A FINITE ELEMENT MODEL FOR DETERMINING THE EFFECTS OF BLOOD FLOW ON THE FINGER TEMPERATURE DISTRIBUTION

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The Physiological Characteristics of the Human Finger

- The vessel network is well developed
- Compared to the other parts in human body, there are fewer muscles
- When human body receives an inside and outside stimulus, the physiological behavior in the hand will vary obviously.

The Mechanical Characteristics of the Human Finger

- The human finger has high sensory and motor capacities
- Convey information about (a) mechanical, (b) thermal and (c) tissue damaging events occurring on the skin of the hand

Some Physiological Phenomena and Diseases Related to Finger Skin Temperature

- After cigarette smoking, the peripheral circulation becomes worse and the skin temperature decreases. (Cleophas,T.J.M, et al. 1982, Bornmyr, S. et al. 1991)
- While in the state of stress or fatigue, the finger skin temperature decreases (Nketia,P. and Reisman,S. 1997).
- Thermoregulation abilities for men and women are different (Cooke,J.P. et al. 1990)
- Raynaud’s syndrome

Research Objective

- What is the mechanism of thermoregulation and circulation diseases in periphery.
- Numerous thermal models have been presented, few models focused on the relationship between haemodynamic changes and heat transfer.

The possible applications

Developing human sensory sensor used in the areas like:

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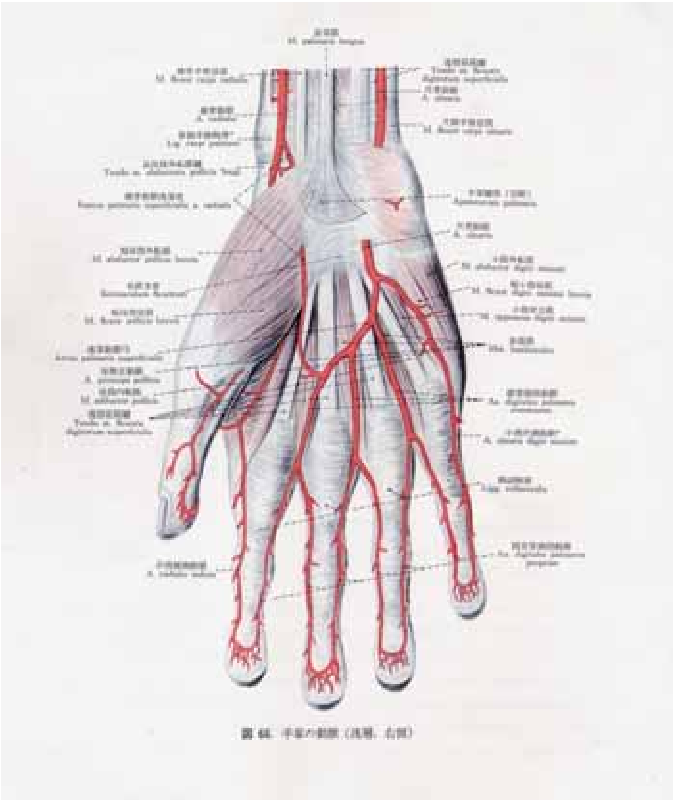
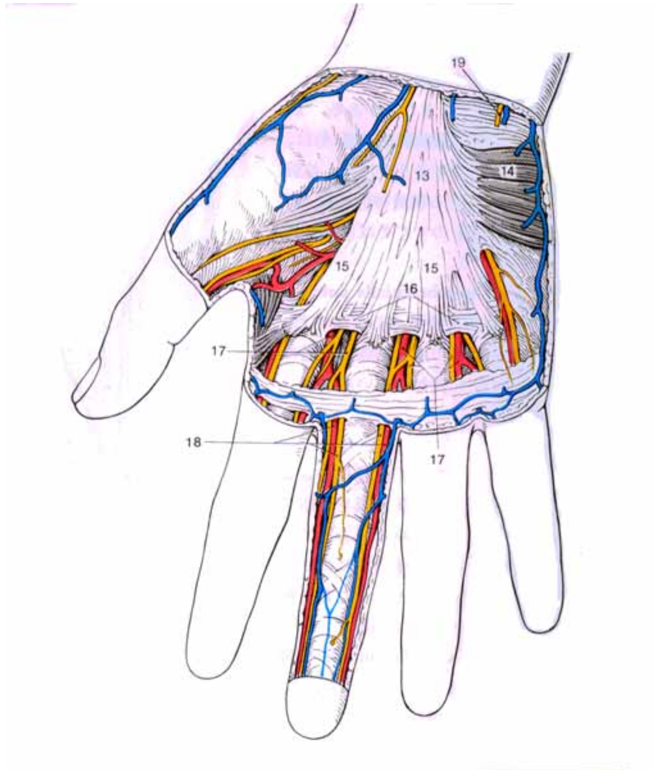
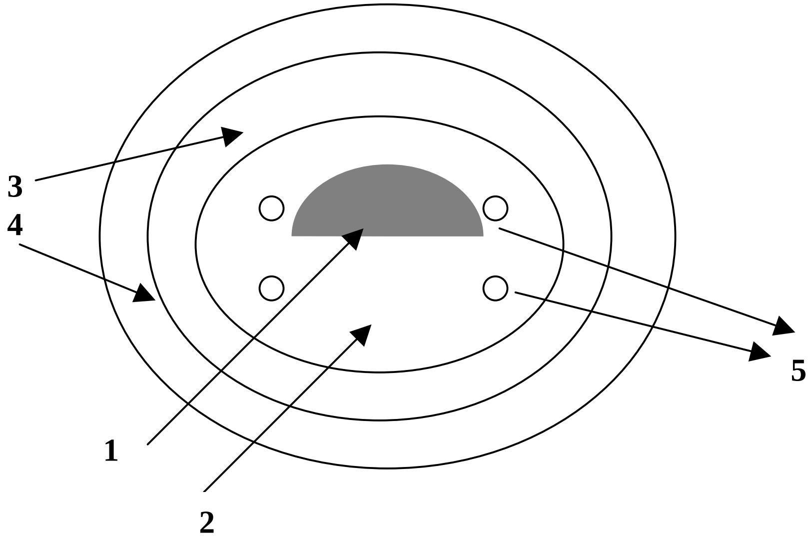
- Health management for monitoring physiological parameters
- Safe driving
- Family robot and prosthetic hands

