Study on a thermophysiological model for health assessment of showering environment in China

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Abstract. In China, the thermal environment of family showers in old communities is quite different from that of other living spaces, especially when the thermal environment changes drastically during showering, which can easily cause health problems. The human thermal physiological model is an effective tool to predict and evaluate the non-uniform and unstable shower thermal environment and human health risks. In this research, the showering experiment was carried out in a typical bathroom in an old community in China, during which environmental parameters such as air temperature, wall temperature and water temperature of the bathroom during the showering were recorded, and physiological parameters such as skin temperature, core temperature and blood pressure during the whole showering process were detected. Based on the multi-node numerical human body model of Stowljik and a cardiovascular control model with human body temperature as the driving force, a temperature-blood pressure coupling prediction model was established. The validity of the proposed model was examined for blood circulation. This predictive model can accurately reflect changes in physiological parameters and is verified as suitable for the health assessment of showering environment in residential buildings.

1. Introduction

The thermal environment of a residence has an important influence on the safety, health and comfort of its residents. In the literature on the regulation and control of indoor thermal environment, researchers have paid relatively little attention to bathrooms, which have thermal environments that differ substantially from those of other residential spaces (bedrooms, living rooms, etc.). In China, residential communities built in the 1980s and 1990s are facing renovation because they cannot meet the demands of contemporary life. In a large number of old residential communities in China, the bathrooms pose particular problems. Typically, the bathroom is a composite space with the functions of washing, defecation and showering (Figure 1). The thermal environment of the narrow bathroom is unevenly distributed for the lack of external wall insulation (Figure 2). When the residents take showers (especially in winter), the uneven and drastic change in the thermal environment causes the human body’s thermal physiological reaction, which brings thermal discomfort.

Studies show that changes in the thermal environment can impact human body temperature [1], blood pressure [2] and other physiological indicators. Drastic changes in blood pressure and blood flow are easy to induce various cardiovascular and cerebrovascular diseases [3][4]. The existing health assessment of built environment focuses on buildings [5], built environment [6] and environmental factors [7], etc., and has a weak correlation with human body health. It is helpful to evaluate the health...
of the thermal environment of residential buildings by clarifying the influence of dynamic thermal environment changes on human thermal physiological indexes. The thermal physiological model [8] can simulate the changes of human thermal physiological indexes in a thermal uneven environment [9] and establish a direct relationship with human body health.

Stolwijk developed a multi-node model [10] that predicts the temperature of the human body, but it does not consider the influence of countercurrent exchange on blood flow and the blood flow characteristics in local tissues. The multi-element model [11][12] simulates arteries and veins to predict human temperature and blood pressure, but it is too complex and has poor applicability. Research on theoretical models of the human cardiovascular control system has promoted the development of blood pressure prediction. Mette. S [13] explored the changes of blood pressure and blood flow during posture change and developed and validated a blood pressure prediction model under the influence of instantaneous posture change. Yoshioka [14], Hokoi et al. [15] coupled the human body temperature model with the cardiovascular control model to evaluate the changes of blood pressure in people’s daily lives. However, few studies have investigated the quantitative relationship between changes in the thermal environment and human physiological reaction mechanisms, and there is no research on the prediction of human body temperature and blood pressure in a Chinese showering environment.

Based on the human body temperature model and human cardiovascular control model, this study conducted showering experiments in typical cases. The aim was to establish a coupled calculation model of human body temperature and blood pressure for the Chinese residential showering environment and use it for evaluating shower environments. The results of this study will contribute to the optimal design of bathroom environments in residential buildings and will provide a scientific basis for the optimal design of healthy buildings.

![Figure 1. Bathroom Section Map.](image1)

![Figure 2. Bathrooms in Old Community.](image2)

