Los Alamos Northern New Mexico section (LANNM)

Computer Science Chapter of IEEE

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Unified Lattice Boltzmann Computation for Patient-specific Hemodynamics in Healthy and Diseased Aorta

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Contributors

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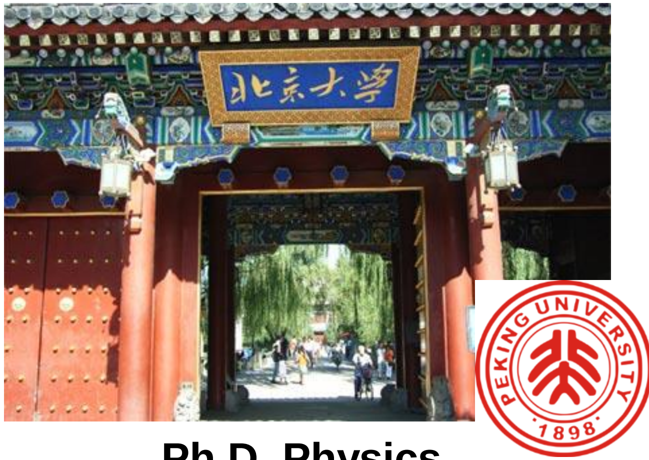
Kent State: Ye. Zhao and Zhiqiang Wang

IU Medicine: Shawn D. Teague

IUPUI

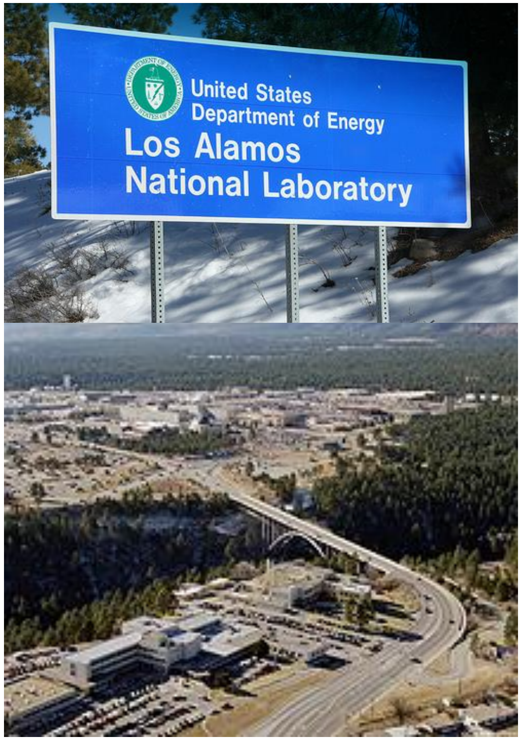
B.S., Physics



Ph D, Physics

Ph D, Aerospace Engineering

Postdoc



Postdoc

Assistant Professor

Previous Research Experience

- **Turbulence computation (modeling and simulation)**

  Kinetic CFD, lattice Boltzmann method
  - Decaying isotropic turbulence w/wo rotation —Texas A&M
  - Turbulent rectangular jets — Texas A&M
  - Flaming in reacting flow — Texas A&M
  - Heat/mass transfer in natural convection — Los Alamos
  - Binary scalar mixing with equal and unequal masses — Texas A&M
  - Peristaltic transport in gastrointestinal tract — Penn State

  Hydrodynamic CFD, Navier-Stokes equations
  - Compressible Rayleigh-Taylor instability w/wo combustion, massive parallel — Los Alamos

- **Applied fluid mechanics**
  - Linear stability analysis of compressible RT instability in cylindrical geometry — Los Alamos
  - Rapid distortion theory in compressible turbulence — Texas A&M
  - Public turbulence database enabled analysis for Lagrangian turbulence — Johns Hopkins

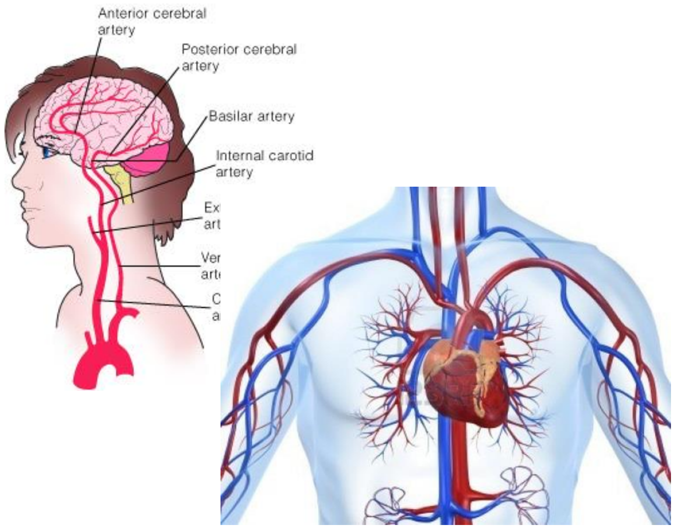
- **Cyber CFD and database technology (computational and experimental data)**
  - Web-accessed turbulence database, “cyber fluid dynamics” — Johns Hopkins
  - Cohesive experimental database for predicting long-term corrosion/erosion of steel exposed to flowing liquid lead/lead bismuth eutectic — Los Alamos

Outline

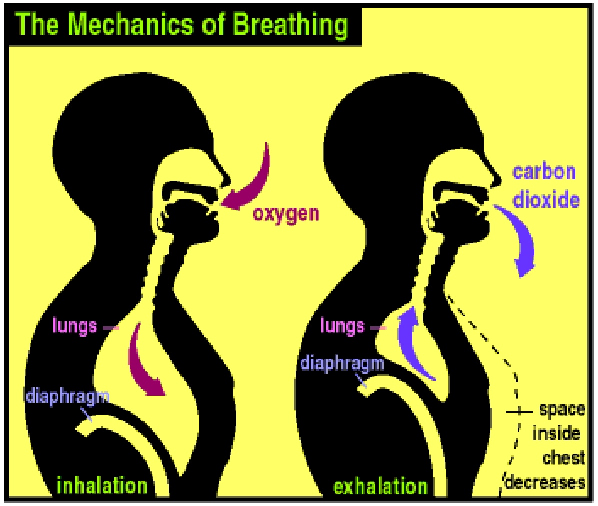
- Background and research motivation
- Unified computation platform for patient-specific computational hemodynamics using lattice Boltzmann method
- Preliminary results on patient-specific hemodynamics in healthy and diseased aorta
- Summary

Flows in Human Body

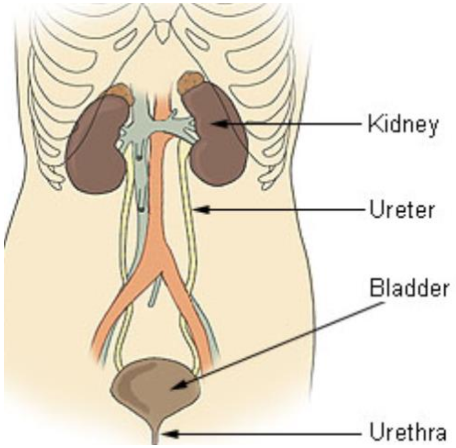
Circulatory System



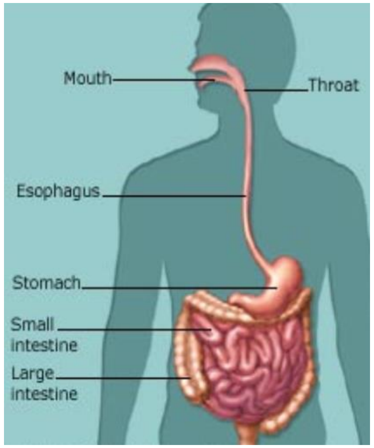
Respiratory System



Urinary System



Digestive System



Fluid-structure interaction

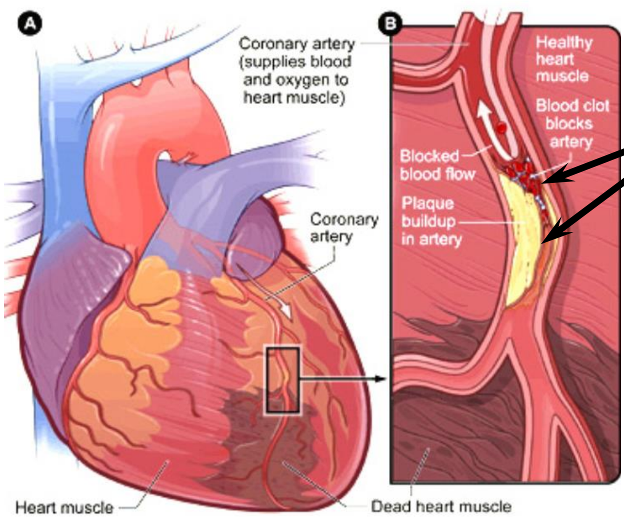
Structure:	**Fluid/flow:**
Arbitrary geometry	Pulsatile
Bifurcations	Laminar/turbulence
Deformable	Non-Newtonian
Willfully/compliantly moving	Multiphase

Cardiovascular Disease Facts

from www. CDC.gov

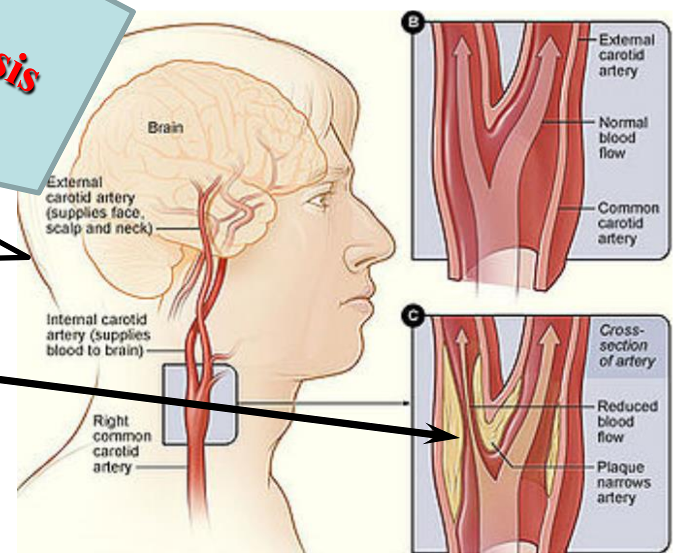
Heart Attack

- Killing **600K** people, **1 in every 4 deaths**
- **One** heart attack every **34 seconds**
- **$108.9 billion** for coronary heart disea



Athrosclerosis

Blockage



Stroke

- Killing **130K** people, **1 in every 19 deaths**
- **One** heart attack every **34 seconds**
- **$38.6 billion** for health care, medication, lost productivity

Hypothesis: **hemodynamics likely reveals the mechanism of plaque disruption or embolization**

Hemodynamics: In Vivo Imaging

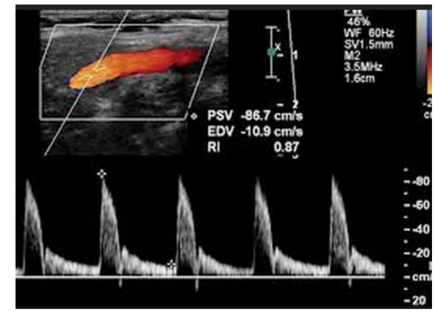
Phase-Contrast Magnetic Resonance Imaging

J Thorac Imaging • Volume 28, Number 4, July 2013

REVIEW ARTICLE

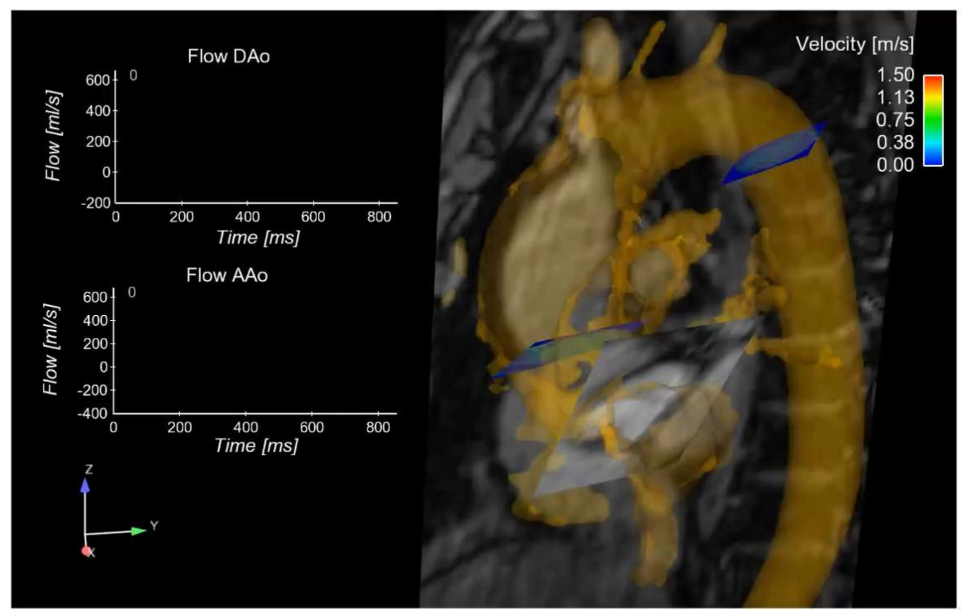
Cardiothoracic Magnetic Resonance Flow Imaging

Michael D. Hope, MD, Tony Sedlic, MD,* and Petter Dyverfeldt, PhD*†‡*



Challenges for clinical application

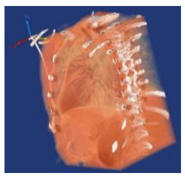
- Long scan time (hours)
- Data processing
  (time consuming,
  specific operator skills)
- Lack of proven clinical applications
- Limited to heart and great vessels

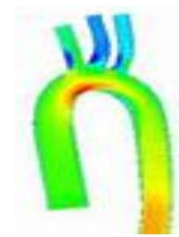


Patient-specific Computational Fluid Dynamics

CT/MRI images → **Mimics Materialise**: Segmentation → **Pro-Engineer**:
- Geometry format
- Geometry scaling

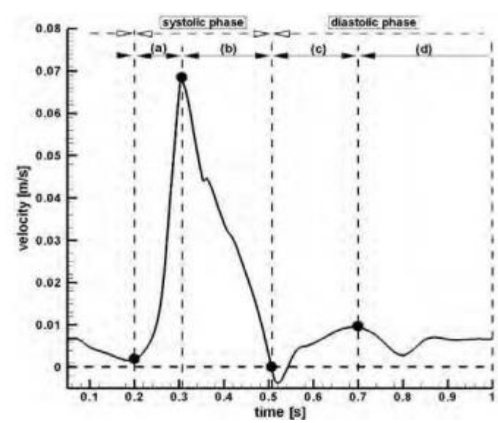
→ **T-Grid**: Volume mesh → **Ansys-Fluent**: CFD → **4D hemodynamics**





Limitations:

1. Inadequate for pulsatile flow
2. Modeling — FSI, Multiphase, etc.
3. GPU parallel computing



Unified Computation Platform

Integration

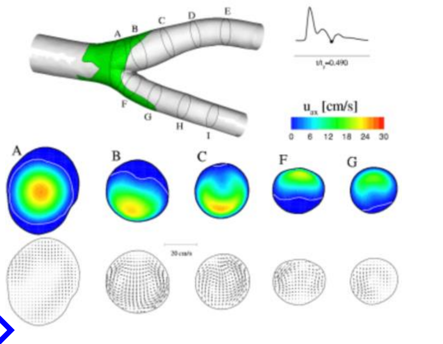
Segmentation — CT/MRI

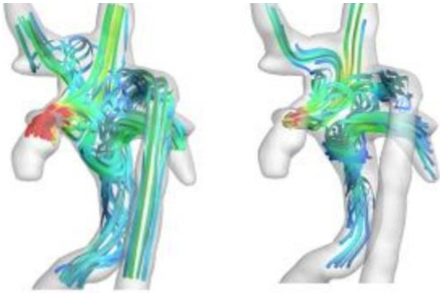
Fluid-structure Interaction

Turbulence — pulsatile flow

Multiphase — non-Newtonian

Parallelism — GPU



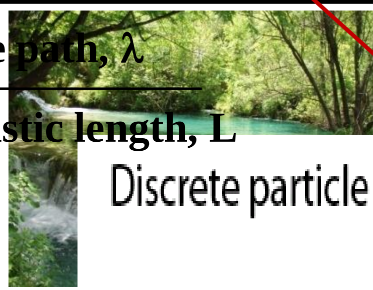


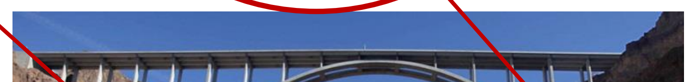
Lattice Boltzmann Method

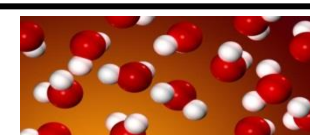
Descriptions of Fluid Dynamics

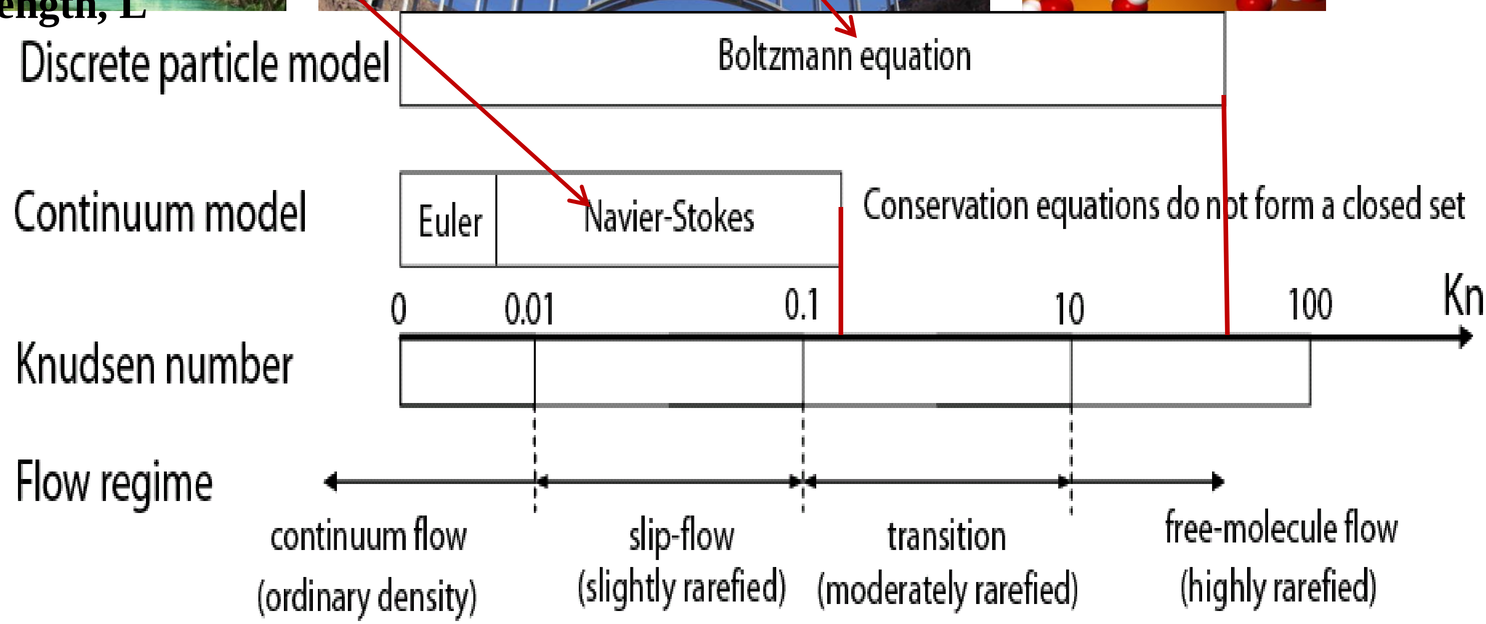
	Macroscopic	Mesoscopic	Microscopic
Theory	Hydrodynamics	Kinetic Theory	Molecular Dynamics
Equations	Navier-Stokes	Boltzmann	Newton-Hamilton
subject	Continuum variables	Particle distribution function	Particle trajectories

$$Kn \equiv \frac{\text{Mean free path, } \lambda}{\text{Characteristic length, } L}$$









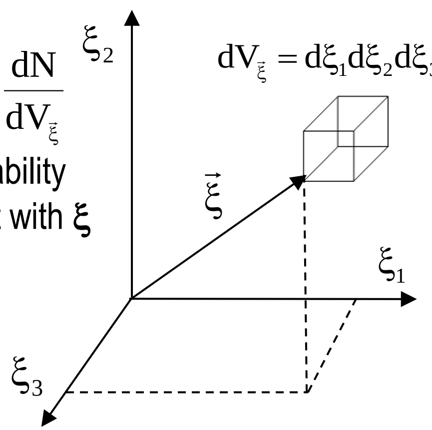
The diagram is adapted from Anderson J., *Hypersonic and high temperature gas dynamics*, McGraw-Hill, 1989.

Boltzmann Equation

Key variable: particle distribution function

$$f(\vec{x},\vec{\xi},t) = \frac{\rho}{N}\lim_{dV_{\xi}\to 0}\frac{dN}{dV_{\xi}}$$

density weighted probability to find a particle at **x**, t with **ξ**



Molecular phase space

$$\frac{\partial f}{\partial t} + \vec{\xi}\cdot\nabla f + \frac{\partial f}{\partial \vec{\xi}}\cdot\vec{F} = J(f)$$

$J(f)$ ← collision operator

$$\int\begin{bmatrix}1\\ \vec{\xi}\\ (\vec{\xi}-\vec{u})^2\end{bmatrix}J(f)d\vec{\zeta} = \begin{bmatrix}0\\0\\0\end{bmatrix}$$

Collision satisfies conservation laws

$$\frac{\partial\rho}{\partial t} + \frac{\partial(\rho u_i)}{\partial x_i} = 0$$

$$\rho\left(\frac{\partial u_i}{\partial t} + u_j\frac{\partial u_i}{\partial x_j}\right) + \frac{\partial P_{ij}}{\partial x_i} = \rho f_i$$

$$\rho\left(\frac{\partial e}{\partial t} + u_j\frac{\partial e}{\partial x_j}\right) + \frac{P_{ij}\partial u_i}{\partial x_j} + \frac{\partial q_i}{\partial x_i} = 0$$

P_{ij}, and q_i closures

Higher order moments

Beyond NS

N-S Equations

Hydrodynamic variables

Density	$\rho(\vec{x},t) = \int f(\vec{x},\vec{\xi},t)d\vec{\xi}$
Momentum	$\rho\vec{u}(\vec{x},t) = \int \vec{\xi} f(\vec{x},\vec{\xi},t)d\vec{\xi}$
Internal Energy	$\rho e(\vec{x},t) = (1/2)\int \vec{c}^2 f(\vec{x},\vec{\xi},t)d\vec{\xi}$
Stress tensor	$P_{ij}(\vec{x},t) = -\int c_i c_j f(\vec{x},\vec{\xi},t)d\vec{\xi}$
Heat flux density	$\vec{q}(\vec{x},t) = (1/2)\int \vec{c}(\vec{c}\cdot\vec{c}) f(\vec{x},\vec{\xi},t)d\vec{\xi}$

$$\vec{c} \equiv \vec{\xi} - \vec{u}$$

…………..

Non-hydrodynamic moments

Remarks:

1. BE covers NS, and more than NS
2. Once f known, hydrodynamics known

Bhatnagar-Gross-Krook (BGK) approximation

$$\frac{\partial f}{\partial t} + \vec{\xi}\cdot\nabla f + \frac{\partial f}{\partial \vec{\xi}}\cdot\vec{F} = -Z(f - f_M)$$

Z: Average collision frequency

f_M: Maxwell-Boltzmann equilibrium distribution function

A Passage from BGKBE to BGKLBE

BGK or SRT model

X. He and L-S Luo, PRE 56, 6811(1997)

$$\partial f / \partial t + \vec{\xi} \cdot \nabla f = -Z(f - f_M), \quad f = f(\vec{x}, \vec{\xi}, t)$$

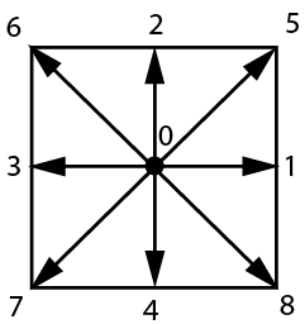
1. Discretization of time

$$\tau = 1/(Z\delta t)$$

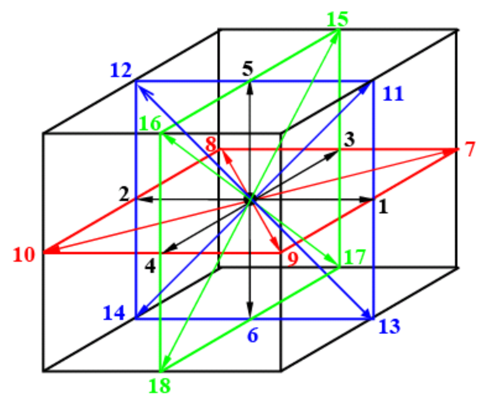
$$f(\vec{x} + \vec{\xi}\delta t, \vec{\xi}, t + \delta t) = f(\vec{x}, \vec{\xi}, t) - [f(\vec{x}, \vec{\xi}, t) - f_M(\vec{x}, \vec{\xi}, t)] / \tau$$

2. Discretization of physical space and molecular velocity space coherently in finite directions satisfying conservation laws and symmetry needs

3. Taylor expand f_M at low Mach number limit and determine coefficients based on conservation laws and symmetry needs



$$\vec{e}_\alpha = \begin{cases} (0,0) & \alpha = 0 \\ (\pm 1, 0), \quad (0, \pm 1) & \alpha = 1-4 \\ (\pm 1, \pm 1) & \alpha = 5-8 \end{cases}$$



$$\vec{e}_\alpha = \begin{cases} (0,0) & \alpha = 0 \\ (\pm 1, 0, 0), \quad (0, \pm 1, 0), \quad (0, 0, \pm 1) & \alpha = 1-6 \\ (\pm 1, \pm 1, 0), \quad (\pm 1, 0, \pm 1), \quad (0, \pm 1, \pm 1) & \alpha = 7-18 \end{cases}$$

$$f_\alpha(\vec{x} + \vec{e}_\alpha \delta t, t + \delta t) = f_\alpha(\vec{x}, t) - [f_\alpha(\vec{x}, t) - f_\alpha^{(eq)}(\vec{x}, t)] / \tau$$

$$\tau = 3\nu / (c\delta x) + 0.5$$

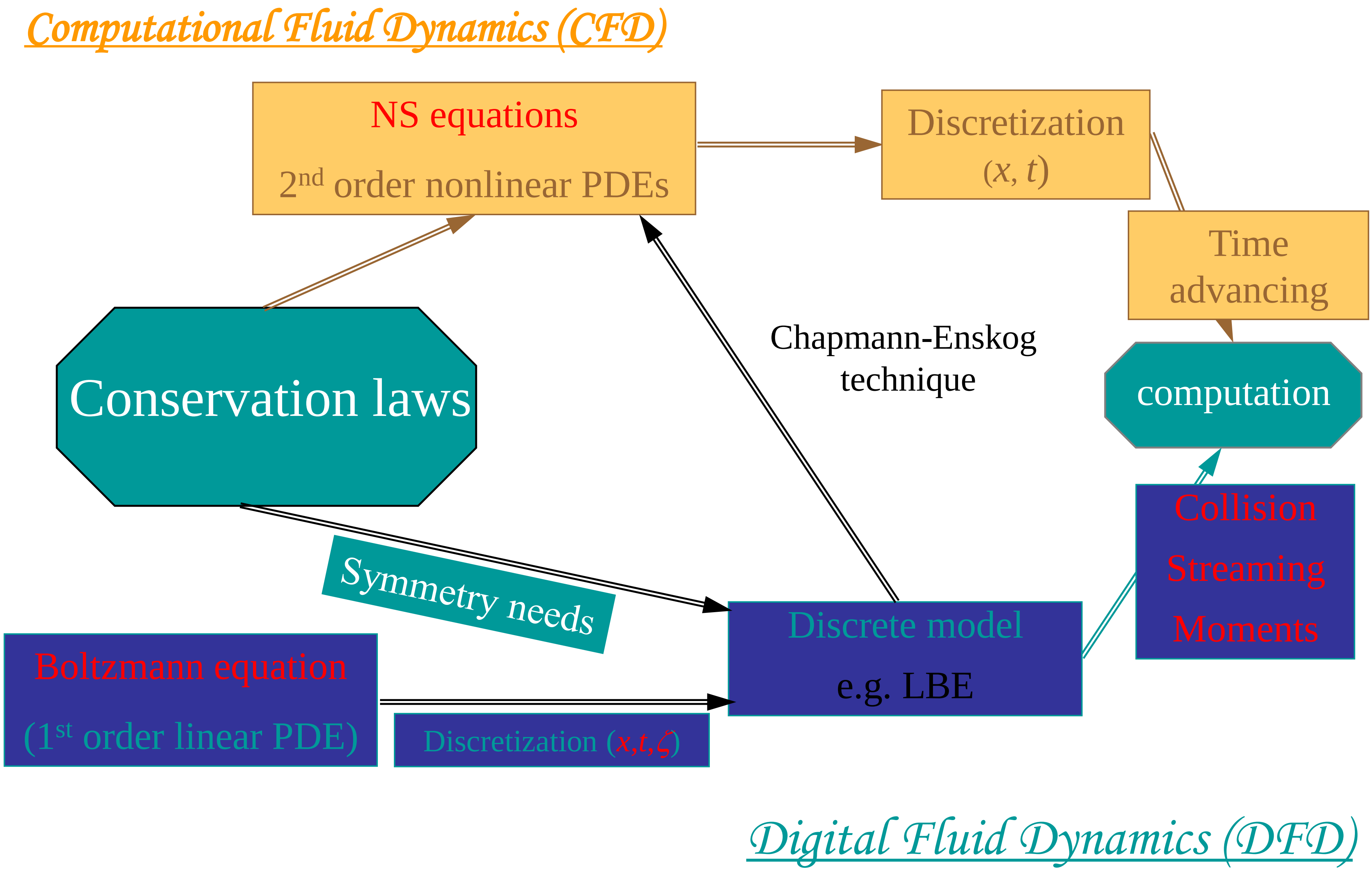
Chapmann-Enskog technique

$$\rho = \sum f_\alpha$$

$$\rho \vec{u} = \sum c \vec{e}_\alpha f_\alpha$$

$$\nabla \cdot \vec{u} = 0, \quad \partial \vec{u} / \partial t + \vec{u} \cdot \nabla \vec{u} = -\nabla p / \rho + \nu \nabla^2 \vec{u}$$

Computation Methodologies



Potential Advantages of LBM

$$f_\alpha(\vec{x}+\vec{e}_\alpha\delta t, t+\delta t) = f_\alpha(\vec{x},t) - [f_\alpha(\vec{x},t) - f_\alpha^{(eq)}(\vec{x},t)]/\tau$$

$$\rho = \sum f_\alpha, \rho\vec{u} = \sum \vec{e}_\alpha f_\alpha$$

- **Simpler implementation**

  Linear equation
  Discrete equation
  Single variable
  Arithmetic calculation
  (no derivative involved)

- **More physical concepts: collision and streaming**

  e.g. Single phase: self collision
  Multiphase: self and mutual collisions
  Miscible: attracting
  Immiscible: repelling
  No-slip boundary: bounce-back

