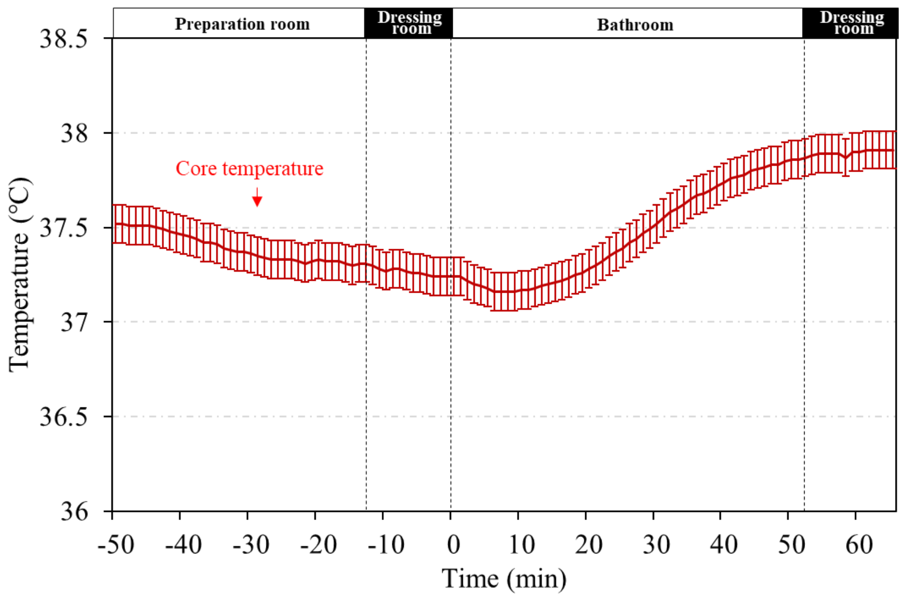


Figure 2-5 Experimental results of core temperature

Generally speaking, the normal tympanic temperature is 36.8 ± 0.7°C. The upper limit of normal for teenagers and adults is 37.5°C. When the temperature exceeds 37.5°C, it means a fever [2-5]. Figure 2-5 shows the measured tympanic temperature. In this experiment, the average temperature of the tympanic is 36.6 °C. Compared with the rectum, the tympanic is closer to the air environment, and the distance from the air to the tympanic is shorter. Hence, the change in tympanic temperature is more obvious than rectal temperature.

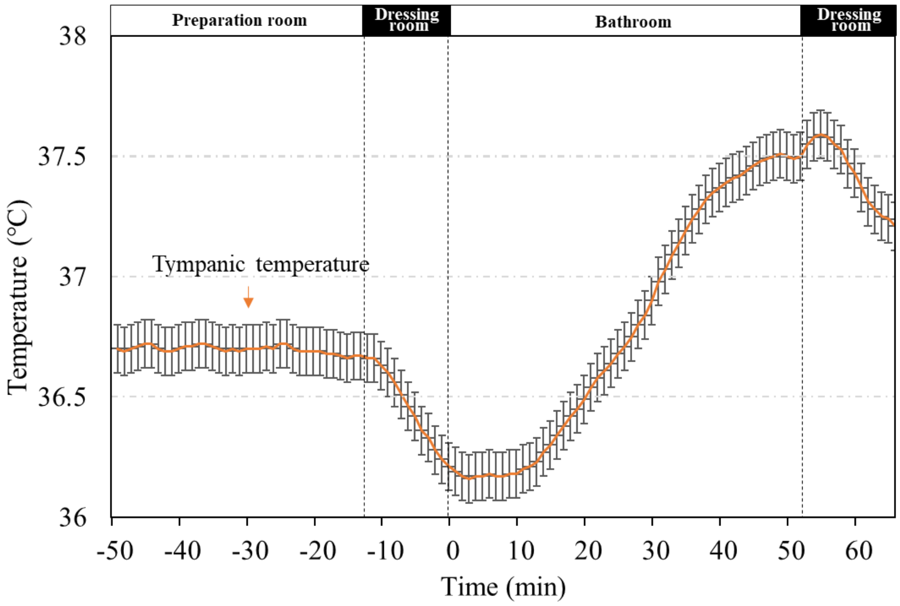


Figure 2-6 Experimental results of tympanic temperature

2.3.3 Blood pressure and pulse pressure

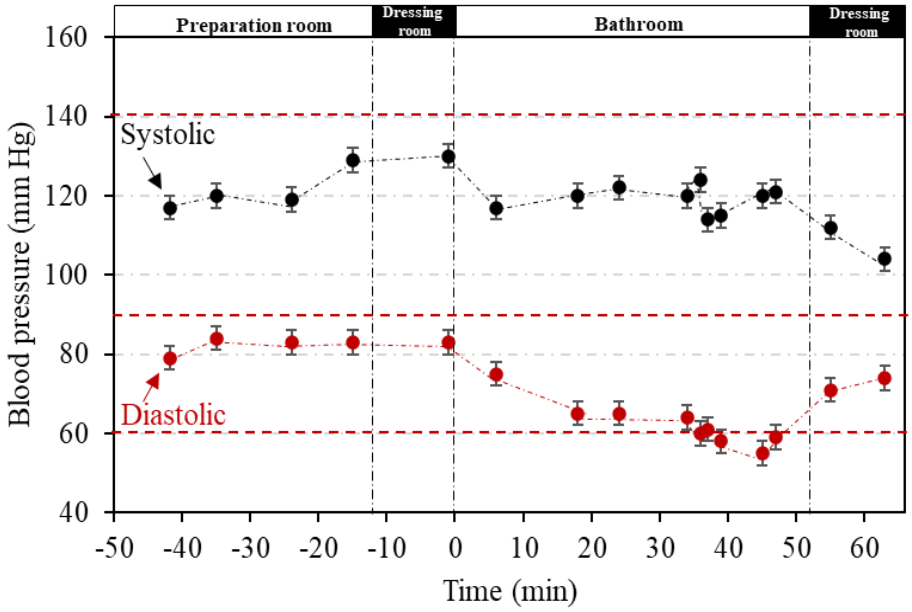


Figure 2-7 Blood pressure variation during the bathing experiment

Figure 2-7 shows the variation in blood pressure during the bathing experiment. The healthy blood pressure range for a normal adult at rest is from 90 to 140 mm Hg (systolic) and from 60 to 90 mm Hg (diastolic). Generally, blood pressure below 90/60 mm Hg is considered hypotension. Generally, T_{amb} and blood pressure are negatively correlated. High T_{amb} causes the blood vessels to dilate and the blood resistance to decrease, then the blood pressure decreases.

As shown in Figure 2-7, the participant's blood pressure was within the healthy range in the stable thermal environment of the preparation room. During bathing, the systolic blood pressure gradually decreased from 130 to 116 mmHg, and the diastolic blood pressure significantly decreased from 182 to 56 mmHg. After 38 min of bathing, the diastolic blood pressure was 56 mmHg, which was lower than 60 mm Hg, representing hypotension [2-6].

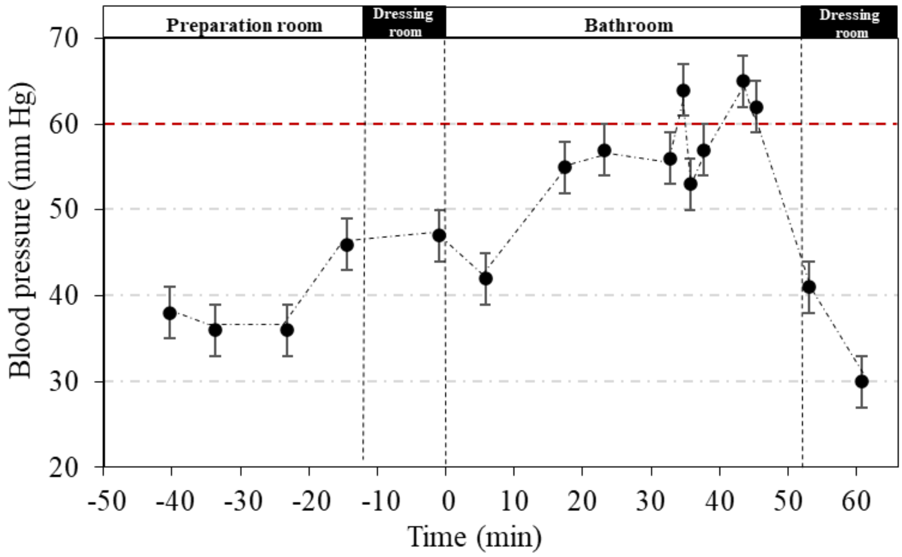


Figure 2-8 Pulse pressure variation during the bathing experiment

Figure 2-8 shows the variation in pulse pressure during the bathing experiment. The systolic pressure minus the diastolic pressure is the pulse pressure. For example, if the resting blood pressure is 120/80 mm Hg, then the pulse pressure is 40, which is considered healthy. Measuring pulse pressure can help healthcare providers predict the risk of heart events, including heart attacks or strokes.

As shown in Figure 2-8, the participant's pulse pressure was without the cardiovascular disease risk in the stable thermal environment of the preparation room. However, from t = 0 to t = 32, the pulse blood pressure gradually increased from 42 to 56 mm Hg and significantly increased from 56 to 65 mmHg from t =32 to t = 45. Pulse pressure greater than 60 is considered a risk factor for cardiovascular disease, especially for the elderly [2-7].

2.3.4 Heart rate

Figure 2-9 shows the heart rate variation during the bathing experiment. As shown in Figure 2-9, the participant's heart rate quickly decreased when moved from the preparation room to the dressing room before bathing, then significantly increased from 72 to 98 bpm in the bathroom during bathing. The changing trend of the heart rate and T_{skin} (as shown in Figure 2-4) are similar. It demonstrates that heart rate is significantly affected by skin temperature.

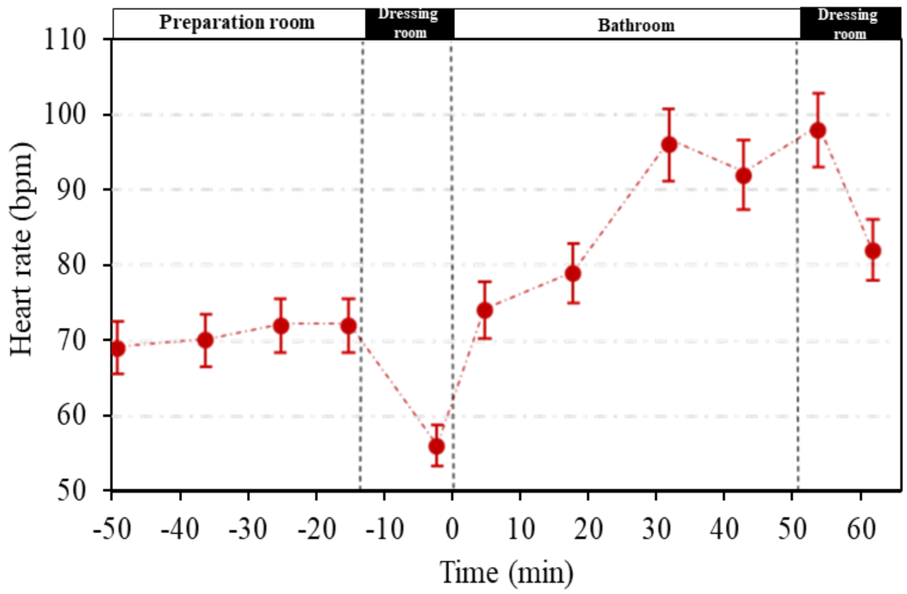


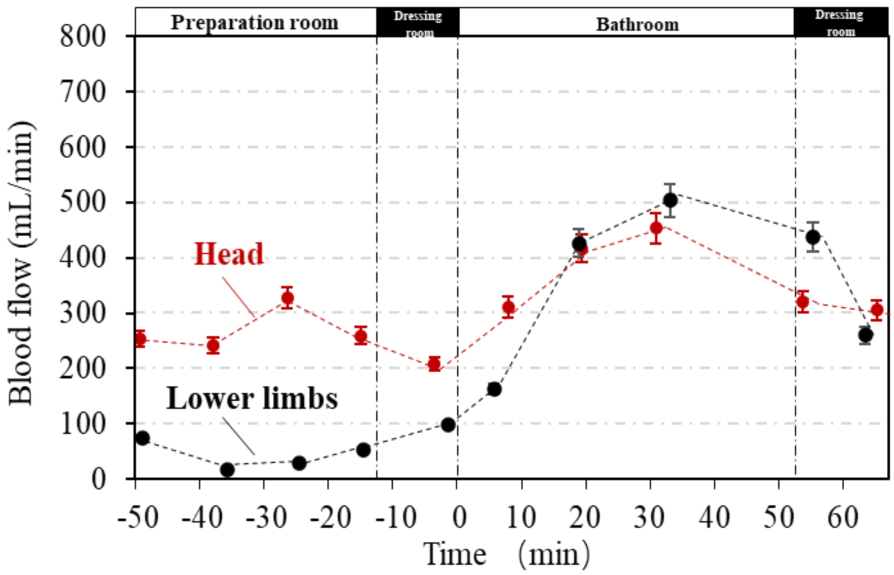
Figure 2-9 Heart rate variation during the bathing experiment

2.3.5 Blood flow volume

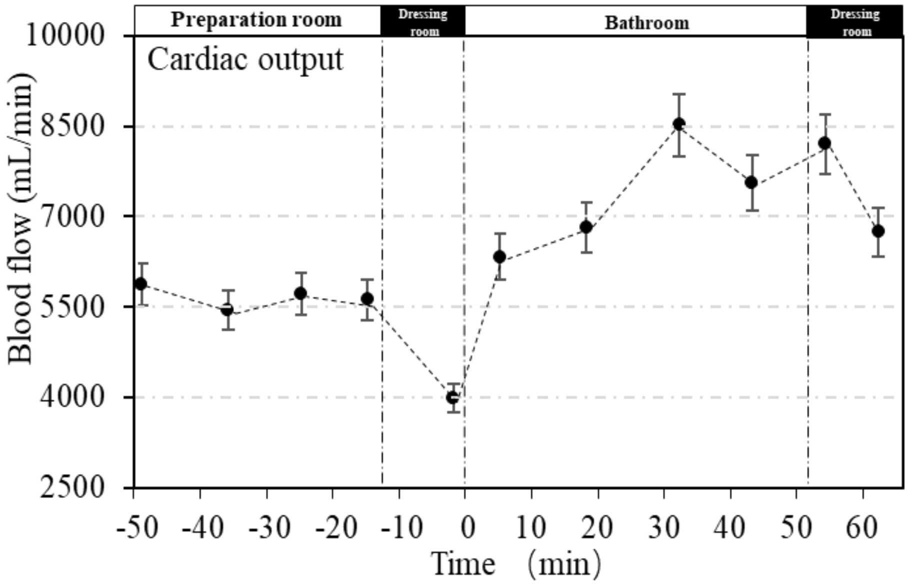
Figure 2-10 shows the blood flow volume of the cardiac output, head, and lower limbs during the bathing experiment. In general, the increase in blood flow is due to the increase in heart rate; moreover, as mentioned above, high T_{amb} causes blood vessels to dilate, reducing blood resistance, and resulting in increased blood flow.

As shown in Figure 2-10, before bathing, in the preparation room, the blood flow volume of each part fluctuated only slightly. During bathing in the bathroom, the blood flow volume of the head, lower limbs, and cardiac output increased approximately 2, 4.7, and 1.4 times, respectively. Before bathing, the head and lower limbs were in a space with the same air temperature, and the blood flow volume remained relatively stable.

Notably, the environments of the head and lower limbs differed during bathing. The lower limbs were in the hot bathwater environment (39 to 41 °C), while the head was in the air environment (20.5 to 22 °C), which was colder than the bathwater. As a result, the blood flow volume changes in the lower limbs varied more than that in the head. After bathing, the blood flow volume in both parts decreased.



(a) Blood flow volume of the head and lower limbs



(b) Cardiac output

Figure 2-10 Variation in the blood flow volume of the cardiac output, head, and lower limbs during the bathing experiment

2.3.6 Blood flow ratio

To study the influence of a non-uniform bathing thermal environment on blood flow redistribution in each body part, the blood flow ratio of each part was calculated. The blood flow ratio refers to the percentage of blood flow volume of each part in cardiac output, as shown in Figure 2-11. For example, the blood flow of the head at the beginning of the bathing, as shown in Figure 2-10, is about 313.25 mL/min, and the cardiac output is about 6327 mL/min; thus, the blood flow ratio of the head at the beginning of the bathing is 313.25 /6327 (mL/min) =0.495≈5%.

Figure 2-11 shows the blood flow ratio of the head, lower limbs, and other parts at the start of bathing and after 35 min of bathing. During bathing, the body is in a non-uniform thermal environment; the head, upper half of the trunk, and upper limbs are in an air environment, while the lower half of the trunk and the lower limbs are submerged in hot water. We measured the blood flow volume of the head (in an air environment) and lower limbs (in the hot bathwater).

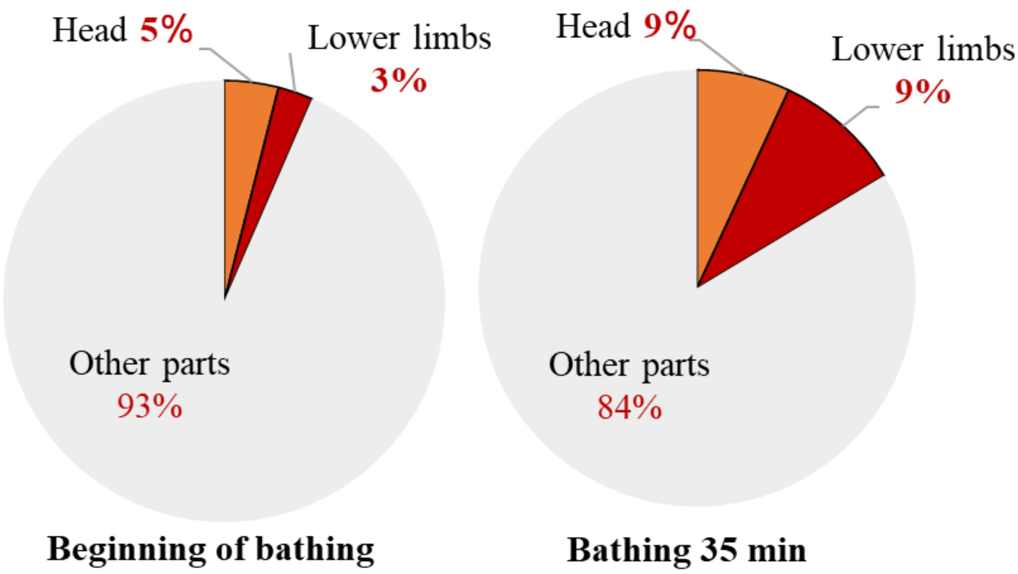


Figure 2-11 The blood flow ratio of the head, lower limbs, and other body parts at the start and after 35 min of bathing

By comparing the results at the start of bathing with those after 35 min of bathing, we found that the blood flow ratio of the lower limbs increased from 3% to 9%, that of the head increased from 5% to 9%, and that of the other parts decreased from 93% to 84%. Therefore, the increase in blood flow percentage in the lower limbs (in the hot water environment) was significantly larger than that in the head (in the air environment). Such changes demonstrate that bathing behavior could change blood flow distribution in some body parts under different environmental conditions. A smaller proportion of head blood flow is also one of the health risks of cardiovascular disease.

2.3.7 Skin blood flow of earlobe

Figure 2-12 shows the skin blood flow of the earlobe changes during the bathing experiment. Increased skin blood flow volume generally results from increased skin temperature. Furthermore, as mentioned above, the ambient temperature increase causes the blood vessels to dilate, the blood resistance to decrease, and the skin blood flow to increase.

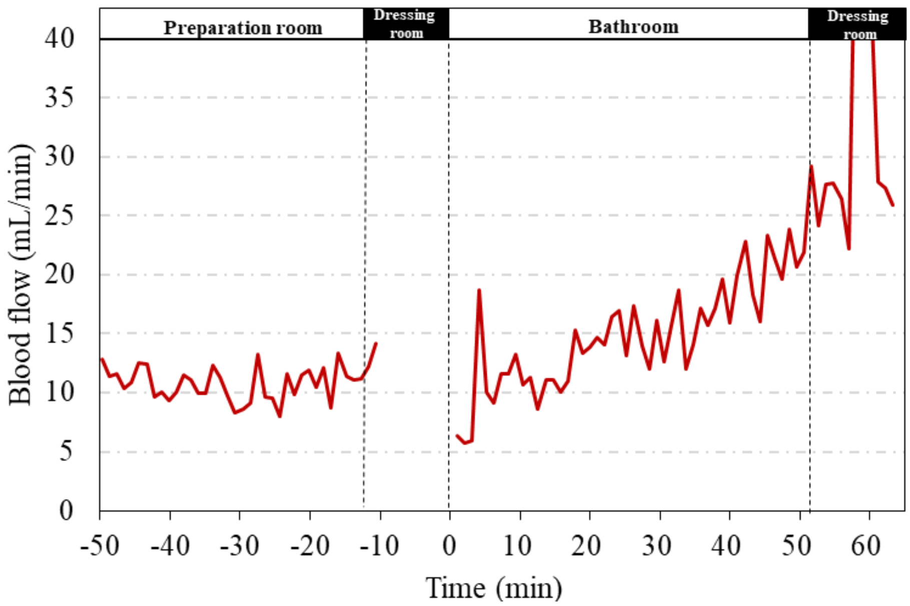


Figure 2-12 Variation in the skin blood flow of the earlobe during the bathing experiment

As shown in Figure 2-12, before bathing, in the preparation room, the skin blood flow volume of the earlobe fluctuated only slightly. The blood flow volume of the head increased approximately 2 times, but the skin blood flow of the earlobe increased approximately 2.5 times during bathing. It is noteworthy that the earlobe is a part of the head, but the skin blood flow of the earlobe increases more than that of the whole head, indicating that the growth of the blood flow of the other part of the head is much less than that of the earlobe skin and the whole head. As a result, the skin blood flow changes more obviously than other parts under the bathing thermal environment.

2.3.8 Thermal sensation (Seven-point sensation scale)

Figure 2-13 shows the thermal sensation of the participant during the bathing experiment. It decreased in the preparation room and increased in the bathtub. After bathing, the thermal sensation decreased again. By comparing Figures 2-4 and 3-13, it can be seen that before bathing, T_{skin} decreased slowly, while thermal sensation decreased to the lowest level (−3). However, T_{skin} increased rapidly soon after entering the bathroom and gradually increased further during bathing, and the thermal sensation also increased, corresponding to the T_{skin} changes. The thermal sensation subsequently dropped to −2 in the dressing room. However, despite the decrease in thermal sensation, T_{core} continued to increase after bathing.

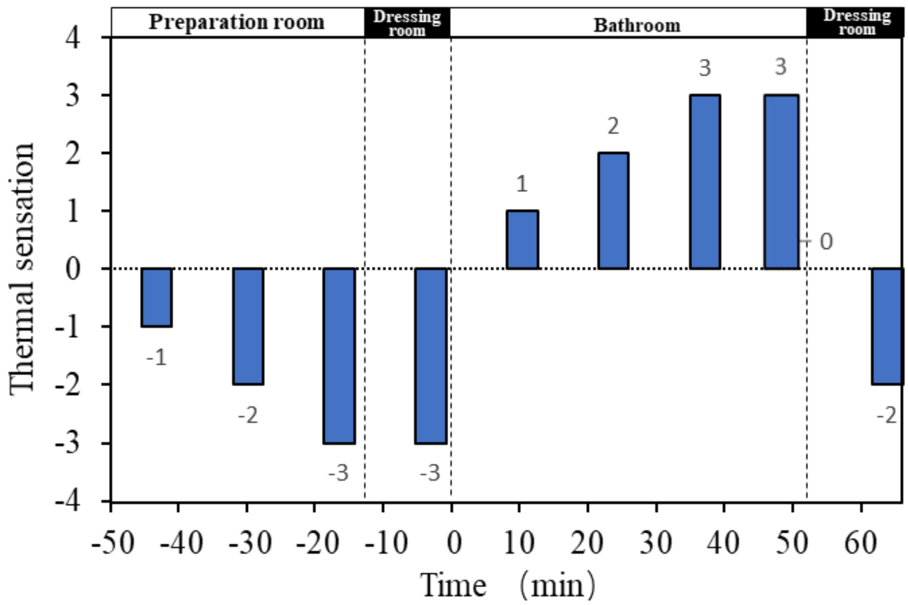


Figure 2-13 Variation in thermal sensation during the bathing experiment

2.3.9 Bodyweight

The method of measuring the amount of dehydration in this experiment is to measure the body weight change during bathing. The body weight decreases after bathing due to the loss of water from the human body during bathing due to respiration, sweating, and infestation. Before bathing, the weight of the participant was 69.28kg, and the weight decreased 0.27 kg (0.4%) to 69.01 kg after 49 min of bathing.

2.4 Conclusion

In this chapter, the outline of the experiment, the experiment purpose, and the results of the thermal physiological response considering skin temperature, core temperature, heart rate, blood pressure, and blood flow volume of the participant were investigated.

1) Experiment Summary

The bathing experiment was conducted in winter (24 January 2020) with a 50-year-old man. The thermophysiological responses under the bathing environment were measured, which included the skin temperature, core temperature, blood pressure, heart rate, and blood flow.

2) Skin temperature

The differences in skin temperature and changes over time under different thermal environments were observed. During bathing, the skin temperature changes less in the air environment than in the hot bathwater environment.

3) Core temperature

The T_{amb} varied, and the T_{core} changed more gently than the T_{skin} under the bathing thermal environment; the T_{core} increased slowly during the bathing and was affected by the T_{amb} over time. The change in tympanic temperature is more obvious than that of rectal temperature.

4) Blood pressure and pulse pressure

There were health risks of hypotension and high pulse pressure shown during bathing in this bathing experiment. After 38 min of bathing, the participant showed hypotension; the diastolic blood pressure was lower than 60 mm Hg. From t =35, a cardiovascular disease risk factor (pulse pressure over 60 mmHg) was shown, and the pulse pressure increased to 65 mmHg.

5) Heart rate

The bathing thermal environment significantly affects the heart rate, and especially the heart rate increased 1.4 times during the bathing process.

6) Blood flow volume

Affected by the bathing environment, the blood flow volume greatly changed during bathing. In addition, the changes in the blood flow volume of the head and lower limbs vary greatly in different temperature environments of air and hot bathwater.

7) Blood flow ratio

The bathing behavior changed blood flow distribution in some body parts under different environmental conditions. The increase in blood flow percentage in the lower limbs (in the hot water environment) was significantly larger than that in the head (in the air environment).

8) Skin blood flow of earlobe

The skin blood flow of the earlobe increased approximately 2.5 times during bathing, which is greater than the blood flow volume of the head increased approximately 2 times. As a result, the skin blood flow changes more obviously than the core part under a bathing thermal environment.

9) Bodyweight

The body weight was lost about 0.27 kg (0.4%) due to the water loss during bathing from respiration, sweating, and insensible perspiration.

10) Thermal sensation (Seven-point sensation scale)

The thermal sensation varied dramatically in the transient and non-uniform bathing thermal environment, from as low as -3 in the cold undressing room to as high as +3 after 35 minutes of bathing.

Chapter 2 References

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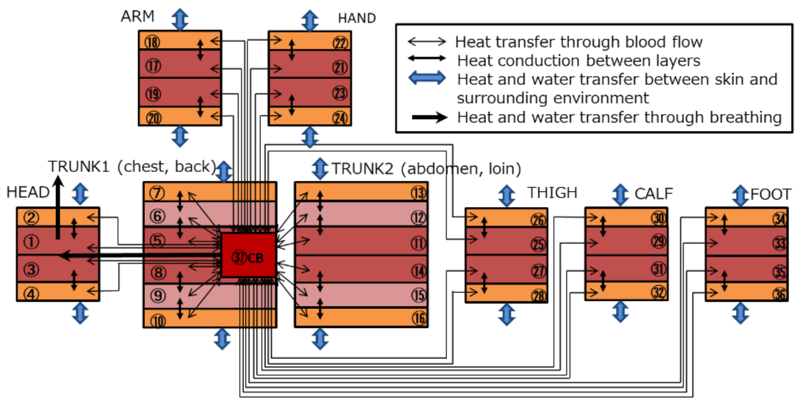
Chapter 3 Development of Thermo-Cardiovascular Regulation Model*

3.1 Introduction

In this chapter, to predict the human physiological response, including skin temperature, core temperature, blood pressure, and blood flow volume during bathing, we proposed a thermo-cardiovascular regulation model based on the model by Masugi et al. [3-1], which couples the Stolwijk [3-2] and Windkessel models [3-3]. We considered the changes in metabolic rate by examining the actual heart rate to improve the Stolwijk model and examined the changes in compliance by the actual heart rate to improve the Windkessel model. It can well predict the human physiological responses. The detailed coupling thermo-cardiovascular regulation model is introduced as follows:

3.2 Human Thermoregulation Model

As a part of the coupling thermo-cardiovascular regulation model, we developed a novel Human Thermoregulation Model (HTM) based on Stolwijk's model to well predict the body to predict the body temperature during bathing. Figure 3-1 shows a schematic of the HTM. The whole-body divides into 8 segments, i.e., head, trunk 1, trunk 2, arm, hand, thigh, calf, and foot. Each segment consists of a core and a skin layer (only the trunk includes a muscle layer in addition to these layers). As a result, the proposed model consists of 37 nodes, including the central blood pool. To calculate the water movement on the skin surface, we refer to Jones et al. [3-4].



*The content of this chapter has been expanded by the author based on a portion of the author's papers [6-1] submitted to Building and Environment.

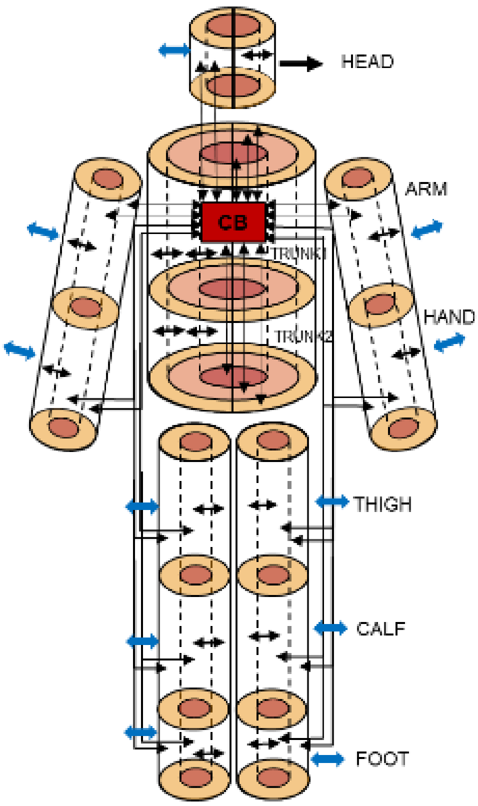


Figure 3-1 Human Thermoregulation Model

3.2.1 Basic formula

3.2.1.1 Heat balance formula for each part of the human body

The heat balance for each node is expressed using Equation (3-1). The heat balance in each part of the human body except for the CB pool (i = 1 to 36) consists of heat production and heat loss. Heat production mainly includes basal metabolism, shivering, and exercise. Heat loss mainly includes heat released by respiration, insensible perspiration, and regulated sweating; heat from the CB through convection; conduction heat to the adjacent layer; and convection and radiation heat to the layers in contact with the skin surface (clothing layer, air layer). Equations (3-2) to (3-8) express the heat balance for each body part.

$$C_i \frac{dT}{dt} = MTB + SHV + EXS - EVR - EVI - SWT - BF - CD - ENV \qquad (3-1)$$

where

C: heat capacity of the body segment [J/K]

T: temperature [°C]

t: time [s]

MTB: metabolism [W]

SHV: heat production by shivering [W]

EXS: heat production by exercise [W]

EVR: heat loss by respiration [W]

EVI: evaporative heat loss by insensible perspiration [W]

SWT: evaporative heat loss by sweat [W]

BF: heat exchange between blood and tissues [W]

CD: heat conduction between two segments [W]

ENV: sensible heat loss from skin [W]

subscript *i*: segment number (1–36)

(1) Head core layer

$$C_i \frac{dT_i}{dt} = MTB_i + SHV_i - EVR_i - BF_i - CD_i \qquad (3-2)$$

(2) Trunk core layer

$$C_i \frac{dT_i}{dt} = MTB_i - EVR_i - BF_i - CD_i \qquad (3-3)$$

(3) Limb core layer

$$C_i \frac{dT_i}{dt} = MTB_i + SHV_i + EXS_i - BF_i - CD_i \qquad (3-4)$$

(4) Trunk muscle layer

$$C_i \frac{dT_i}{dt} = MTB_i + SHV_i + EXS_i - BF_i - CD_i \qquad (3-5)$$

(5) Each node of the skin layer

$$C_i \frac{dT_i}{dt} = MTB_i - EVI_i - SWT_i - BF_i - CD_i - ENV_i \qquad (3-6)$$

Here,

$$ENV_i = Sr_i \cdot S(CHR_i + CHC_i)\Delta T_{i,e} \qquad (3-7)$$

where $\Delta T_{m,n} = T_m - T_n$.

