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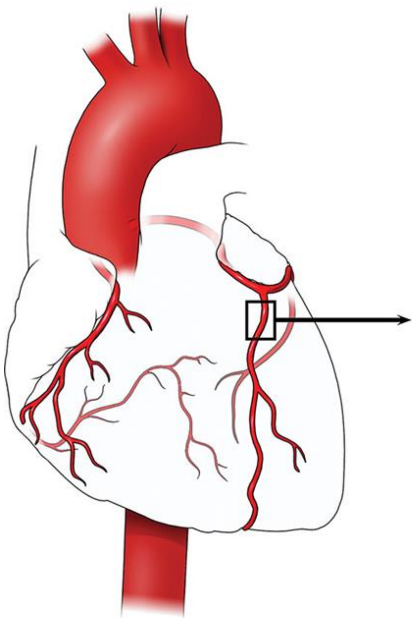
Computer simulations of bench testing for the investigation of coronary bifurcation stenting

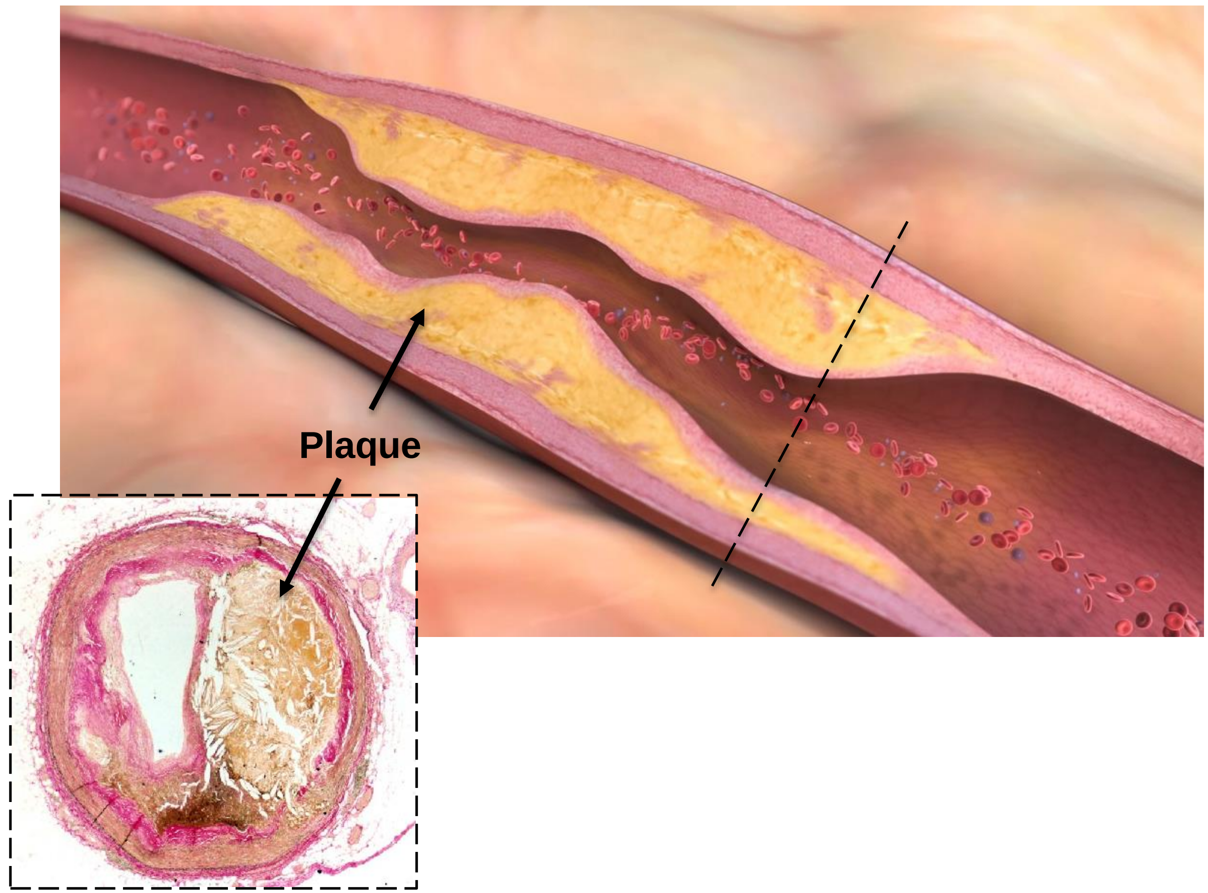
Claudio Chiastra

Milan – June 20th, 2017

Coronary heart disease

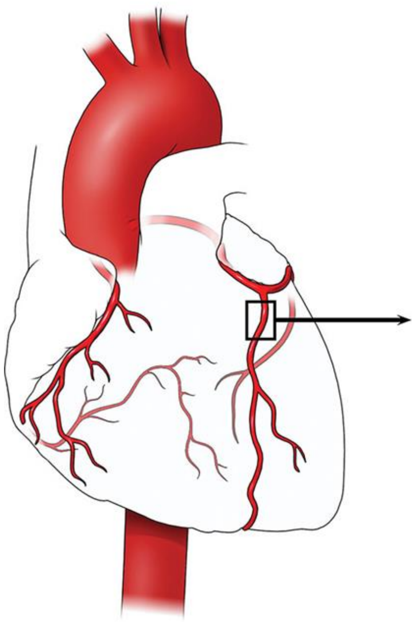
- Every year **> 1.8 million deaths** in the **European Union**