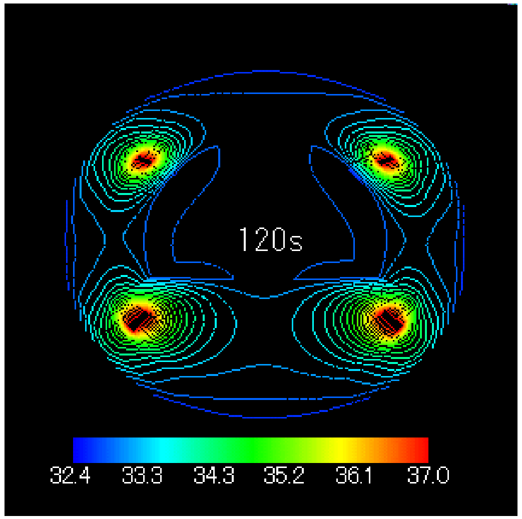




The peripheral circulation system in the hand

(cited from Angiology and Taschenatlas der Anatomie)

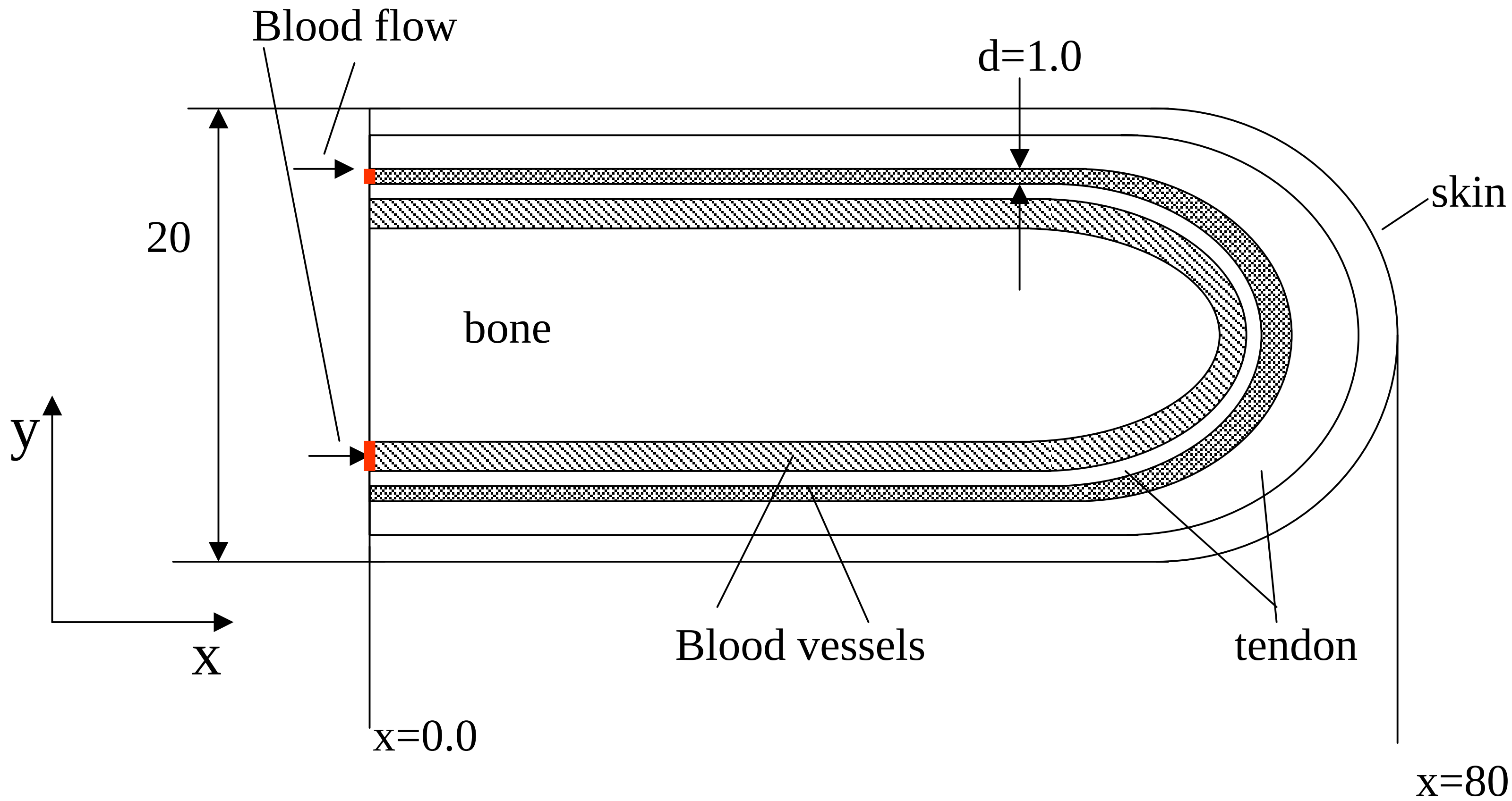




1. Bone 2. Tendon 3. Dermis 4. Epidermis 5. Artery

Two-dimensional thermal model of the middle finger

The geometric model of the finger in longitudinal direction



Blood flow:

Laminar flow

Blood vessels:

rigid tube, the tube elasticity is not considered.

Governing Equations in Blood Vessels

- Navier-Stokes equation

$$\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \cdot \nabla)\mathbf{u} = -\nabla p + \frac{1}{\mathrm{Re}} \Delta \mathbf{u}$$

- Continuity equation

$$\nabla \cdot \mathbf{u} = 0$$

- Energy equation

$$\frac{\partial \mathbf{T}}{\partial t} + (\mathbf{u} \cdot \nabla) = \frac{1}{Pe} \Delta \mathbf{T}$$

u:	velocity
p:	pressure
T:	temperature
Re:	Reynolds number
Pe:	Peclet number

Energy Equation in tissues

$$\frac{\partial \mathbf{T}}{\partial t} = \frac{1}{Pe_t}\Delta \mathbf{T} + \frac{\psi}{Pe_b} W(1-\mathbf{T}) + \frac{\psi}{Pe_b} q_{met}$$

u: velocity

T: temperature $T = \frac{T^* - T_\infty^*}{T_a^* - T_\infty^*}$

Pe: Peclet number $Pe_t = \frac{U_\infty D}{\alpha_t}$

W: dimensionless volumetric blood perfusion rate $W = \frac{(\omega_b \rho_b c_b) D^2}{\lambda_b}$

