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Influence of plaque geometry and composition on numerically simulated balloon angioplasty outcomes

Bernard AL-Helou¹, Claire Dupont¹, Aline Bel-Brunon², Adrien Kaladji¹, Pascal Haigron¹

¹ Université de Rennes 1, CHU Rennes, INSERM, LTSI – UMR 1099, F-35000 Rennes, France

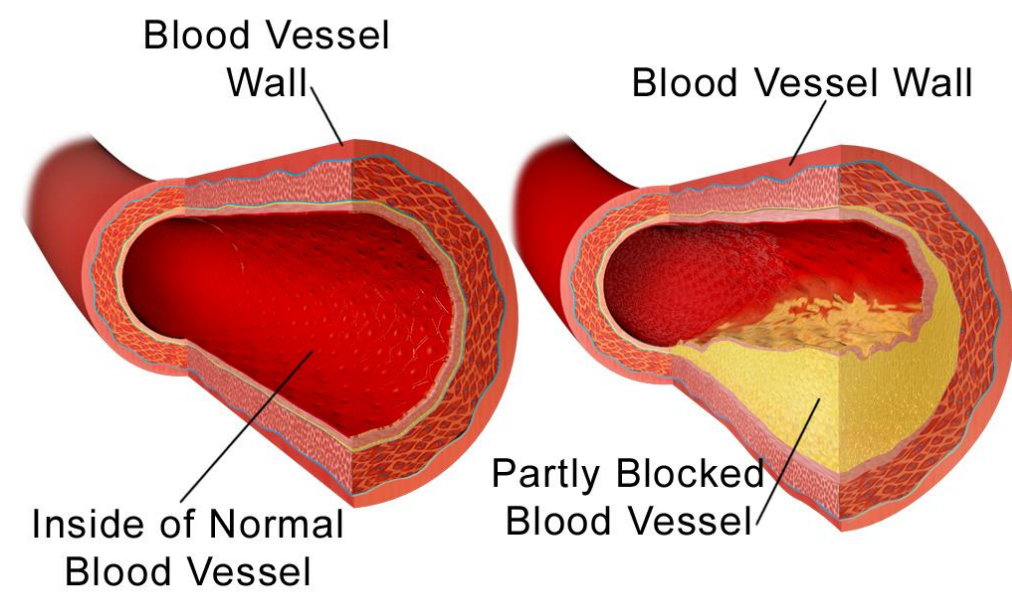
² Univ Lyon, INSA-Lyon, CNRS UMR5259, LaMCoS, F-69621 Lyon, France