- **Coronary artery atherosclerosis**

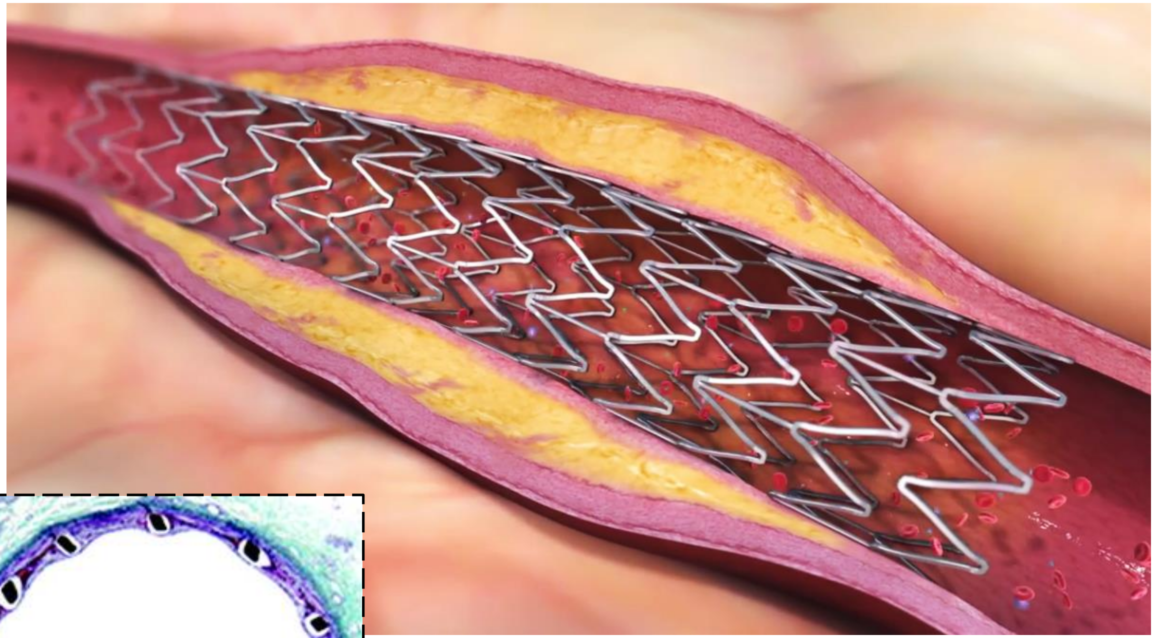


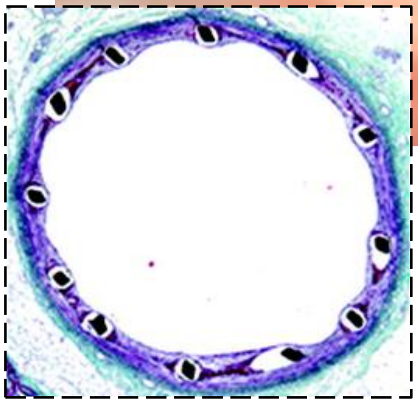


Coronary artery stenting

- **Most commonly used technique** to treat coronary atherosclerotic lesions
- In-stent **restenosis** is a major complication







Cross-section

Coronary artery stenting

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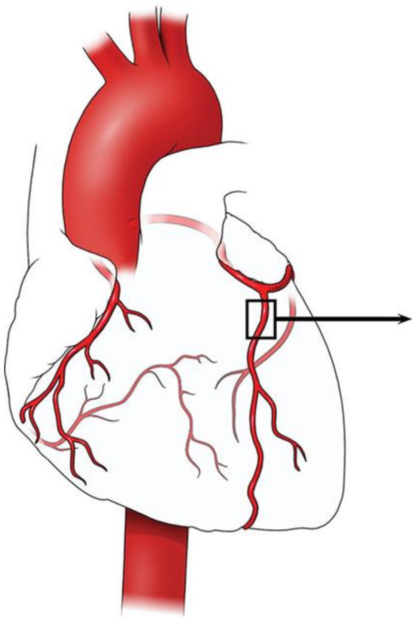

