Numerical and Experimental Study of the Relationship between Blood Circulation and Peripheral Temperature

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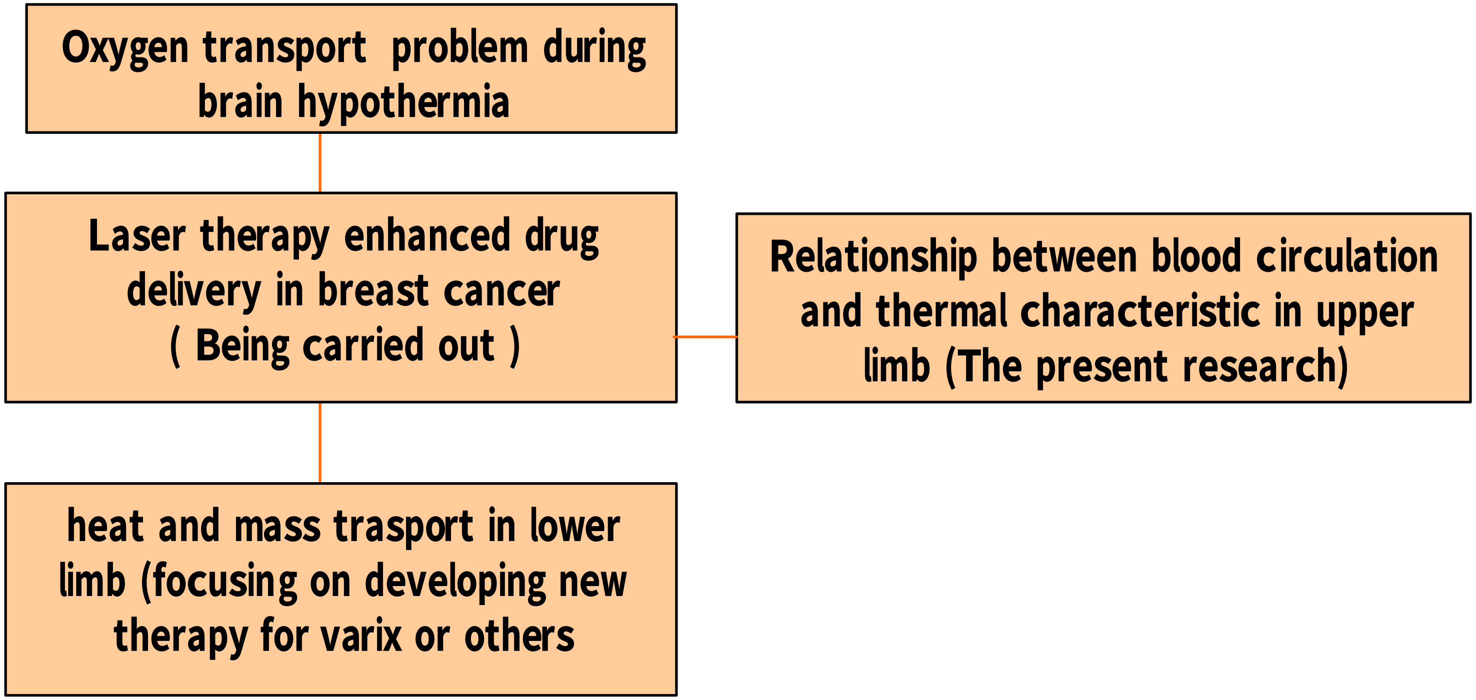
Research Background

- Circulatory system is not only related to the diseases of blood-vascular system, but also important for the development and treatment of diabetes, tumors, and so on.
- It is necessary to coupling the circulatory system with the organs to investigate heat and mass transport phenomena in living tissues

The Research plan on Numerical Analysis of Heat and Mass Transfer in living Tissues



Research Background (2)

- Blood Circulation significantly affect body temperature. The factors to affect the blood circulation will cause the variation of body temperature (especially the peripheral part).

→ Aging , Exercising, mental stress, Smoking etc…

- Diagnosing blood circulation illness by measuring skin temperature (such as by thermography)

- The relationship between blood circulation and peripheral temperature should be further investigated.

The research about thermal behavior of human body

- Two-dimensional thermal model of human finger
- Two-dimensional FE thermo-fluid model of human finger
- A thermo-fluid model of blood flow in compliant tubes
- A thermo-fluid model of blood circulation in upper limb

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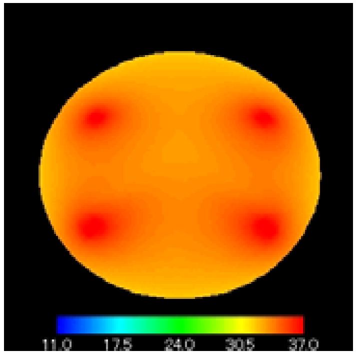
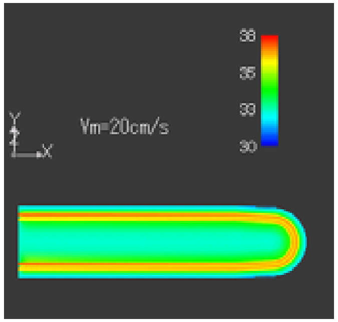
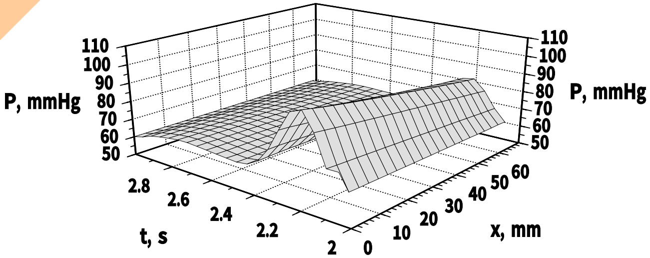






