血流循環と生体熱輸送現象に関する数値と実験的研究
--末梢の温度調節および温熱療法による腫瘍血流の変化--

Numerical and Experimental Study on the Human Blood Circulation and Heat Transport Phenomena--Thermoregulation in the Periphery and Hyperthermia-induced Tumor Blood Flow--

Ying HE[1] , Shirazaki MINORU[1], Hao LIU[2,1],

Ryutaro HIMENO[1], and Tetuya KAWAMURA[3]

[1]Computational Biomechanics Unit, RIKEN

[2]Department of Electronics & Mechanical Engineering, Chiba University

[3]Graduate School of Humanities and Sciences, Ochanomizu University

- Research Background
- Study on the thermoregulation in the periphery
    - ♦ Two-dimensional thermal model of the human finger
    - ♦ Two-dimensional FEM thermo-fluid model of the human finger
    - ♦ One-dimensional blood circulation model in the upper limb and the coupling analysis with the thermal model of the finger
    - ♦ Experimental observation
- Variation of tumor blood perfusion rate induced by hyperthermia
- Summary

Temperature research range in biological system

Higher than the physiological temperature of warm-blooded organisms: 40ºC ~ 120ºC

1. **Use of high temperatures to treat undesirable tissue**

Application of laser technique in surgery

hyperthermia: infrared, microwave, etc.

analysis of burn wound

Physical range of warm-blooded organisms: 36ºC~40ºC

1. **Microscale:** protein motors

2. **Mesoscale**: Effect of blood flow on tissues

3.macroscale: relationship between human body and thermal environment

Lower than the physiological temperature of warm-blooded organisms: 36ºC~-27ºC

1. **Above freezing**

2. **Below freezing**

Hypothermia

cryosurgery

cryobiology: preserve biological tissues and cells

Research Background (2)

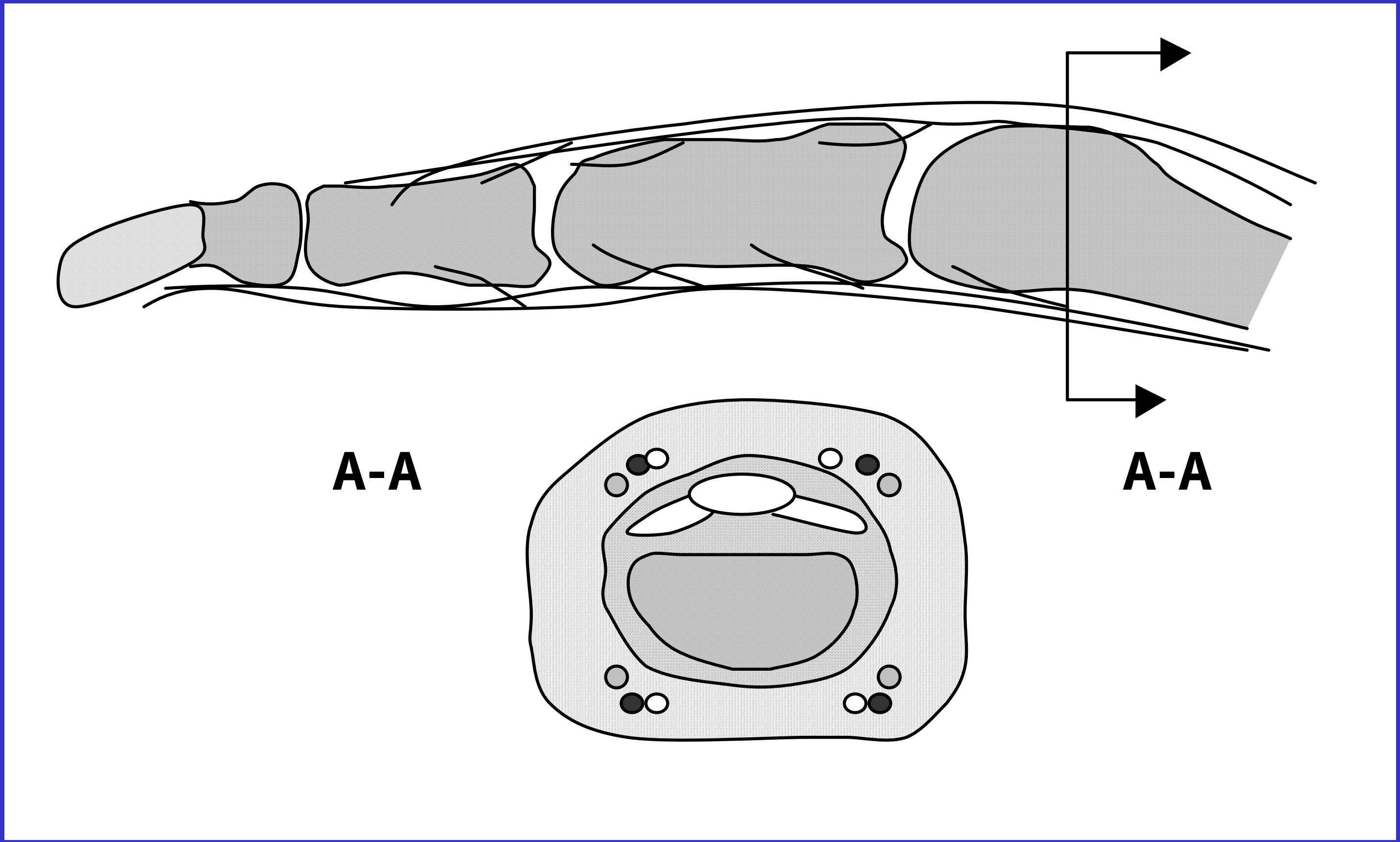
- Circulatory system is not only related to the diseases of blood-vascular system, but also important for the development and treatment of diabetes, tumors, and so on.

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

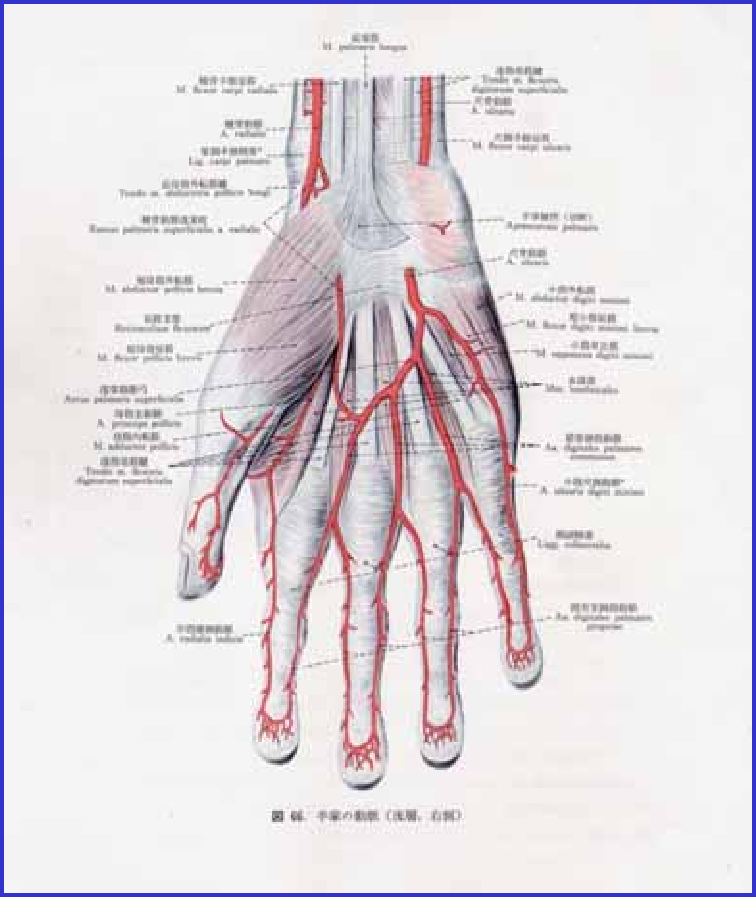
→ Aging , Exercising, mental stress, Smoking etc…

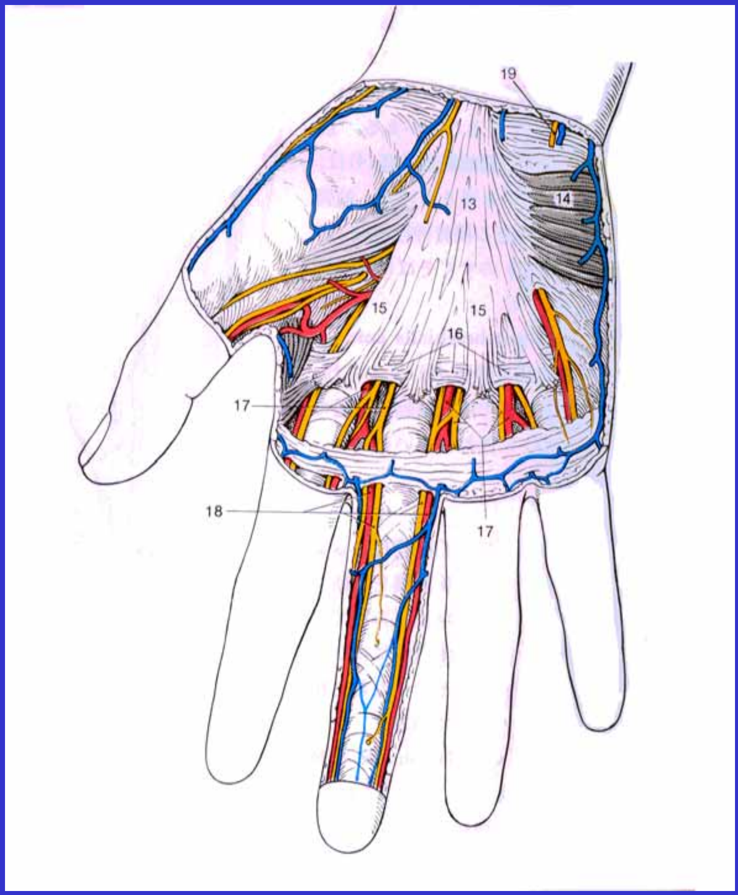
- Diagnosing blood circulation illness by measuring skin temperature (Finger skin temperature is widely used as a parameter for the investigation of cold-induced vasoconstriction)

- How to maintain hand dexterity and comfort , how to avoid cold injury during cold exposure when hand work is involved



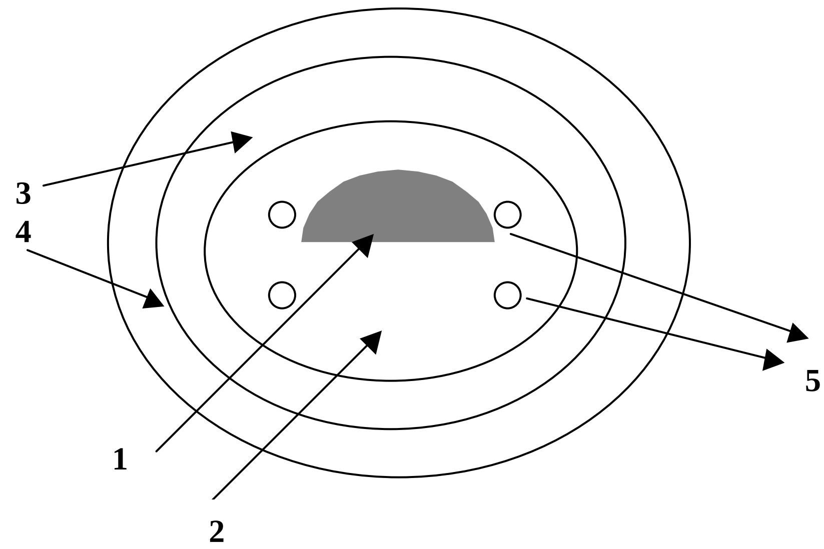
Arteries and the cross section structure of a finger
(cited from Tachenatlas Der Anatomie)