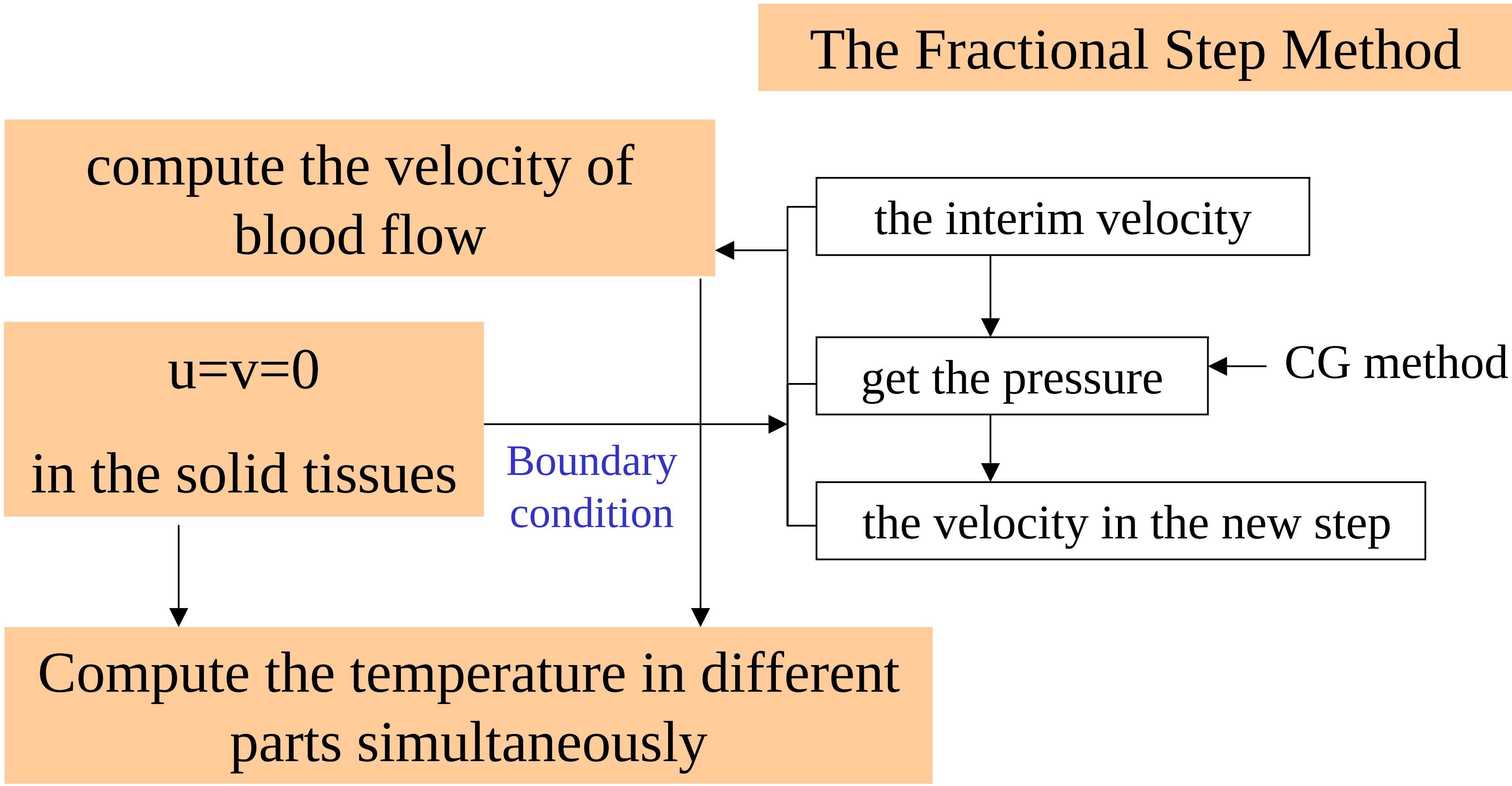
ψ: dimensionless ratio of blood to tissue thermal inertia $\psi = \frac{\rho_b c_b}{\rho c}$

$q_{met:}$ dimensionless volumetric heat generation rate $q_{met} = \frac{q_{met}^* D^2}{(T_a^* - T_\infty^*)\lambda_b}$

subscripts

t: tissue

b: blood


The Fractional Step Method
compute the velocity of blood flow
the interim velocity
u=v=0
in the solid tissues
get the pressure
CG method
Boundary condition
the velocity in the new step
Compute the temperature in different parts simultaneously

Characteristics and limitations

- The Governing equations of fluid are suitable for the whole domain (fluid and solid part)
- No necessary to consider the boundary conditions between fluid and solid part
- Can deal with the problem with different thermal properties in different place
- Be applicable to the thermo-fluid problem in low Reynolds number
- not easy for mesh generation
- The computational time is increased

Boundary conditions

- 1. Inlet part: $u=1, v=0, T=1$
- 2. Outlet part: $p=p_{out}$
- 3 . Solid tissue (inside): $u=v=0$
- 4. Cross section (solid): $u=v=0$