- Easy handling of complicated geometry or boundary
  e.g. porous media, bio-transport, etc.
- Ideally suited for multi-phase flows
  e.g. interfacial dynamics, fluid structure interaction, etc
- Good candidate for problems beyond Navier-Stokes,
  e.g. rarified gas, plasma, micro/nano fluidics
- Well suited for large-scale, parallel (GPU) computing

A Historic View of LBM

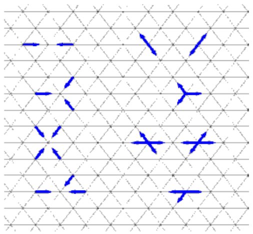
Lattice gas automata (LGA)

Frisch, Hasslacher, and Pomeau, PRE, 1986

$n_\alpha(x + \delta_t e_\alpha, t + \delta_t) = n_\alpha(x, t) + C_\alpha(\{n_\beta\})$, $C_\alpha(\{n_\beta\})$: collision operator

Main drawbacks: $n_\alpha \in [0,1]$: Boolean particle number

Intrinsically noisy; lack of Galilean invariance,
unphysical pressure; unphysical conserved quantities



Discrete molecular phase space

Ensemble Average of LGA: $f_\alpha = \langle n_\alpha \rangle \in [0,1]$, G. McNamara and G. Zanetti, PRE, 1988

Lattice Boltzmann method (LBM)

Qian, d'Humières, Lallemand, Europhys. Lett. (1992) , H Chen, S Chen, and Matthaeus, Phys. Rev. E, 1992,

$f_\alpha(x + \delta_t e_\alpha, t + \delta_t) = f_\alpha(x, t) + \Omega_\alpha(x, t)$*

f_α: particle number with e_α at x
Ω_α: collision operator

Bhatnagar-**G**ross-**K**rook approximation
$\Omega_\alpha(x, t) = -[f_\alpha(x, t) - f_\alpha^{(eq)}(x, t)]/\tau$

* Empirical evolution of LGA historically. Mathematical proof by Abe, JCP(1997), He&Luo, PRE (1997)

Restrictions: — incompressible flow
Small Mach number assumption; Small knudsen number assumption;
thermal model numerically unstable; not clear how to extend beyond NS

Moment expansion, Shan & He, PRL,1998

Kinetic theory representation of hydrodynamic Navier-Stokes and beyond

Shan, Yuan, and Chen, JFM, 2006

Breakthroughs:
Compressible, shocks, rarified, thermodynamic effect

Courtesy of Prof. Ye Zhao and his student

LBM for Imagine Processing

Image segmentation

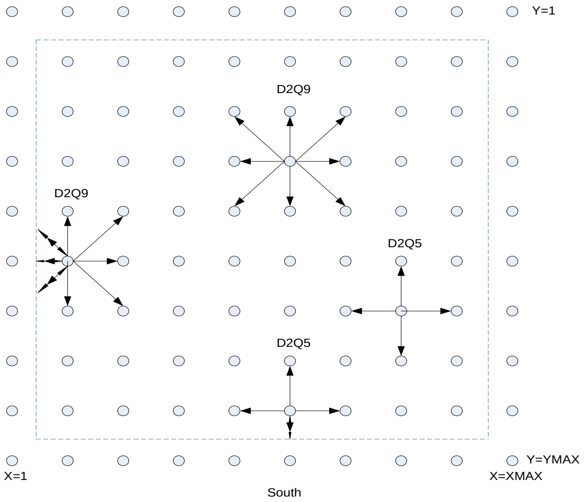
Image denoising

Image Filtering

Image lighting

- Zhao, Y., *Lattice Boltzmann based PDE solver on the GPU.* Visual Computer, 2008.
- Zhao, Y. *GPU-Accelerated Surface Denoising and Morphing with Lattice Boltzmann Scheme*, in *IEEE International Conference on Shape Modeling and Applications*, 2008.
- Hagan, A. and Zhao, Y., *Parallel 3D Image Segmentation of Large Data Sets on a GPU Cluster*, in *the 5th International Symposium on Visual Computing,* 2009.
- Cahang, Q. and Yang, T., *A lattice Boltzmann method for image denoising.* IEEE Transactions on Image Processing, 2009.
- Zhang, W. and Shi, B., *Application of Lattice Boltzmann Method to Image Filtering.* Journal of Mathematical Imaging and Vision, 2012.
- Balla-Arabé, O. and Gao, X., *A fast and robust level set method for image segmentation using fuzzy clustering and lattice Boltzmann method.* IEEE Trans Syst Man Cybern B., 2012.

Modern Graphics and Visualization



- Modern images are digitized.
- PDEs are widely used in graphics and visualization applications
  - Image processing
  - Surface processing
  - Volume graphics and visualization

Image Segmentation

Caselles, Kimmel, and Sapiro, Int. J. Comp. Vision, 1997.

Geometric Active Contour (GAC) model:

inward normal

$$\frac{\partial \vec{C}}{\partial t} = [g(\kappa + \alpha) - (\nabla g \cdot \vec{N})]\vec{N}$$

I_0: original image
C: evolving curve
κ: curvature
g: edge-stopping function
σ: smooth parameter

Image smoothing

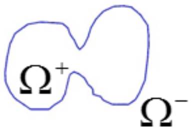
$$g = \frac{1}{1 + |\nabla(G_\sigma * I_0)|^2}$$

gradient of a Gaussian smoothed data

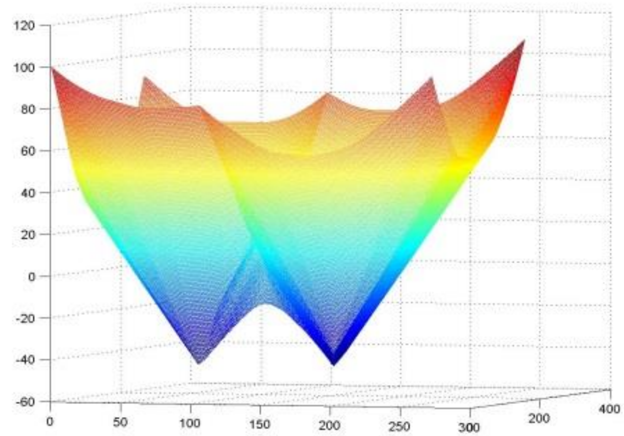
Level set formulation — diffusion equation with an external force

$$\frac{\partial u}{\partial t} = \nabla \cdot (g \nabla u) + F$$

u: level set function — distance field of the active contour
F: $g\alpha$



Contour (zero level set)

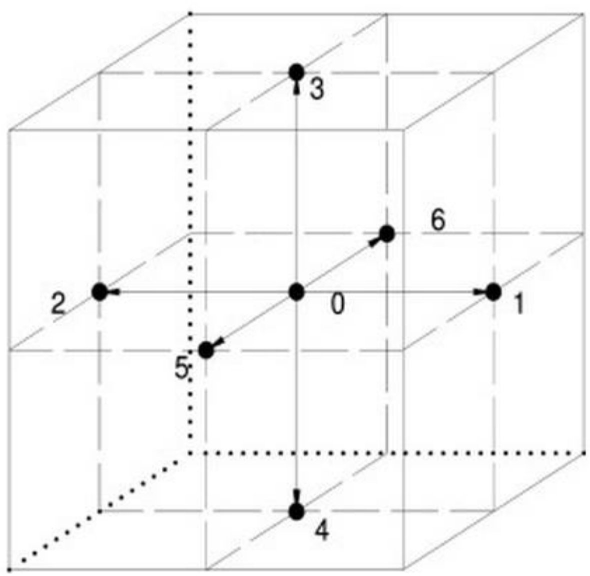


LB-GAC Model

$$f_i(\vec{x}+\Delta t\cdot\vec{e}_i, t+\Delta t) - f_i(\vec{x},t) = \omega\cdot[f_i^{eq}(\vec{x},t) - f_i(\vec{x},t)] + \Delta t F_i$$

$$(i = 1,\ldots,7)$$

D3Q7 lattice



$$\omega = 2/\left(1+6\Delta t g\right)$$

$$F_i(\vec{x},t) = \frac{1}{7}F(\vec{x},t)$$

$$f_i^{eq}(\vec{x},t) = \frac{1}{7}u(\vec{x},t)$$

$$u(\vec{x},t) = \sum_{i=1}^{7} f_i(\vec{x},t)$$

I. Ginzburg, Equilibrium-type and Link-type Lattice Boltzmann models for generic advection and anisotropic-dispersion equation, Adv Water Resour, 2005

Segmentation Flow Chart

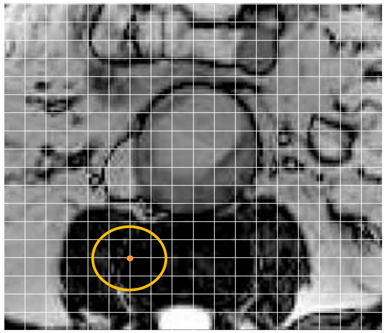
Given image data $I_0(\vec{x}) \Rightarrow g(\vec{x})$

$$F_i(\vec{x},0) = \alpha g(\vec{x},0)/7$$

Initialization

$$u(\vec{x},t)\begin{cases} < 0, \text{inside} \\ > 0, \text{outside} \\ = 0, \text{int erface} \end{cases}$$

$$f_i(\vec{x},0) = f_i^{eq}(\vec{x},0) = u(\vec{x},0)/7$$



LBM collision

$$f'_i(\vec{x},t) = f_i(\vec{x},t) + \omega \cdot [f_i^{eq}(\vec{x},t) - f_i(\vec{x},t)] + \Delta t F_i$$

streaming

$$f_i(\vec{x} + \Delta t \cdot \vec{e}_i, t + \Delta t) = f'_i(\vec{x},t)$$

Updated distance function

$$u(\vec{x}, t+\Delta t) = \sum_i f_i(\vec{x}, t+\Delta t)$$

Update $u(\vec{x}, t+\Delta t) = 0$

$$f_i^{eq}(\vec{x}, t+\Delta t) = u(\vec{x}, t+\Delta t)/7$$

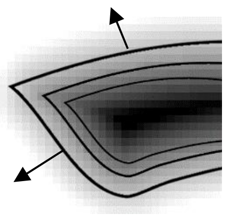
Solid volume

Voxelise a 3D triangular-polygon mesh to compute the volume of boundary cell

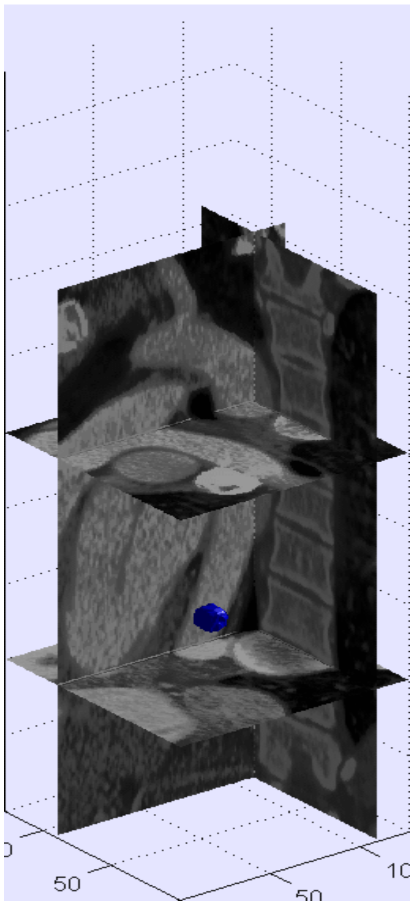
$$0 < p(\vec{x}) = V_s / V < 1$$

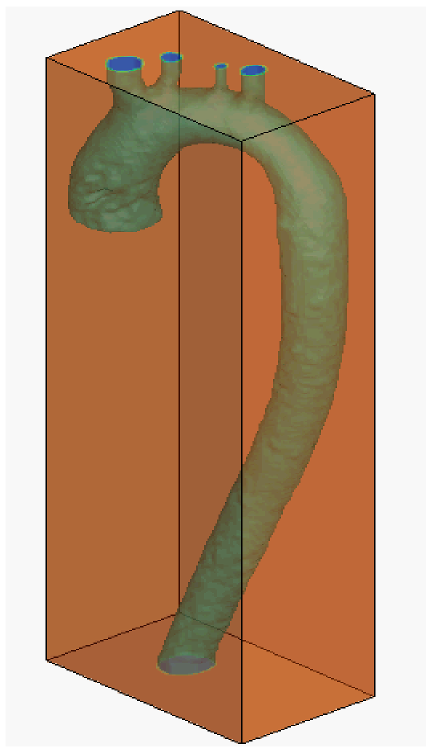
Wall normal direction

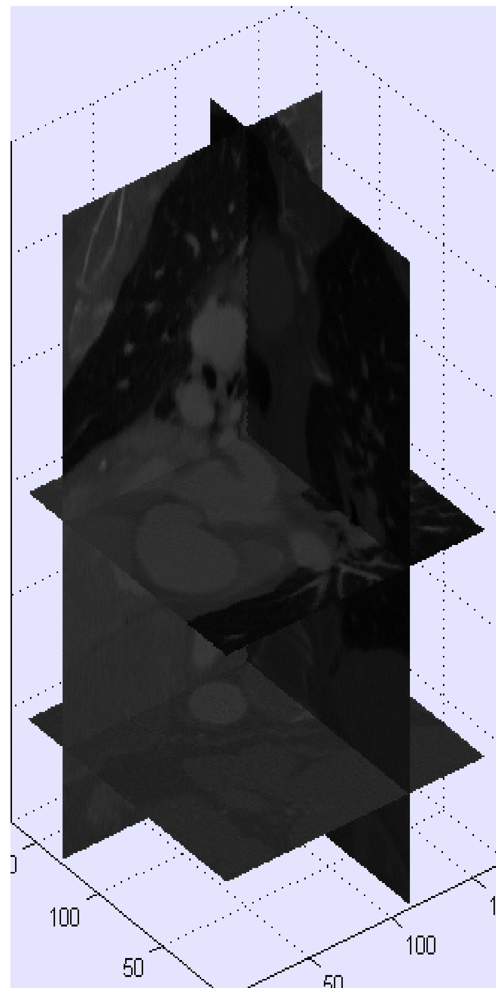
$$\vec{N} = \frac{\nabla u}{|\nabla u|}$$

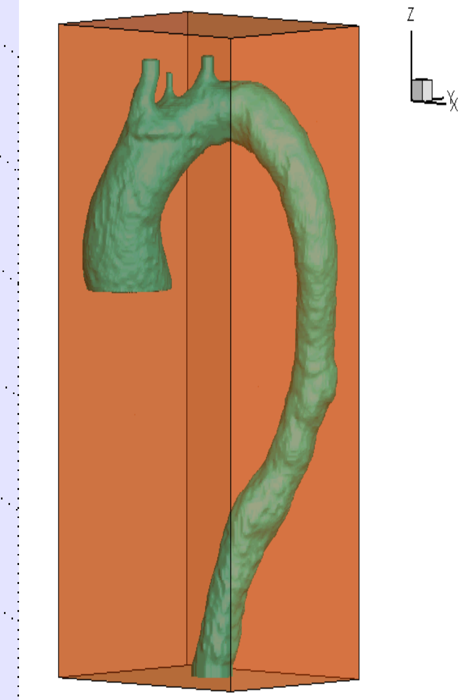


Healthy and Diseased Aortas from CT Images









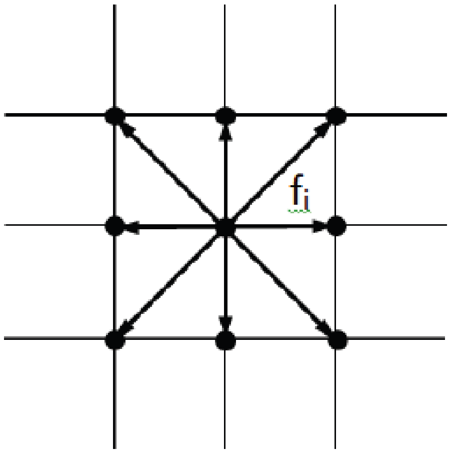
Mass-conserved Volumetric LBM

Node-based LBM

Time evolution of particle distribution functions

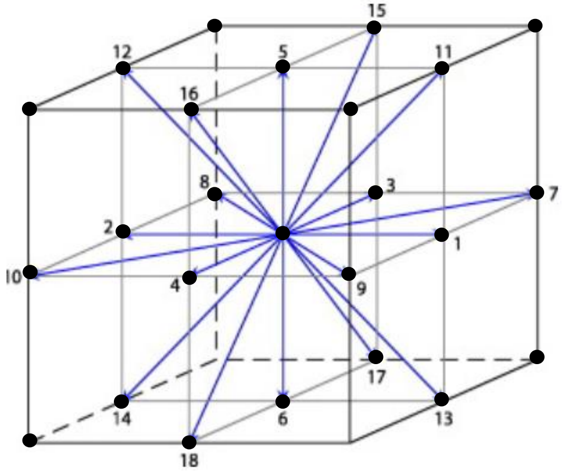
$$f_\alpha(\vec{x}+\vec{e}_\alpha\Delta t, t+\Delta t) = f_\alpha(\vec{x},t) + \Omega_\alpha(\vec{x},t)$$

