Workshop: **Optimal Transport in the Human Body: Lungs and Blood** – IPAM, UCLA, May 19–23, 2008

Blood Flow Induced Cooling Effect in Radio Frequency Ablation for Hepatic Carcinoma

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Importance of RFA Simulation

Medical Background

Hepatic Tumors

- Liver common location for carcinoma (both primary and metastatic)
- $> 1\,000\,000$ new cases per year worldwide

Classical Therapy Forms

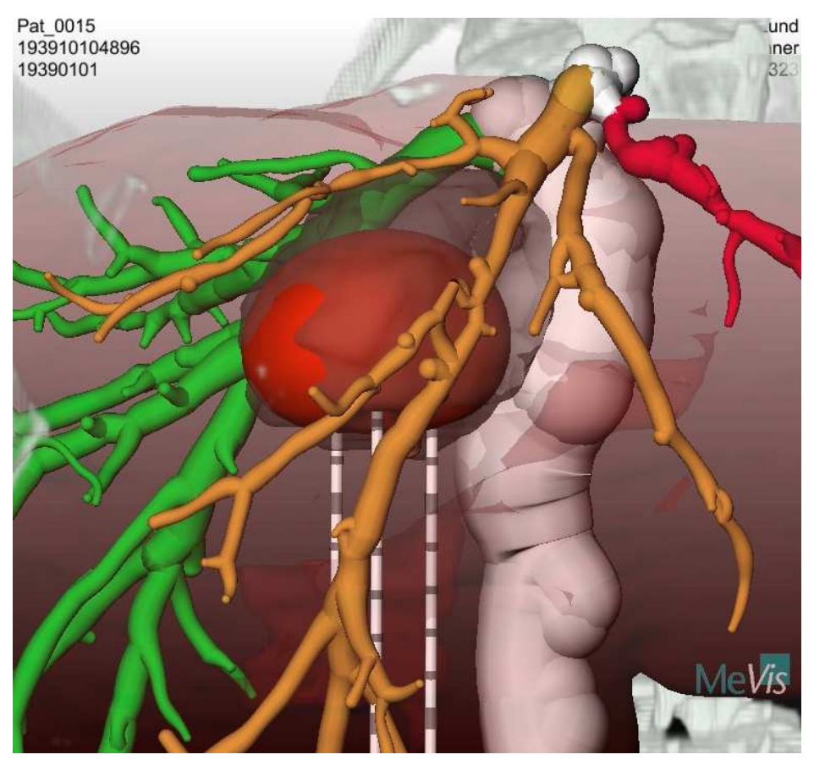
- Chemo therapy: often not effective
- Surgical resection:
  - Only in $\approx 25\,\%$ applicable
  - Extensive and expensive

Minimally Invasive Therapy Forms

- Radio Frequency Ablation (RFA)
- Laser Induced Thermo Therapy (LITT)
- Hyperthermia
- Cryotherapy

Principle of RFA

- Probe(s) inserted into the tissue
- Connected to an electric generator ($\approx 500\,\mathrm{kHz}$)
- Heat is produced (Joule's law)
- Cell proteins coagulate

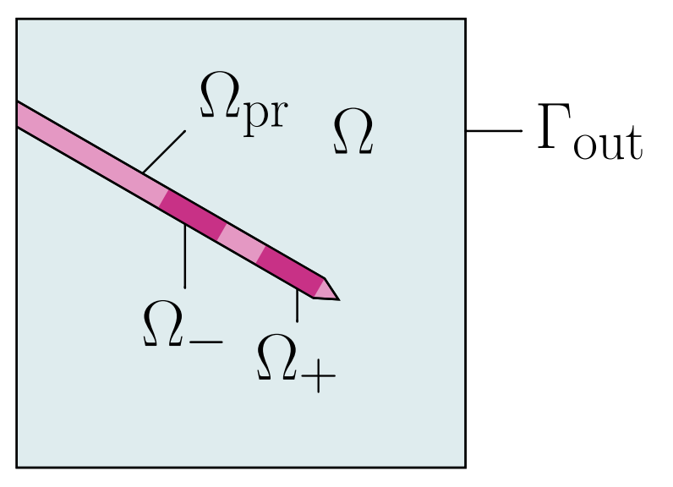


Value of Numerical Simulation

- Planning of intervention (currently only by experience)
- Decision for either therapy
- Physician's training