The previous studies

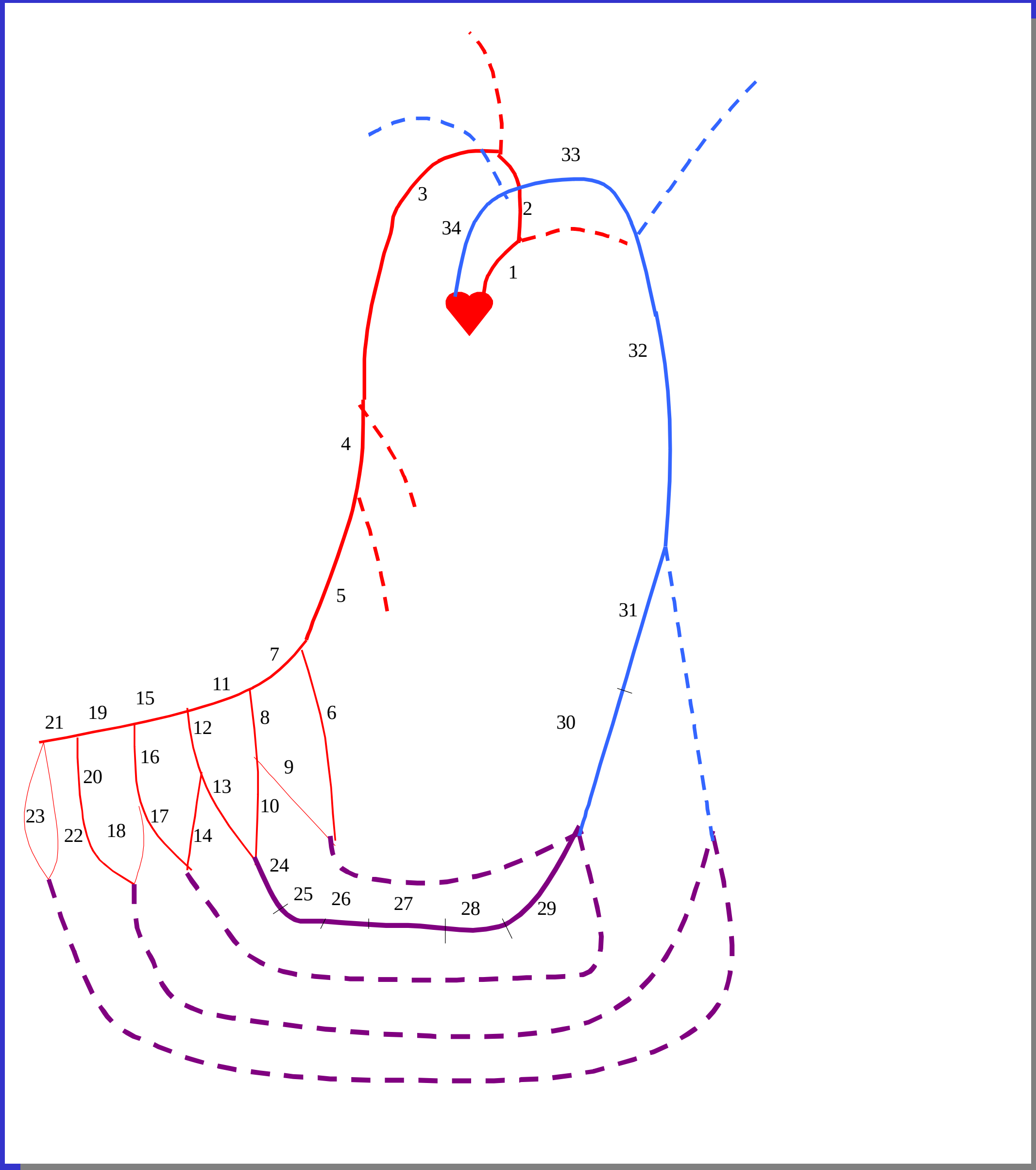
Hemodynamic models:

- Blood flow in arteries with structured –tree model (Olufsen, et al 2000)
- Blood flow in the cerebral circulation of man (Zagzoule, et al, 1986)
- Blood flow in the whole human circulation (Sheng, et al, 1995)
- The analysis of blood flow in branched arteries (Kitawaki and Himeno, 2000)
- Multi-scale model of blood flow (Liu, 2002)

Thermal model:

- Keller and Seiler's model (1971)
- Human thermal model (Takemori, et al, 1995)

Schematic diagram of the circulation system in upper limb



One dimensional model of elastic blood vessel

Continuity equation

$$\frac{\partial A}{\partial t} + \frac{\partial q}{\partial x} = 0$$

momentum equation

$$\frac{\partial q}{\partial t} + \frac{\partial}{\partial x}\left(\frac{q^2}{A}\right) + \frac{A}{\rho}\frac{\partial P}{\partial x} = -\frac{2\pi \nu R}{\delta}\frac{q}{A}$$

state equation

$$P(x,t) - P_0 = \frac{4}{3}\frac{Eh}{r_0}\left(1 - \sqrt{\frac{A_0}{A}}\right)$$

The equation by substituting state equation into momentum equation

$$\frac{\partial q}{\partial t}+\frac{\partial}{\partial x}\left(\frac{q^2}{A}+B\right)=-\frac{2\pi\nu R}{\delta}\frac{q}{A}+C$$

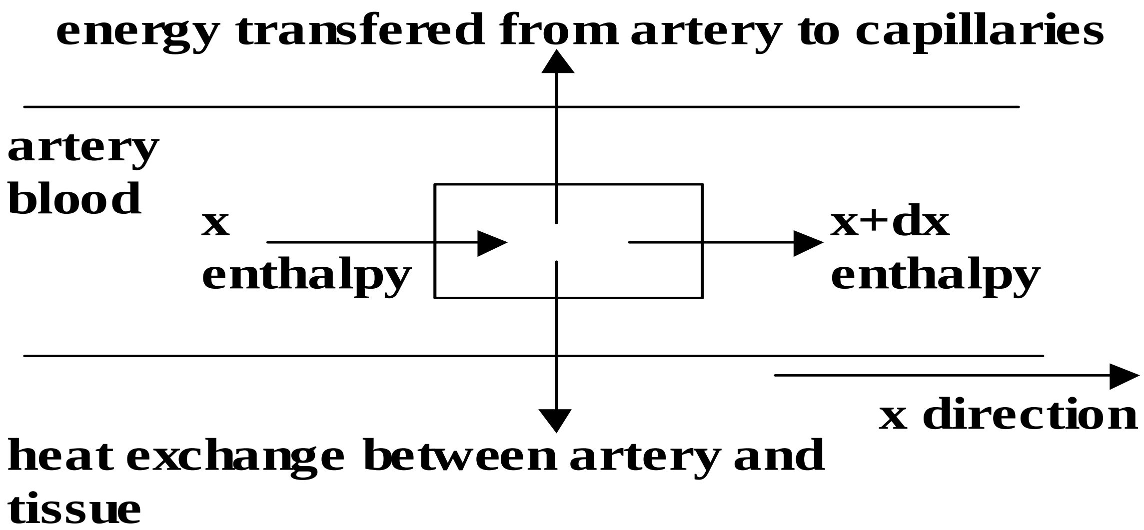
$$B=\sqrt{\pi A}\frac{1}{\rho}\frac{4}{3}Eh$$

$$C=\sqrt{\pi A}\frac{8}{3}\frac{1}{\rho}\frac{\partial}{\partial x}(Eh)-\frac{4}{3}\frac{A}{\rho}\frac{\partial}{\partial x}\left(\frac{Eh}{r_0}\right)$$

Energy equation

$$\frac{\partial(AT_a)}{\partial t}+\frac{\partial(qT_a)}{\partial x}=-\omega AT_a-\frac{(hA_s)}{\rho_b c_b}(T_a-T_t)$$

