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 (Nkетia, 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:

- 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)

Two-dimensional thermal model of the middle finger
The geometric model of the finger in longitudinal direction

- Bone
- Blood vessels
- Skin
- Tendon
- Blood flow

Dimensions:
- x=0.0
- x=80
- y=0
- y=20
- d=1.0
Blood flow:
Laminar flow

Blood vessels:
rigid tube, the tube elasticity is not considered.
Governing Equations in Blood Vessels

- Navier-Stokes equation

\[ \frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \cdot \nabla) \mathbf{u} = -\nabla p + \frac{1}{\text{Re}} \frac{\partial}{\partial t} \mathbf{u} \]

- Continuity equation

\[ \nabla \cdot \mathbf{u} = 0 \]

- Energy equation

\[ \frac{\partial T}{\partial t} + (\mathbf{u} \cdot \nabla) T = \frac{1}{\text{Pe}} \frac{\partial}{\partial t} T \]

\[ \text{u: velocity}\]
\[ \text{p: pressure}\]
\[ \text{T: temperature}\]
\[ \text{Re: Reynolds number}\]
\[ \text{Pe: Peclet number}\]
Energy Equation in tissues

\[
\frac{\partial T}{\partial t} = \frac{1}{Pe_t} \nabla T + \frac{\psi}{Pe_b} W (1 - T) + \frac{\psi}{Pe_b} q_{\text{met}}
\]

- **u**: velocity
- **T**: temperature \( T = \frac{T^* - T_x^*}{T_a^* - T_x^*} \)
- **Pe**: Peclet number \( Pe_t = \frac{U_x D}{\alpha_t} \)
- **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_{\text{met}}**: dimensionless volumetric heat generation rate \( q_{\text{met}} = \frac{q_{\text{met}} D^2}{(T_a^* - T_x^*)\lambda_b} \)

**Subscripts**
- **t**: tissue
- **b**: blood
The Fractional Step Method

- Compute the velocity in the new step

- Get the pressure

- CG method

Boundary condition:

- Compute the temperature in different parts simultaneously

- u=v=0 in the solid tissues
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: \( p=p_{\text{out}} \)

• 3. Solid tissue (inside): \( u=v=0 \)

• 4. Cross section (solid): \( u=v=0 \)

\[ T=T_1(y,t) \text{ or } T=T_1(y) \]

• 5. Skin surface: \( u=v=0 \)

Temperature

\[
\left. \frac{\partial T}{\partial n} \right|_\Gamma = BiT \left|_\Gamma + \frac{h_{ra} D}{\lambda_s} \right| + E_{\text{diff}}
\]

a. In the air:

\( Bi: \) Biot number
Table 1. Thermophysical properties and blood perfusion rate of tissues

<table>
<thead>
<tr>
<th>Property</th>
<th>bone</th>
<th>tendon</th>
<th>skin</th>
<th>blood</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho$ (kg/m$^3$)</td>
<td>1418</td>
<td>1270</td>
<td>1200</td>
<td>1100</td>
</tr>
<tr>
<td>$c$ (J/kgK)</td>
<td>2094</td>
<td>3768</td>
<td>3391</td>
<td>3300</td>
</tr>
<tr>
<td>$\lambda$ (W/mK)</td>
<td>2.21</td>
<td>0.35</td>
<td>0.37</td>
<td>0.50</td>
</tr>
<tr>
<td>$\omega$ (ml/ml/min)</td>
<td>2.0/100</td>
<td>3.43/100</td>
<td>24/100</td>
<td>–</td>
</tr>
<tr>
<td>$\mu \times 10^6$ (N.s/m$^2$)</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>2085</td>
</tr>
<tr>
<td>$q_{met}$ (W/m$^3$)</td>
<td>352</td>
<td>368</td>
<td>273</td>
<td>–</td>
</tr>
<tr>
<td></td>
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<tr>
<td>---------------------</td>
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<td></td>
</tr>
<tr>
<td>Arterial temperature</td>
<td>37°C</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Outlet pressure</td>
<td>20 mmHg</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ambient temperature (by infra-red thermography)</td>
<td>19°C</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Arterial blood velocity (by bi-directional Doppler DVM-4300)</td>
<td>6, 10, 20 cm/s</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Convective heat transfer coefficient</td>
<td>4W/m²K</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Radiative heat transfer coefficient</td>
<td>4.7W/m²K</td>
<td></td>
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</tr>
</tbody>
</table>
A part of finite element grid network of the modeled finger in longitudinal direction

- elements: 19234
- time increment: $2 \times 10^{-5}$
- $2 \times 10^{-3}$ (only in the energy equation)
a. Velocity distribution  
b. Isotherm contours of model-A finger in longitudinal direction for different blood velocity
Temperature profile in a cross section of a finger for different blood flow conditions.
a. The comparison of the measured skin temperature and the computed skin temperature

b. The thermograph of a finger (ambient temperature $T_{amb}=19^\circ C$)
Isotherm contour and temperature profile of model-B finger

C–C cross section

Temperature, °C

position in y direction, mm
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.