Context & Objectives

Atherosclerotic Plaque

- Accumulation of lipids, calcium and fibrin at the inner wall of the arteries

- Reducing blood flow mobility
- Effecting irrigated organs



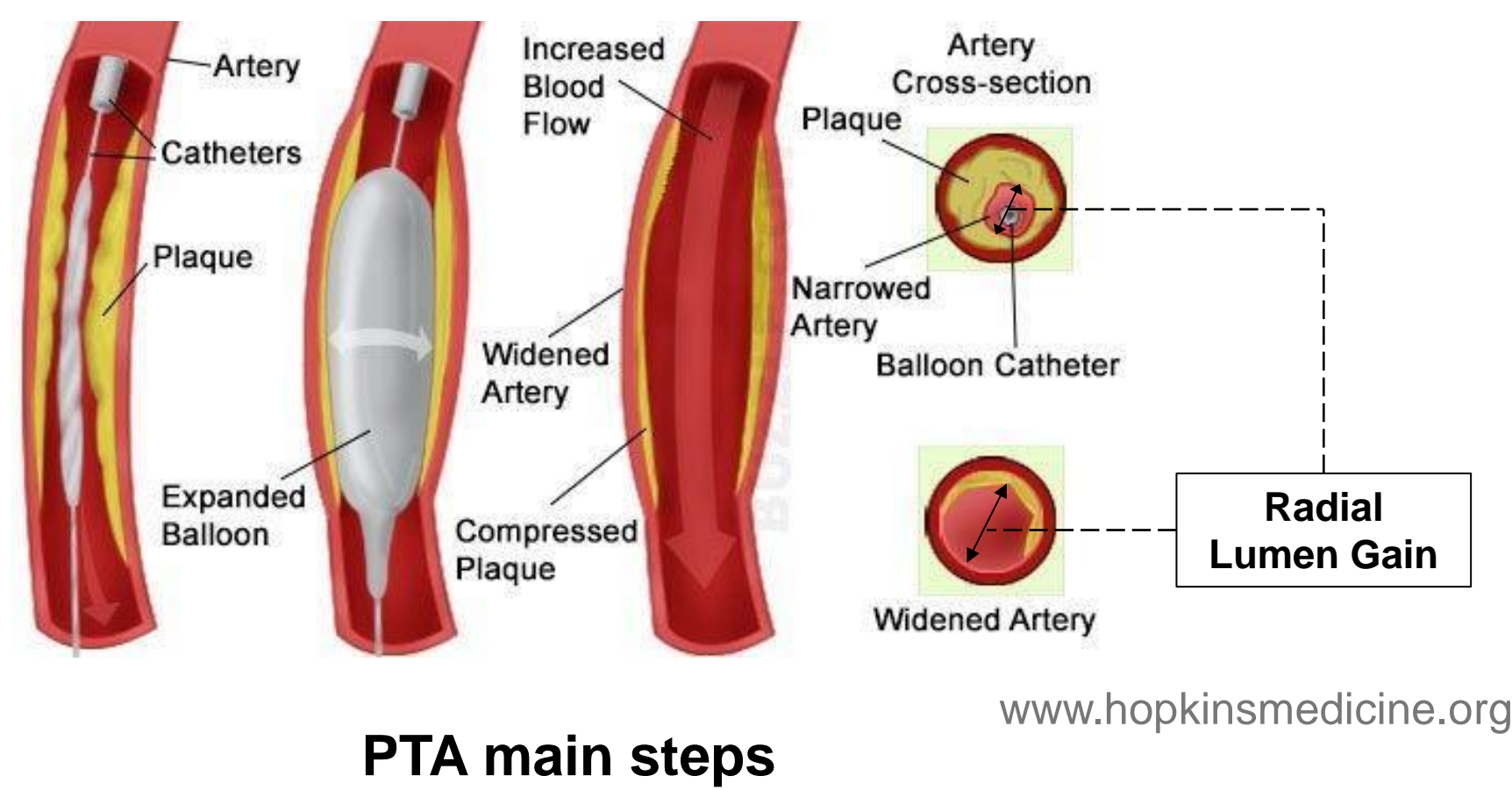
Healthy vessel Stenosed vessel

www.study.com

Localization

- Carotid arteries → 20% of ischemic strokes
- Peripheral arteries → claudication

Percutaneous transluminal angioplasty (PTA)



PTA main steps

www.hopkinsmedicine.org

Advantages (benefits): Disadvantages (risks):

- Endovascular treatment
- Mini-invasive procedure
- Fewer risks
- Restenosis
- Dissection (wall tear)
- Perforation (hole development)

Challenging for the surgeons: choosing the adequate balloon, maximizing lumen gain, without damaging the arterial tissue

State of the Art

- Several FEM studies modelled PTA in 2D geometries, others in 3D idealized geometries and few others in Patient-Specific geometries

(Sadat et al., 2010; Karimi et al., 2013; Auricchio et al. 2011)

- However, Endovascular Treatment prediction using FEM still limited by:

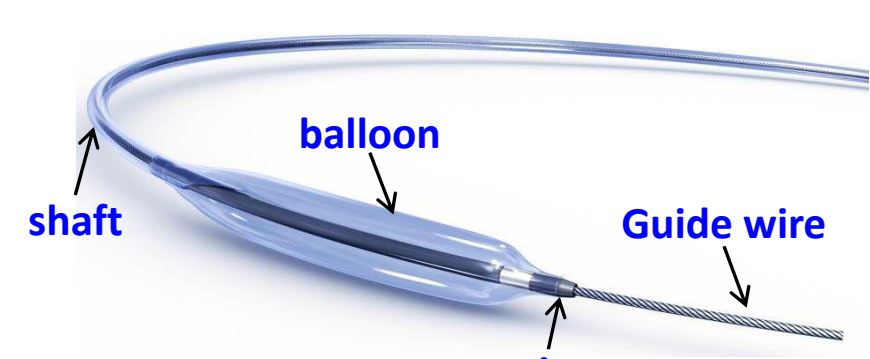
- Atherosclerotic plaque material composition and mechanical behaviors modeling
- Residual deformations modeling after PTA