A Mathematical Model of RF Ablation

Simplified Overview



- σ, ρ, c, λ material parameters

Electric Potential $\varphi(t,x)$

$$\begin{aligned} -\nabla\cdot(\sigma\nabla\varphi) &= 0 && \Omega\setminus\overline{\Omega_\pm} \\ \varphi &= \pm 1 && \overline{\Omega_\pm} \\ n\cdot\nabla\varphi &= \tfrac{n\cdot(s-x)}{|s-x|^2} && \Gamma_{\mathrm{out}} \end{aligned}$$

Temperature $T(t,x)$

$$\begin{aligned} \rho c\partial_t T-\nabla\cdot(\lambda\nabla T) &= \sigma|\nabla\varphi|^2 && \Omega\setminus\overline{\Omega_{\mathrm{pr}}} \\ T &= T_{\mathrm{body}} && \overline{\Omega_{\mathrm{pr}}} \\ n\cdot\nabla T &= 0 && \Gamma_{\mathrm{out}} \end{aligned}$$

Further Aspects

Tissue Damage

Chemical reaction: Arrhenius [1] formalism:

$$D(t,x) = \int_{t_0}^{t} A_{\mathrm{A}}\exp\left(\frac{-E_{\mathrm{A}}}{RT(s,x)}\right)ds$$

Scaling of Electric Power

- Electric generator reacts nonlinearly on tissue impedance changes

Evaporation of Cell Water

Dry-out $\Rightarrow \sigma\to 0 \Rightarrow$ Steady state

Non-Const. Material Parameters

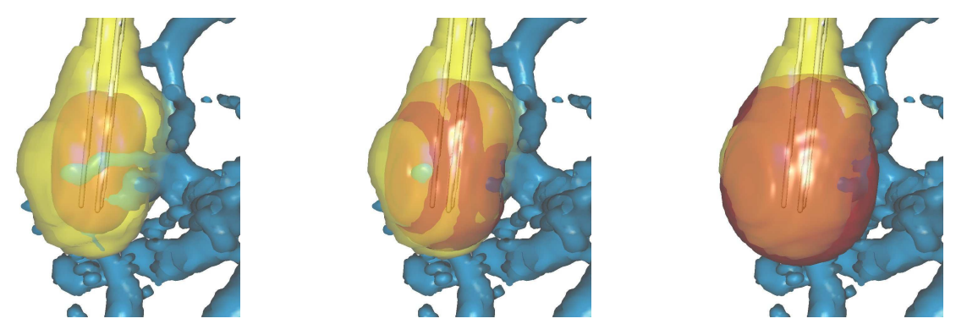
Tissue-dependent • State-dependent • Uncertain

Blood Flow

Heat is transported away $\Rightarrow$ Cooling effect

Comparison to a Real Ablation

We thank P. Pereira and D. Schmidt from the University Hospital of Tübingen for the CT data set.



Modeling of Cooling due to Blood Flow

Standard Models

Pennes [2]

$$\partial_t(\rho cT)-\nabla\cdot(\lambda\nabla T) = Q_{\mathrm{pc}} + \nu(T_{\mathrm{blood}}-T)$$

- Derived using mathematical homogenization under certain assumptions [3]

Weighted Pennes

$$\partial_t(\rho cT)-\nabla\cdot(\lambda\nabla T) = Q_{\mathrm{pc}} + \nu(x)(T_{\mathrm{blood}}-T)$$

- $\nu(x)$ large inside vessels, small outside vessels

Jain [4]

$$\partial_t(\rho cT)-\nabla\cdot(\lambda(x)\nabla T) = Q_{\mathrm{pc}}$$

- $\lambda(x)$ large inside vessels, small outside vessels

Dirichlet Boundary Condition

$$T\equiv T_{\mathrm{body}} \qquad \text{on large vessels}$$

- Change of computational domain for T
- Cannot respect thrombus formation

Alternative Ideas

Advection term

$$\partial_t(\rho cT)-\nabla\cdot(\lambda\nabla T) + \vec{v}\cdot\rho c\nabla T = Q_{\mathrm{pc}}$$

