Project Update

Explore the effects of blood vessels in thermal ablation using sensitivity analysis

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CBC Lab Meeting

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Background

- ***Bioheat transfer in vascularized tissues and sensitivity analysis of vessel structure and tissue properties in thermal ablation***

- <u>**Motivations**</u>
  - (1) To optimize the outcome of thermal ablation, it is critical to conduct bioheat transfer and damage analyses in treatment planning
  - (2) A comprehensive model, capable of patient-specific image-based simulation, is needed for bioheat transfer coupled with blood perfusion and thermal damage

- <u>**Aims**</u>
  - (1) Develop comprehensive bioheat transfer model, which is rigorously and systematically derived from fundamental conservation and thermodynamics laws
  - (2) Estimate the effect of vascular structure, aiming for the determination of the level of vascular tree to which one needs to consider in bioheat transfer
  - (3) Characterize the effect of changing tissue properties and microvascular perfusion due to tissue damage on temperature distribution and tissue damage

Preliminary Results

- Bioheat transfer model based on continuum mixture theory, which considers thermal non-equilibrium between blood flow and tissue.

Energy equations:

$$\rho^S c^S \frac{\partial \theta^S}{\partial t} = \nabla \cdot (n^S k_q^S \nabla \theta^S) + k_e (\theta^L - \theta^S) + n^S r,$$

$$\rho^L c^L \frac{\partial \theta^L}{\partial t} = \nabla \cdot (n^L k_q^L \nabla \theta^L) - \rho^L c^L \mathbf{v}_L \cdot \nabla \theta^L + k_e (\theta^S - \theta^L) + n^L r$$

$$+ k_v^L \mathbf{v}_L \cdot \mathbf{v}_L + n^L \Phi,$$

Directional   Nondirectional

Mass equation:

$$\nabla \cdot (\rho^L \mathbf{v}_L) = 0,$$

Momentum equation:

$$\rho^L \frac{D^L \mathbf{v}_L}{Dt} = \rho^L \mathbf{b} + \nabla \cdot \mathbf{T}^L + p^L \nabla n^L - k_v^L \mathbf{v}_L$$
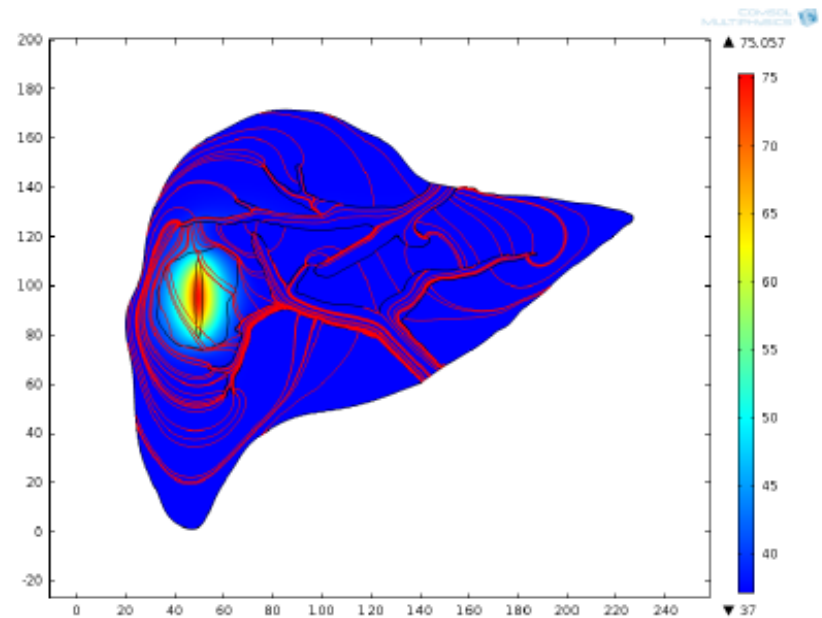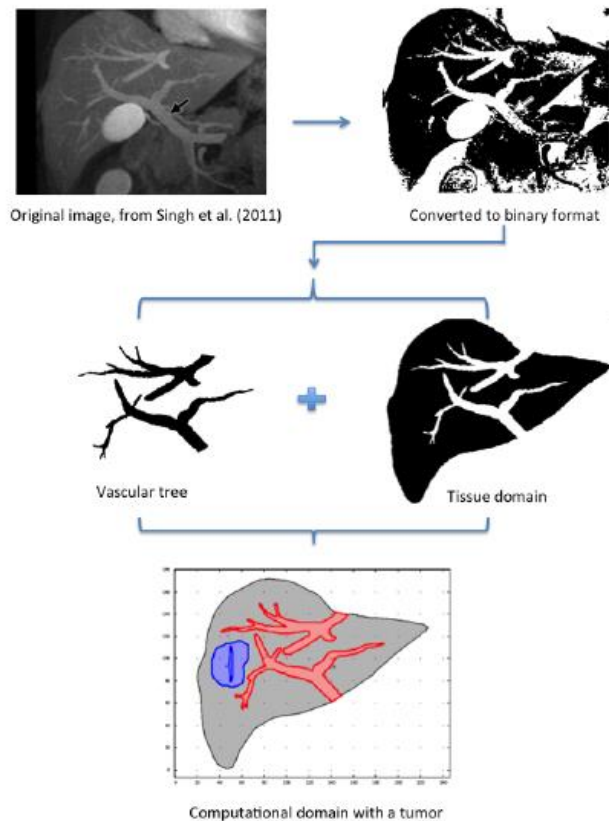
Convection