α=0,1,…,8



D2Q9

α=0,1,…,18



D3Q19

Node-based LBM for Curved Boundary

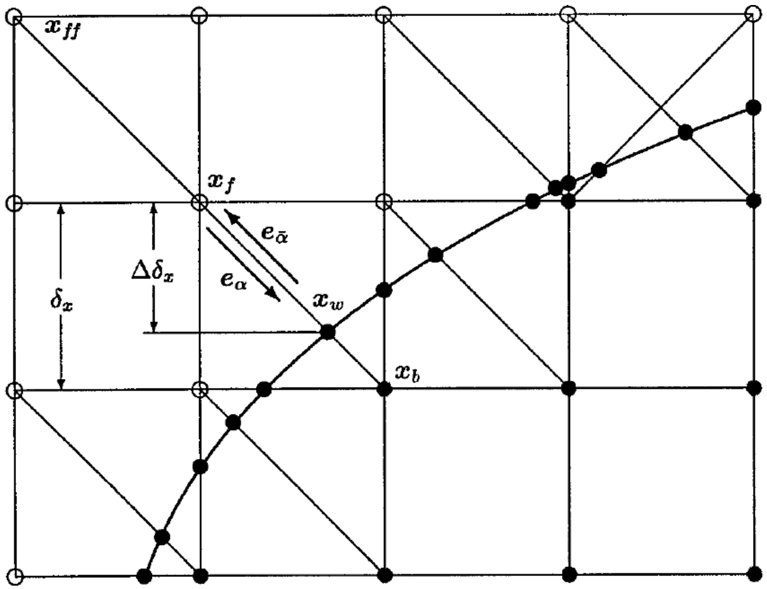


FIG. 2. *Layout of the regularly spaced lattices and curved wall boundary. The thick curve marks the boundary location. The solid circles (•) mark the positions where particle-boundary collision occurs. The empty (○) and shaded (•) circles are fluid sites and solid sides, respectively.*

R. Mei, L-S Luo, and W. Shyy, NASA/CR-2000-209854, ICASE Report No. 2000-6

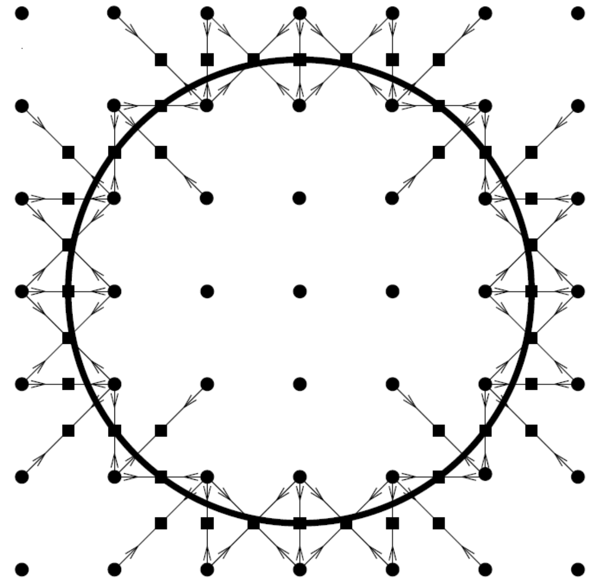


FIGURE 2. Location of the boundary nodes for a circular object of radius 2.5 lattice spacings. The velocities along links cutting the boundary surface are indicated by arrows. The location of the boundary nodes are shown by solid squares and the lattice nodes by solid circles.

A. J. C. Ladd, JFM, 1994

Bases of schemes:

1.Point-wise particle distribution interpolation

2.particle distribution transformation into local curve-linear coordinate system

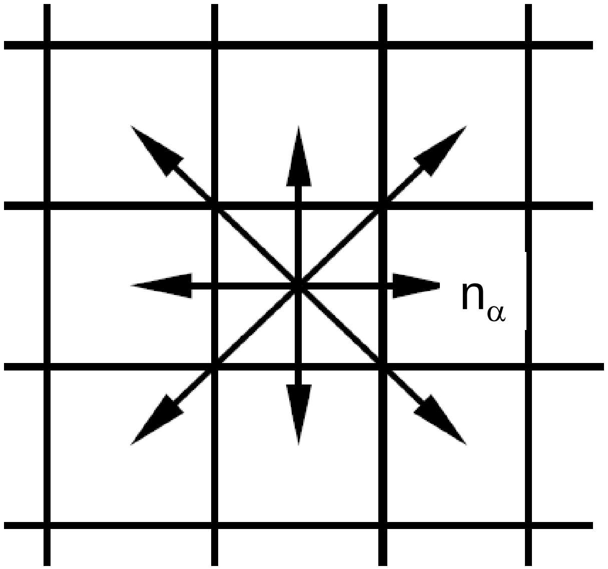
Main drawback: mass conservation of fluid not insured.

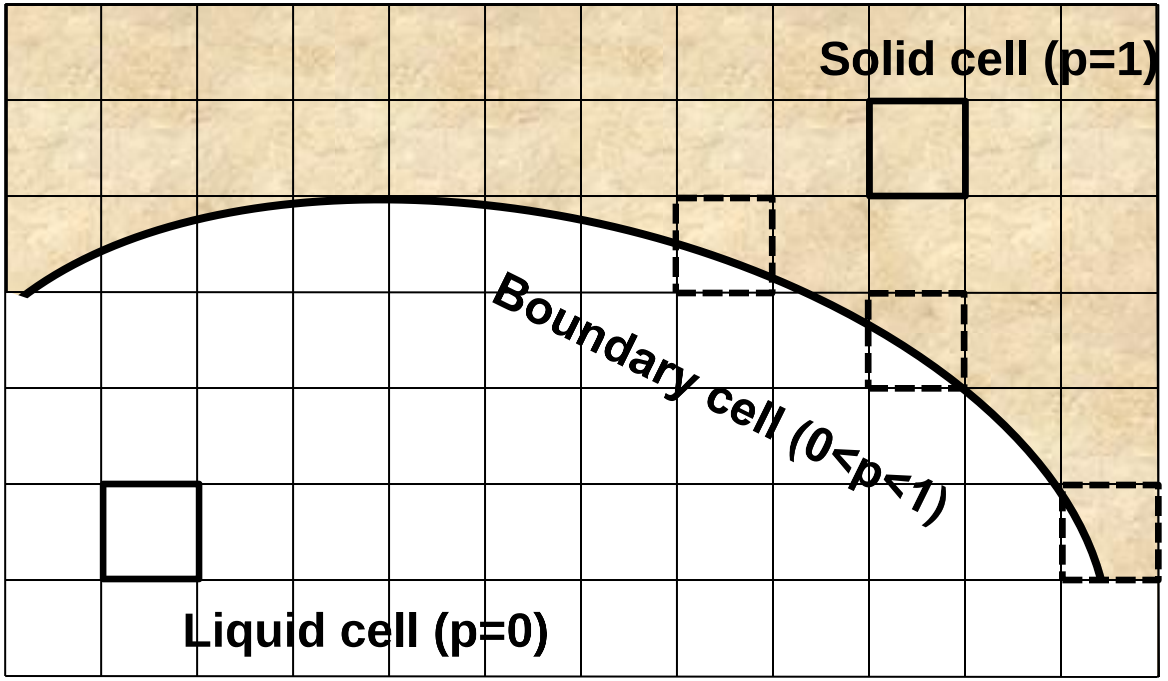
— **May not reliable/placticla for arbitrary moving boundaries**

Volumetric Representation

$$p(\vec{x},t) = \frac{\Delta v_s(\vec{x},t)}{\Delta v} \qquad \Delta V = \Delta V_s + \Delta V_f$$

$$n_\alpha = f_\alpha \Delta V_f$$





When ΔV_s=0, ΔV_f=ΔV, volumetric representation recovers node-based description

H. Chen, *Phys. Rev. E.* **98**, 3955 (1998)

Volumetric Lattice Boltzmann Equations

Time evolution of particle population

$$n_\alpha(\vec{x}+\vec{e}_\alpha \Delta t, t+\Delta t) = n_\alpha(\vec{x}, t) + \Omega_\alpha(\vec{x}, t)$$

$$\alpha = 0,1,\ldots,8$$

$$N = \sum_\alpha n_\alpha$$

$$\vec{u}(\vec{x}, t) = \frac{\sum_\alpha \vec{e}_\alpha n_\alpha}{N}$$

$$\rho(\vec{x}, t) = \frac{N}{(1-p)\Delta V}$$

Particle population evolution consists of

- **Collision**

  Momentum exchange between solid and fluid accounted
- **Streaming**

  Volumetric bonce-back included
- **Boundary induced particle migration**

  Mass conservation of fluid guaranteed

Collision

$$\Omega_\alpha(\vec{x},t) = -\frac{1}{\tau}\left[n_\alpha(\vec{x},t) - n_\alpha^{eq}(\vec{x},t)\right] \qquad \tau = \frac{1}{2} + \frac{3\nu}{c^2\delta t}$$

$$n_\alpha^{eq}(\vec{x},t) = Nw_\alpha\left[1 + \frac{3(\vec{e}_\alpha \cdot \vec{U})}{2c^2} + \frac{9(\vec{e}_\alpha \cdot \vec{U})^2}{2c^4} - \frac{3U^2}{2c^2}\right] \qquad \vec{U} = \vec{u} + \delta\vec{u}$$

$$\delta\vec{u}(\vec{x},t) = \tau p(\vec{x},t)\vec{u}_b(\vec{x},t) + \frac{\tau}{N(\vec{x},t)}\sum_{\beta=1}^{8} p(\vec{x}+\vec{e}_\beta,t)n_\beta(\vec{x},t)\vec{u}_b(\vec{x}+\vec{e}_\beta,t)$$

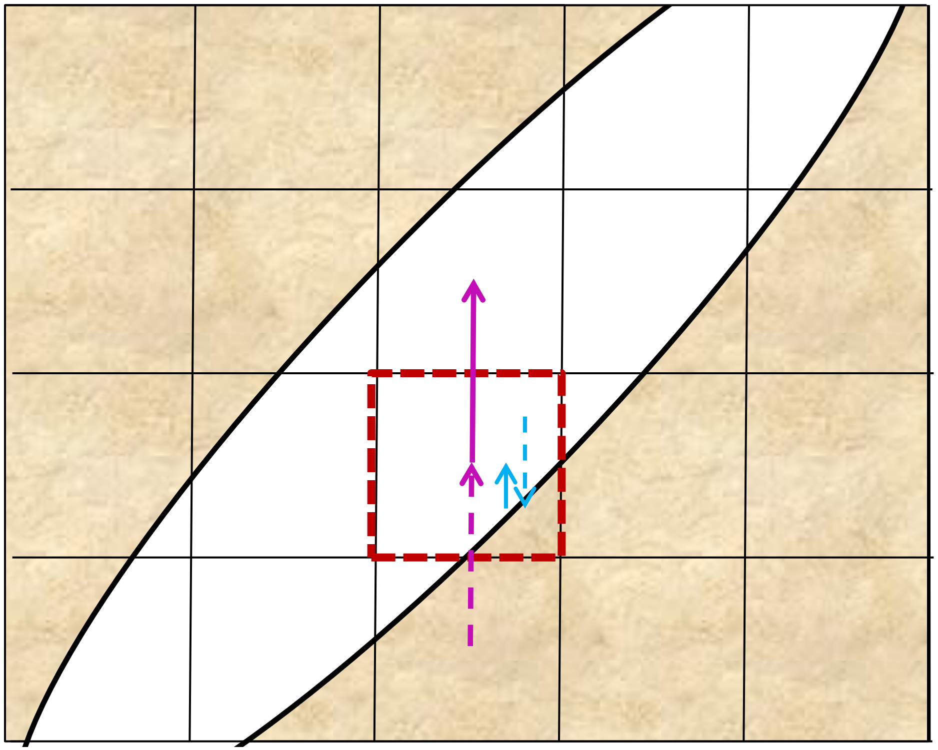
1. Reflecting momentum change due to boundary movement ($\vec{u}_b \neq 0$)
2. Only for boundary cells and their neighboring fluid cells
3. Satisfying mass conservation in boundary cells

Streaming

(Generalized bounce-back condition)

$$n''_\alpha(\vec{x}, t+\Delta t) = [1 - p(\vec{x}, t+\Delta t)]n'_\alpha(\vec{x} - \vec{e}_\alpha \Delta t, t) \quad \leftarrow \text{Upwind streaming}$$

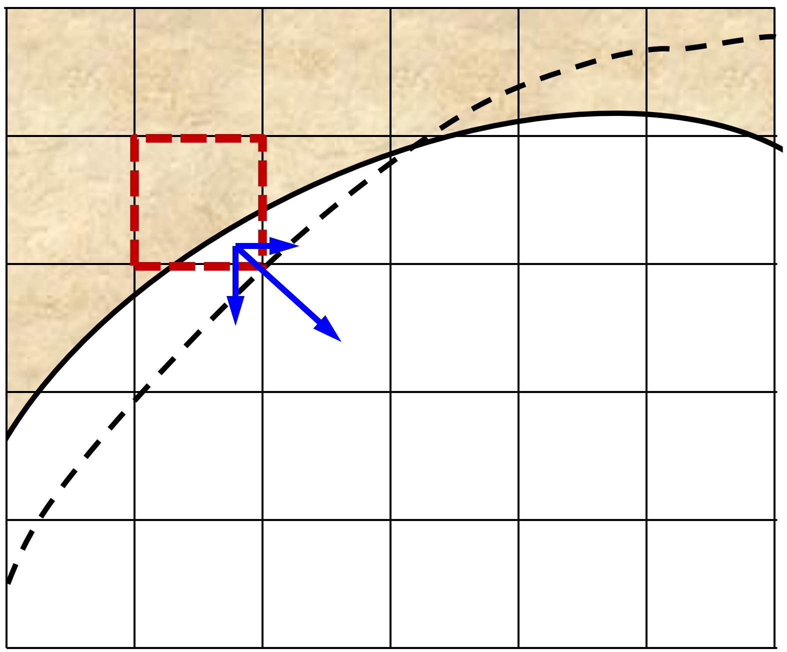
$$+ p(\vec{x} + \vec{e}_{\alpha^*}, t+\Delta t)n'_{\alpha^*}(\vec{x}, t) \quad \leftarrow \text{Downwind bounce-back}$$