2. Methodology

2.1. Questionnaire survey

The Chengxian Street community, a typical old community in Nanjing, Jiangsu Province, China, was selected as the research object. According to the climate division, the research object is located in the cold winter and hot summer zone [16]. In this survey, 58 questionnaires were distributed to the residents in the community, of which 49 were valid. The research content included two parts: showering habits and equipment use. The investigation of showering behaviors included showering time, showering duration, body posture during showering, and position changes before and after showering. The investigation of equipment use in showering included ventilation habit during showering, the use of heating equipment, and the use of hot water equipment. The research results on showering behavior provided the basis for the showering process of the subjects in the later showering experiment.
2.2. Showering experiment
In this study, 96 residential flats in the Chengxian Street community were examined, and one of the typical residential bathrooms was selected for surveying and mapping (Figure 1) and for the showering experiment. During this experiment, the thermal environment parameters of the showering space and the physiological parameters of the human body were measured (Figures 3 and 4). The thermal environment parameters of the showering room included object temperature and air temperature. The object temperatures of six points were measured: interior wall (R1), exterior wall (R2), heating equipment (R3), floor (R4), window (R5), and hot water temperature (R6). In order to explore the influence of the air temperature difference in different positions on the thermal physiology before and after showering, four air temperature measurement points were arranged: two in the showering position (close to the head [A1] and close to the foot [A2]), one in the indoor bathroom (A3) and one in the outdoor (A4) in the bathroom. The physiological parameters of the human body included skin temperature, core temperature and blood pressure. The skin temperature was measured at the forehead (C1), abdomen (C4), arm (C5), thigh (C6), instep (C7) and chest (C8). Blood pressure was measured at the arm (C2) at the same height as the heart, and the core temperature was the rectal temperature (C3). The instruments used in the measurement were, blood pressure: Omron automatic sphygmomanometer (accuracy ±3mmHg), core temperature: Testo176T4 four-channel thermocouple temperature recorder (accuracy ±0.2℃), surface temperature of human body and objects: Grahtec GL240 thermocouple temperature recorder (accuracy ±0.2℃(0℃-+70℃)), air temperature: Hobo temperature and humidity self-meter (accuracy ±0.3℃).

The subject of the showering experiment was a 27-year-old male in good health. Based on the results of the previous questionnaire survey, the subject simulated the general showering behaviors investigated in 2.1. The experiment was divided into four stages: (1) preparation and rest before undressing; (2) taking off clothes and turning on the heating equipment in the bathroom; (3) turning on the hot water for showering; (4) turning off the hot water, wiping the body and staying in the bathroom. To increase the reliability of the data, four experiments were conducted. Average and standard deviation of four sets of data were calculated, and one set was selected to input into the prediction calculation model.

2.3. Predictive model
A predictive model of the human body’s thermal physiological response in a typical showering environment was established in the form of FORTRAN language. Based on the human cardiovascular control model proposed by Yoshioka et al. [14], the multi-node thermal physiological model proposed by Stolwijk [10] was optimized, and a coupled calculation model of human body temperature and blood pressure was established. In the iterative calculation of the model, the cycle calculation time interval of the temperature model is 30 s, and that of the blood pressure model is 0.001 s. The environmental
boundary parameters of the model come from the air temperature, hot water temperature, object temperature and so on.

The heat transfer between human body and surrounding thermal environment occurs through convection, radiation and conduction, such as equation (1) \( ENV: \) Convective heat transfer and radiation heat transfer on the body surface [W]; \( CHR: \) Radiation heat transfer coefficient [W/m²/k]; \( CHC: \) Convective heat transfer coefficient [W/m²/k]; \( Sr: \) The ratio of body surface area of each node; \( S: \) Body surface area [m²]; \( T: \) Temperature [°C]; \( i: \) Node number of each part of human body). The surrounding thermal environment includes the air temperature, hot water temperature, heating equipment temperature and object surface temperature, including 9 nodes. The human body was divided into following parts: head core layer \((i = 7)\), trunk core layer \((i = 2,11)\), trunk muscle layer \((i = 3,5,12,14)\), limbs core layer \((i = 16,19,22,25,29)\), skin layer \((i = 4,6,8,9,10,13,15,17,18,20,21,23,24,28,26,27,30,31)\) and central blood \((i = 1)\), with 31 nodes (Figure 8) in total. From the heat balance equation (2) of the human body, the nodal total balance equation (3) of the human body can be obtained (\( C: \) Human body heat capacity [kJ/k]; \( t: \) Time [s]; \( MTB: \) Basal metabolism heat production [W]; \( SHV: \) Shivering heat production [W]; \( EXS: \) Exercise heat production [W]); \( EVR: \) Respiration heat loss [W]; \( EVI: \) Insensitive evaporation heat loss [W]; \( SWT: \) Sweating heat loss [W]; \( BF: \) Blood flow transfers heat [W]; \( CD: \) Heat transfer between layers [W]). The amount of blood in the blood vessels of the human body is constant. When the environment temperature causes the expansion of blood vessels to increase or decrease, the blood volume of each node of the cardiovascular system increases and decreases correspondingly. The equation for the cardiovascular equilibrium node is shown in equation (4) (\( G: \) Vascular compliance [L/mmHg]; \( P: \) Node pressure (blood pressure) [mmHg]; \( R: \) Blood flow resistance between nodes [mmHg/s/L]). On the basis of the human body temperature model, the cardiovascular regulation formula is put into the body temperature blood pressure coupling calculation model. In addition, the correlation coefficients of thermal radiation, heat convection, interlayer conduction, blood circulation, evaporation, perspiration, shivering, metabolism and other functions in the Stolwijk model were modified based on the measured data from the field showering experiment in 2.2.

