# 生物组织内血流，温度及氧输送特性的有限元分析

# Finite Element Analysis of Blood Flow, Temperature, and Oxygen Transport

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贺缨

# 概要

- 不同充血状态下的手指动态温度响应的有限元分析

- 激光照射下肿瘤组织内血流，温度及氧输送特性的有限元分析

- 扭曲渗透型微血管及周围组织内的流体流动特性分析

# 手指温度变化与心血管机能相互关系的实验与数值模拟

# Experimental and Numerical Study on the Relationship between Fingertip Temperature and Cardiovascular Function

# 内皮功能评价—血管响应性测试

内皮功能障碍是心血管疾病发生的源头。

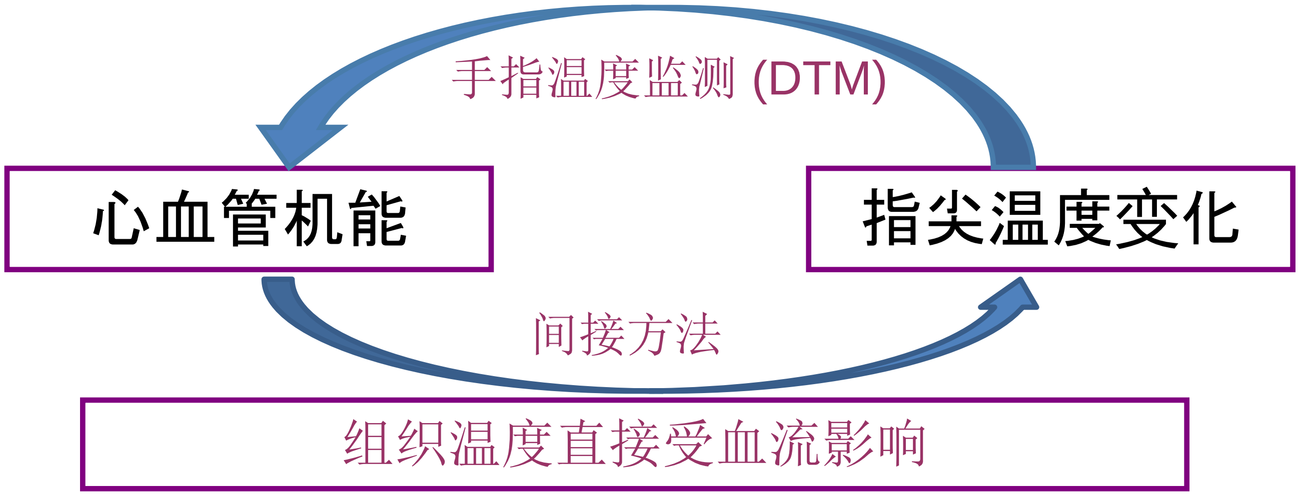
- 血管内皮细胞的功能

  调整血管张力以及血管直径，可以用血管响应性(Vascular Reactivity, VR)来反映内皮细胞的功能。

- 血管响应性测试的主要方法

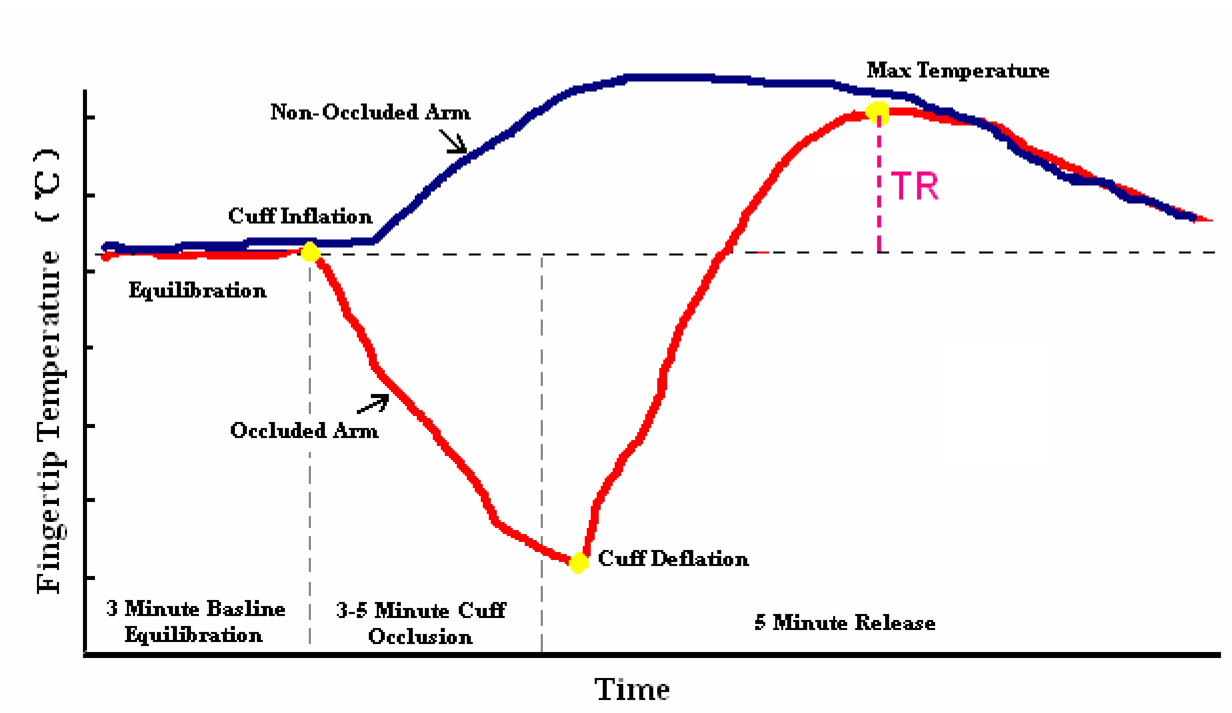
  通过观察动脉对闭塞以及再灌注（充血）的响应情况来衡量。对高血压、糖尿病以及其他一些病症的患者来说，他们的血管舒张功能减弱，因此充血响应也变弱了。

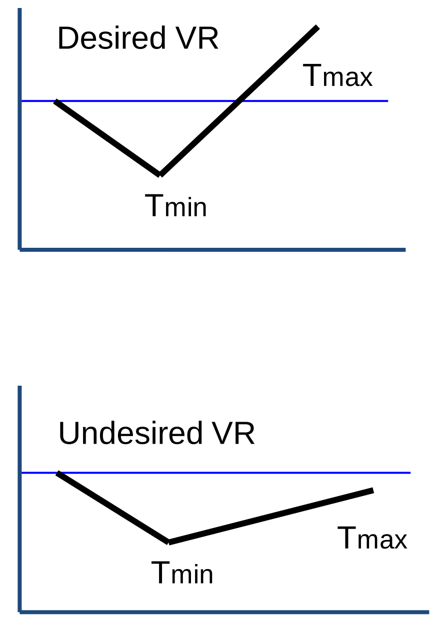
# 研究目的




开发有效的非接触性监测指尖温度变化的方法，并运用数学模型分析心血管机能对末梢组织温度的影响，为开发个人健康信息管理系统打下基础。

# 不同充血响应的手指温度变化



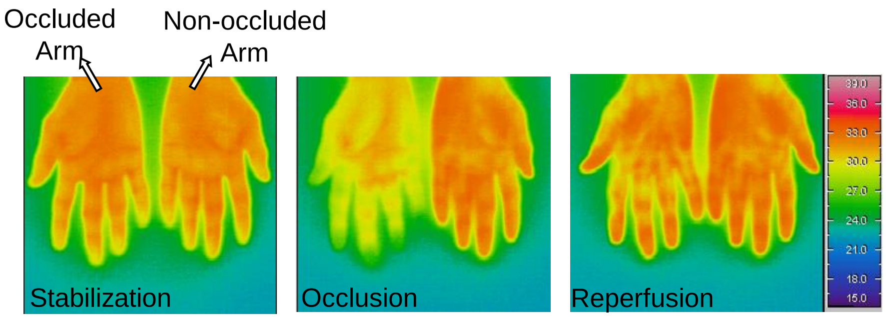




Digital Thermal Monitoring（DTM）
技术测试结果示意图

健康人与心血管疾病患者的
VR测试结果对比图

# 实验测试方法

- 被测者　：5人，20～30岁，健康
- 实验设备：NEC TH5100红外热像仪
- 实验条件：环境温度18℃，湿度40%RH
- 实验准备：让被测者以最舒服的姿势坐立，并使其双臂平放在面前安置好的支架上，在被测者的右手臂上安装气动袖带。
- 实验过程：使用红外热像仪连续记录VR测试过程中双手的温度
  - 拍摄稳定状态下的双手红外热图像3分钟
  - 快速使用气动袖带对右臂加压到200mmHg并拍摄双手的红外热图像3.5分钟
  - 快速释放气动袖带里的气体并拍摄双手的红外热图像4.5分钟。