(6) Central blood flow

The heat balance in CB is expressed by blood's heat transfer between each part.

$$C_{37}\frac{dT_{37}}{dt} = \sum_{i=1}^{36} BF_i \qquad (3-8)$$

where

CHC: convective heat transfer coefficient [W/m^2/K]

CHR: radiant heat transfer coefficient [W/m^2/K]

Sr_i: body surface area ratio of that node [n.d.]

S: body surface area [m^2]

subscript *i*: node number

subscript *e*: layer in contact with the skin surface

3.2.1.2 Thermoregulation formula

Metabolic rate, heat production by shivering, heat loss by respiration, evaporative heat loss skin blood flow, and muscle blood flow are determined by the difference between head core temperature, mean skin temperature, mean muscle temperature, and their set points.

(1) Metabolic rate

The metabolic rate formula is as follows:

According to a study published in *Arbeitsphysiologie* [3-5], cardiovascular exercise increases body temperature and heart rate, stimulating metabolic processes to produce energy [3-6]. Hence, the heart rate–related metabolic rate changes are considered in the proposed model. The metabolic rate in the Stolwijk model has a constant value of 50 [W/m^2]. In our study, we use Equation (3-9) and (3-10), which Malchaire et al. [3-7]

proposed regarding the relationship between heart rate and metabolic rate.

$$MTB_i = MTB_0 \cdot S \cdot Mr_i \qquad (3-9)$$

where

MTB_i: basal metabolic rate of each segment [W]

MTB_0: basal metabolic rate [W/m^2]

Mr_i: weight ratio of each segment [n.d.]

S: skin surface area [m^2]

$$M = \frac{(M_{\max} - M_0)}{(HR_{max} - HR_0)}(HR_{wm} - HR_0) + M_0 \qquad (3-10)$$

Where

M_{max}: maximal work capacity [W/kg]

M_0: resting metabolic rate [W/kg]

HR_{max}: maximum heart rate [bpm]

HR_0: heart rate at rest [bpm]

HR_{wm}: average heart rate during the observation period [bpm]

M: corresponding metabolic rate [W/kg]

(2) Heat production by shivering.

$$SHV = 60 \cdot \Delta T_{hc,hcset} \cdot \Delta T_{sk,skset} \cdot \left(\frac{4186}{3600}\right) \qquad (3-11)$$

Where

$\Delta T_{hc,hcset} \geq 0.0$ or $\Delta T_{sk,skset} \geq 0.0$

$\Delta T_{hc,hcset} \cdot \Delta T_{sk,skset} = 0$

T_{hc}: head core temperature [°C]

T_{hcset}: head core temperature setpoint 36.6 (reference value for Stolwijk model) [°C]

T_{sk}: average skin temperature [°C]

T_{skset}: mean skin temperature setpoint 34.1 (reference value for Stolwijk model) [°C]

(3) Heat loss by respiration

$$EVR = EVR_{st} \cdot Weight/Weight_{st} \quad (3-12)$$

where

EVR_{st}: heat loss by respiration in the Stolwijk model [W]

$Weight_{st}$: weight of the Stolwijk model (71.0) [kg]

(4) Heat exchange between blood flow and tissues

$$BF_i = bf_i \cdot c\rho_{bl} \cdot (T_i - T_{CB}) \quad (3-13)$$

where

bf_i: blood flow rate at part *i* [m^3/s]

$c\rho_{bl}$: specific heat of blood [$J/K/m^3$]

T_{CB}: temperature of CB [°C]

(5) Evaporative heat loss

$$SWE_i = \alpha'_{e,i} \cdot \left(X_{skin,i} - X_{e,i}\right) \cdot H \quad (3-14)$$

$$X_{skin,i} = \frac{\alpha'_{skin,i} \cdot X_{satskin,i} + \alpha'_{e,i} \cdot X_{e,i} + m_{sw}}{\alpha'_{skin,i} + \alpha'_{e,i}} \quad (3-15)$$

$$m_{sw} = \frac{EVI_i + SWT_i}{S \cdot Sr_i \cdot H} \quad (3-16)$$

$$EVI_i = Sr_i \cdot EVI_{st} \cdot \frac{S}{S_{st}} \quad (3-17)$$

$$SWT_i = Sr_i \cdot (68 \cdot \Delta T_{hc,hcset} \cdot \Delta T_{sk,skset} + 200 \cdot \Delta T_{hc,hcset} \cdot \Delta T_{ms,msset}) \cdot (4186/3600) \quad (3-18)$$

Where

SWE: evaporative heat loss [W]

α'_e: moisture conductance of skin–skin periphery [kg/m^2/s/(kg/kg')]

X_{skin}: absolute humidity of skin [kg/kg']

X_e: absolute humidity of the layer in contact with the skin surface [kg/kg']

H: phase change heat [J/kg]

α'_{skin}: skin moisture conductance [kg/m^2/s/(kg/kg')]

$X_{satskin}$: absolute humidity when the skin is saturated [kg/kg']

m_{sw}: sweat rate [kg/m^2/s], S_{st}: body surface area in the Stolwijk model [m^2]

T_{ms}: average muscle temperature [°C]

T_{msset}: mean muscle temperature setpoint 35.88 (reference value for Stolwijk model) [°C]

3.3 Cardiovascular Regulation Model

To predict changes in blood pressure and blood flow volume in humans during bathing, we developed a simplified blood circulation system based on the Windkessel model. Figure 3-2 shows the proposed CRM schematic. This model divides the cardiovascular system into the heart, body, and pulmonary circulatory systems. Furthermore, the body's circulatory system is divided into the head, upper limbs, trunk, and lower limbs. The heart is further divided into the left and right atria and ventricles. The circulatory systems, apart from the heart, have an artery and a vein. The CRM simplifies the human blood circulatory system into multiple electrical closed loops. This model is equivalent to an electric circuit. The blood pressure plays the role of the voltage; blood flow volume, the current; blood flow resistance, the resistance; and capacitance, the capacitor.

3.3.1 Basic formula

The volume change in each capacity system is expressed by Equation (3-19) using adjacent capacity systems' inflow and outflow volumes. Blood flow is determined by the pressure difference between the front and rear systems and the resistance between the circulating systems and is expressed by Equation (3-20). The relationship between the volume and pressure of each capacitive system is expressed by Equation (3-21).

$$\frac{dV}{dt} = Q_{in} - Q_{out} \tag{3-19}$$

$$Q = \frac{P_{in} - P_{out}}{R} \tag{3-20}$$

$$V = COMP * P \tag{3-21}$$

Where

V: volume [L]

Q: blood flow [L/s]

R: flow resistance [mm Hg·s/L]

COMP: compliance [L/mm Hg]

P: blood pressure [mm Hg]

subscript in: inflow side

subscript out: outflow side.

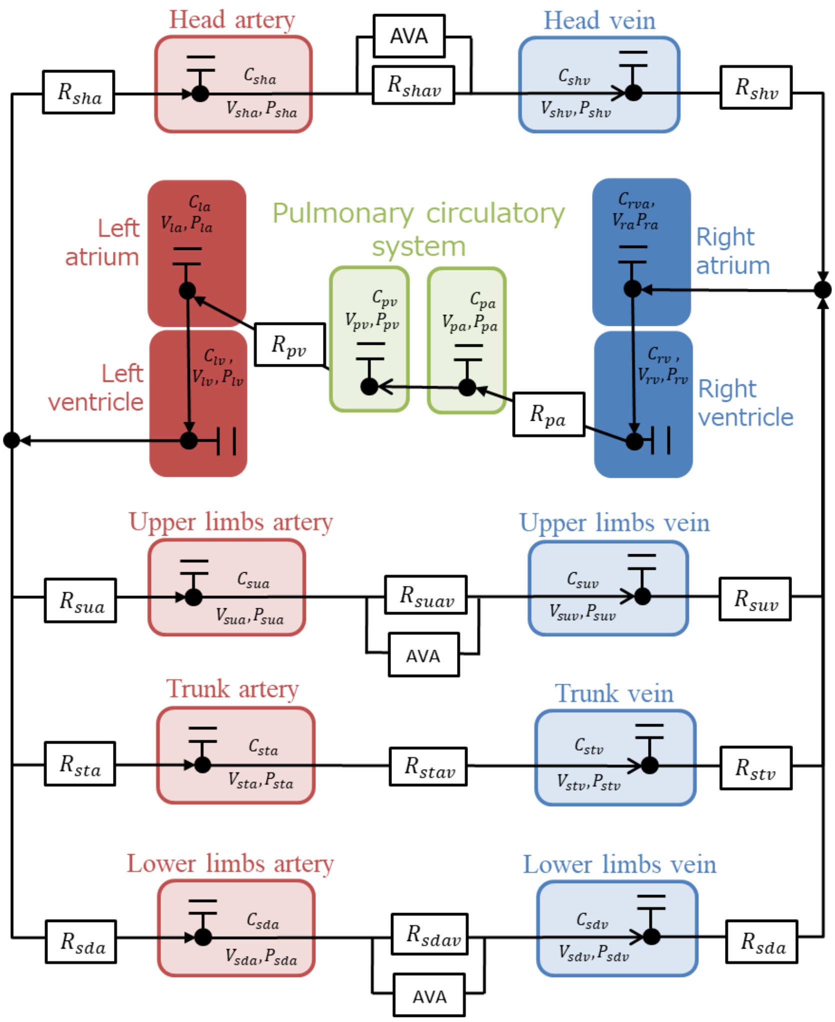


Figure 3-2 Cardiovascular Regulation Model

3.3.2 Arteriovenous anastomoses (AVAs)

AVAs are particular vascular structures of human thermoregulation that are especially suited to heat exchange. These vessels within the upper and lower limbs' skin layer [3-8,9] form a direct connection between small arteries and small veins and play an essential role in the human thermoregulatory system. As the ambient temperature rises, AVAs will open to provide a low-resistance connection between arteries and veins and accommodate high blood flow volume [3-10,11]. AVAs regulate heat transfer from the body's core to the skin by contracting or expanding depending on the body temperature. In our model, parallel blood flow through capillaries and AVAs is assumed.

The resistance in AVAs changes continuously depending on the body temperature calculated in the HTM. The degree of opening of AVAs in the upper and lower limbs is calculated using Equations (3-22,23), which is based on Takemori's AVA model [3-12]. The AVA resistance is expressed as Equation (3-24). The resistance between an artery and a vein in the upper and lower body vessels, R [3-13], is calculated as Equation (3-25)

$$O_{hand} = 0.148(T_{skin} - 34.0) + 0.532(T_{core} - 36.8) + 0.510 \qquad (3-22)$$

$$O_{foot} = 0.148(T_{skin} - 35.4) + 0.532(T_{core} - 37.0) + 0.510 \qquad (3-23)$$

If $O \geq 1$, *then* $O = 1$, *and* *if* $O \leq 0$, *then* $O = 0$.

$$R_{AVA} = \frac{R_{AVA,min}}{O^2} \qquad (3-24)$$

$$R = \frac{1}{\frac{1}{R_p} + \frac{1}{R_{AVA}}} \qquad (3-25)$$

Where

T_{skin}: mean skin temperature [°C]

T_{core} : core temperature [°C]

R_{AVA}: AVA resistance [mmHg・s/L]

$R_{AVA,\,min}$: minimum AVA resistance [mmHg・s/L]

R_p: capillary resistance

O: degree of opening of AVA [n. d.]

subscript AVA: AVA vessel

subscript p: capillary vessel

3.3.3 Change in Ventricular compliance considering heart rate

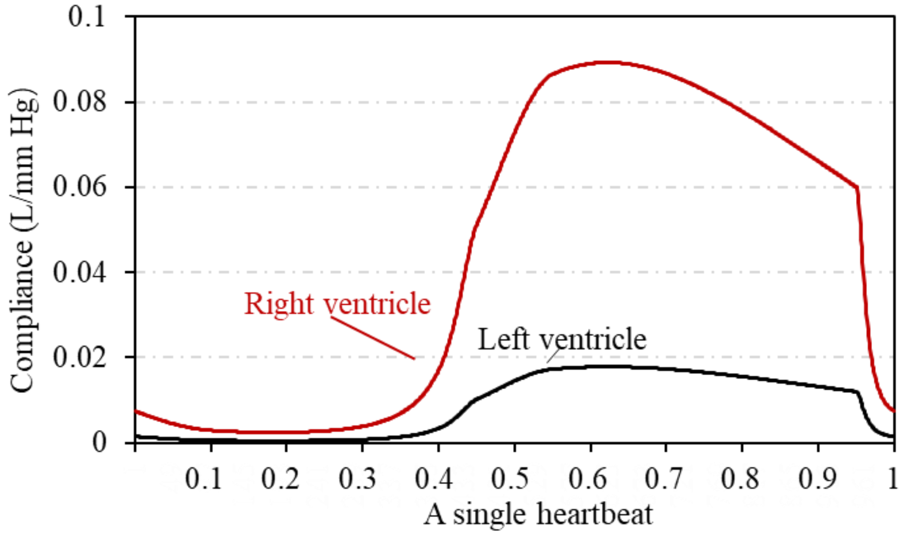


Figure 3-3 Cyclic change of ventricle compliance [3-14].

Compliance, expressing vessels' extensibility, is important in CRM because it affects the heart and vessels' volume and pressure. Heart compliance [3-14] in the specific circulatory systems is assumed to change to express physiological mechanisms in the proposed model.

The periodical change in compliance of the ventricle is considered in this chapter. The heart is the pump of the circulatory system, sending blood to the entire body by repeated contraction and expansion. The cyclic change in compliance of the left and right ventricles with each heartbeat is shown in Figure 3-3. We input the actual heart rate changes obtained from the experimental results into the model to accurately predict blood pressure and blood flow volume.[1]

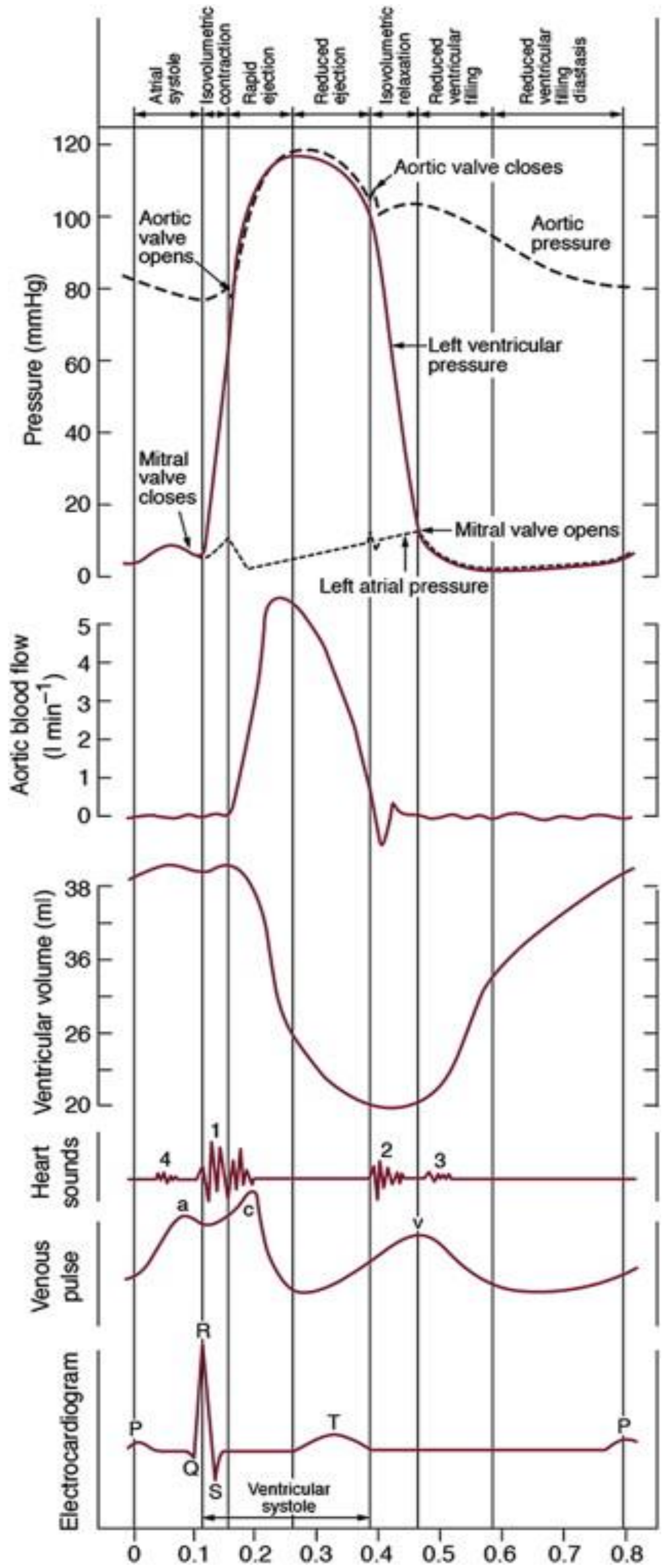


Figure 3-4 Blood pressure and volume during the cardiac cycle [3-15]

3.3.4 Venous compliance

Compliance of veins helps the veins return blood to the heart in the cardiovascular system. Due to particularly low vein pressure, the vein cannot return enough blood to the heart only by the pressure under the influence of gravity. However, the vein can change compliance by pressure (sympathetic constrictor fiber) to help the blood return [3-16]. We assume the veins compliances of the upper and lower limbs change depending on their pressure, as shown in Figure 3-5.

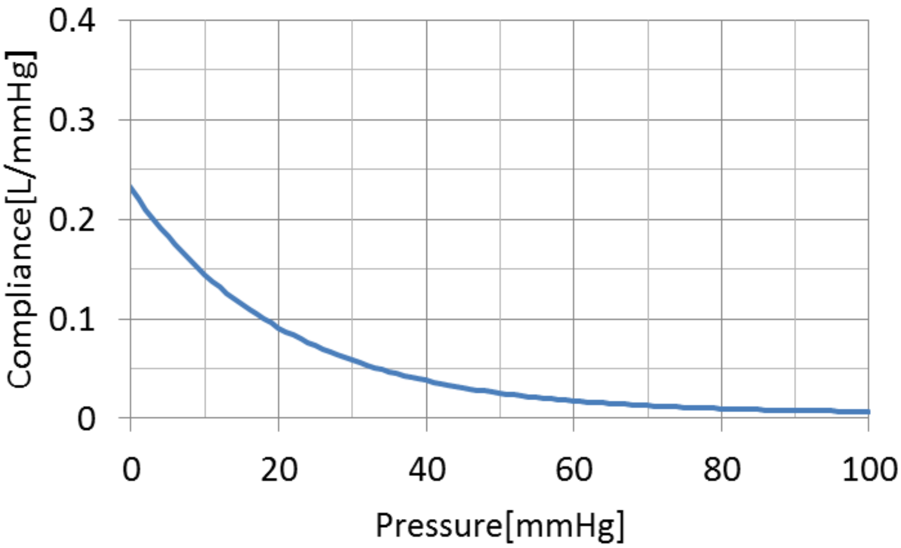


Figure 3-5 Compliance of veins of upper body and lower body.

In this chapter, Marcelo et al. were used to give comp alliances of upper and lower veins. The comp alliances of the upper and lower veins varied according to each venous pressure. Also, since venous compliance changes only in obliterating veins, the compliance of the head vein and vena cava does not change. Based on the curve fitting, the veins compliances of the upper and lower limbs can be expressed as Equations (3-28).

$$C = 0.28e^{-0.048(P+4.5)} + 0.005 \qquad (3-28)$$

3.4 Thermo-Cardiovascular Regulation Model

3.4.1 Brief overview of the model

In the HTM, heat loss is calculated by the blood flow between each segment and the central blood flow pool (CB). The blood flow with the temperature of the CB goes to each part, heat exchanges according to the temperature difference between each part, and the blood finished the heat exchange returns to the CB again. Furthermore, in the Stolwijk model, skin blood flow, muscle blood flow, and core blood flow are calculated (formula) using the core temperature, mean skin temperature, and their set points, and it is distributed to each part according to the skin surface area ratio and weight ratio. In this chapter, the blood flow of each part in the human thermoregulation model is calculated using the blood flow calculated by the CRM.

3.4.2 Relationship of blood flow between HTM and CRM

In the CRM, arteries and veins are provided for each part, and the upper and the lower parts have parallel blood vessels of capillary and arteriovenous anastomosis (AVAs) between arteries and arteries. As shown in Equation (3-20), the blood flow in accordance with the pressure difference between each circulatory system and the blood resistance is calculated. Figure 3-6 shows the relationship between each part and the blood flow in the HTM and CRM.

The blood flowing through the head of the systemic circulatory system in the CRM is applied to the head of the HTM, the blood flowing through the upper limbs of the CRM is applied to the hands and arms of the HTM, and the blood flowing through the lower limbs of the CRM is applied to the thigh, calf, and foot. Blood flow through the trunk of CRM is applied to the chest, back, abdomen, and loin of the HTM. The blood flow of each part is distributed according to each part's weight ratio of the HTM.

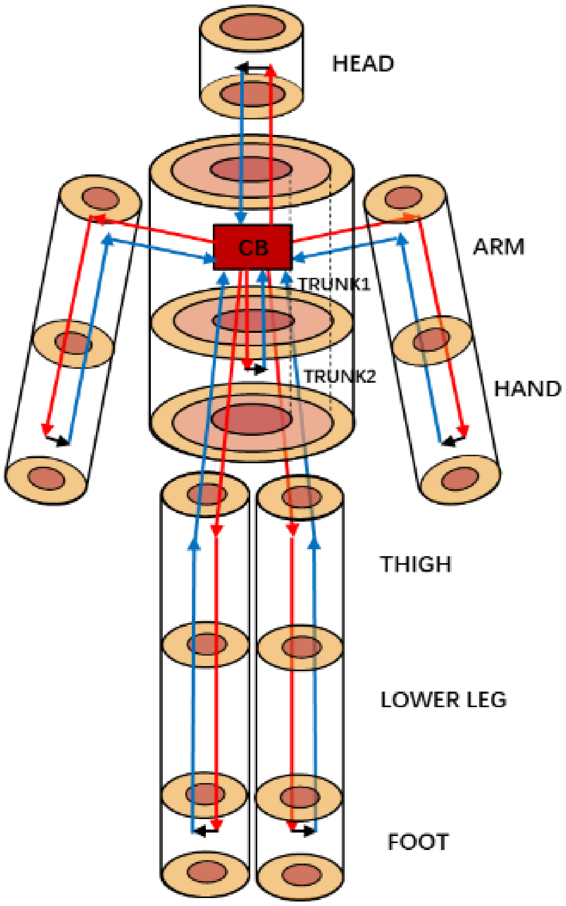


Figure 3-6 Relationship between segments and blood flow in both models.

The blood flow to the muscle layer and core layers are all involved in heat exchange. In the skin layer, the blood flow further diverges into blood flow through capillaries and blood flow through arteriovenous anastomoses (AVAs) near the skin surface. Arteriovenous anastomosis is a short-circuit route that does not pass through capillaries, and it flows near the surface of the skin and dissipates heat from the surface of the skin, regulating body temperature. Therefore, in this chapter, the blood flow that exchanges heat with the skin layer is assumed to be only the blood flow through the capillaries.

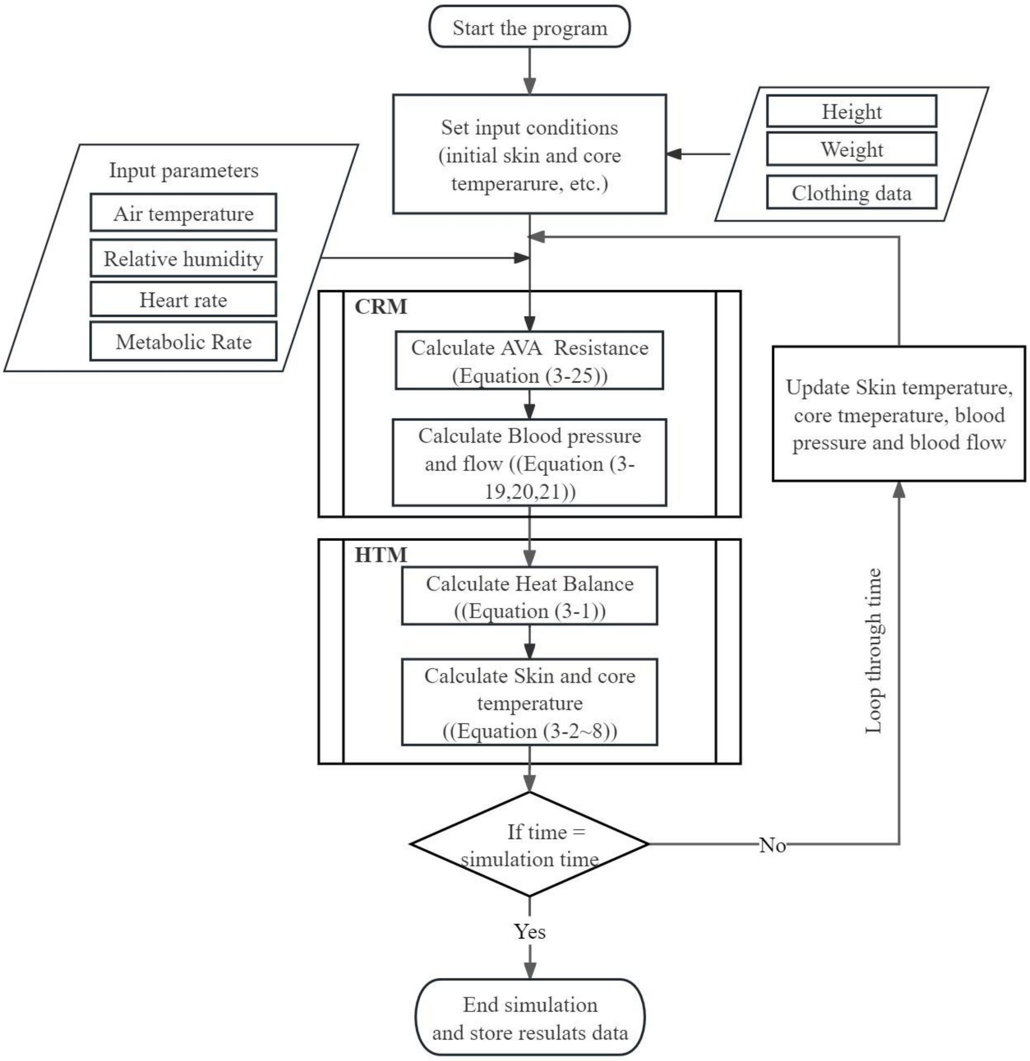


Figure 3-7 Thermo-cardiovascular regulation model Calculation Flowchart.

In this chapter, the input conditions of the thermo-cardiovascular regulation model are ambient temperature and relative humidity as environmental conditions and heart rate as a human response condition. The output conditions are skin and core temperatures, blood pressure, and blood flow volume. First, we calculated T_{skin} and T_{core} via the HTM and obtained the AVA resistance, Rava. Subsequently, the blood flow volume was calculated by inputting Rava into the CRM. Finally, the obtained blood flow volume was input into the HTM. The proposed thermo-cardiovascular regulation model provides the predicted skin and core temperatures, blood pressure, and blood flow volume results, as shown in Figure 3-7.

3.5 Conclusion

To predict the human physiological response including blood pressure and blood flow volume during bathing more accurately and the bathing risks, we developed a thermo-cardiovascular regulation model that combines the thermoregulation regulation model and the cardiovascular regulation model.

1) **Human thermoregulation model (HTM)**

   Considering the non-uniform bathing thermal environment divides body into 37 segments. Proposed a human thermoregulation model considering the human thermal physiological mechanism and metabolic rate changes to predict the skin temperature and core temperature under a transient and non-uniform thermal bathing environment.

2) **Cardiovascular Regulation Model (CRM)**

   Increase number of divisions in systemic circulatory system to better adapt the HTM. Proposed a cardiovascular regulation model considering the blood circulation mechanism of the cardiovascular system and heart rate changes to predict the blood pressure and blood flow under the bathing thermal environment.

3) **Thermo-Cardiovascular Regulation Model**

   Considering the corresponding segmented parts of the body in HTM and CRM. We proposed a thermo-cardiovascular regulation model that merged a human thermoregulation model (HTM) and a cardiovascular regulation model (CRM), to predict the human physiological response in a transient and non-uniform bathing environment considering blood flow volume and the thermal environment. The correspondence between the blood flow in the HTM and CRM is consistent blood flow.

Chapter 3 References

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Chapter 4 Analysis of Thermo-Cardiovascular Regulation Model Prediction Results*

4.1 Introduction

In this chapter, as a starting point for proposing a thermo-cardiovascular regulation model, that can be used during bathing, we examine the applicability of the thermo-cardiovascular regulation model in the bathing condition. Specifically, we describe the transient and non-uniform bathing thermal environments by inputting the changes in temperature and humility in the thermo-cardiovascular regulation model and reproduce the experimental results of physiological responses considering skin temperature, core temperature, blood pressure, and blood flow volume during bathing. In addition, sensitivity analysis is performed for each parameter of the model, and the effect on the calculation results is discussed.

4.2 Analysis conditions and prediction results of the optimized model

4.2.1 Analysis conditions and determination of each parameter

To validate the proposed human thermo-cardiovascular regulation model, we simulated the bathing process under the same conditions as those used in the experiment. The compliance of the atrium during each heartbeat is illustrated in Figure 3-3. The parameters refer to those used in the model coupling the Stolwijk and Windkessel models, as proposed by Masugi et al. [4-1], which has been validated to predict postural blood pressure changes during bathing.

Table 4-1 shows a comparison of the Stolwijk model [4-6] and the physique of the participant in the experiment in Chapter 3, and Table 4-2 shows the correspondence between segments of the model and measurement points. The subject's body surface area was calculated using the Equation (4-1) of Kurasumi et al. [4-7]) based on height and weight.

*The content of this chapter has been expanded by the author based on a portion of the author's papers [6-1] submitted to Building and Environment.

$$\text{Body surface area } [m^2] = 100.315 \cdot (Weight[kg]^{0.383} \cdot height[cm]^{0.693} \cdot 10^{-4}) \quad (4-1)$$

Table 4-1 Comparison of Stolwijk model and subject's body size

	Stolwijk model	Participant	Ratio
Height [cm]	—	172	
Weight [kg]	71.0	69.28	0.98
Body surface area [m^2]	1.83	1.80	0.98

Table 4-2 Correspondence between segments of the model and measurement points

Segments of model	Segments No.	Measuring points
Mean temperature of trunk segments	5,8,11,14	Rectal
Upper forehead skin layer	2	Forehead
Upper hand skin layer	22	Back of hand
Upper forearm skin layer	18	Forearm
Upper trunk 1 skin layer	7	Chest
Lower trunk 1 skin layer	10	Back
Upper trunk 2 skin layer	13	Abdomen
Lower trunk 2 skin layer	16	Waist
Upper thigh skin layer	26	Front of thigh
Lower thigh skin layer	28	Back of thigh
Upper leg skin layer	30	Front of calf
Lower leg skin layer	32	Back of calf
Upper foot skin layer	34	Foot

The conditions (clothing, bathing, undressing) are shown in Table 4-3, and the thermal conductance between the skin and surrounding environment for each experiment (clothing and undressing) is shown in Tables 4-4 and 4-5. Various constants related to clothing are shown in Table 4-6, thermal conductance between each layer is shown in Table 4-7, the body surface area ratio of each part is shown in Table 4-8, and the mass ratio of each part is shown in Table 4-9. We assumed that the effect of the age difference is small and that the parameters shown in Tables 4-10 and 4-11, as proposed by Masugi et al., can be applied to the 50-year-old participant in this chapter. The ventricle compliance parameters (Table 4-10) are adapted in accordance with the heart rate changes of our participant, and the individual height, weight, and basal metabolic rate values of our participant were used. The compliance values and resistance values in each system of the thermo-cardiovascular regulation model are shown in Tables 4-10 and 4-11.