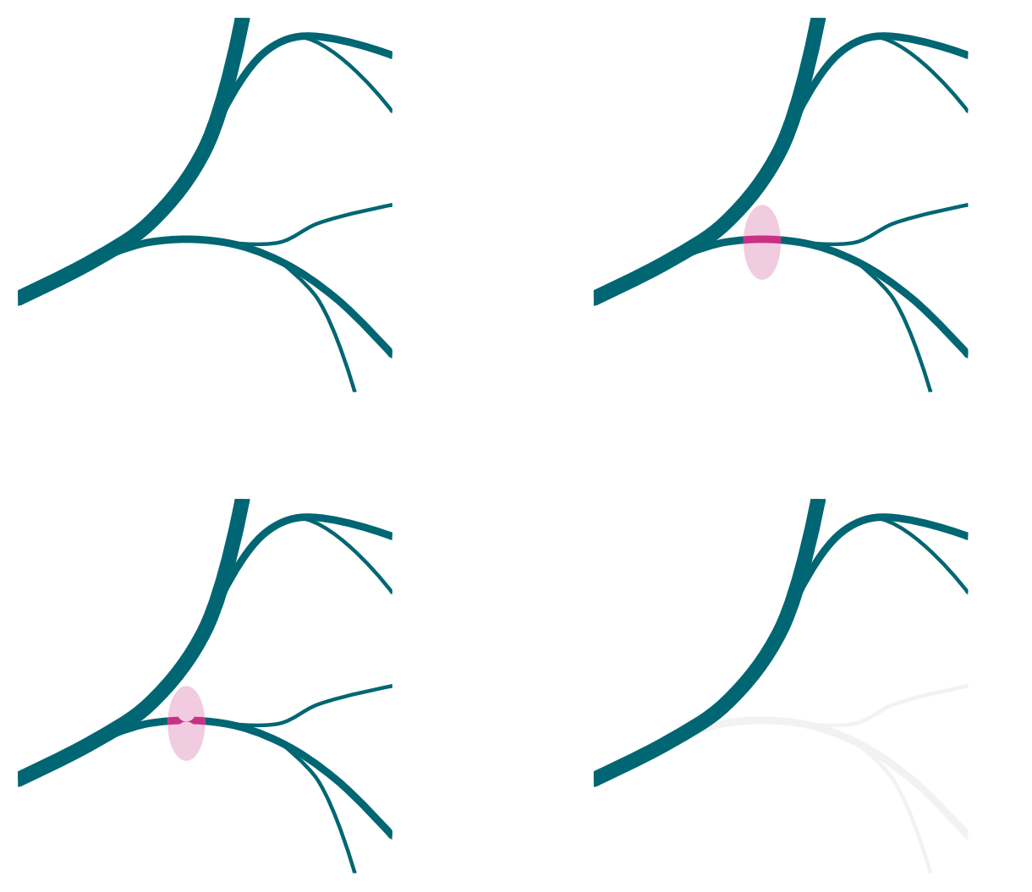
- $\vec{v}$ difficult to determine, in particular at branch points
- Difficult to solve since $|\vec{v}|$ large ($\approx 9\,\mathrm{cm/s}$)
- Thrombus formation might lead to inconsistent $\vec{v}$ (i.e. $\nabla\cdot\vec{v}\neq 0$)

Navier–Stokes Equations for $\vec{v}$

- Much too slow

Current Work

- Combination of Dirichlet boundaries and Navier–Stokes
- Perform preliminary simulation experiments:
  - Navier–Stokes on simple geometries
  - Find simple model for thrombus formation
  - Based on $\nabla T\cdot n$ on vessel boundary, vessel size, time
- For main simulation:
  - Dirichlet conditions for T
  - Measure $\nabla T\cdot n$ on vessel boundary, apply simple model
  - When thrombus is formed, disable Dirichlet condition on whole vessel subtree