The Derivation of the Energy Equation



Energy Balance equation in Arteries

$$\frac{\partial(\rho_b c_b A T_a)}{\partial t} = -\frac{\partial(\rho_b c_b u A T_a)}{\partial x} - \omega \rho_b c_b A T_a - h A_s (T_a - T_t)$$

When the blood vessel becomes partially collapsed

$$P - P_0 = k_p \left[1 - \left(\frac{A}{A_0} \right)^{-3/2} \right] \qquad while \quad 0 \le \frac{A}{A_0} \le 1$$

$k_{p:}$ a parameter proportional to the bending stiffness of the tube wall

$$\frac{\partial q}{\partial t} + \frac{\partial}{\partial x}\left(\frac{q^2}{A} + B \right) = -\frac{2\sqrt{\pi}\nu}{\delta} \frac{q}{\sqrt{A_{equiv}}}$$

$$B = -\frac{3}{\rho}\sqrt{\frac{A_0^3}{A}k_p}$$

$$A = \frac{A_{total}}{n}$$

Initial and Boundary Conditions

Initial condition

$$P = P_0 \qquad q = 0 \qquad A = A_0 \qquad T = T_0$$

Inflow condition

- flow rate in physiological form (Mcdonald,1974)

$$q_{in} = q_{\max}(0.251 + 0.290(\cos\Phi + 0.97\cos 2\Phi + 0.47\cos 3\Phi + 0.14\cos 4\Phi)$$

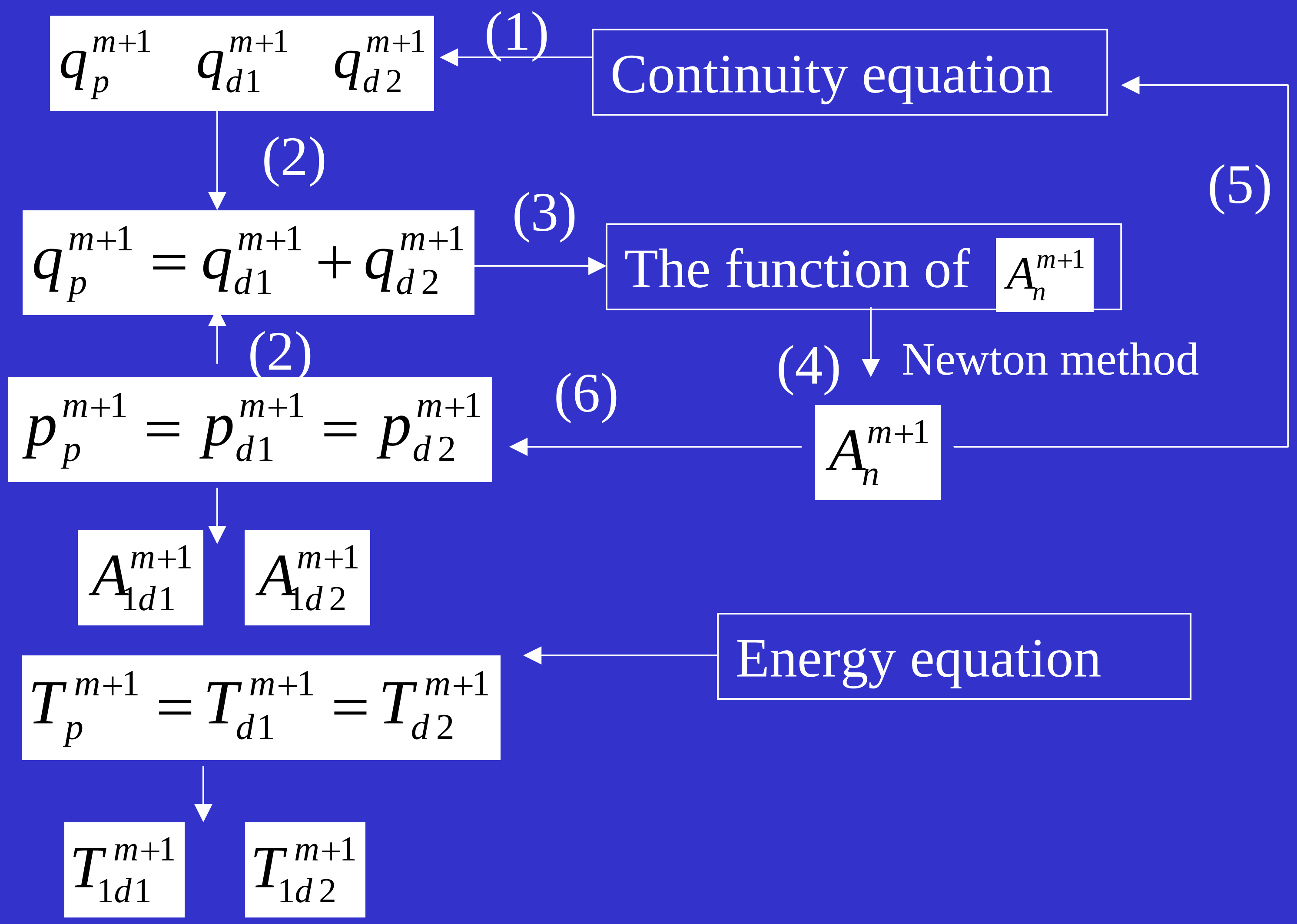
$$\Phi = \omega t - \sqrt{\frac{\omega}{\pi}}$$