Table 4-3 Surrounding environment for each measuring point

Measuring points	Preparation room	Dressing room	Bathing room
Forehead	Air	Air	Air
Back of hand	Air	Air	Air
Forearm	Inside clothes	Air	Air
Chest	Inside clothes	Air	Air
Back	Inside clothes	Air	Air
Abdomen	Inside clothes	Air	Air
Waist	Inside clothes	Air	Air
Front of thigh	Inside clothes	Inside clothes	Air
Back of thigh	Inside clothes	Inside clothes	Air
Front of calf	Air	Air	Air
Back of calf	Air	Air	Air
Foot	Air	Air	Air

Table 4-4 Thermal conductance between the skin and environment (clothing)

	Surrounding environment	Conductance [W/m²/K]	
		Siting	Standing
Forehead	Skin - Air	9.0	9.0
Back of hand	Skin - Air	15.0	15.0
Forearm	Skin - Cloth - Air	7.1	7.1
Chest	Skin - Cloth - Air	9.3	9.3
Back	Skin - Cloth - Air	9.0	9.0
Abdomen	Skin - Cloth - Air	9.0	9.0
Waist	Skin - Cloth - Air	9.0	9.0
Front of thigh	Skin - Cloth - Air	8.1	8.1
Back of thigh	Skin - Cloth - Air	8.1	8.1
Front of calf	Skin - Air	7.1	7.1
Back of calf	Skin - Air	7.1	7.1
Foot	Skin - Air	6.0	6.0

Table 4-5 Thermal conductance between the skin and environment (undressing)

	Surrounding environment	Conductance [W/m²/K]	
		Siting	Standing
Forehead	Skin - Air	9.0	9.0
Back of hand	Skin - Air	15.0	15.0
Forearm	Skin - Air	7.1	7.1
Chest	Skin - Air	9.3	9.3
Back	Skin - Air	9.0	9.0
Abdomen	Skin - Water	150.0	9.0
Waist	Skin - Water	150.0	9.0
Front of thigh	Skin - Water	150.0	8.1
Back of thigh	Skin - Water	150.0	8.1
Front of calf	Skin - Water	150.0	7.1
Back of calf	Skin - Water	150.0	7.1
Foot	Skin - Water	150.0	6.0

Table 4-6 Constants related to clothing

Constants	Unit	Value
Thermal conductivity of clothing	W/m/K	0.20
Thickness	m	0.0004

Table 4-7 Thermal conductance between each layer [W/K]

Segment	Layer	Stolwijk model	Participant
Head	Core - Skin	3.06	3.00
Trunk	Core – Muscle	5.64	5.52
	Muscle - Skin	26.74	26.20
Upper and lower limbs	Core - Skin	20.58	20.17

*The participant's thermal conductance was calculated based on the body surface ratio of the Stolwijk model.

Table 4-8 Body surface area ratio of each segment

Segment		Stolwijk model	Ration used in this model
Head	Front	0.09	0.045
	Back		0.045
Trunk 1	Front	0.37	0.0925
	Back		0.0925
Trunk 2	Front		0.0925
	Back		0.0925
Hand	Front	0.54	0.0215
	Back		0.0215
Arm	Front		0.0755
	Back		0.0755
Thigh	Front		0.057
	Back		0.057
Calf	Front		0.085
	Back		0.085
Foot	Front		0.031
	Back		0.031
Total		1	1

Table 4-9 Weight ratio of each segment

				Stolwijk model	Ration used in this model
Head		Core	Front	0.067	0.0335
			Back		0.0335
		Skin	Front	0.005	0.0025
			Back		0.0025
Trunk		Core	Chest	0.341	0.08525
			Back		0.08525
			Abdomen		0.08525
			Waist		0.08525
		Muscle	Chest	0.165	0.04125
			Back		0.04125
			Abdomen		0.04125
			Waist		0.04125
		Skin	Chest	0.019	0.00475
			Back		0.00475
			Abdomen		0.00475
			Waist		0.00475
Extremities	Hand	Core	Front	0.356	0.00345
			Back		0.00345
	Arm		Front		0.00425
			Back		0.00425
	Thigh		Front		0.0645
			Back		0.0645
	Calf		Front		0.1006
			Back		0.1006
	Foot		Front		0.0052
			Back		0.0052
	Hand	Skin	Front	0.028	0.00025
			Back		0.00025
	Arm		Front		0.00335
			Back		0.00335
	Thigh		Front		0.0041
			Back		0.0041
	Calf		Front		0.0059
			Back		0.0059
	Foot		Front		0.0004
			Back		0.0004
Central blood flow				0.019	0.019
Total				1	1

In addition, the bathing environment is a non-uniform thermal environment. Half of the participant's body is immersed in hot bathwater. The heat transfer coefficient between the skin and air differs from that between the skin and hot water. The heat transfer coefficient between the body and the air is based on the Stolwijk model, using the combined coefficient (radiant transfer and convective heat transfer). The heat transfer coefficient between hot water and skin is calculated by considering natural convection.

The measured results of the thermal environment around the participant were used as the boundary conditions. In addition, the proposed model's variable factors, metabolic rate, and heart rate were considered, as explained in chapter 3.

Table 4-10 Compliance values: a proposed model

Circulatory system	Segments		Compliance [L/mm Hg]
Body circulatory system	Head	Artery	0.0004
		Vein	2.0
	Upper limbs	Artery	0.0004
		Vein	※1
	Trunk	Artery	0.0005
		Vein	0.02
	Lower limbs	Artery	0.0005
		Vein	※1
Pulmonary circulatory system	Artery		0.001
	Vein		0.01
Heart	Ventricle	Left ventricle	※2
		Right ventricle	※2
	Atrium	Left atrium	0.001
		Right atrium	0.0275

※1: Compliance changes according to pressure [4-2] (chapter 3)

※2: Compliance changes per heartbeat [4-3,4] (chapter 3)

Table 4-11 Resistance values of each system

Front system	Rear system	Resistance [mm Hg·s/L]
Left ventricle	Head artery	15.0
	Upper limbs artery	20.0
	Trunk artery	15.0
	Lower limbs artery	15.0
Head artery	head vein	1875.0
Upper artery	Upper limbs vein	※
Trunk artery	Trunk vein	2.5
Lower artery	Lower limbs vein	※
Head vein	Right atrium	7.5
Upper vein		7.5
Trunk vein		5.0
Lower vein		5.0
Right atrium	Right ventricle	37.5
Right ventricle	Pulmonary artery	37.5
Pulmonary artery	Pulmonary vein	625.0
Pulmonary veins	Left atrium	7.5
Left atrium	Left ventricle	37.5

※: Synthetic resistance due to constant changes in capillary and AVA resistance according to body temperature [4-5]

4.2.2 Prediction results of the optimized model

4.2.2.1 Skin temperature and core temperature

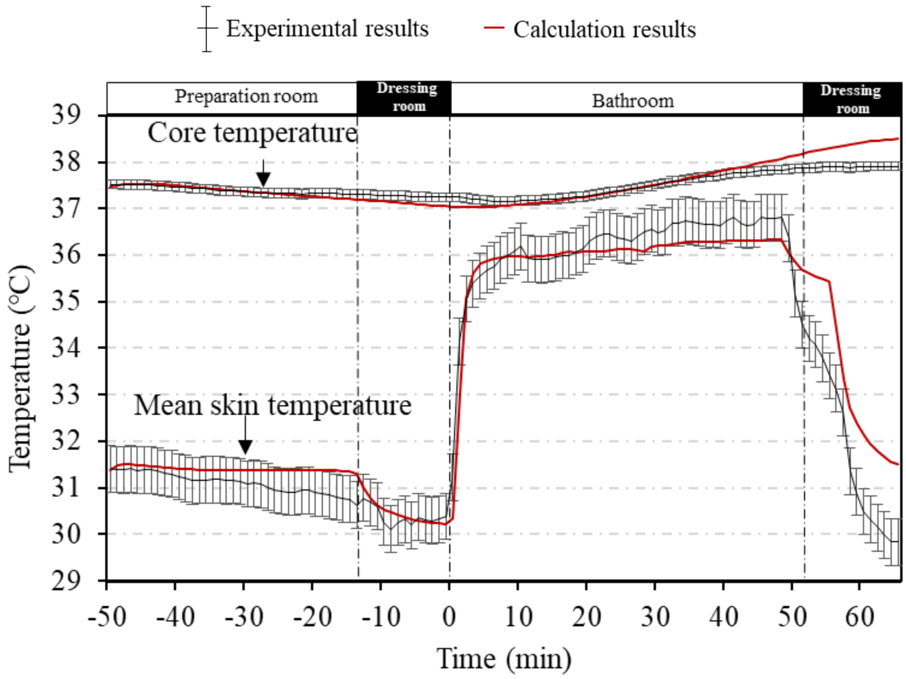


Figure 4-1 Experimental and calculation results of mean skin and core temperature.

Figure 4-1 shows the compared results of T_{skin}, T_{core}, and blood pressure between the experiment and calculation. During bathing in the bathroom, the calculation results show that the T_{skin} increased from 30.5 to 36.4 °C (T_{skin} experimental results: 30.4 to 36.9 °C). As shown in Figure 10 (a), the calculation results are consistent with the experimental results. The calculation results of T_{core} increased from 37.0 to 38.1 °C (T_{core} experimental results: 37.2 to 38.0 °C) during bathing; although the calculation results at the end of bathing are slightly larger than the experimental results, the overall change trend is the same. Hence, the T_{skin} and T_{core} calculated by the proposed model have good agreement with the experimental results.

4.2.2.2 Blood pressure

As shown in Figure 4-2, the proposed model also predicts blood pressure well. The calculation results show that diastolic blood pressure was lower than 60 mmHg from t = 38 min, which was close to the bathing risk (hypotension) and consistent with experimental results. Thus, the comparison results demonstrate the effectiveness of the proposed thermo-cardiovascular regulation model.

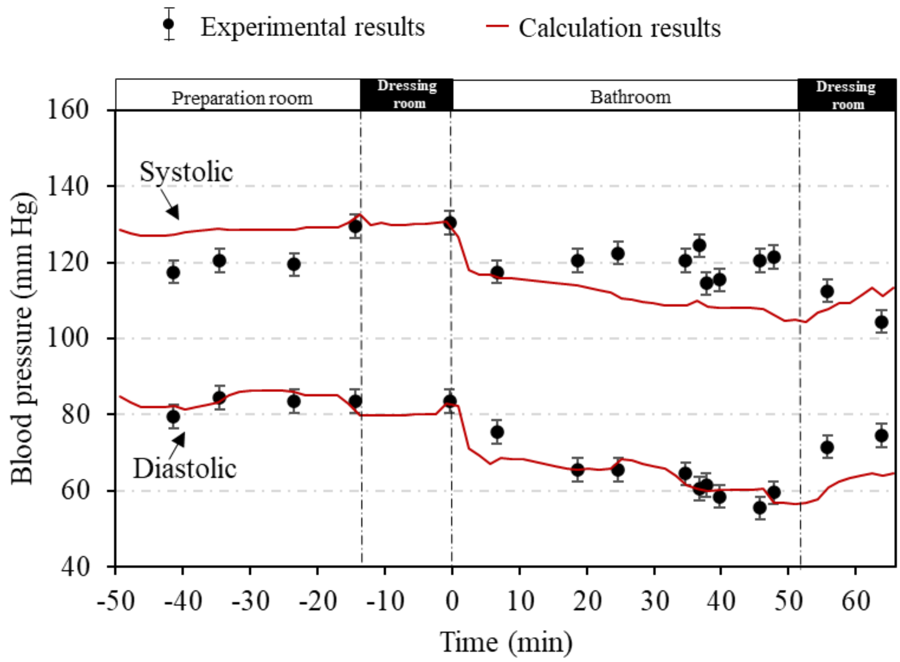
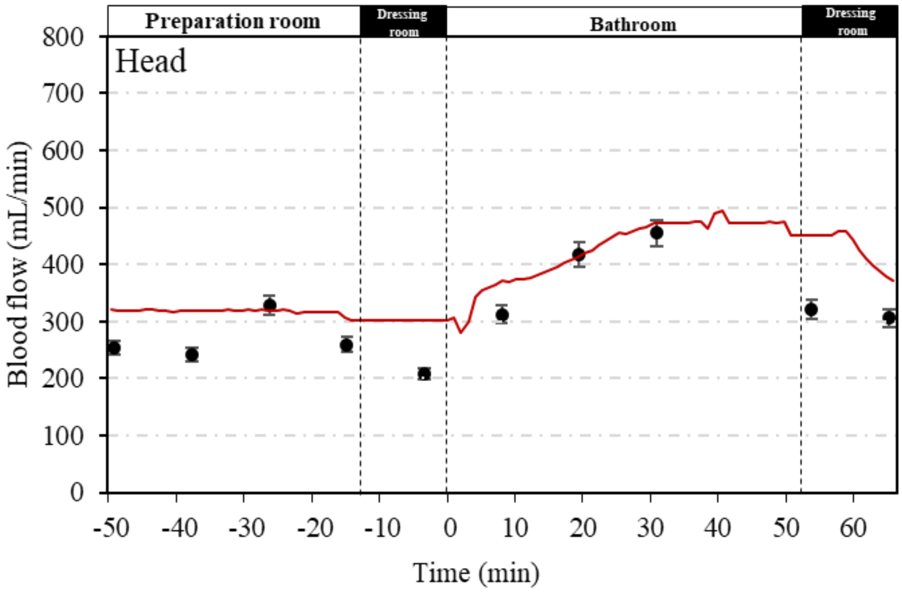


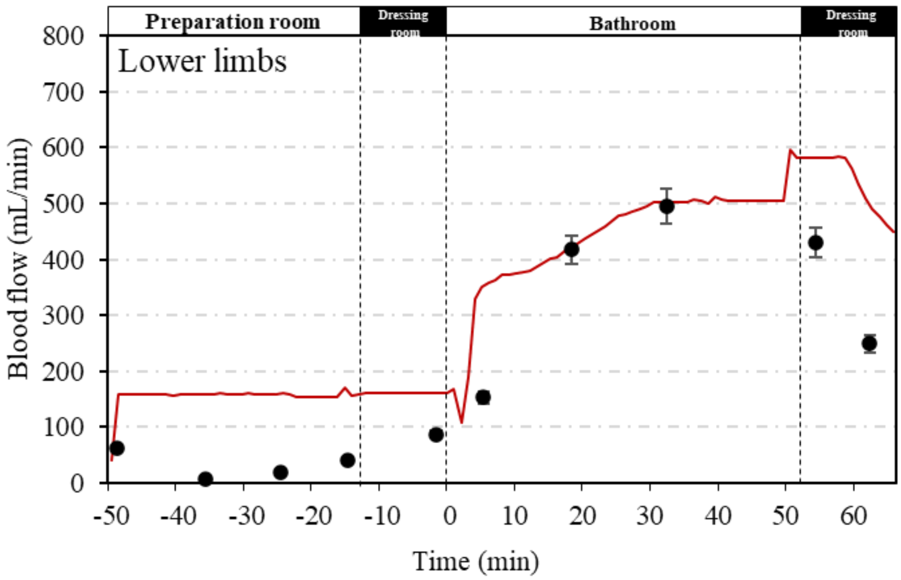
Figure 4-2 Experimental and calculation results of blood pressure

4.2.2.3 Blood flow

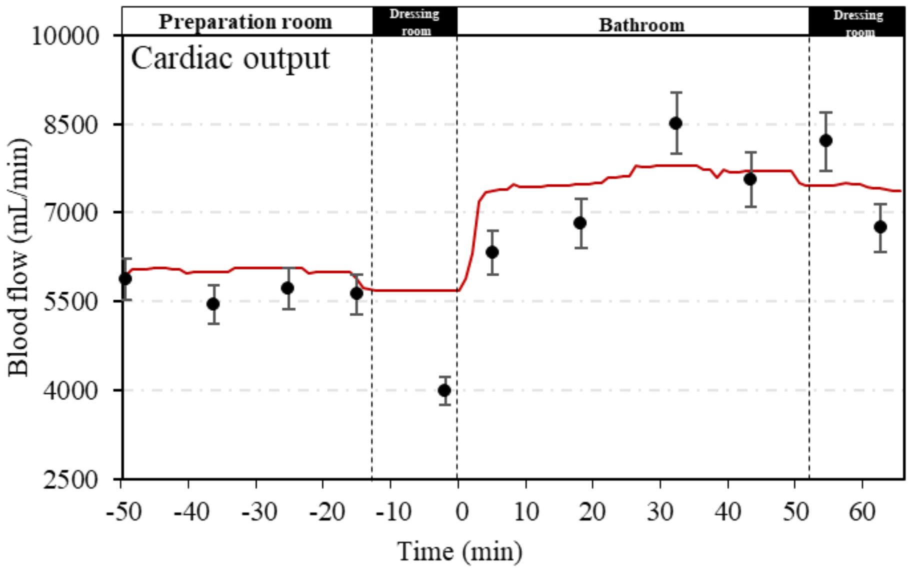
Figure 4-3 shows the experimental and calculation results of the blood flow volume (head, lower limbs, and cardiac output). Similar to the experimental results, the calculation results of the blood flow volume of each part in the preparation room were stable. During bathing, the blood flow volume of the head, lower limbs, and cardiac output increased approximately by 1.69, 4.66, and 1.22 times, respectively. Although the calculation results of the blood flow volume have some differences from the experimental results, the proposed thermo-cardiovascular regulation model can predict the blood flow volume during bathing well. In particular, when the participant was experiencing changes in the thermal environment in the bathtub, the calculated blood flow volume of each part showed good agreement with the changing trend.



(a) Blood flow volume: head



(b) Blood flow volume: lower limbs



(c) Blood flow volume: cardiac output

Figure 4-3 Comparison of results of blood flow between experimental and calculation

4.3 Sensitivity analysis

Based on the analysis in Section 3, the metabolic rate which has an important influence on the HTM, and the metabolic rate change which is related to the heart rate should be considered. In addition, compliance which expresses the extensibility of vessels is an important parameter in the CRM, the compliance change should be considered to express physiological mechanisms in the proposed model.

To improve the prediction accuracy of the proposed model for human physiological response, including blood pressure and blood flow volume during bathing, we improved the HTM and CRM by adjusting the parameter values related to metabolic rate and compliance. To clarify the impact of the parameters, we conducted comparative studies of the parameters with variable and constant values.

4.3.1 Consider changes in metabolic rate

First, the influence of metabolic rate changes on human physiological response was analyzed. The original model only adopts a constant metabolic rate. The proposed model considers the changes in metabolic rate in accordance with the heart rate; the remaining parameters of the two models are the same as mentioned in chapter 3.

Figure 4-4 shows the comparison results of the mean skin temperature, and core temperature under variable and constant metabolic rate conditions. It shows the changes in metabolic rate had only a slight influence on mean skin temperature. However, compared with the experimental results and calculations under variable metabolic rate conditions, the core temperature was markedly lower under constant metabolic rate condition, especially during and after bathing.

Figure 4-5 shows the comparison results of the blood pressure under variable and constant metabolic rate conditions. Before bathing, in the preparation and dressing rooms, the calculated blood pressure showed a minimal difference between variable and constant metabolic rate conditions. However, during and after bathing, the blood pressure, especially diastolic blood pressure under constant metabolic rate condition becomes much higher than that under variable metabolic rate condition, which cannot predict hypotension well. The inaccurate prediction of systolic blood pressure should be improved in the future.

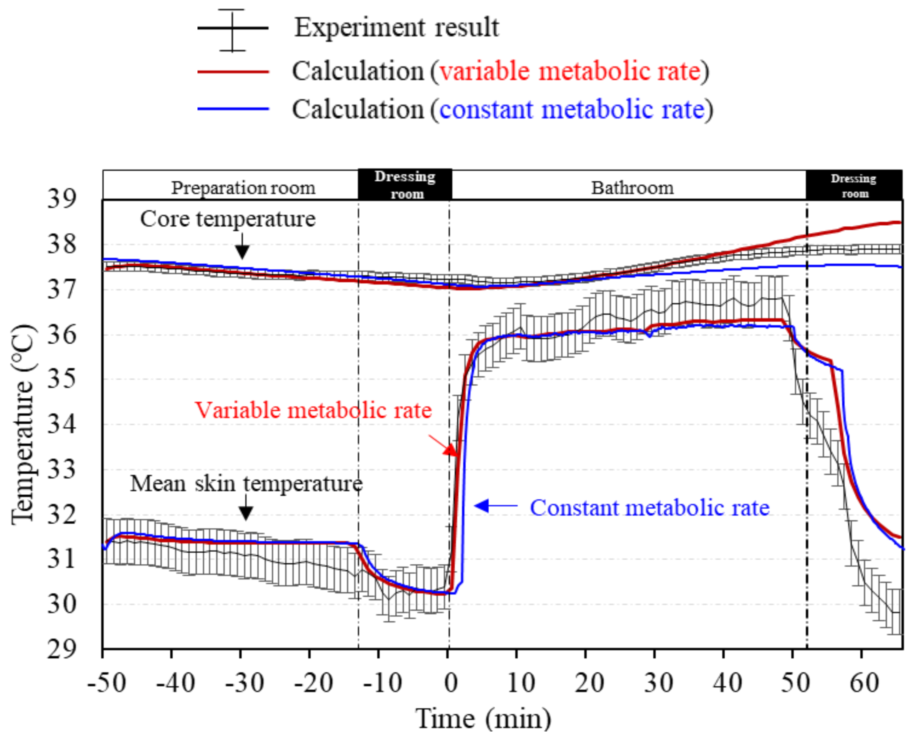


Figure 4-4 Comparison results of the mean skin temperature and core temperature

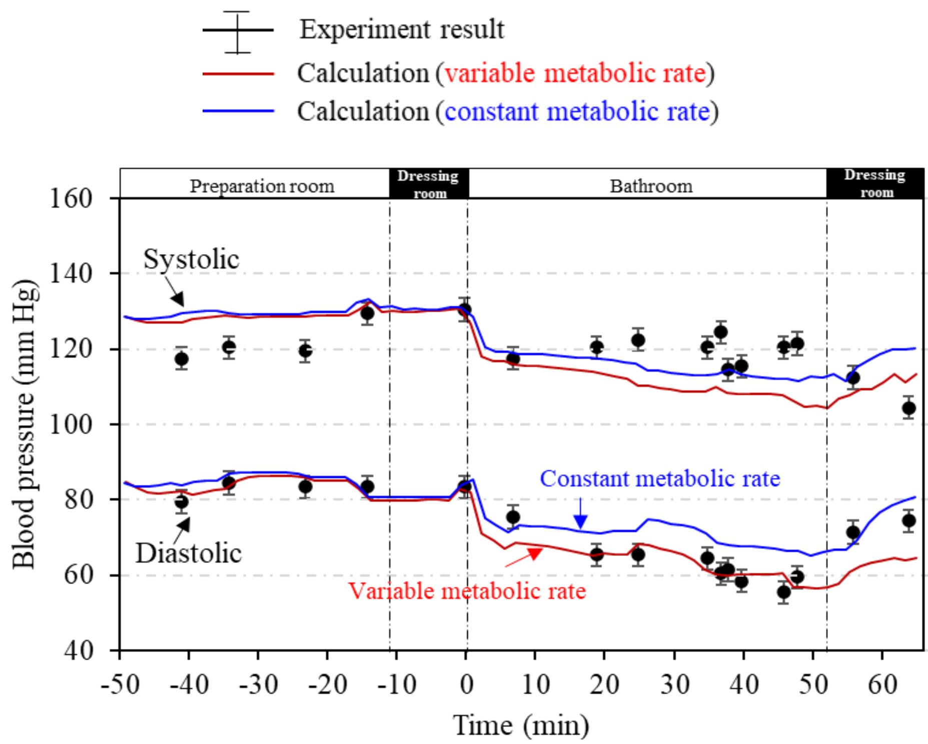
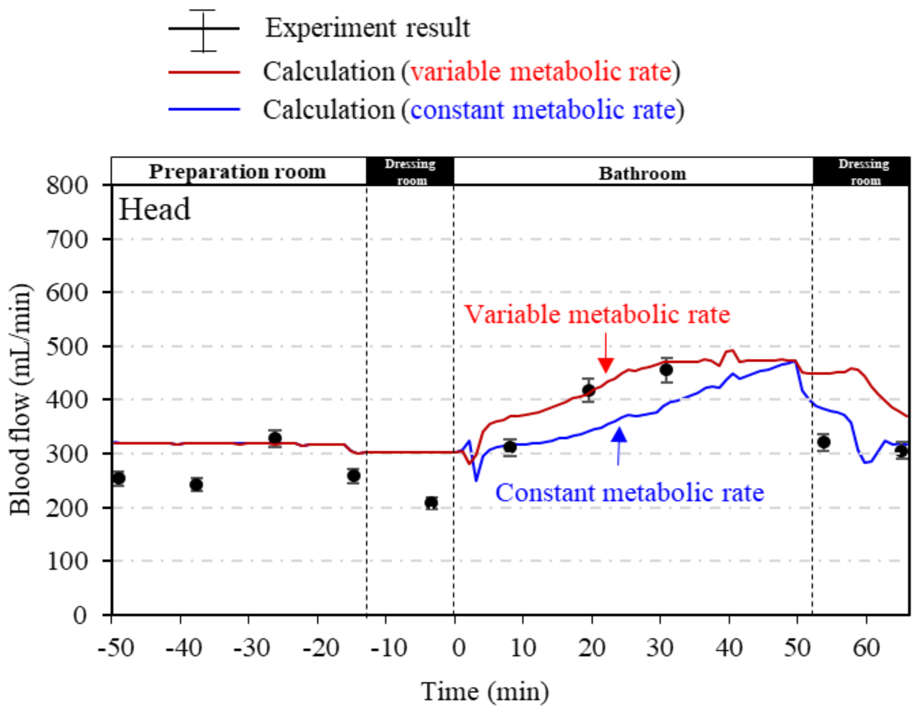
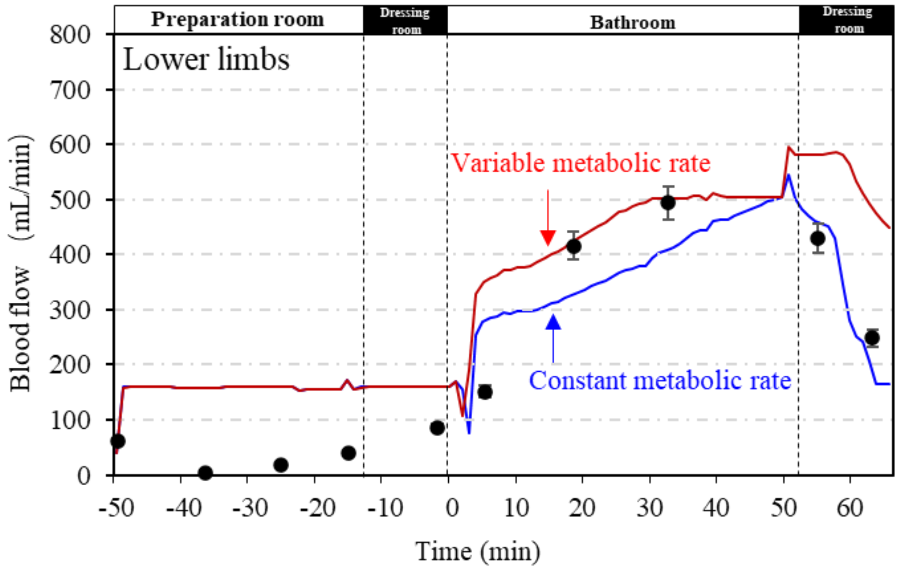


Figure 4-5 Comparison results of the blood pressure

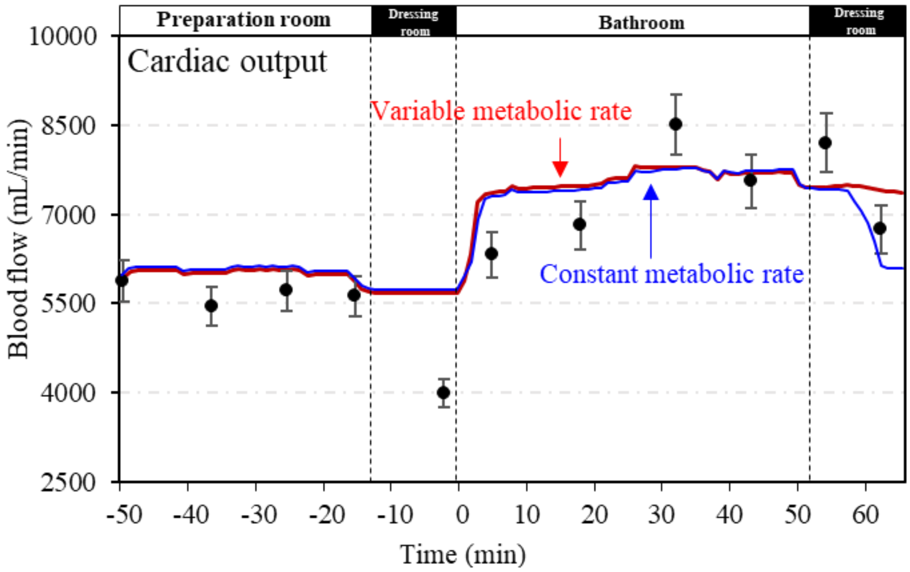
Figures 4-6 compare the blood flow of the head, lower limbs, and cardiac output under variable (measured heart rate) and constant heart rate conditions. Under constant heart rate condition, the blood flow volume in the participant's head increased by 179 mL/min during bathing; however, under variable heart rate condition, it increased by 213 mL/min—a result that is much closer to the experimental results. Given that the lower limbs are immersed in hot bathwater, the blood flow volume in the lower limbs is mainly influenced by the water temperature. The heart rate changes had minimal effect on the blood flow volume in the lower limbs. Under constant heart rate condition, the cardiac output increased by 1403 mL/min during bathing; under variable heart rate condition, it increased by 2133 mL/min—much closer to the experimental result of 2188.2 mL/min.



(a) Blood flow volume: head



(b) Blood flow volume: lower limbs



(c) Blood flow volume: cardiac output

Figure 4-6 Comparison results: blood flow volume

Hence, the proposed model considering the metabolic rate change has good accuracy in predicting the core temperature, blood pressure, and blood flow, especially during bathing.

4.3.2 Consider changes in heart rate

Heart rate and ventricle compliance are important factors that influence blood flow volume. In the original model, frequency change in ventricle compliance was set at an assumed heart rate of 60 bpm. However, the experimental results showed that the thermal environment significantly influenced the heart rate, especially during bathing. Therefore, the proposed model considered the actual heart rate changes, while the remaining parameters of the two models were the same, as shown in chapter 3.

Figure 4-7 shows the comparison results of mean skin and core temperatures under variable (actual heart rate) and constant heart rate conditions. The results between the two models showed minimal difference before bathing in the preparation and dressing rooms. During bathing, both the mean skin temperature and the core temperature under variable heart rate condition were higher than the corresponding values under constant heart rate condition. The calculated results of core temperature under constant heart rate condition showed a larger difference than that under variable heart rate condition, particularly from t = 20 min (20 min after immersion in the bathwater), when the participant's heart rate increased rapidly as shown in Figure 4-7.

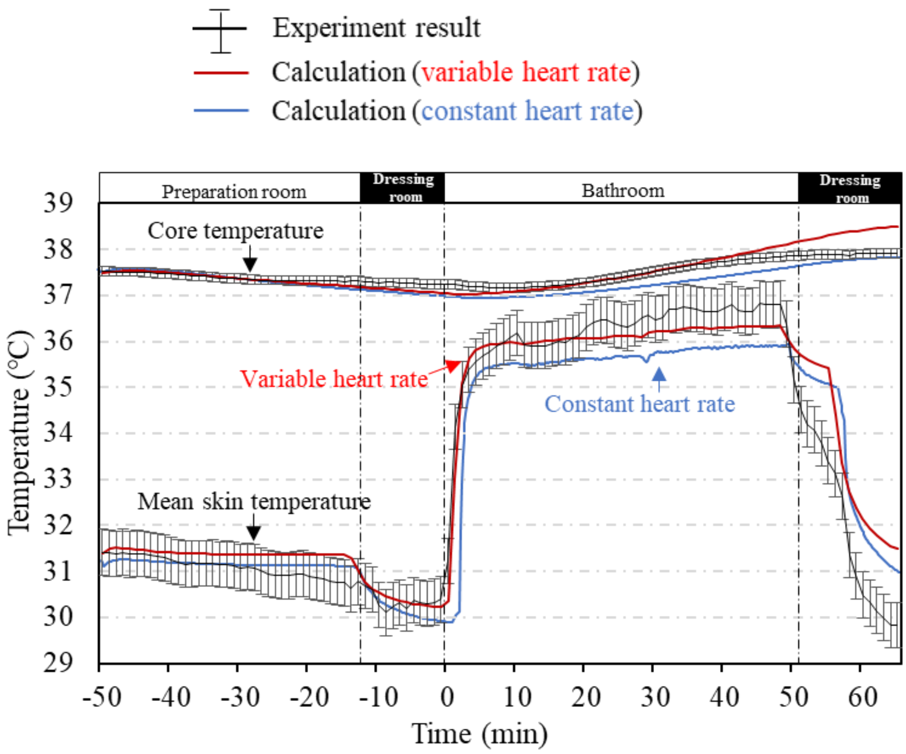


Figure 4-7 Comparison results: mean skin temperature, core temperature

Figure 4-8 shows the comparison results of blood pressure under variable and constant heart rate conditions. The systolic blood pressure under a constant heart rate condition was higher than the corresponding values under a variable heart rate condition. However, the diastolic blood pressure under a constant heart rate condition was notably lower than that under a variable heart rate condition. Especially the hypotension (diastolic blood pressure below 60 mm Hg), under constant heart rate condition, the original model showed hypotension 20 min after bathing. Conversely, under variable heart rate condition, the proposed model shows hypotension after 38 min of bathing, which agrees well with the experimental results.