  $T=T_1(y,t)$ or $T=T_1(y)$
- 5. Skin surface: $u=v=0$

  Temperature $$\left.\frac{\partial T}{\partial n}\right|_{\Gamma} = BiT\Big|_{\Gamma} + \left.\frac{h_{ra}D}{\lambda_s}\right| + E_{diff}$$

  a. In the air:

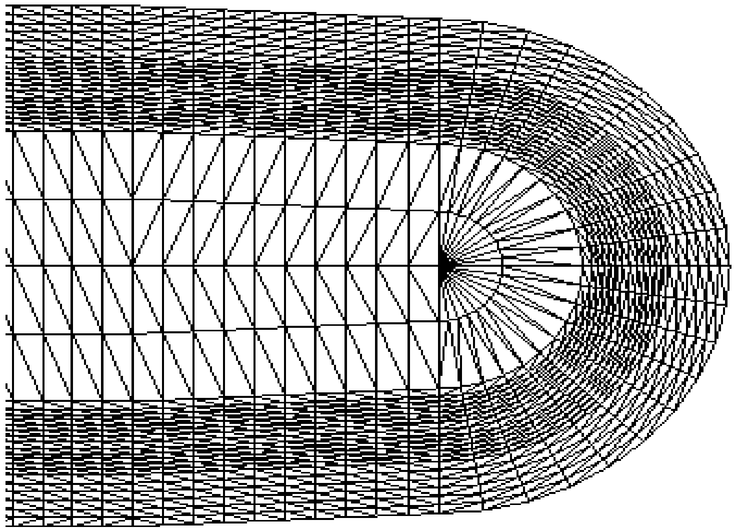
Bi: Biot number

Table 1. Thermophysical properties and blood perfusion rate of tissues

	bone	tendon	skin	blood
ρ(kg/m^3)	1418	1270	1200	1100
c(J/kgK)	2094	3768	3391	3300
λ(W/mK)	2.21	0.35	0.37	0.50
ω(ml/ml/min)	2.0/100	3.43/100	24/100	–
$\mu\times10^6$(N.s/m^2)	–	–	–	2085
q_{met}(W/m^3)	352	368	273	–

Arterial temperature	37^oC
Outlet pressure	20 mmHg
Ambient temperature (by infra-red thermography)	19^oC
Arterial blood velocity (by bi-directional Doppler DVM-4300)	6, 10, 20cm/s
Convective heat transfer coefficient	$4W/m^2K$
Radiative heat transfer coefficient	$4.7W/m^2K$