The peripheral circulation system in the hand

(cited from Angiology and Taschenatlas der Anatomie)



1. Bone 2. Tendon 3. Dermis 4. Epidermis 5. Artery

The geometrical model of the middle finger

Pennes bioheat equation (1948)

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

$\rho_t c_t$ volumetric specific heat of tissue

q_{met} metabolic heat generation

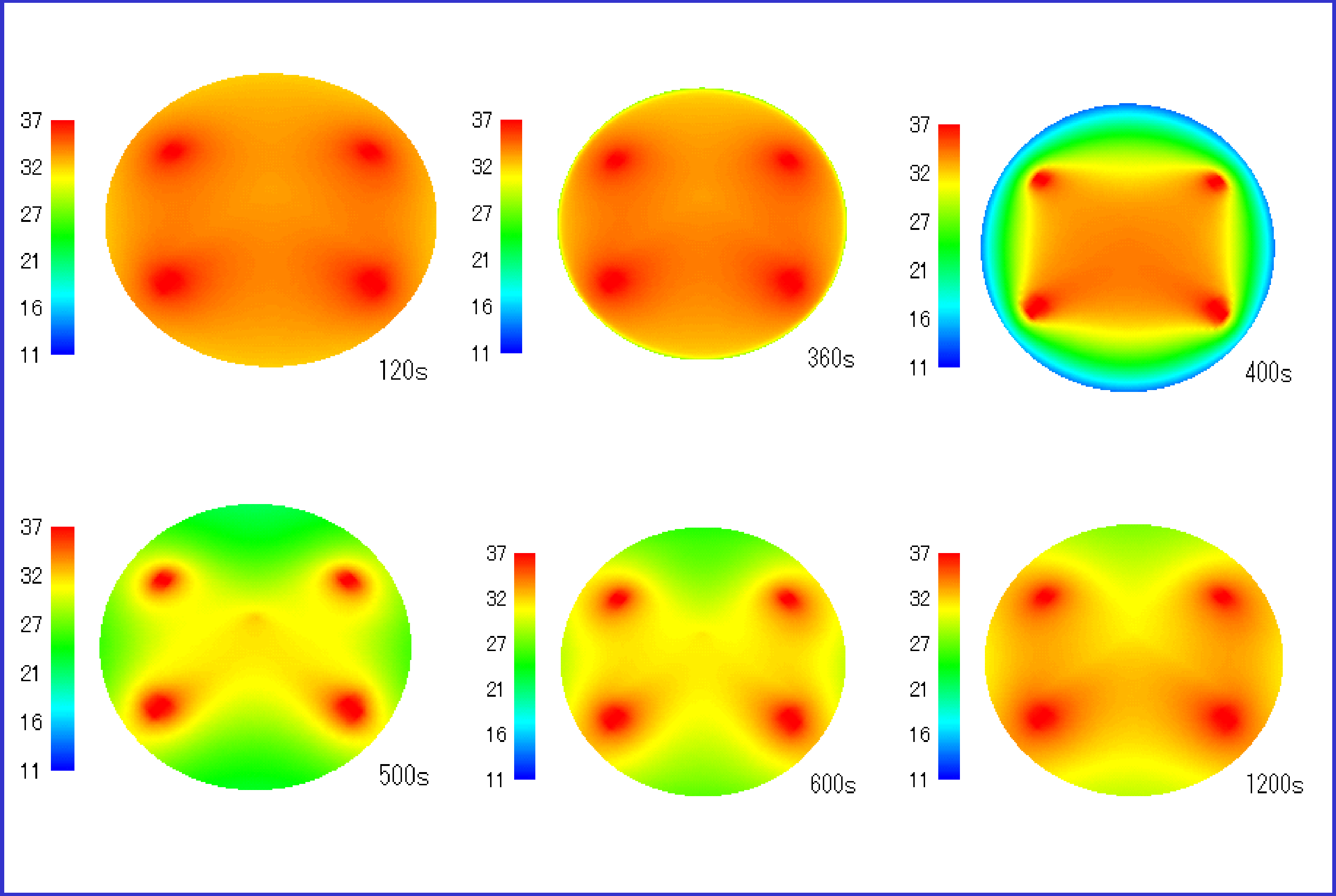
$\rho_b c_b$ volumetric specific heat of blood

k_t thermal conductivity of tissue

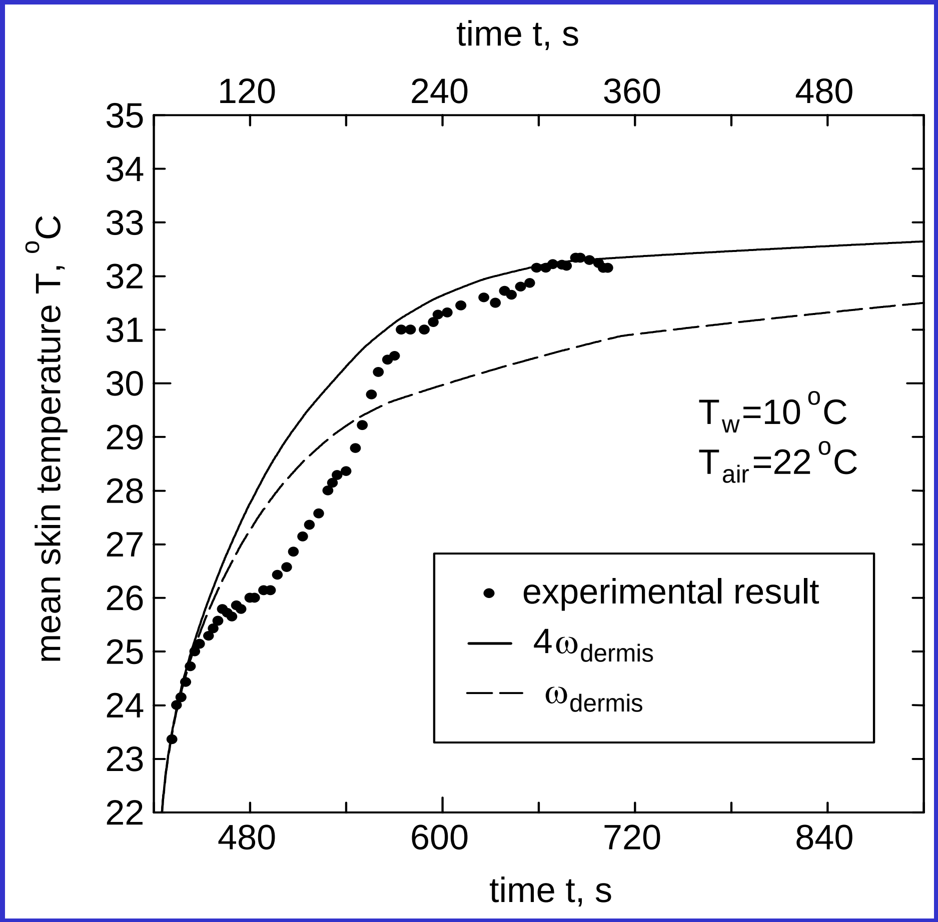
ω blood perfusion rate

T_a temperature of artery

T_v temperature of vein, assumed to be equal to the local tissue temperature



Transient Temperature Distribution of the Middle Finger in the Air and Cold Water



The variation of mean skin temperature

(the comparison between simulated results and the experimental result)

Summary

- Two dimensional temperature distribution of the human finger including the effect of main arteries was obtained
- The blood perfusion rate becomes larger after cold stimulus
- The re-warm speeds are different around the finger. The side part re-warms faster.

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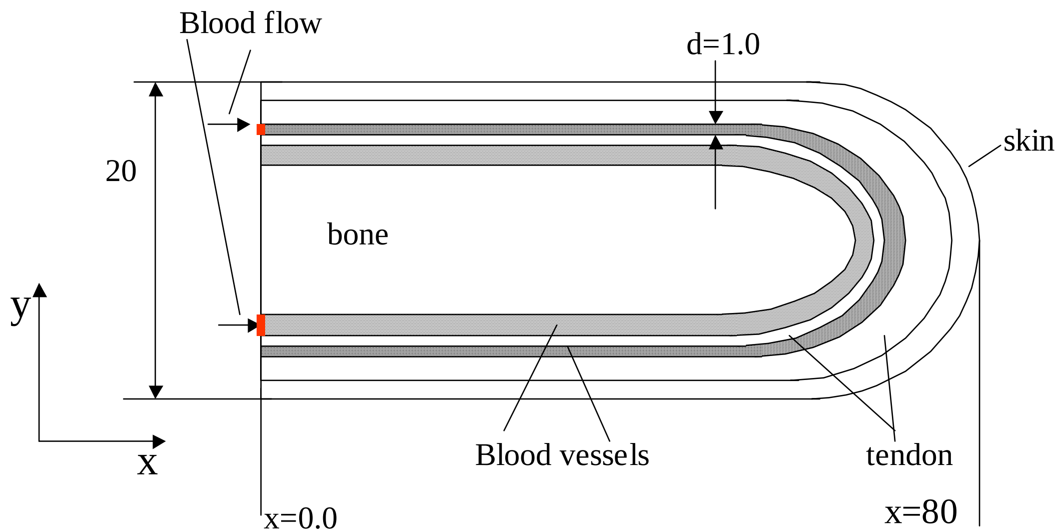
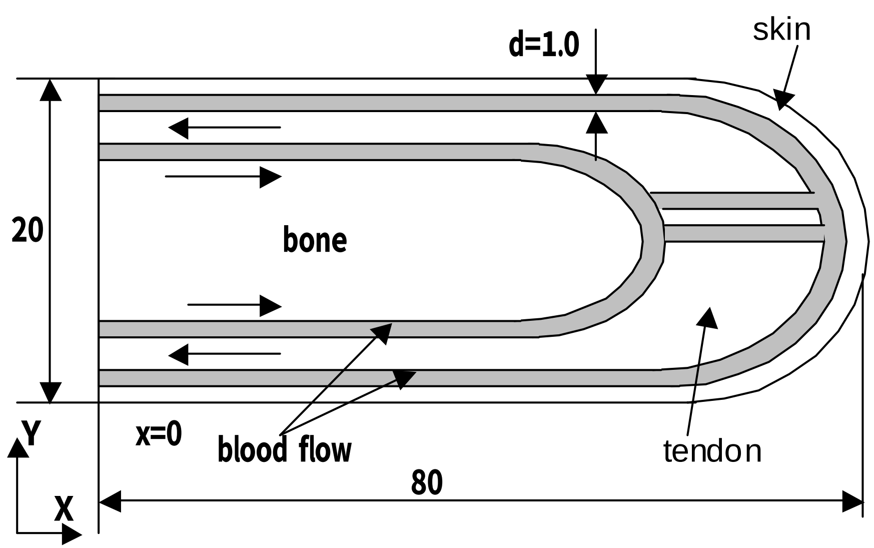
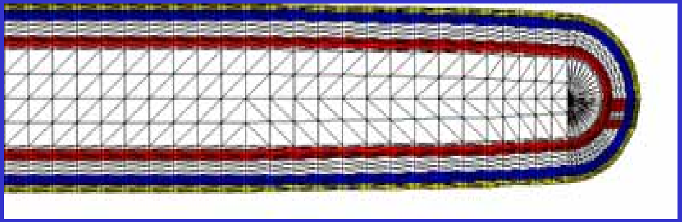
A FE thermo-fluid model to investigate the blood flow inside vessels and heat transfer in solid tissues