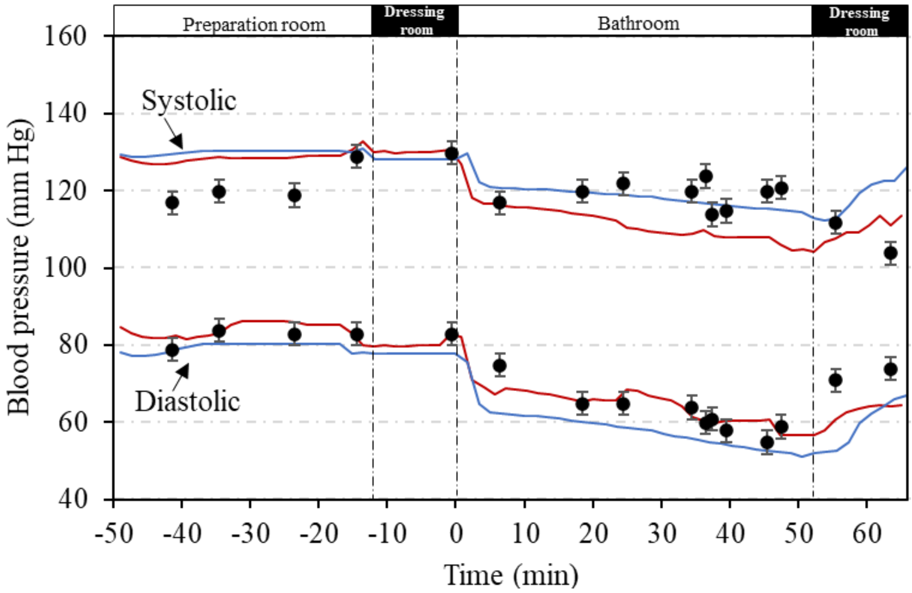
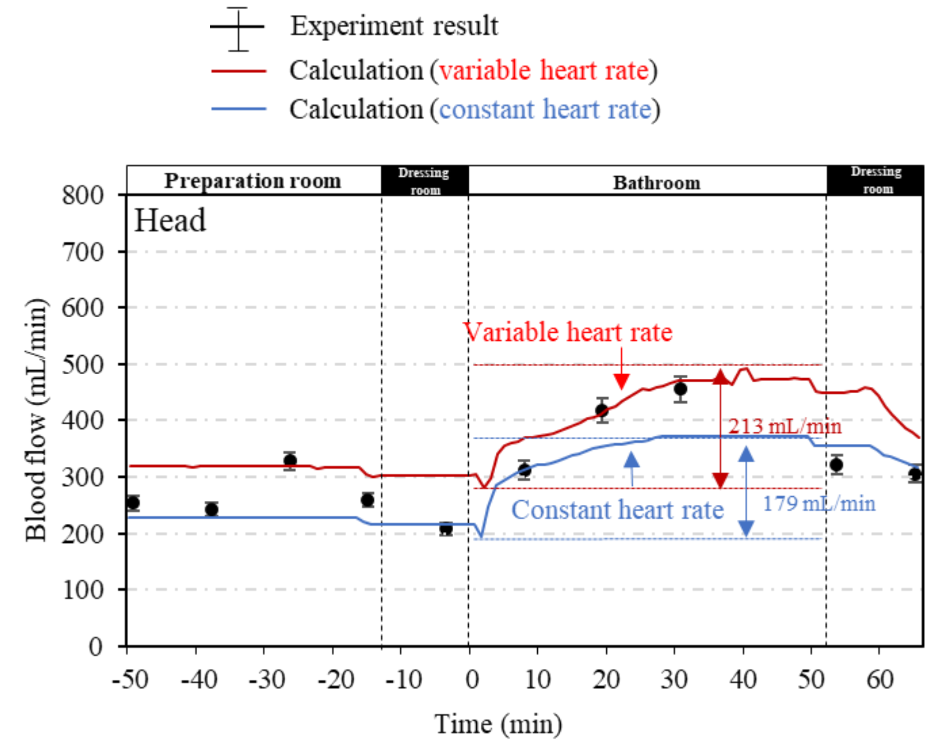


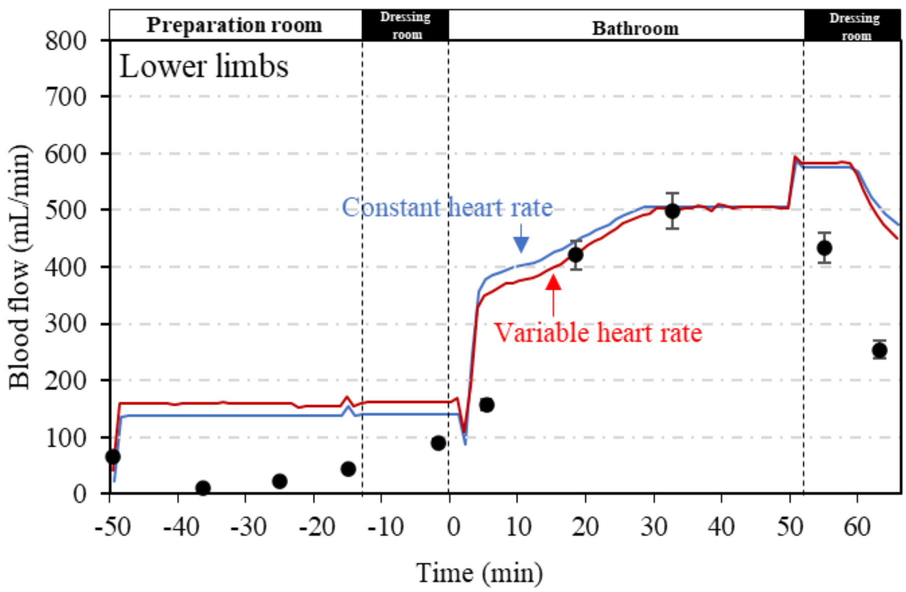
Figure 4-8 Comparison results: blood pressure

Figures 4-9 compare the blood flow of the head, lower limbs, and cardiac output under variable (measured heart rate) and constant heart rate conditions. Under constant heart rate condition, the blood flow volume in the participant's head increased by 179 mL/min during bathing; however, under variable heart rate condition, it increased by 213 mL/min—a result that is much closer to the experimental results. Given that the lower limbs are immersed in hot bathwater, the blood flow volume in the lower limbs is mainly influenced by the water temperature.

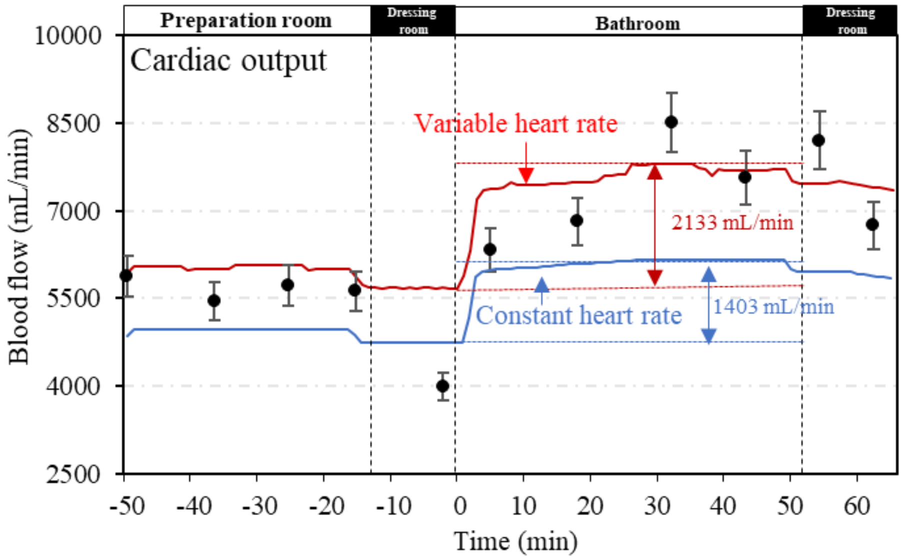
The heart rate changes had minimal effect on the blood flow volume in the lower limbs. Under constant heart rate condition, the cardiac output increased by 1403 mL/min during bathing; under variable heart rate condition, it increased by 2133 mL/min—much closer to the experimental result of 2188.2 mL/min.



(a) Blood flow volume: head



(b) Blood flow volume: lower limbs



(c) Blood flow volume: cardiac output

Figure 4-9 Comparison results: blood flow volume

The results demonstrate that the heart rate changes significantly impact the mean skin temperature, core temperature, blood pressure, and blood flow. The proposed model can better predict the human physiological response during bathing by considering the actual changing heart rate.

It should be noted that, after bathing, a series of actions, such as water wiping and contact with the floor, takes place. These factors are difficult to be considered in the model, which leads to a certain difference in the prediction results after bathing. However, this period has minimal effect on the bathing risks and is not the focus of this paper. In further research, we will improve the accuracy of blood flow volume prediction after bathing.

4.4 Conclusion

In this chapter, sensitivity analysis is performed for the changes in metabolic rate and heart rate of the model, and the effect on the calculation results is discussed. The main conclusions are summarized as follows:

1) **Proposed thermo-cardiovascular regulation model**

   The results of the experiment and calculation demonstrate that the proposed thermo-cardiovascular regulation model can predict the physiological response during bathing well, including the mean skin temperature, core temperature, blood pressure, and blood flow.

2) **Sensitivity analysis considering metabolic rate and heart rate**

   The changes in metabolic rate and heart rate significantly affect the physiological response, especially blood pressure and blood flow volume, during bathing. The consideration of the changes in metabolic rate and heart rate improved the prediction accuracy of the thermo-cardiovascular regulation model.

Chapter 4 Reference

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Chapter 5 Bathing Experimental Study on 25-, 52-, and 71-years-old Participants*

5.1 Introduction

In this chapter, 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. 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 (i.e., the upper body was exposed to air, whereas the lower body was immersed in hot bathwater).

5.2 The purpose of the bathing experiment at different ages

To study and compare the physiological responses considering the blood circulation system of different ages participants (young, middle, and old) in the bathing thermal environment. Physiological parameters and attempts were made to explain the changes in each physiological parameter by considering the differences in human physiological conditions of participants of different ages.

5.3 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 a 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

*The content of this chapter has been expanded by the author based on a portion of the author's papers [6-2] submitted to Building and Environment.

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 Figure 5-5. Figure 5-1 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 ℃). The hot bathwater temperature was set at 40.5 ℃; 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 ℃), and the lower body (waist, abdomen, and lower limbs) was immersed in bathwater (39.6–40.8℃), with a temperature difference of about 17 ℃ (Figure 5-2).

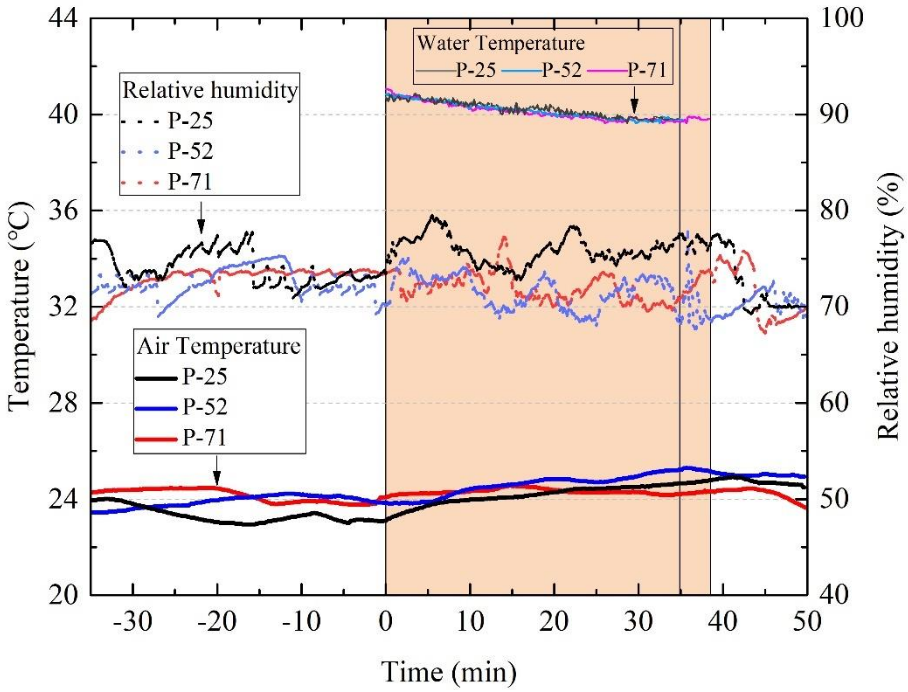


Figure 5-1 Experiment results of humidity, air, and bathwater temperature

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 (Figure 5-1). However, the humidity varied a lot between them. Additionally, in some instances, the RH of 25 years old (P-25) was 10% higher than that for 52 years old (P-52). Specifically, the RHs of P-25, P-52, and 71 years old (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 RHs of all participants were not markedly different.

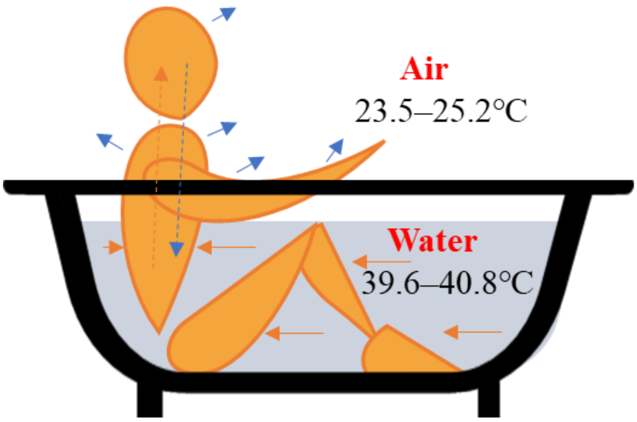


Figure 5-2 Schematic of experiment

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

5.3.1 Experiment protocol

This chapter 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.

5.3.2 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 5-1 shows the detailed data of the three participants.

Table 5-1 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

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 to report any discomfort during the experiment to prevent injury.

5.3.3 Measurements

Figure 5-2 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 5-2 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 the ASHRAE scale 55 [5-1] on a 7-point scale, hot (+3), warm (+2), slightly warm (+1), neutral (0), slightly cool (–1), cool (–2), and cold (–3).

Table 5-2 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.

Table 5-2 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

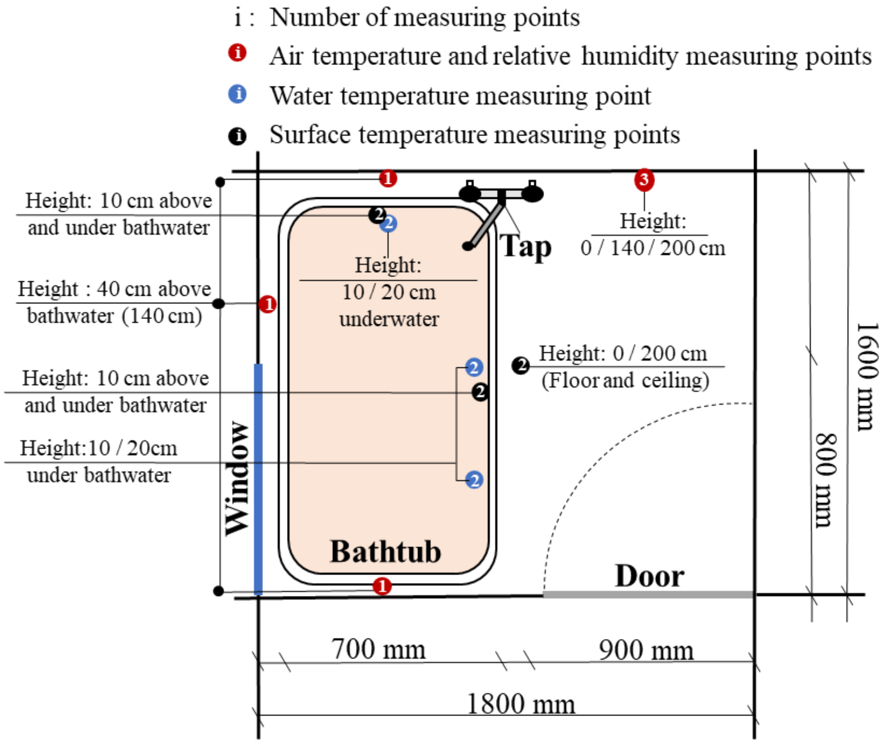


Figure 5-3 Measuring points of the environmental parameters

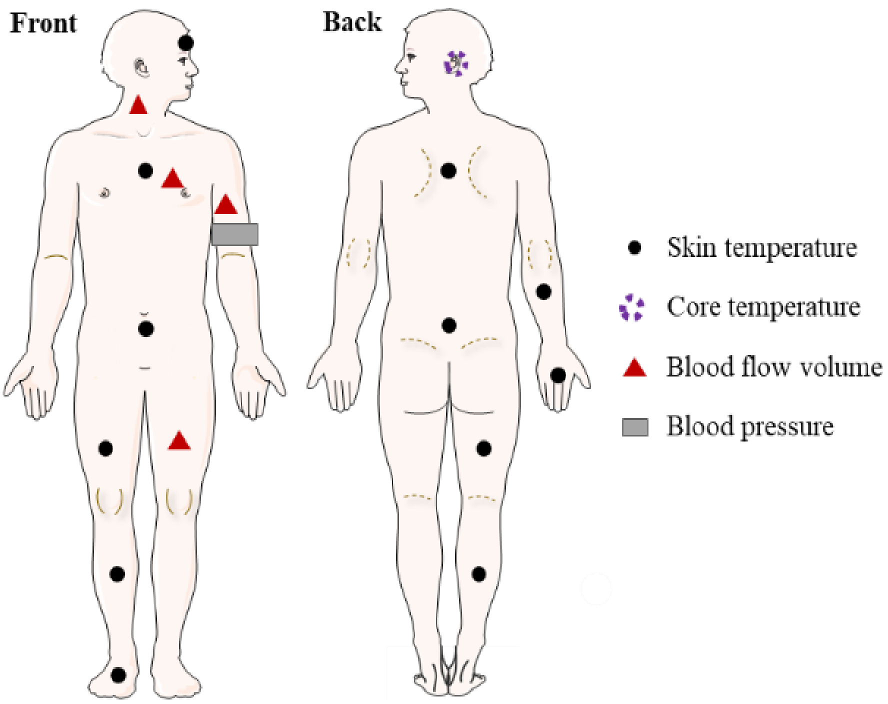


Figure 5-4 Measuring points of the thermal physiological response parameters

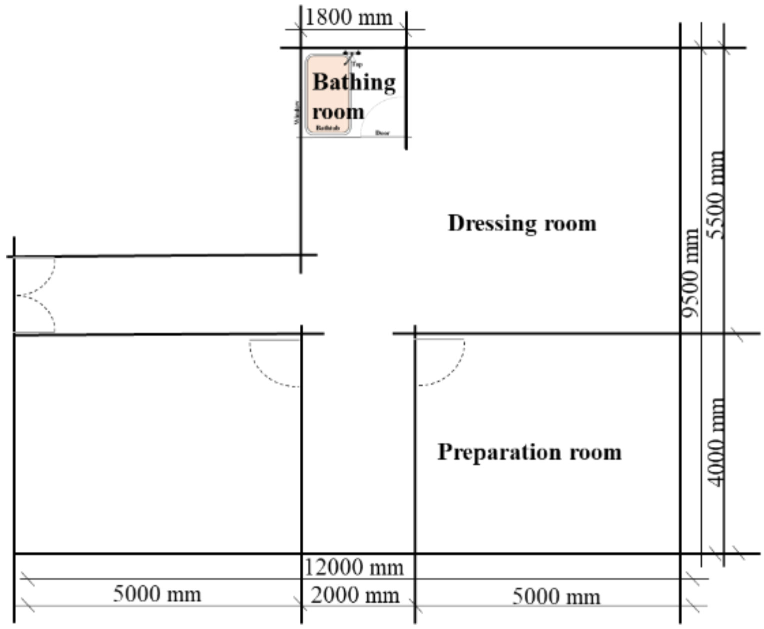


Figure 5-5 Layout of the experiment rooms

Table 5-3 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%

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.

5.4 Results

5.4.1 Thermal sensation

Figure 5-6 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.

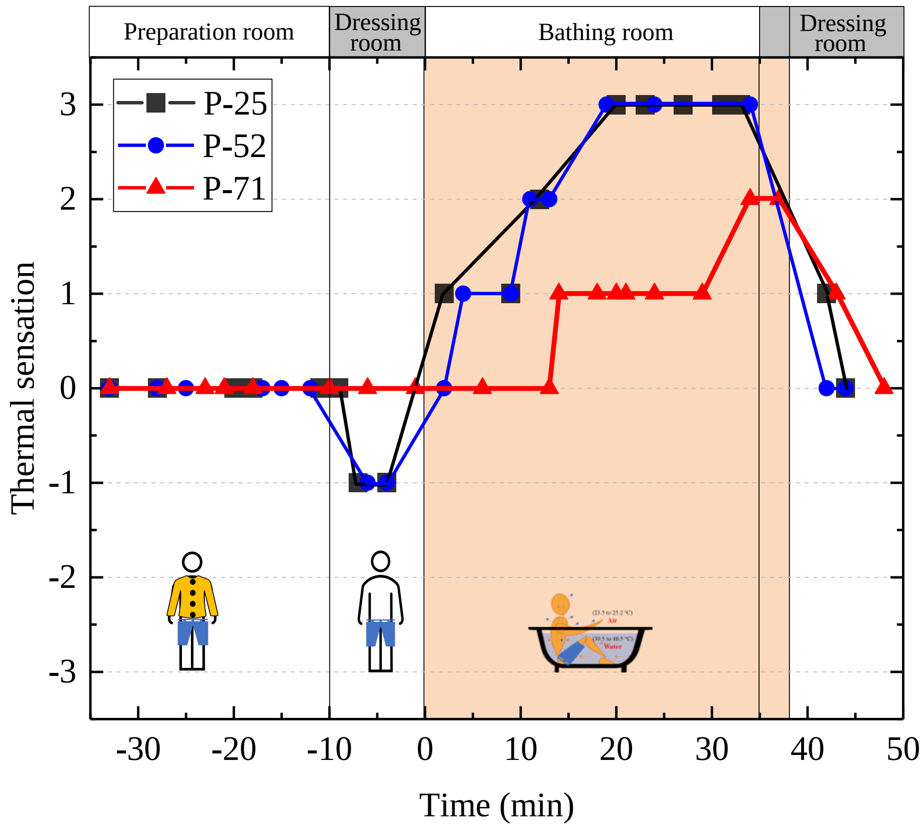


Figure 5-6 Thermal sensation experiment results of the P-25, P-52, and P-71

5.4.2 Mean skin temperature

Figure 5-8 shows the experimental results of the mean skin temperatures. The mean skin temperatures (T_{mean}) were affected by the ambient temperatures (Figure 5-1). 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, Figure 5-7 shows the mean skin temperature changes in the air and water parts during the whole experimental process. Figure 5-7 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. Figure 5-8 shows that the T_{mean} 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.

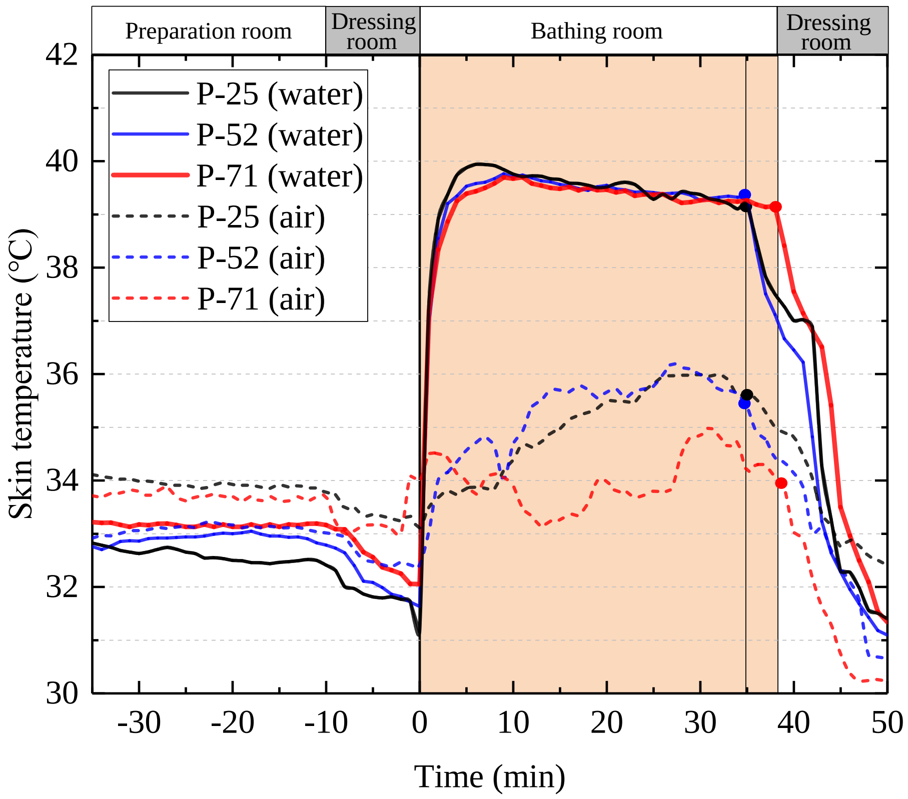


Figure 5-7 Experimental results of T_{mean} of the skin parts in the bathwater and air environment.

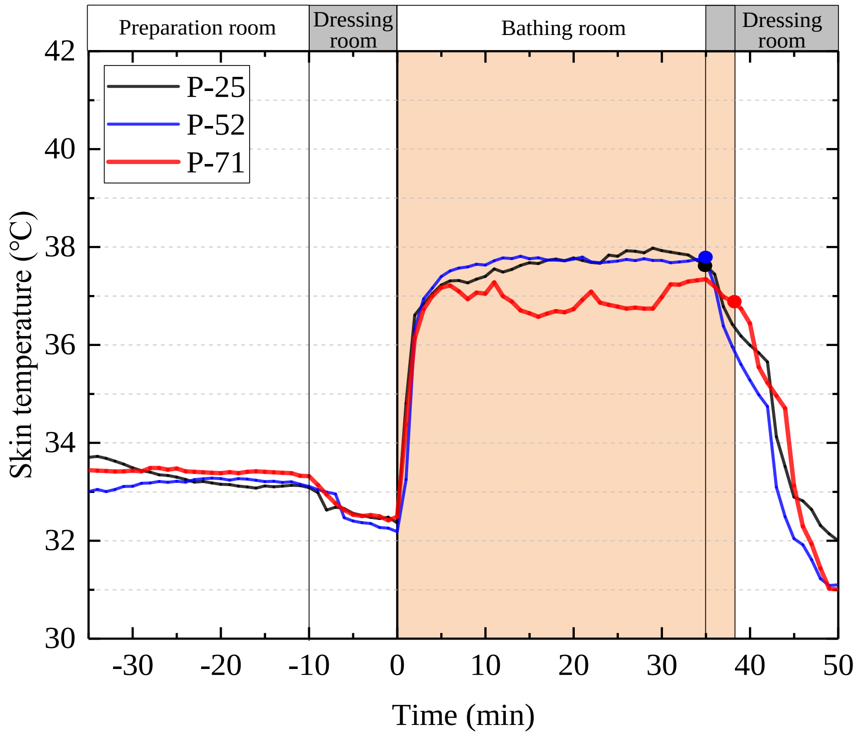


Figure 5-8 Experimental results of T_{mean} of the whole-body surface.

5.4.3 Core temperature

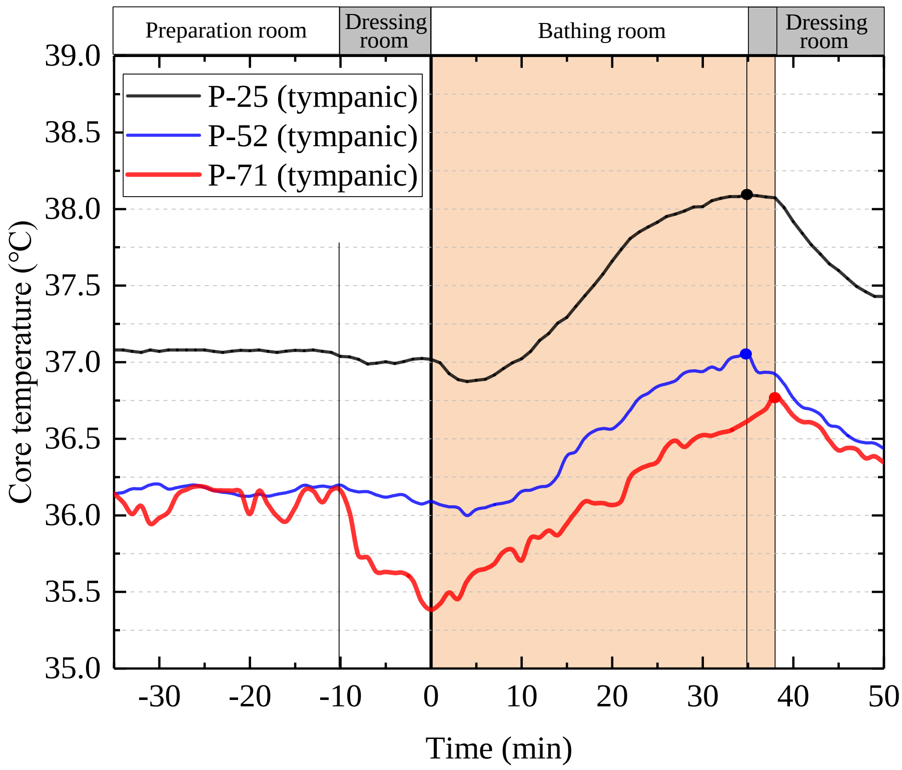


Figure 5-9 Experimental results of core temperature (tympanic).

Figure 5-9 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) ℃, 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) ℃ in the first 35 min, respectively.

5.4.4 Blood pressure and pulse pressure

Figure 5-10 shows the experimental results of BP. Most healthy adults have regular blood pressure when their systolic and diastolic pressures are less than 120 and 80, respectively. Therefore, systolic and diastolic pressures of 120 and 80 mmHg or higher, respectively, are considered as being characteristic of high blood pressure [5-2]. Low BP, or hypotension, is BP below 90/60 mmHg in healthy adults [5-3]. 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.

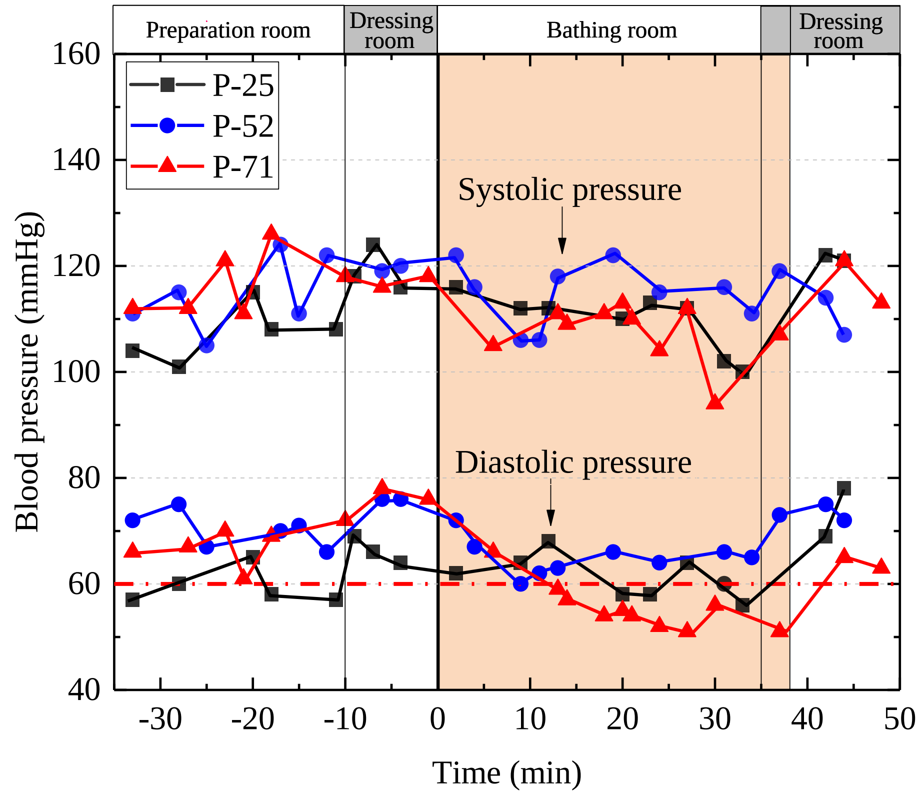


Figure 5-10 Experimental results of blood pressure

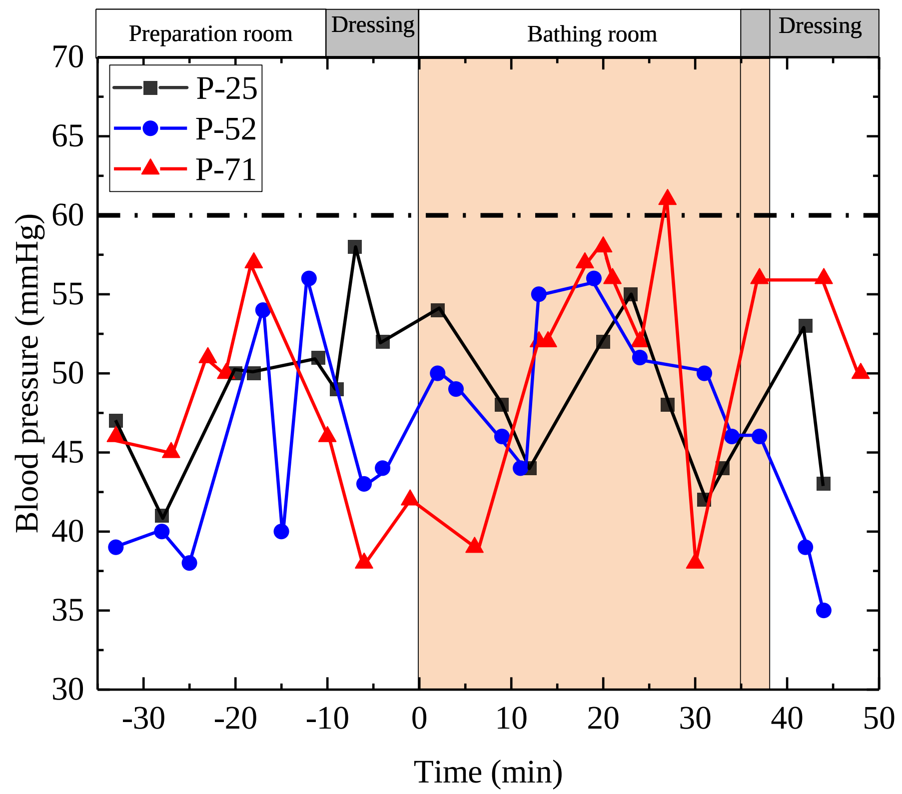


Figure 5-11 Experimental results of pulse pressure

Figure 5-11 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 [5-4]. In Figure 5-11, 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.