Main objective

- Modeling Permanent deformations following PTA using FEM:
 - Non-compliant balloon simulated in idealized stenosed artery with symmetric vs. non-symmetric plaque geometries

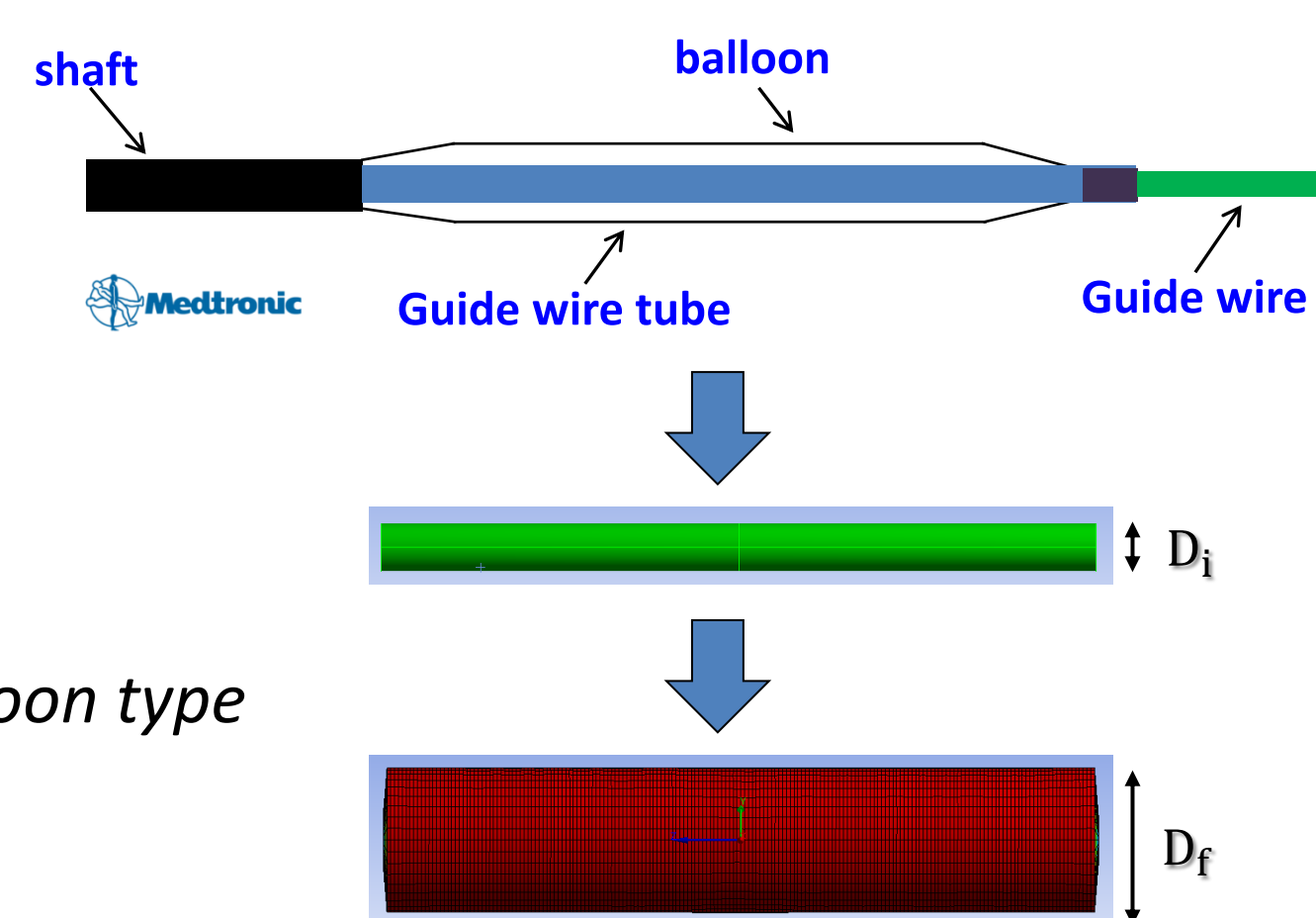
Balloon Catheter Model

Balloon Geometry in reality:



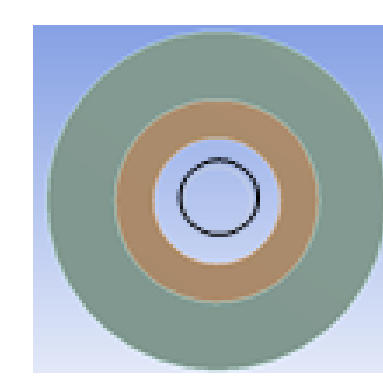
- Displacement-driven balloon → mimicking the Non-compliant (very stiff) balloon type

- Inflation Ratio: $\frac{D_f}{D_i} = 3$

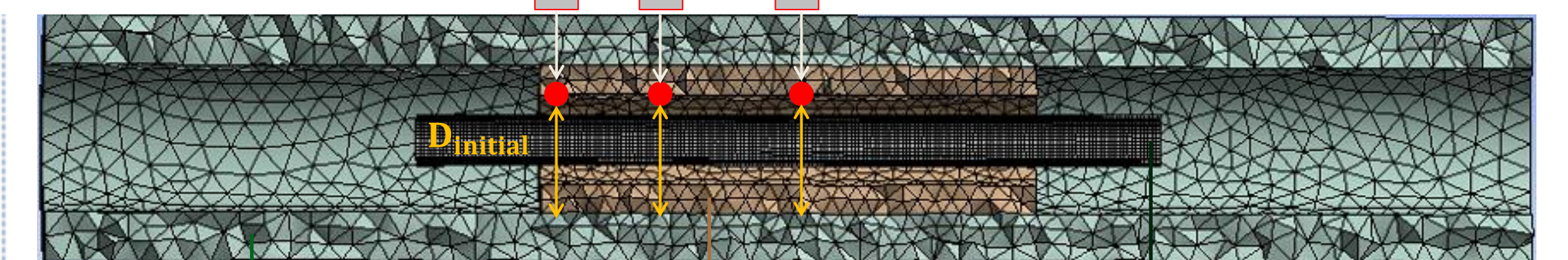


Symmetric plaque geometry: Lipid vs. Calcified

Axial View



Longitudinal Cut View



Geometry & Mesh:

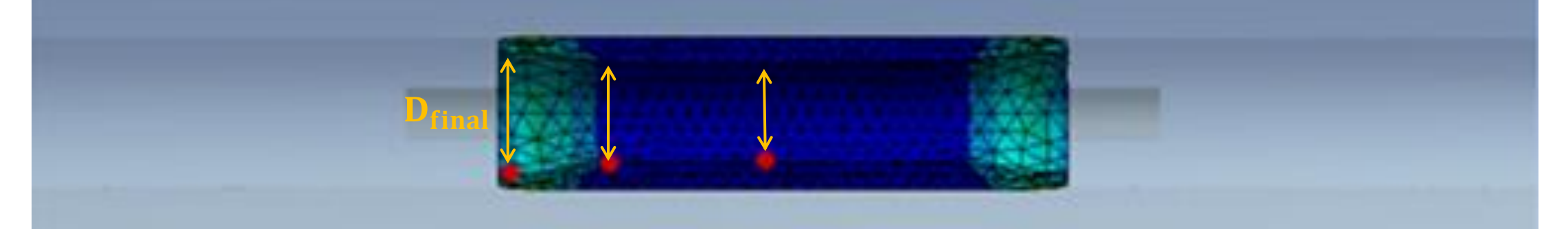
Artery: Tetrahedral solid elements Plaque: 60% stenosis, Tetrahedral solid, Calcified vs. Lipid Balloon: Quadrilateral shell elements

Material Model:

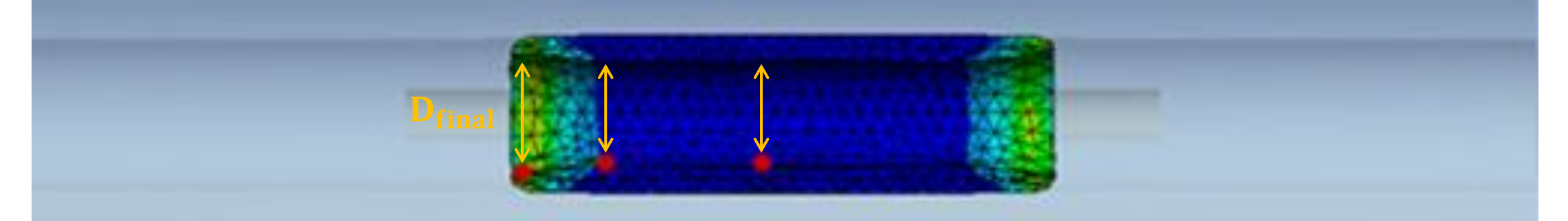
Neo-Hookean Bilinear Plastic

Plastic strain after Balloon deflation

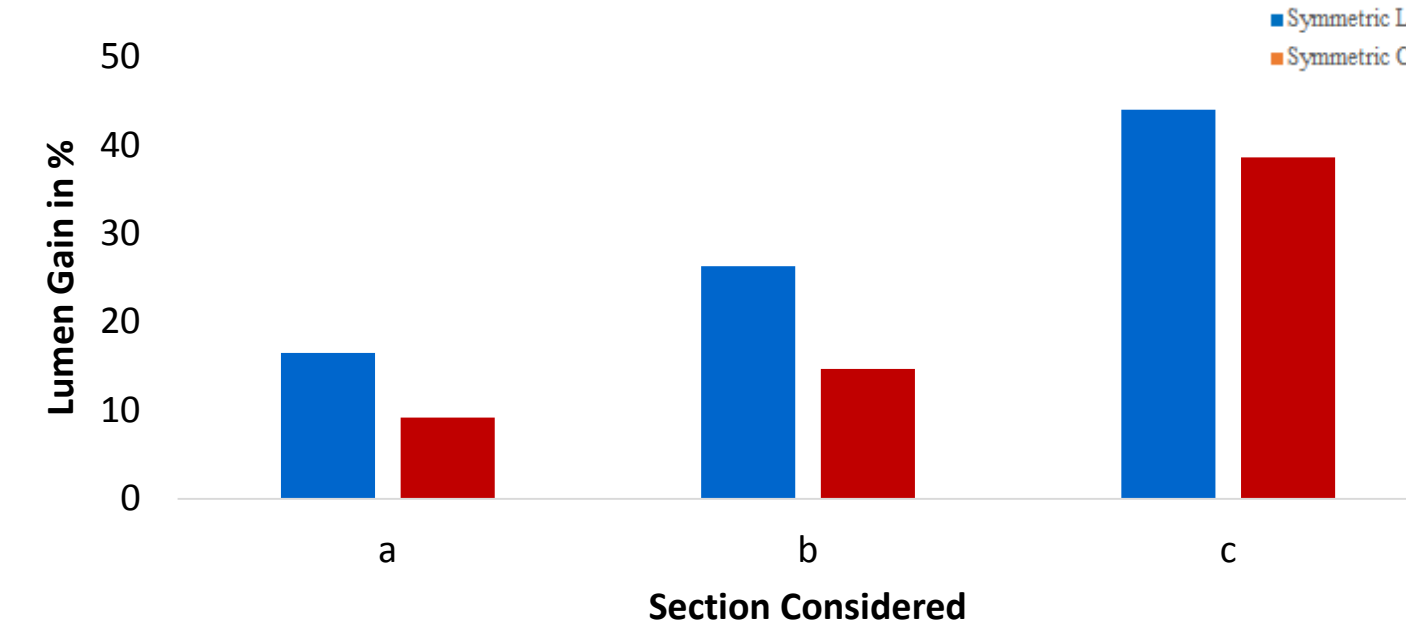
Lipid Plaque



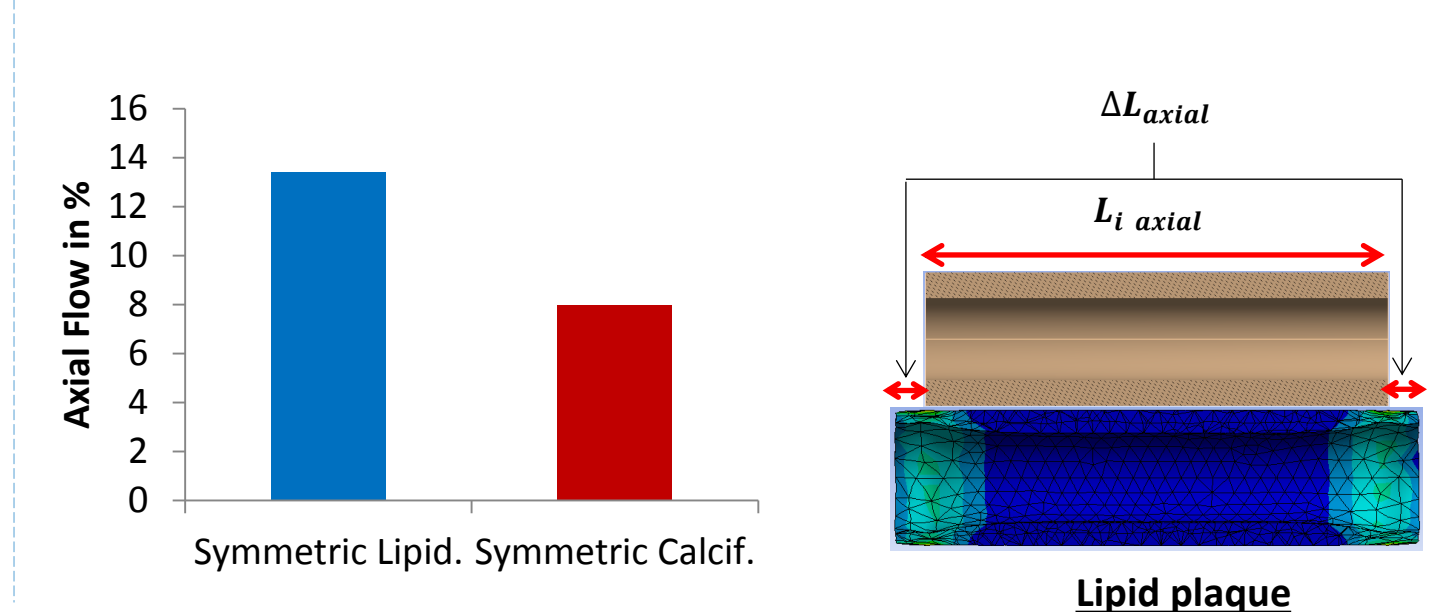
Calcified Plaque



Lumen Gain in % after balloon deflation:



Plaque Axial Flow in % after balloon deflation:



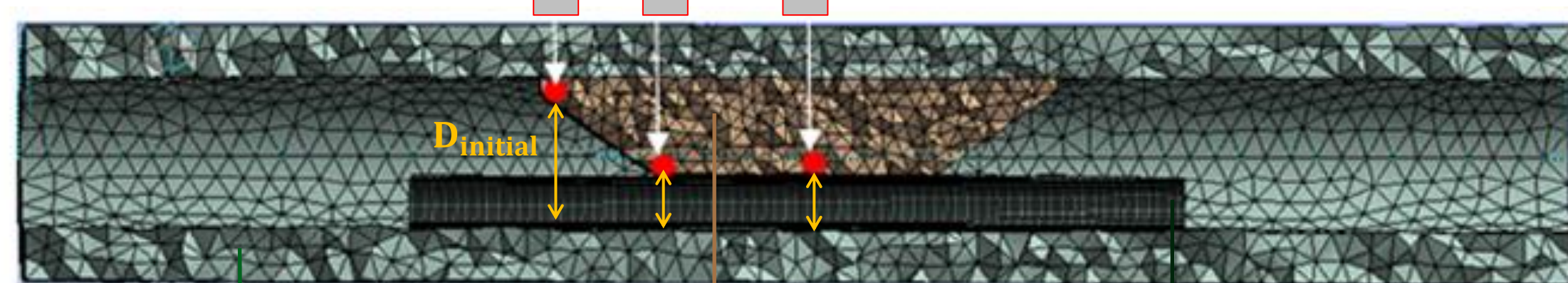
- Lumen gain (LG) increases towards plaque edges ($LG_c > LG_b > LG_a$)
- Higher lumen gain and axial flow along lipid plaque (blue vs. orange): softer plaque → Importance of modeling PTA in 3D

Non-symmetric plaque geometry: Lipid vs. Calcified

Axial View



Longitudinal Cut View



Geometry & Mesh:

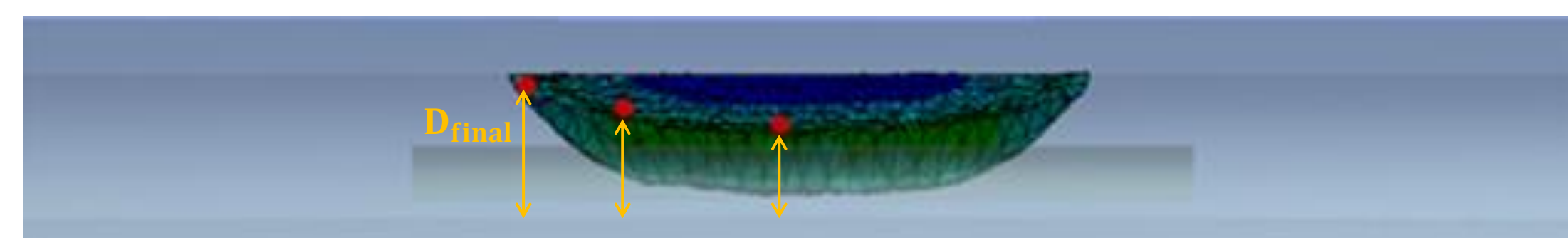
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Material Model:

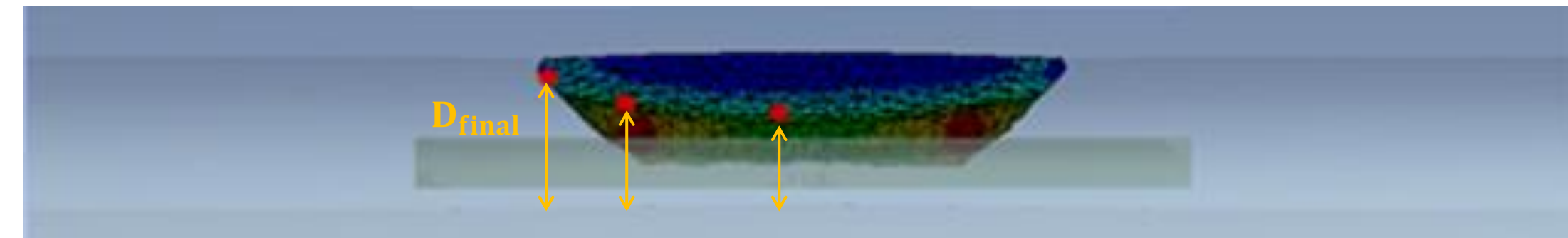
Neo-Hookean Bilinear Plastic

Plastic strain after Balloon deflation

Lipid Plaque



Calcified Plaque

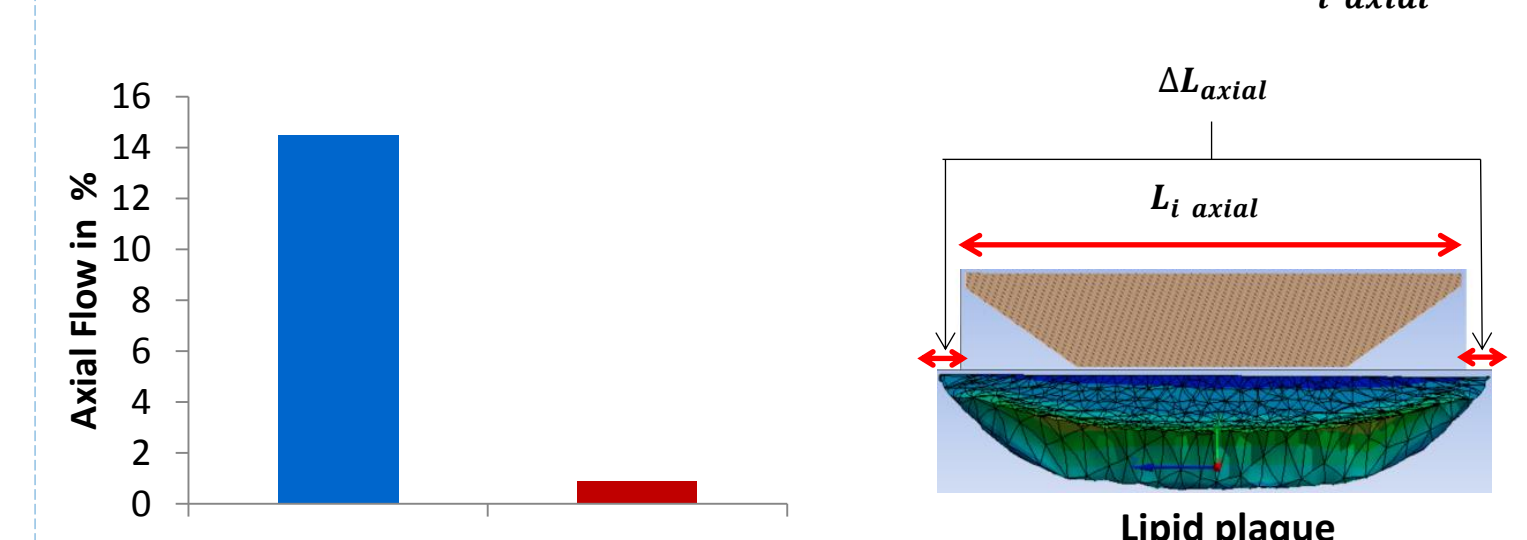
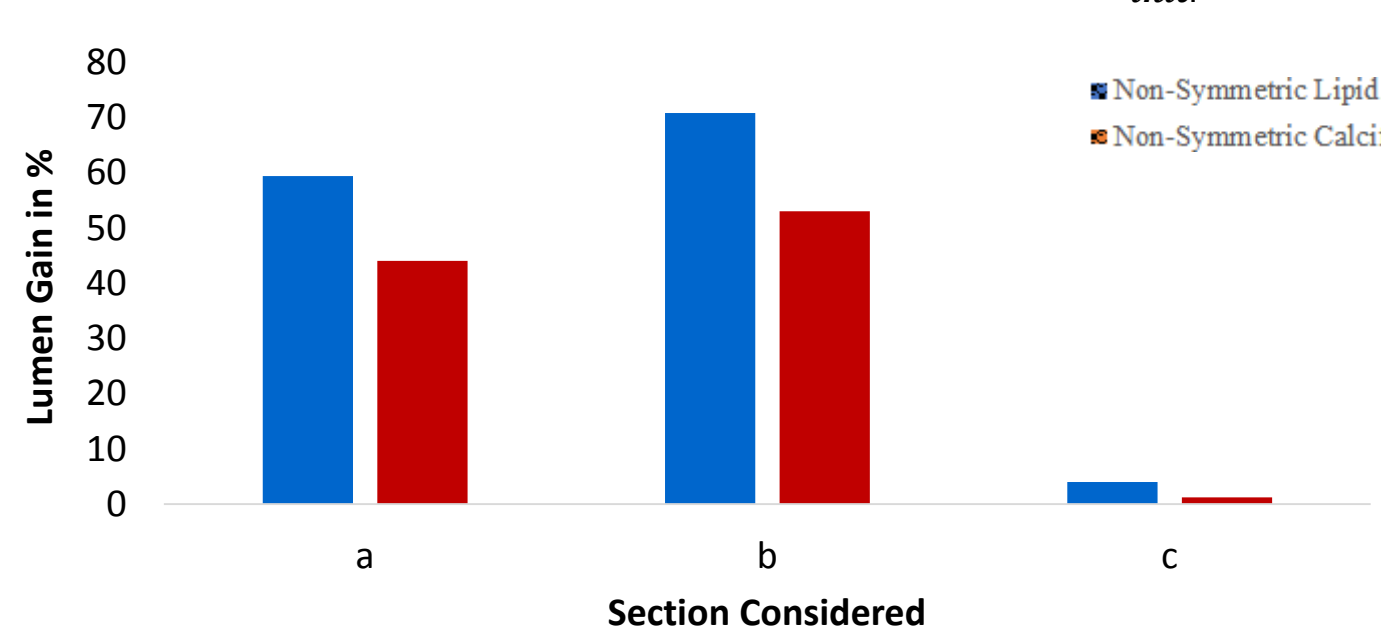


Lumen Gain in % after balloon deflation:

$$LG = \left(\frac{D_{final}}{D_{init}} - 1 \right) \times 100$$

Plaque Axial Flow in % after balloon deflation:

$$AF = \frac{\Delta L_{axial}}{L_i axial} \times 100$$



- Higher lumen gain (LG) along lipid plaque (at a, b and c: blue vs. orange): softer plaque
- LGs are of high values at sections a and b while low at c → Plaque thickness highly influences LGs
- Higher axial flow in lipid plaque: lower deformation resistance → Importance of PTA 3D modeling

Conclusion

- Lipid plaques experiences higher lumen gains and axial flows (composition influences)
- Thicker plaques experiences higher LGs (geometric influences)
- Both radial LGs and axial flows exists → PTA should be modelled in 3D
- Perspectives: Patient-Specific Balloon Angioplasty simulations in stenosed arteries