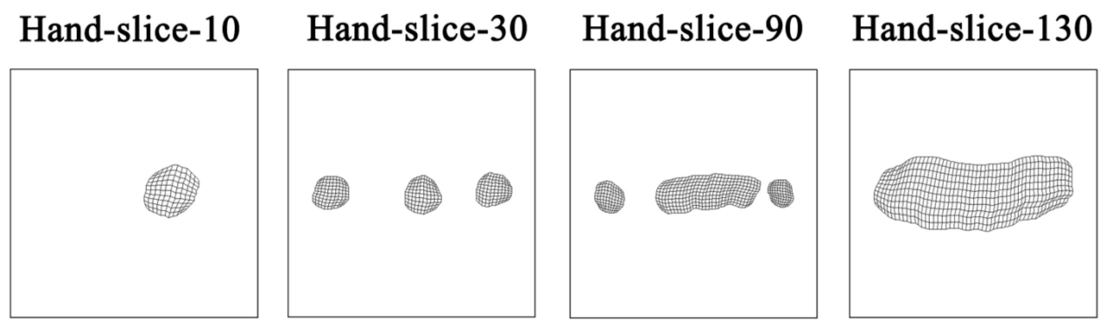


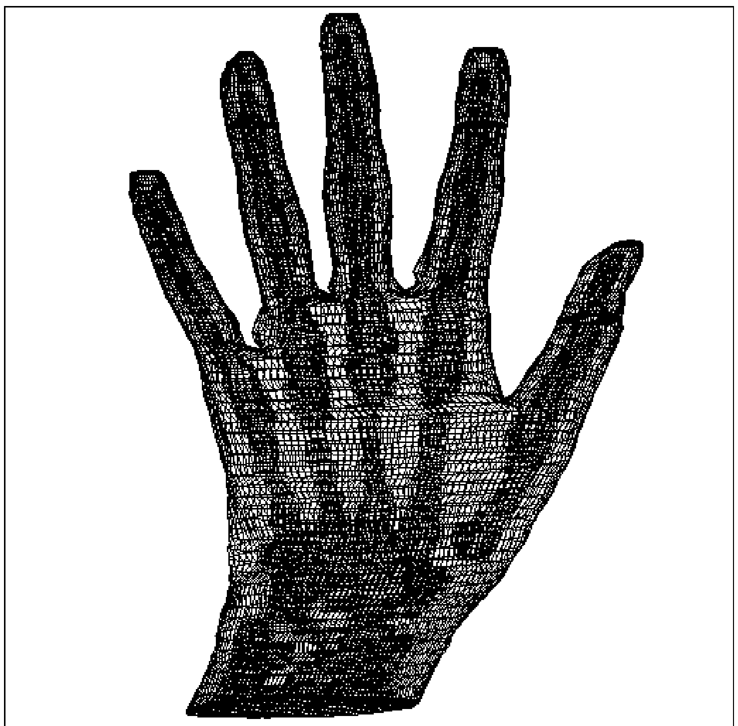
# 分析手部组织内血流及温度分布的基本思路

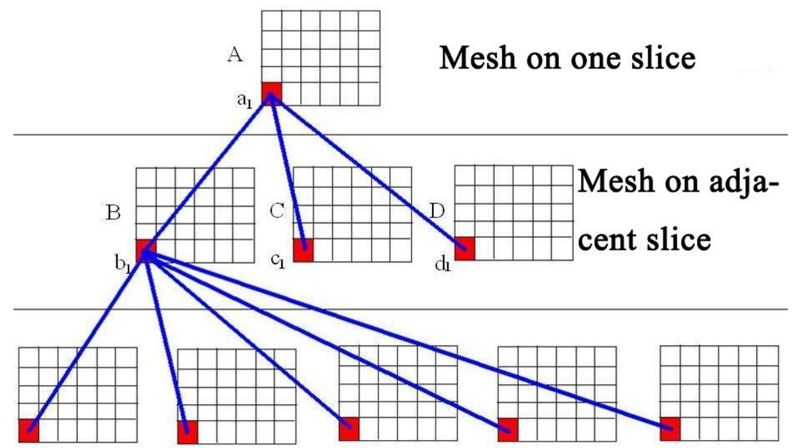
**三部分工作**

- 上肢循环的血流动力学模拟 → 基于弹性血管内流动的一维血流动力学模型
- 生物组织传热模型 → 多孔介质理论及**Pennes**生物传热方程
- 基于医学影像的真实结构几何建模 → 图像处理及基于超限插值的网格生成