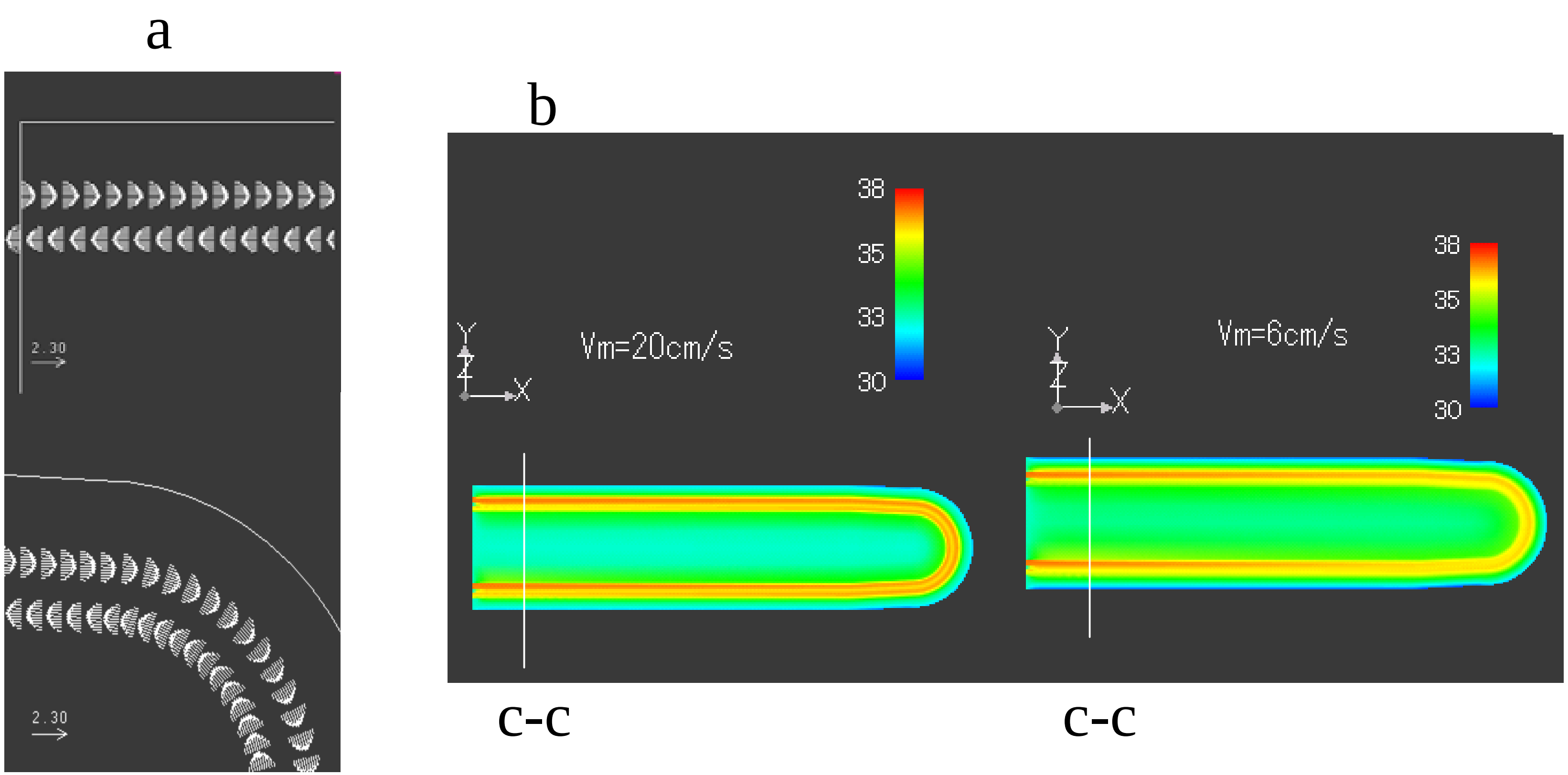
A part of finite element grid network of the modeled finger in longitudinal direction