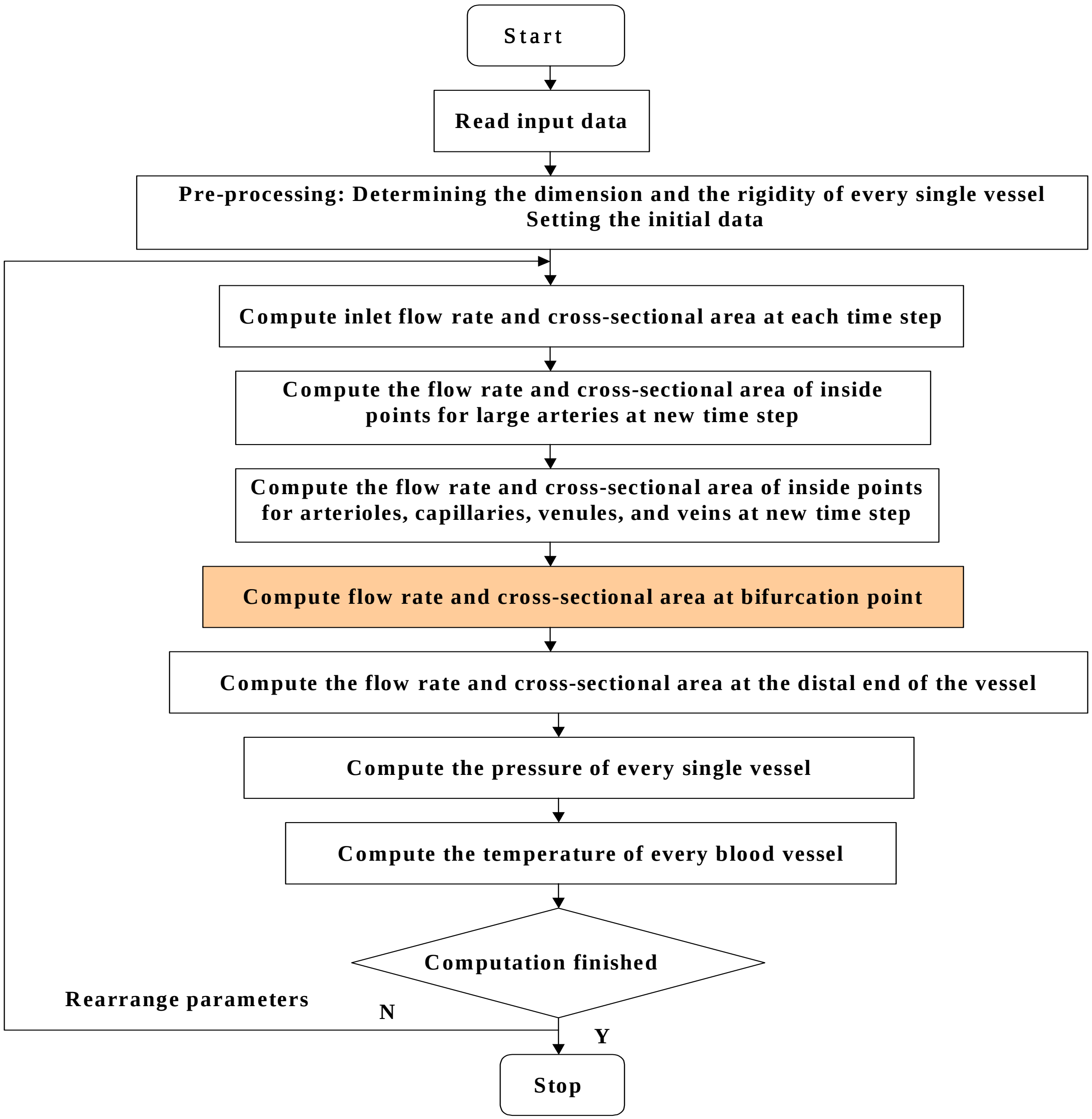
- inflow pressure

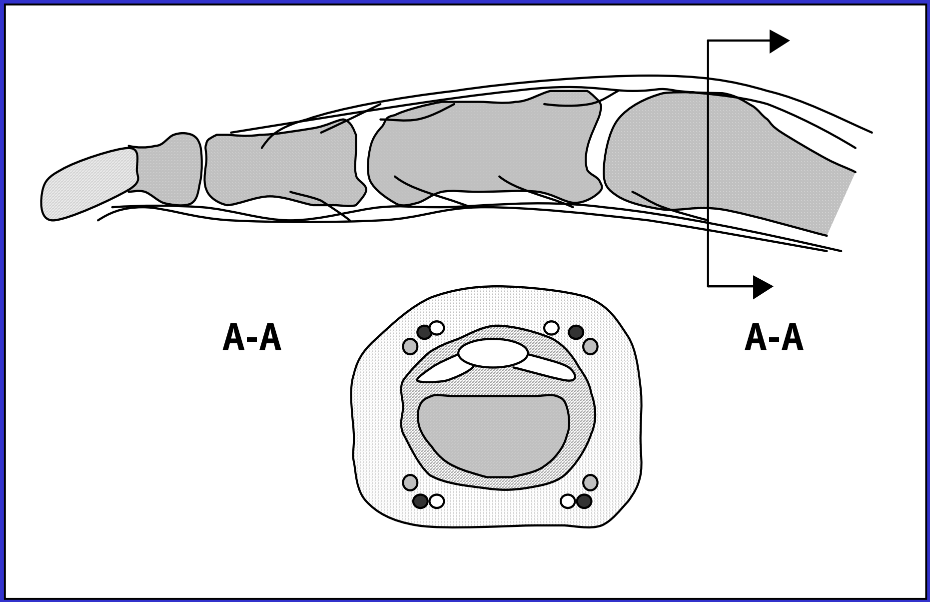
outflow condition

$$P = 5mmHg$$

Internal boundary conditions at bifurcation points

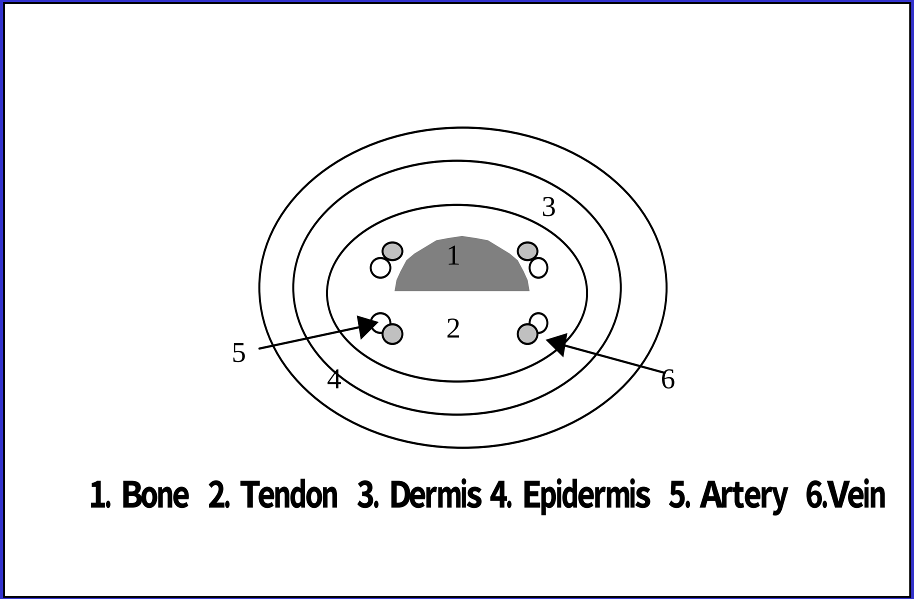


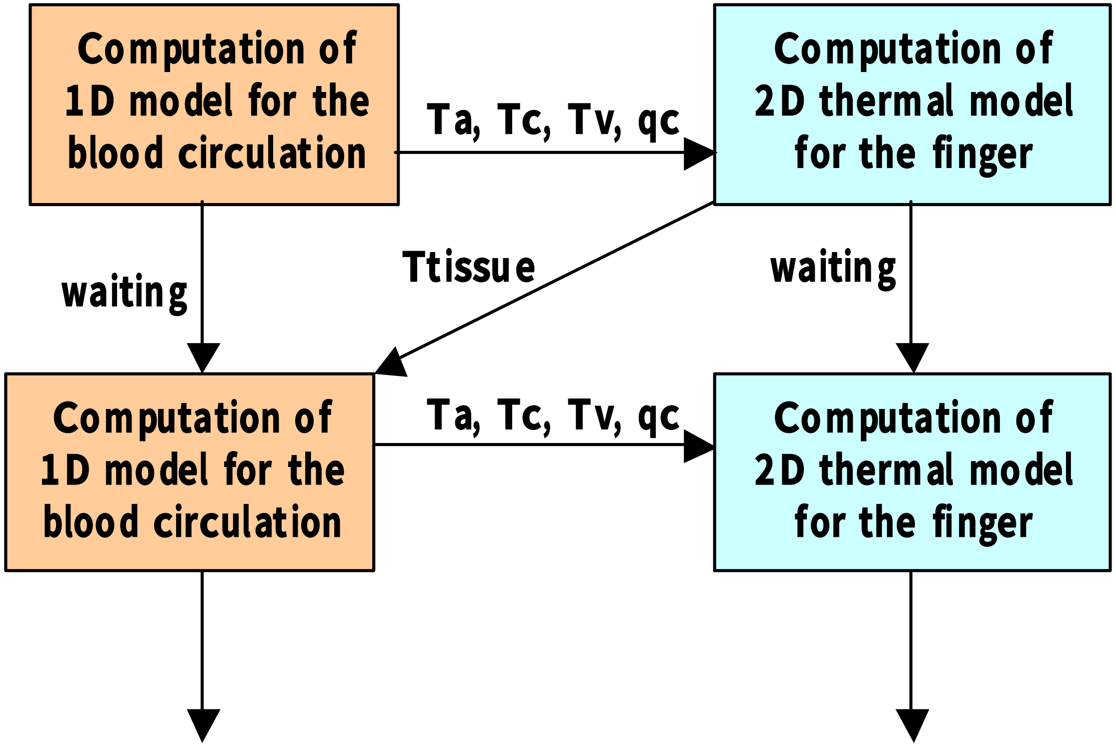

Start
Read input data
Pre-processing: Determining the dimension and the rigidity of every single vessel
Setting the initial data
Compute inlet flow rate and cross-sectional area at each time step
Compute the flow rate and cross-sectional area of inside points for large arteries at new time step
Compute the flow rate and cross-sectional area of inside points for arterioles, capillaries, venules, and veins at new time step
Compute flow rate and cross-sectional area at bifurcation point
Compute the flow rate and cross-sectional area at the distal end of the vessel
Compute the pressure of every single vessel
Compute the temperature of every blood vessel
Computation finished
Rearrange parameters
N
Y
Stop



The anatomical structure of the finger

The schematic of the modeled finger





The Coupling Method for the Blood Circulation Model and the Thermal Model

Pennes bioheat equation

$$\rho_t c_t \frac{\partial T_t}{\partial t} = \nabla(k_t \nabla T_t) + q_{met} + \omega \rho_b c_b (T_{cap} - T_t)$$