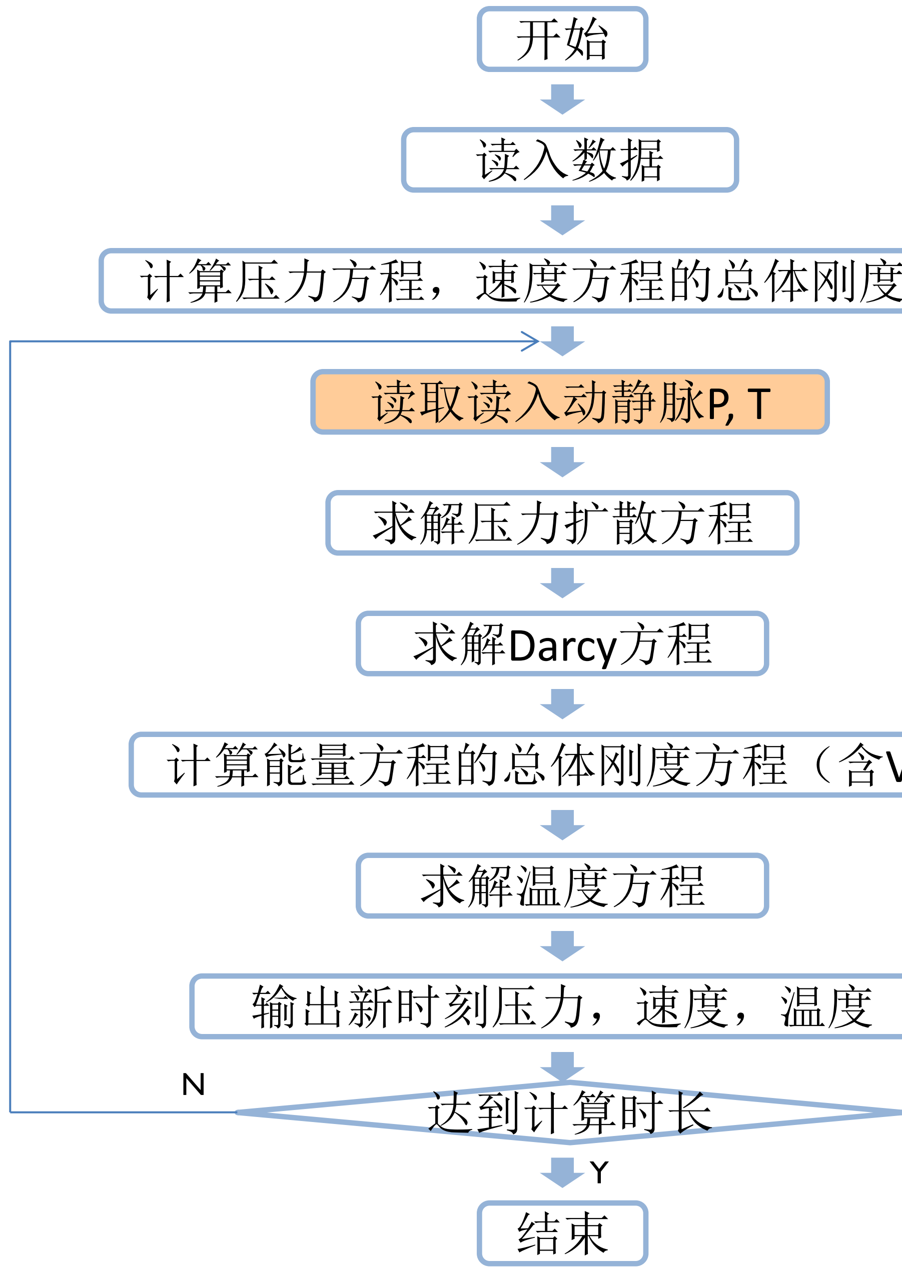
# 网格划分及连接方式


Hand-slice-10
Hand-slice-30
Hand-slice-90
Hand-slice-130

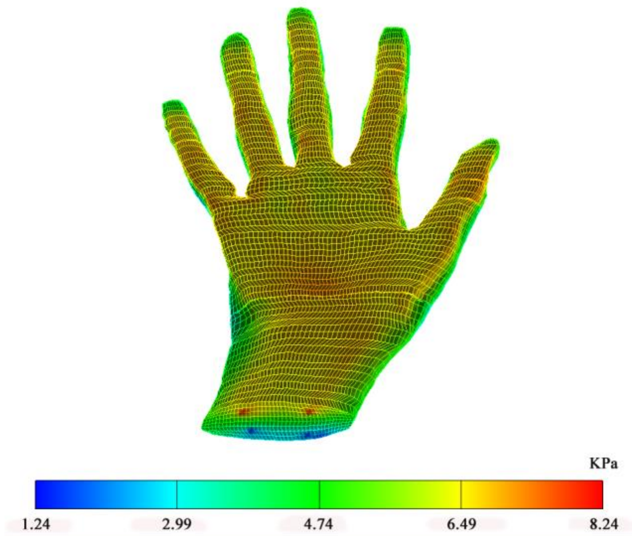


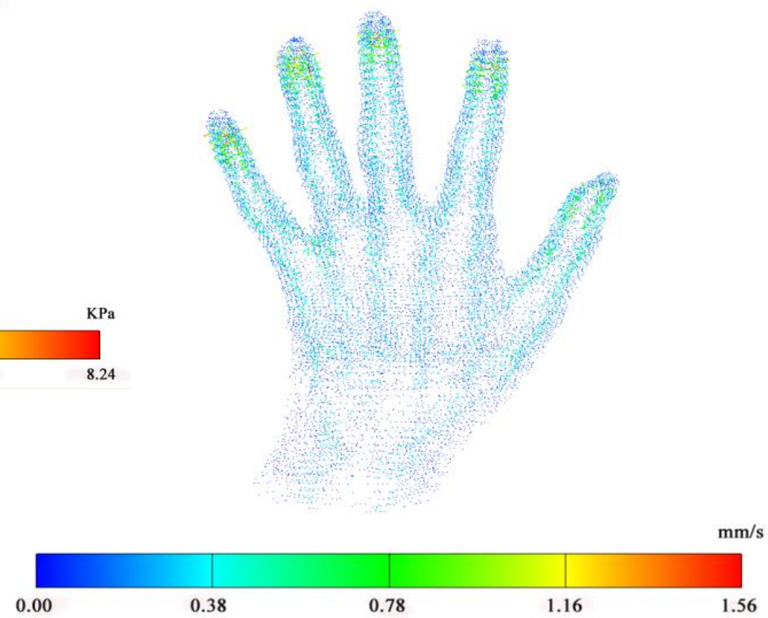

A
$a_1$
Mesh on one slice
B
$b_1$
C
$c_1$
D
$d_1$
Mesh on adja-
cent slice

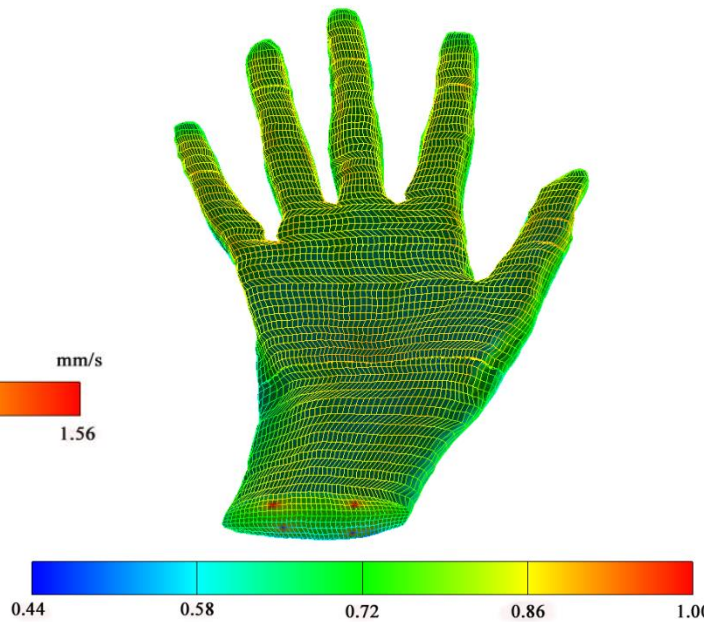
# 组织内血流及温度变化的分析流程



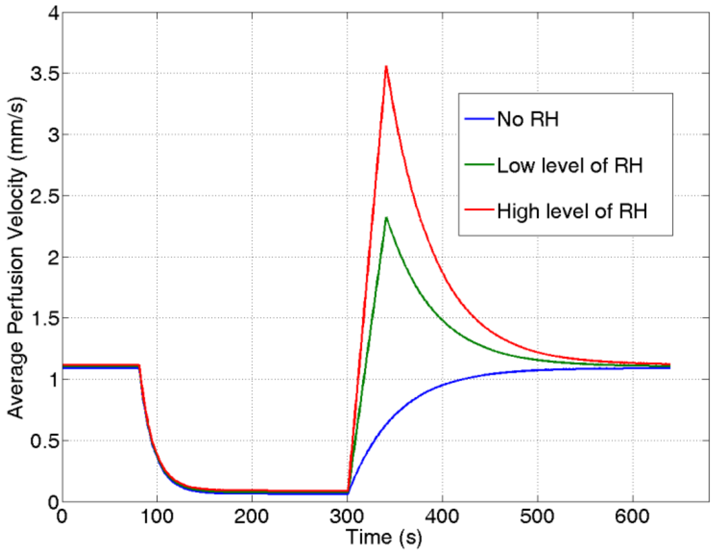
安静状态，室温下的组织血流压力，速度及温度分布

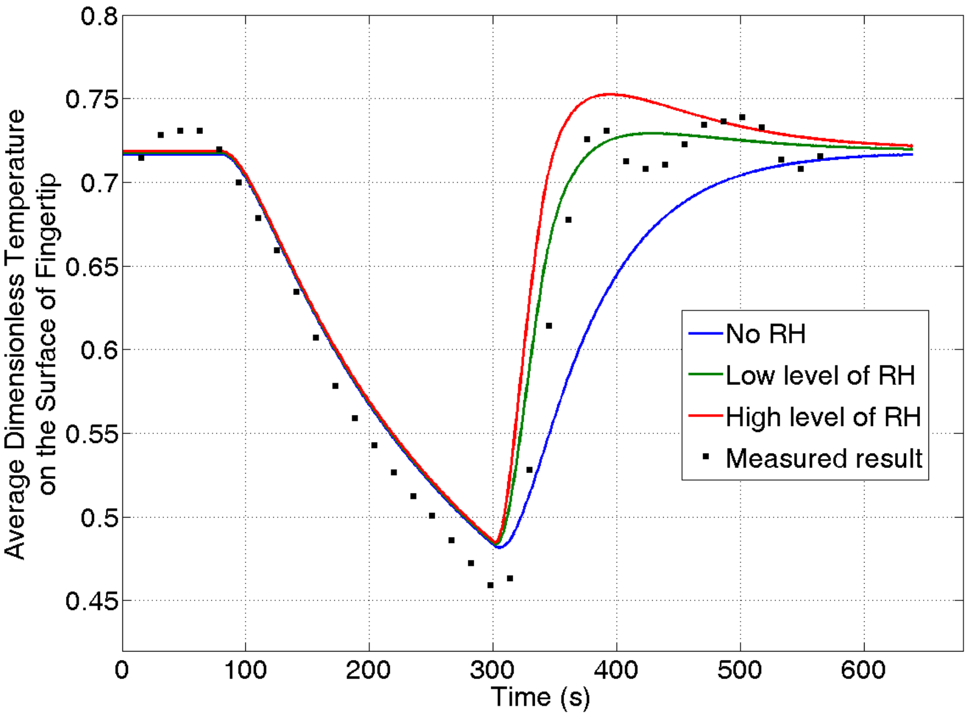


# 不同充血响应下指尖微血管内的平均流速以及平均温度的计算值与实验值的比较



# 总结

- 基于多孔介质理论的有限元分析很好地再现了指尖的充血响应，结果表明，指尖温度变化与微血管内的血流速度密切相关。
- 如何发展上肢血流模型以使其能够分析内皮细胞功能变化将是今后的工作重点。

# Numerical Study of Blood Perfusion Rate in Human Tumors Under Laser Irradiation

**Physiological barriers to drug delivery in tumors: blood vessel wall, interstitial space, cancer cell membrane**

↓

- **Radiotherapy**
- **Hyperthermia**
- **Immunotherapy**
- **Chemotherapy**

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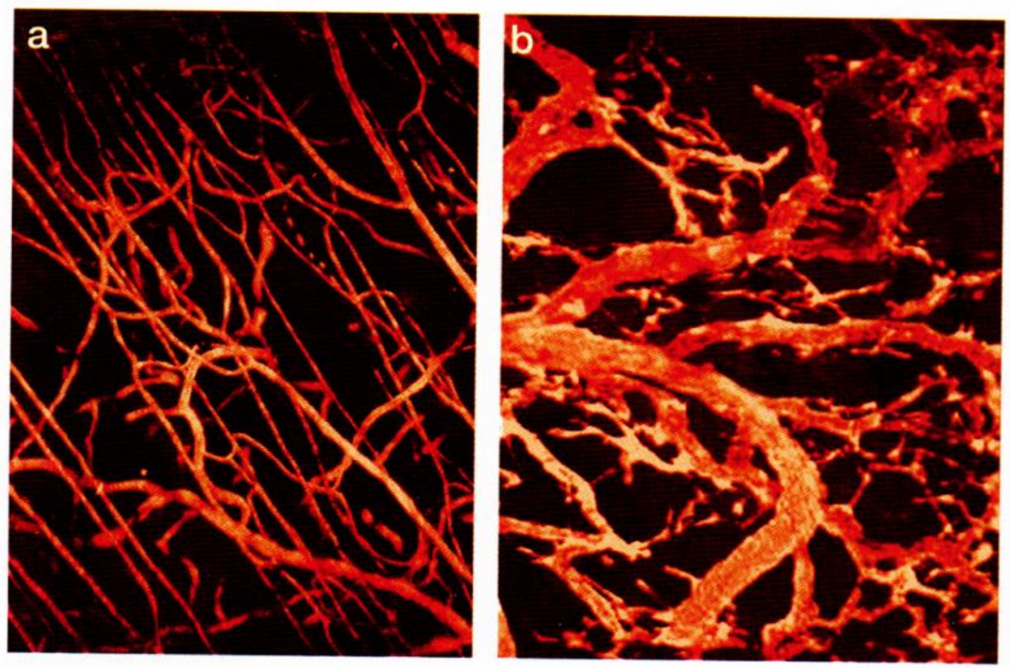
**Control of Tumor Blood Flow**

↓

**Improve the efficiency of cancer treatment**

## Normal and Tumor Vasculature

Tumor Vasculature: heterogeneous, permeable, and rigid

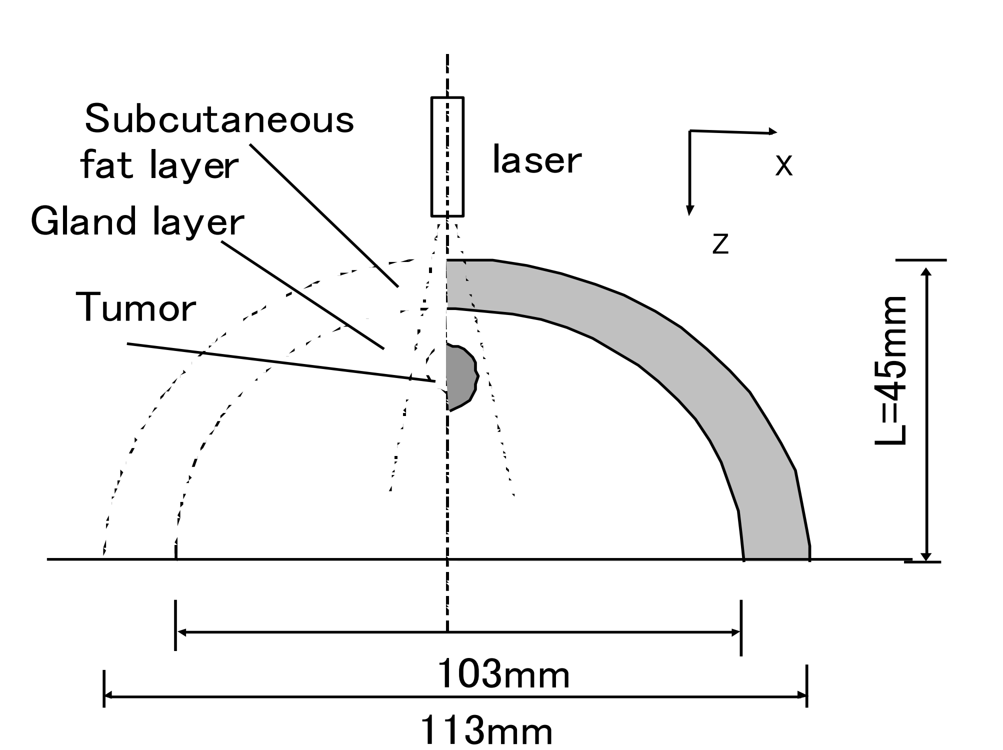



Vessels of Death or Life, by Jain, R. and Carmeliet. P, 日経サイエンス, 2002, No. 3)

## Objectives of the Study

- Investigate the thermal and hemodynamic response of tumor blood flow under moderate laser irradiation
- Investigate variation of oxygen transport under different blood flow.