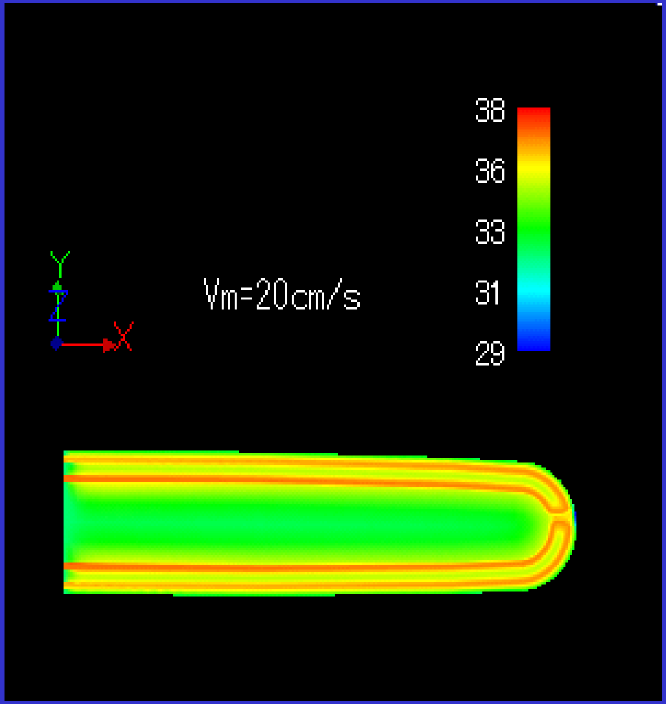
The geometric model of the finger in longitudinal direction

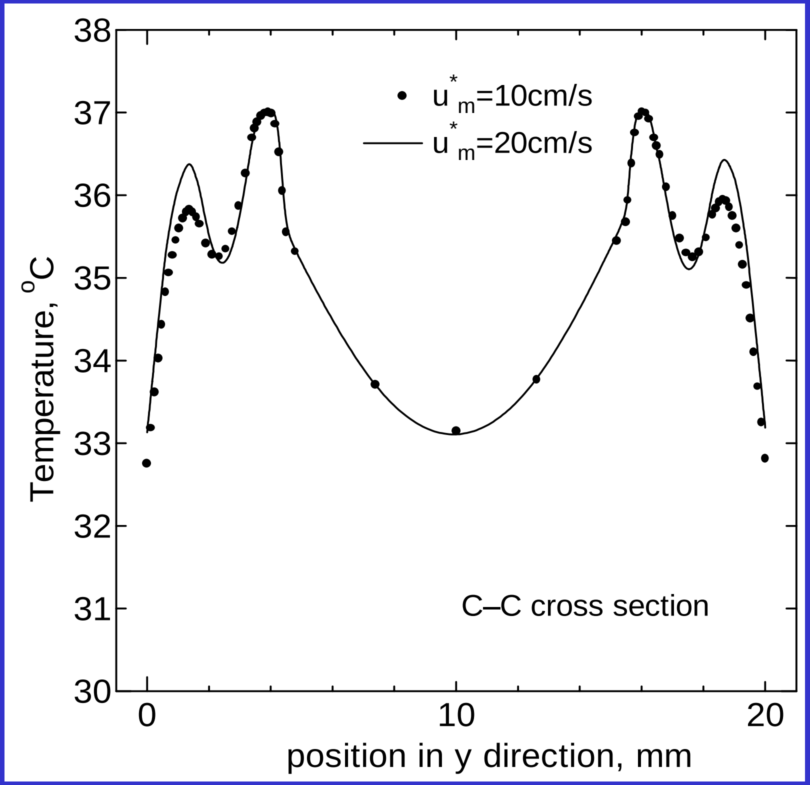




Isotherm contour and temperature profile of model-B finger







Summary and Discussion

• The effect of blood flow on the temperature distribution of the finger is investigated by FEM model. The results show that there is a temperature difference in veins with different blood velocities.

Problems:

- Long computation time
- Difficult to model the vascular structure
- The effects of blood pressure and blood vessels are not known

↓

One-dimensional thermo-fluid model of blood circulation

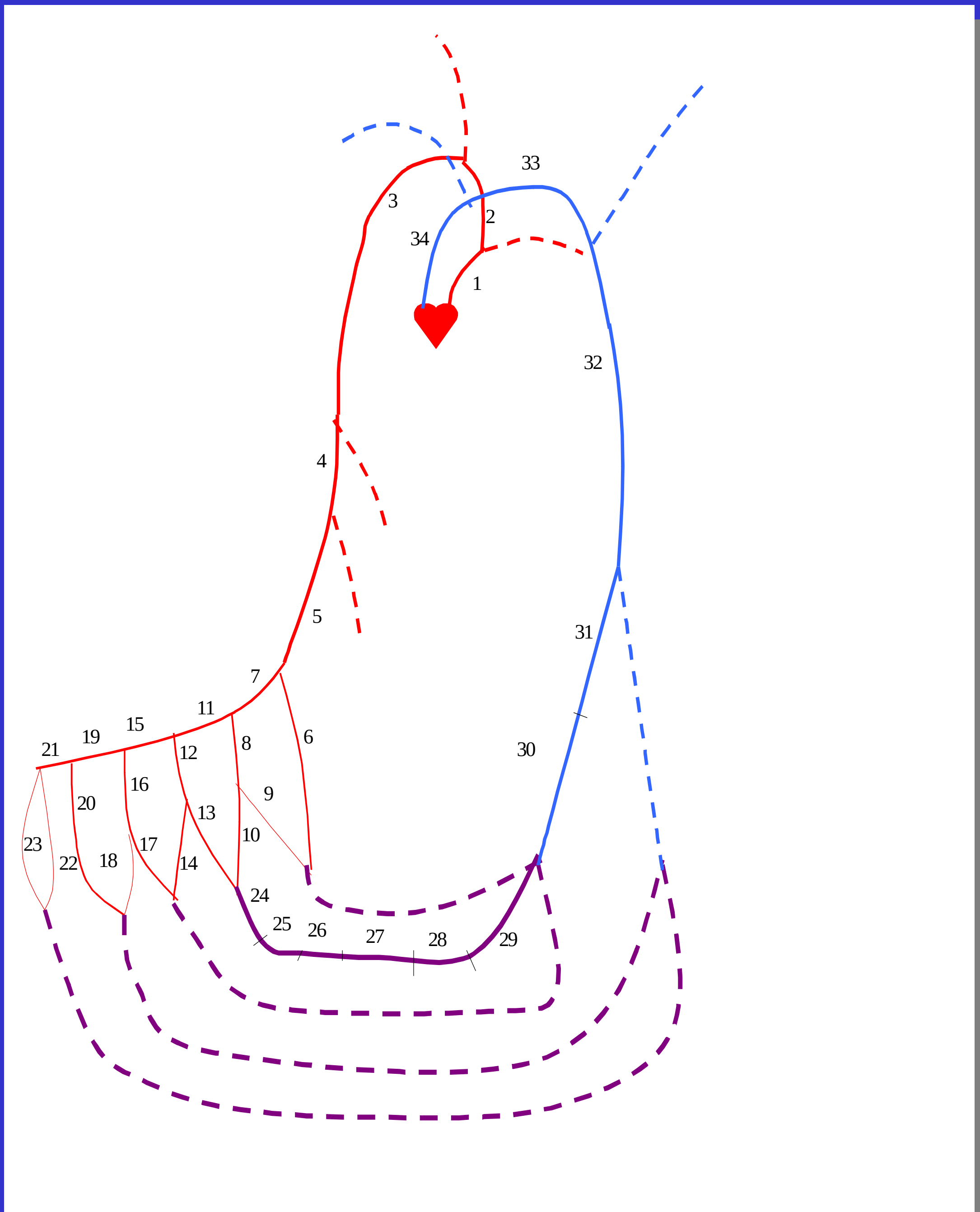
The previous studies on the one-demensional model of blood flow

- 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 analyses of viscous resistance and viscoelasticity (Kitawaki et al. 2003)
- Multi-scale model of blood flow (Liu, 2002)

The objectives of the present study

- Apply the one-dimensional fluid model in the thermal analysis of blood flow
- Couple the blood-circulation model with the thermal model of the solid tissue

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

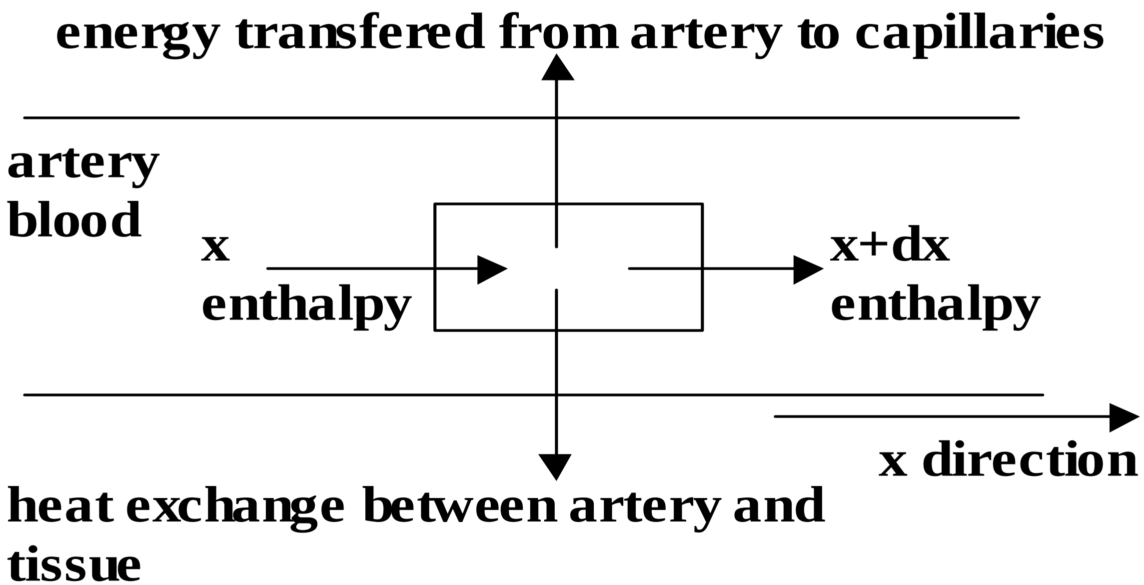
$$\frac{\partial q}{\partial t} + \frac{\partial}{\partial x}\left(\frac{q^2}{A}\right) + \frac{A}{\rho}\frac{\partial P}{\partial x} = -\frac{2\pi \nu R}{\delta}\frac{q}{A}$$

state equation

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

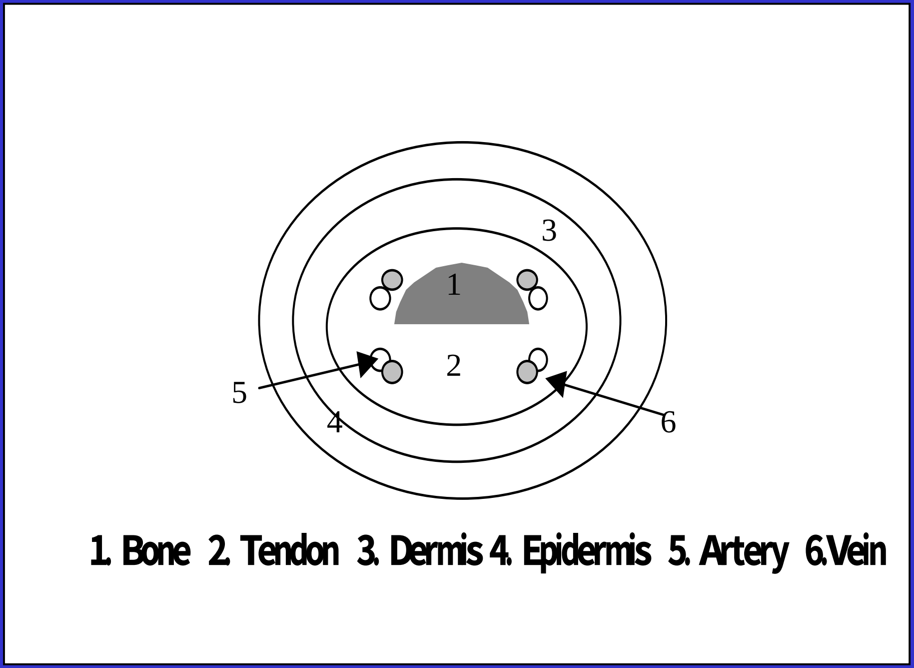
$$P - P_0 = k_p\left[1 - \left(\frac{A}{A_0}\right)^{-3/2}\right] \quad while \quad 0 \le \frac{A}{A_0} \le 1$$

