Numerical models of cerebral aneurysm biomechanics

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Gabriele Dubini, Francesco Migliavacca
ANEURISK project aim: to evaluate aneurysm rupture risk
Realistic geometries: ANEURISK database

Different locations and geometries

Internal Carotid Artery
Anterior Communicating Artery
Basilar Artery
Middle Cerebral Artery
Aim of the study

ANEURISK project aim: to evaluate aneurysm rupture risk
Realistic geometries: ANEURISK database

Internal Carotid Artery

Internal Carotid Artery: U bend

✓ Rupture risk?
✓ Formation site?

Collection of longitudinal patient-based information
Aim of the study

ANEURISK project aim: to evaluate aneurysm rupture risk
Realistic geometries: ANEURISK database

Internal Carotid Artery

Internal Carotid Artery: U bend

✓ Rupture risk ?
✓ Formation site ?

Adopted approach: investigation on aneurysm initiation
Aim of the study

The project aim
✓ The investigation of the phenomena linked to aneurysms development from a biomechanical point of view.
✓ To achieve this target, the research has to be developed in different topics: structural aspects, adaptive phenomena and fluid dynamics

The specific goal
✓ Development of theoretical models and implementation of numerical tools able to simulate the aneurysm initiation and early development: from healthy vessel to bulge formation

The path
✓ To implement a constitutive model for cerebral vascular wall
✓ To develop an adaptive law to mimic the development of aneurysm
✓ To couple structural features with fluid dynamics boundary conditions
Biomechanical models of cerebral aneurysms: constitutive, adaptive and fluid dynamic approaches

Structural studies: elastic behavior
- Kyriacou and Humphrey (1996); Ryan and Humphrey (1999); Humphrey and Canham (2000): non linear incompressible isotropic strain energy function on a membrane (cerebral aneurysms)

Structural studies: adaptive behavior
- Watton et al. (2004): strain-based micro structural recruitment model
- Baek et al. (2005; 2006): stress-mediated matrix turnover on fusiform and saccular aneurysms
- Kroon and Holzapfel (2007): stress-mediated matrix turnover on saccular aneurysms

CFD studies

already developed aneurysms

Very few studies on the aneurysm initiation
Biomechanical models of cerebral aneurysms: constitutive, adaptive and fluid dynamic approaches

Structural studies: elastic behavior
- Wuyts et al. (1995), Humphrey and Rajagopal (2002), Zulliger et al. (2004), Holzapfel et al. (2005), Gasser and Holzapfel (2006): non linear incompressible anisotropic material with matrix and fibers (healthy vessels)
- Kyriacou and Humphery (1996); Ryan and Humphrey (1999); Humphrey and Canham (2000): non linear incompressible isotropic strain energy function on a membrane (cerebral aneurysms)

Structural studies: adaptive behavior
- Watton et al. (2004): strain-based micro structural recruitment model
- Baek et al. (2005; 2006): stress-mediated matrix turnover on fusiform and saccular aneurysms
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CFD studies

Aneurysms initiation studies
- Wulandana and Robertson (2005): inelastic behaviour (not fluid dynamics and adaptive behaviours)
- Feng et al. (2006), Chatziprodromou et al. (2006): fluid-structure approach (simple elastic behaviour and not adaptive behaviour)

Work Novelty: Numerical model that couple passive, adaptive and fluid dynamics features of cerebral vascular wall on aneurysms genesis
**The anisotropic constituent-based computational model for cerebral vascular wall**

**Mechanical properties of cerebral vessels**

Cerebral vessel wall behaviour:
- **Anisotropy** (Finlay and Canham 1998; Monson et al, 2006)
- **Large Deformations** (Fung, 1983; Holzapfel et al, 2005)
- **Incompressibility constraint** (Holzapfel et al, 2003, 2005)

**Constitutive relationship**

\[ S_{ij} = \frac{\partial W}{\partial E_{ij}} \]

**Incompressibility constraint**

\[ W = W_{vol}(J) + W_{iso}(I_1, I_2, I_4) \]