$\rho_t c_t$ volumetric specific heat of tissue

q_{met} metabolic heat generation

$\rho_b c_b$ volumetric specific heat of blood

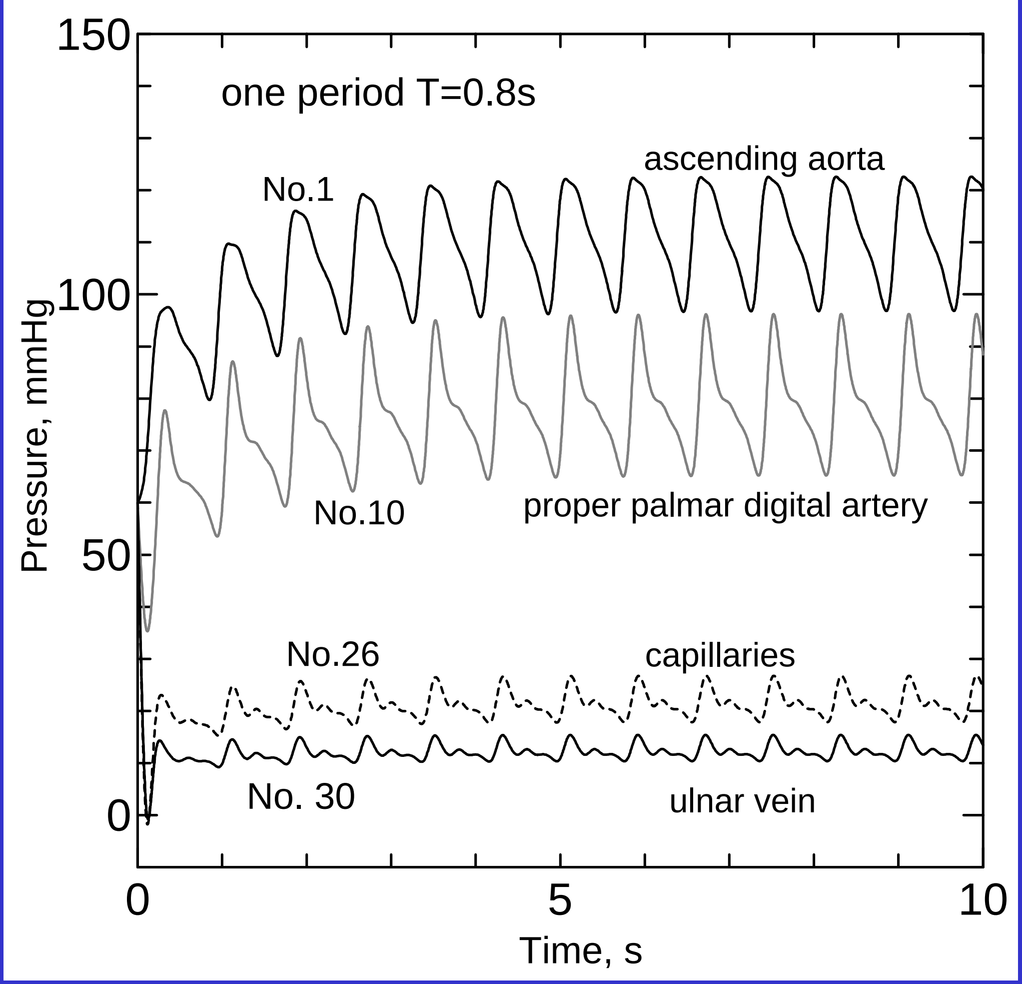
k_t thermal conductivity of tissue