# Schematics of laser irradiated tissues




Laser Type: Nd-Yag laser

Wave Length $\lambda$: 1064nm

Coolant Temperature: $10^{o}C$

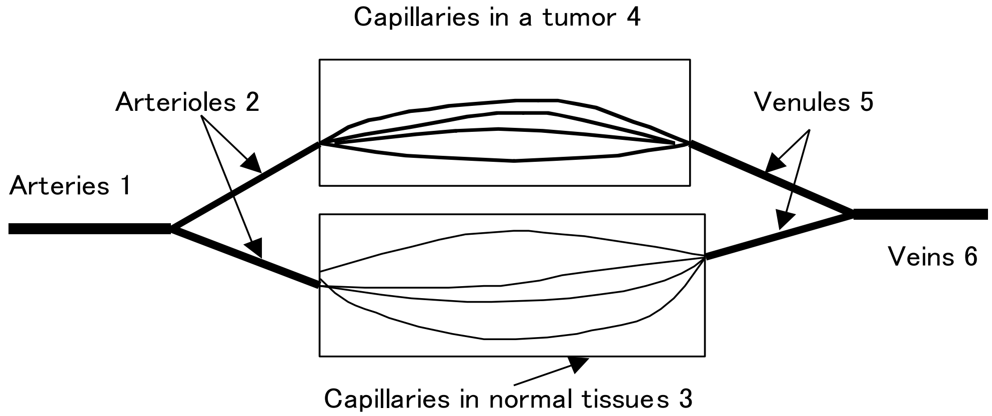
Maximum Power: 100W

# Tumor and Normal Tissue Vascular Bed in the Breast Model

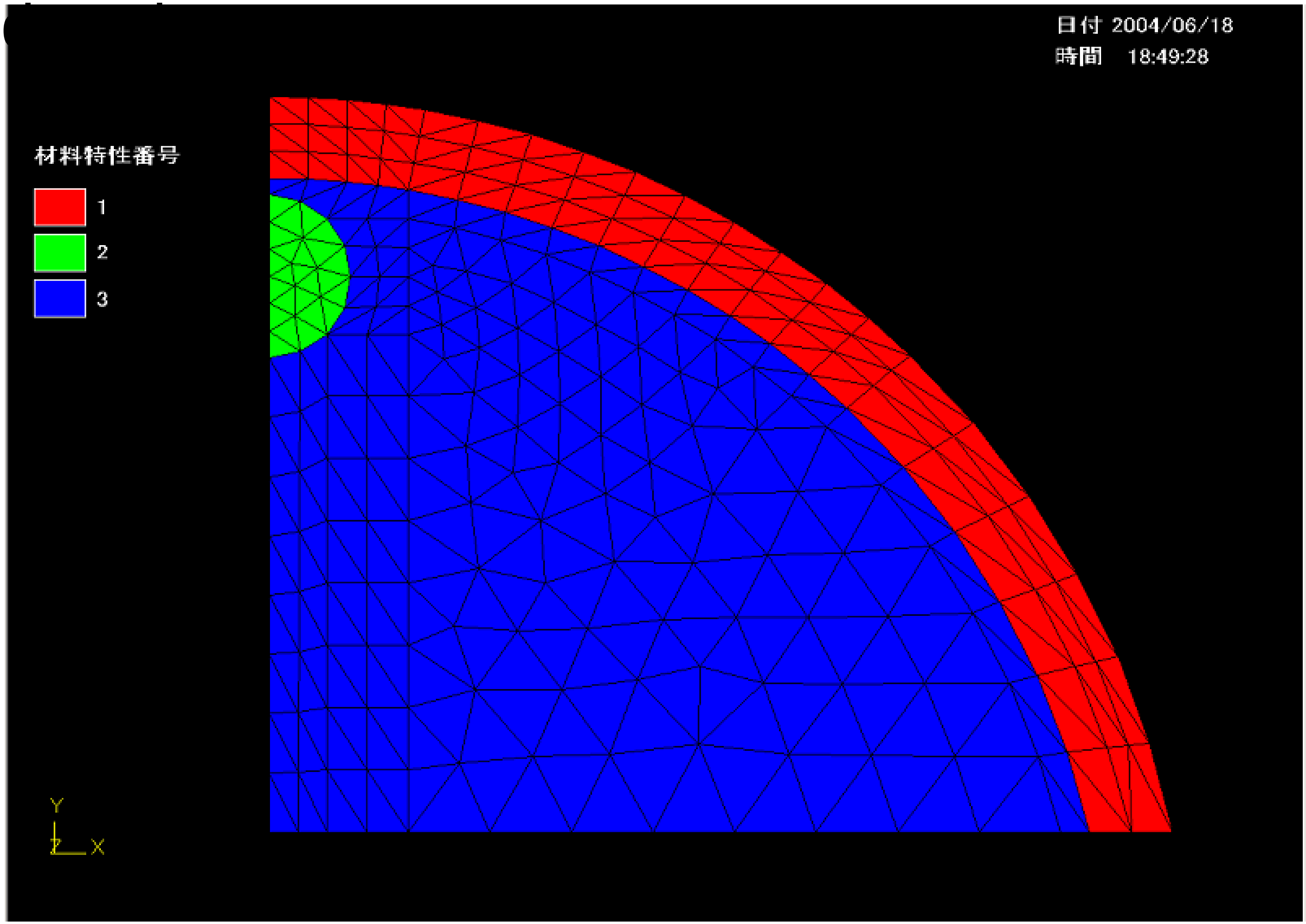
**Characteristics of tumor vessels:** **higher permeability,**

**larger diameter**

**shorter length**



# The element network of the computing



# Governing Equations

$$\rho_t c_t \frac{\partial T_t}{\partial t} = \lambda_t \left( \frac{\partial^2 T}{\partial^2 r} + \frac{1}{r}\frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial^2 z} \right) + Q + \omega \rho_b c_b (T_b - T_t)$$

⇦ Tissue Temperature

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

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

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

$$p - p_0 = k_p \left[ 1 - \left( \frac{A}{A_0} \right)^{-3/2} \right]$$

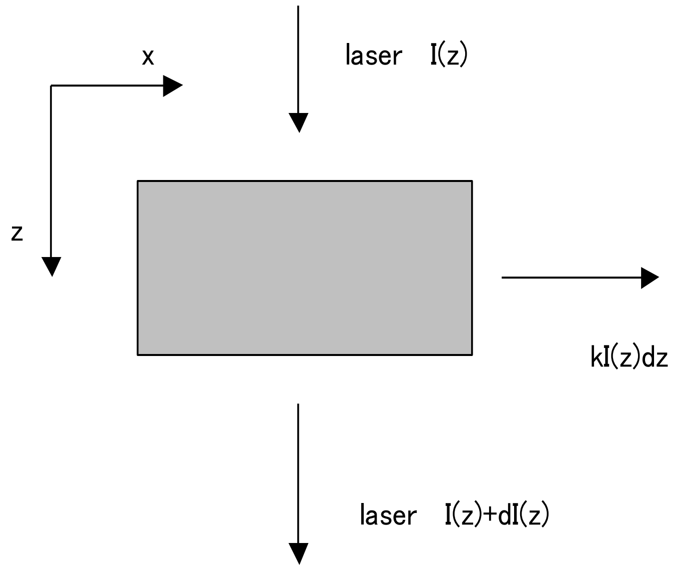
$$\frac{\partial T_b}{\partial t} + \frac{q}{A}\frac{\partial T_b}{\partial x} = -\omega T_b - \frac{h_{ves} A_s}{\rho_b c_b A}(T_b - T_t)$$

⇦ Blood circulation

# Heat Generation

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

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




$a$ : Absorption coefficient 0.1mm$^{-1}$

$s$ : Scattering coefficient, neglected

## Lambert - Beer's law

# Assumption of tumor vessel response to the temperature variation

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

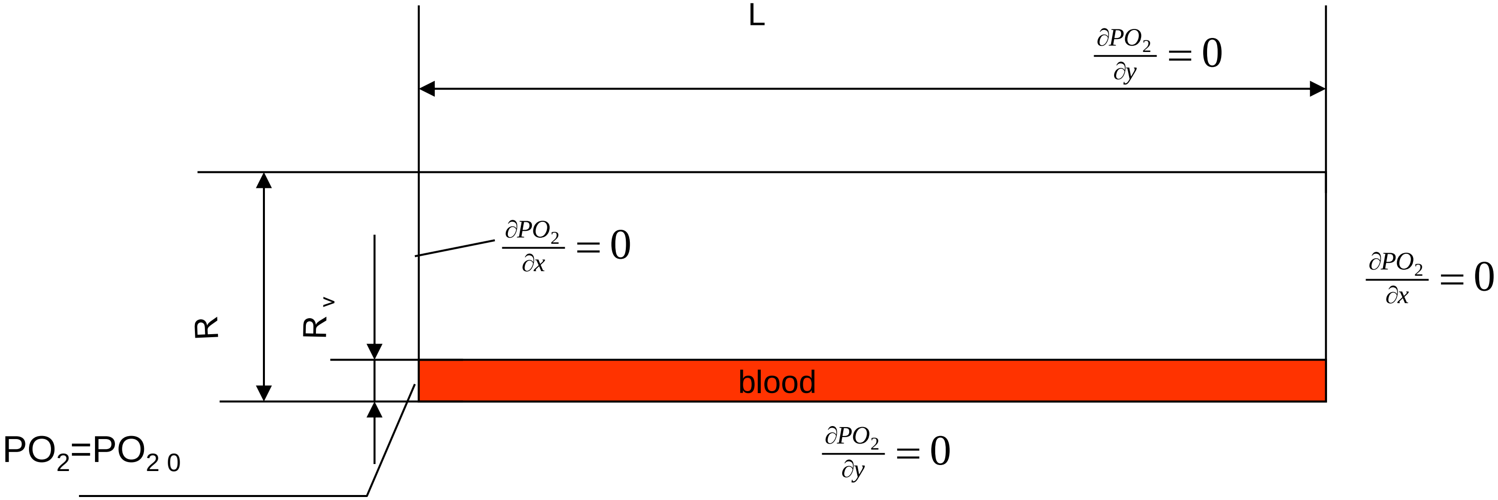
$A_0$ $T_0$ cross sectional area and blood temperature before heating

b variation coefficient

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

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

# Krogh Tissue Cylinder Model




Normal Tissue

R=30 μm

$R_v$=3 μm

L=500 μm

Tumor Tissue

R=60 μm

$R_v$=6 μm

L=100 μm

# Convection and diffusion transfer of oxygen

$$\alpha\frac{\partial PO_2}{\partial t}+u\alpha\frac{\partial PO_2}{\partial x}=D_{eff}\alpha\left(\frac{\partial^2 PO_2}{\partial x^2}+\frac{\partial^2 PO_2}{\partial y^2}\right)-M$$