The Derivation of the Energy Equation

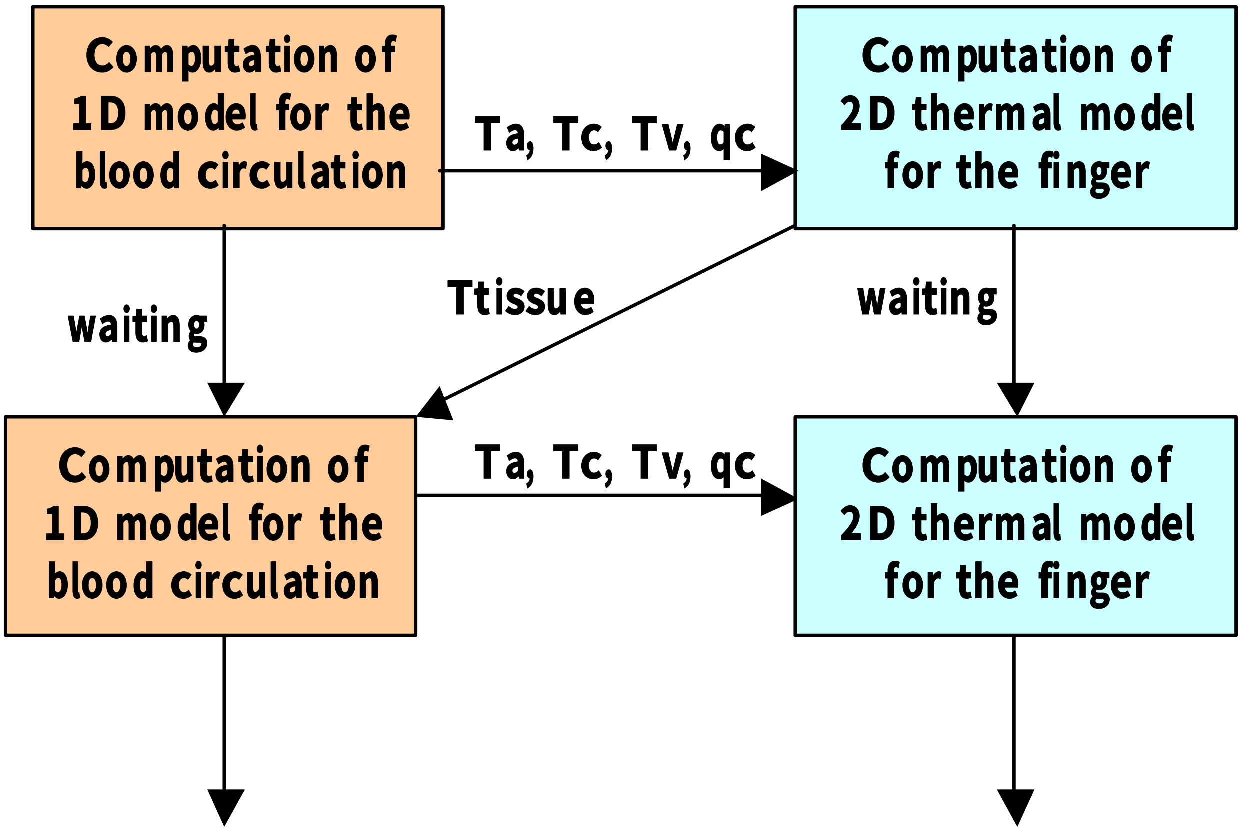


Energy Balance equation in Arteries

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

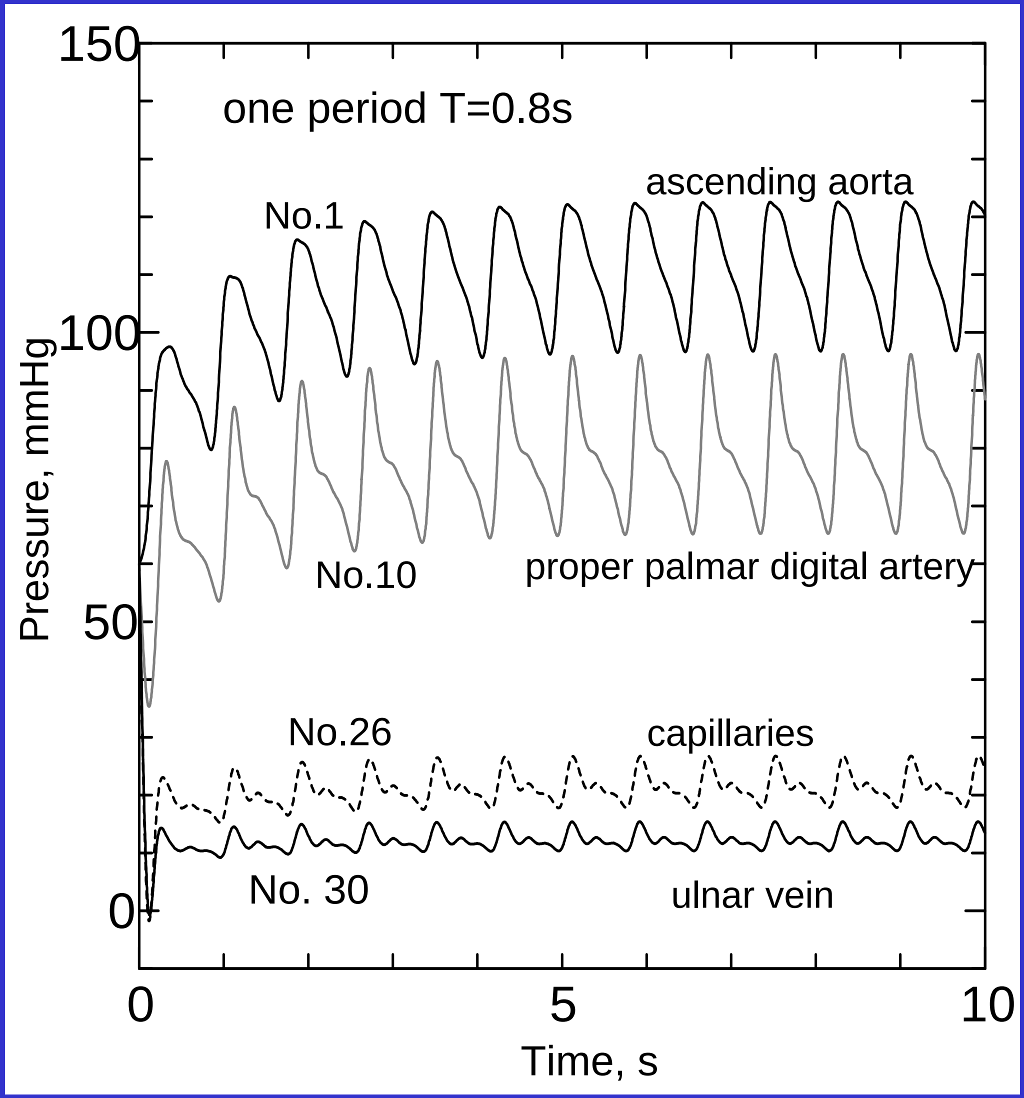


The schematic of the modeled finger

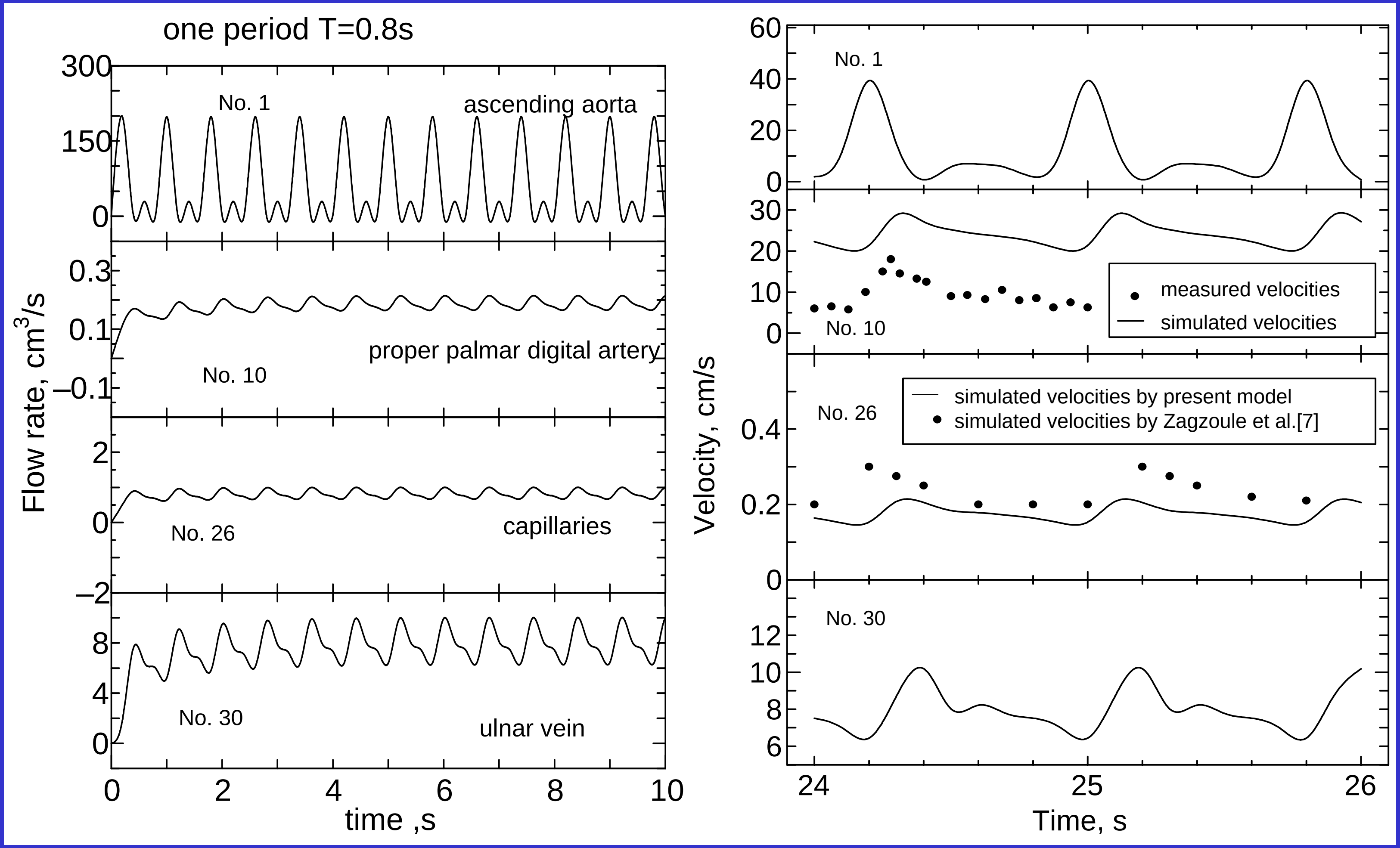


The Coupling Method for the Blood Circulation Model and the Thermal Model

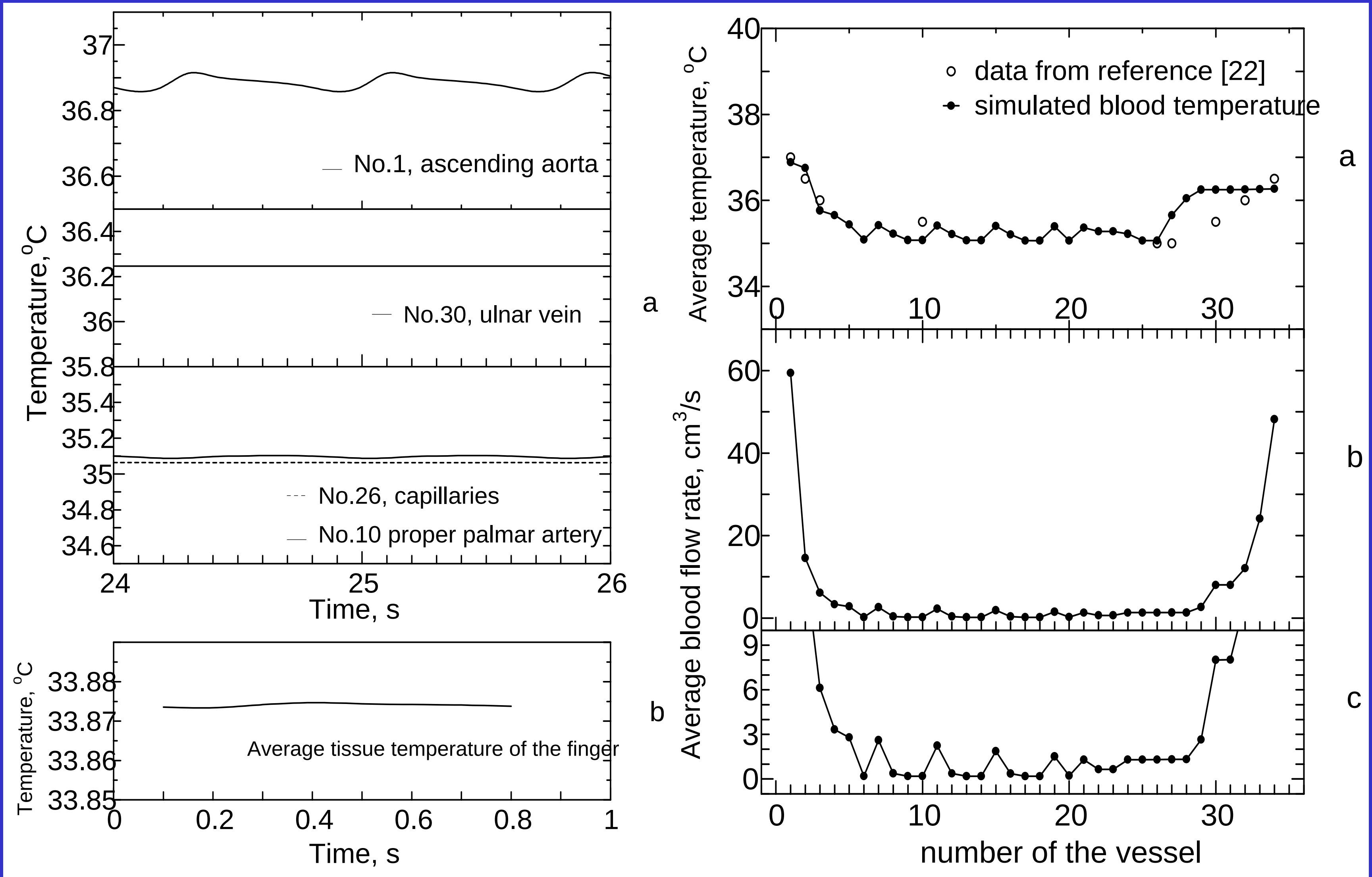