5.4.5 Heart rate

Figure 5-12 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.

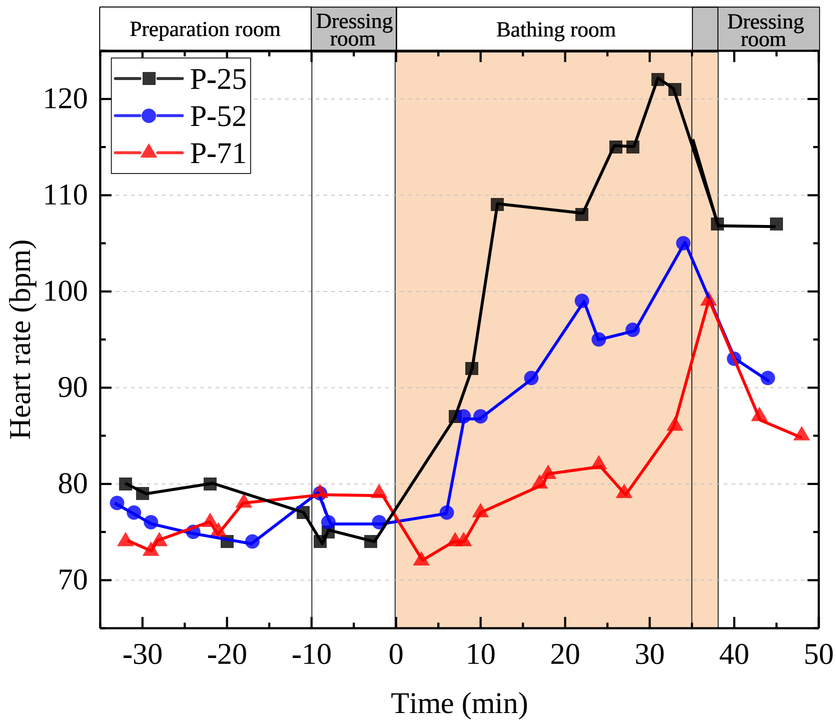


Figure 5-12 Experiment results of heart rate

The TS level of P-71 was 0 or 1 from 0 to 28 min but increased to 2 from 34 to 37 min (Figure 5-6). 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).

5.4.6 Blood flow

5.4.6.1 Stroke volume and cardiac output

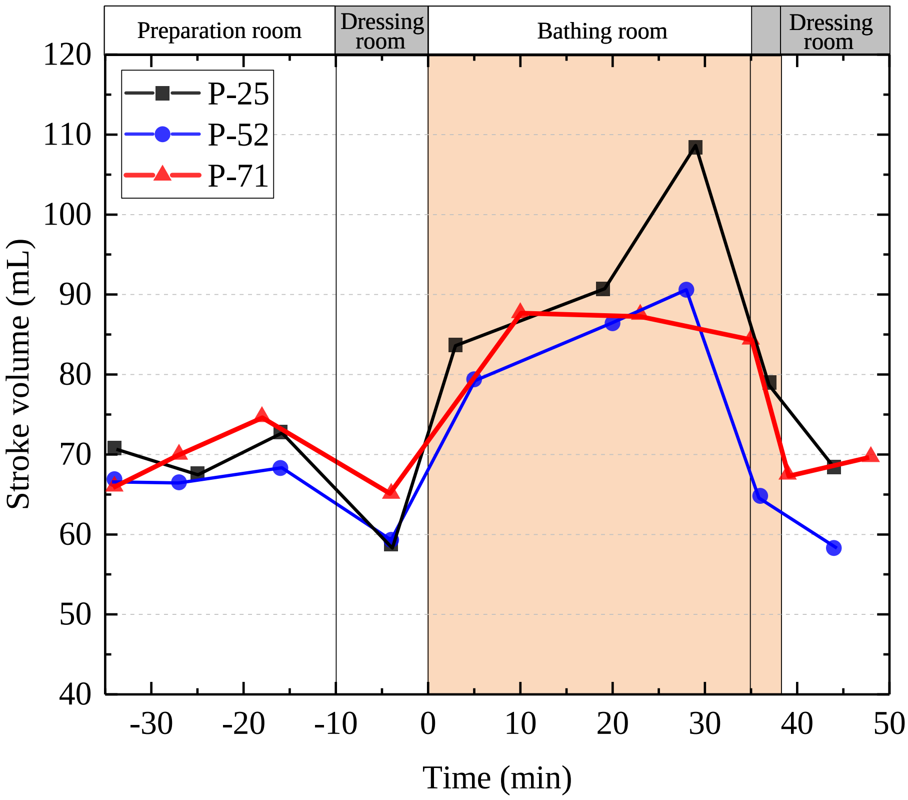


Figure 5-13 Experiment results of stroke volume

Stroke volume is the blood pumped from the heart during each systole [5-5]. Stroke volume was relatively stable before bathing for P-25, P-52, and P-71 (Figure 5-13). However, during bathing, P-25 showed the fastest and most significant increase, whereas P-71 showed the slightest change.

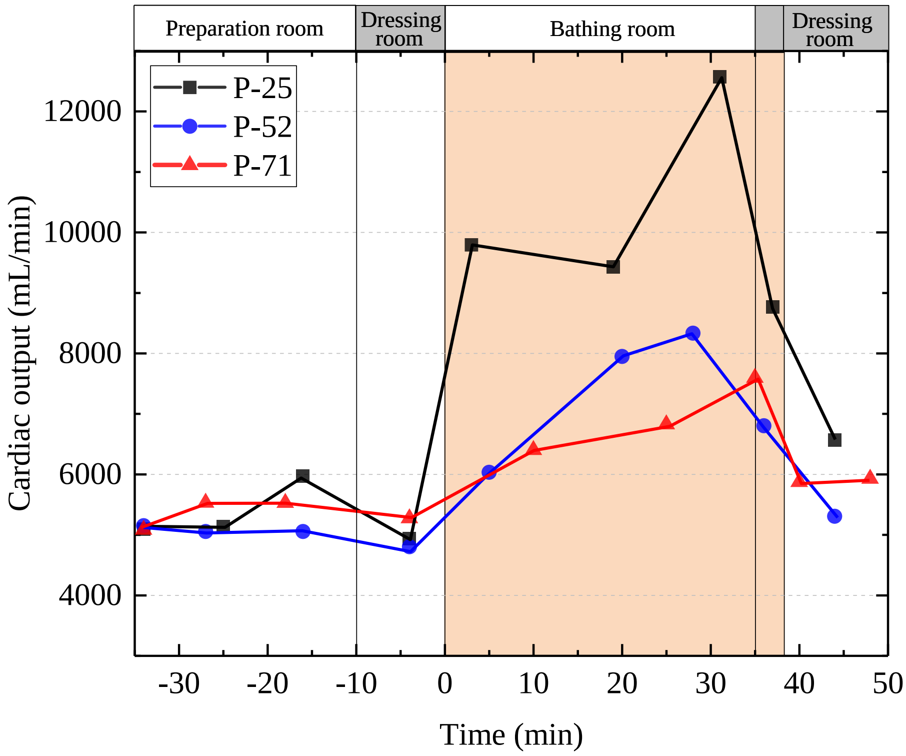


Figure 5-14 Experiment results of cardiac output

Cardiac output is the blood pumped to various body parts, especially the brain and other vital organs, by the heart per minute [5-6]. Cardiac output was calculated by multiplying stroke volume with HR [5-7]. The cardiac output of P-25, P-52, and P-71 increased by 2.3, 1.6, and 1.4 times, respectively, during bathing (Figure 5-14). 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 Figure 5-12. 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.

5.4.6.2 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 (Figure 5-15). 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 (as shown in Figure 5-16).

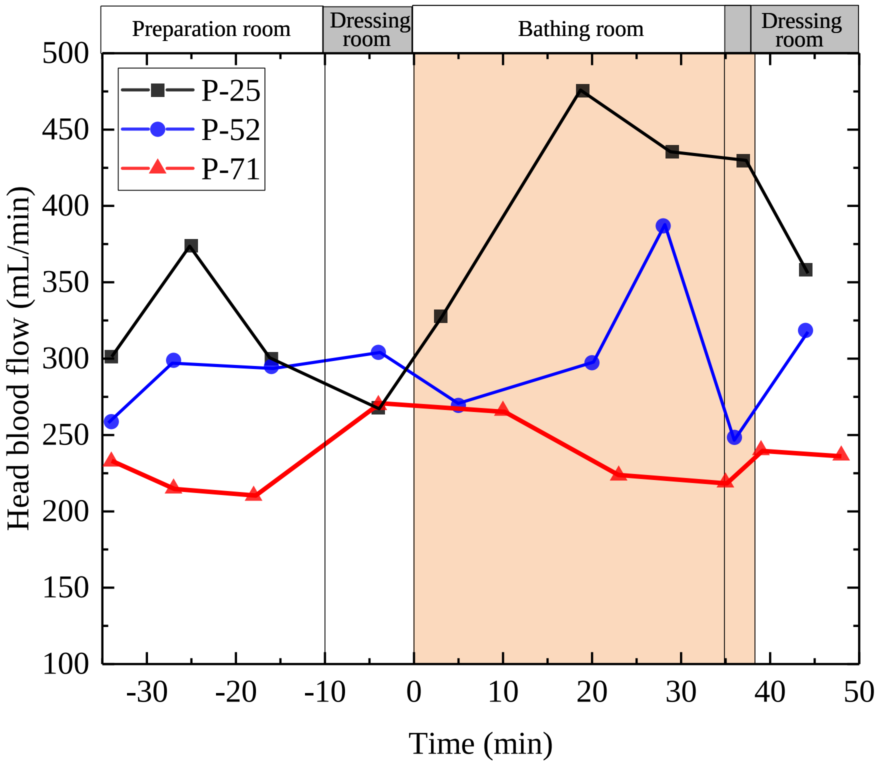


Figure 5-15 Experiment results of the head blood flow.

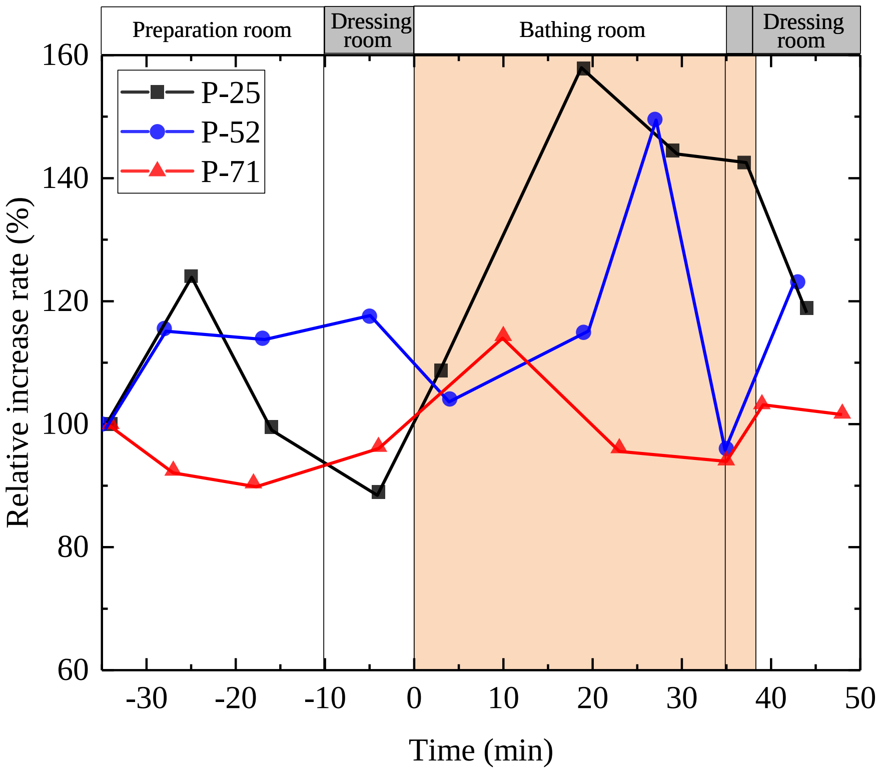


Figure 5-16 The relative increase in the head blood flow.

5.4.6.3 Blood flow to the upper and lower limbs

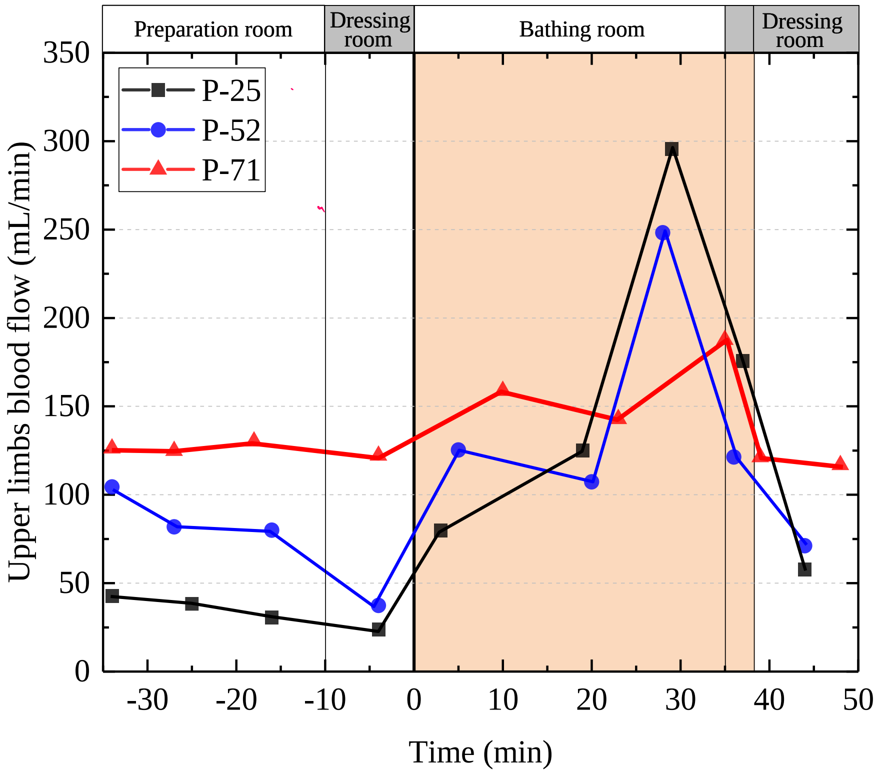


Figure 5-17 Experiment results of the blood flow to the upper limbs

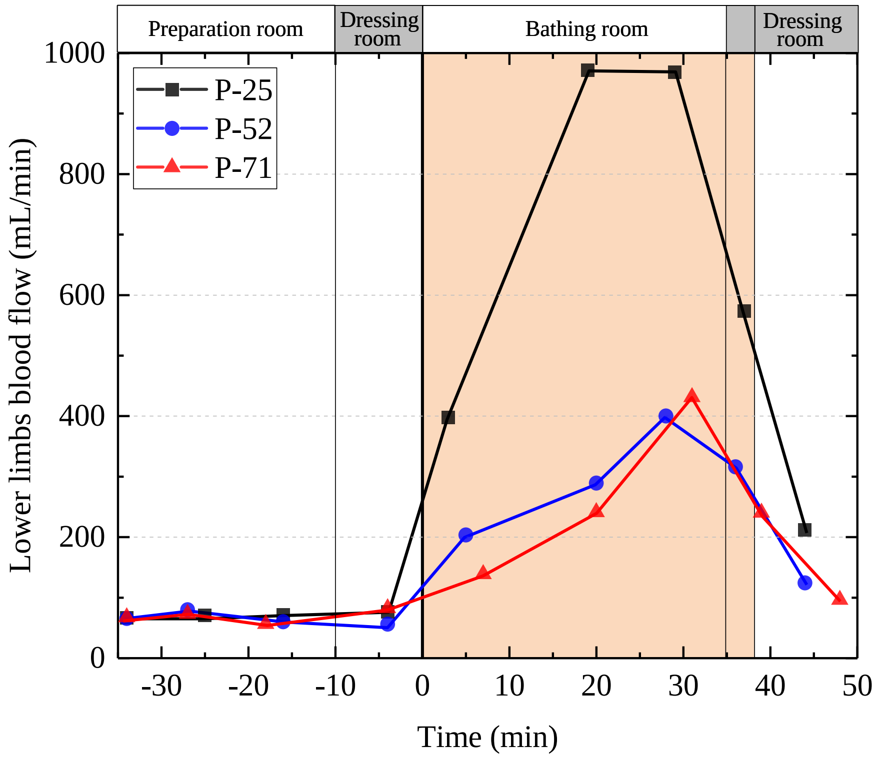


Figure 5-18 Experiment results of the blood flow to the lower limbs

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. Figure 5-17 shows the experimental results of the BF of 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) (Figure 5-1). 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 (Figure 5-17). 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 (Figure 5-18). 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.

5.4.7 SpO2

SpO_2 is the amount of blood oxygen [5-8]. The body's organs and tissues require oxygen to function, and oxygen is transported through red blood cells to other parts [5-9]. Most healthy adults have a normal healthy SpO_2 range of 95%–100%. If the SpO_2 decreases below this range, the human body will not receive adequate oxygen. The SpO_2 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. 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 SpO_2 of all three participants returned to the value before bathing. Although the SpO_2 of the three participants changed during bathing, they were within the healthy range. The change in SpO_2 may not pose a thermal health risk within 35 minutes of bathing.

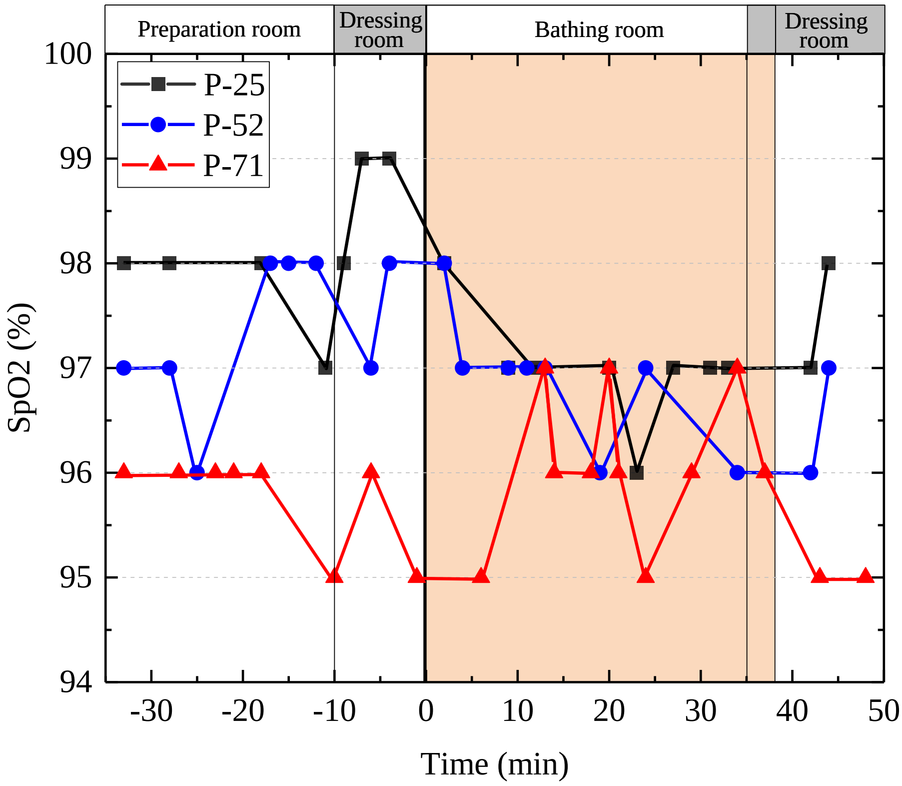


Figure 5-19 Experiment results of SpO2

5.4.8 Bodyweight

Table 5-4 Body weight before and after bathing.

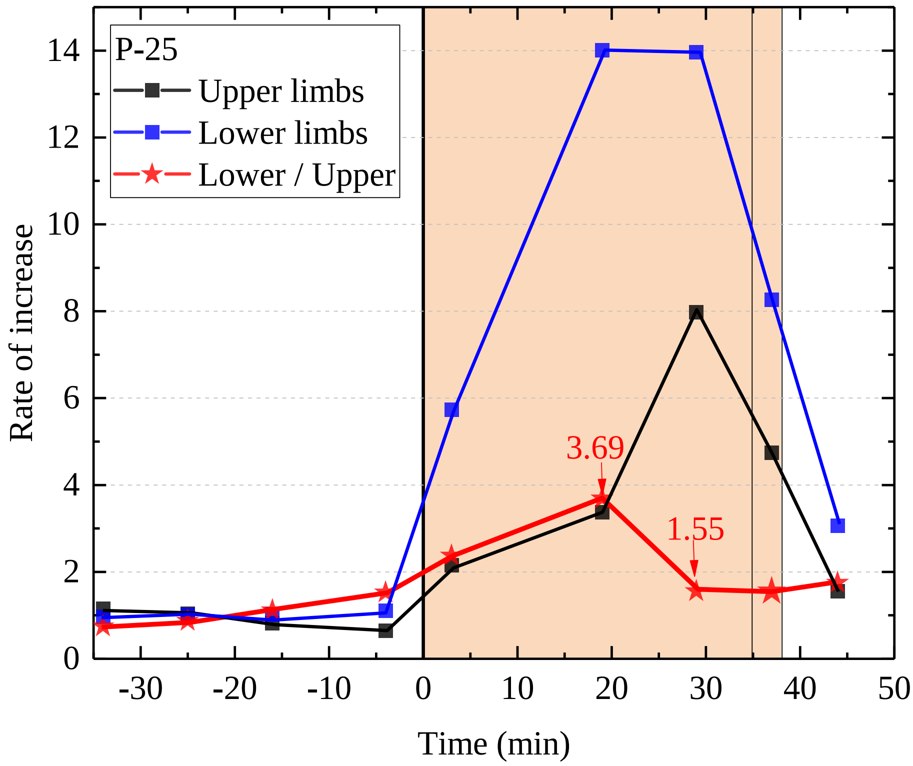
	Before bathing (naked)	**After bathing (naked)**	**Weight change**
P-25	54.356	54.11	–0.246 kg
P-52	69.037	68.895	–0.142 kg
P-71	56.378	56.206	–0.172 kg

Table 5-4 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) [5-10]. Dehydration, if severe enough, can impair physical and mental performance, with the severity of these impairments being greater in hot environments [5-11]. Excessive fluid loss can cause dehydration, a common and severe thermal health risk. Although the change in body weight in this chapter 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 [5-12].

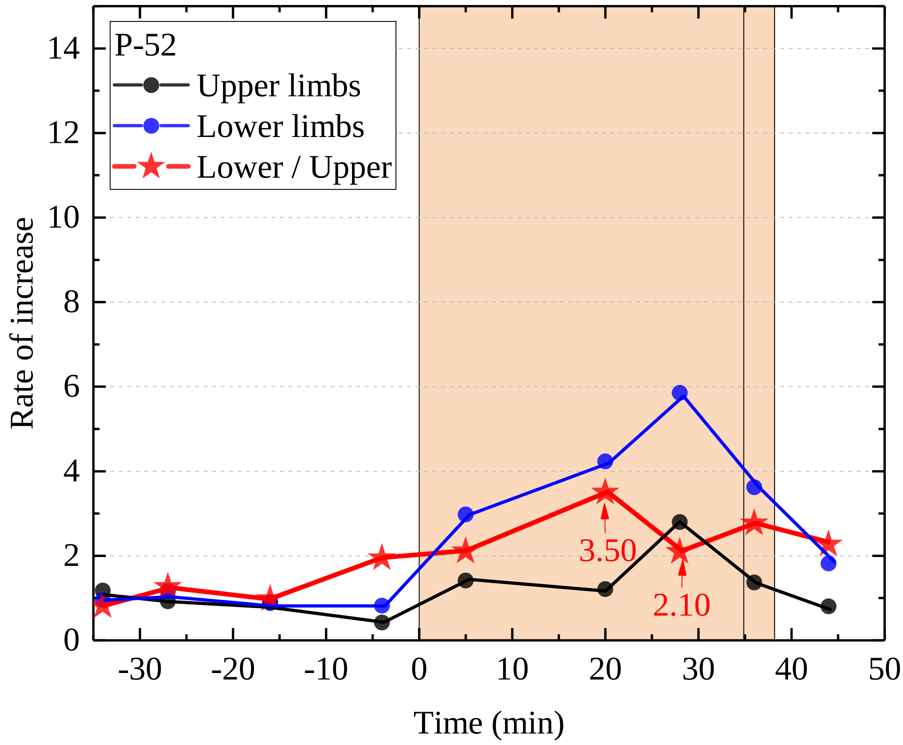
5.5 Discussion

5.5.1 Rate of increase of upper and lower limbs' blood flow

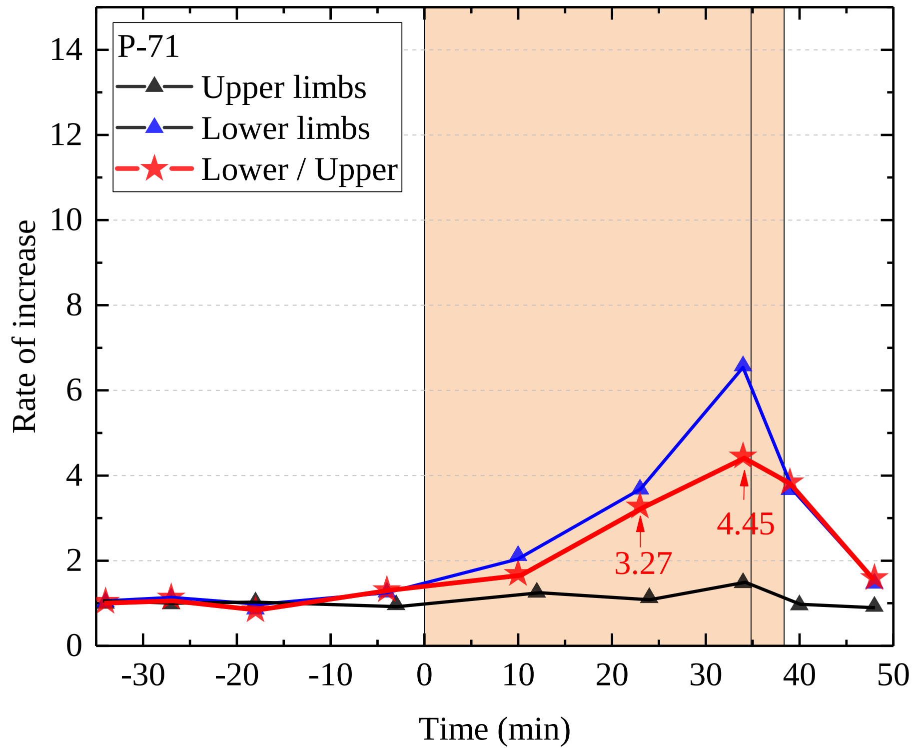
In the non-uniform bathing thermal environment, the lower limbs are in the hot bathwater environment with high temperatures, and the upper limbs are in the air environment with low temperatures. The process of heat transfer should be that the lower limbs absorb heat from the hot bathwater, the blood brings the heat from the lower limbs to the whole body through blood circulation, the upper limbs absorb the heat from the blood, and then the upper limbs dissipate heat into the air environment.



(a) P-25



(b) P-52



(c) P-71

Figure 5-20 rate of increase in upper and lower limbs' blood flow

Therefore, the change in the rate of increase in lower and upper limbs' blood flow represents a human's heat absorption and dissipation capacity. The ratio of the rate of increase in lower and upper limbs' blood flow indicates the ratio of heat absorption and dissipation of humans and the blood distribution under a non-uniform thermal environment.

Figure 5-20 shows the rate of increase in upper and lower limbs' blood flow. The P-25 had the highest growth rate of blood flow in the upper and lower limbs in the non-uniform bathing thermal environment. The rate of increase in the lower limbs' blood flow of P-52 and P-71 were similar, but the rate of increase in the upper limbs' blood flow of P-52 was significantly higher than that of P-71. Regarding the ratio of the rate of increased blood flow in the lower and upper limbs, the rate of increase in the lower limbs' blood flow was greatly higher than that in the upper limbs before t = 20 min. Between t = 20 min and 30 min, the ratio of the rate of increase of lower limbs to upper limbs of P-25 decreased from 3.69 to 1.55, P-52 decreased from 3.5 to 2.1, but the P-71 continuously increased from 3.27 to 4.45. The blood flow of the upper limb did not increase with the blood flow of the lower limb, indicating that the blood flow 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. These results show that, in the same non-uniform thermal environment, the body absorbs almost the same heat in a bathing thermal environment. Still, the ability of P-71 to dissipate heat to the environment is significantly lower than that of P-25 and P-52.

5.5.2 Blood flow ratio of head

The head is a very important part of the body because the brain is in the head. It is well known that insufficient blood supply to the head is a serious health risk. At the same time, in the non-uniform bathing thermal environment, the head is also a part of the air environment to help the body dissipate heat. Therefore, it is necessary to analyze the changes in head blood flow.

The ratio of blood flow in various body parts has been changed because of the redistribution of blood flow in the non-uniform bathing thermal environment (as shown in Figure 5-21). Regarding the ratio of head blood flow, both the P-25 and P-52 increased in the non-uniform bathing thermal environment during bathing. After bathing, the head-blood flow ratio almost returned to the level before bathing. The P-71 had the opposite trend for the ratio of head blood flow. The ratio of head blood flow decreased from 4.15 to 2.88 %, and after bathing for 10 min, it increased to 3.99 %, still much lower than the level before bathing. The recovery ability of the P-71's head blood flow ratio was also worse than that of the other two participants. It can be seen that P-71 is easy to cause the health risk of insufficient blood supply under the non-uniform bathing thermal environment, even lasting for some time after leaving that environment.

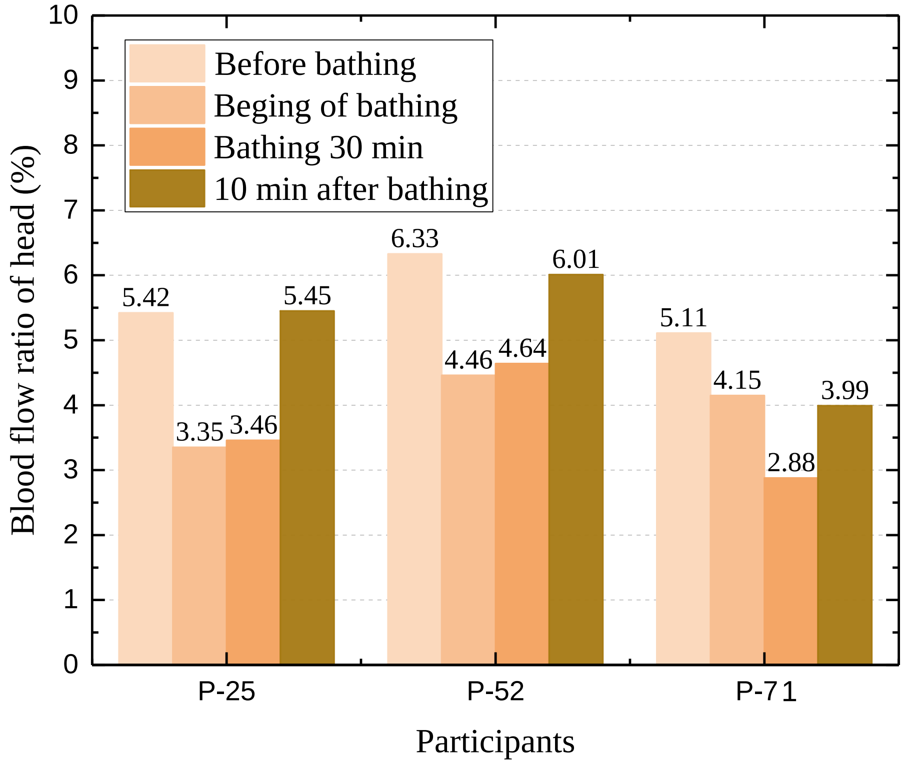
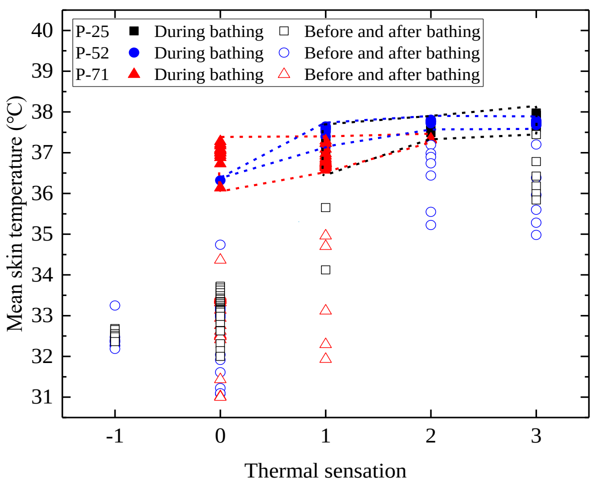


Figure 5-21 Experiment results of the ratio of head BF

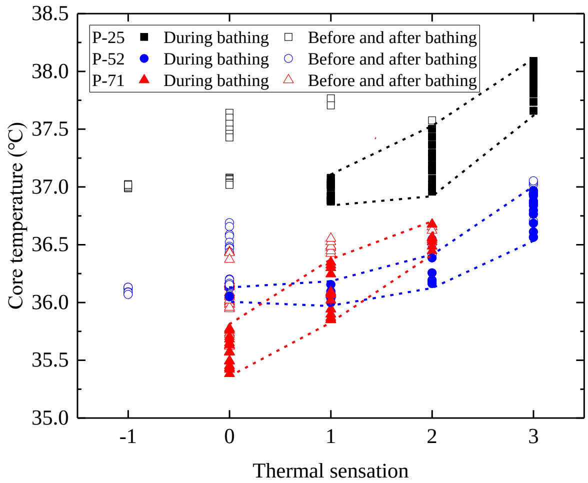
5.5.3 Correspondence between physiological response and TS

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 (Figure 5-6).