ω blood perfusion rate

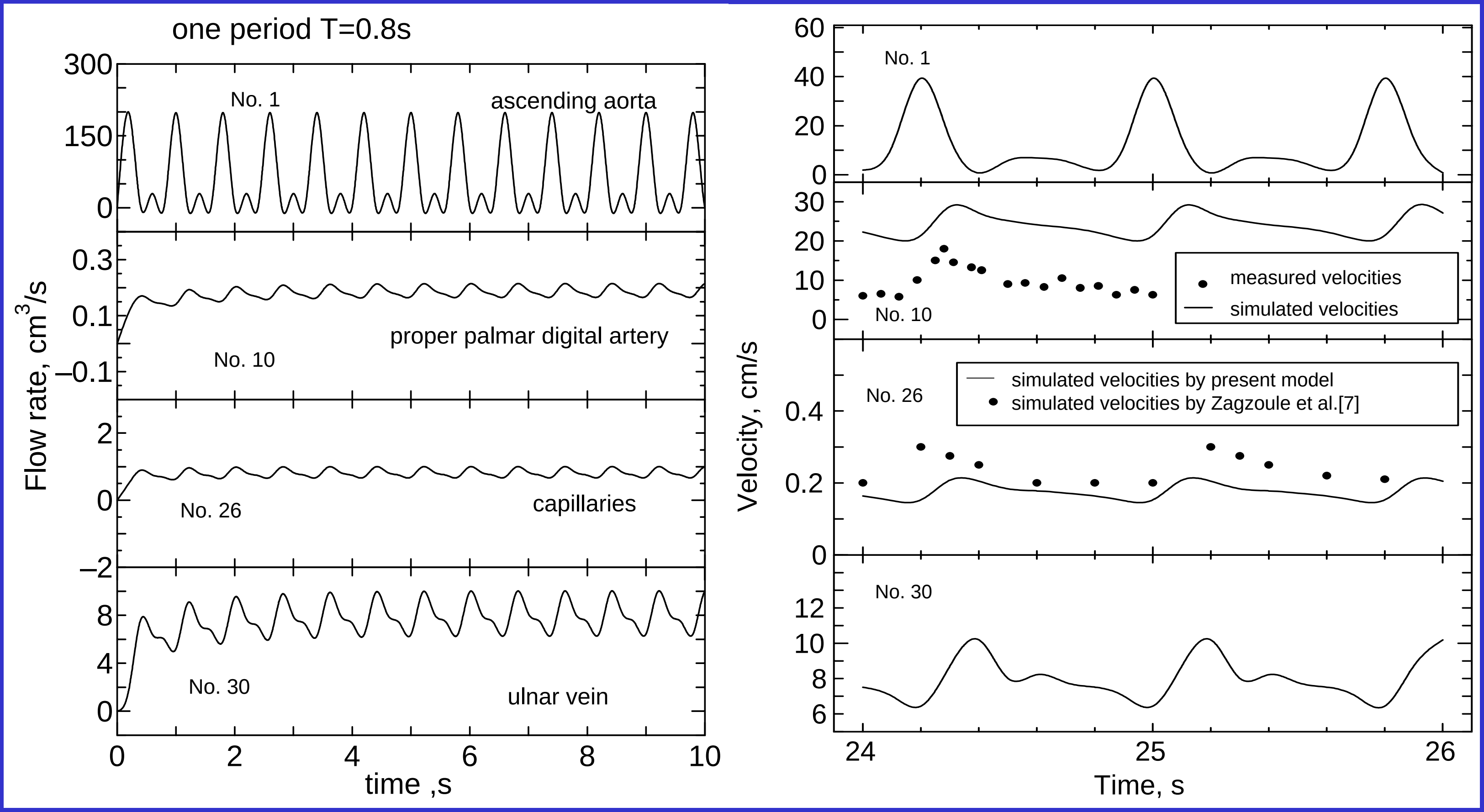
T_{cap} temperature of capillary

T_t temperature of the local solid tissue

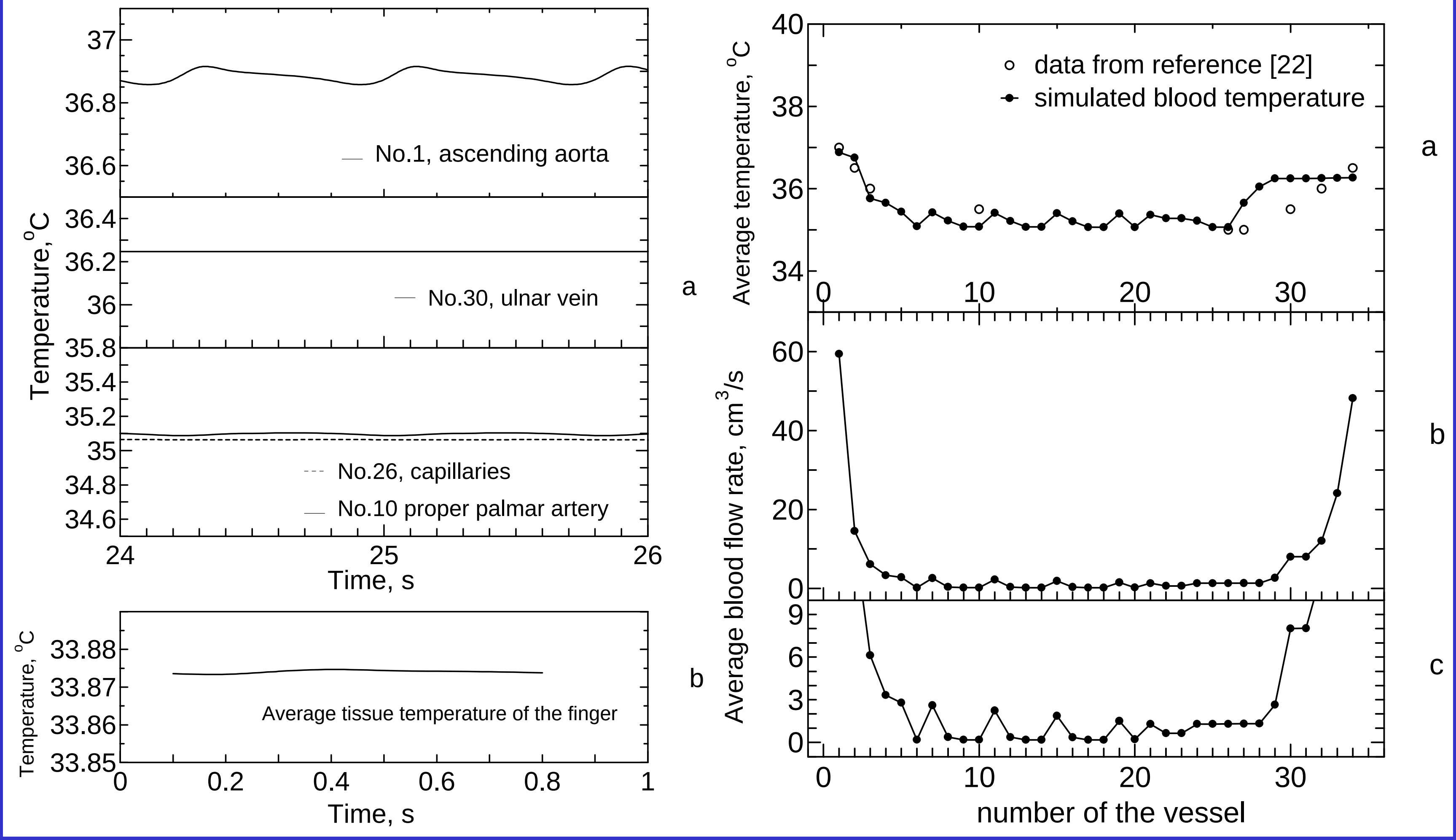
Computed Pressure signals in different vessels