Computed Pressure signals in different vessels



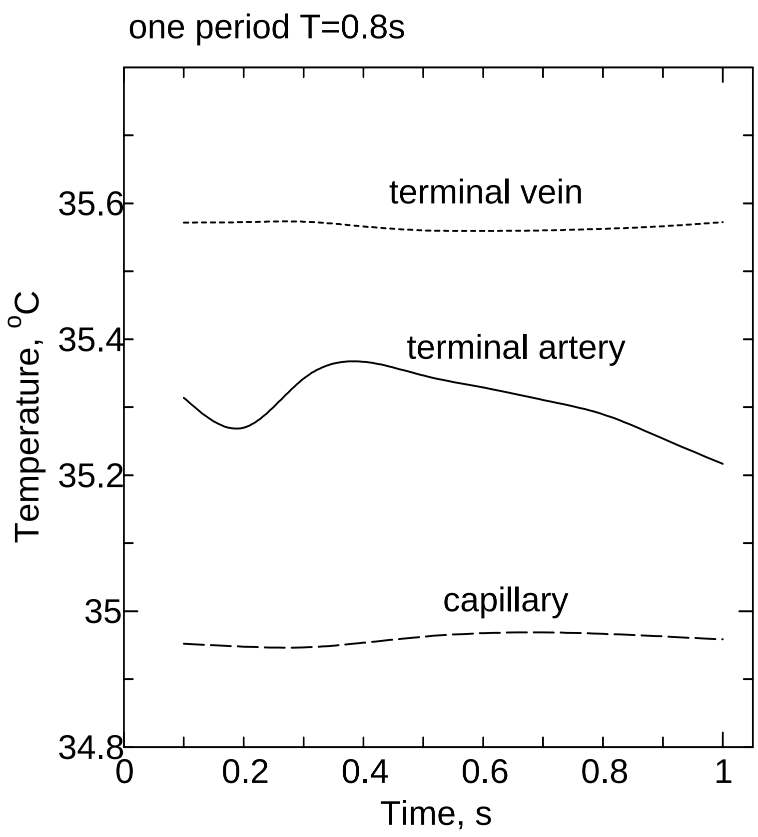
Computed flow rate signals in different vessels

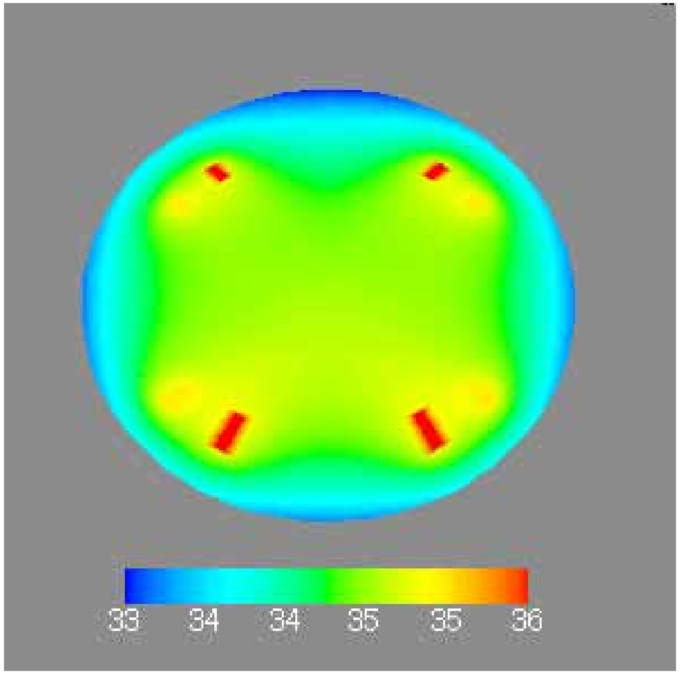


Computed temperature signals in different vessels

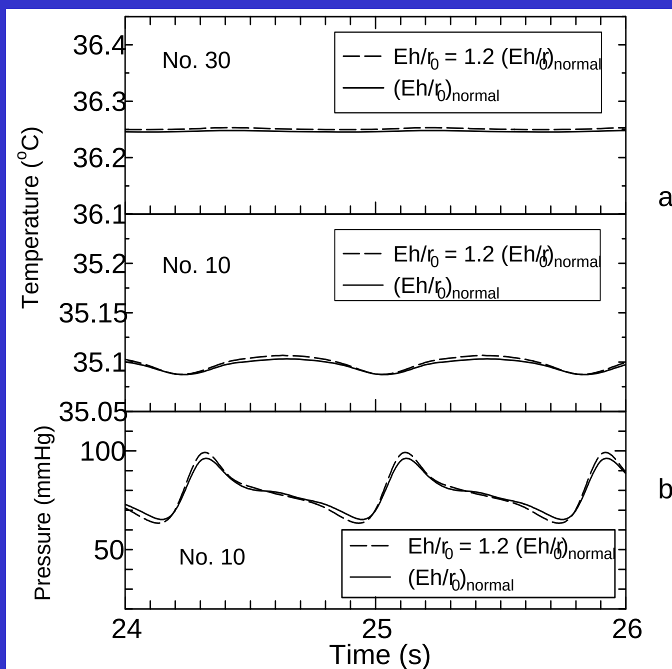


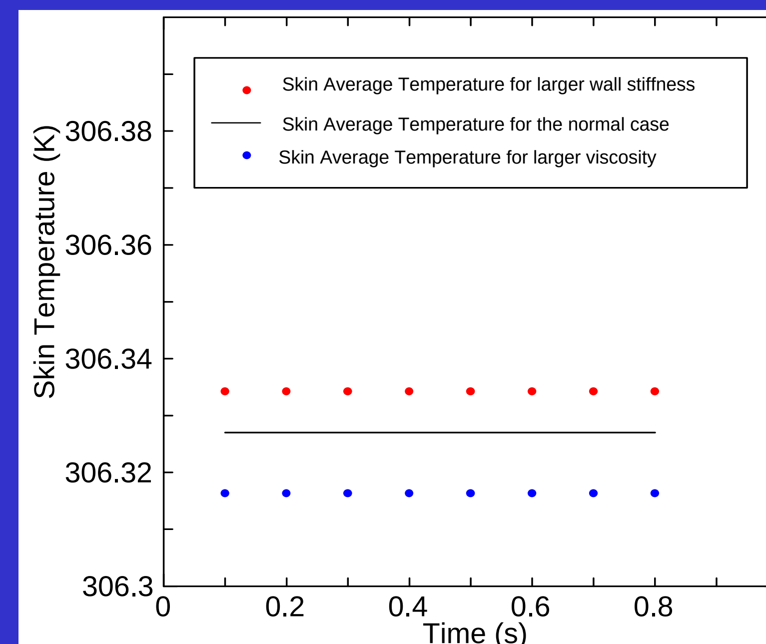
Temperatures in Artery, Vein, Capillary, and Solid Tissues of the Modeled Finger