Boundary-induced Particle Migration

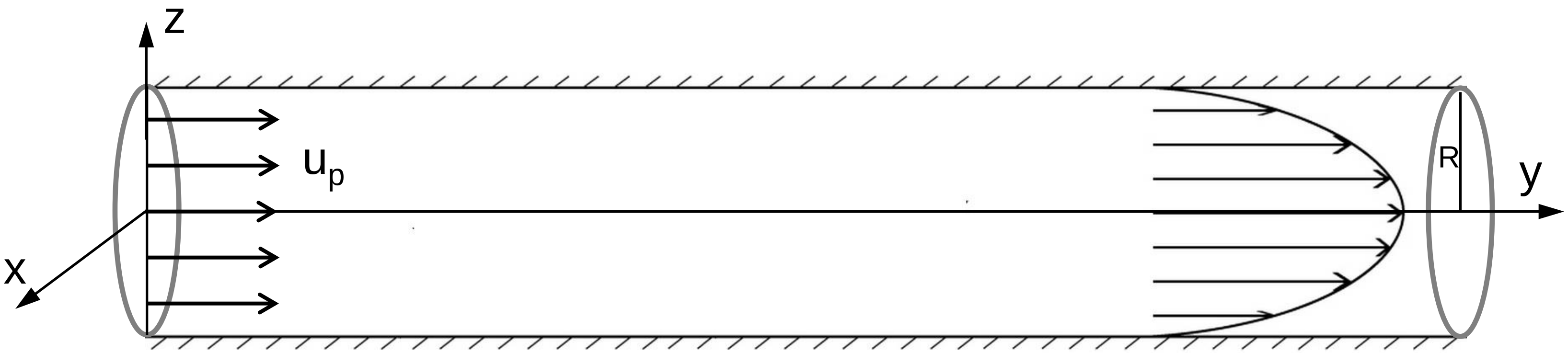
(mass conservation)

$$n_\alpha(\vec{x}, t+\Delta t) = [1 - p(\vec{x}, t+\Delta t)]n''_\alpha(\vec{x}, t+\Delta t) + \sum_{\beta=1}^{b} \tilde{n}_{\alpha,\beta}(\vec{x} - \vec{e}_\alpha \Delta t, t+\Delta t)$$



$$\tilde{n}_{\alpha,\beta}(\vec{x}, t+\Delta t) = p(\vec{x}, t+\Delta t)n''_\alpha(\vec{x}, t+\Delta t)\frac{[1 - p(\vec{x} + \vec{e}_\beta \Delta t, t+\Delta t)]n_\beta(\vec{x}, t)}{\sum_{k=1}^{8}[1 - p(\vec{x} + \vec{e}_k \Delta t, t+\Delta t)]n_k(\vec{x}, t)}$$

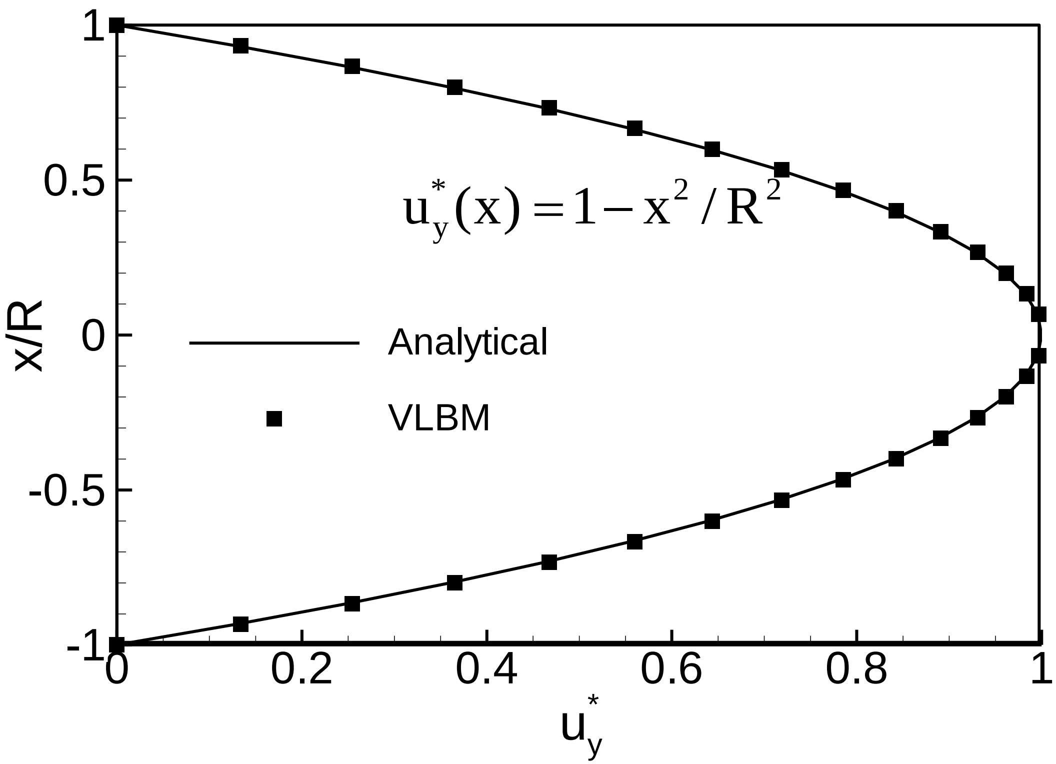
Steady Pipe Flow



$$\frac{\partial^2 u_y}{\partial x^2} + \frac{\partial^2 u_y}{\partial z^2} = -\frac{1}{\mu}\frac{dp}{dy}$$

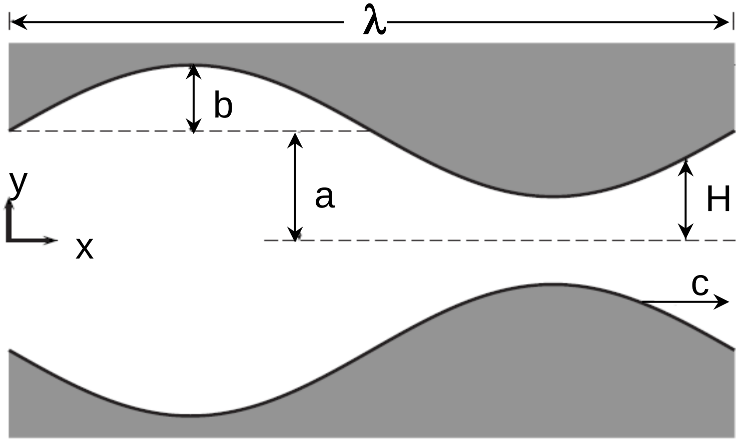
$$u_y(x,z) = 2u_p\left(1 - \frac{x^2 + z^2}{R^2}\right)$$

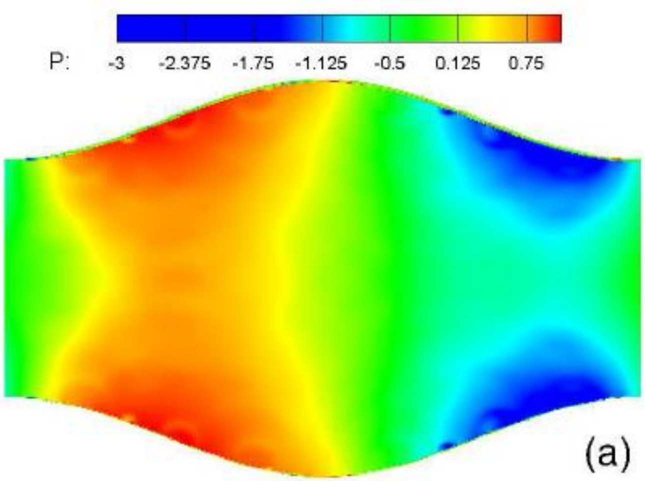
$$u_p = \frac{1}{8R^2}\left(\frac{1}{\mu}\frac{dp}{dy}\right)$$



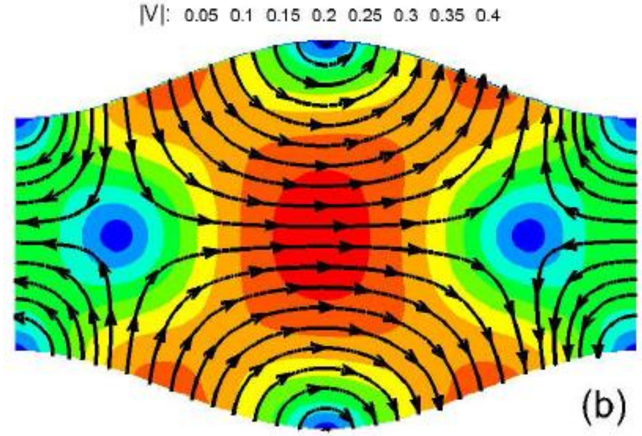
Peristaltic Flow

$$H(x,t) = 1 + \frac{b}{a}\cos\left(\frac{2\pi(x-ct)}{\lambda}\right)$$





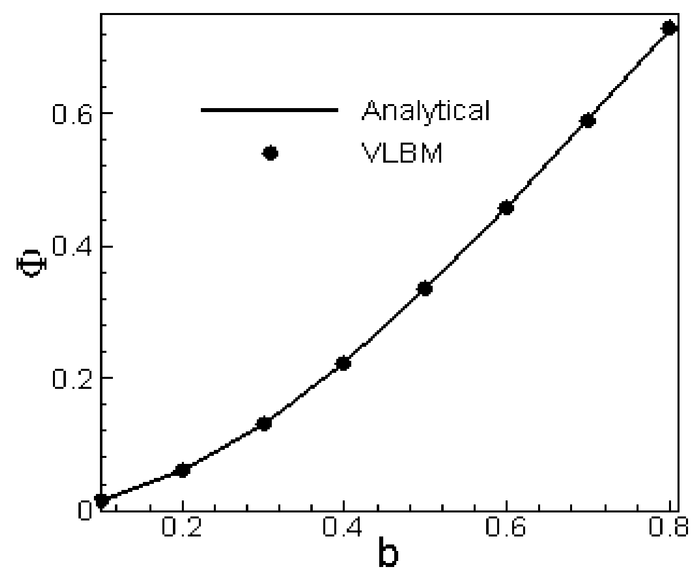
(a)



(b)

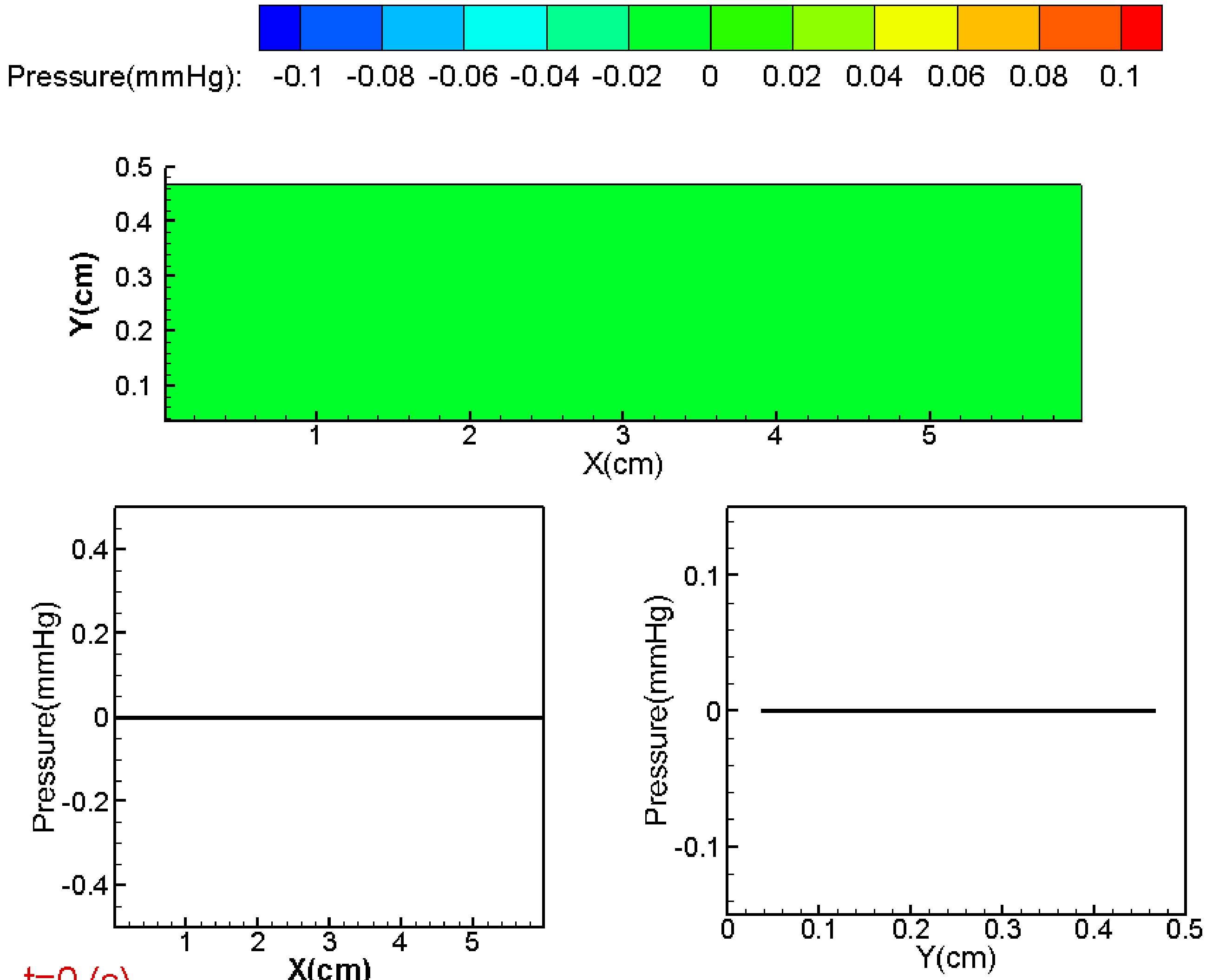
$$\Phi = \frac{Q}{ac} = \frac{3b^2}{2a^2 + b^2}$$

Shapiro, Jaffrin, and Weinberg, JFM 1969
Jaffrin and Shapiro, Annu Rev Fluid Mech 1971



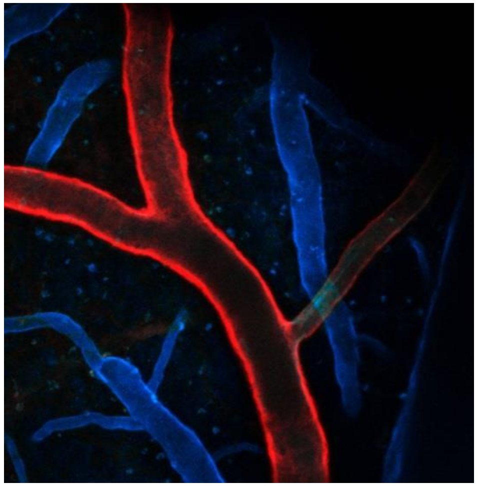
$$\frac{a}{\lambda} = \frac{\pi}{80}, \quad \mathrm{Re} = \frac{2ac}{\nu} = 4$$