$PO_2$: Partial pressure of oxygen

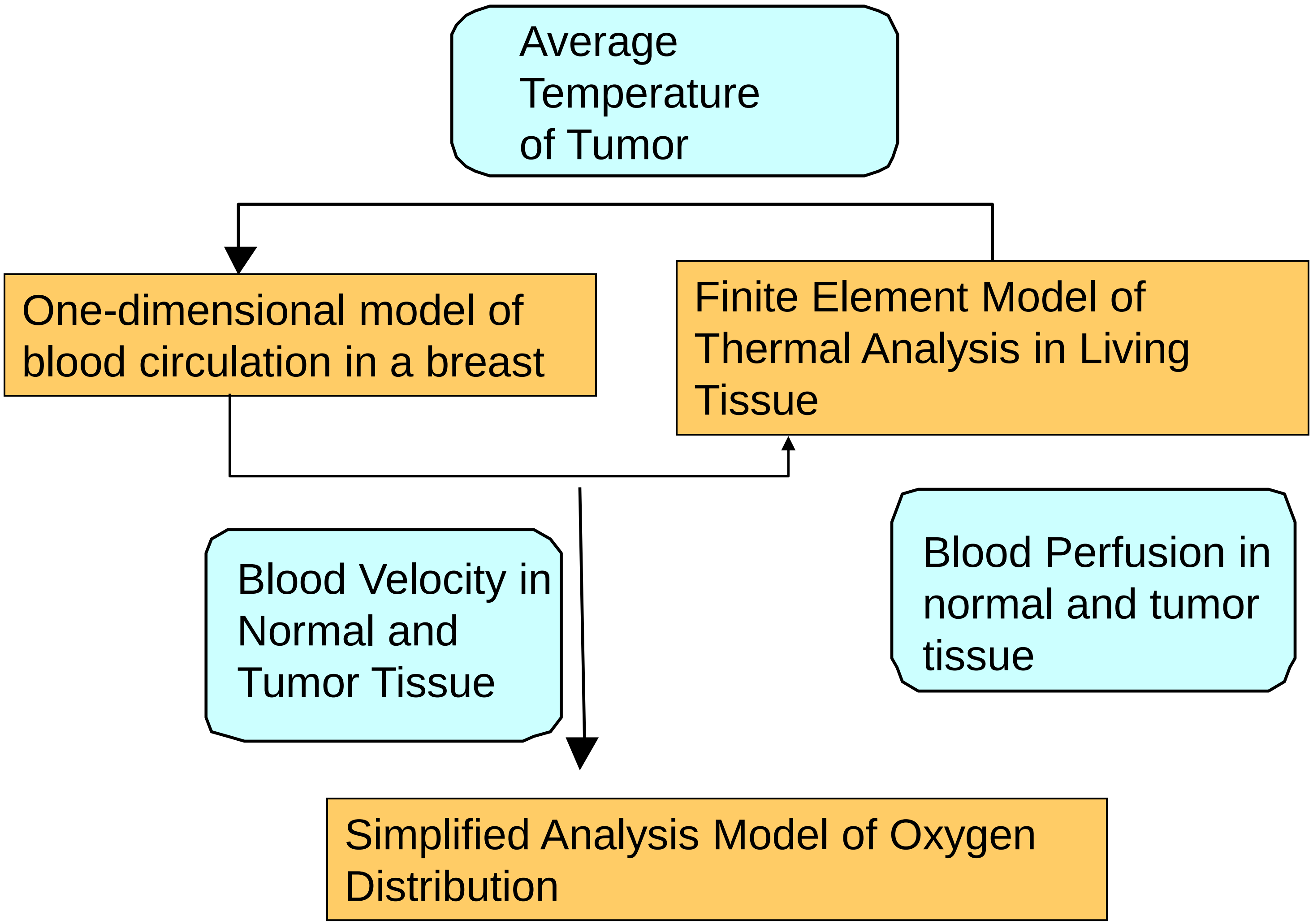
$D_{eff:}$ effective diffusion coefficient

$\alpha$: oxygen solubility

M: oxygen consumption

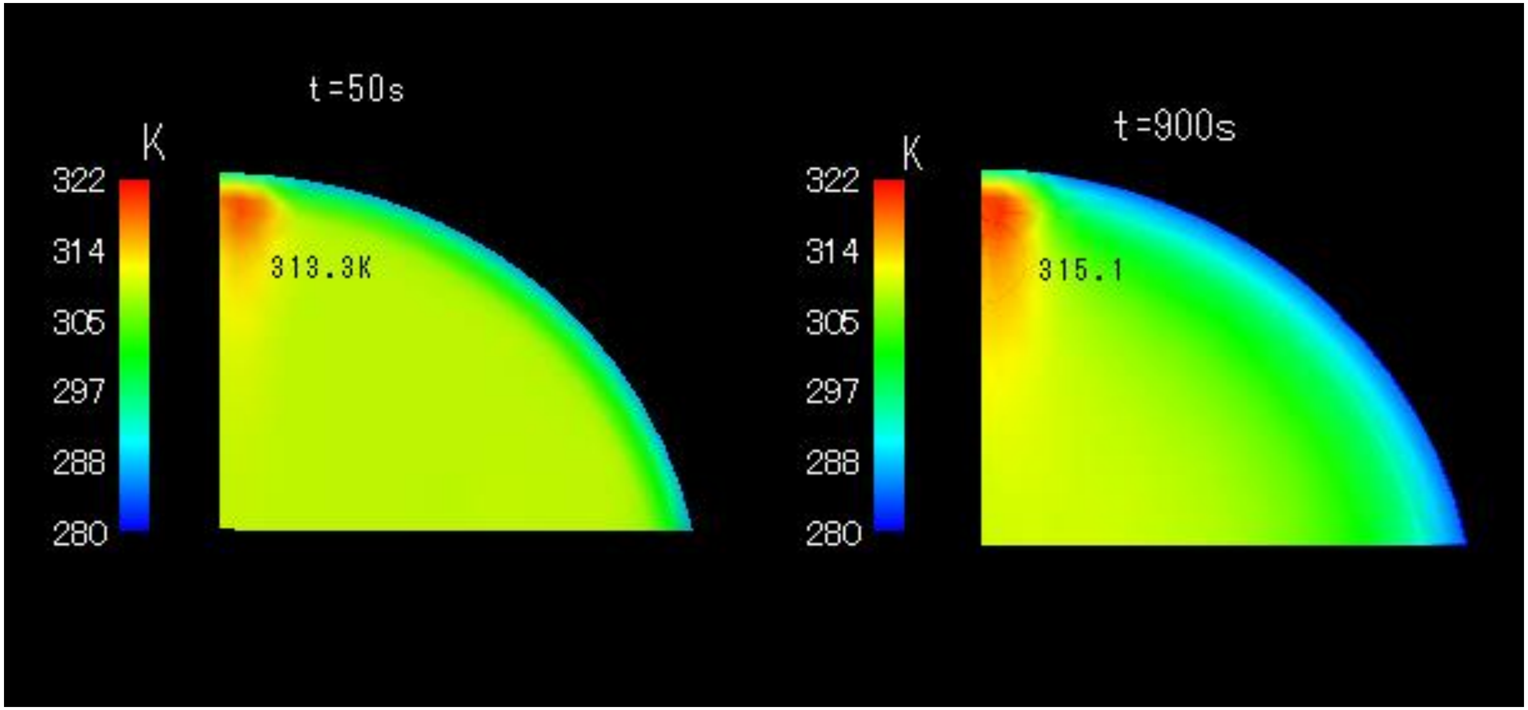
U: blood velocity （from blood circulation model）

# Numerical Solution and Data Transfer

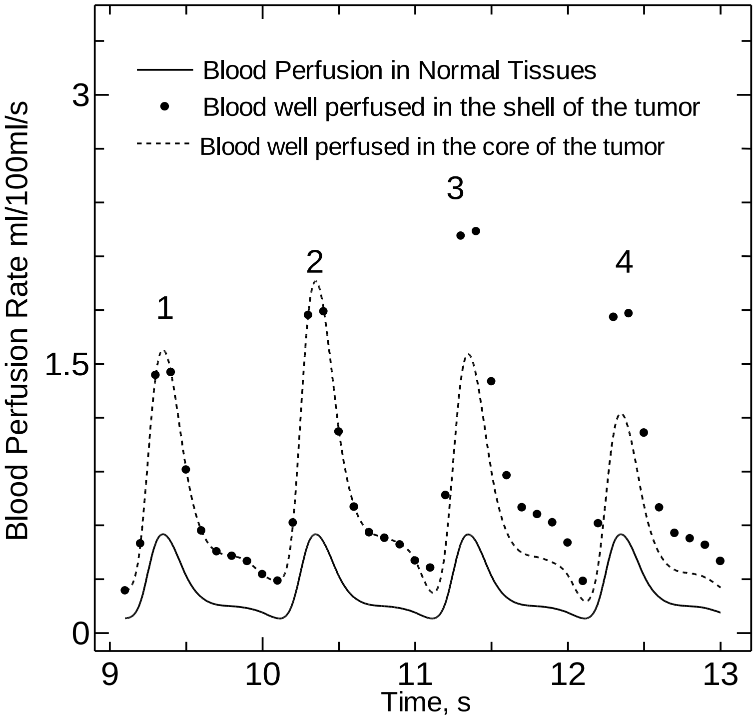


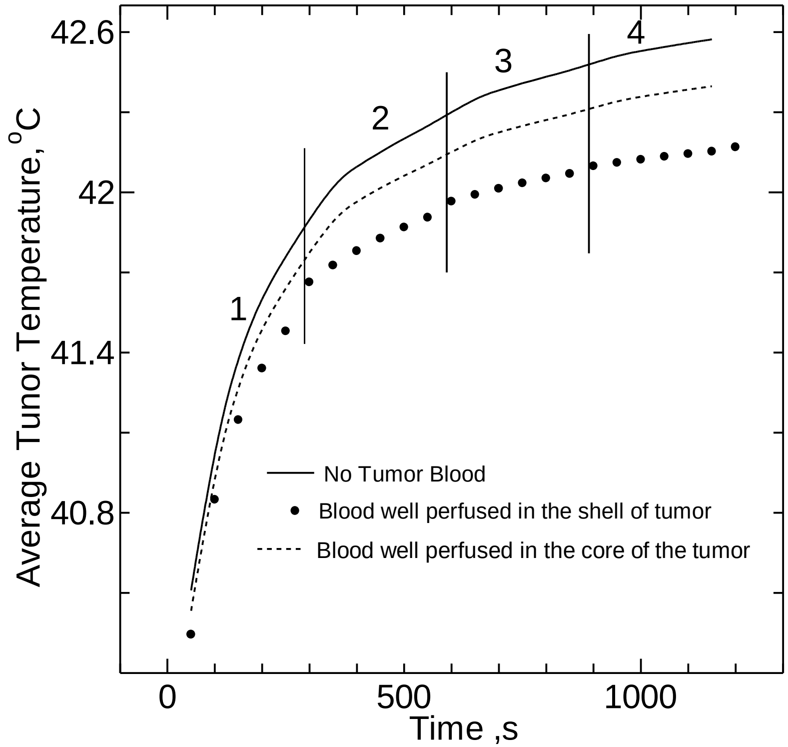
Temperature Distribution inside Living Tissues