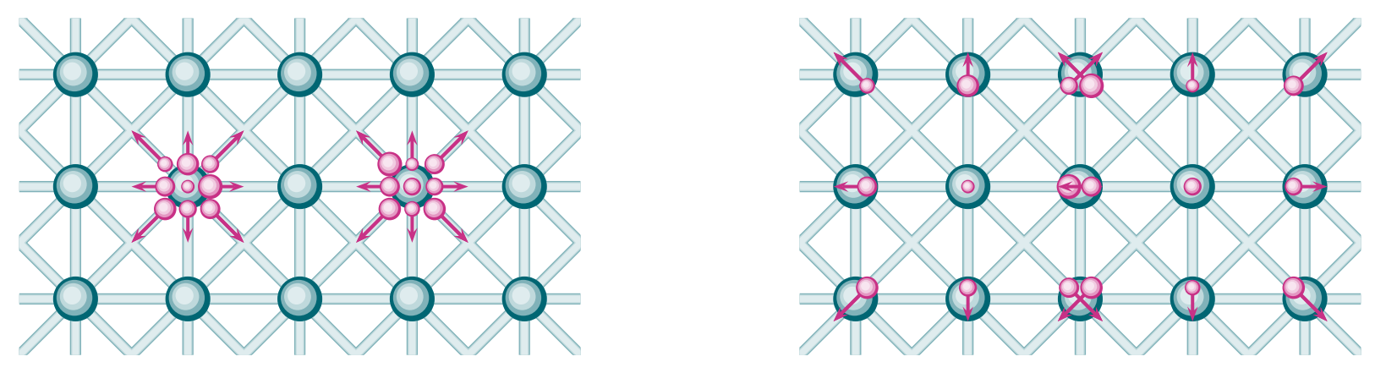


Numerical Simulation of Blood Flow and Thrombus Formation with a Lattice–Boltzmann Scheme

Flow Simulation with LB Schemes

Idea of LB Schemes

- Uniform grid with 9 particle densities at each node
- Two-step scheme: Advection step plus collision step



- Navier–Stokes equations can be recovered via a Chapman-Enskog expansion

Details of My Implementation

- Extension to incompressible flow [5, 6]
- Extension to axisymmetric flow [7, 8]
- No-slip boundary condition at vessel wall via bounce-back rule
- In/outflow boundary condition via extrapolation method [9], but only first order [10]

Additional Equations

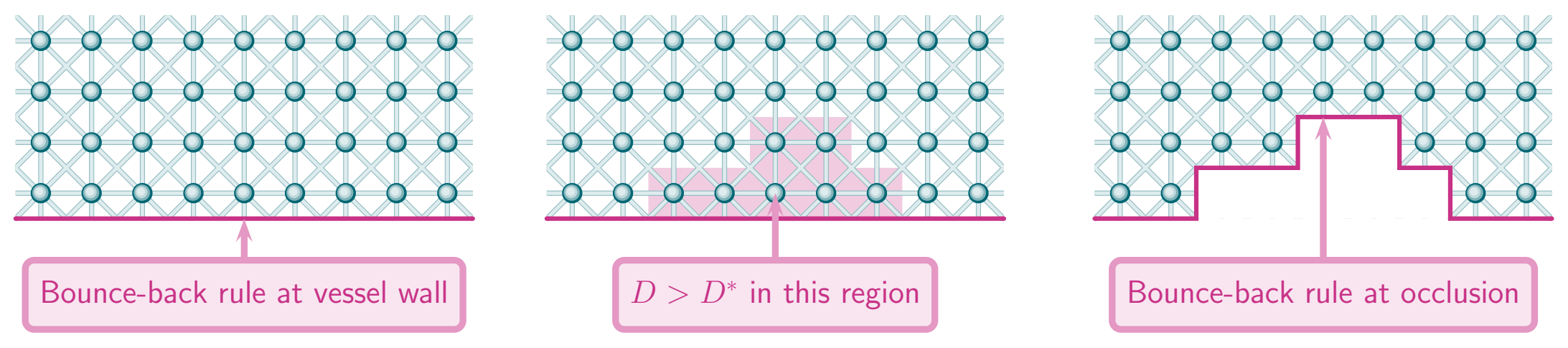
Heat Transfer

$$\begin{aligned} \partial_t(\rho cT)-\nabla\cdot(\lambda\nabla T)+\vec{v}\cdot\rho c\nabla T &= Q_{\mathrm{pc}} && \Omega \\ T &= T_{\mathrm{body}} && \Gamma_{\mathrm{inflow}} \\ \vec{n}\cdot\nabla T &= 0 && \Gamma_{\mathrm{outflow}} \\ q = q(t,x)\ \text{user-defined} \rightarrow \qquad \vec{n}\cdot\nabla T &= q && \Gamma_{\mathrm{shell}} \end{aligned}$$

Damage

$$\begin{aligned} \partial_t D+\vec{v}\cdot\nabla D &= A_{\mathrm{A}}\exp\left(\frac{-E_{\mathrm{A}}}{RT}\right) && \Omega \\ D &= 0 && \Gamma_{\mathrm{inflow}} \\ \vec{n}\cdot\nabla D &= 0 && \Gamma_{\mathrm{outflow}}\cup\Gamma_{\mathrm{shell}} \end{aligned}$$