Artery Wall Motility



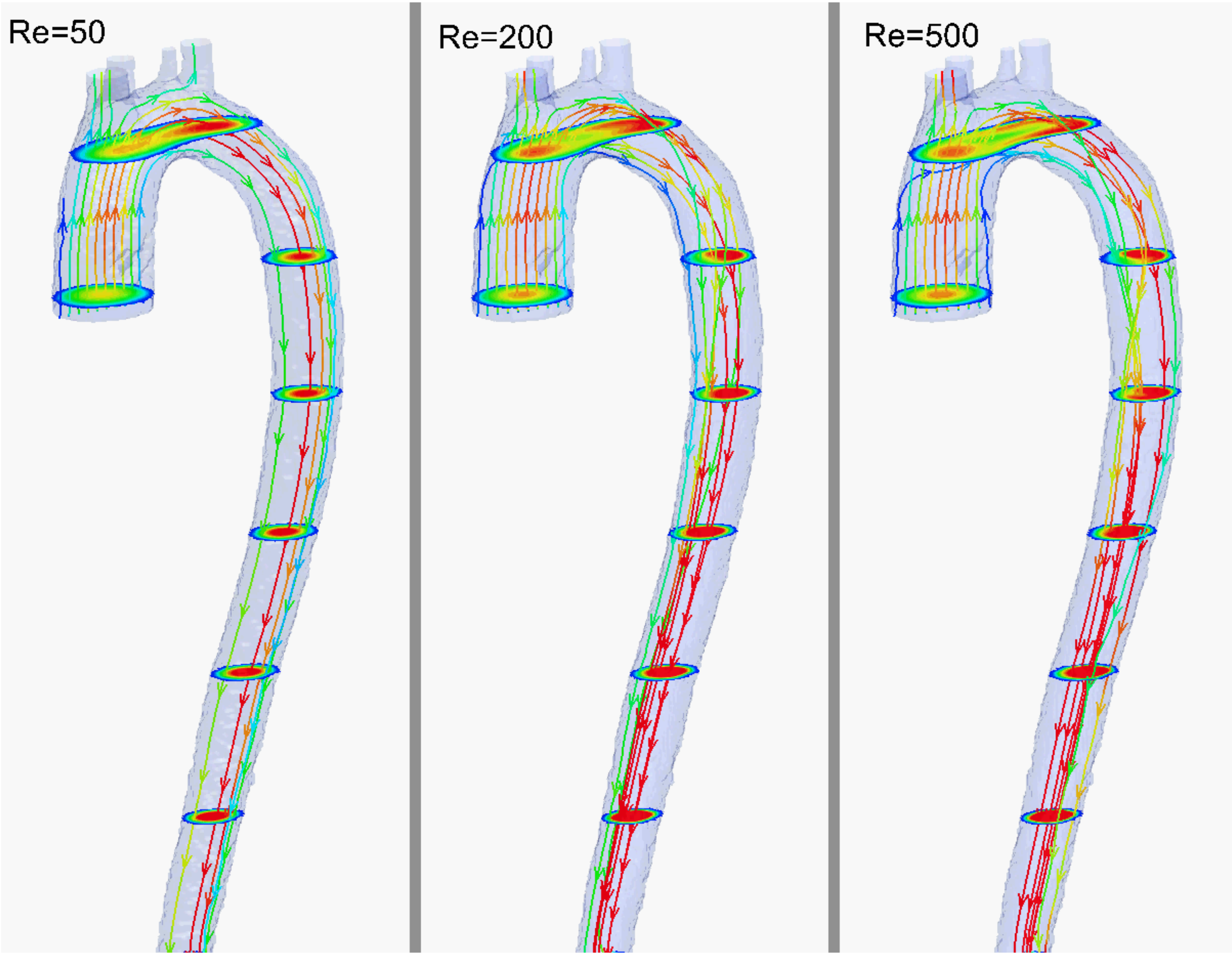
t=0 (s)