- The advantages of this model
  - (1) Derived in the framework of mixture theory, based on fundamental conservation and thermodynamics laws
  - (2) Includes auxiliary mass and momentum equations for blood flow field
  - (3) Capable of patient-specific image-based simulation, provided imaging data

Preliminary Results (cont'd)

- Preliminary results are obtained using our bioheat transfer model

  Based on a MRI image of human liver, tissue domain and vascular tree was generated. An artificial tumor region was embedded in the computational domain. The major steps are shown below.

Original image, from Singh et al. (2011)

Converted to binary format

Vascular tree

Tissue domain

Computational domain with a tumor

Temperature field after thermal ablation treatment for 15 minutes. The blood flow field is represented by streamlines.
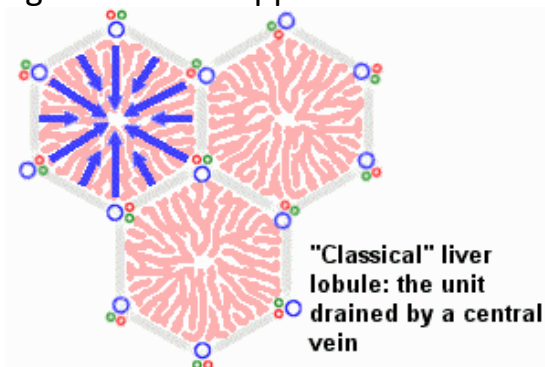
Proposed Research - 1

- **Goal #2** : Estimate the effect of vascular tree on the temperature distribution and thermal damage; determine the level of vascular tree to which we need to consider in modeling and simulation of bioheat transfer in thermal ablation

- **Proposed method**:
    (1) Survey typical vessel structure based on human physiology

Liver:

Vessel diameter: 16 mm ~ 0.1 mm, before reaching microvascular beds (arterioles, capillaries, venules)