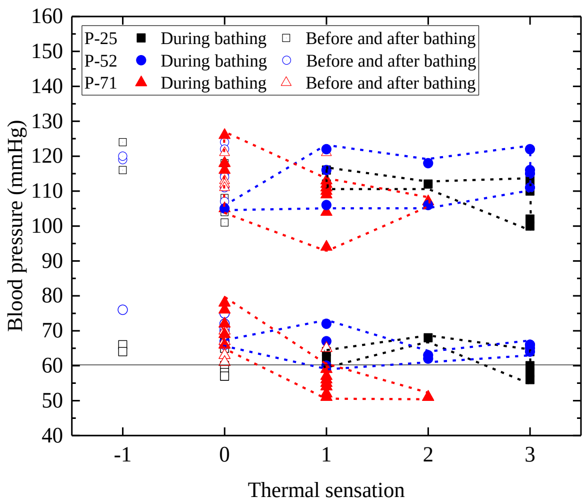
Regarding the mean skin temperature (Figure 5-7, 8), P-71 showed a significant decrease in the dressing room before bathing, whereas the TS (Figure 5-6) did not change. The other two younger participants' TSs decreased from 0 to –1 with the decrease in skin temperature. During bathing, the older participant P-71 had a significantly slower and weaker TS than the other two younger participants. Figure 5-22 (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.



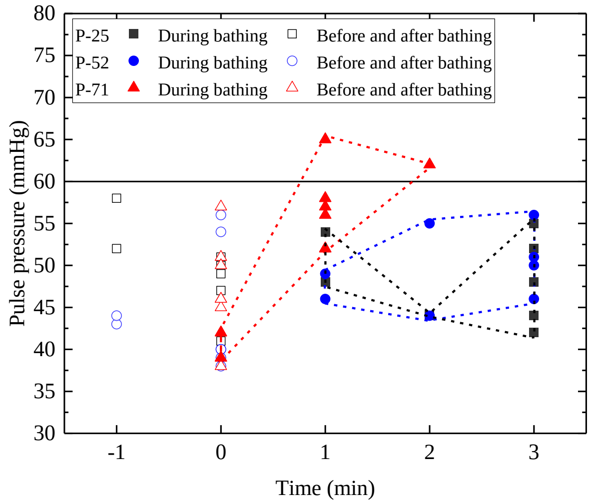
(a) Mean skin temperature



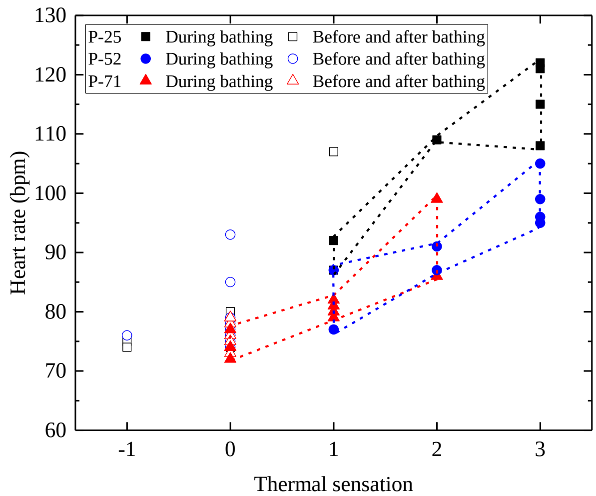
(b) Core temperature



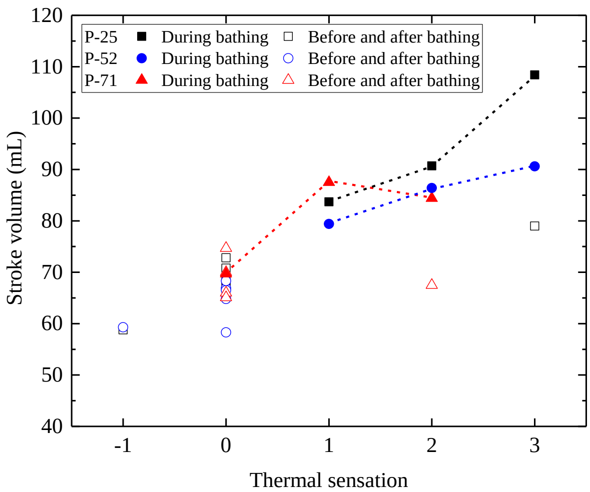
(c) Blood pressure



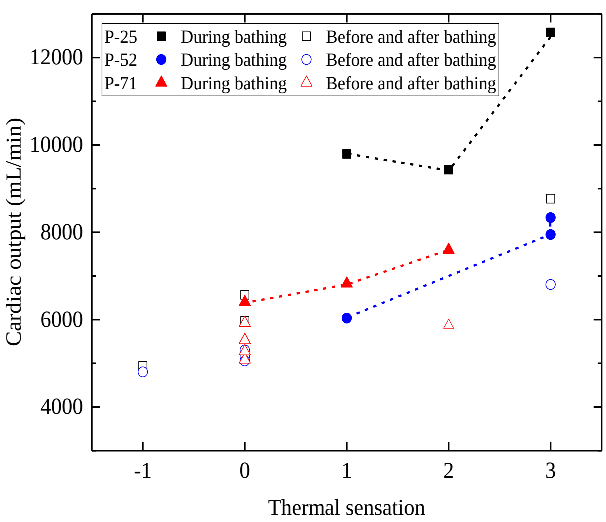
(d) Pulse pressure



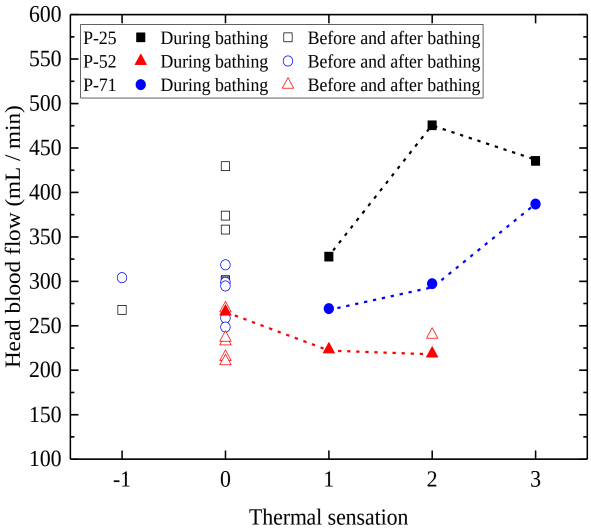
(e) Heart rate



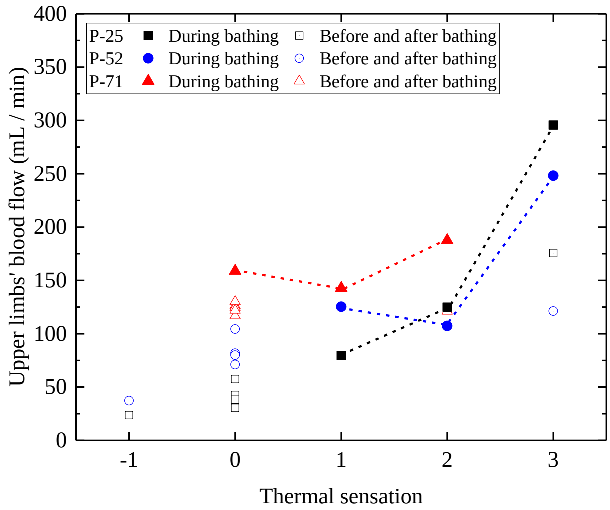
(f) Stroke volume



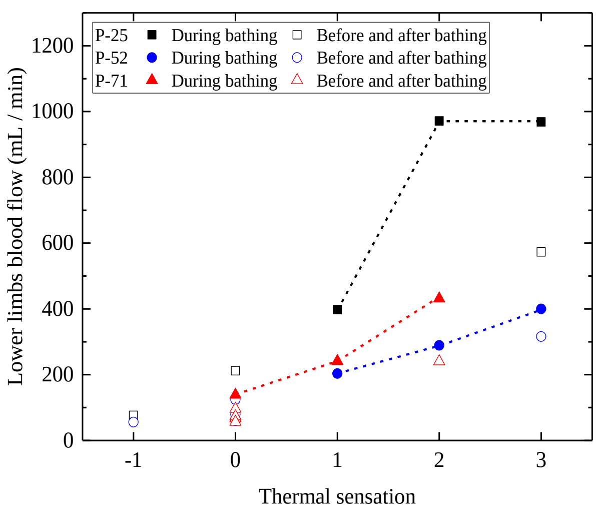
(g) Cardiac output



(h) Head blood flow



(i) Upper limbs blood flow



(j) Lower limbs blood flow

Figure 5-22 Correspondence between physiological response and thermal sensation.

Figure 5-22 (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 ℃ (36.56 to 35.89 ℃) compared to P-52 (0.17 ℃; 35.99 to 36.16 ℃) and P-25 (0.2 ℃; 36.87 to 37.07 ℃). The changes in P-71's core temperature are considered to be the closest to 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.

Regarding the BP and pulse pressure during bathing (Figure 5-10, 11), P-71 did not feel hot (+3) or any thermal discomfort (Figure 5-6), 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 (Figure 5-22 (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 (Figure 5-12) and cardiac output change (Figure 5-14) was similar to that of the TS (Figure 5-6). Among the three participants, P-71 had the slowest and least HR and cardiac output response, corresponding to the lowest TS. Figure 5-22 (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 (Figure 5-22 (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 (Figure 5-22 (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 (Figure 5-22 (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 was not usually associated with the change in BP. Nevertheless, in the case of older adults, special attention should be paid to the relationship between the TS increase and the BP decrease.

5.5.4 Mechanism of heat transfer in non-uniform bathing environment

Many models created to predict thermophysiological responses under different thermal environments [5-13,14,15] 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 [5-16] and thermo-cardiovascular regulation models [5-17]. 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, Figure 5-7 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), indicating 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 (Figure 5-17, 18). This BF response in the lower limbs is reflected in the core temperature increase. Figure 5-23 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.

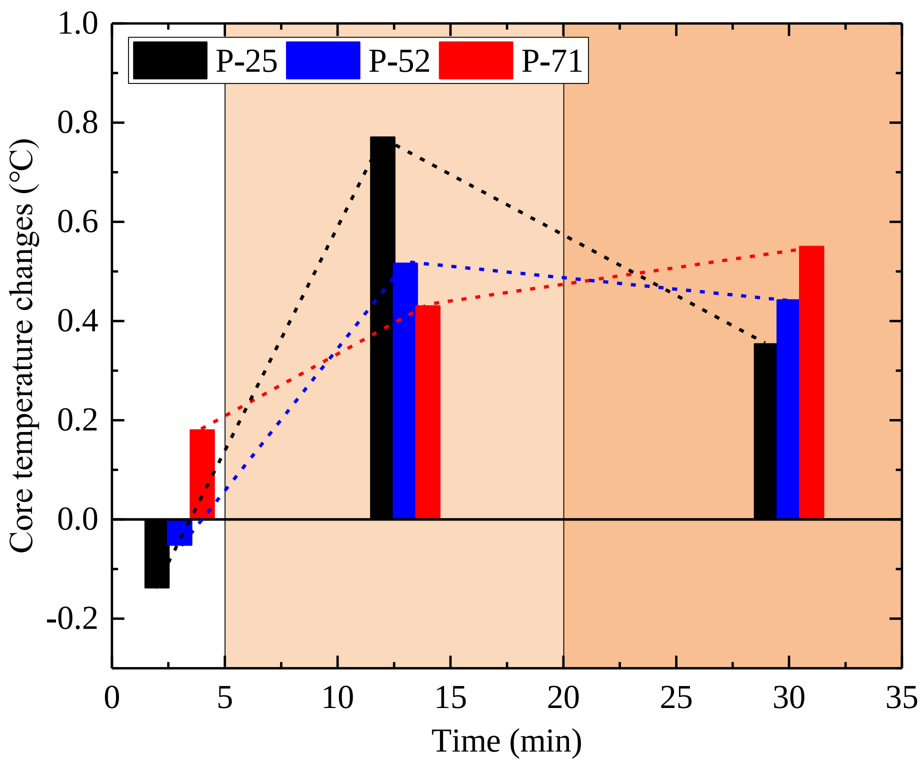


Figure 5-23 Changes in the core temperature of participants during bathing.

At 20 < t < 35, P-71 still had the slowest lower and upper limb BF response than those of P-25 and P-52 (Figure 5-17, 18). 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.

5.5.5 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.

5.6 Conclusions

In this chapter, 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, SpO_2, 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.

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Chapter 6 Optimization Thermo-Cardiovascular Regulation Model Considering Age*

6.1 Introduction

Chapters 3 developed a thermo-cardiovascular regulation model (TCRM), which successfully reproduced the thermal response (skin temperature, core temperature, blood flow, and blood pressure) of a 50-year-old participant in a bathing environment. However, model predictions of thermal responses in participants of other ages have not been validated. This chapter optimizes the original TCRM to an individual TCRM by considering the calculation of AVAS resistance and aging physiological parameters.

6.2 Methodologies

The original TCRM was developed in chapters 3 [6-1]. TCRM is a coupled model of the human thermal regulation model (HTM) and cardiovascular regulation model (CRM) developed based on the Stolwijk model and the Windkessel model. Figure 6-1 shows the computational logic flow chart of TCRM. Environmental factors (temperature and humidity) and human body parameters (heart rate, height, and weight) are input into the TCRM, and an iterative calculation is performed every 0.001 seconds. The model was validated to reproduce the thermal responses (skin temperature, core temperature, blood pressure, and blood flow) of 50-year-old participants in a bathing experiment in a non-uniform bathing thermal environment.

The 50-year-old participant participated in another bathing experiment two years later to verify the optimization results of the proposed TCRM of this chapter. In this chapter, the new experiment's (two years later than the previous experiment) environmental data and the original TCRM's physiological parameters of the participant were input into the model to predict the physiological thermal response. The calculated results mostly matched the experimental results of the 52-year-old participant. The rationale and correctness of TCRM have been reaffirmed.

Furthermore, to enhance the precision of predicting blood flow across different body regions, we have refined the original model as outlined below.

*

*The content of this chapter is an expansion based on a portion of a paper that the author intends to submit to Building and Environment.

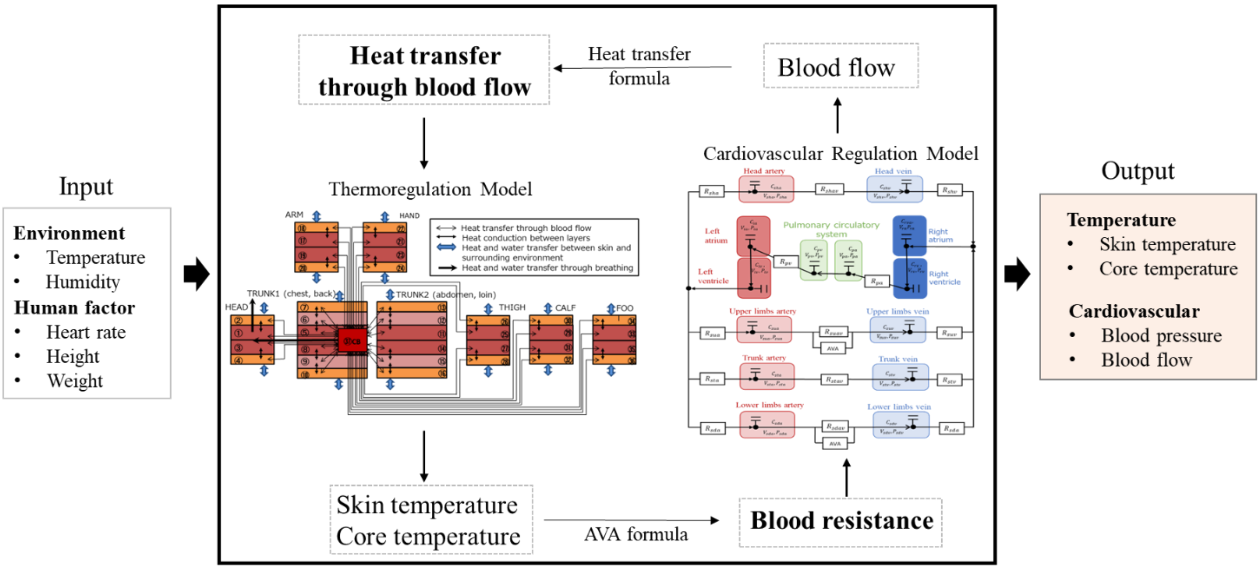


Figure 6-1 computational logic flow chart of this TCRM

6.2.1 Optimization of the original TCRM considering AVAs

In the proposed TCRM, the blood heat transfer between the layers of HTM is calculated through the blood flow in the CRM as shown in Figure 6-2 shows the heat exchange between the layers and the blood flow in each layer. The blood flow in HTM was divided into several segments depending on the weight ratio of each segment. The blood flow obtained in each part is further shunted to the skin, muscle, and core layers. The blood flowing into a skin layer is further divided into the blood flow in a capillary and AVAs near the skin.

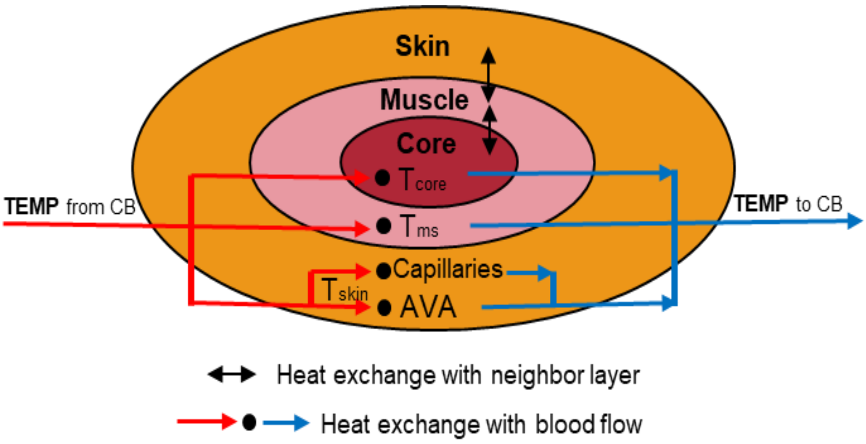


Figure 6-2 A detailed schematic of blood heat exchange

6.2.1.1 Local skin temperature in the calculation of AVAs

AVAs have a substantial effect on the thermoregulation system and contract or expand to increase or decrease blood flow from the body's center to the skin [6-2,3]. The original TCRM calculates blood resistance considering the capillary resistance and the AVAs resistance, which referred to Takemori's AVA model [6-4], in which the calculation of blood resistance through AVA opening and closing only considered the body's upper and lower limb systems. In this calculation method, the whole-body mean skin temperature is used to calculate the degree of opening and closing of AVAs in the upper and lower limbs.

However, based on the literature reviewed, it is widely accepted that the human thermal regulation system is primarily influenced by both the core temperature and local skin temperature [6-5]. Moreover, our previous research found that when participants were in the non-uniform bathing thermal environment, the thermal environment and skin temperature of the head, upper limbs, and lower limbs were significantly different. Therefore, in order to more accurately calculate the results of blood flow and heat transfer in various parts of the body, in this paper, TCRM is optimized by considering the changes in local skin temperature (calculated by HTM).

6.2.1.2 AVAs in head system

Furthermore, studies have shown that AVAs exist not only in the upper and lower limb systems but also on the skin surface of the head [6-6,7], these results show that the skin area of the nose supplied by the angular artery contains AVAs. Moreover, our previous research found that when participants were in the non-uniform bathing thermal environment, the thermal environment and blood flow of the head, upper limbs, and lower limbs were significantly different. Therefore, in this chapter, we considered the AVA changes in the head to calculate the changes in blood flow resistance.

For the head AVA calculation method, we refer to the calculation method of the upper and lower limbs, which the calculation formula is as Equations (6-1,2). By considering the change in blood resistance of the head, the difference in blood flow in the head and the heat transfer between the head and other body parts can be calculated more accurately. Therefore, in order to more accurately calculate the results of blood flow and heat transfer in various parts of the body, in this paper, TCRM is optimized by considering the changes in local skin temperature (calculated by HTM). Equations (6-1,2,3) show the optimized blood resistance calculation formula.

$$O_{hand} = 0.148(T_{handskin} - 34.0) + 0.532(T_{core} - 36.8) + 0.510 \quad (6-1)$$

$$O_{foot} = 0.148\left(T_{footskin} - 35.4\right) + 0.532(T_{core} - 37.0) + 0.510 \quad (6-2)$$

$$O_{head} = 0.148(T_{headskin} - 34.0) + 0.532(T_{core} - 36.8) + 0.510 \quad (6-3)$$

If $O \geq 1$, then $O = 1$, and if $O \leq 0$, then $O = 0$

$$R_{AVA} = \frac{R_{AVA,min}}{O^2} \quad (6-4)$$

$$R = \frac{1}{\frac{1}{R_p} + \frac{1}{R_{AVA}}} \quad (6-5)$$

Where

$T_{handskin}$: skin temperature

$T_{footskin}$: skin temperature

$T_{headskin}$: skin temperature

T_{core}: core temperature

R: blood resistance between an artery and a vein in the upper and lower body vessels

$R_{AVA,\ min}$: minimum AVA resistance

O: degree of opening of AVA [n. d.]

subscript AVA: AVA vessel

subscript p: capillary vessel.

6.2.2 Optimization of the original TCRM considering the age

After proposing and validating the original TCRM for two years, we conducted three participants, aged 25, 52, and 71, to the bathing experiment, and measured the thermophysiological responses of the three participants in the non-uniform bathing environment. From the conclusion of the previous experimental study, we found that each participant had different thermal reactions in the hot environment of bathing, and the main differences were reflected in the changing trend of skin temperature in various parts, core temperature, blood pressure changing trends, and blood flow in various parts.

The primary characteristic in the advancement of the TCRM incorporating the factor of age involves the capacity to account for various physiological changes within the cardiovascular system. These changes involve the BMR, threshold temperature for sweating, arterial system compliance, blood distribution, and capillary resistance. The original TCRM proposed in chapters 3 and 4 [6-1] will undergo modifications considering the physiological differences associated with aging concerning predicting the blood flow of the body's local parts, blood pressure, skin temperature, and core temperature of different age adults. The TCRM that has been constructed, incorporating an age factor, will undergo validation using published experimental data [6-2]. This data includes physiological responses in non-uniform bathing thermal environments from participants of three distinct ages, namely 25 years old (P-25), 52 years old (P-52), and 71 years old (P-71).

The original TCRM was calculated based on the physiological data of P-52. In order to predict the thermal response of younger P-25 and older P-71, this chapter optimized the original TCRM to consider age-related physiological values. Table 7-1 provides the percentage change from P-52 to P-25 and P-71 in physiological data. The increase or decrease in these physiological data values is related to the basal metabolic amount, the temperature threshold of thermal response, the basic condition of blood vessels, and blood flow distribution. Table 7-1 presents a summary of physiological values used in the proposed individual TCRM of basal metabolic rate, sweating values, blood flow distribution, compliance, and capillary resistance.

6.2.2.1 Basal metabolic rate

The original TCRM incorporates the BRM of each segment within the human body when calculating the overall heat balance of the body. The basal metabolic rate demonstrates a progressive decline that adheres to an almost linear trajectory as individuals advance in age [6-8,9]. Numerous thermophysiological models of older adults incorporate variations in basal metabolic rate (BRM) between older individuals and younger adults [6-10,11]. These models suggest that accounting for BRM alterations significantly influences the estimation of core temperature. This chapter not only investigated the influence of age factor on BRM, but also considered weight, height, and gender by referencing Ganpule et al.'s proposed BRM prediction equation [6-12,13], which is shown in Equation (6-6,7).

$$BMR\ (MALES) = (0.0481 * W + 0.0234 * H - 0.0138 * A - 0.4235) * \frac{1000}{4.186} \quad (6-6)$$

$$BMR\ (FEMALES) = (0.0481 * W + 0.0234 * H - 0.0138 * A - 0.9708) * \frac{1000}{4.186} \quad (6-7)$$

Where

BMR: basal metabolic rate [kcal/d]

W: weight (kg)

H: height (cm)

A: (age)

6.2.2.2 Threshold temperature for sweating

The chapter found a substantial correlation between age and sweat rate, indicating that as age increases, there is a decrease in the amount of sweating and heat released across the body [6-14]. Several physiological thermal models for older adults consider the correlation between age and heat loss caused by perspiration [6-15]. Hirata et al. [6-16] found that older adults have a threshold temperature for sweating approximately 1.5 °C higher than younger adults. The act of sweating is initiated by specific threshold parameters associated with either the temperature of the body's core or the skin's temperature. The data used in the proposed individual TCRM is summarised in Table 2, which considered the results of changes in sweat threshold characteristics in both younger and older individuals reported by Sagawa et al. [6-17].

6.2.2.3 Blood flow distribution

With increasing age, there is a notable decline in cutaneous blood flow [7-18,19]. Tsuchida et al. suggested that the epidermal blood flow may decrease to 40% of its level at age 20 by the time an individual reaches age 70 [7-20,21]. This chapter refers to the experimental table presented by Kenney and Havenith (1993) [7-22], which compares the cutaneous blood flow between young and elderly persons under various environmental situations.

Simultaneously, there is a correlation between advancing age and muscle mass decline and decreased blood flow in muscles, particularly in individuals over 50 [7-23,24]. Based on the blood flow distribution value (in the skin, muscle, and core layer) of the original TCRM (for P-52), this chapter adjusted the percentage of blood flow changes about age differences. The results are presented in Tables 1 and 2, demonstrating the proposed individual TCRM of both increases and decreases in blood flow distribution from the original TCRM (for P-52).

6.2.2.4 Compliance

Aging is linked to alterations in the mechanical and structural characteristics of the vascular wall, resulting in a decline in arterial elasticity and diminished arterial compliance [7-25]. In individuals who do not have cardiovascular disease or risk factors, the compliance of both big and small arteries increases in those under the age of 30. It then reaches a stable level around 30 but decreases after this age [7-26]. This pattern remains consistent in individuals aged 50 and above, which is a negative correlation between age [7-27]. A study found a negative connection of -0.551 between arteriolar compliance and generation in individuals ranging from 21 to 82 years old. Duprez et al. conducted a preliminary study that revealed a 27% reduction in arterial compliance among individuals aged 70 and above compared to those below 70 [7-28,29].

6.2.2.5 Capillary resistance

In the context of aging and its impact on microvascular hemodynamics, several key factors contribute to an increase in capillary flow resistance. Aging is often associated with a decrease in the elasticity of blood vessels, a condition commonly referred to as arteriosclerosis [7-30]. This loss of elasticity can lead to an increased resistance to blood flow. The thickening of the vessel walls, a process known as vascular remodeling, can occur with age [7-31,32]. This thickening reduces the internal diameter of the vessels, thereby increasing resistance to blood flow. Aging can be accompanied by changes in the composition of the blood, such as increased blood viscosity, which can also contribute to increased flow resistance [7-33]. The health of the vascular endothelium is crucial for maintaining hemodynamics. With aging, endothelial function can be impaired, leading to increased vascular resistance [7-34]. The value of capillary resistance is adjusted through model calculation, as shown in Table 2-3.

Table 7-1 The percentage change in physiological value from P- 25 to P-52 and P-71

Physiological parameters in proposed TCRM		**Percentage change of value (%)**			**Reference**
		P-25	**P-52**	**P-71**	
BMR (W)		110	100	84	[37-43]
Blood flow distribution (%)	Skin layer	130	100	79	[44-46]
	Muscle layer	110	100	94	
	Core layer	96	100	102	
Compliance [L/mm Hg]		110	100	79	[12-13] [54-56]
Capillary resistance [mmHg*s / L]		83	100	120	[57-61]

Table 7-2 Physiological values used in proposed TCRM of basal metabolic rate, sweating values, blood flow distribution, compliance, and capillary resistance

Physiological parameters affected by age factor		Value in proposed TCRM			Reference
		P-25	**P-52**	**P-71**	
1 BMR (W)		80	73	61	[37-43]
2 Threshold temperature for sweating (°C)	Core temperature threshold	36.5	36.8	37.0	[44-46]
	Skin temperature threshold	34.1	34.5	35.6	
3 Blood flow distribution (%)	Skin layer	5	3.8	3	[48-53]
	Muscle layer	20	18	17	
	Core layer	75	78.2	80	
4 Compliance [L/mm Hg]	Artery of head system	0.00044	0.0004	0.000316	[12-13] [54-56]
	Vein of head system	2.2	2.0	1.58	
	Artery of upper limb's system	0.00044	0.0004	0.000316	
	Vein of upper limb's system	※1	※1	※1	
	Artery of trunk system	0.00055	0.0005	0.000395	
	Vein of trunk system	0.022	0.02	0.0158	
	Artery of lower limb system	0.00055	0.0005	0.000395	
	Vein of lower limb system	※1	※1	※1	
	Pulmonary artery	0.0011	0.001	0.00079	
	Pulmonary vein	0.011	0.01	0.0079	
	Heart left ventricle	※2	※2	※2	
	Heart right ventricle	※2	※2	※2	
	Heart left atrium	0.0011	0.001	0.00079	
	Heart right atrium	0.03025	0.0275	0.021725	
5 Capillary resistance [mmHg*s / L]		1250	1500	1800	[57-61]

※1: Compliance changes according to pressure

※2: Compliance changes per heartbeat.

6.3 Simulation results

The TCRM model developed in chapters 3 and 4 successfully predicted the thermal physiological response of a 50-year-old middle-aged man in the thermal environment of bathing. The original TCRM was initially enhanced by considering the local skin temperature and head AVAs while estimating AVA resistance. Comparing the calculation results of the previous study and this chapter, it can be seen that the precision of forecasting skin temperature and head blood flow in the physiological response of the middle-aged participant was improved.

In this section, the optimized TCRM is validated by comparing the published experimental results of mean skin temperature, core temperature, blood pressure, and blood flow of participants aged 25, 52, and 71 years [7-2] with their corresponding predicted values.