**Anisotropy**: matrix + families of fiber (α)

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**LaBS**

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**Mechanical properties of cerebral vessels**

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**Constitutive relationship**

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S_{ij} = \frac{\partial W}{\partial E_{ij}}
\]

**Incompressibility constraint**

\[
W = W_{\text{vol}} (J) + W_{\text{iso}} (I_1, I_2, I_4)
\]

**Anisotropy**

\[
W = \mu (I_1 - 3) + \frac{K_1}{K_2} f_n \left( \exp \left( \frac{K_2}{1 - \rho} (I_1 - 3)^2 + \rho (I_4 - 1)^2 \right) - 1 \right)
\]
The anisotropic constituent-based computational model for cerebral vascular wall

Constitutive parameters identification

- Several histological studies (Finlay and Canham 1998, Canham et al, 2003)
  \( \alpha \) : circumferential and longitudinal directions
- Scarce and not complete literature on cerebral vessels
  (Scott et al, 1972; Steiger et al, 1989; Monson et al, 2003)
- A recent single study on biaxial tensile tests (Monson et al, 2006)

\[
W = \mu (I_1 - 3) + \frac{K_1}{K_2} f_n \exp \left( K_2 \left( (1 - \rho) (I_1 - 3)^2 + \rho (I_4 - 1)^2 \right) \right) - 1
\]

- Longitudinal fibers
  \( K_1 = 0.045 \text{MPa} \)
  \( K_2 = 47.5 \)
- Matrix
  \( \mu = 0.0756 \text{MPa} \)
  \( K_1 = 0.11 \text{MPa} \)
  \( K_2 = 23.75 \)
- Circumferential fibers
  \( \rho = 0.75 \text{MPa} \)
The anisotropic constituent-based computational model for cerebral vascular wall

**Important results**

- A constituent-based computational model regarding non linearity, anisotropy and large deformations was implemented in a displacement-based commercial code (ABAQUS, 3DS, USA)
- An identification of proper constitutive parameters allow us to reproduce the elastic behaviour of cerebral vessels
- Realistic constitutive modeling is a prerequisite to quantifying changes in the structure and function of tissue in response to altered mechanical stimulus

**Future Developments**

- To consider a multi-layer structure to better reproduce vascular histology

**Critical Issues**

- To identify constitutive parameters based on more accurate experimental tests
Finite element approach for the tissue growth and remodeling in aneurysms development

The adaptive law implementation

Adaptive phenomena are implemented as inelastic mechanisms: multiplicative decomposition of deformation gradient tensor (Skalak, 1989; Rodriguez et al, 1994; Taber et al, 1998; Humphrey et al, 1999)
The adaptive law implementation

- Perturbation: increase of pressure (Kroon and Holzapfel, 2007)
- Definition of the suitable stimulus: strain energy density of fibers (Watton et al., 2004; Baek et al., 2006)
- Definition of the adaptive effects: fiber lengthening, change of fiber density (Watton et al., 2004, Baek et al., 2006)
- Definition of the adaptive law: linear relationship (Rodriguez et al., 1994; Watton et al., 2004; Baek et al., 2006; Kroon and Holzapfel, 2007)

\[
\dot{\lambda}_p = K_p \left( \frac{W^f}{f_n W_0^f} - 1 \right)
\]

\[
\dot{f}_n = K_f \left( \frac{W^f}{f_n W_0^f} - 1 \right)
\]
Finite element approach for the tissue growth and remodeling in aneurysms development

Saccular simplified model

Stable response for all kf/kp
Finite element approach for the tissue growth and remodeling in aneurysms development

Saccular simplified model

Stable response only for higher kf/kp values

Saccular model

Figure: Graphs showing stimulus response over time for different models.
Finite element approach for the tissue growth and remodeling in aneurysms development

- **Radial displacement**
- **Fusiform model**
- **Stimulus**
- **Stable response for higher kf/kp**
- **Fiber density**
- **Fiber lengthening**
Finite element approach for the tissue growth and remodeling in aneurysms development

Radial displacement

Fusiform model

Different adaptive behaviour according to different constitutive models

Finite element approach for the tissue growth and remodeling in aneurysms development
Finite element approach for the tissue growth and remodeling in aneurysms development

**Important results**
- The mechanisms of growth (change in reference configuration) and remodeling (change of volumetric fiber density) are competing mechanisms.
- The proposed computational model for growth/remodeling is capable of simulating the time evolution of stable and unstable aneurysms.
- The boundary conditions imposed could influence the adaptive behaviour.

