Computational Modeling and Brain Aneurysms

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Outline

- Our research
- How I started to work in this area
- Working with doctors
- Working with companies
Translational Research

“A way of thinking about and conducting scientific research to make the results of research applicable to the population under study” - wikipedia

Objective: translate fundamental or basic research into practical applications and clinical practice
Clinically driven research: close collaboration with Intervntnl. Neuroradiology, Inova Fairfax Hospital (Dr. C.Putman)

Main theme: blood flow and cerebral aneurysms

Focus areas:
1) Understanding basic mechanisms responsible for the formation, progression and rupture of aneurysms
2) Identifying key factors to improve risk assessment
3) Understanding the effects of different treatment strategies and devices for treatment planning
4) Analysis of performance of different devices

Approach: image-based CFD modeling to connect hemodynamics (simulation) information to clinical data
Research Area: Brain Aneurysms

- Local dilatation of the cerebral arteries
- Tend to be silent until rupture
- Advances in neuroimaging result in more incidental aneurysms being detected
- Treatment still carries a significant risk
- If unruptured aneurysms should be treated has been debated for over a decade
- Need to identify aneurysms at risk of growth and rupture
Risk Assessment

- Aneurysmal anatomical information, patient's age and clinical status provide some help in predicting natural history of brain aneurysms

- Currently, the size (and aspect ratio) of aneurysms is the only reliable anatomical risk factor

- But aneurysms below the identified size threshold still account for a majority of aneurysmal ruptures

- So, this anatomical information is not sufficient to identify those cases at a higher risk

- Hemodynamics is thought to play a fundamental role in the mechanisms governing aneurysm growth and rupture, so adding hemodynamics information can help improve prognostication
Combine clinical, imaging and simulation data to test hypotheses about mechanisms of aneurysm evolution and to answer specific clinical questions.
Methodology: Image-Based CFD

\[ \rho v_t + \rho \nabla \cdot v + \nabla p = \nabla \cdot (\mu \nabla v) \]

\[ \nabla \cdot v = 0 \]

Study: Hemodynamics & Rupture
Qualitative Characterization – Flow Pattern: Simple & Complex
Qualitative Characterization –
Flow Stability: Stable & Unstable
Qualitative Characterization – Impingement Size: Large & Small
Qualitative Characterization – Inflow Stream: Diffuse & Concentrated
Qualitative Characterization – Associations with Rupture

Case Study 1: Aneurysm before its Rupture

Concentrated inflow + complex flow $\Rightarrow$ aneurysm ruptured

Case Study 2: Aneurysm Before Rupture

- Concentrated inflow
- Small impaction
- Complex flow
- Asymmetric flow division

Quantitative Hemodynamic Characterization

neck delineation

aneurysm removal

neck triangulation

model subdivision

variable quantification

Max WSS
Inflow concentration
Shear concentration
Low shear area
Viscous dissipation
Kinetic energy

Hemodynamic Measures

- Maximum wall shear stress
- Inflow concentration index
- Shear concentration index
- Low shear area
- Low shear index
- Kinetic energy ratio
- Viscous dissipation ratio

\[ MWSS = \max_{A_a} (|\tau|) \]
\[ ICI = \frac{Q_i / Q_v}{A_i / A_n} \]
\[ SCI = \frac{F_h / F_a}{A_h / A_a} \]
\[ LSA = \frac{A_l}{A_a} \]
\[ LSI = \frac{F_l \cdot A_l}{F_a \cdot A_a} \]
\[ F_h = \int_{A_h} |\tau| \, dA, \quad F_a = \int_{A_a} |\tau| \, dA \]
\[ VDR = \frac{\int_{\Omega_a} 2\mu / \rho (e_{ij} e_{ij}) \, d\Omega / V_a}{\int_{\Omega_{nv}} 2\mu / \rho (e_{ij} e_{ij}) \, d\Omega / V_{nv}} \]
\[ KER = \frac{\int_{\Omega_a} 1/2 \rho u^2 \, d\Omega / V_a}{\int_{\Omega_{nv}} 1/2 \rho u^2 \, d\Omega / V_{nv}} \]
Treatment of Intracranial Aneurysms

- Clipping
- Coiling
- Balloon & stent assisted coiling
- Flow Diversion stenting alone
Difficulties

• Large and giant aneurysms have high rates of coil recompaaction and recannalization
• Many wide neck / segmental aneurysms are very difficult or impossible to treat with clips or coils alone
• Flow diverters offer an option for these otherwise untreatable aneurysms
Issues

- Self-expanding stents are typically oversized to achieve good wall apposition

- When deployed, these stents tend to recover their reference configuration

- Final pore size and shape depends on artery and stent diameters and manner of deployment

- **Question**: for a given stent design, how does its hemodynamic performance change with oversizing?
Methods: Image-Based Modeling

