F: Physical responses & physiology
F.2. Health assessment (incl. Thermal comfort)

MEASUREMENTS OF BLOOD FLOW AND BLOOD PRESSURE UNDER DIFFERENT INDOOR TEMPERATURE AND BODY POSTURAL CONDITIONS, AND DEVELOPMENT OF A NEW HUMAN SIMULATION MODEL

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SUMMARY

Numerical simulation with human thermophysiological model is one of the useful methods in order to evaluate the health risks caused by severe thermal environments. In addition, sudden changes in blood pressure (BP) and inadequate blood flow are key factors of those health problems. Therefore, we are developing a new human thermophysiological model, which can predict BP and blood flow as well as body temperature. In this study, we measured human physiological responses including BP and blood flow, because little experimental data on BP and blood flow were available to be referred. The measurements were carried on a healthy young man under three different conditions; 28^{o}C Sedentary, 35^{o}C Sedentary and 28^{o}C Standing. The BP was measured with the oscillometric method, and the blood flow was measured with an ultrasound imaging equipment and a laser blood flow meter. In these measurements, we observed the quantitative changes in blood flow, BP, stroke volume and heart rate due to indoor temperature and body position. On the other hand, we developed a simulation model of the cardiovascular system to be integrated into the new human model. The simulation results by this model were found to be reasonably matched with the measurements.

INTRODUCTION

Severe thermal environments cause human health problems, e.g. heat illness, cerebral stroke, heart attack, etc. and those incidences in Japan are increasing as the population ages (Ministry of the environment government of Japan, 2014; Tokyo metropolitan institute of gerontology, 2013). In the mechanism of those diseases, inadequate blood flow in vital organs and sudden changes in BP are key factors. Under hot environments, increase in skin blood flow is very important to prevent hyperthermia, while it can bring about cerebral ischemia or undue stress on heart (Ministry of the environment government of Japan, 2014). On the other hand, sudden changes of thermal environment cause sudden changes of BP because of vasodilation or vasoconstriction, and consequently cerebral stroke or heart attack occurs (Y. Tochihara, 2012). Furthermore, those health problems are affected not only by thermal environments but also by individual behaviours (posture and activity level), physical constitutions (size, composition, etc.) and predispositions (pre-existing disorder, age, etc.). That is to say, the risks of those health problems are attributed to the combined effects of them.

Numerical simulation with human thermophysiological model is one of the useful methods in order to evaluate the health risks mentioned above. However, conventional human models cannot predict BP, and their predictions of blood flow are not sufficiently validated. Thus, no models are presently available to predict BP and blood flow. One reason is that the conventional models have been developed mainly for predicting body temperature. Another reason is that those values are difficult to measure, and hence little reference data are available.

Our final goal is the development of a new human thermophysiological model, which can predict not only body temperature but also BP and blood flow. Figure 1 shows the schematic of the developing model. The present study was carried out as a first step to this goal. In this study, we measured human physiological responses including BP and blood flow in order to collect reference data. And also we developed a cardiovascular model (1.B in Figure 1), which is one of the sub-models to be integrated in our new human model.