Occlusion Formation



Features

- Pulsatile flow with prescibed flow profile (also with backflow), implemented via time dependent in/outflow boundary conditions
- Prescribed time and space dependent Neumann boundary conditions for T
- Automatic occlusion detection

Runtimes (on a Standard Linux Cluster)

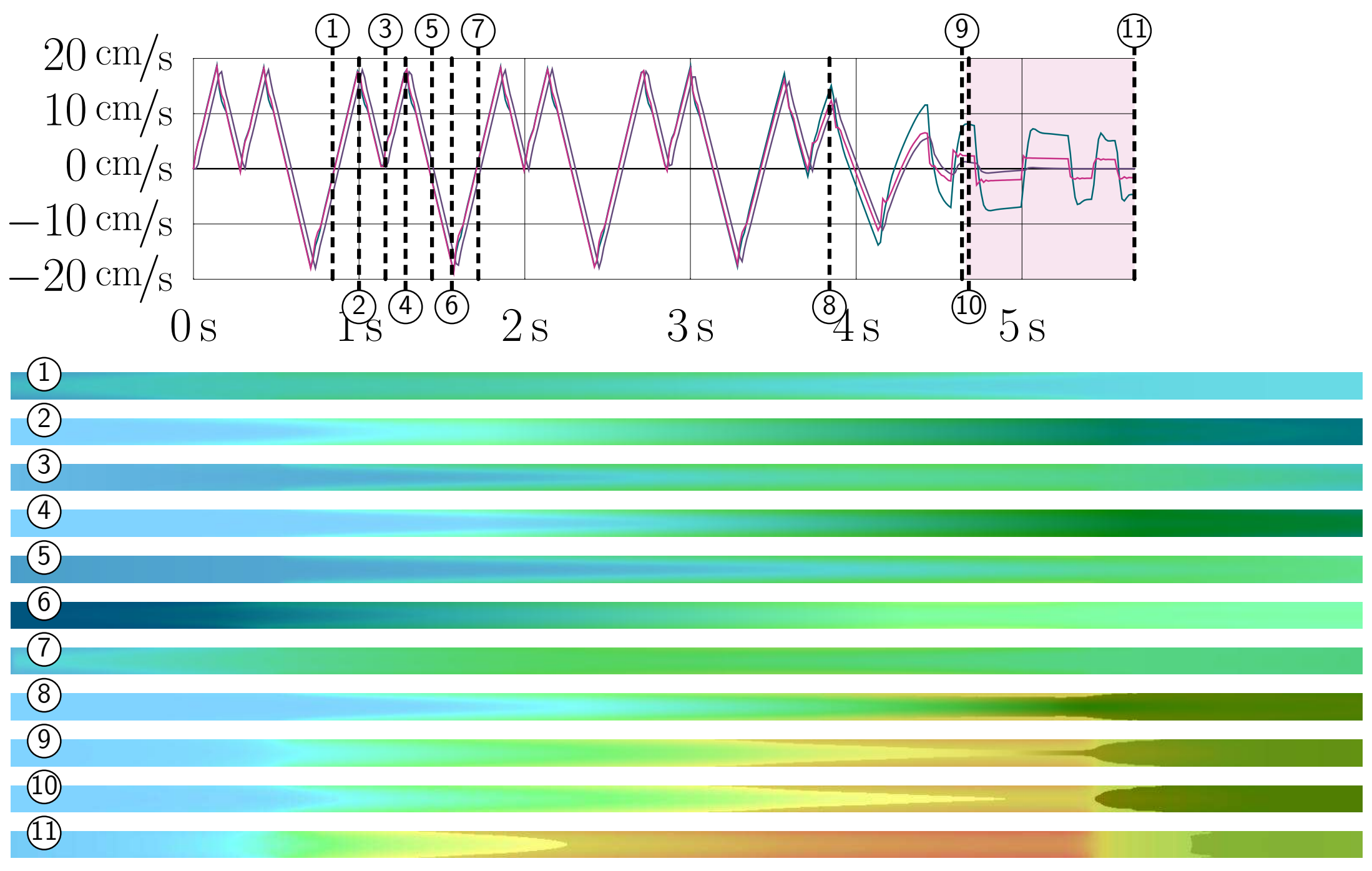
- Vessel length 5 cm, diameter 1 mm, grid width 0.03 mm
- Simulation of 1 s flow in 30600 time steps