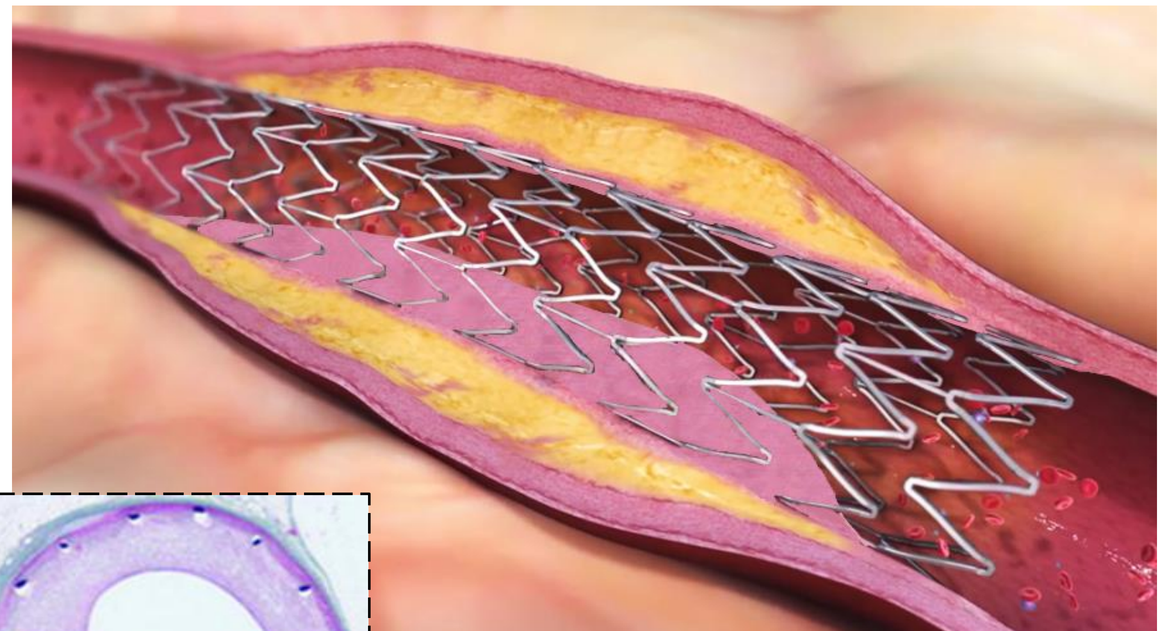

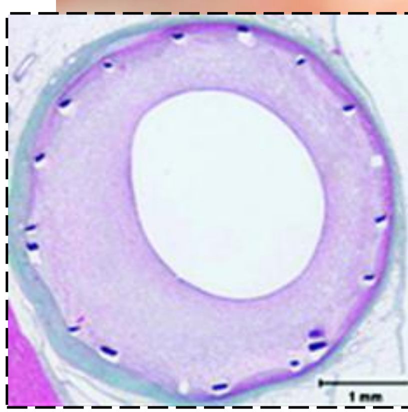

Cross-section

1 out of 6 stents fails

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Coronary bifurcation lesions

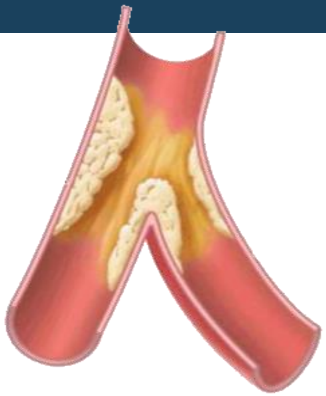
- **Challenging** for interventional cardiologists*
  - Lower success rate
  - Higher restenosis rate

> 10% failure rate

- Several issues:
  - No optimal stenting technique
  - Critical assessment of lesion severity by FFR
  - Plaque/carina shift