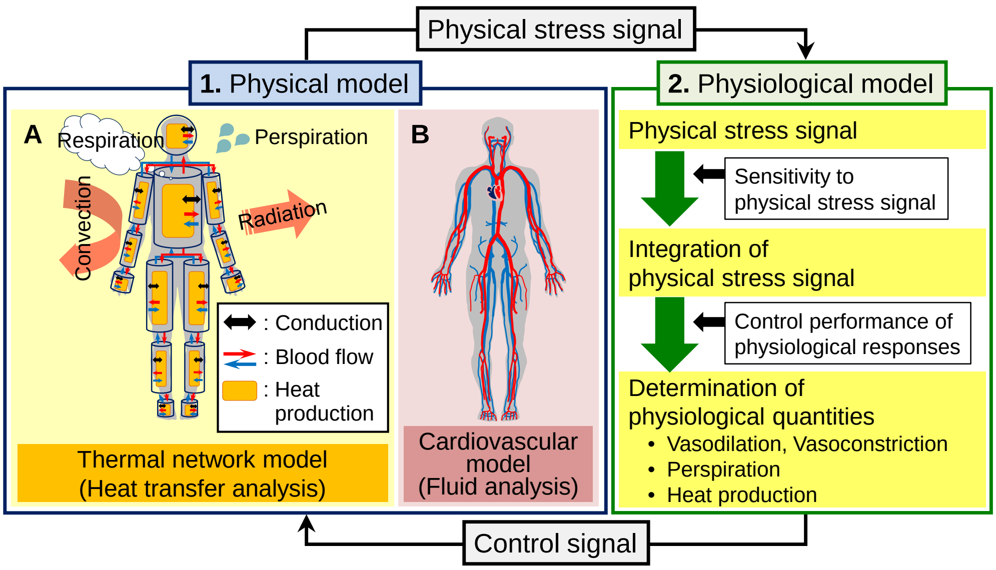

Figure 1. Schematic of new human thermophysiological model

METHODOLOGIES

Subjective Experiment

In this experiment, we focused on indoor temperature and body postural condition from among the influence factors on human physiological responses. The experiments were performed from November 30 to December 28 of 2013 and from August 5 to 26 of 2014, in a climate chamber. A healthy young male participated as a subject. Tables 1 and 2 respectively show the experimental conditions and measurement items. 28^{o}C Sedentary case was considered to be a thermally neutral and basic condition. 35^{o}C Sedentary case was a hotter condition, and 28^{o}C Standing case was a different body posture condition from the basic one. These cases were all steady state conditions although diseases are strongly related to unsteady conditions. Because we should well understand human responses in steady conditions and validate our simulation model for steady conditions before unsteady conditions.

Table 1. Experimental conditions

Case	Indoor temperature	Humidity	Air velocity	Radiant temperature	Clothing insulation	Metabolic rate
28 °C Sedentary	28 °C	Not controlled	Below 0.1 m/s	The same as indoor temperature	0.06 clo	1.0 met
35 °C Sedentary	35 °C					1.0 met
28 °C Standing	28 °C					1.2 met

Table 2. Measurement items

Measurement items	Measuring point
Arterial blood flow	Fifteen points (Table 3)
Skin blood flow	Sixteen points (Table 3)
Blood pressure	Upper arm, Ankle
Heart rate	Chest
Skin temperature	Forehead, Neck, Upper arm, Forearm, Hand, Thigh (front, back), Leg (front, back), Foot, Chest, Abdomen, Back, Waist
Core temperature	Tympanic
Heat flux	Forehead, Neck, Upper arm (front, back), Forearm (front, back), Hand (palm, dorsum), Thigh (front, back), Leg (front, back), Foot (dorsum, sole), Chest, Abdomen, Back, Waist

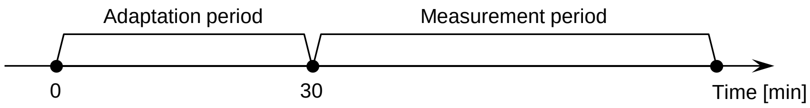

Figure 2. Experimental procedure

Table 3. Measuring points of blood flow rate

Measuring points of arterial blood flow		Measuring points of skin blood flow	
(1) Common carotid artery	(9) Femoral artery	(1) Forehead	(9) Hand (palm)
(2) Vertebral artery	(10) Deep femoral artery	(2) Chest	(10) Hand (dorsum)
(3) External artery	(11) Popliteal artery	(3) Abdomen	(11) Thigh (front)
(4) Internal artery	(12) Posterior tibial artery	(4) Back	(12) Thigh (back)
(5) Brachial artery	(13) Anterior artery	(5) Upper arm (front)	(13) Leg (front)
(6) Radial artery	(14) Abdominal artery	(6) Upper arm (back)	(14) Leg (back)
(7) Ulnar artery (central side)	(15) Left ventricular outflow tract	(7) Forearm (front)	(15) Foot (dorsum)
(8) Ulnar artery (peripheral side)		(8) Forearm (back)	(16) Foot (sole)