Hexagonal hepatic lobules
Homogenized -> no apparent direction

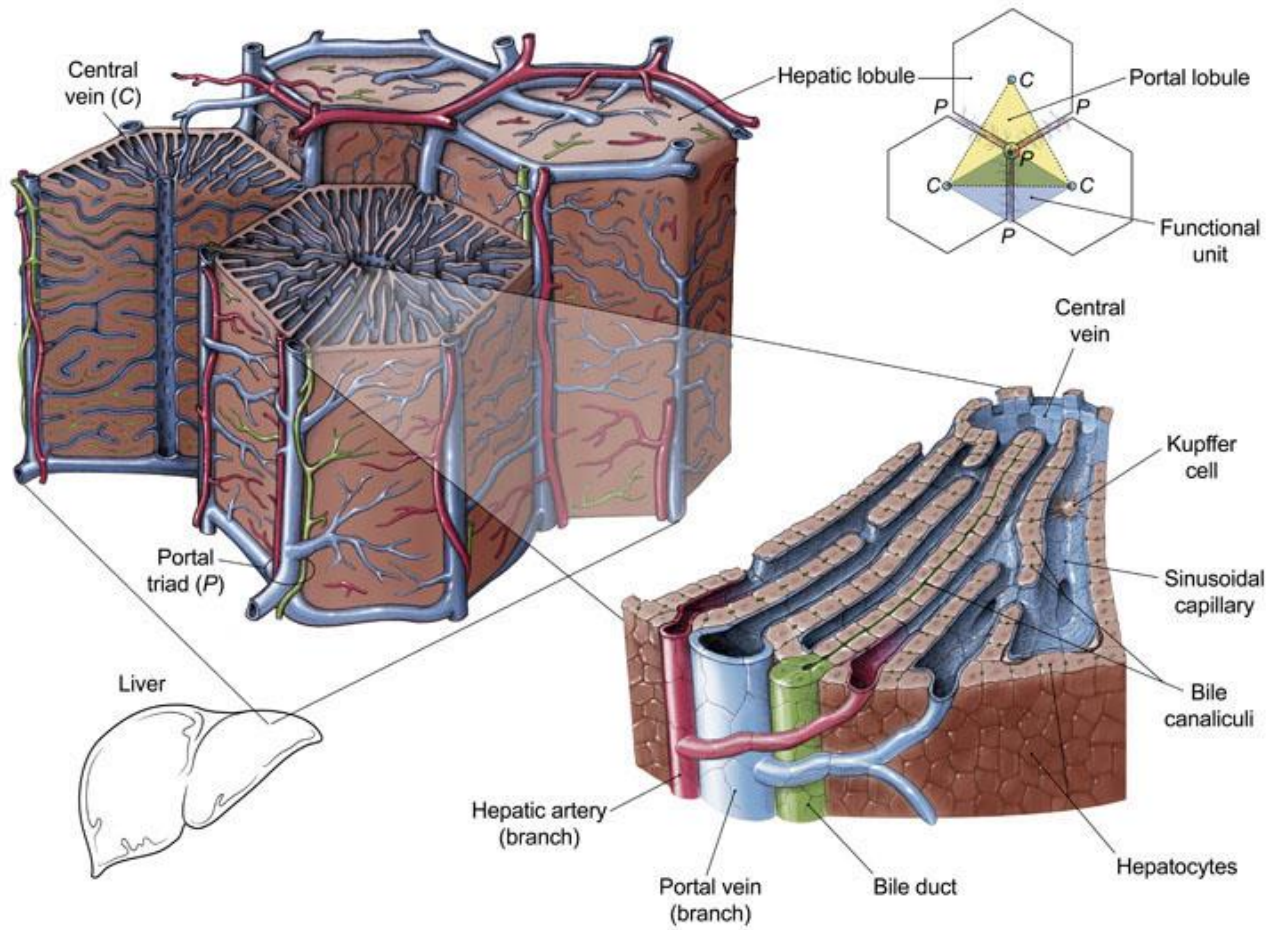"Classical" liver lobule: the unit drained by a central vein

$$\rho^S c^S \frac{\partial \theta^S}{\partial t} = \nabla \cdot (n^S k_q^S \nabla \theta^S) + k_e (\theta^L - \theta^S) + n^S r,$$

$$\rho^L c^L \frac{\partial \theta^L}{\partial t} = \nabla \cdot (n^L k_q^L \nabla \theta^L) - \rho^L c^L \mathbf{v}_L \cdot \nabla \theta^L + k_e (\theta^S - \theta^L) + n^L r$$

$$k_e = \frac{4 n^L}{D} \frac{Nu \cdot k_q^L}{D} \simeq \rho^L c^L \omega$$

Depth of lobules: 1.5~2 mm
Diameter of lobules: 1~1.3 mm

Central vein (C)

Hepatic lobule

Portal lobule

P

P

C

P

Functional unit

C

C

P

Central vein

Kupffer cell

Sinusoidal capillary

Portal triad (P)

Bile canaliculi

Liver

Hepatic artery (branch)

Portal vein (branch)

Bile duct

Hepatocytes

Depth of lobules: 1.5~2 mm
Diameter of lobules: 1~1.3 mm

Proposed Research – 1 (cont'd)

- **Proposed method (cont'd)**:
  (1) Survey typical vessel structure based on human physiology
  (2) Determine topology and geometric parameters for sensitivity study
  (3) Conduct systematic study to characterize the effect on the temperature field and tissue damage induced by RF ablation by the clinically relevant measure of tolerance (safety margin, 1 cm)

*Blood vessels: explicitly or implicitly considered?*

j	Vessel	% Vascular volume	r_j (mm)
1	Large arteries	6.59	1.5
2	Arterial branches	5.49	0.5
3	Terminal arterial branches	1.55	0.3
4	Arterioles	2.75	1E−2
5	Capillaries	6.59	4E−3
6	Venules	12.09	1.5E−2
7	Terminal veins	3.30	0.75
8	Venous branches	29.67	1.2
9	Large veins	24.18	3