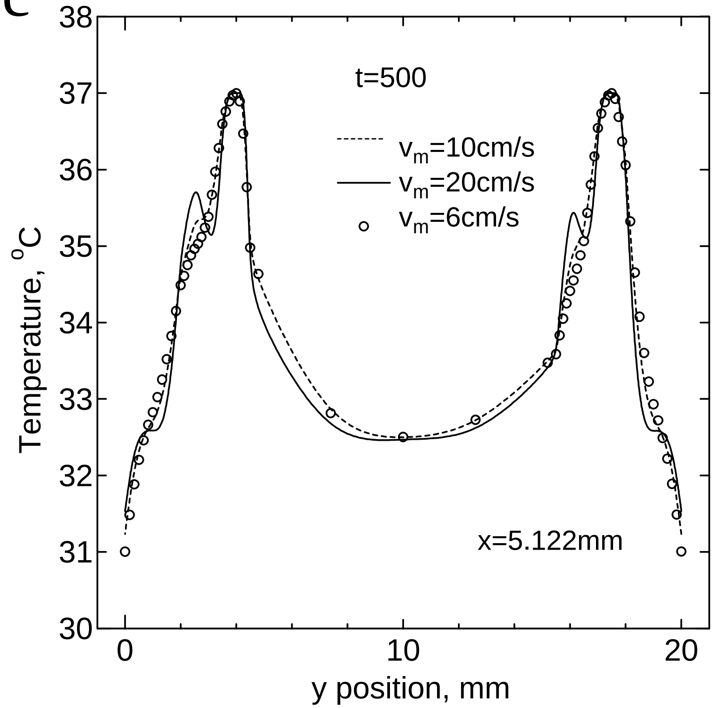
elements: 19234

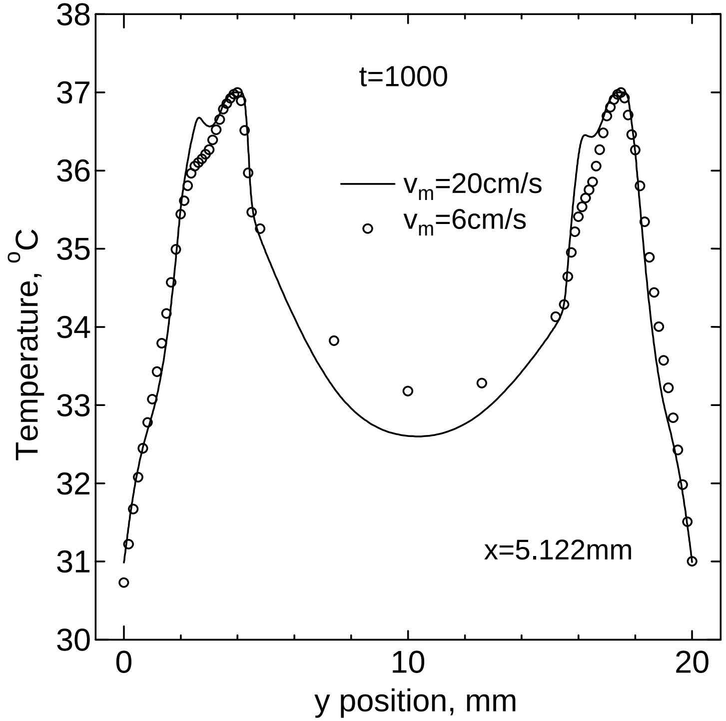
time increment: 2×10^{-5}

2×10^{-3}(only in the energy equation)

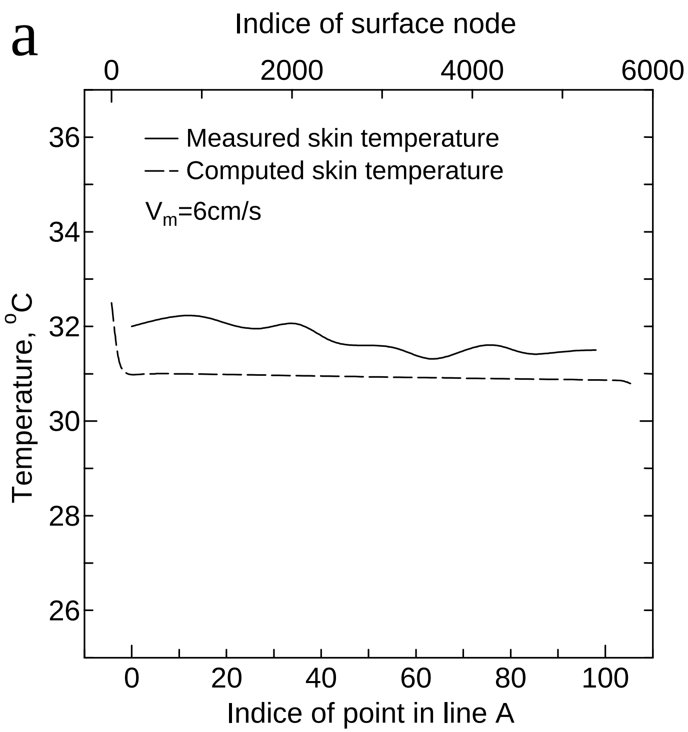