Stent Deployment Methodology

Stent Design Mapping

Reference stent design

Foreshortening due to oversizing

Map to cylindrical surface
Study: Effects of stent oversizing

Case 1

Case 2

Case 3
Case 1: Giant ICA aneurysm

Pre                  3.5mm                    4mm                  4.5mm

ΔQ≈33% ∆Q≈10% ∆Q≈7%
Case 2: Large ICA cavernous aneurysm

Pre  4.5mm  5mm  5.5mm

ΔQ≈16%  ΔQ≈9%  ΔQ≈8%
Case 3: ICA sup. hypophys. aneurysm

<table>
<thead>
<tr>
<th>Pre</th>
<th>3.5mm</th>
<th>4mm</th>
<th>4.5mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>∆Q≈86%</td>
<td>∆Q≈67%</td>
<td>∆Q≈61%</td>
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Study: Comparing Stent Designs
Iso-Velocity Surfaces

Pre-Stenting  Silk  Enterprise

inflow inflow blocking inflow disruption
Study: Effects on Side Branches
Flow Reduction

\[ \Delta p = Q \cdot R \]

\[ R = \frac{8 \mu L}{\pi a^4} \]
Integration of CFD in clinical practice
Clinical Application

Image-based CFD modeling has become a mature technology
But… its clinical application will depend on:

• Strong statistical results demonstrating clinical relevance
• Validation, reproducibility and sensitivity studies
• Acceptance of technology by clinical community
• Commercial advantage perceived by medical companies
Personal History

How did I get involved in this research?
Studies

Joined PhD in computational sciences
• Interest in multi-disciplinary program
• Interest in methods for computational modeling

Finished PhD in computational mechanics (development of algorithms for fluid-structure interaction)

Now what?
Methods or Applications?

- Traditional work in numerical methods / computational mechanics consists in development of methods
- Area quite mature & many commercial tools available
- Alternative: application driven development
- Objective: contribute in an application area (develop what is needed to advance this area)
- Multi-disciplinary applications less developed (and more exciting…)
- Modeling of natural phenomena require data assimilation (some information is always missing…)
- Funds typically go to applications…

→ applications it is…
What Application?

Typical CFD application areas:
• Military (planes, missiles, explosions, unmanned vehicles, submarines, torpedoes, propellers, …)
• Civil (bridges, cars, planes, turbines, windmills, …)
• Natural phenomena (weather, space sciences, biological systems, medicine, …)

World Congress in Computational Mechanics
• Lecture on computational modeling of blood flows
“That’s what I want to do…”

Reasons:
- Highly multi-disciplinary (image-processing, computational geometry, numerical methods, high performance computing, computer graphics and visualization, anatomy & physiology, neuroradiology, …)
- Can help improve medical practice and patient care

Objective: contribute in the field of medicine

Metric: publish in medical journals

Now what?
Preliminary Work

Developed tools for patient-specific modeling
Reproduced results published in the literature
Identified a few possible specific applications
Started to visit doctors from local hospitals and give talks
  • Georgetown University Hospital
  • George Washington University Hospital
  • Walter Reed Medical Center
  • NIH – National Library of Medicine

Then one day…
Things Start to Move

- Made contact with Neurosurgeon from Inova Fairfax Hospital
- He immediately understood what we could do and put us in contact with the right people (Neuroradiology)
- To start we defined a project on carotid artery disease (“will go further up to the brain later”…) and got funding from the Whitaker Foundation
- Then, Interventional Neuroradiology got a new director … another visit…
- Once he showed him what we could do, he got very excited and started formulating questions, hypotheses, possible projects, …
Now We Need Data

How to get the imaging data from the scanner?
Contacted imaging company

They started to ask questions:
• Why do you want that data?
• What are you doing with it?

…and got interested… and suggested aneurysms…

So aneurysms it is…
Aneurysms…

- Started publishing in medical journals
- Started new collaborations
- Got funds from Philips, AHA, NIH (NINDS), Boston Scientific
- Funds allowed us to form a (small) research group
- Became insider / outsider of different communities: medical imaging, computational mechanics, biomedical engineering, neuroradiology, …
- Learnt to “speak many languages”
- Field has tremendously expanded and many groups are now working in this area
Working with Clinicians

- Clinicians know the relevant problems and ask the right questions (most of the time…)
- Clinicians have patient data (or they think they have it…)
- Clinicians have little time for research and usually are not compensated for doing research (but research gives them recognition and prestige…)
- Clinicians need to understand the capabilities and limitations of the technologies used in research
- Clinicians need to help keep the research focused and clinically relevant
Working with Clinicians

- Most MDs are “nice” and “can give you all the data you want”, but that’s not enough…
- Finding the right collaborator is difficult, but not impossible…
- Speaking their language helps tremendously ("doctors need to give me the boundary conditions…")
- Identifying MDs that “can make things happen” can tremendously help making the right connections

- Working with clinicians is very rewarding since it means that the research is contributing to the clinical practice and patient care
Working with Medical Companies

- Companies have a commercial purpose
- Companies keep the research very practical and focused
- Companies want quick turn-around
- Companies will want confidentiality (but research could be published as “generic” studies)
- Companies may want exclusivity
- Companies may restrict publication (but research results are usually good for them…)
- Need to negotiate IP if project will likely produce inventions
- Companies have little restrictions on how funds are used (but typically they do not provide large amounts…)
Working with Companies

- Companies can suddenly shift their focus or interest
- Company decisions are not based only on science (marketing, costs, economy, engineering, …)
- Contacts within companies change quite rapidly

- Being involved in industry-sponsored research is quite exciting since it typically means that the research is producing something useful to the community