#CPUs	1	2	4	8	16	24	32
Runtime (s)	4395	2154	1319	682	347	231	176
Speedup	1.00	2.04	3.33	6.44	12.67	19.03	24.97

Open Questions

- Applicability of overall model
- Clinically relevant flow velocities and pulsatility profiles [11, 12]
- Arrhenius parameters of blood
- Viscosity of blood, Non-Newtonianity (Fung [11]: apparent viscosity is 4.0 cp above 0.1 mm diameter)
- Turbulent flow – sensible spatial resolution
- Consideration of non-rigid vessel wall
- Stopping criterion if no occlusion occurs

First Numerical Results



Brightness = Pressure Color = Temperature

References

[1] Arrhenius, S.: Über die Reaktionsgeschwindigkeit bei der Inversion von Rohrzucker durch Säuren. Z. Phys. Chem **4** (1889) 226–248

[2] Pennes, H.H.: Analysis of tissue and arterial blood temperatures in a resting forearm. J. Appl. Physiol. **1** (1948) 93–122

[3] Deuflhard, P., Hochmuth, R.: Multiscale analysis of thermoregulation in the human microcascular system. Math. Meth. Appl. Sci. **27** (2004) 971–989

[4] Jain, R. K., Grantham, F. H., Gullion, P. M.: Blood flow and heat transfer in walker 256 mammary carcinoma. J. Natl. Cancer Inst. **69** (1979) 927–931

[5] Zou, Q., Hou, S., Chen, S., Doolen, G.D.: An improved incompressible lattice boltzmann model for time-independent flows. J. Stat. Phys. **81** (1995) 35–48

[6] He, X., Luo, L.S.: Lattice boltzmann model for the incompressible navier-stokes equation. J. Stat. Phys. **88** (1997) 927–944

[7] Halliday, I., Hammond, L., Care, C., Good, K., Stevens, A.: Lattice boltzmann equation hydrodynamics. Phys. Rev. E **64** (2001) 011208

[8] Lee, T., Huang, H., Shu, C.: An axisymmetric incompressible lattice bgk model for simulation of the pulsatile flow in a circular pipe. Int. J. Numer. Meth. Fluids **49** (2005) 99–116

[9] Chen, S., Martinez, D., Mei, R.: On boundary conditions in lattice boltzmann methods. Phys. Fluids **8** (1996) 2527–2536

[10] Guo, Z., Shi, B., Wang, N.: Lattice bgk model for incompressible navier-stokes equation. J. Comp. Phys. **165** (2000) 288–306

[11] Fung, Y.C.: Biomechanics. Springer (1990)

[12] Taylor, K.J., Burns, P.N., Woodcock, J.P., Wells, P.: Blood flow in deep abdominal and pelvic vessels: Ultrasonic pulsed-doppler analysis. Radiology **154** (1985) 487–493

[13] Preusser, T., Weihusen, A., Peitgen, H.O.: On the modelling of perfusion in the simulation of RF-ablation. In: Proceedings of Simulation and Visualization (SimVis), Magdeburg (2005)

[14] Deuflhard, P., Weiser, M., Seebaß, M.: A new nonlinear elliptic multilevel fem applied to regional hyperthermia. Comput. Vis. Sci. **3** (2000) 115–120

[15] Jain, M.K., Wolf, P.D.: A three-dimensional finite element model of radiofrequency ablation with blood flow and its experimental validation. Ann. Biomed. Eng. **28** (2000) 1075–84

[16] Stein, T.: Untersuchungen zur Dosimetrie der hochfrequenzstrominduzierten interstitiellen Thermotherapie in bipolarer Technik. Volume 22 of Fortschritte in der Lasermedizin. Müller and Berlien (2000)

[17] Tungjitkusolum, S., Staelin, S.T., Haemmerich, D., et al.: Three-dimensional finite-element analyses for radio-frequency hepatic tumor ablation. IEEE Trans. Biomed. Eng. **49** (2002) 3–9

[18] Kröger, T., Altrogge, I., Preusser, T., Pereira, P.L., Schmidt, D., Weihusen, A., Peitgen, H.O.: Numerical simulation of radio frequency ablation with state dependent material parameters in three space dimensions. In: Proc. MICCAI. Volume 4191 of Springer LNCS. (2006) 380–388