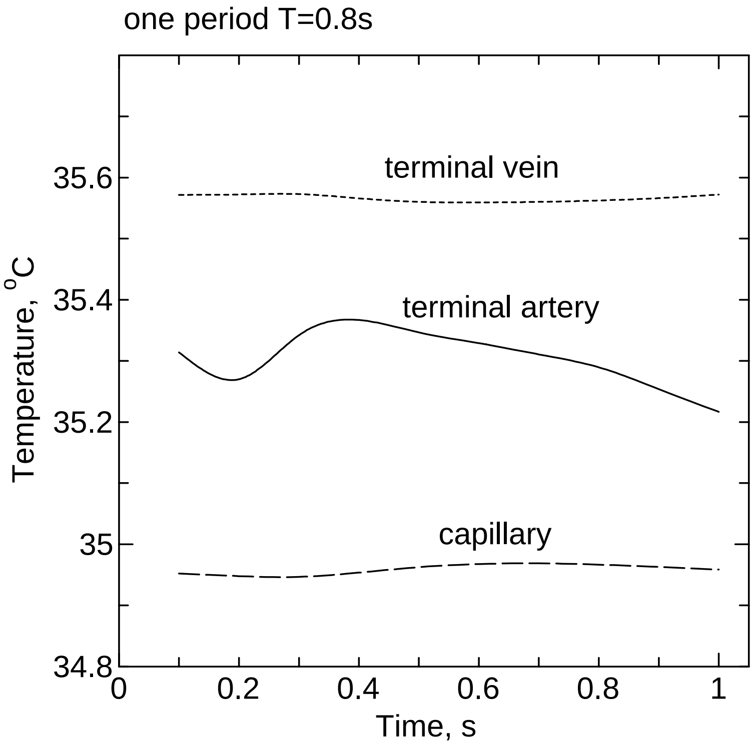
Computed flow rate signals in different vessels