Laser Power : 1.3W/cm$^2$

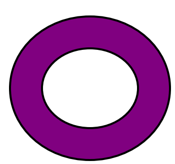


# Variation of Blood Perfusion and Tumor Temperature Under Laser Irradiation

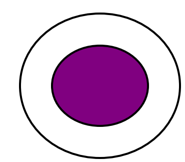


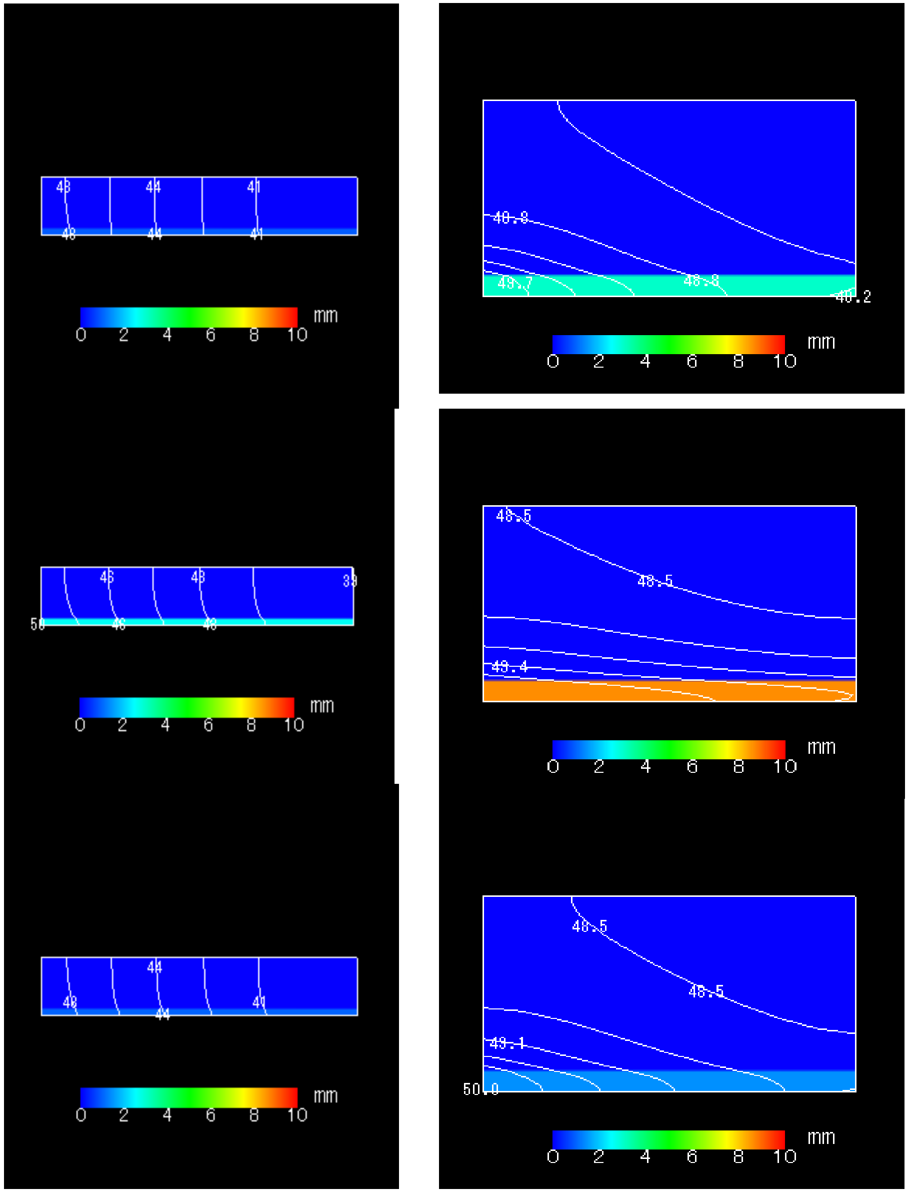

● Blood well perfused in the shell of the tumor

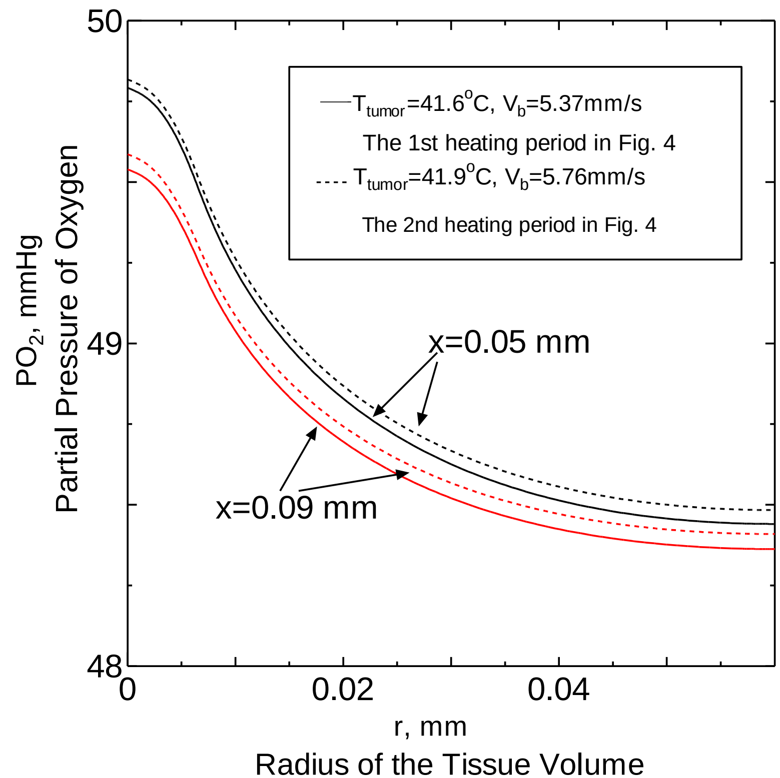


Blood well perfused in the core of the tumor



# Oxygen distribution in a normal and tumor unit within a period



## Summary

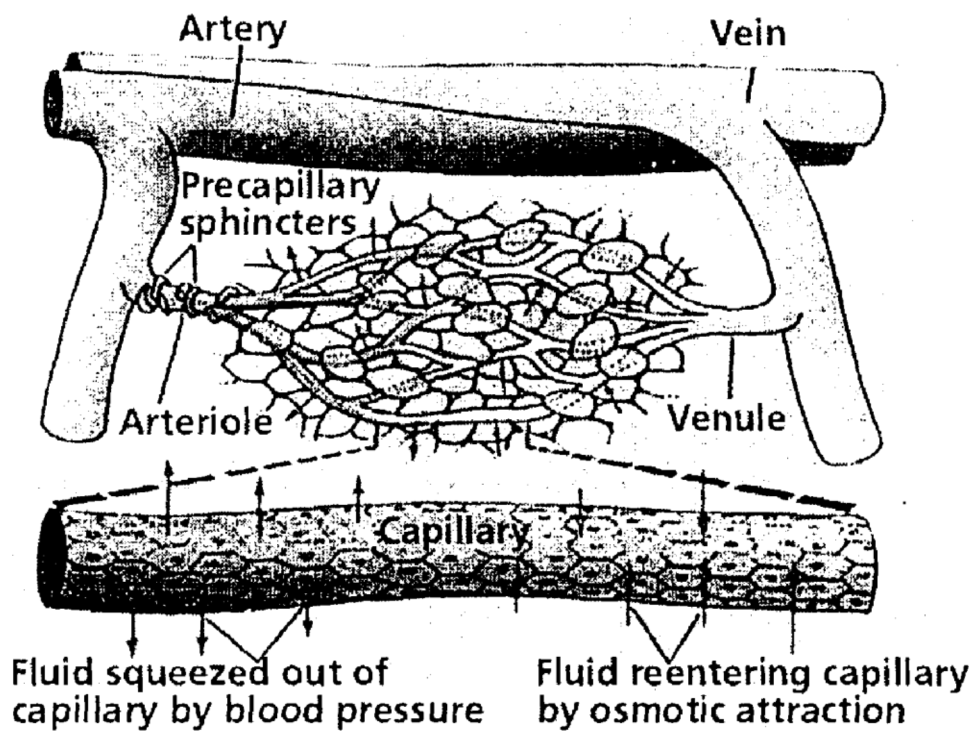
- A numerical study is carried out to investigate the tumor blood flow under laser irradiation by coupling the FE thermal model with the blood circulation model.
- The variation of tumor temperature is largely dependent on the tumor vasculature. The laser-induced blood flow changes can lead to the variation of partial pressure of oxygen.
- Further study may be carried out to investigate the effect of vessel permeability and tortuosity on oxygen transport

# Finite Element Analysis on the Fluid Filtration in a Permeable Curved Capillary and Tissue System

## Research Background

- The role of microcirculation : providing oxygen and nutrients, and removing waste products.

