Aneurysm Rupture Evaluation: Contributions of CFD

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Intracranial Aneurysms: The Problem

- High prevalence (3-8% of the population)
- Incidental aneurysms increasingly detected
- Rupture Risk (~0.1-3%) < Intervention Risk (10-14%)
- Many aneurysms preventively treated due to devastating consequences of SAH

⇒ **Need**: reliable risk assessment to recommend treatment or conservative observation (beyond size)

⇒ **Requires**: understanding the mechanisms of aneurysm pathogenesis and rupture

⇒ **Challenge**: define appropriate end points for clinical investigations and gather corresponding data
Mechanisms of Aneurysm Evolution

- rupture
- abnormal hemodynamics
- endothelial dysfunction
- lipid accumulation
- inflammation
- thrombus formation
- loss of mural cells
- degradation of collagen structure
- change of mechanical properties
- aneurysm enlargement

- rupture
Image-Based CFD Modeling

imaging → geometry modeling → meshing → flow visualization

flow conditions

mathematical model

\[ \rho \frac{\partial \mathbf{v}}{\partial t} + \rho \mathbf{v} \cdot \nabla \mathbf{v} + \nabla p = \nabla \mu \nabla \mathbf{v} \]

\[ \nabla \cdot \mathbf{v} = 0 \]

Aneurysm Flow Characteristics

Inflow jet

WSS

Flow structure
Example Inflow Jets

Strong Inflows

Weak Inflows
Flow Patterns
Flow Structures
Wall Shear Stress Distributions
Hemodynamic Characterization

Inflow Jet:
• Inflow rate
• Inflow concentration

Flow Pattern:
• Velocity
• Kinetic energy
• Viscous dissipation
• Vorticity
• Shear rate

Flow Structure:
• Vortex core-line length
• POD entropy

WSS Distribution:
• Mean, Max, Min
• Area under low WSS
• WSS concentration
• Oscillatory shear index
Aneurysm Database

~2000 aneurysms: clinical info + 3DRA images
>1400 aneurysm CFD models
Contributions: Inova, Mt. Sinai, Medellin, UCLA
Ruptured vs Unruptured: Cross Sectional Data

N=210

Size AR MWSS ICI SCI VDR KER LSA LSI
* * * * *
Growing vs Stable: Longitudinal Data

N=33

[Bar chart with comparison between Growing/Stable and Ruptured/Unruptured categories for various metrics like ICI, KER, SRR, VER, VOR, VDR, WSSMAX, WSSMIN, WSS, SCI, LSI, OSI, CORELEN. Notations include * and † for significance.]
Posterior vs Anterior Circ.: BAtip vs ICA bif

BAtip and ICA bif aneurysms have different rupture rates. Can hemodynamics explain this difference?
Results

Higher flow conditions & more complex flows in R aneurysms

Higher flow conditions in BAtip aneurysms
Results

Hemodynamic differences between BAtip and ICA bif aneurysms more important in small and medium size aneurysms
Examples: BAtip

Ruptured

WSS  inflow jet  flow pattern  vortex cores

Unruptured
Examples: ICA bifurcation

Ruptured

WSS

inflow jet

flow pattern

vortex cores

Unruptured
Flow & Wall Inflammation & Degeneration: Histology Data

Surgical Clipping

Tissue Harvest

Immunohistochemistry

3D Imaging

Pulsatile Flow

CFD Modeling

GMU

Wall Structure

Compare

Flow Dynamics (WSS)

n=20

Helsinki

CD45

Neg

CD31

Thrombus

GMU

Flow & Wall Inflammation & Degeneration: Histology Data
Results: Inflammation

Inflammation Associated w Rupture

Inflammation Associated w Abnormal WSS

Inflammation Associated w Endothelium Damage

Inflammation Associated w Organized Thrombus
Results: Flow Conditions

High Flow Associated w Inflammation

- WSS
- Vorticidy
- Dissipation
- Shear rate

High Flow Associated w Endothelium Damage

- Vorticidy
- Dissipation
- Shear rate

Low Min WSS Associated w Organized Thrombus

- WSSmin

Intact vs Damaged

No Organized Thrombus vs Organized Thrombus
Examples

High Inflammation

CD45          WSS          inflow jet          flow pattern          vortex centers

brown=leukocytes
blue=cell nuclei

No Inflammation
Flow and Wall Structure & Mechanics: Tissue Data

Surgical Clipping

Tissue Harvest

Mechanical Testing

AGH / Helsinki

Multic-Photon Microscopy

UPitt

3D Imaging

Wall Properties

Compare

Collagen & Cells

Compare

Flow Dynamics

UPitt

n=9

CFD Modeling

GMU
Mechanical Behavior of Unruptured Aneurysms

The graph depicts the Cauchy stress (MPa) vs. stretch for unruptured and control arteries. The unruptured arteries are categorized as strong and vulnerable. The graph shows different lines representing various arterial segments, each identified by a label (e.g., CA-1, CA-11, etc.). The control arteries are shown on the right side of the graph.
Flow & Ultimate Strain (Strength)

- Inflow rate
- Mean velocity
- Mean WSS
Example 2

inflow

flow pattern

luminal side

vortex cores

WSS

abluminal side

0-120 μm

120-200 μm
Conclusions

• There is a connection between intra-aneurysmal flow characteristics and aneurysm growth and rupture

• Inflamed walls seem to be associated with higher levels of wall shear stress (& high flow conditions in general)

• There seem to be two sub-populations of unruptured IAs: one with vulnerable walls, another with stronger walls

• High flow conditions seem also to be associated with weaker and stiffer aneurysm walls

• Hemodynamics could potentially be used to identify aneurysms with weaker walls, at risk of growth and of developing inflammation and undergo rupture
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