\[
ENV_i = Sr_i \cdot S(CHR_i + CHC_i)\Delta T_i
\]

\[
C_i \frac{dT_i}{dt} = MTB_i + SHV_i + EXS_i - EVR_i - EVI_i - SWT_i - BF_i - CD_i - ENV_i
\]

\[
T_i(t) = \left\{ \frac{(MTB_i(t) + SHV_i(t) + EXS_i(t) - EVR_i(t) - EVI_i(t) - SWT_i(t) - BF_i(t) - CD_i(t) - ENV_i(t))}{C_i(t) \cdot MR_i(t)} \right\} + T_i(t)\]

\[
G_i(t) \cdot P_i(t) = \left[ \frac{P_i(t' + d) - P_i(t')}{R_1} - \frac{P_i(t) - P_i(t' + d)}{R_2} \right] \cdot dt + G_i(t) \cdot P_i(t')
\]

3. Results

3.1. Showering behaviors

According to the questionnaire survey, the showering duration in winter was mostly 10–20 minutes (39%), followed by 20–30 minutes (27%) and more than 30 minutes (24%). In the simulation, the showering duration in the showering experiment was set to 25 minutes. The showering time of the residents in the old community was mostly in the afternoon or evening (Table 1), so the showering experiment time was set for winter evenings. During showering, 82% of the residents maintained a standing posture, while 78% of them did not change their posture drastically. Ninety percent of the residents undressed and dressed in the bathroom. Many households closed their windows (36%) and used ceiling-mounted radiant heaters (58%) (Table 2). The hot water temperature was set at 40–45 °C.
Table 1. Showering Time

| Gender | Before Breakfast | After Breakfast | Before Lunch | After Nap | Before Supper | After Supper | Before Sleep |
|--------|-----------------|-----------------|--------------|-----------|---------------|--------------|-------------|
| Male   | 4.08%           | 2.04%           | 0%           | 6.12%     | 0%            | 16.32%       | 10.20%      |
| Female | 8.16%           | 0%              | 0%           | 8.16%     | 4.08%         | 18.36%       | 22.45%      |
| Total  | 12.25%          | 2.04%           | 0%           | 14.29%    | 4.08%         | 34.69%       | 32.65%      |

Table 2. Heating Equipment in Winter

| Heating Equipment | Heating Radiation (fixed) | Heating Radiation (mobile) | Heating Convection (fixed) | Heating Convection (mobile) | None | Others |
|-------------------|---------------------------|----------------------------|----------------------------|----------------------------|------|--------|
| Percentage        | 58%                       | 2%                         | 3%                         | 10%                        | 5%   | 25%    |

3.2. Thermal environment of showering

The air, hot water and wall temperatures were measured before and after showering. In winter, the temperature of the showering environment was about 10 °C. The measured air temperature data in Figure 5 show that the thermal environment was unevenly distributed in the vertical direction (the air temperature difference is more than 10 °C). It can be seen from the measured data of object surface temperature in Figure 6 that before showering, the surface temperatures of inner wall (R1), outer wall (R2), outer window (R5) and floor (R4) are similar, with an average temperature difference of 5.2 °C; while showering, the temperature difference on the surface of the object is 12.4 °C.

![Figure 5](image1.png)  ![Figure 6](image2.png)

3.3. Thermophysiological characteristics

The temperature changes of rectum, forehead, arm and instep can be seen from the measured data of human physiological temperature in Figure 7. At the second stage of showering, the rectal temperature of the subjects remained constant, and the forehead skin temperature was 34.7 °C. In stage 3, hot water had a great effect on forehead skin temperature, and the highest forehead skin temperature was 37.7 °C. At stage 3, the core body temperature continued to rise during showering. At the end of stage 3, the core temperature was 38 °C. After stage 3, the core temperature continued to rise to 38.7 °C. After reaching the peak value, the rectal temperature decreased slowly at a rate of 0.02 °C/min.

The changes of blood pressure and heart rate can be seen in Figure 9. During the shower, blood pressure increased, then decreased and then increased. Before stage 2, average blood pressure was 123/78 mmHg (±3mmHg). In stage 2, average blood pressure was 129/81 mmHg (±3mmHg). Average blood pressure was 118/75 mmHg (±20mmHg) during the shower; after stopping the hot water supply, it was 119/77 mmHg (±20mmHg). The highest heart rate was 138 beats/min, and rate variability was large.