- Pathological Conditions are more affected by events within the vessel wall of microcirculation



# Research Background： the Fluid Flow and Mass Transfer through Permeable Tubes/Membrane

**Biomedical Engineering**

- Excretion of Urine in Nephron
- Fluid Convection in the Treatment of Cancer by the Therapeutic Macromolecules

- Artificial Kidney and Liver

**Industrial Processes**

- Cross Flow and Dead-end Filtration
- Water Treatment
- Heterogeneous Catalytic Reactions
- Solidification of Metal Alloy

## Previous Studies

**Boundary Element Method:**

- Blood and Interstitial Flows through a Solid Tumor with a Single Tube or a Vascular Network Inside (Pozrikidis,2003, 2009,2010)
- Fluid Flows through a Solid Tumor with a Curved Single Tube(Sun, et al, 2007)

**Pertubation Method**

- Two Phase Model in a Permeable Capillary (Shahed, 2004)
- Blood Flow in a Porous Channel Being Exposed in an Electromagnetic Filed Environment (Misra, 2011)
- Laminar Fluid Flow in a Porous Channel with Wall Injection or Suction for the Application to Water Treatment (Moussy, 2009)

**Homotopy Analysis Method**

- Laminar Fluid Flow in a Porous Channel with Expanding or Contracting Moving Walls (Si, et al 2011)

**Three or Double Porous Media Model for Describing Fluid Flow in Solid Tumor (Lei, 1998, Chapman, 2008)**

**Finite Element Analysis**

- Finite Element Analysis for Cross-flow Microfiltration (Hanspal et al 2009)

## Objective of the Study

Investigate the Fluid Filtration in a Complex Vasculature. The Ultimate goal is to study oxygen and macromolecular transport in Tumor Tissue

# Blood Flow in the Capillary-- Stokes Flow

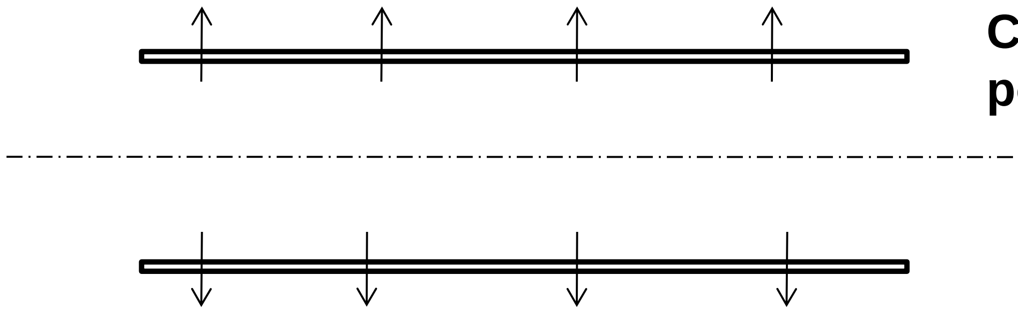
Governing Equations

$$-\nabla P + \mu \nabla^2 \mathbf{U} = 0$$

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

Laplace Equation

$$\nabla^2 P = 0$$



**Capillary wall :**
**porous media**

## Darcy Flow in Interstitial Tissue

$$\mathbf{U} = -\kappa \nabla P_b$$

$$\kappa : 10^{-12} - 10^{-10}\, cm^4 / dyn \cdot s$$

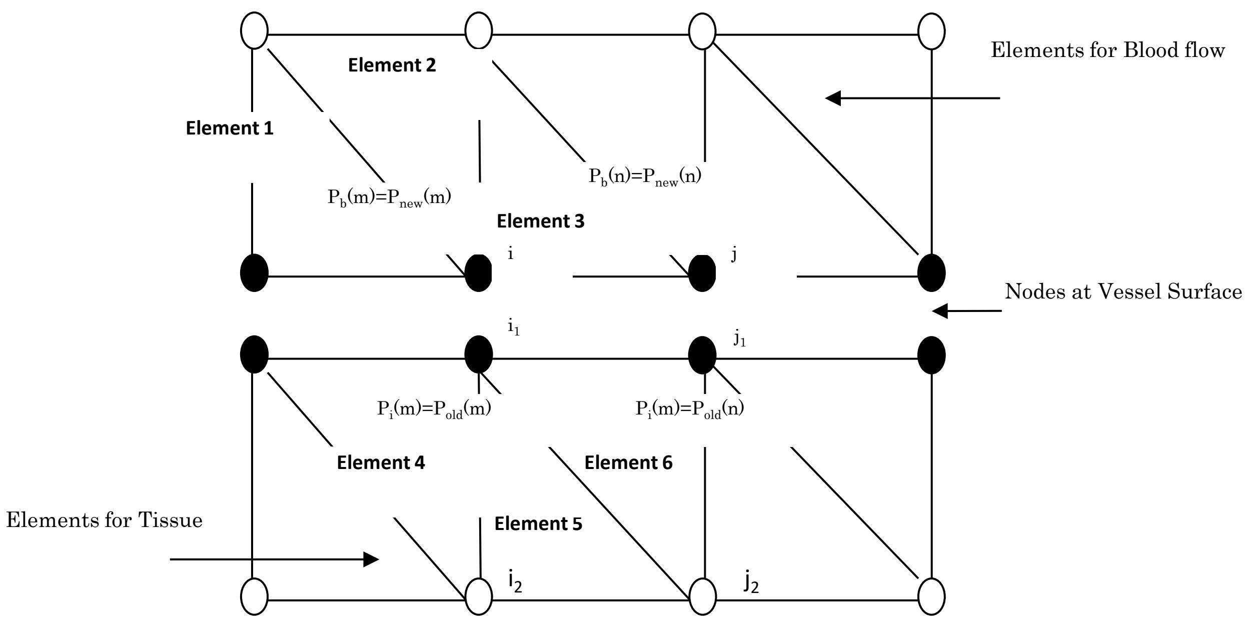
**Hydraulic conductivity of vessel wall**

$$\frac{\partial P}{\partial n} \equiv \mathbf{n}(\mathbf{x}) \cdot \nabla P_b(\mathbf{x}) \cong -\frac{q_e}{\kappa} = -\frac{L_p}{\kappa}(P_b - P_a)$$