a. Velocity distribution b. Isotherm contours of model-A finger in longitudinal direction for different blood velocity c-c

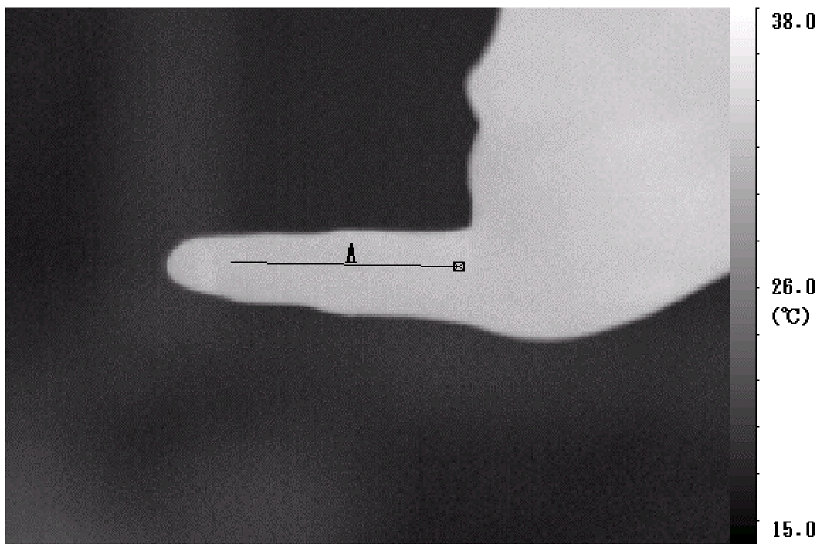




Temperature profile in a cross section of a finger for different blood flow conditions a