Blood Temperature and Pressure and Pressure

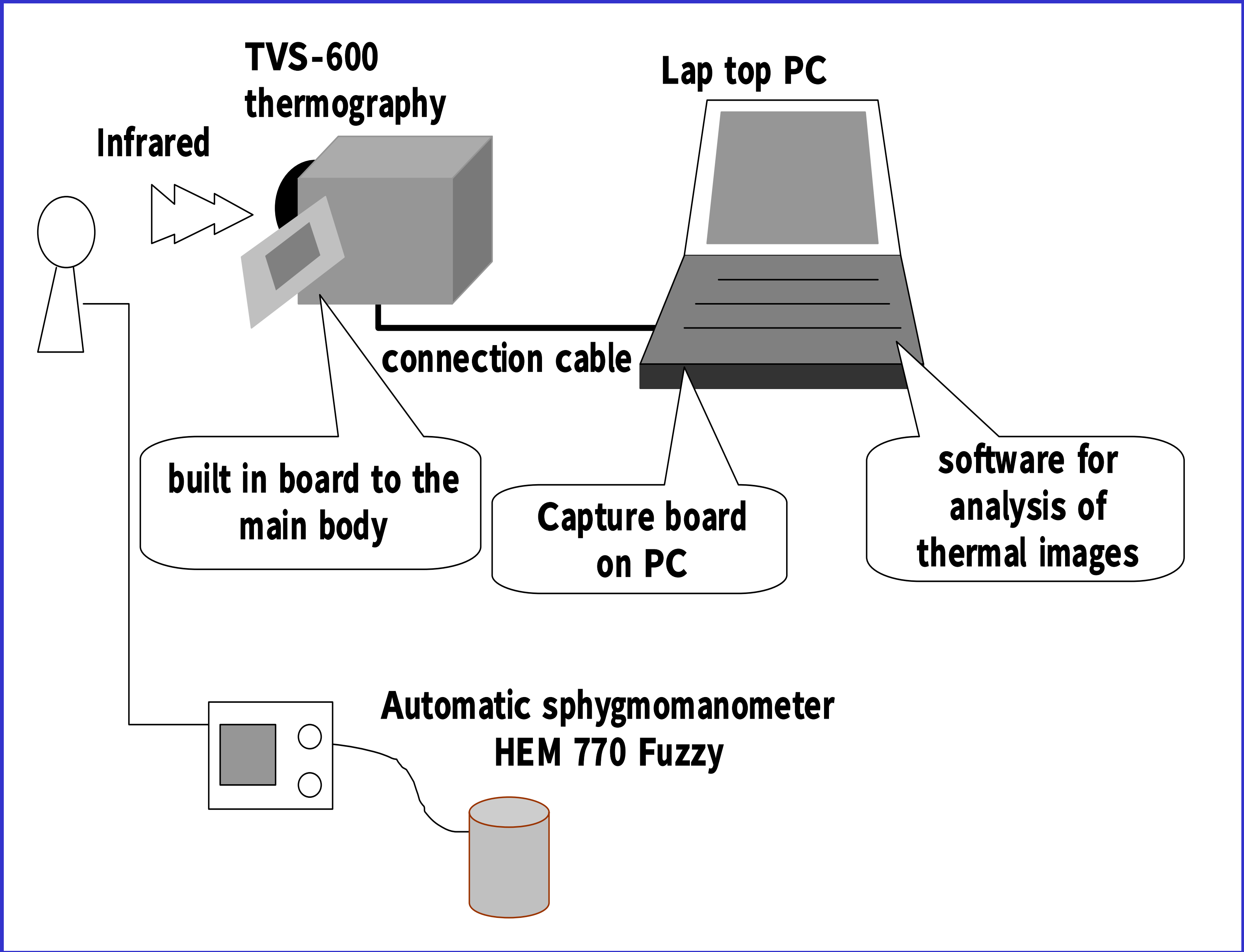




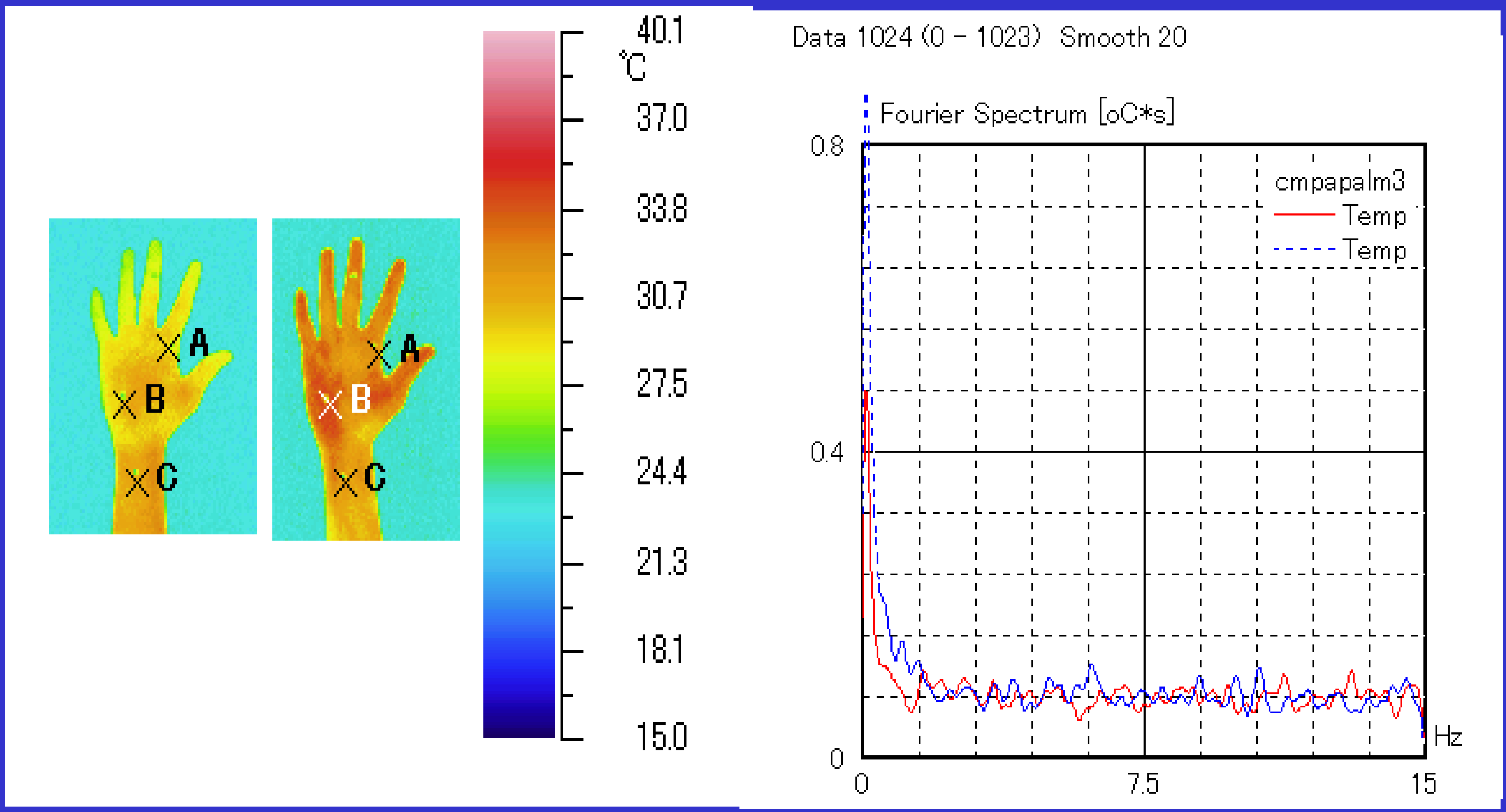
Objectives of the Experiment

- 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



(a)Thermal Images of the Palm (b) Spectrum Analyses of the Temperature in the Palm 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

レーザー照射による生体組織と血流の熱解析

Numerical Study of the Blood Flow and Living Tissue under Laser Irradiation

Microcirculation plays an important role in the growth, metastasis, detection, and treatment of tumors.

Radiotherapy

Hyperthermia

Immunotherapy

Chemotherapy

+

Prevention of neoplastic vascularization

Improve the efficiency of cancer treatment

Research Background

- **Advantages of laser power**

  Low invasive

  High power densities

  Precise irradiated area

  A wide range of wavelengths

- **Response of the tissue to the laser Irradiation**

  Optical Response

  Thermal Response

  Laser Irradiation as a "cytotoxic measure"

  Laser Irradiation as an adjuvant measure

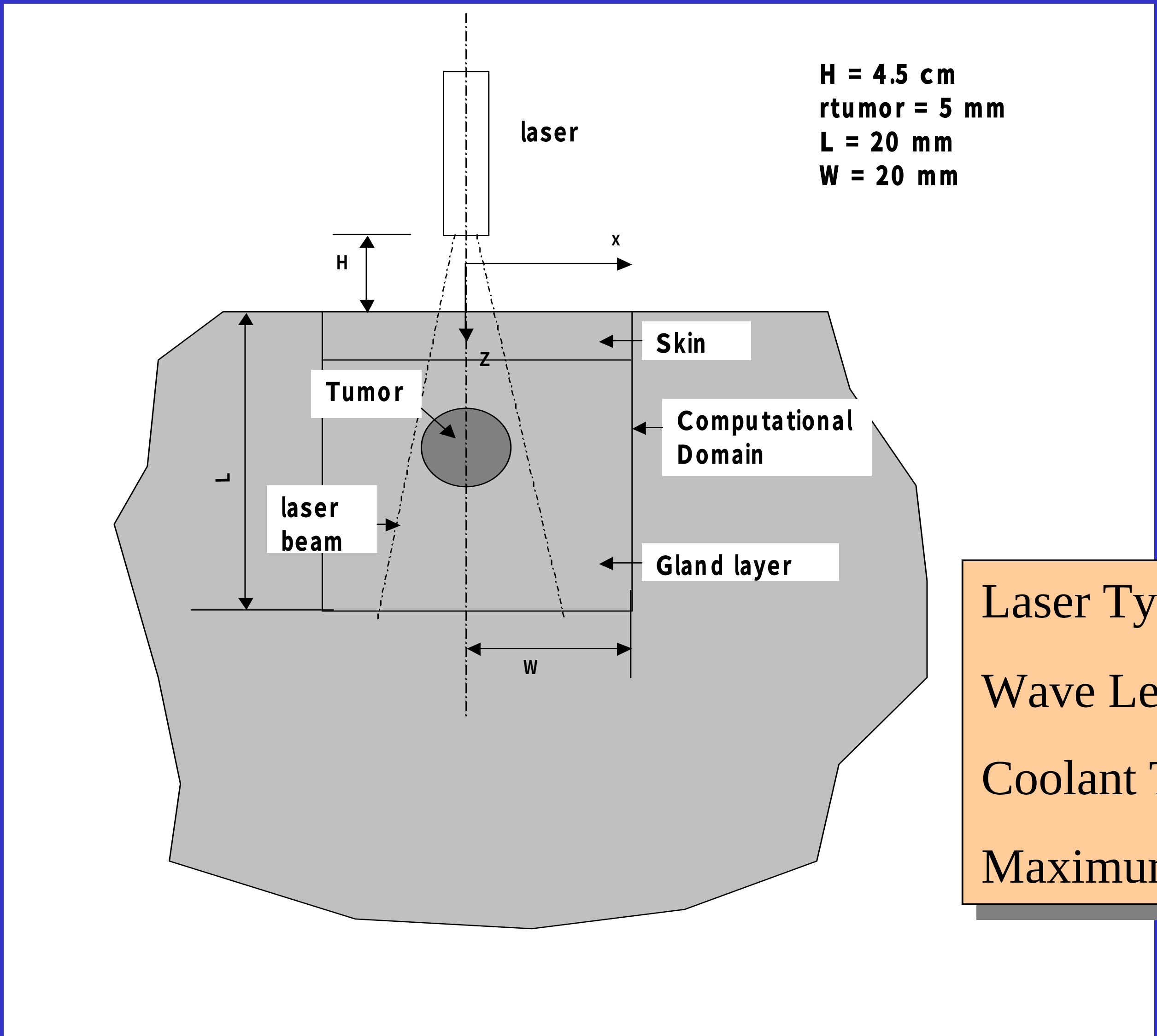
Objective of the Study

- How does the tumor blood flow respond to the Laser irradiation?
- How does the tumor blood flow affect the laser-irradiated tissues?

