Understanding Cerebral Aneurysms through HPC-based Computational Modelling

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Severo Ochoa Research Seminar Series
BSC & HPC in Biomedical Research
BSC-CNS Research Departments

Computer Science
Performance tools
Computer architectures
Programming models

Earth Science
Air quality

Life Science
Genomics
Proteomics

Computer Applications in Science and Engineering (CASE)
BSC-CNS is the only supercomputing center with +60 researchers devoted to HPC-based Biomedical Research:

Bioinformatics (45 Life Science Department)

Biomechanics (15 - 20 CASE Department)
Computational Biomechanics
Organ Systems vs. Levels of Organizations
Keywords

Drug action
Drug delivery
Treatment planning
Medical training

Design: prosthesis, stents, valves, bio-materials, experimental and manufacturing kits...
Study surgical procedures and treatments

Targets

Biomedical research: know better and deeper, improve diagnose and treatment
Pharma industry: reduce time and costs of “from-design-to-market” cycle
Medical devices manufacturers: design better devices
Biomechanical Systems

**Medical doctors:**

Healing is the final objective
Diagnose and treatment planning

Understanding biological systems
Physiological models

They provide the main motivation and insight to the problem

**Computational scientists:**

Developing computational tools to run simulations
Provide the required simulation capacity

**Bio-engineers:**

Develop the Physiological models
Deal with medical image processing
Design data acquisition tools

Friday, September 27, 13
Alya Red

HPC-based Biomechanical Simulations
Multi-physics modular code for High Performance Computational Mechanics
Born in 2004

Designed from scratch to solve multiphysics problems with high parallel efficiency

Numerical solution of PDE’s
Variational methods are preferred (FEM, FVM)
Hybrid meshes, non-conforming meshes
Explicit and Implicit formulations
Coupling between multi-physics (loose or strong)
Advanced meshing issues

Parallelization by MPI and OpenMP
Automatic mesh partition using Metis
Portability is a must
Porting to new architectures: MICs, GPUs, ...
Benchmark

Aneurism geometry provided by R. Cebral
Uniform refinement up to 1.6B tetrahedra

Incompressible flow
Implicit formulation
Algebraic Fractional Step: BCGStab + Deflated CG
Alya Red

HPC-based Biomechanical Simulations

Cardiac computational models
Respiratory system
**Cerebral aneurisms rupture risk**
Long skeletal muscles
Biomaterials and tissue engineering
Cerebral Aneurysms

High prevalence
Devastating consequences
Low risk if not treated...
... but treatment carries risk
Incidentally detected

5% have aneurysms but
0.1% will break

50% of the broken cause death
60% of survivors suffer strong impairment
Cerebral Aneurysms

High prevalence
Devastating consequences
Low risk if not treated...
... but treatment carries risk
Incidentally detected

... then, treat or observe?

Observe:
How often?
How to lower risk factors?

Treat:
Surgically or endovascularly?
Which device?
Surgical

Guide of Practice:
Treatment for all larger than 1cm
But most of the broken ones are smaller than 0.7cm!
# Cerebral Aneurysms

## Risk Factors

<table>
<thead>
<tr>
<th>Anatomical factors</th>
<th>Clinical factors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size</td>
<td>Previous SAH</td>
</tr>
<tr>
<td>Irregular shape</td>
<td>Smoking</td>
</tr>
<tr>
<td>Location:</td>
<td>Female gender (2/3 are women)</td>
</tr>
<tr>
<td>Posterior circulation</td>
<td>Hypertension</td>
</tr>
<tr>
<td>Communicating arteries</td>
<td>Co-morbidities</td>
</tr>
<tr>
<td>Circle of Willis</td>
<td>Age</td>
</tr>
</tbody>
</table>

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Cerebral Aneurysms

Risk Factors and Mechanisms


Abnormal flow => wall biology => wall deteriorates

Weakening, expansion and geometry change
Cerebral Aneurysms

Mechano-biology
Wall shear stress (wss) determines endothelial growth

Vessel wall and blood flow
Cerebral Aneurysms

Human Cerebral Artery (basilar) (confocal microscopy)