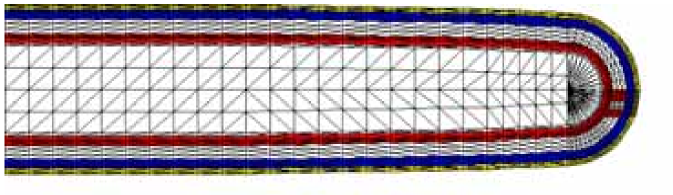


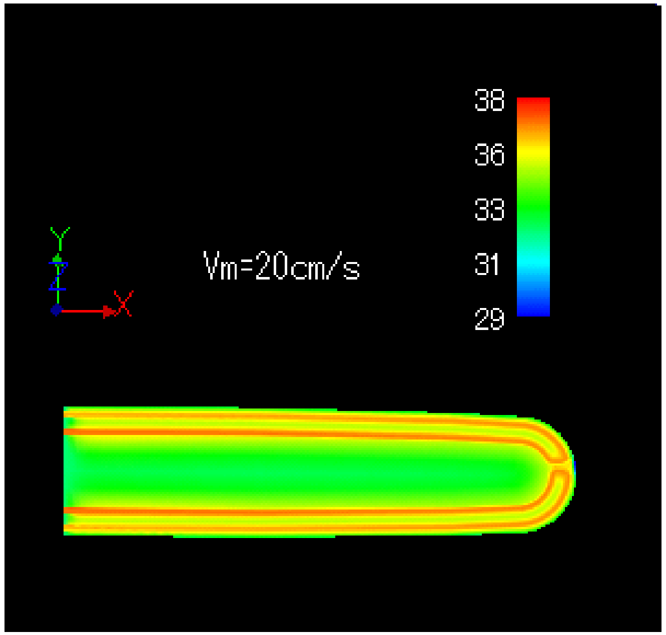
b

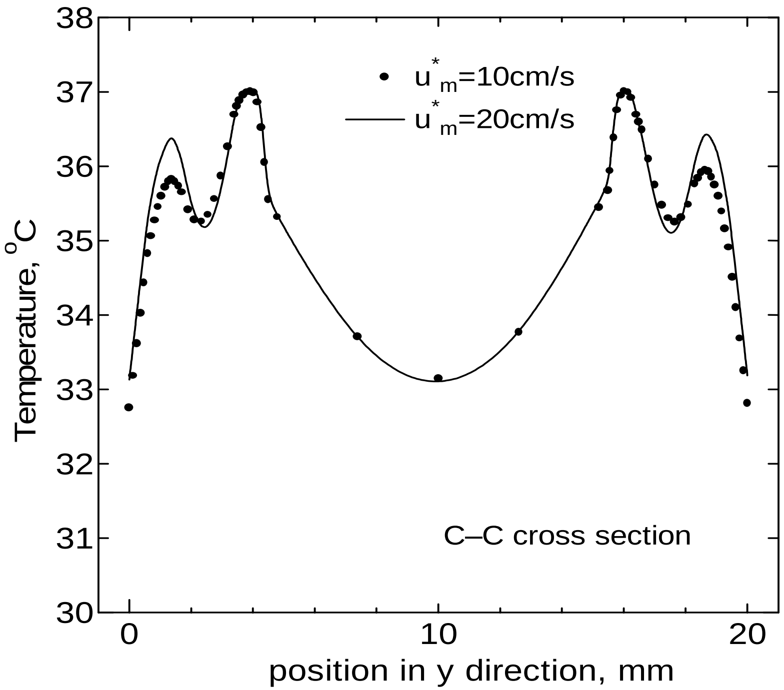


a. The comparison of the measured skin temperature and the computed skin temperature b. The thermograph of a finger (ambient temperature T_{amb}=19°C)

Isotherm contour and temperature profile of model-B finger







Concluding Remarks

- A FE thermo-fluid model is presented to investigate the effect of blood flow on the temperature distribution in a finger.

- In indoor environment, with the velocity in larger blood vessels increasing, the skin temperature increases. However, the variations of the skin temperatures in different blood velocities are quite small .

- The comparison of the results of model A and B suggest that the heat transport in the superficial vein is important.

Discussion

- The flexibility of the blood vessel, the waveform velocity, and the transmural pressure may be considered in examining the relationship between the flow rate and temperature in the peripheral circulation.

- In order to simulate the thermal characteristic of human body in the dynamic state, the coupling of one-dimensional elastic model and FE thermal model is expected.