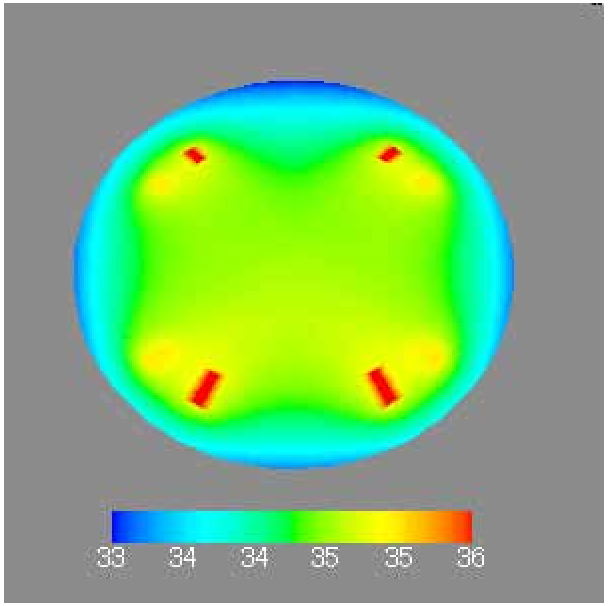


Computed temperature signals in different vessels



Temperatures in Artery, Vein, Capillary, and Solid Tissues of the Modeled Finger



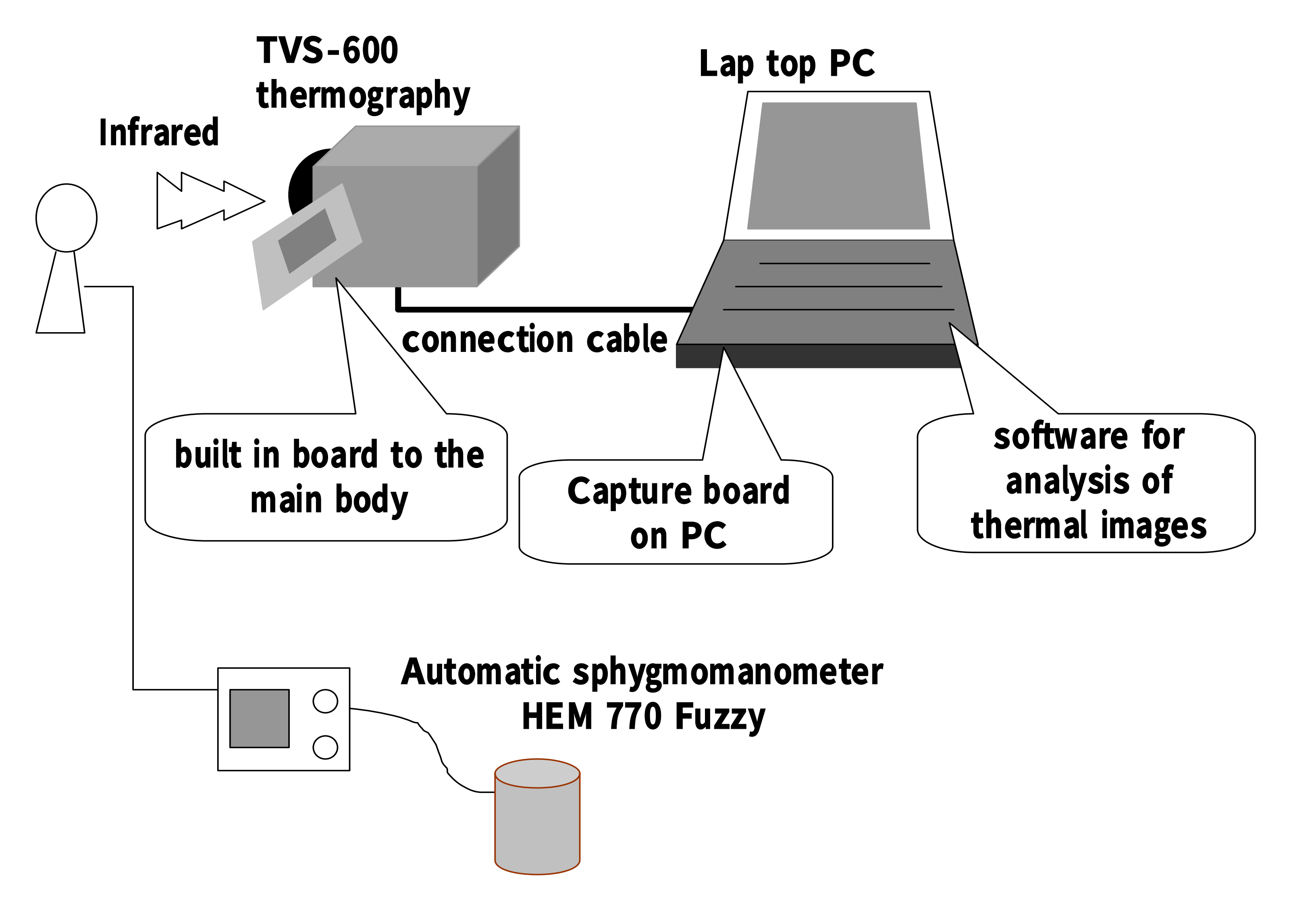


Objectives of the Experiment

- The detail observation of temperature variation; especially near the blood-vessel areas

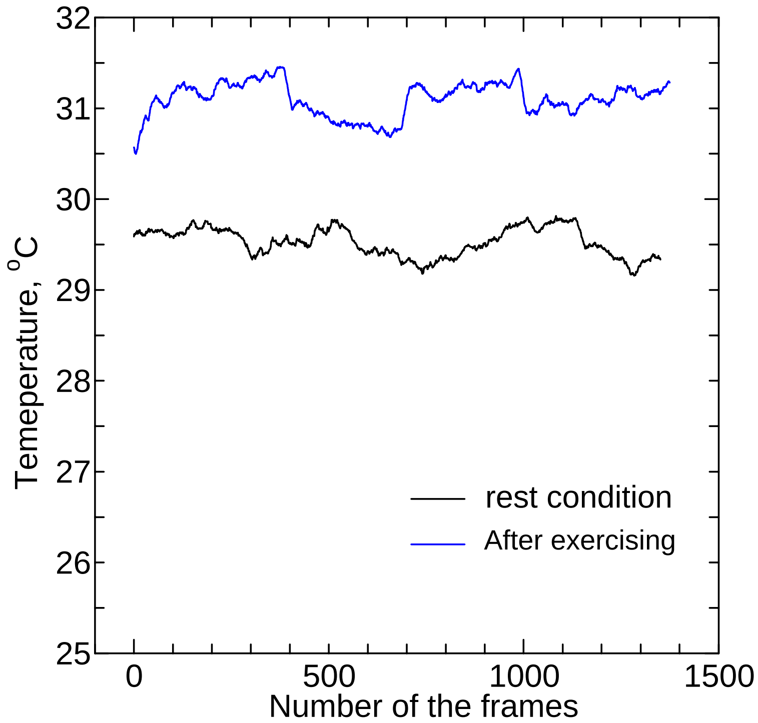
- Comparing the experimental results and the predicted results by the one-dimensional thermo-fluid model of blood circulation and the thermal model

The Experimental System

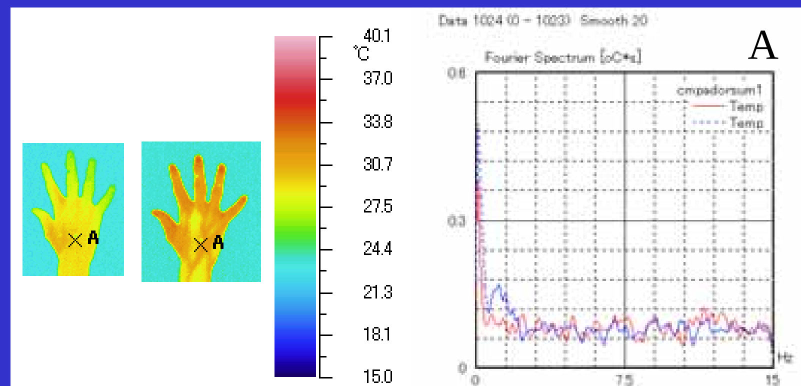


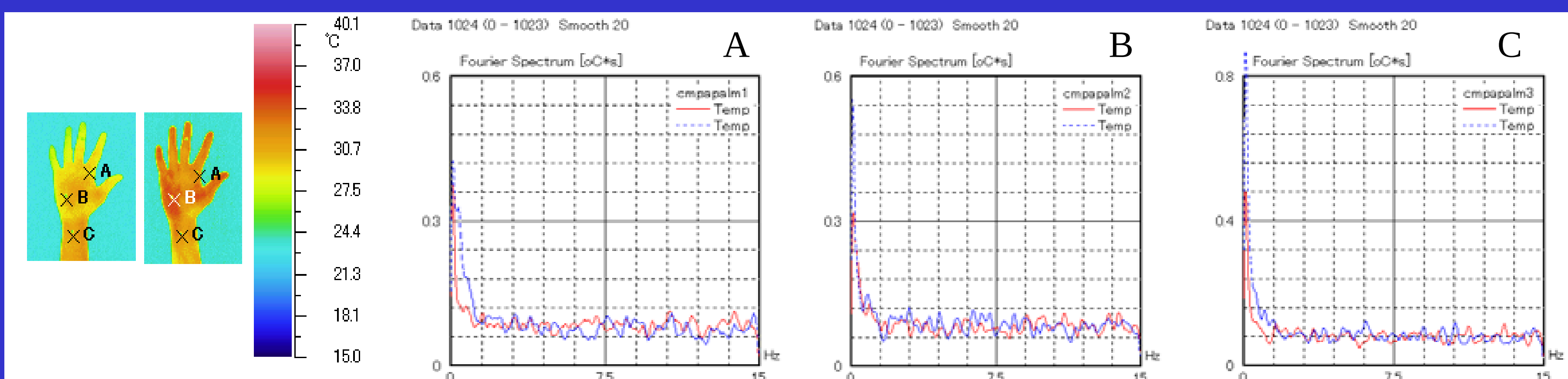
Measured data before and after exercising

	subject 1	
	before exercising	after exercising
highest pressure (mmHg)	103	128
lowest pressure(mmHg)	74	84
flow rate(beats/min)	75	104
time for jogging (min)	20	
environmental temperature(K)	295	



Thermal Images and Spectrum Analyses of the Temperature Variations in the Corresponded Points Before and After Exercising





Summary

- A one-dimensional thermo-fluid model is developed to investigate the relationship of flow rate, pressure, and temperature in upper limb

- The temperature of the solid tissue is computed by coupling the 1D blood-circulation model and the thermal model. Thus, it becomes possible to simulate the temperature variation with the blood circulation

- The periodic skin temperature near the vessel was detected after exercising