Figure 2 shows the experimental procedure. The subject adapted to the experimental conditions during 30 min before starting measurements. After the adaptation period, we measured BP at upper arm and leg, and then started to measure blood flow at each point. Table 3 shows the measuring points of arterial blood flow and skin blood flow. Arterial blood flow rate was calculated by multiplying blood flow velocity by cross-sectional area of the artery, which both were measured with an ultrasound imaging equipment (Aplio SSA-700A, TOSHIBA). Skin blood flow rate was measured at sixteen points with a laser blood flowmeter (FLO-Lab, OMEGAWAVE). The other items were measured continuously during the measurement period.

Numerical Simulation

In this study, we developed a simulation model of human cardiovascular system based on Liang et al. (2009), which will be integrated in our developing new human thermophysiological model (Figure 1). As shown in Figure 3, this cardiovascular model consists of one-dimensional (1-D) model and lumped parameter (0-D) model, and can calculate BP and blood flow. The 1-D model describes arterial tree which consists of 63 arteries. The governing equations of the 1-D model are shown in Table 4. The blood flow phenomenon at each artery is calculated from these equations, and that of each bifurcation is calculated based on the mass conservation and continuity of pressure. The 0-D model describes the remaining cardiovascular system which consists of 140 segments, i.e. peripheral circulation, veins, heart, pulmonary circulation. Each segment is expressed by a RLC circuit as shown in Figure 3, and these RLC circuits are connected each other. The governing equations of the 0-D model are shown in Table 5.

Liang et al. (2009) had provided quantitative values for the model parameters, e.g. vessel radius, compliance and so on. We referred to their values, but made some adjustments of personal characteristics for simulating the experimental subject of this study. On the other hand, some of the parameters such as the vessel compliance must change in nature due to thermal stress and body position. However, we have not included yet those physiological regulations in this model. Thus, only 28^{o}C Sedentary case was simulated in this study.

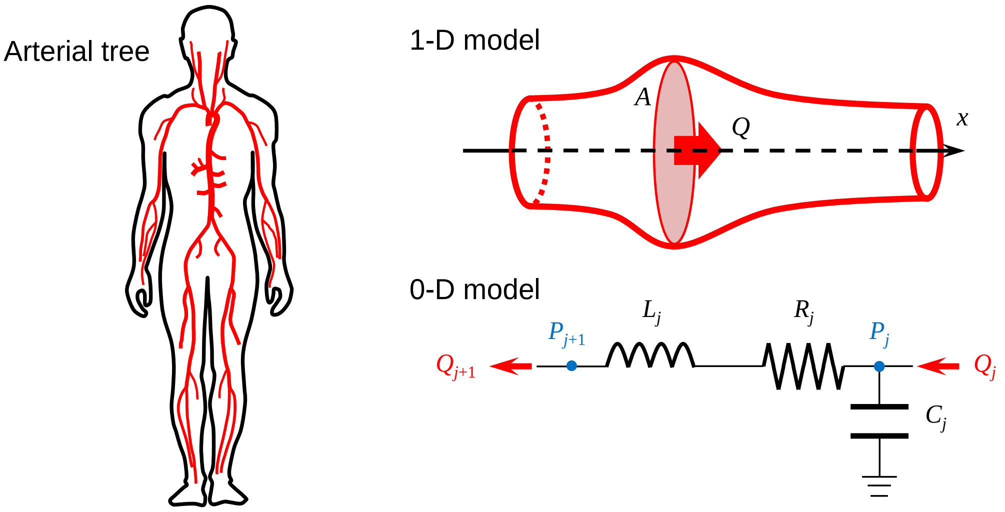

Figure 3. Schematic of cardiovascular model

Table 4. Equations of 1-D model

$$\frac{\partial A}{\partial t}+\frac{\partial Q}{\partial x}=0 \quad (1)$$

$$\frac{\partial Q}{\partial t}+\frac{\partial}{\partial x}\left(\frac{Q^2}{A}+\frac{A}{\rho}P+gAH\right)+\frac{2\pi r\nu}{\delta}\frac{Q}{A}=0 \quad (2)$$