Artery walls in the brain

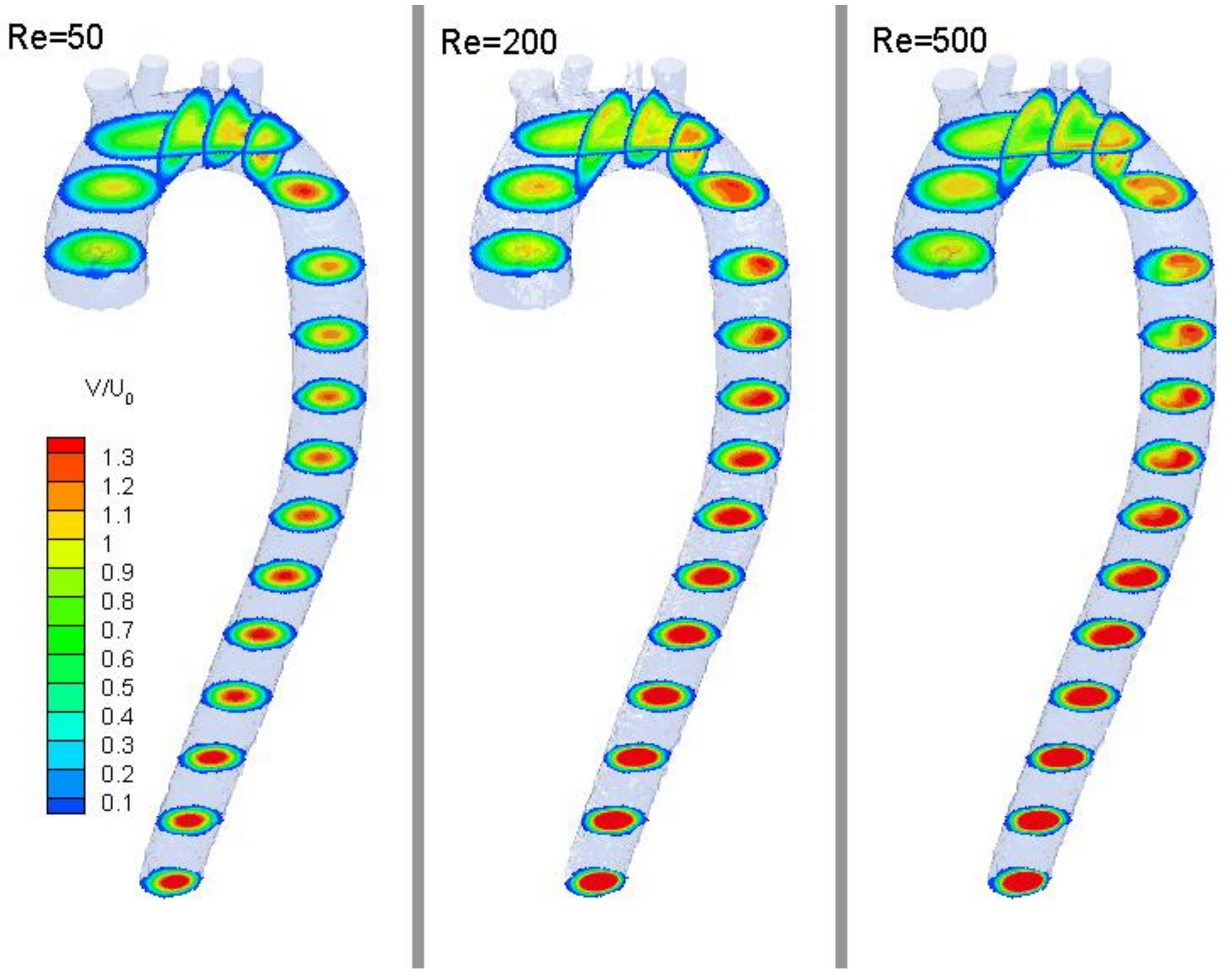


Preliminary Results of Hemodynamics in Healthy and Diseased Aortas

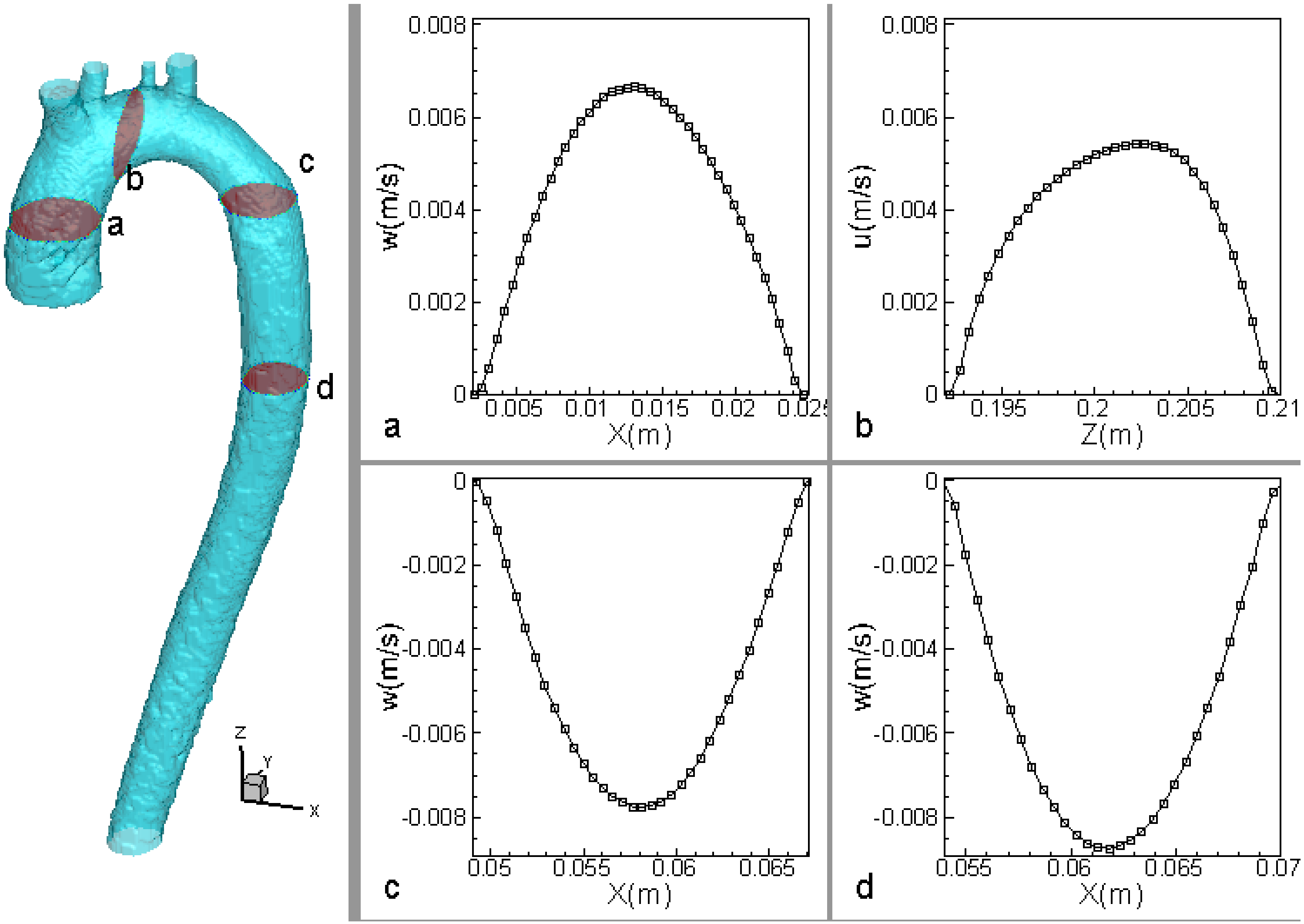
Healthy, Streamlines



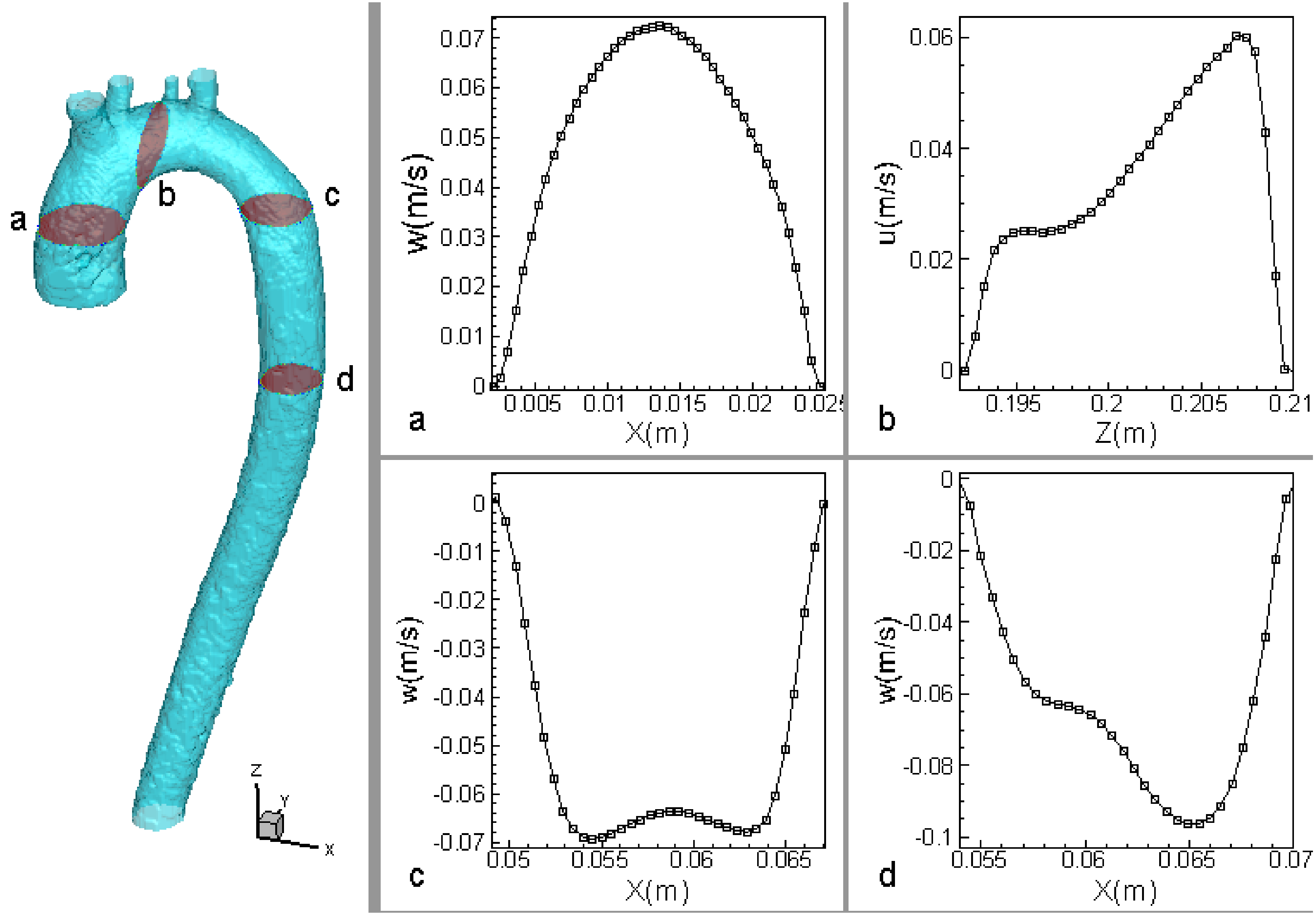
Healthy Velocity



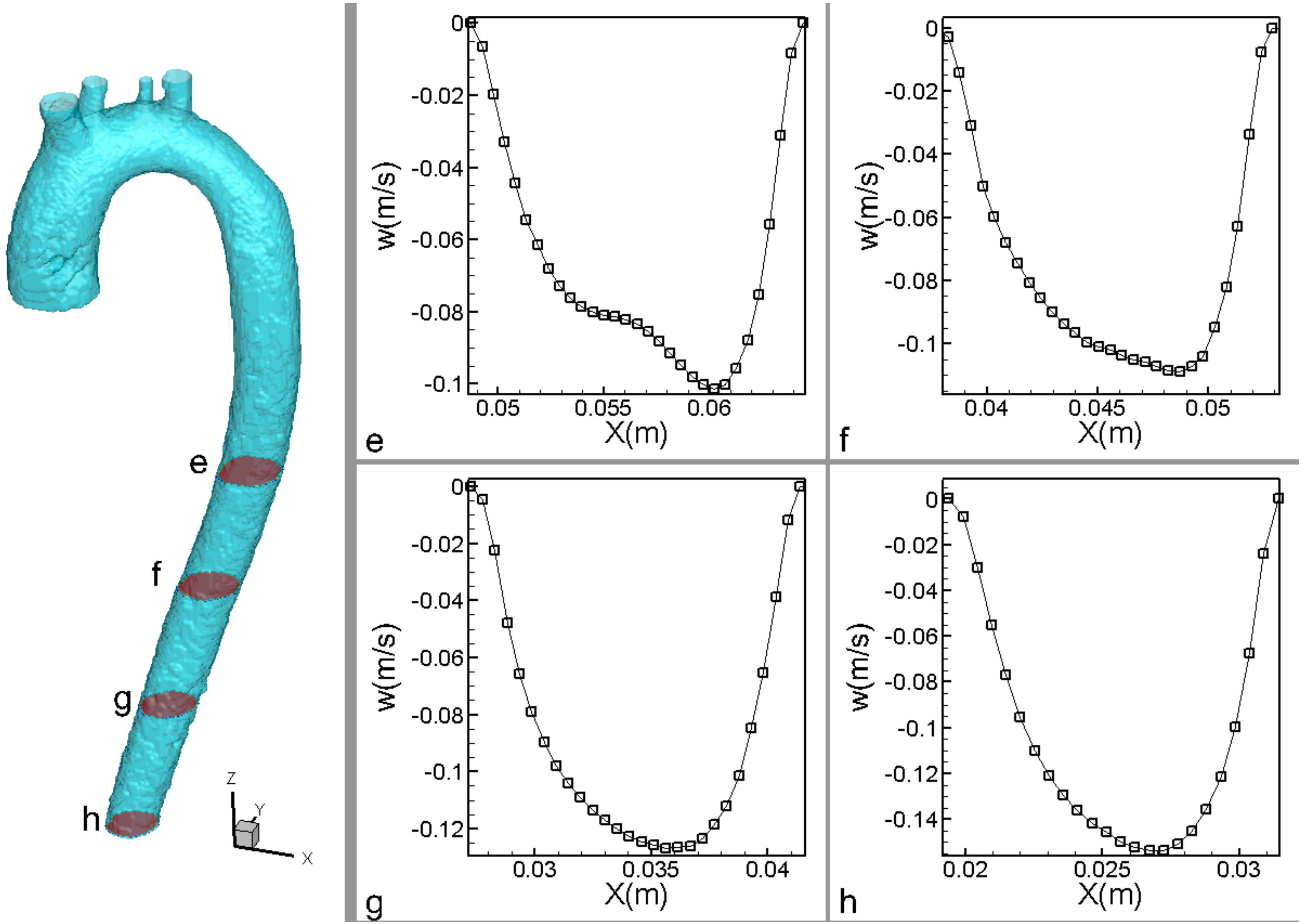
Healthy Velocity , Re=50



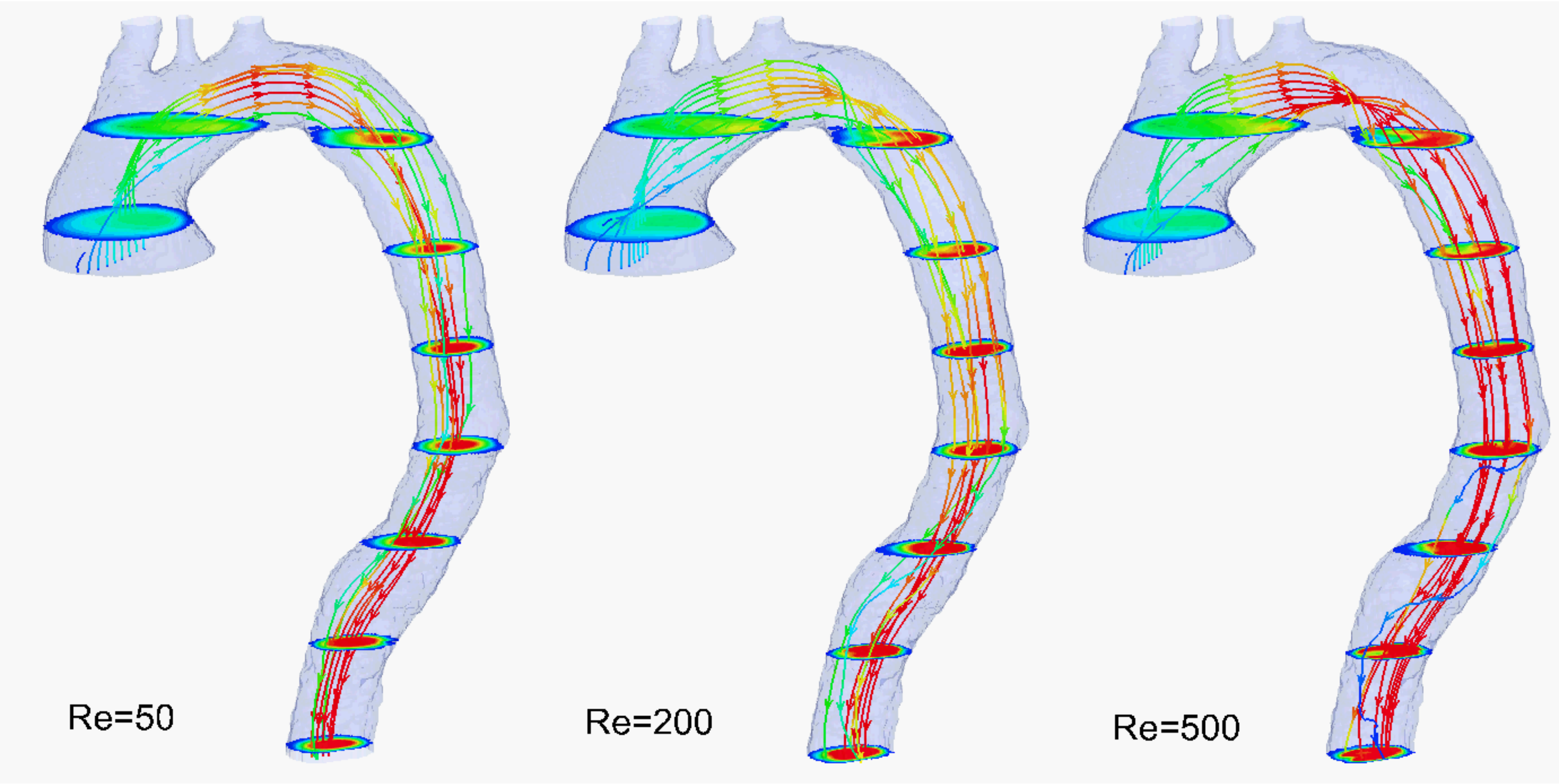
Healthy Velocity, Re=500



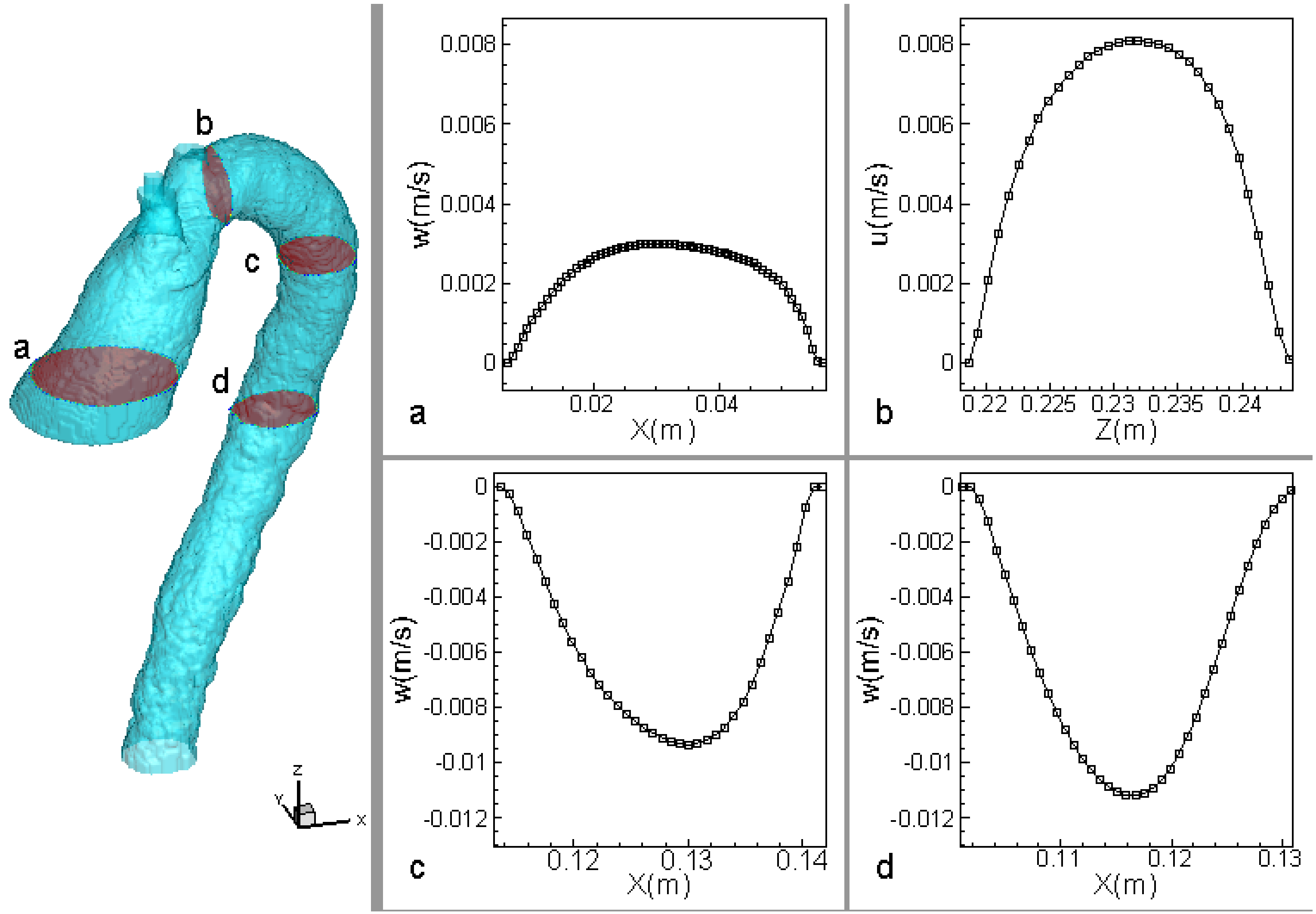
Healthy Velocity, Re=500, cont'd



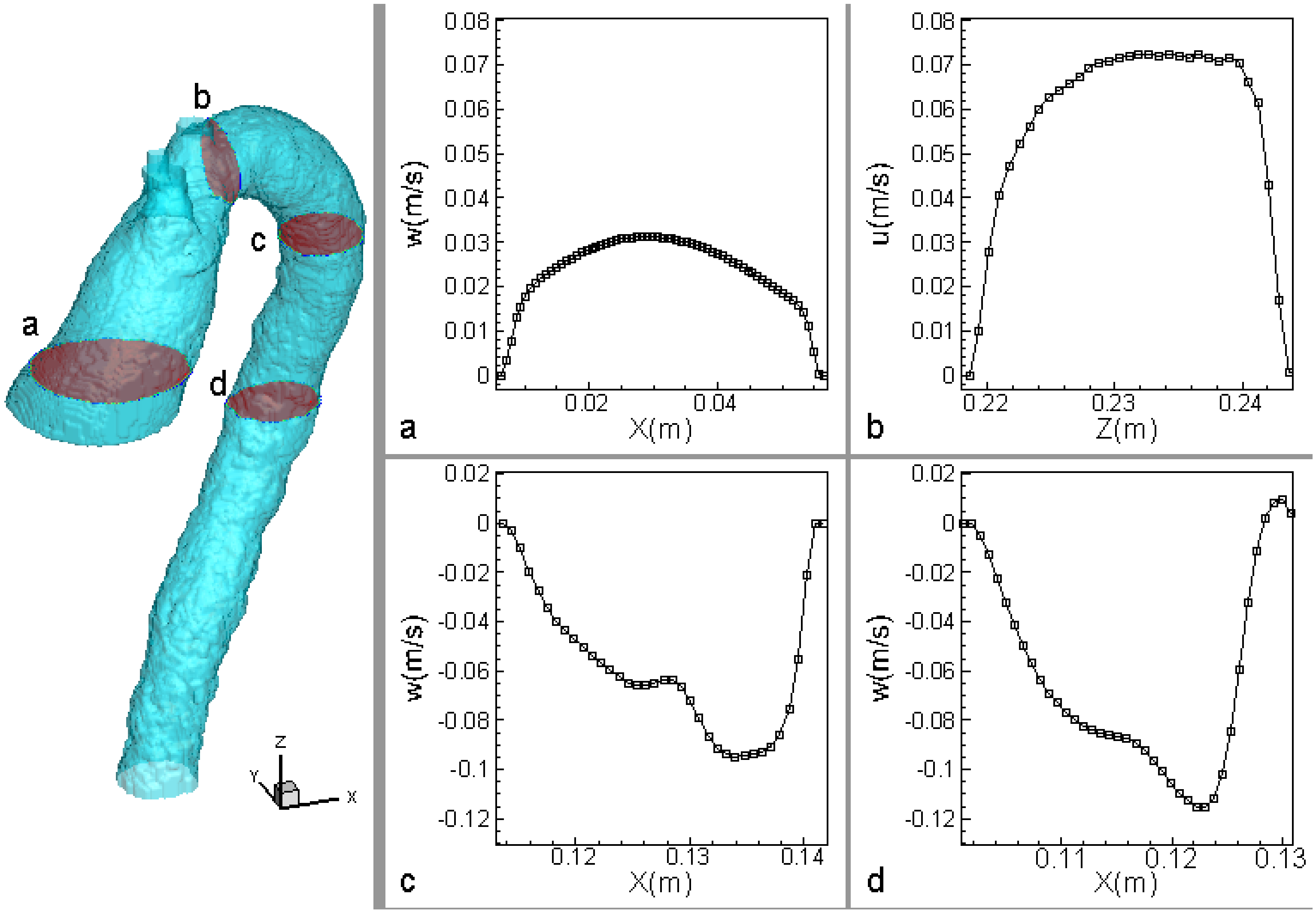
Dilated, Streamlines



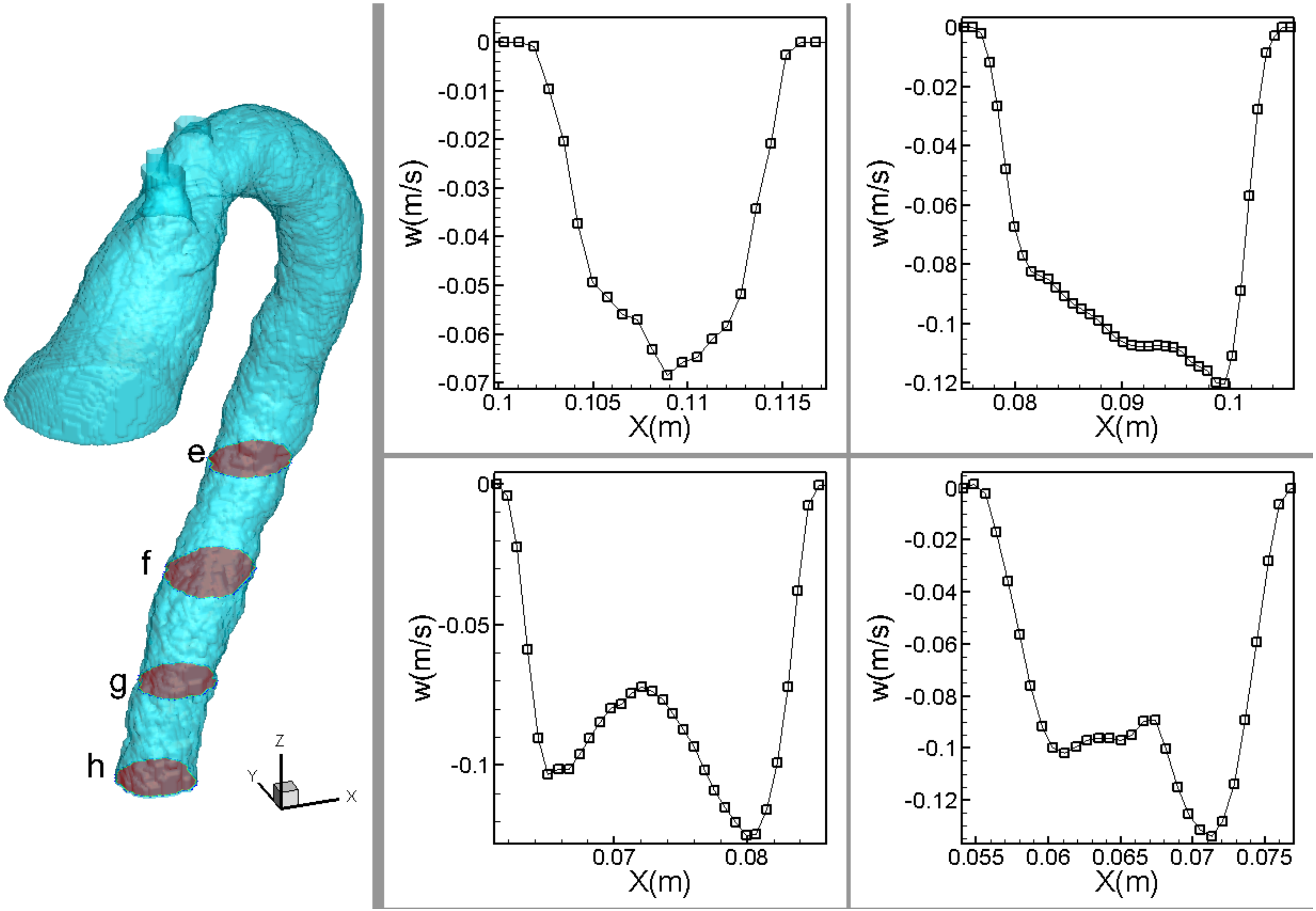
Dilated Velocity, Re=50



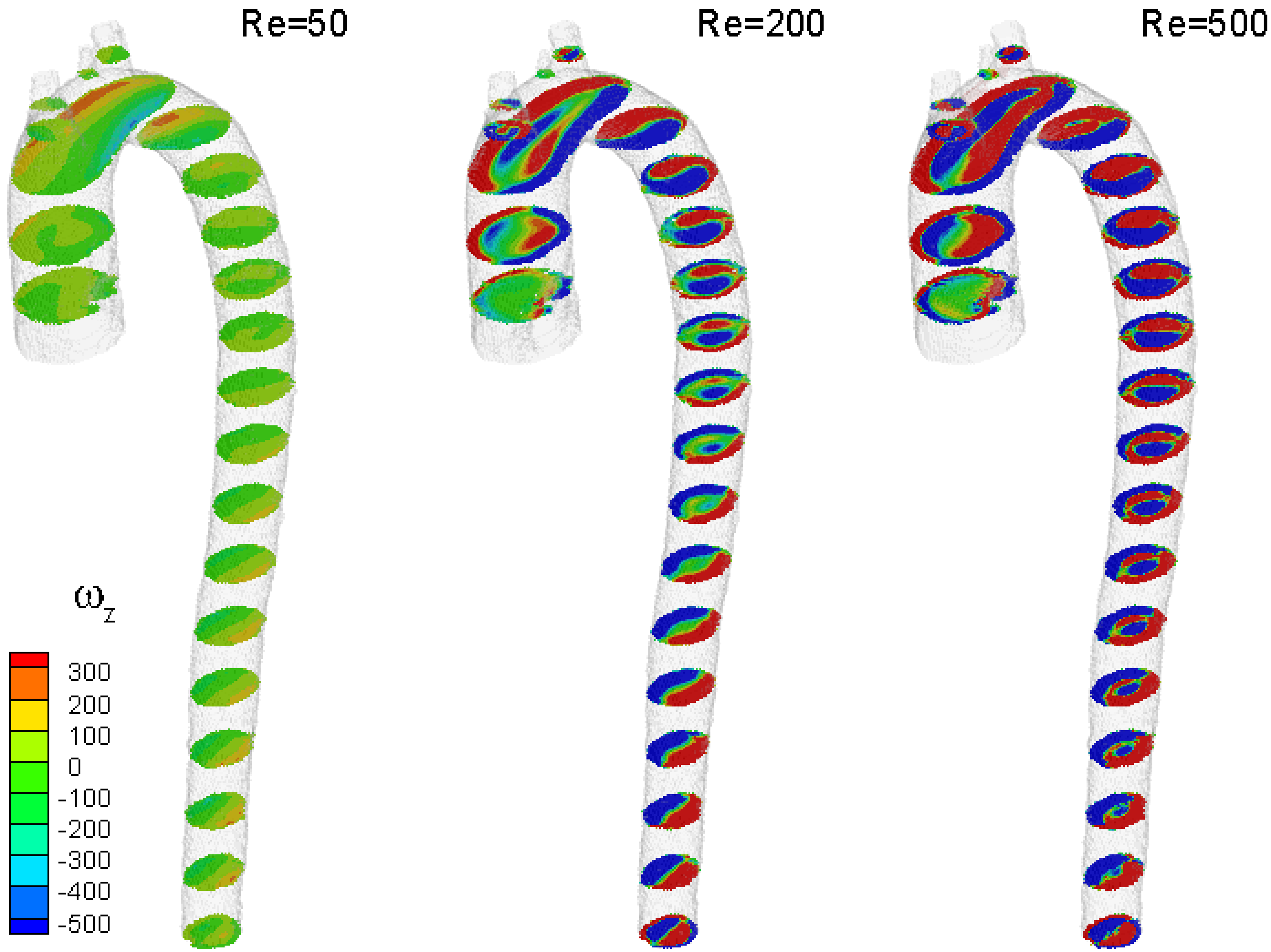
Dilated Velocity, Re=500



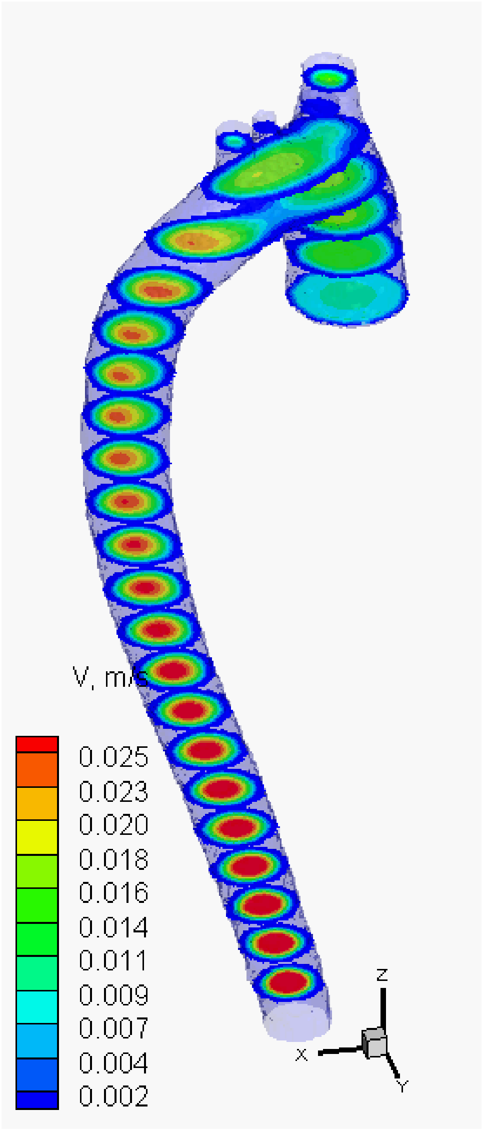
Dilated Velocity, Re=500, cont'd

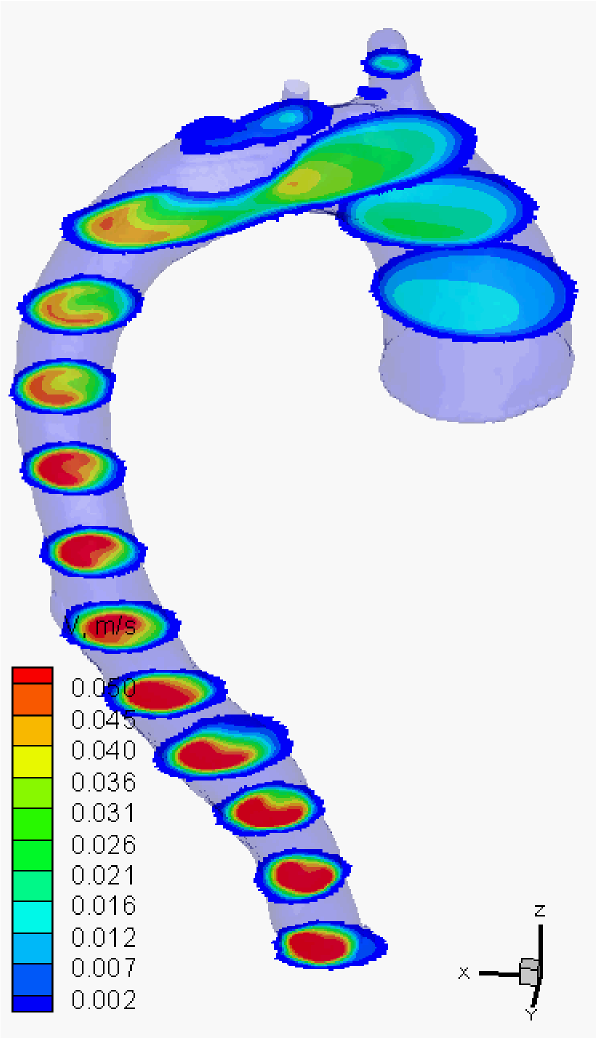


Healthy, Vorticity