6.3.1 Skin temperature

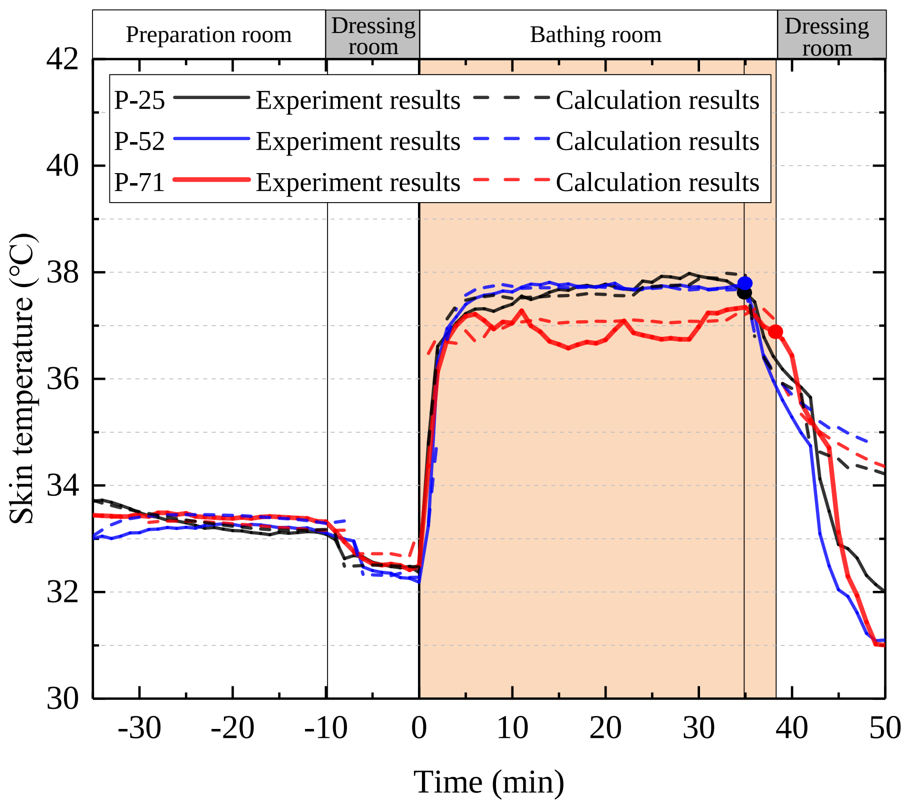


Figure 6-3 Experimental and calculation results of mean skin temperatures

Figure 6-3 delineates the experimental and computational outcomes of the mean skin temperatures of three participants. In general, the simulation results closely approximate both the amplitude and trends observed in the experimental outcomes for the three participants. The computational findings effectively replicate alterations in average skin temperature during bathing, particularly in the pre-bathing and bathing phases. The calculated post-bathing skin temperature tends to be lower than the experimental results, attributed to the substantial influence of bathwater on skin surfaces and post-bathing physical movements. This discrepancy is linked to variations in skin water content across different regions and the concurrent heat evaporation and water loss from the skin surface. The current study, however, predominantly concentrates on delineating skin temperature alterations during bathing and does not account for these post-bathing dynamics.

Additionally, concerning the calculation results for P-71, while the overall trend aligns closely with observed changes, the calculated outcomes fail to capture temperature fluctuations during the interval 10 <t <30. Calculation results exhibit greater stability compared to experimental counterparts. The rationale behind the observed fluctuation in average skin temperature between 10 <t <30 in experimental data remains unclear; hence, this phenomenon has not been incorporated into the computational model.

6.3.2 Core temperature

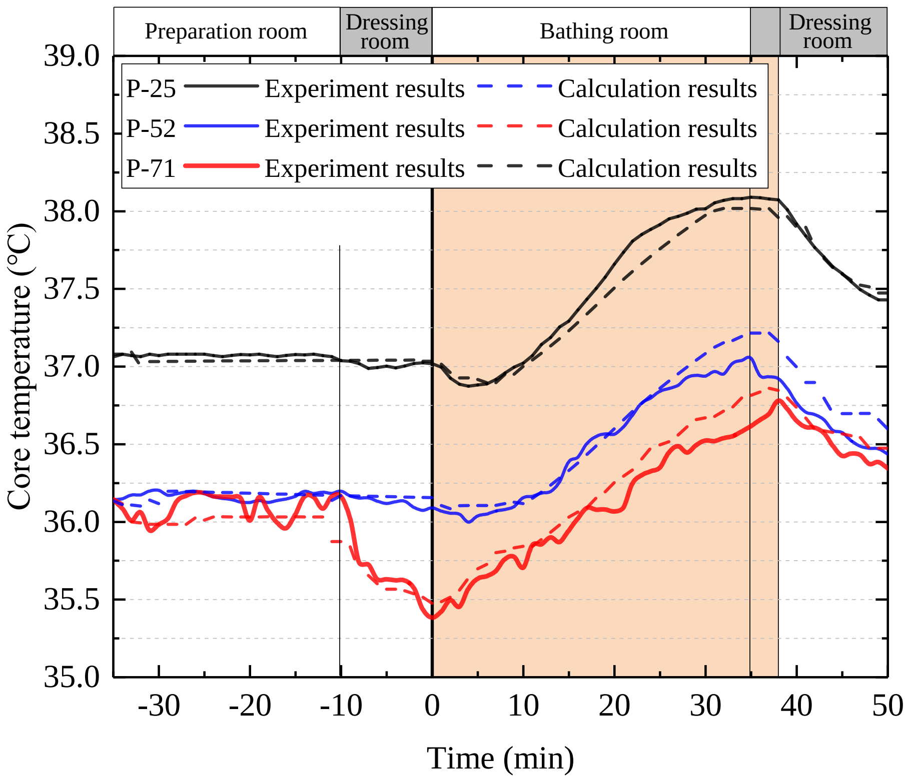
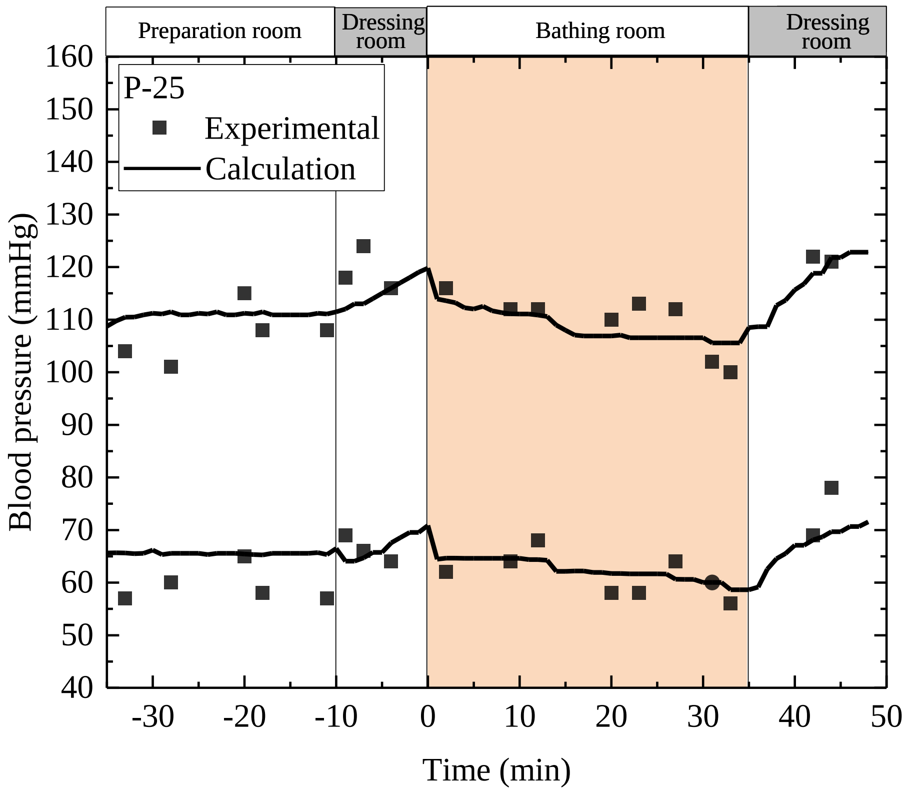


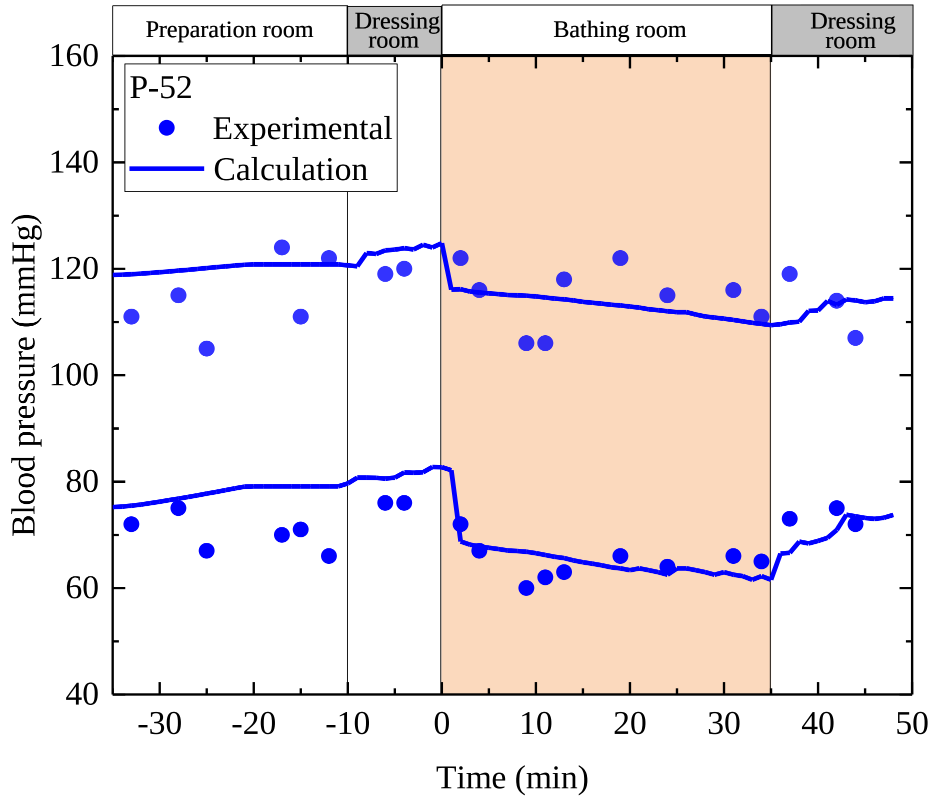
Figure 6-4 Experimental and calculation results of core temperatures

Figure 6-4 illustrates the simulation and experimental results of core temperature. Each participant exhibits unique core temperature dynamics, likely due to individual physiological differences in thermoregulation. P-25 and P-52 have similar responses in the bathing room, with P-25 showing a slightly higher peak temperature. The calculated results for P-25 mimic the general trend throughout the whole protocol but a little underestimate of the core temperature in the bathing room. The calculated results for P-52 display a smoother increase, following similar experimental results overall trajectory. The calculated results for P-71 capture the overall pattern, indicating a significant resemblance between the model's predictions and the actual response. Across all participants, the calculated results tend to smooth out fluctuations, suggesting that the model may not fully account for transient thermal responses. In conclusion, the simulation reveals distinct thermoregulatory patterns among the participants, with the model providing a general approximation.

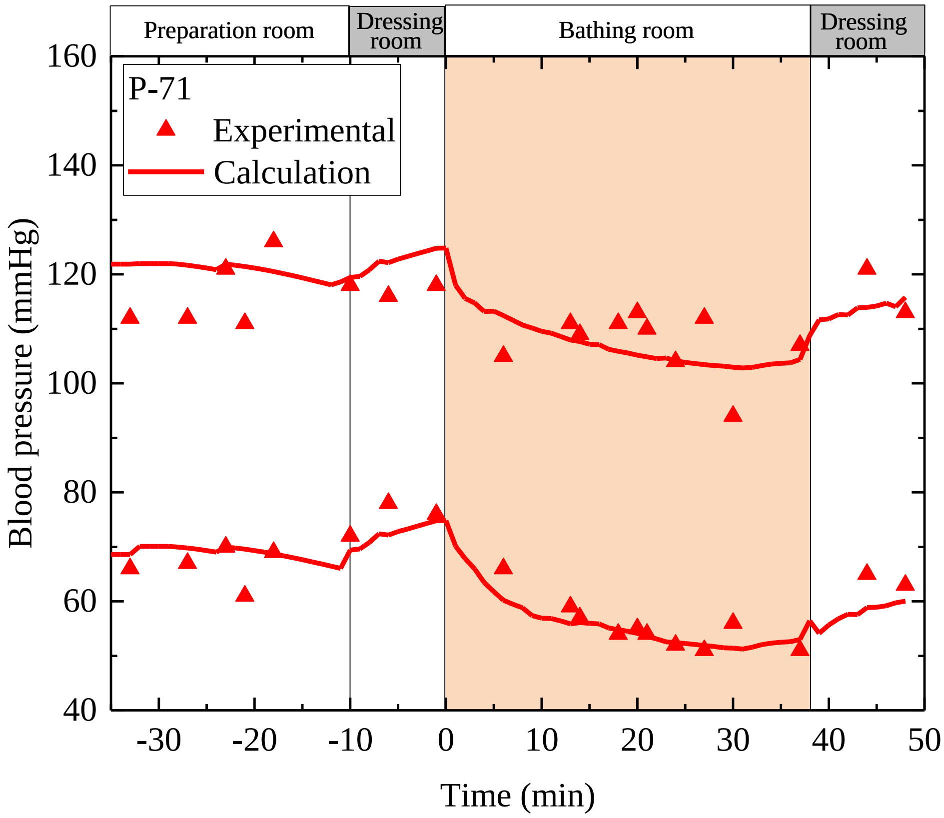
6.3.3 Blood Pressure



(a) P-25



(b) P-52



(c) P-71

Figure 6-5 Experimental and calculation results of blood pressure

Figure 6-5 shows the experimental and calculation results of blood pressure. Figure 6-5 (a) demonstrates a little decrease in blood pressure of P-25 during bathing, with experimental points scattering around the calculated line, the calculation practically closely with the experimental results. Figure 6-5 (b) portrays a more stable blood pressure profile than P -25, with experimental measurements suggesting a slight decline upon entering the bathing room, which the calculation accurately mirrors, albeit with a smoother curve. Figure 6-5 (c) presents a pronounced hypotensive response in the subject's blood pressure as they transition from the dressing room to the bathing room, with bathing experimental measurements revealing a substantial decrease, followed by a gradual recovery upon returning to the dressing room. The calculated trajectories successfully accounted for this decrease, indicating a basic similarity between the model's predictive power and the participants' physiological responses to thermal stimulation.

Overall, Figure 6-5 shows that the proposed individual TCRM successfully predicted the blood pressure response to the thermal environment of bathing in three participants and highlights individual differences in the cardiovascular response of thermal environment stress to blood pressure.

6.3.4 Blood flow

6.3.4.1 Cardiac output

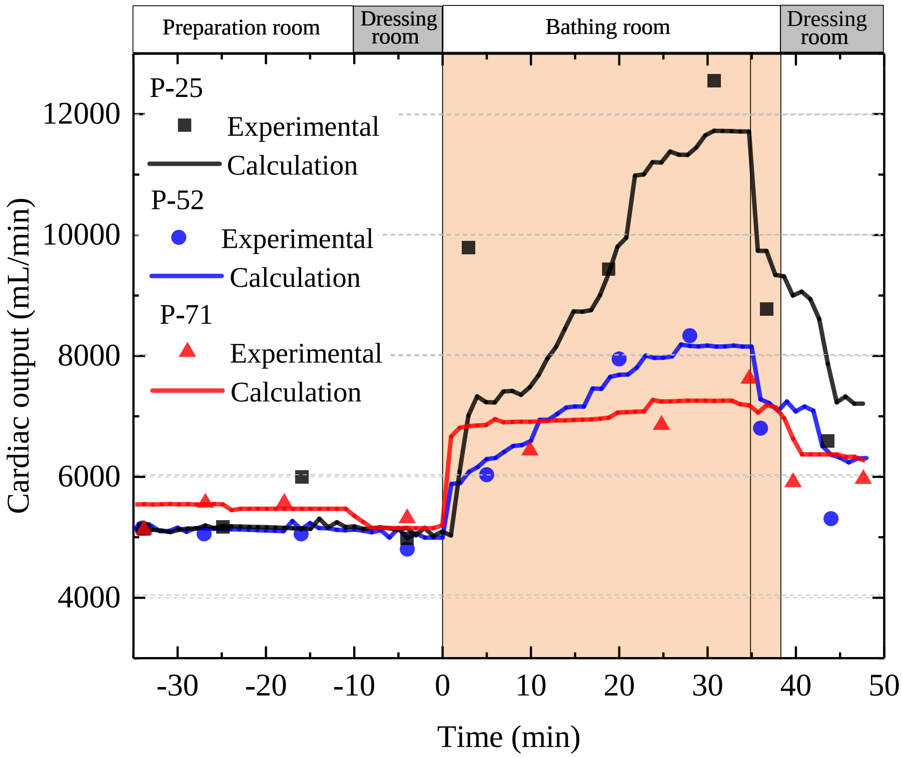


Figure 6-6 Experimental and calculation results of cardiac output

Figure 6-6 shows the experimental and calculation results of cardiac output. The experimental results of P-25 show a stable cardiac output during the preparation and dressing room phases, with a significant rise upon entry into the bathing room, followed by a sharp decrease upon return to the dressing room. The calculated results closely follow the experimental trend, with minor deviations, particularly at the peak in the bathing room. P-52's experimental cardiac output displays a gradual increase in the bathing room, but the rise is less pronounced than that of P-25. The calculated curve for P-52 exhibits a similar pattern to the experimental results, indicating a good fit of the model to the subject’s physiological response (as shown in Figure 6-6). The calculated curve for P-71, while generally mirroring the experimental data, does not capture the sharp peak. All participants show an increase in cardiac output upon entering the bathing room, which the model successfully predicts, demonstrating the model's effectiveness in simulating the cardiac output response to thermal stress.

6.3.4.2 Head blood flow

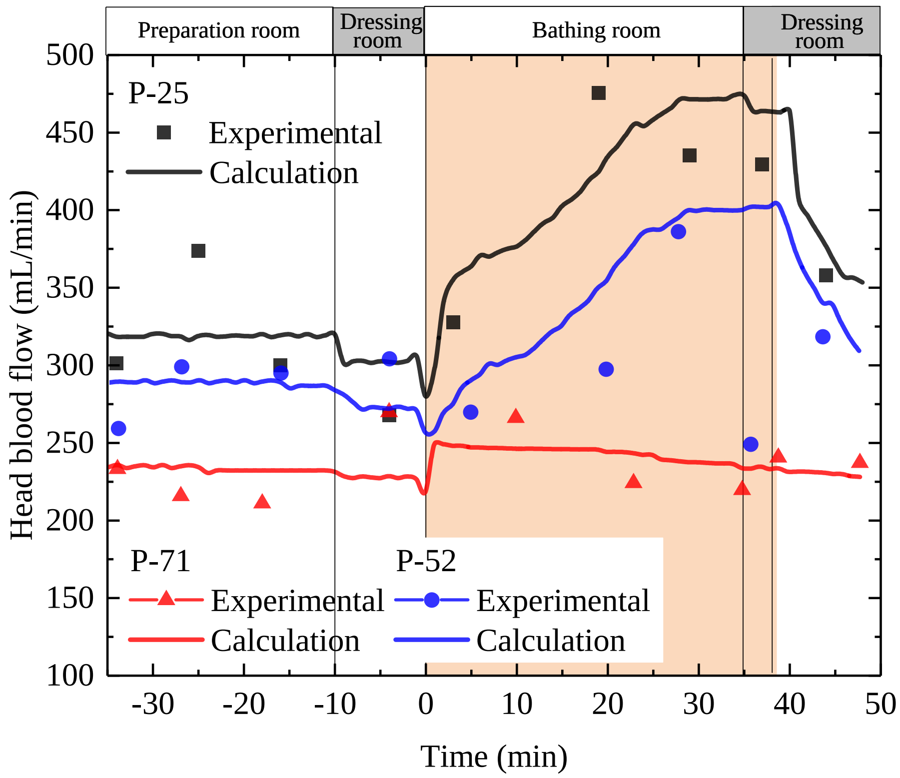


Figure 6-7 Experimental and calculation results of head blood flow

Figure 6-7 shows the experimental and calculation results of head blood flow. The experimental data of P-25 shows relative stability in cerebral blood flow in the preparation and dressing rooms, with a substantial increase in the bathing room, followed by a sharp decrease upon returning to the dressing room. The calculated results of P-25 align closely with the experimental data, capturing both the magnitude and the trend of the response accurately, suggesting. P-52's experimental results indicate a slight increase in cerebral blood flow in the bathing room, which is less pronounced than in P-25. The model's calculations track this change well.

P-71's experimental cerebral blood flow is characterized by a marked decrease in the bathing room, diverging significantly from the other participants. The model's calculation was successful in predicting this decrease. The model demonstrates good accuracy in tracking the general trends of cerebral blood flow changes across different environmental conditions for P-25, P-52, and P-71.

6.3.4.3 Lower limbs blood flow

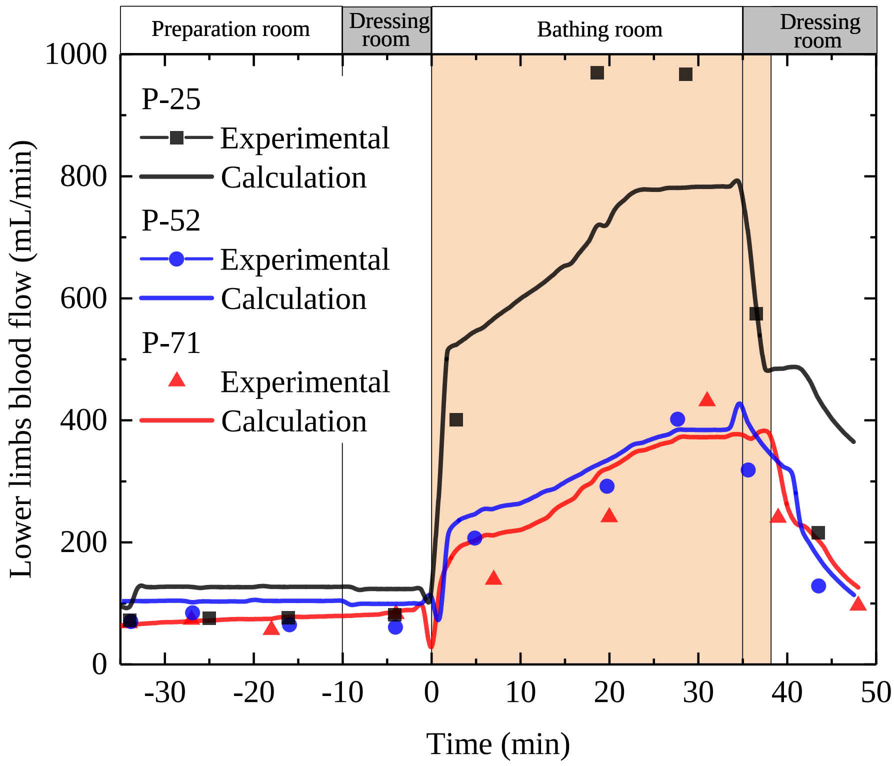


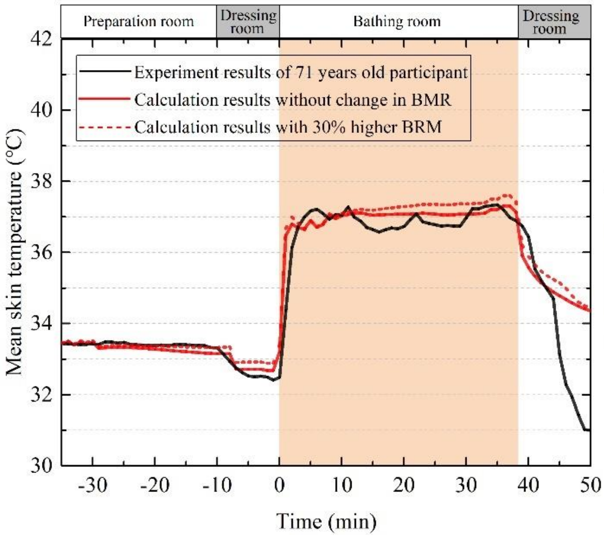
Figure 6-8 Experimental and calculation results of blood pressure, mean skin and core temperatures

Figure 6-8 illustrates the experimental and calculation results of blood pressure, mean skin, and core temperatures. The overall trend of P-25 is captured by the model, with both showing increases and decreases at similar times. however, there's a variance between the experimental and calculated data points in the bathing room where the experimental data peaks higher than the calculated data. P-52's experimental and calculated blood flow remain quite close throughout the entire time course, indicating that the model's predictions are highly accurate for this individual. There is a sharp increase in blood flow upon entering the bathing room, followed by a sharp decline after exiting, which the model captures well.

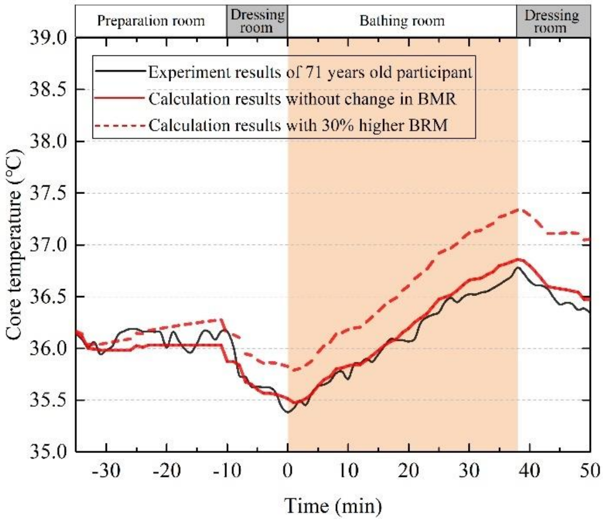
The experimental data of P-71 shows a smaller increase in blood flow in the bathing room compared to the other participants, which the model also reflects, although with a slightly lower peak. This suggests that while the model captures the general trend, individual nuances could be further refined. The proposed individual TCRM accurately predicts the general trend of increased blood flow in the bathing room and subsequent decrease upon exiting for all participants.

6.4 Sensitivity analysis

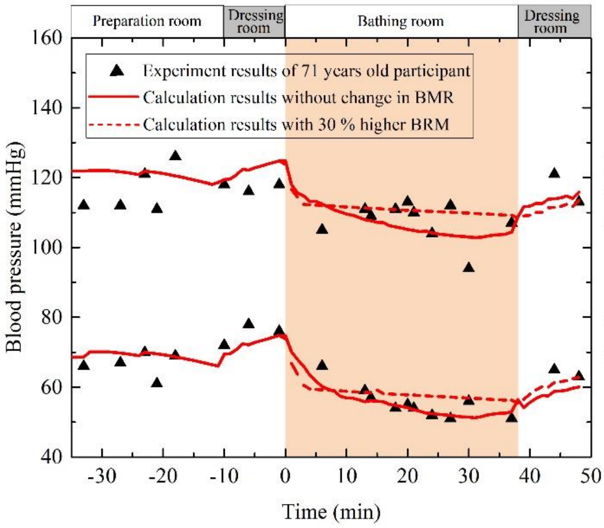
6.4.1 Influence of BMR change



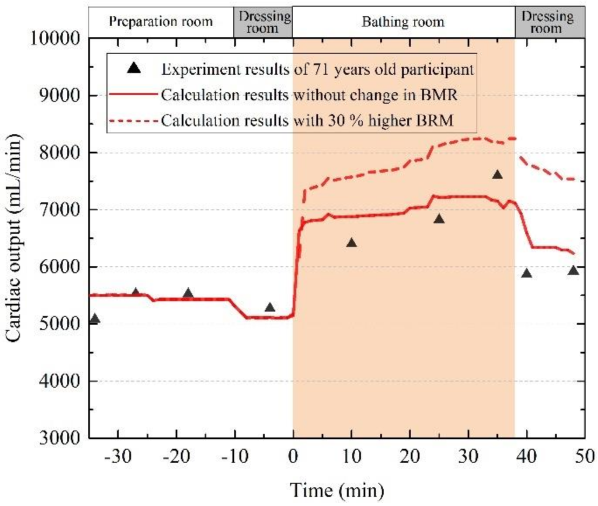
(a) mean skin temperature



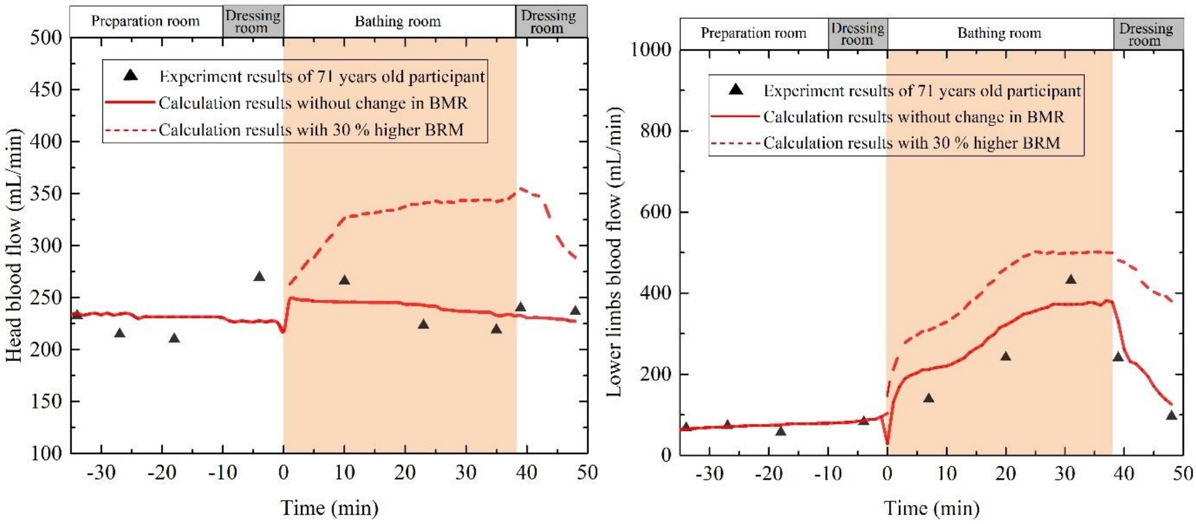
(b) Core temperature



(c) Blood pressure



(d) Cardiac output



(e) Head blood flow (f) Lower limbs blood flow

Figure 6-9 Comparison results: mean skin temperature, core temperature, blood pressure, and blood flow

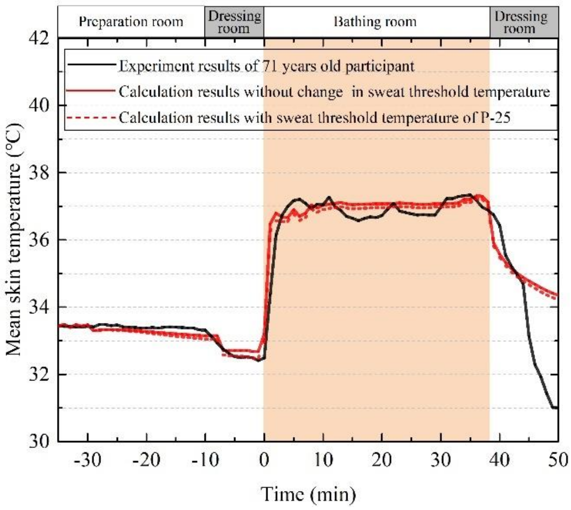
Figure 6-9 shows the comparison results considering the BMR: mean skin temperature, core temperature, blood pressure, and blood flow. The calculation results with 30% higher BMR consistently show higher skin and core temperatures than the calculation results without change in BMR, with a higher peak temperature within the bathing phase and a more marked decrease post-exposure. Variations in basal metabolic rate significantly impact skin and core temperature, with an elevated BMR correlating with higher rises and falls in temperature. This result serves to underscore the complexity of human thermoregulation and the significant role that metabolic factors play in influencing skin and core temperature.

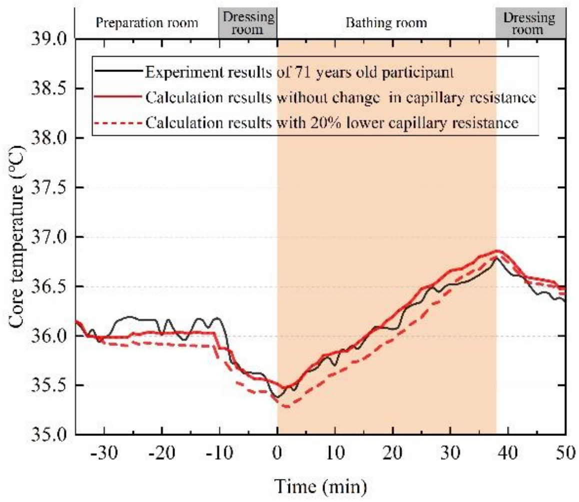
The sensitivity analysis of BMR within the model indicates a marked impact on blood pressure prediction. The blood pressure prediction results after increasing the basal metabolic rate by 30% weakened from the downward trend, and the results were closer to those of the two younger participants P-25 and P-71.

The results with heightened BMR overestimate the increase during bathing and post-bath reduction of cardiac output, suggesting a potential overestimation of the bath-induced cardiovascular response when BMR is augmented. From Figure 6-9 (e), BMR increases significantly influence head blood flow, especially in the bathing environment. The enhanced BMR model predicts an exaggerated increase in lower limb blood flow.

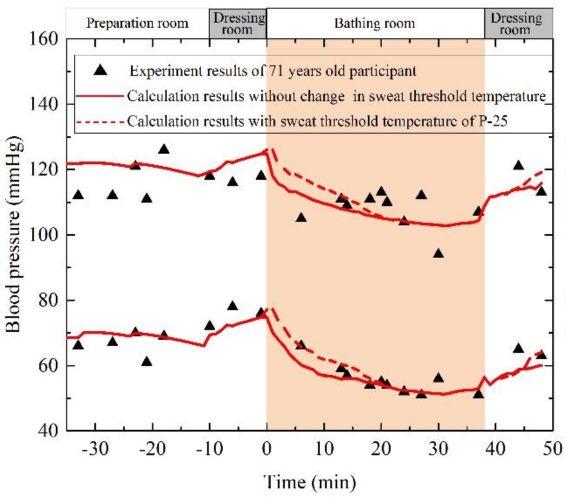
In summary, the heightened BMR models tend to overestimate the physiological responses, particularly regarding blood flow to extremities and the heart's output. This discrepancy underscores the importance of age-related BMR in TCRM.