$$P=\frac{Eh}{r_0(1-\sigma^2)}\left(\sqrt{\frac{A}{A_0}}-1\right) \quad (3)$$

Table 5. Equations of 0-D model

$$C_j\frac{dP_j}{dt}=Q_j-Q_{j+1} \quad (4)$$

$$P_j-P_{j+1}=Q_jR_j+L_j\frac{dQ_j}{dt}+\rho gH \quad (5)$$

RESULTS AND DISCUSSION

Subjective Experiment Results

Figure 4 shows measurement results of arterial blood flow rate. Most of the highest values were found in 35°C Sedentary case. It was due to thermoregulation for accelerating heat release from the body. Comparing to 28°C Sedentary case, the values in 28°C Standing case increased at femoral and deep femoral arteries but decreased at common carotid and abdominal arteries. It is possibly because oxygen demand at legs increased in the standing case than in the sedentary case.

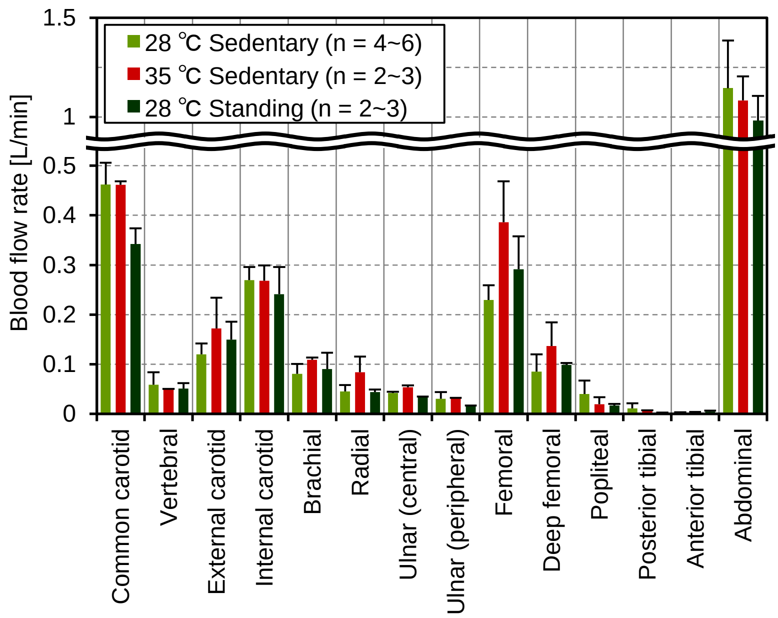

Figure 4. Arterial blood flow rate

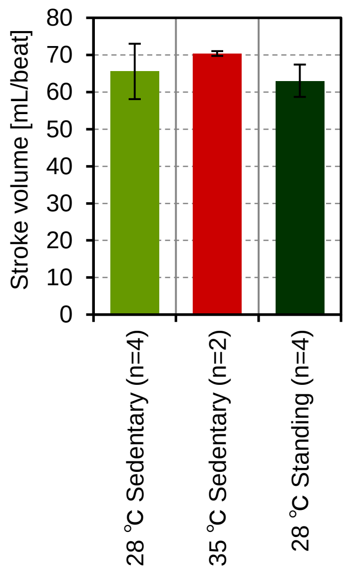

Figure 5. Stroke volume

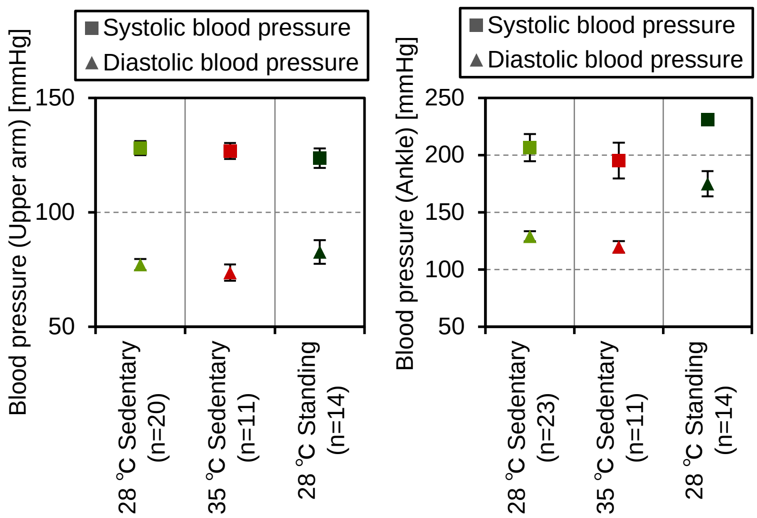

Figure 6. Blood pressure (Upper arm, Ankle)

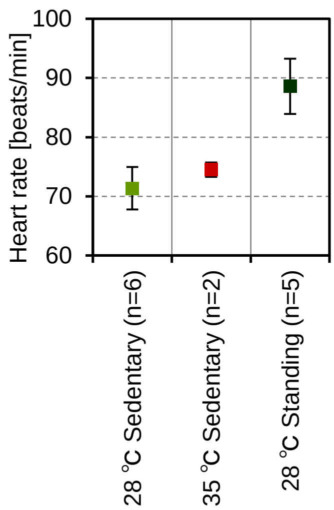

Figure 7. Heart rate

Figures 5, 6 and 7 show stroke volume, BP and heart rate respectively. The highest stroke volume was found in 35°C Sedentary case, and the BP in this case was slightly lower than that in 28°C Sedentary. It must be due to vasodilation. Additionally, the heart rate in this case was higher than that in 28°C Sedentary case. It also helped to increase the blood flow rate. In 28°C Standing case, the BP at ankle increased largely than 28°C Sedentary case. It was because the gravitational pressure increased at legs according to the change in vertical distance between the heart and legs. On the other hand, the stroke volume in the standing case seemed to be slightly lower than the sedentary case. It might be caused by blood stagnation in the legs whose veins were expanded by the pressure increase. The heart rate in the standing case was much higher than the sedentary case. It was for increasing blood flow, and possibly for coping with the stroke volume decrease, too.

Figure 8 shows skin blood flow rate. That in the 35°C Sedentary case was higher than in the other cases at almost all places, especially at arm and thigh. As discussed above, it was resulted from vasodilation of blood vessels.