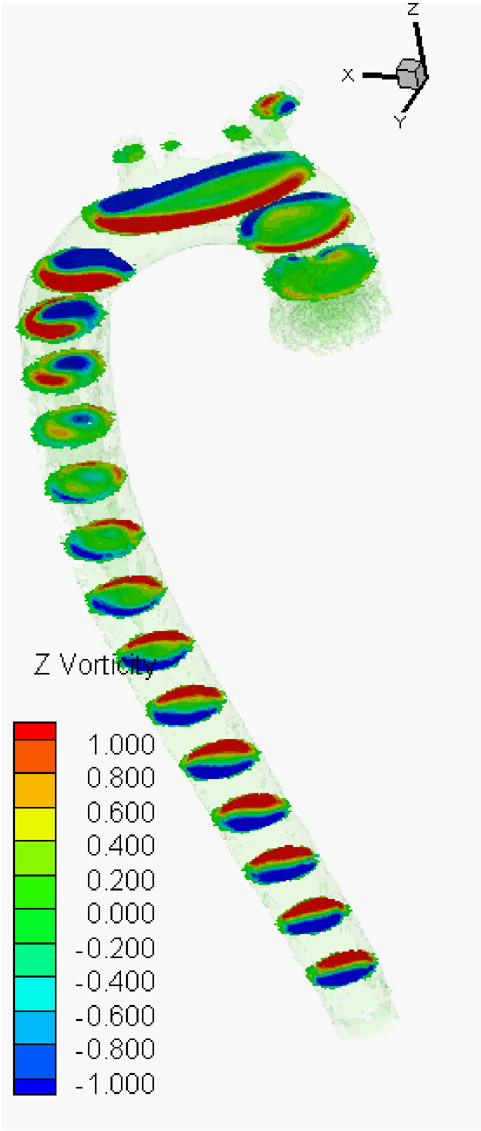


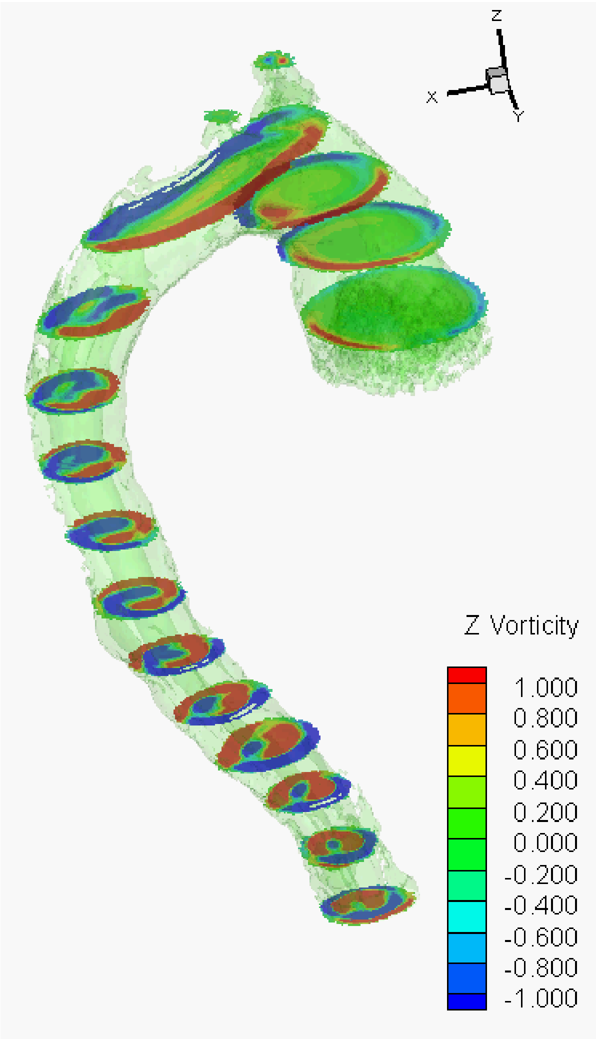
Healthy vs. Dialted, Velocity



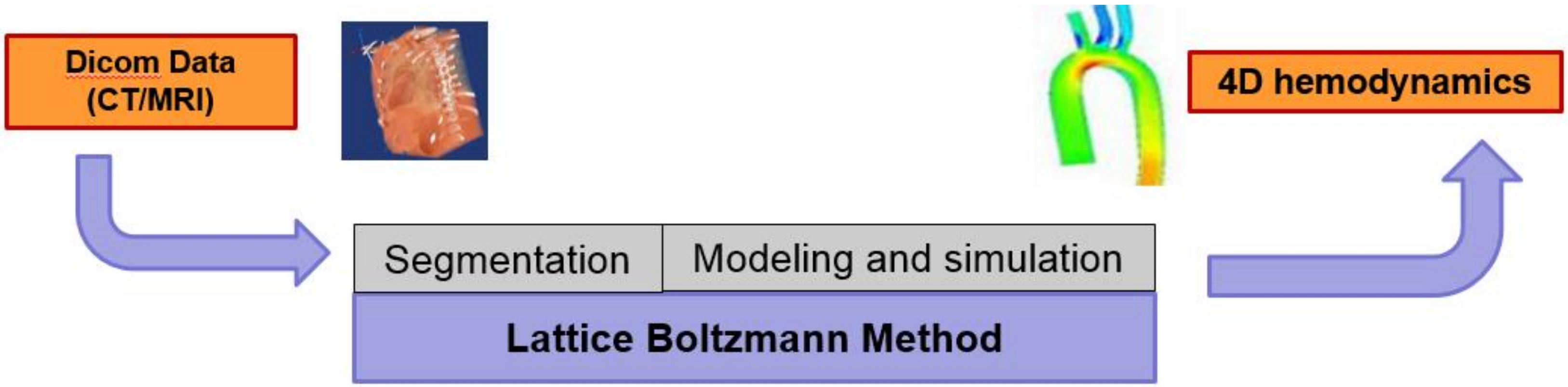


Healthy vs. Dilated Vorticity





Take-Home Messages



Unified computation platform

1. Good for patient-specific flows in human organs

   Cardiovascular blood flow in coronary, aorta, carotid --- heart attack, stroke

   Peristalsis in stomach, esophagus, urine --- cancers

2. Pulsatility --- Laminar, transitional, turbulence
3. Non-Newtonian --- multiphase
4. GPU parallel computation

Medical focus

1. Patient-specific hemodynamics in carotid artery --- Hemodynamic indicators to distinguish symptomatic and asymptomatic carotid stenosis to stroke

2. Supplemental device to CT/MRI to reveal real-time hemodynmaics in diseased human organs.