Previous Studies

- Makuuchi, M. et al.(1997): Study on development of multi-channel laser coagulation method using surface cooling
- Majumdar and Sharma (2003): FE analysis on the thermal response of laser-irradiated tissue
- He, Y. et al. (2003): Numerical and experimental study on the blood circulation and temperature distribution in the human upper limb

Schematics of laser irradiated tissues



Laser Type: Nd-Yag laser

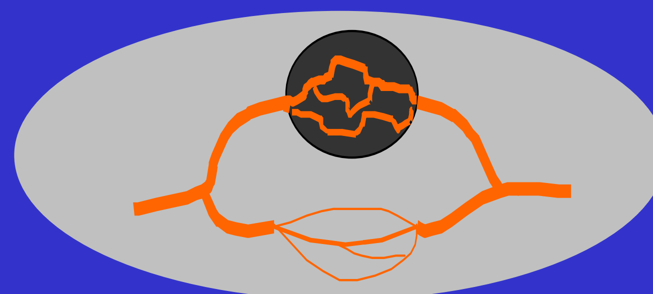
Wave Length λ: 1064nm

Coolant Temperature: 10ºC

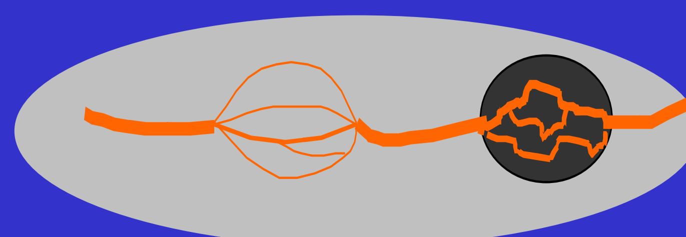
Maximum Power: 100W

Three Type of Geometric Relationship between Normal tissue and Tumor vascular bed (C. W. Song):

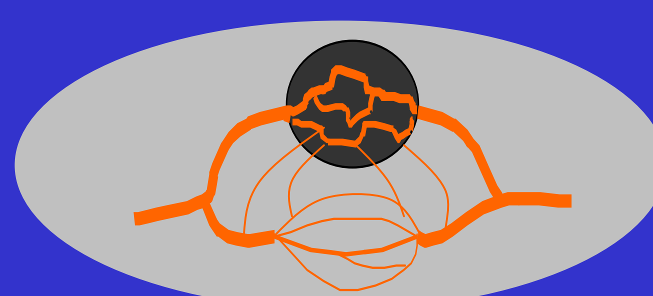
Parallel



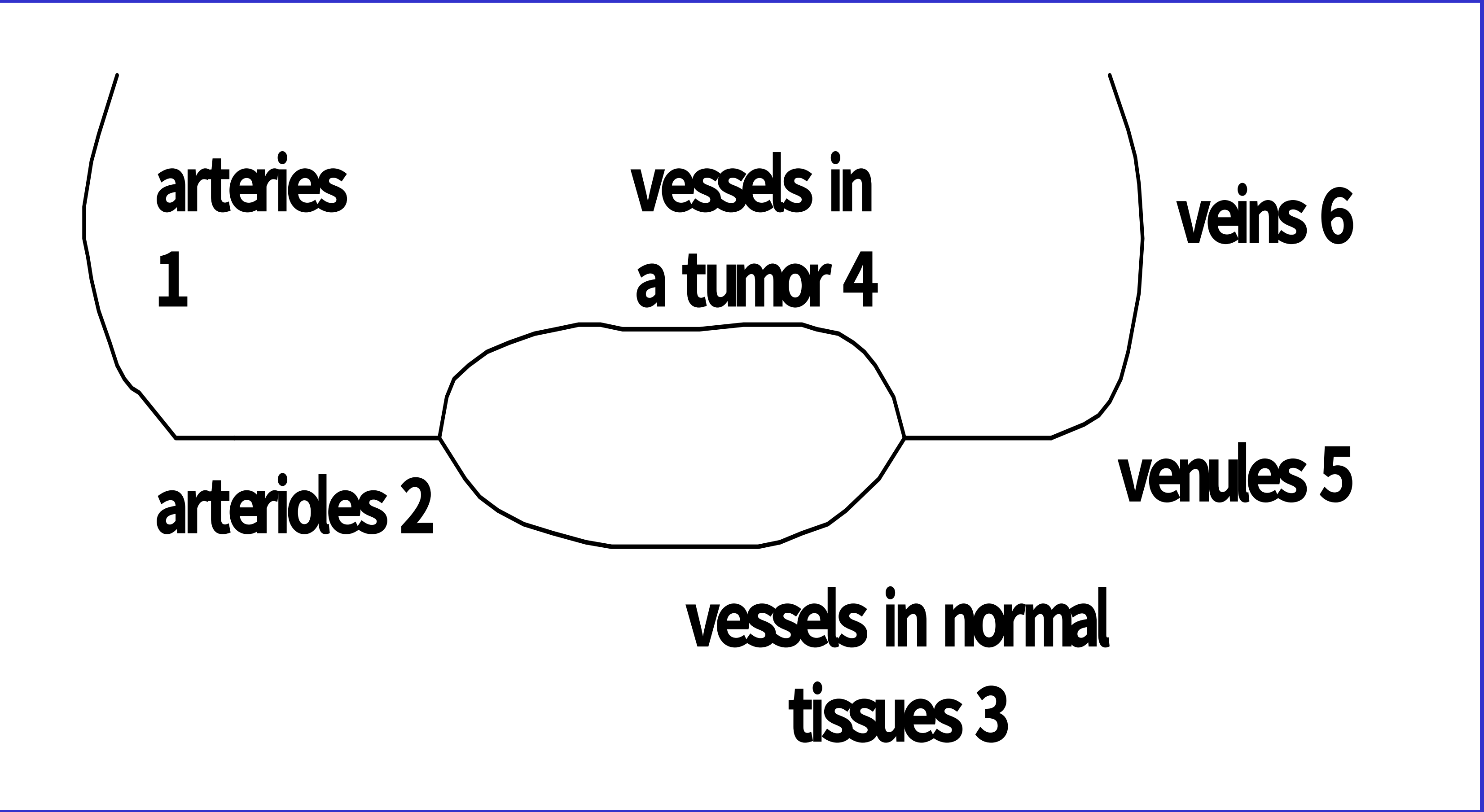
Series



Parallel and Series



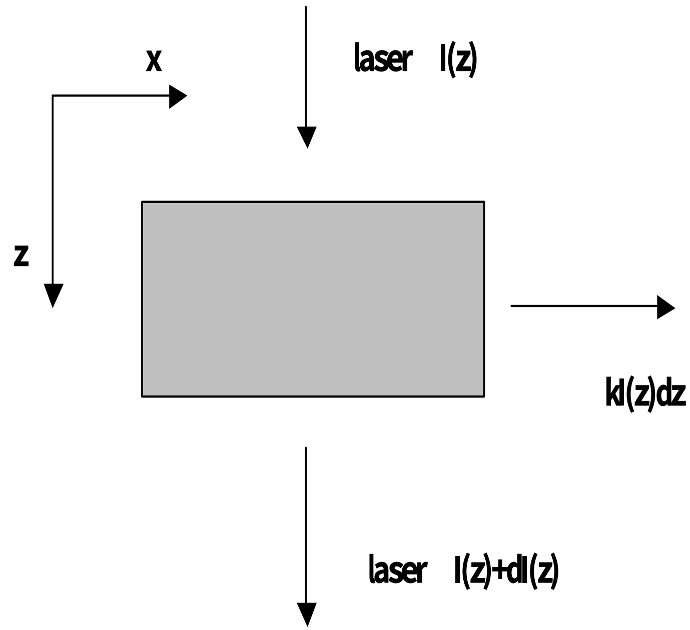
Tumor and Normal Tissue Vascular Bed in the Laser Irradiation Model