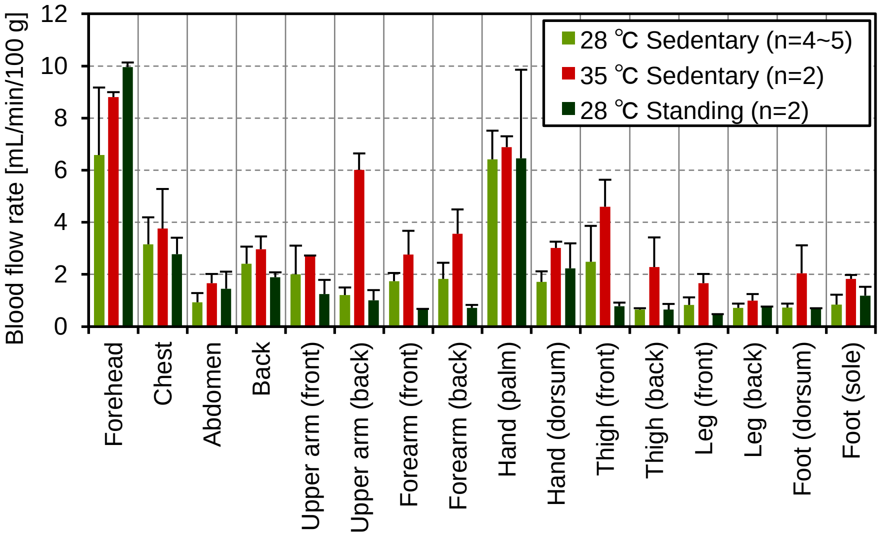

Figure 8. Skin blood flow rate

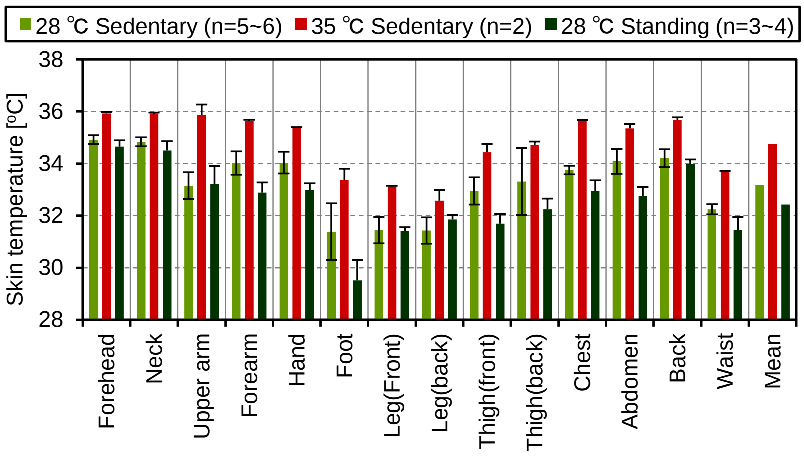

Figure 9. Skin temperature

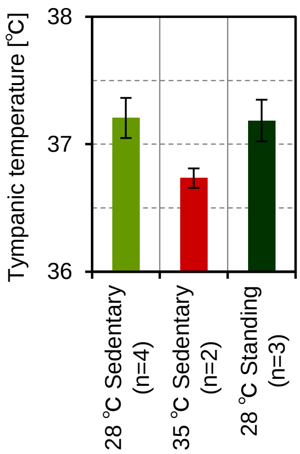

Figure 10. Tympanic temperature

Figures 9 and 10 show skin temperature and tympanic temperature respectively. The skin temperature in 35°C Sedentary case was the highest at every point because of the high thermal load and high skin blood flow rate. However, tympanic temperature in this case was the lowest. It can be explained as some kind of excessive thermoregulatory response against the hot environment. On the other hand, skin temperature in 28°C Standing case was lower than that in 28°C Sedentary case at almost all points. It may be due to higher sweat rate in the standing case, although the sweat rate was not measured in this experiment.

Numerical Simulation Results

Figures 11 and 12 compare the numerical simulation and experiment (28°C Sedentary) on arterial blood flow rate and stroke volume respectively. Those numerical results were found to be reasonably matched with the measurements.

Figure 13 shows the comparisons of BP. The simulated diastolic blood pressure was different from the experiment approx.10 mmHg at both arm and ankle, whereas the simulated systolic blood pressure was well agreed with the experiment. The diastolic pressure must be improved by more elaborative adjustments of model parameters.