3.4. Model evaluation
As shown in Figure 7(a), the prediction accuracy of the model for the change range and rate of the core body temperature during showering was high, and the correlation between the measured and the simulated values was 0.972. The prediction accuracy of the predictive model was within 0.17 °C, and that of the change rate was within 0.04 °C. In stage 2, the simulated value of the core body temperature decreased at a rate of 0.006 °C/min. The measured temperature was unchanged. The simulated value can be considered to objectively simulate the actual core temperature variation. The core temperature increased to 38.2 °C. The change rate of the simulated and measured values of the core temperature was 0.037 °C/min and 0.033 °C/min, respectively, and the difference between the measured and the simulated values of the core temperature was only 0.004 °C, with high accuracy. In stage 4, the core temperature of the measured and the simulated values continued to rise, to 38.7 °C and 38.5 °C, respectively, and then decreased slowly. The temperature drop rate of the simulated and measured core temperature was 0.025 °C/min and 0.021 °C/min, respectively. Due to the direct contact between hot water and the body surface, skin temperature was greatly disturbed by the water temperature. Figures 7(b–d) show that the trend of the skin temperature prediction model matched that of the measured temperature values.

The change range of the simulated and the measured blood pressure values was consistent, and the simulated blood pressure value accurately reflected the actual blood pressure change rate and change range (see Figure 9). At stage 2, the simulated and measured mean blood pressures were 135/82 mmHg and 129/81 mmHg, respectively. Both simulated and measured blood pressures showed an upward trend. At stage 3, the simulated and measured blood pressures were reduced to 110/70 mmHg and 110/68 mmHg, respectively. The simulated blood pressure reflected the trend of blood pressure changes more accurately. At stage 4, the simulated and measured mean blood pressures were 112/72 mmHg and 119/77 mmHg, respectively. The measured blood pressure began to rise at 60 minutes, while the simulated blood pressure increased after 80 minutes. The simulated blood pressure showed a lag compared with the measured value. This may be due to the fact that the decrease of body temperature in the first 20 min did not cause significant changes in blood flow or vascular dilation.

Figure 7. Temperature Measured and Simulated.
4. Discussion

Through field investigation and measurement and the establishment of a human thermophysiological predictive model, the showering environment in old residential areas in China can be assessed. As the goal of this study was to evaluate the health of the showering environment, the experiment was carried out in a real residence. From the survey of residents’ showering behaviors, it was found that residents adapted their showering behaviors to the showering space. When the showering space was narrow, most residents chose to stand in the shower for 10-20 minutes. When showering in the afternoon or evening in winter, residents preferred to close the windows, turn on the radiant heater, and undress and dress in the bathroom. From the field measurement of the thermal environment of the shower, it can be seen that the temperature distribution of the showering environment was uneven, and the air temperature difference in the vertical direction was more than 10 °C. Before and after showering, the air and wall temperatures in the showering space changed significantly, which led to health hazards. The results of the showering experiment showed that the core body temperature increased both during and after showering, rising to over 38 °C. Blood pressure increased by more than 5–10 mmHg within 2–3 minutes after stripping (similar pattern of four experiments); blood pressure during the shower was less than or equal to the daily average blood pressure. When the hot water supply stopped, blood pressure was greater than or equal to blood pressure during the shower.

To more quantitatively establish the relationship between thermal environment and human physiological response mechanisms, based on Stolwijk’s human body temperature model and Yoshioka and Hokoi’s human cardiovascular control model, a coupled temperature-blood pressure predictive model suitable for such showering environment was established. The environmental parameters and human physiological parameters measured in the field provided boundary conditions and check references for the predictive model. Overall, the predictive model accurately predicted changes in core
temperature and blood pressure when showering, and was a supplement case study for physiological changes of human body bathing in winter [17]. The model established a quantitative correlation between human body pressure, blood flow and changes in the thermal environment, which can provide a reference for research on human health under uneven thermal environments in architectural design, human thermal engineering, basic medicine, aerospace and other fields.

This study had two limitations. Although the use of four experiments avoided the contingency of measurement results, the study was limited to a single case study that lacked testing instruments and individual differences in subjects’ cases. Moreover, the health assessment of the showering environment focused on human body temperature and blood pressure. Additional health-related physiological indicators need to be explored.

5. Conclusion
This study aimed to establish a coupled, predictive human body temperature and blood pressure model suitable for the showering environment in old residential communities in China. The main conclusions are as follows:

1. Residents adapt their showering behavior to the size of their showering spaces.
2. The temperature distribution of the showering environment was uneven, and the air temperature difference in the vertical direction was large (>10 °C). Before and after showering, the air and wall temperatures in the showering space changed significantly, which tends to cause health risks.
3. The model established in this study accurately reflects changes in human body temperature and blood pressure. We believe our model can be also applied to modern bathrooms under much milder thermal environment. The model is thus suitable for the health assessment of showering environment in residential buildings.

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