**Boundary Condition for the capillary wall**

# Schematic Representation for Linking of Stokes and Darcy Regimes

- Interfacial Pressure

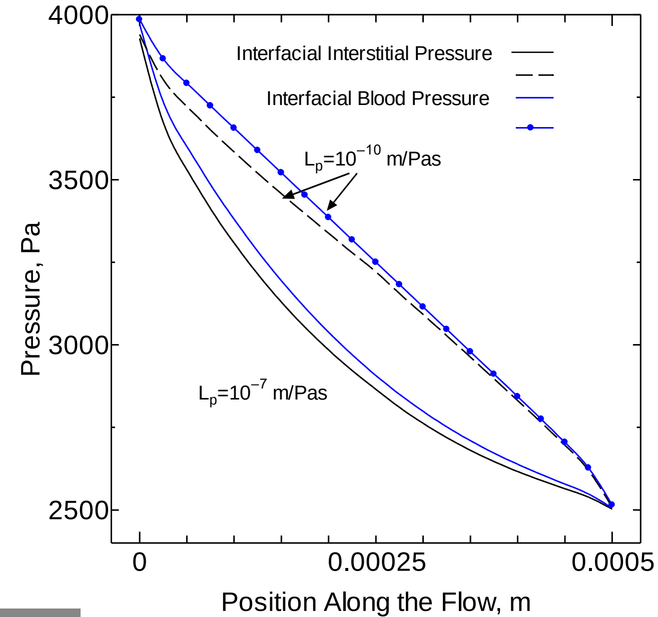


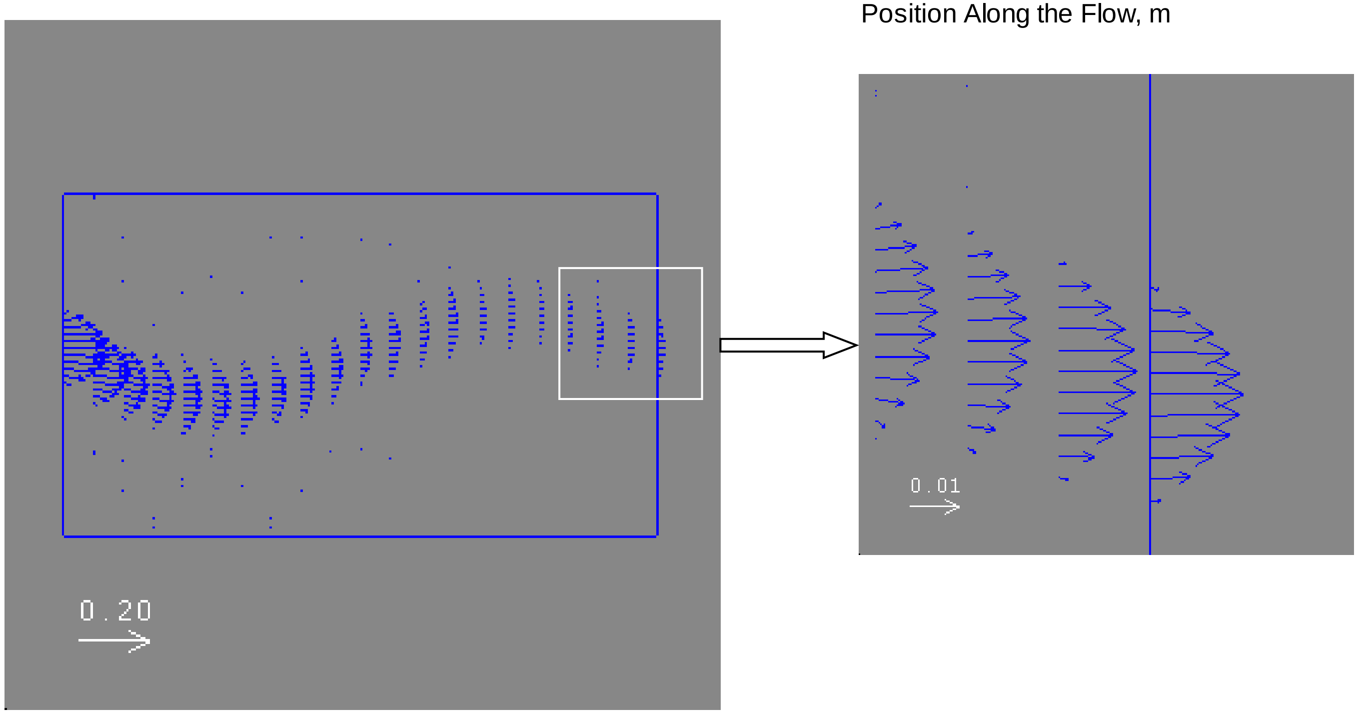

- Velocity

Direct Linking -- Considering the Interfacial Nodes as the Internal Nodes

# Interfacial Pressure Variation and Velocity Distribution along the Flow Direction for Different Filtration Coefficient

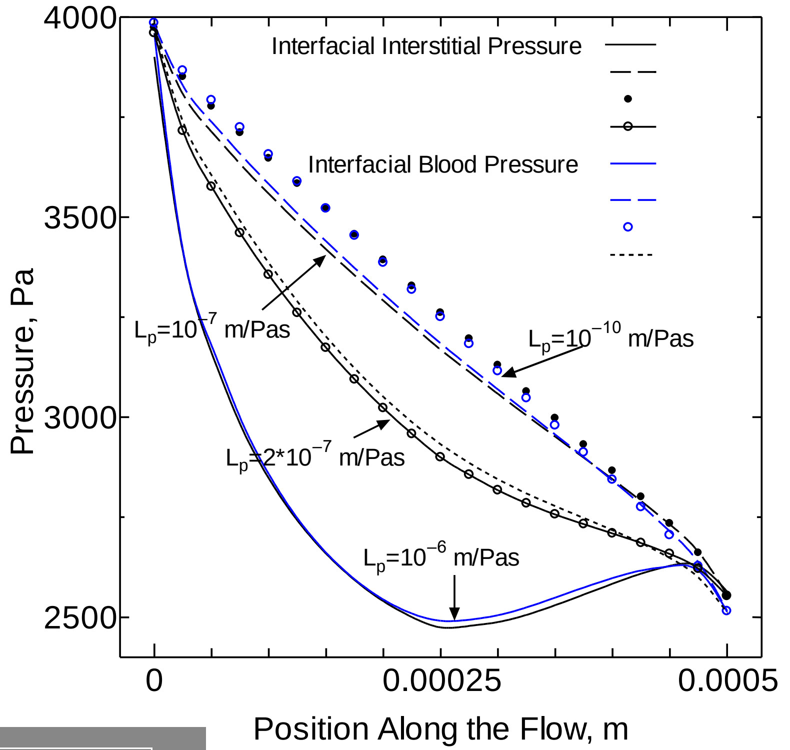
**Tissue Boundary Pressure: 2500 Pa**

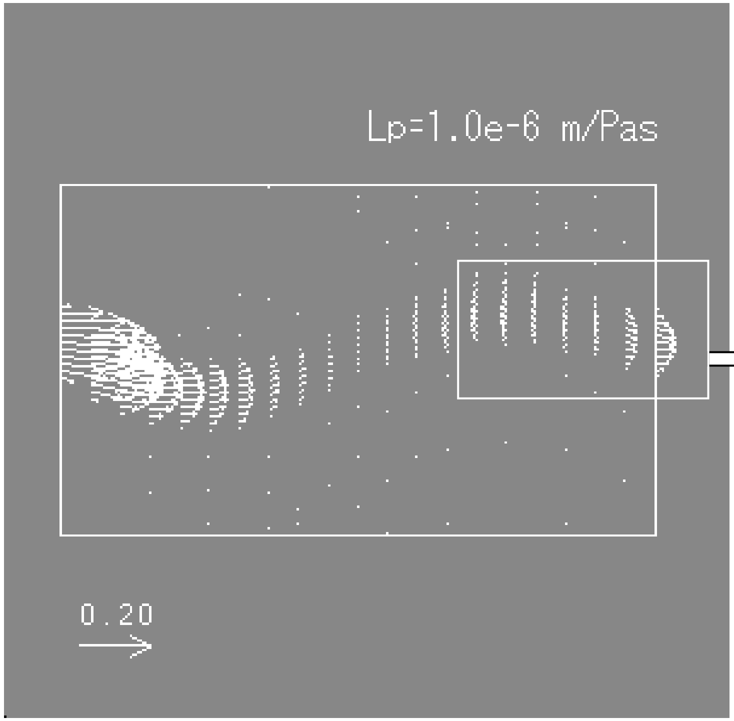


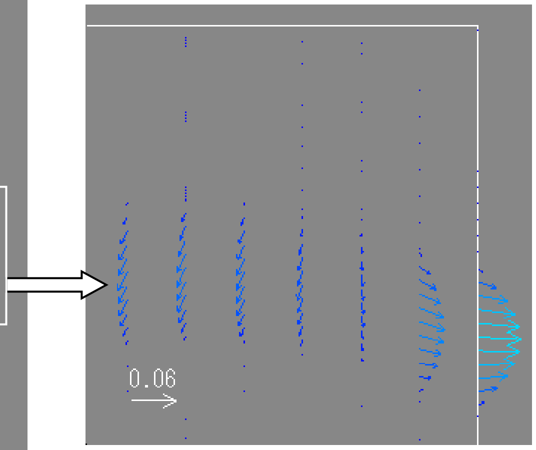



**Interfacial Pressure Variation and Velocty Distribution along the Flow Direction for Different Filtration Coefficient**

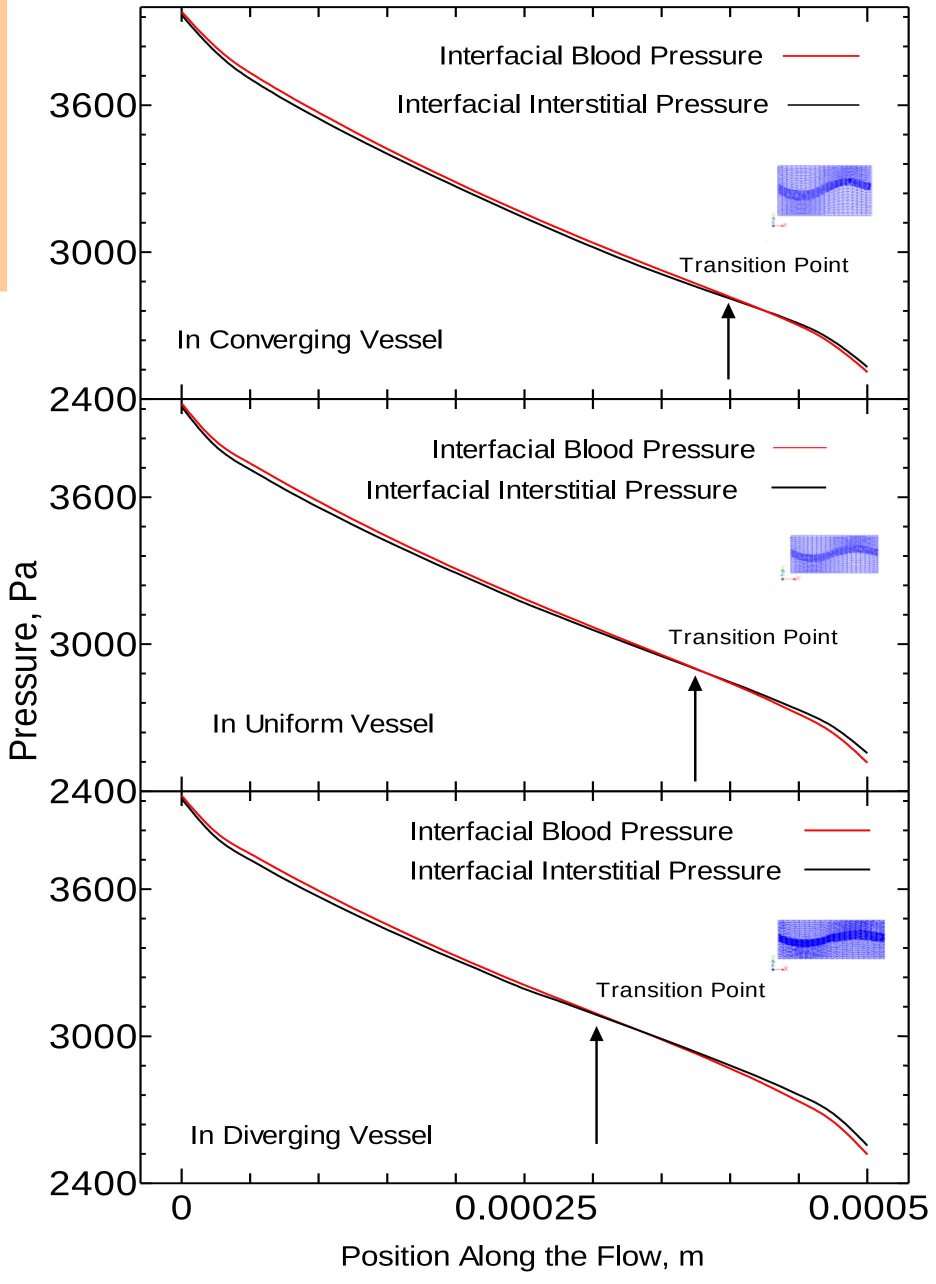
**Tissue Boundary Pressure: 3500 Pa**



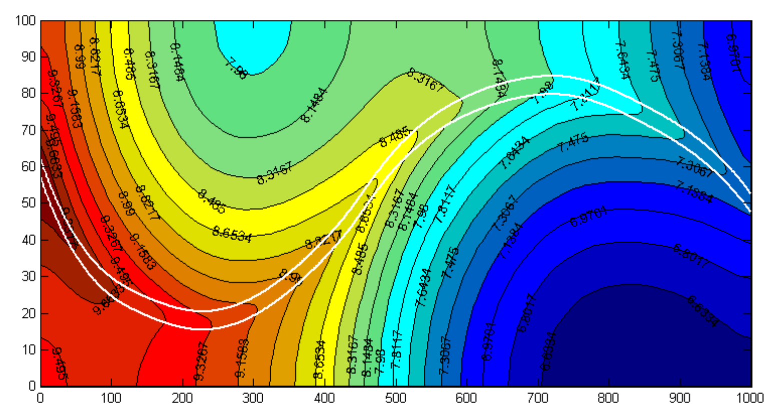
**Interfacial Pressure Variation in a Converging and Diverging Vessel**
**Tissue Boundary Pressure: 3500 Pa**



# Concluding Remarks

- Interfacial pressure variation and velocity distribution are significantly dependent on the wall permeability and surface pressure. When the wall permeability is extremely large, reversal flow will appear
- Vessel converging can efficiently enhance filtration, whereas diverging can re-absorption
- It is suggested from the velocity distribution that higher permeability may lead the oxygen distribution more heterogeneous

Oxygen distribution in tissue with a non-permeable curved tube



# 总结

- ✓ 多尺度建模，多孔介质理论以及有限元分析是分析生物组织内多物理过程的有效方法。
- ✓ 后续工作会集中在发展袖带加压下的一维血流动力学模型，微血管网及周围组织内的流体流动和物质传输方面。

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## 实验室主页

http://biomech.ustc.edu.cn

# 谢谢！