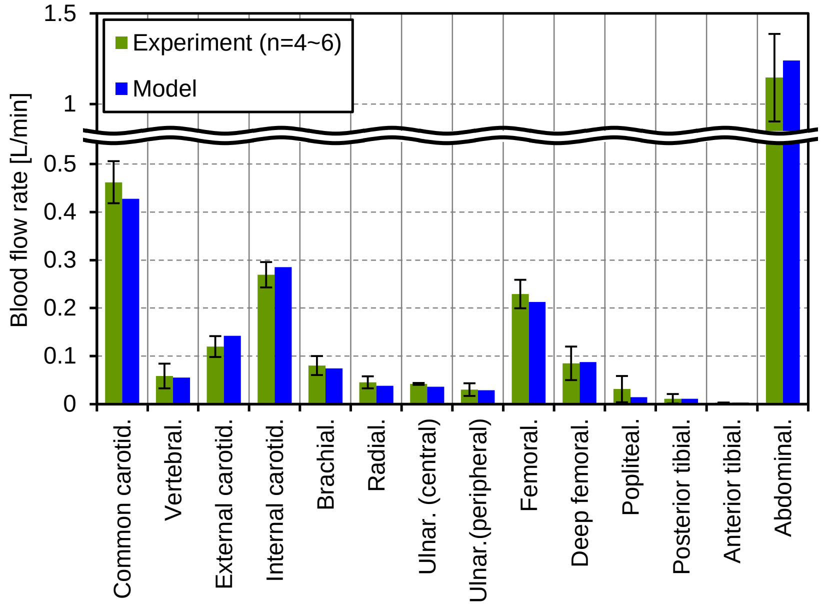

Figure 11. Arterial blood flow rate

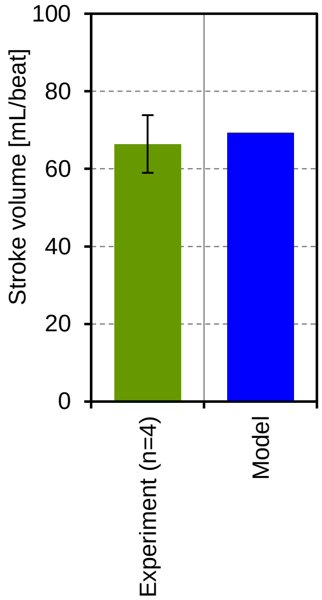

Figure 12. Stroke volume

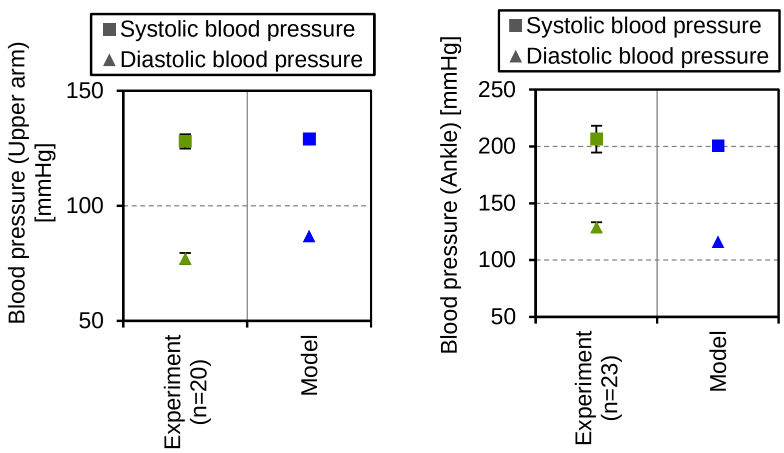

Figure 13. Blood pressure (Upper arm, Ankle)

CONCLUSIONS

We measured thermophysiological responses on a human subject including BP and blood flow in order to collect some reference data for developing a new human simulation model. Under a high indoor temperature condition, we found decrease in BP and increases in stroke volume, heart rate, arterial blood flow rate, and skin blood flow rate. These resulted in skin temperature rise and tympanic temperature fall. We also found changes in blood flow distribution, BP, and heart rate by comparing standing and sedentary conditions. In addition, we developed a simulation model of human cardiovascular system, and confirmed that the simulated arterial blood flow rate and BP were reasonably matched with the measurements.

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NOMENCLATURE

A: cross-sectional area, C: compliance, E: Young's modulus, g: gravitational acceleration, H: relative height, h: wall thickness, L: inertial resistance, P: pressure, Q: flow rate, R: resistance, r: vessel radius, t: time, x: axial coordinate, δ: boundary layer thickness, v: kinematic viscosity, ρ: blood density, σ: Poisson's ratio (=0.5)
Subscripts 0: reference state, j: segment number

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