Heat Generation

$$I(x,z) = I_0(x)e^{-(a+s)(H+z)}$$

$$Q = -\frac{dI}{dz} = aI_0(x)e^{-a(H+z)}$$



Lambert - Beer’s law

Assumption of vessel response to the temperature variation

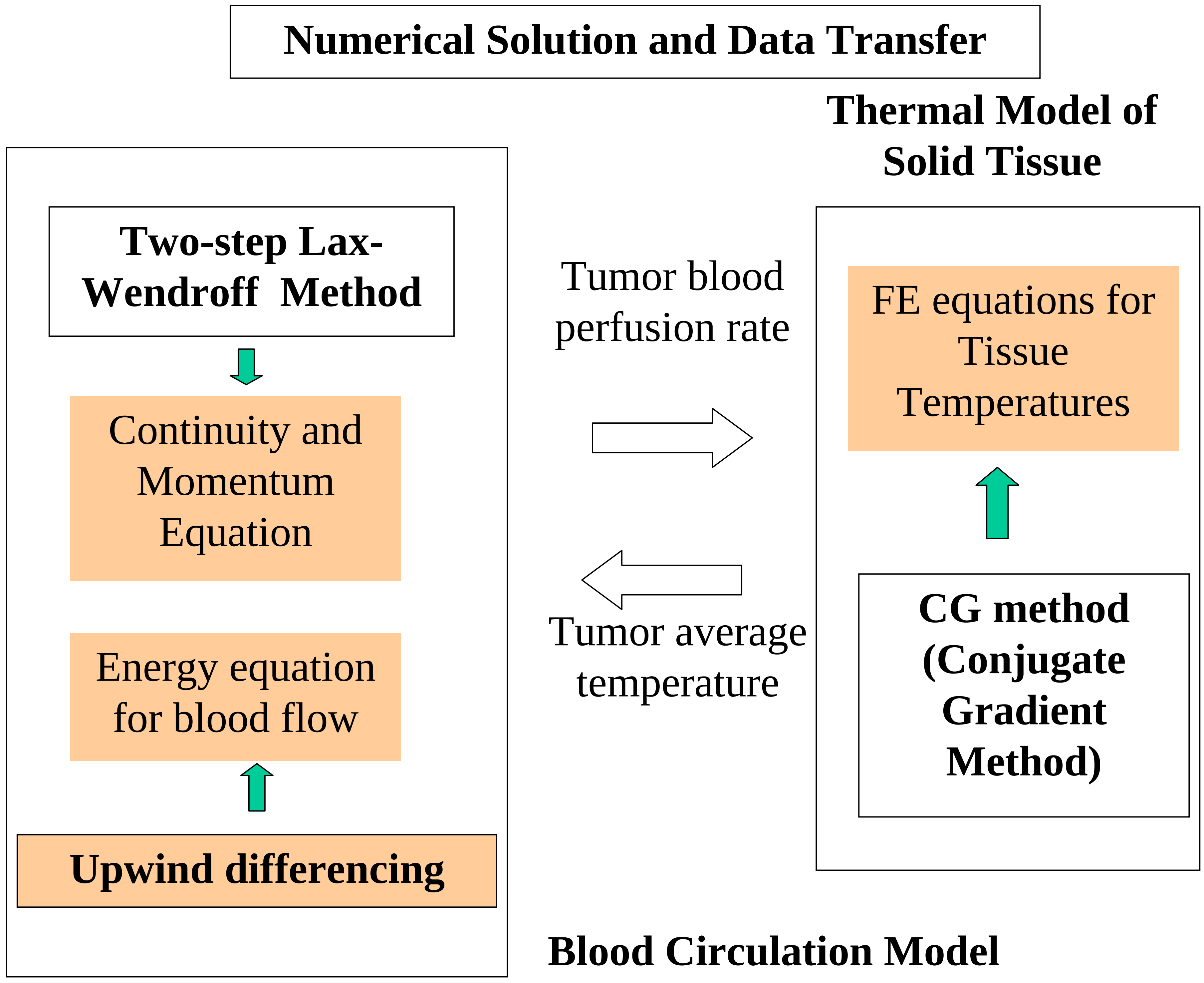
$$A = A_0 e^{b(T - T_0)}$$

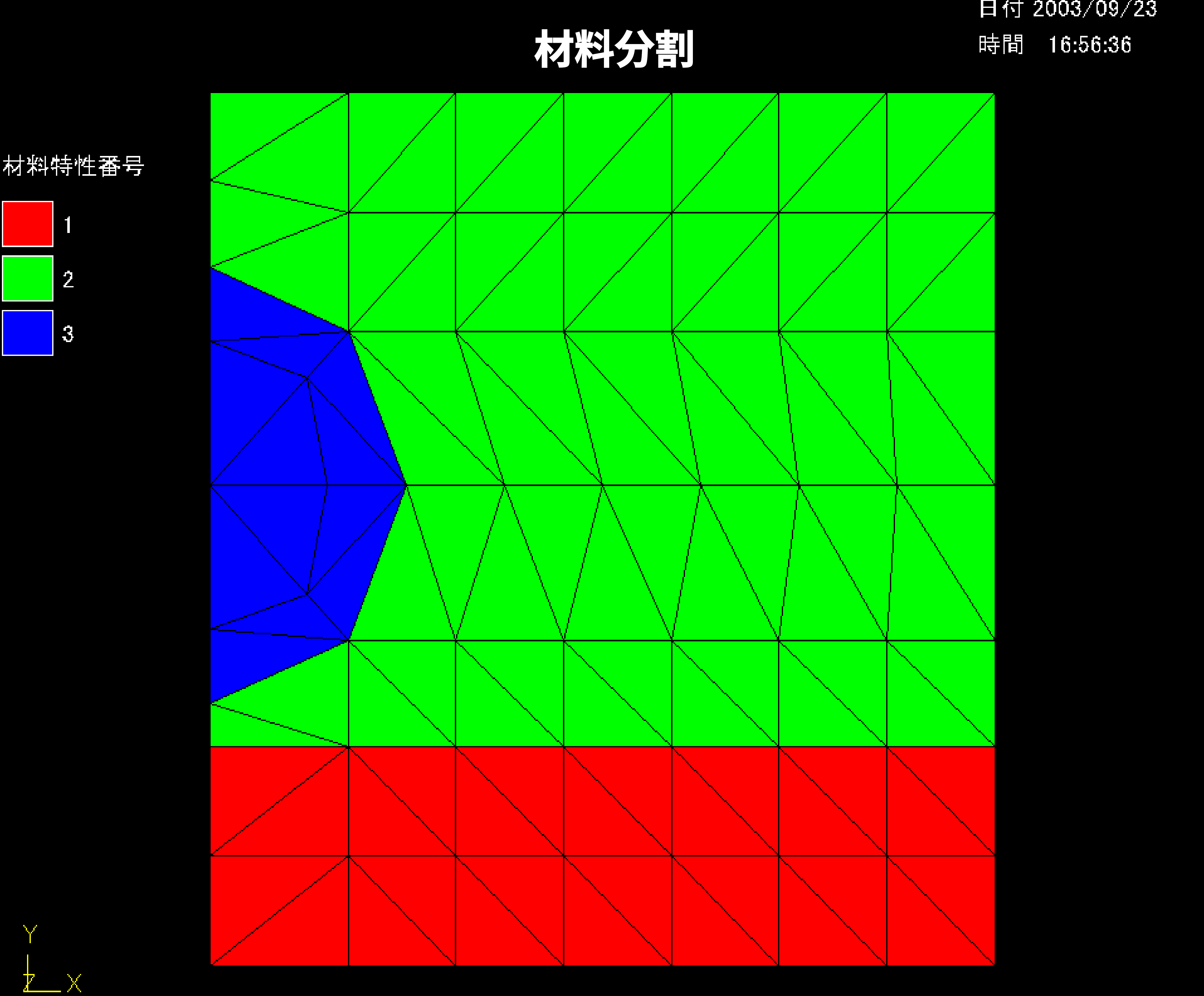
A_0 T_0 cross sectional area and blood temperature before heating

b variation coefficient

$b = 0.1 \qquad T = 39 \sim 42^o C$

$b = -0.1 \qquad T > 42^o C$


Numerical Solution and Data Transfer
Thermal Model of Solid Tissue
Two-step Lax-Wendroff Method
Continuity and Momentum Equation
Energy equation for blood flow
Upwind differencing
Tumor blood perfusion rate
Tumor average temperature
FE equations for Tissue Temperatures
CG method (Conjugate Gradient Method)
Blood Circulation Model



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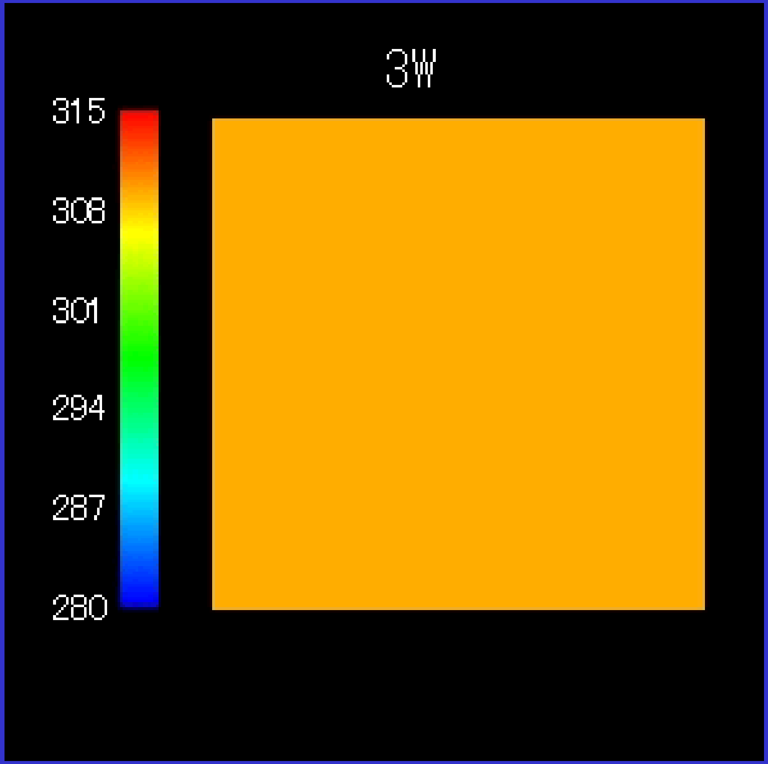
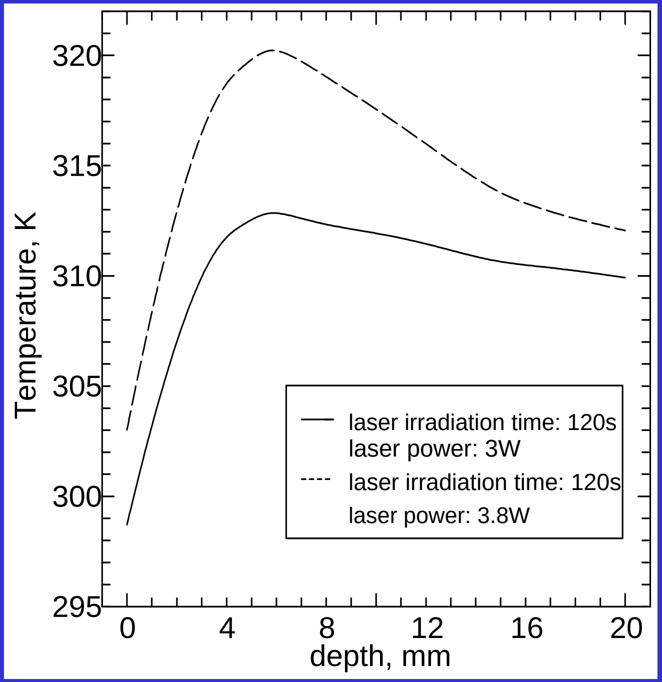
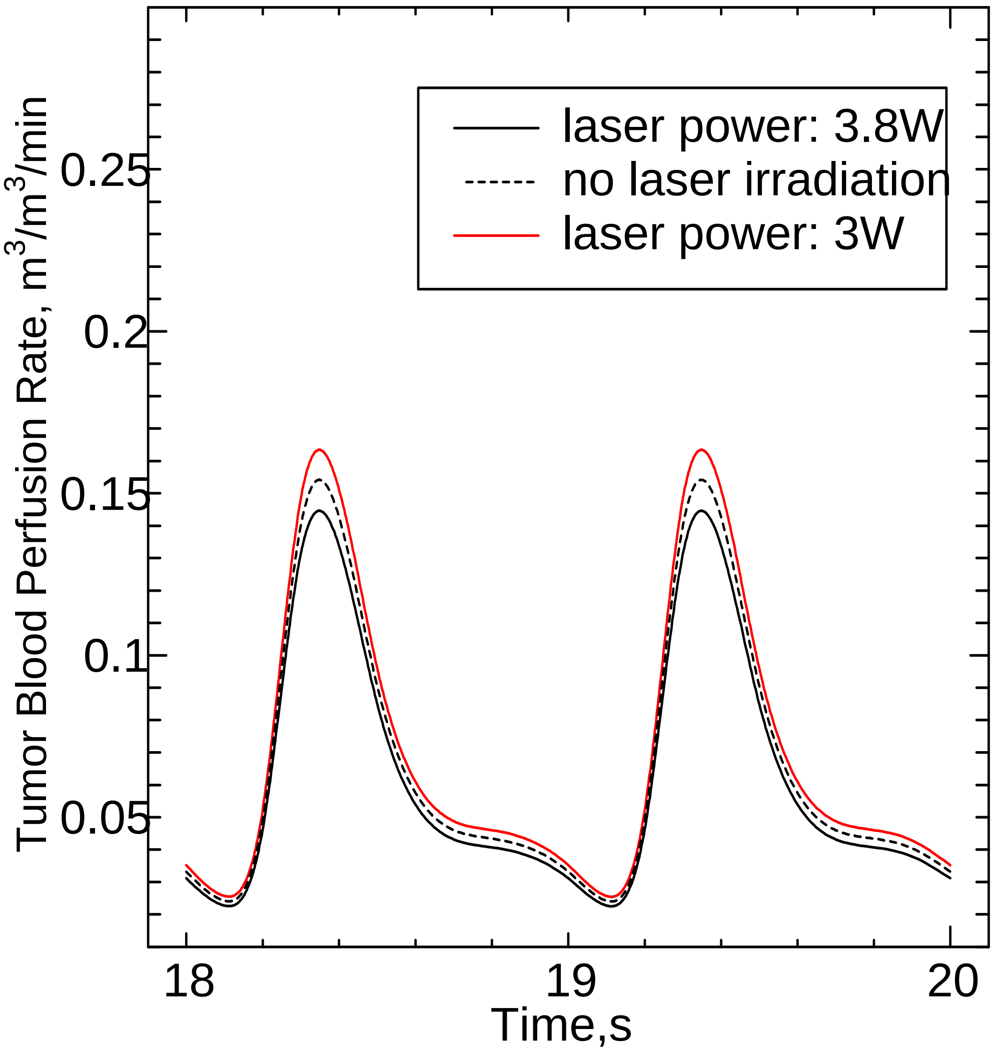
Temperature Distribution inside Living Tissues under the Laser Irradiation





Predicted Tumor Blood Perfusion Rate Under Different Laser Power



Acknowledgements

- I would like to thank Dr. Zhi Gang Sun for his kind assistance with the investigation of tumor blood flow.

Summary

- Detailed work has conducted to investigate the mechanism of thermoregulation in the periphery. The results show that coupling of the one-dimensional blood circulation model and thermal model of the solid tissue is a valid way to investigate the thermal characteristics of biological system.

- An initial study is carried out to investigate the tumor blood perfusion rate using the similar method as that of work for the thermoregulation in the human finger.

- Further experimental and numerical work may be carried out in the investigation of tumor vasculature and blood flow as well as peripheral blood perfusion rate.

Representative Papers

- He, Y., Shirazaki, M., and Himeno, R., “Two dimensional FEM model to investigate the effect of distal blood flow on the human finger”, Thermal Science and Engineering, Vol. 10(2002), No. 3, pp.19-24.

- He, Y., Liu, H., and Himeno, R., “A One-dimensional Thermo-fluid Model of Blood Circulation in Upper Limb of Man”, International Journal of Heat and Mass Transfer, Vol. 47(2004), Issues 12-13, June, pp.2735-2745.

- He, Y., Liu, H., Himeno, R., and Shirazaki, M., Numerical and Experimental Study on the Relationship between Blood Circulation and Peripheral Temperature, Conference Proceedings of 13th International Conference on Mechanics in Medicine and Biology, pp.94-95,12-15 Nov. 2003, Tainan.

- He, Y., Shirazaki, M., Liu, H., and Himeno, R., “Numerical Study of the Blood Flow and Living Tissue under Laser Irradiation”, The 16th Bioengineering Conference by JSME, Jan. 22-23, 2004, pp.192-193, Kitakyushu, Japan.