Vessel diameter, D:
D = 9, 7, 5, 3, 1, 0.5 mm

- Relative orientation b/w applicator and vessel (parallel, perpendicular, various angles)

- Variation of volumetric perfusion rate in capillary beds
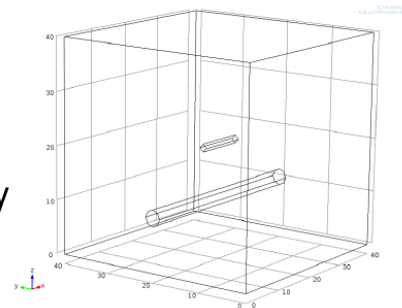
Liver thickness: 6 – 10 cm
Domain size: 4 – 5 cm
Applicator length: 2 cm
Applicator diameter: 1.5 mm

Applicator to vessel distance:
d = 20, 15, 10, 5, 2 mm

Feedback

(1) Goals: a) with available information, how to generate something useful to clinicians; b) given what information, which is currently not known, we can make better prediction

(2) liver tissue: length scale, heat transfer in microvascular beds can be modeled as "subgrid" diffusion + dispersion (porous media concept)

(3) blood vessels: a) consider the density of vessels -> how many vessels need to be considered in the computational domain ; b) quantify the cooling effects: not only the damage volume, but also the distortion of the shape -- penetration into damage zone

(4) parameterization: not just models, consideration of parameters is also important -- how to get or estimate the value, uncertainties, range/constraints

(5) simulation: given tumor region and vascular structure, how to achieve optimal outcome: a) completely destroy tumor; b) less impact to healthy tissue

Planned Items

- Modeling of microstructures: diffusion, dispersion

- Determination of computational domain
  - Domain size
  - Thermal applicator
  - Tumor region

- Effect of single vessel with different diameters
  - Penetration depth into damage zone
  - The changes of volume and shape of damage zone
  - How to quantify the difference

- More realistic situation – The presence of multiple vessels
  - Density of blood vessels of each size
  - Configurations

Proposed Research - 2

- **_Goal #3_** : Characterize the effect of change in tissue properties due to thermal damage on temperature distribution and final lesion size
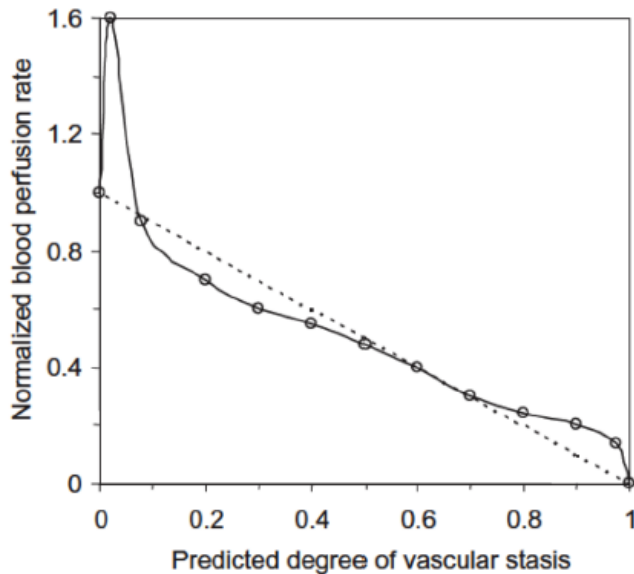
Linear model
$$\omega = \omega_0 \frac{c(t)}{c(0)}$$

Nonlinear model

$$\omega = \omega_0(30DS + 1), \qquad 0 \leq DS \leq 0.02,$$
$$\omega = \omega_0(-13DS + 1.86), \qquad 0.02 < DS \leq 0.08,$$
$$\omega = \omega_0(-0.79DS + 0.884), \qquad 0.08 < DS \leq 0.97,$$
$$\omega = \omega_0(-3.87DS + 3.87), \qquad 0.97 < DS \leq 1.0.$$

- **_Proposed method_**: The change of tissue properties due to damage will be reflected in tissue permeability and convective heat transfer coefficient:

$$K_P = \frac{\omega}{\omega_0} K_P^0$$ Apparent directional perfusion

$$k_e = \frac{\omega}{\omega_0} k_e^0$$ Nondirectional volumetric perfusion

Proposed Research – 2 (cont'd)

- ***Model comparison:***
  how much difference between the predictions resulting from the two models.

- ***Different peak perfusion rates:***
  The nonlinear model is based on the data for kidney tissue.
  Consider the variation from tissue to tissue, organ to organ.