**Future Developments**
- To investigate patient-based geometries.
- To consider more realistic perturbation.
- To consider more realistic boundary conditions.
- To implement more sophisticated adaptive mechanisms.

**Critical Issues**
- To identify proper adaptive constants based on clinical observations: it is difficult to collect longitudinal patient-based information.
Biomechanical analysis of cerebral aneurysms formation in realistic geometries

Realistic geometries: ANEURISK database

Internal Carotid Artery

Internal Carotid Artery: U bend
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Choice of realistic idealized U-bend in terms of diameters and curvature
Biomechanical analysis of cerebral aneurysms formation in realistic geometries

Realistic idealized geometries and realistic perturbations
Interaction with CFD simulations

CFD model (Fluent, Ansys) + Structural and adaptive model (ABAQUS, 3DS)
Realistic idealized geometries and realistic perturbations

Interaction with CFD simulations

**CFD model (Fluent, Ansys)**

- Perturbation: increased flow rate (Feng et al, 2006)
- Output: pressure and wall shear stresses

![Diagram showing pressure (P) and wall shear stress (WSS) visualization in realistic geometries.](image-url)
Realistic idealized geometries and realistic perturbations
Interaction with CFD simulations

CFD model (Fluent, Ansys)

- Perturbation: increased flow rate (Feng et al, 2006)
- Output: pressure and wall shear stresses

Degradation function according to highest wall shear stresses (Wulandana and Robertson 2005, Feng et al 2006)

\[ f_n = K_{deg} \left( \frac{\tau - \tau_h}{\tau_h} \right) \]
Biomechanical analysis of cerebral aneurysms formation in realistic geometries

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Interation with CFD simulations

CFD model (Fluent, Ansys) + Structural and adaptive model (ABAQUS, 3DS)

Result of simulations

Stimulus

Time
Biomechanical analysis of cerebral aneurysms formation in realistic geometries

Realistic idealized geometries and realistic perturbations

Interaction with CFD simulations

**CFD model (Fluent, Ansys)**

**Structural and adaptive model (ABAQUS, 3DS)**

Result of simulations

**Stimulus**

**Time**
Biomechanical analysis of cerebral aneurysms formation in realistic geometries

Realistic idealized geometries and realistic perturbations
Interaction with CFD simulations

CFD model (Fluent, Ansys) + Structural and adaptive model (ABAQUS, 3DS)

Result of simulations
Realistic idealized geometries and realistic perturbations

Works in progress

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Biomechanical analysis of cerebral aneurysms formation in realistic geometries
Realistic idealized geometries and realistic perturbations

Works in progress

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\[
Dean = \frac{Q}{\mu} \cdot \frac{2\rho}{\pi} \left( \frac{1}{R \cdot R_{\text{curv}}} \right)^{\frac{1}{2}}
\]
Conclusions and Future Developments

Conclusions

✓ The developed “fluid-structure” interaction allow us to couple realistic fluid dynamic boundary conditions to a proper structural and adaptive model for cerebral vascular wall
✓ The implemented model represents a novel approach to study the aneurysms initiation
✓ The application to realistic geometry is a potentially useful tool to predict different aneurysms formation site according to geometrical and fluid dynamics features

Future developments

✓ Adaptive perturbation (Pressure and WSS) changing during aneurysm formation and haemodynamic evolution;
✓ To apply the model to more realistic anatomy from clinical data;


3. L. Socci Numerical models of cerebral aneurysm biomechanics *PhD Thesis* on Bioengineering


3. **8th International Symposium on Computer Methods in Biomechanics and Biomedical Engineering. February 27 – March 1, 2008**.

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