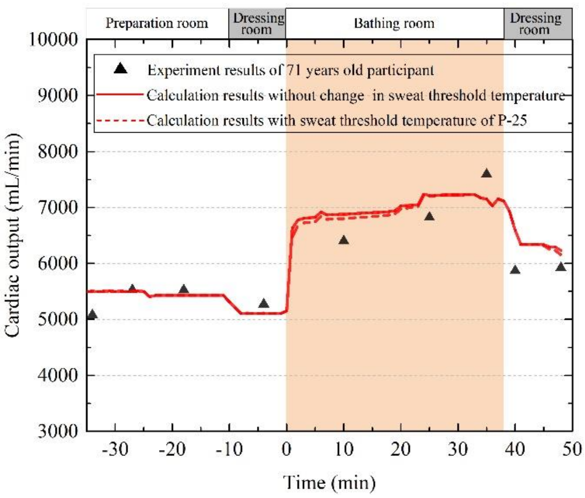
6.4.2 Influence of sweat threshold temperature change



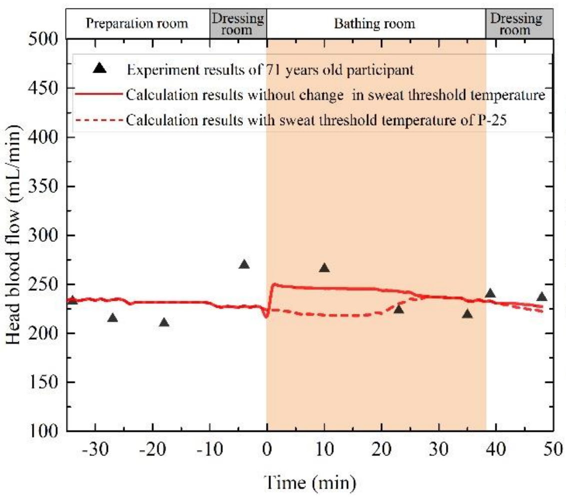


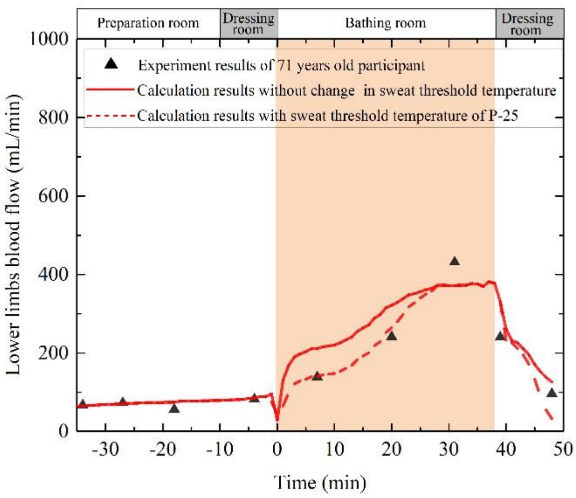
(a) mean skin temperature (b) Core temperature





(c) Blood pressure (d) Cardiac output





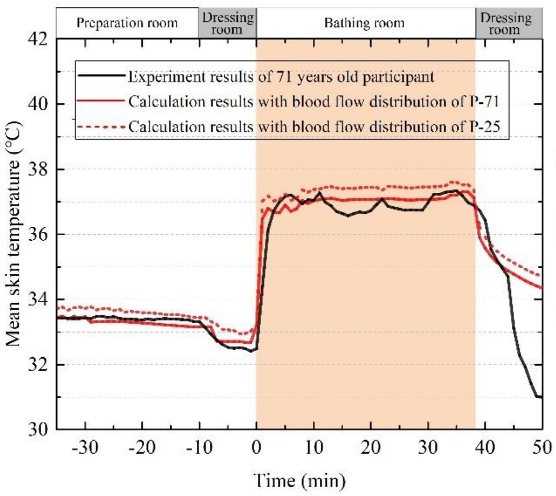
(e) Head blood flow (f) Lower limbs blood flow

Figure 6-10 Comparison results: mean skin temperature, core temperature, blood pressure, and blood flow

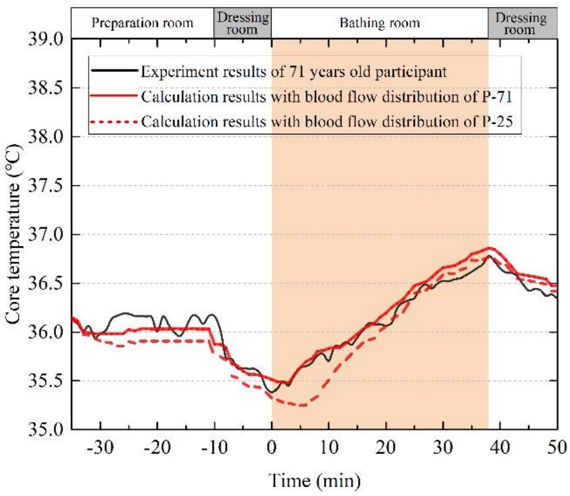
Figure 6-10 shows the comparison results considering the sweat threshold temperature: mean skin temperature, core temperature, blood pressure, and blood flow. P-25 sweating threshold temperature is a value lower than P-71. Increasing the sweating threshold temperature does not significantly affect the average skin temperature. This is due to the effect of hot bath water being much higher than the skin temperature. The results with a lower sweat threshold temperature underestimate this rise in the whole experiment, underscoring the importance of sweating in thermoregulation and its effect on core temperature. Lowering the sweating temperature threshold slows the blood pressure drop during bathing. The effect on cardiac output is small, and blood flow is only slightly reduced in the early stages of bathing. The impact of a decrease in sweating threshold temperature on head blood flow and lower limb blood flow is similar to cardiac output, but the decrease is greater, and the difference is more obvious.

In summation, these comparisons reveal that the initiation of sweating, as represented by the sweat threshold temperature in the models, is a crucial factor in the physiological response to thermal stress. It significantly affects core temperature, blood pressure, and blood flow. Including a sweating parameter in physiological models represents the actual responses better, indicating the critical role of thermoregulatory mechanisms in maintaining homeostasis during thermal challenges.

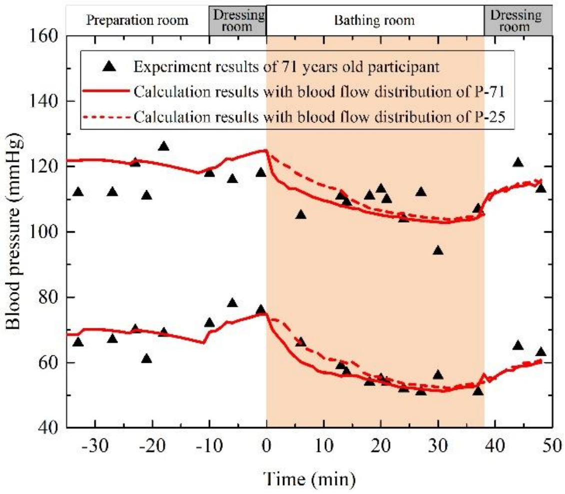
6.4.3 Influence of blood flow distribution change



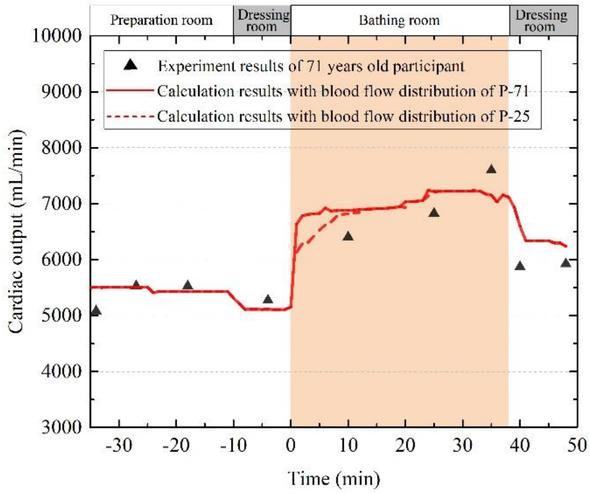
(a) mean skin temperature



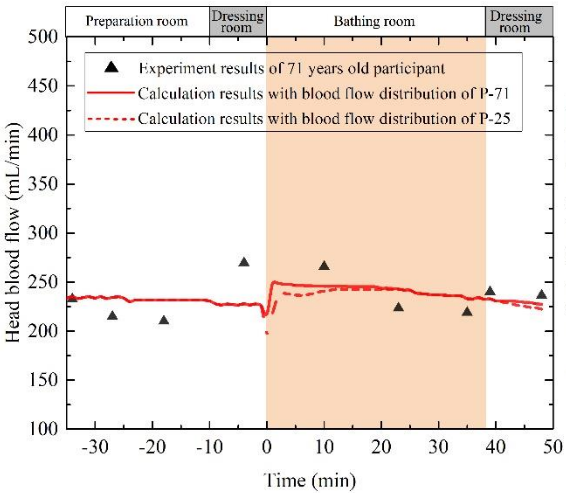
(b) Core temperature



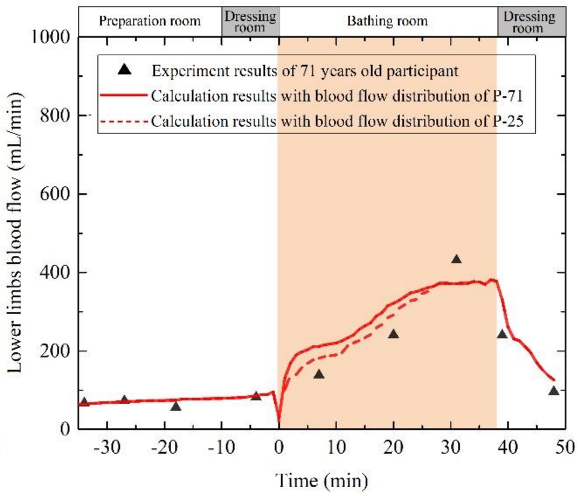
(c) Blood pressure



(d) Cardiac output



(e) Head blood flow



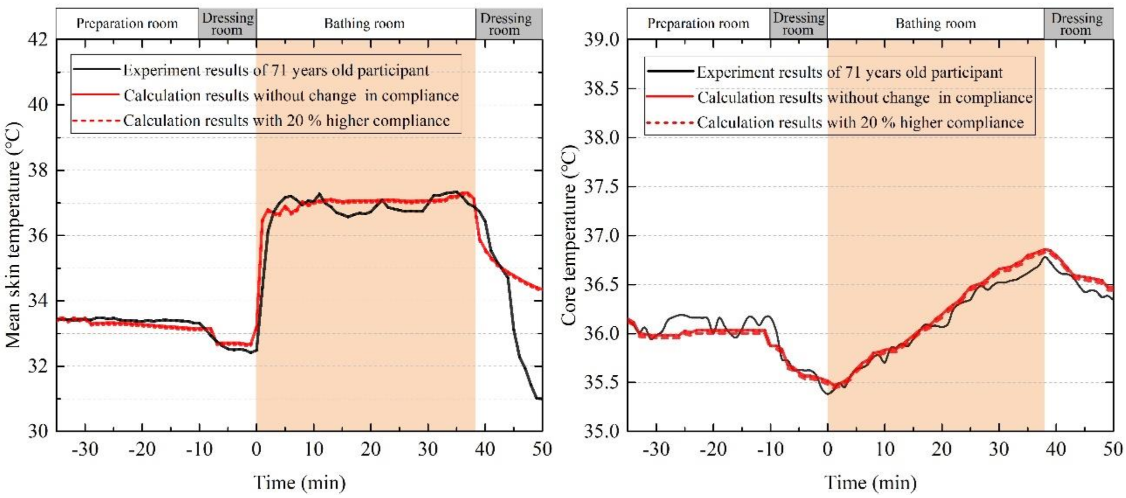
(f) Lower limbs blood flow

Figure 6-11 Comparison results: mean skin temperature, core temperature, blood pressure, and blood flow

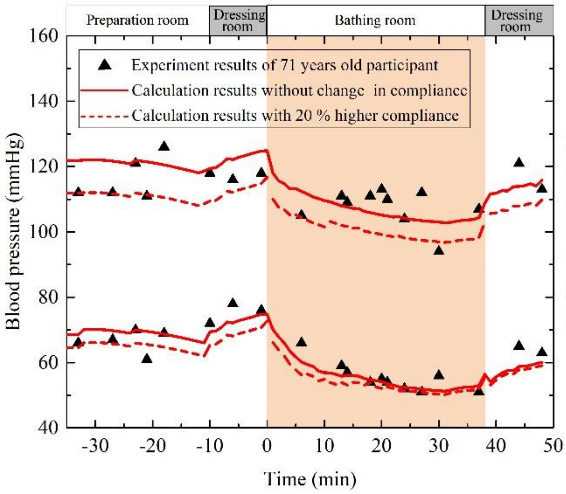
Figure 6-11 shows the comparison results considering the blood distribution: mean skin temperature, core temperature, blood pressure, and blood flow. Changing the blood flow ratio from p-71 to P-25 means an increase in skin and muscle blood flow ratio and a decrease in core blood flow ratio. The results considering the P-25' blood flow distribution show a slightly higher temperature during the bath, indicating that the parameter may be modeling an amplified cutaneous blood flow leading to increased skin temperature. The results of blood flow distribution using P-25 show that the core temperature has a larger downward trend and amplitude than the results of P-25, which delays the time point of the rise. This may reflect an overestimation of metabolic heat production or a reduction in heat dissipation in the model. From Figure 6-11 (e-g), after changing the blood flow ratio of P-71 to P-25, the impact on blood flow is not severe, but it reduces the increase in blood flow at the beginning of bathing. This may be the reason for the proportional reduction in blood flow in the core layer.

These differences underscore the sensitivity of physiological models to the parameters governing blood flow distribution, which are crucial for accurately simulating the thermoregulatory and cardiovascular responses during hyperthermic conditions. It is worth noting that when the sweating temperature threshold decreases, the heat dissipation through sweating increases, and the skin temperature is lower than the results without a change in the sweating threshold temperature (as shown in Figure 6-10 (a)). However, the experimental results show that the skin temperature P-71 with a higher sweating threshold temperature is lower than P-25, inconsistent with the sensitivity analysis of sweat threshold temperature results. Furthermore, the sensitivity analysis of blood flow distribution shows that when the blood flow ratio of the skin layer is increased, the skin temperature will increase accordingly. Hence, the superimposed influence of the two factors can ultimately successfully predict the physiological response of the skin temperature of older adults.

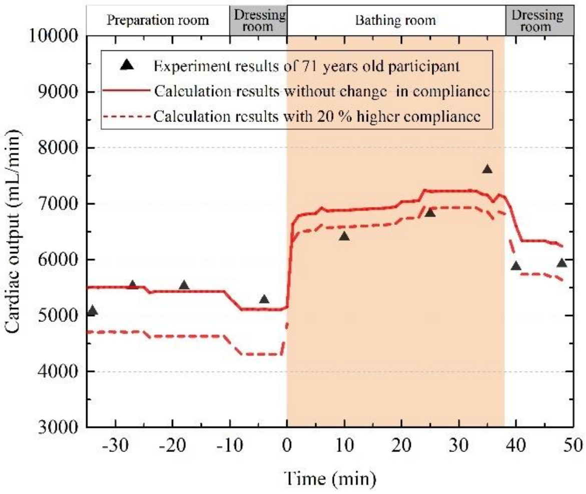
6.4.4 Influence of compliance change



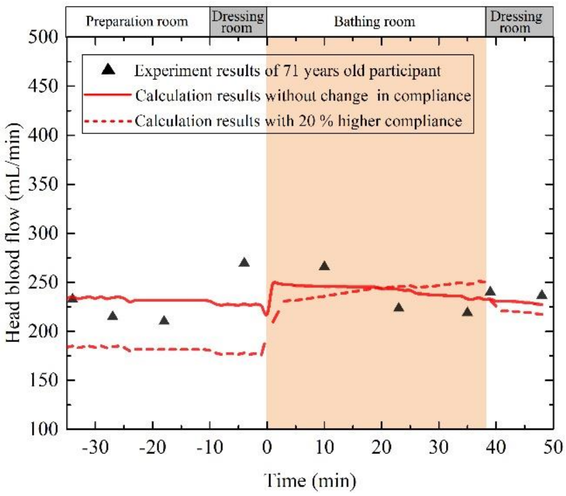
(a) mean skin temperature (b) Core temperature



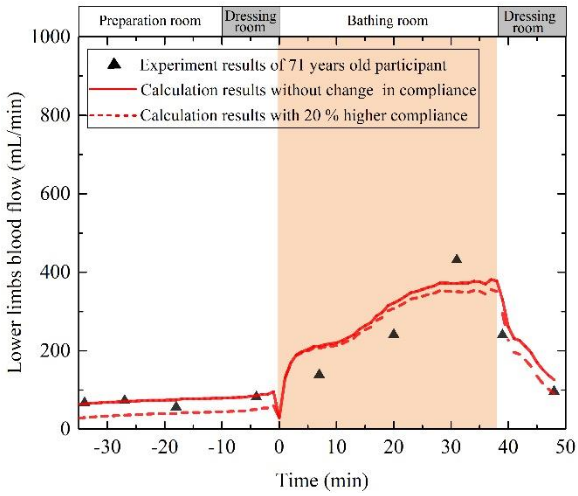
(c) Blood pressure



(d) Cardiac output



(e) Head blood flow



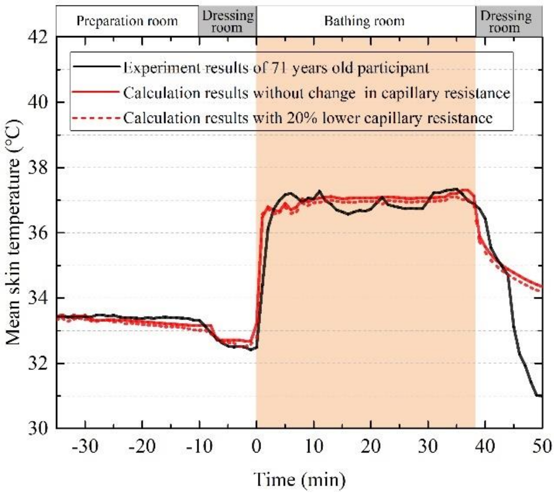
(f) Lower limbs blood flow

Figure 6-12 Comparison results: mean skin temperature, core temperature, blood pressure, and blood flow

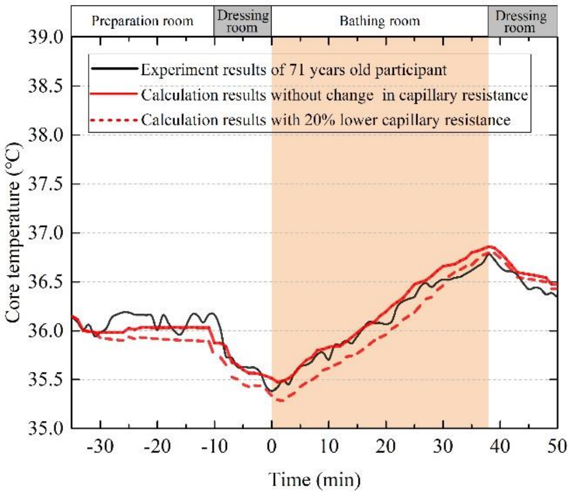
Figure 6-12 shows the comparison results considering the changes in compliance. From Figure 12 (a-b), changes in compliance have a very small impact on the calculation results of average skin temperature and core temperature and can be ignored from the perspective of prediction. The calculation results with 20 % higher compliance consistently overestimate blood pressure throughout the procedure, the difference between systolic and diastolic blood pressure is smaller than the results without a change in compliance (as shown in Figure 6-12 (c)). From Figure 12 (e-f), the 20% increase in compliance affects the overall blood flow is lower than the results without change in compliance, but the increase in blood flow increases significantly at the beginning of bathing.

In summary, the 20% higher compliance significantly affects the extent of the increase in blood flow at the beginning of bathing. That is, when the instantaneous environment changes significantly, the calculation results of higher compliance (younger) blood flow respond more violently, which is consistent with the actual experiment.

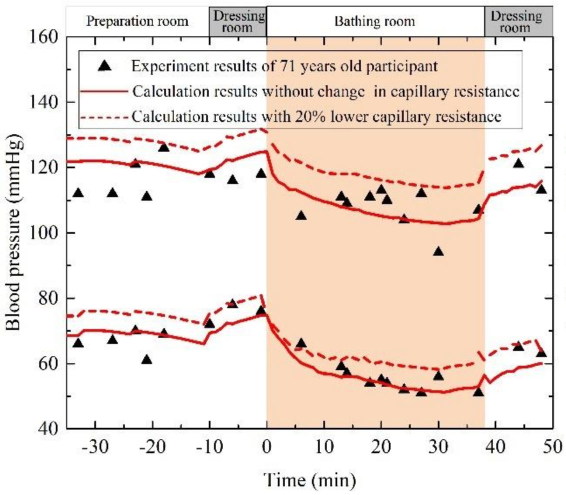
6.4.5 Influence of capillary resistance change



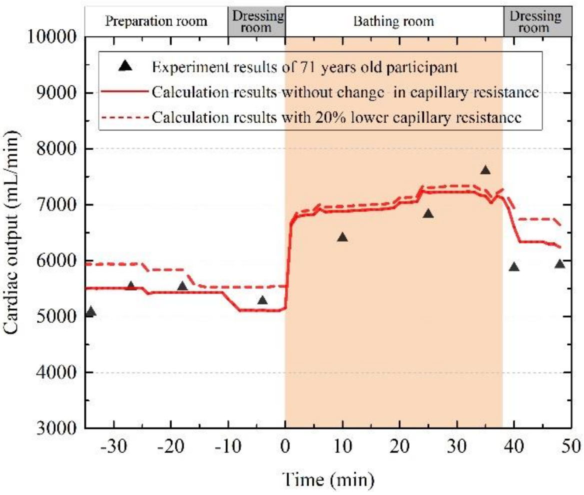
(a) mean skin temperature



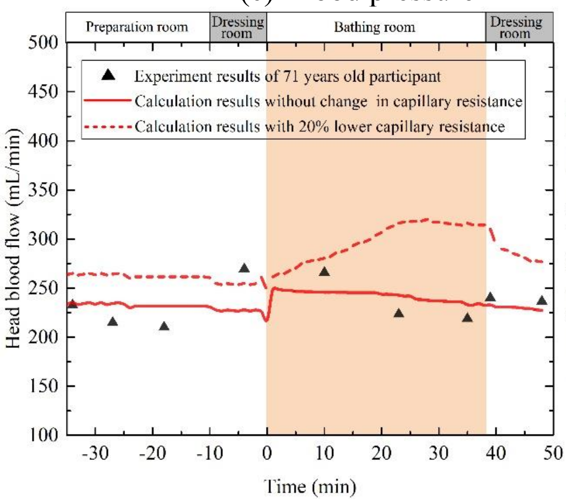
(b) Core temperature



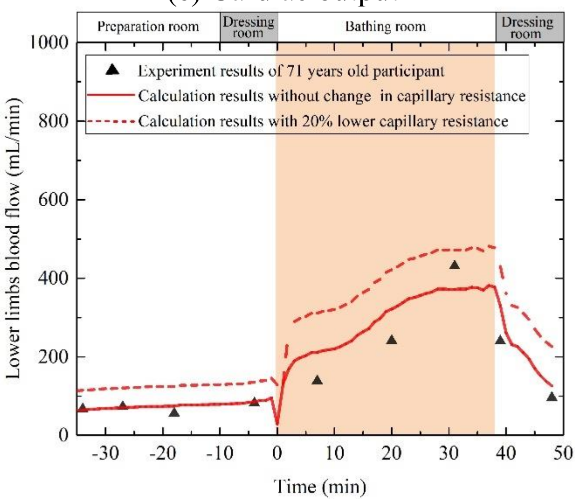
(c) Blood pressure



(e) Cardiac output



(f) Head blood flow



(g) Lower limbs blood flow

Figure 6-13 Comparison results: mean skin temperature, core temperature, blood pressure, and blood flow

Figure 6-13 presents the comparative findings about the influence of capillary resistance. According to the data shown in Figure 6-13 (a-b), a reduction of 20% in capillary resistance has a relatively minor effect on the computed average skin temperature, resulting in a slightly lower value compared to the scenario with constant capillary resistance. The findings from the analysis of core temperature indicate a statistically significant reduction after a 20% decrease in capillary resistance. Notably, the most substantial disparity was observed during the intermediate phase. The diagram in Figure 6-13 (c) indicates that decreased capillary resistance impacts the elevation of blood pressure and decreases its decline. Based on the blood flow data presented in Figure 13 (e-g), it can be observed that a notable enhancement in the overall blood flow, particularly in the head and lower limbs during the bathing process, is evident when capillary resistance is reduced.

In brief, when P-71 calculations consider younger capillary resistance (a 20% decrease)，discrepancies manifest as excessive alterations in core temperature, inadequate blood pressure reductions, and exaggerated blood flow estimations.

The resistance of capillaries plays a crucial role in modulating blood flow, thereby influencing heat transfer between the human body and the environment. However, when predicting changes (such as core temperature etc.) across different age groups, relying solely on variations in this parameter is insufficient. It is essential to consider age-related differences in blood flow distribution and other parameters. By integrating multiple factors that account for age disparities, a more precise prediction of physiological responses to core temperature can be achieved.

6.5 Conclusions

This chapter details the successful optimization of the original TCRM into a personalized version, confirmed through various experimental validations. The specific conclusions are as follows:

1) The model was optimized to enhance prediction accuracy for local skin temperature and head blood flow by incorporating the effects of local skin temperature and head arteriovenous anastomoses (AVAs).

2) Adjustments for aging-related physiological parameters (such as BMR, sweat threshold, blood distribution, arterial compliance, and capillary resistance) allowed the TCRM to suit a broader age range, validated by experiments involving participants aged 25, 52, and 71.

The proposed individual TCRM effectively predicts various physiological responses across different age groups, essential for managing heat stress and ensuring safe bathing conditions for older adults. Future developments include expanding the model to predict the responses of women of various ages to provide a comprehensive assessment of thermal comfort and risk in bathing environments.

Chapter 6 References

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Chapter 7 Conclusions

In this thesis, in order to establish a method for evaluating the thermal environment to achieve comfortable bathing, a thermo-cardiovascular regulation model was developed and validated with various bathing experiments to predict physiological responses (such as skin temperature, core temperatures, blood pressure, and blood flow) in the non-uniform bathing thermal environment. The model was further optimized for different age groups to an individual model, which considered various physiological parameters of aging and accurately reflected age-related differences in physiological responses. It enhances its effectiveness in predicting responses and guiding safe bathing practices.

Chapter 2 Physiological responses in non-uniform bathing thermal environments:

- A bathing experiment involving a 50-year-old male participant was conducted to analyze physiological responses during bathing, measuring skin temperature, core temperature, blood pressure, and blood flow.
- Skin temperature varied less in air than in hot water, while core temperature changes were more gradual, with tympanic temperature showing more pronounced changes than rectal temperature.
- Blood pressure and heart rate were significantly affected, with risks of hypotension and increased pulse pressure observed, alongside substantial variations in blood flow volume and distribution in different body parts.

Chapter 3 Development of the thermo-cardiovascular regulation model:

- Based on the Stolwijk model improve HTM. Considering the non-uniform bathing thermal environment divides body into 37 segments. (Stolwijk model divides body into 14 segments). Improvement of the constant metabolic rate to variable considering the heart rate changes, which affects changes in metabolic heat production.
- Based on the Windkessel model improve CRM. Increase number of divisions in systemic circulatory system to better adapt the HTM. Considering HR experimental results, this study optimized the original model from a constant pumping rate of 60 times per minute (compliance) to varying (real HR).

- Coupling two models to thermo-cardiovascular regulation model. Considering the corresponding segmented parts of the body. In coupling model, using temperature from HTM to calculate the AVA resistance, and effect the BF calculations in CRM, re-affects the amount of blood heat transfer in HTM.

Chapter 4 Validation of the thermo-cardiovascular regulation model:

- Validated through various simulation and experimental bathing studies, the results demonstrate that the proposed model accurately predicts physiological responses during bathing, including mean skin temperature, core temperature, blood pressure, and blood flow.
- Changes in metabolic rate and heart rate significantly affect physiological responses during bathing, especially blood pressure and blood flow volume. The proposed model considering the metabolic rate change has good accuracy in predicting the Tcore, BP, and BF, especially during bathing. The results demonstrate that the heart rate changes significantly impact the mean Tskin, Tcore, BP, and BF.
- Incorporating these changes enhanced the prediction accuracy of the thermo-cardiovascular regulation model.

Chapter 5 Physiological and subjective responses different considering the age:

- Bathing experiments were conducted with three participants of different ages to analyses and compare thermal sensation (TS) and physiological responses in a non-uniform bathing thermal environment. Measurements included thermal sensation, heart rate (HR), blood pressure (BP), pulse pressure, blood flow (BF), SpO2, and body weight.
- In the same non-uniform bathing environment, younger participants experienced a quicker increase in TS compared to the older adult (P-71), who showed delayed and lesser TS during bathing.
- Physiological responses varied significantly with TS change, with P-71 exhibiting a more delayed and lesser thermal physiological response.
- P-71's TS and BP response differed from younger participants; an increase in TS was accompanied by a decrease in BP.
- In short-term bathing, P-71 with a delayed and slow thermal response experienced lower thermal health risks than younger participants.

Chapter 6 Original TCRM to individual TCRM Optimization:

- The original Thermal Cardiovascular Response Model (TCRM) developed in Chapter 3 was optimized by including local skin temperature and head arteriovenous anastomoses (AVAs) to calculate AVA resistance. This optimization improved the prediction accuracy of the bathing experiment results of the middle-aged participant's local skin temperature and head blood flow.
- The TCRM was further tailored for young, middle age, and old participants, considering physiological aging parameters (basal metabolic rate (BMR), sweat threshold temperature, arterial compliance, blood distribution, and capillary resistance), and validated with experimental results.
- The optimized TCRM accurately predicts skin temperature, core temperature, blood pressure, and blood flow for different age groups, aiding in assessing risks and recommending safe exposure times in bathing environments.
- Sensitivity analysis results prove that modifications in basal metabolic rate (BMR), sweat threshold temperature, arterial compliance, blood distribution, and capillary resistance influence physiological responses in bathing. Integrating these factors significantly improves the predictive capability of the thermo-cardiovascular regulation model for different age participants.

Future planning

In future research, we have several considerations for further investigation. Firstly, we plan to conduct longitudinal studies involving a single participant across multiple experimental dates to explore temporal variations in responses to the bathing environment. Additionally, we intend to undertake horizontal studies involving diverse participant groups, including older adults, young adults, and women, to gain insights into variations in thermo-cardiovascular responses among different demographics.

To enhance the thermo-cardiovascular regulation model, our goal is to incorporate a broader set of individual-specific parameters to predict thermal physiological responses in diverse populations, including older adults, young adults, and women. By considering additional factors, we aim to refine the model's predictive capabilities and improve its estimation of heart rate and other physiological responses during bathing.

Looking ahead, we also plan to optimize the thermo-cardiovascular regulation model by considering the impact of fluid loss-induced dehydration during bathing or other scenarios. We will explore experimental methods to measure blood viscosity in real time and involve assessing changes in blood viscosity before, during, and after fluid loss episodes induced by bathing, sleeping, or other conditions. To achieve this, we will integrate physiological parameters related to fluid loss into the model, such as sweat rate, urine output, and water intake. By accounting for these variables, we can more accurately simulate and quantify the effects of fluid loss on blood viscosity, we anticipate obtaining a more comprehensive understanding of the physiological implications of dehydration during bathing or similar contexts. This enriched model will contribute to improved assessments of the impact of fluid loss on cardiovascular health and aid in the development of preventive measures and interventions to mitigate potential health risks associated with dehydration.

By pursuing these research avenues, we anticipate significant advancements in understanding thermo-cardiovascular regulation due to thermal environmental control for keeping healthy and preventing healthy risk.

Papers related to this research

1. Han Liu, Daisuke Ogura, Shuichi Hokoi, Chiemi 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, vol.228, 2023. (JCR Q1, IF=7.093)
2. Han Liu, Daisuke Ogura, Shuichi Hokoi, Chiemi Iba, Thermal Sensation and Physiological Responses in Non-uniform Bathing Thermal Environment: A Comparative Study on 25-, 52-, and 71-year-old Participants. Building and Environment, 2023, accept. (JCR Q1, IF=7.093)
3. Han Liu, Daisuke Ogura, Shuichi Hokoi, Chiemi Iba, Development of blood circulation prediction model for the design of healthy bathing thermal environment. Part 1 Experiment of human physiological response considering blood flow and dehydration during bathing. Architectural Institute Conference of Japan, Chiba, Japan, pp.181-182, 2020.

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