Wall Structure

Adventitia: collagen fiber bundles

Media: collagen and collagen producing cells

Internal elastic lamina IEL: elastin
Cerebral Aneurysms

Human Cerebral Artery (basilar) (confocal microscopy)

Adventitia: collagen fiber bundles

Media: collagen and collagen producing cells

Internal elastic lamina IEL: elastin

Adventitia: collagen fiber bundles

Media: damaged, stop producing collagen

Internal elastic lamina IEL: disappears in aneurysms
Cerebral Aneurysms

Pathobiologic responses to abnormal behavior

Two different ones:

**High Wall Shear Stress**
- EC damage or weakening
- MPP production by mural cells
- ECM degradation
- Medial thinning
- Mural cell apoptosis

**Low Wall Shear Stress**
- Proinflammatory EC are “leaky”
- Inflammatory cell infiltration
- MPP production by macrophages
- SMC proliferation and migration
- Thrombus formation

Which is the right one?
Image based hemodynamics modeling
Image based hemodynamics modeling
Image based hemodynamics modeling

Validation: CFD vs. PIV

Consistent flow pattern
Validation: CFD vs. PIV
Observations

CFD models can be made patient-specific

CFD models can provide quantitative hemodynamics information

Image-based CFD models are able to realistically represent the in vivo flow conditions
Longitudinal data:
Growing vs. Stable

Cross sectional data:
Ruptured vs. Unruptured
Cerebral Aneurysms

Observations

Growing aneurysms tend to have concentrated inflows that induce complex flows and concentrated wall shear stress distributions with large areas of low WSS.

Aneurysms typically grow towards the dome, but also at the body or neck.

Contacts with peri-aneurysmal environment structures can affect the hemodynamics and aneurysm growth.

Local conditions that cause focalized aneurysm growth still under investigation.
Cerebral Aneurysms

Study design:

Compare rupture site with wall tension

mesh (tetra) → CFD → wall shear stress

mesh (prism) → wall thickness

material properties

wall tension

rupture site

CTA

3D angio

inspection

CFD

CSD

stiffness

material properties

Compare rupture site with wall tension
Cerebral Aneurysms

**CFD + CSM**

CFD provides the WSS (peak, mean, max) and the surface mesh

A 3D solid mesh is created by extrusion, 200 - 500 K prisms

Hyperelastic material, large deformations

Each run takes a few minutes in Marenostrum
Cerebral Aneurysms

Solid Mechanics
Cerebral Aneurysms

Nine patients
Cerebral Aneurysms

Strategy

Module material properties from Wall Shear Stress coming from CFD

Hypothesis:
High WSS weakens the wall => make it thinner
Low WSS weakens the wall => make it thinner

Analyze Rankine damage criteria

See whether its maxima coincides with the rupture sites
Show Movie
Cerebral Aneurysms

- uniform
- thin => high
- thin => high
- thin => low
- thin => low
- thick => low
- thick => high
Cerebral Aneurysms

uniform  thin => high  thin => high  thin => low  thin => low
thick => low  thick => high

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Cerebral Aneurysms

Observations

Thinner walls in regions of **high WSS** best explains 7-8 / 9 sites of aneurysm rupture

Thinner walls in regions of **low WSS** best explains 1-2 / 9 sites of aneurysm rupture

Two possible pathways to rupture?

Other factors?
Conclusions
Conclusions

Computer models are a powerful tool for:

Basic Science: propose and test hypotheses about mechanisms of aneurysm formation, growth and rupture

Risk Assessment: identify conditions that predispose aneurysms for rupture

Device Evaluation: test devices on “virtual patients”

Treatment Planning: identify conditions that promote fast and stable aneurysm occlusion after treatment

Improve material models, including material layers
Cerebral Aneurysms

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