*Lassen et al. *Eurointervention*, 2014

Coronary bifurcation lesions



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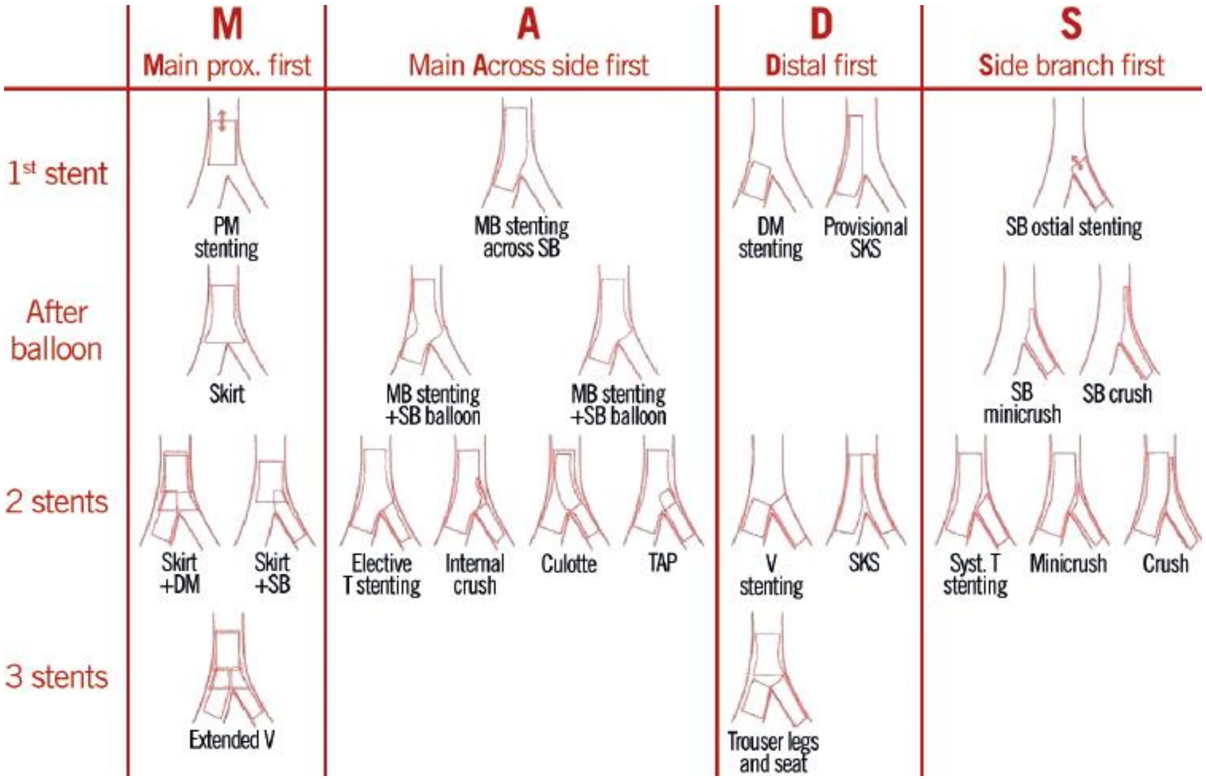

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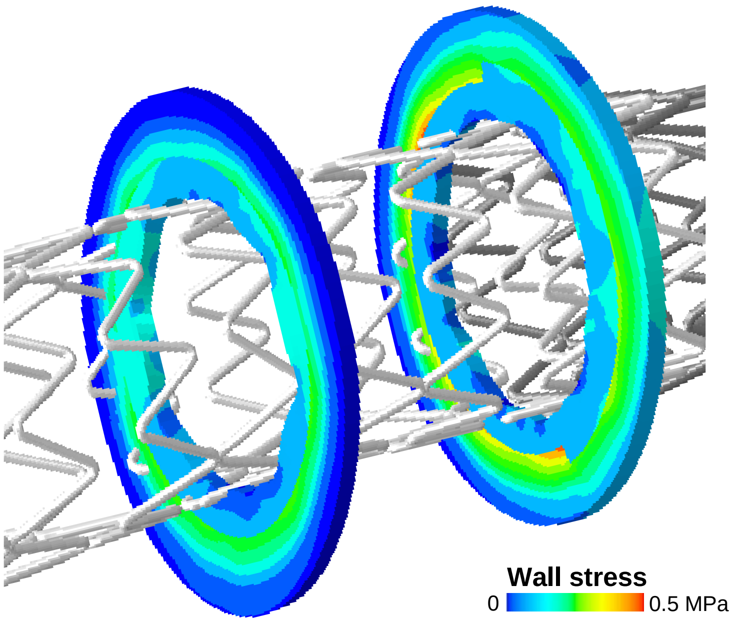
Biomechanical impact of stenting

SOLID MECHANICS



- Vessel wall damage
- Influence on tissue regrowth

FLUID DYNAMICS

- Influence on tissue regrowth

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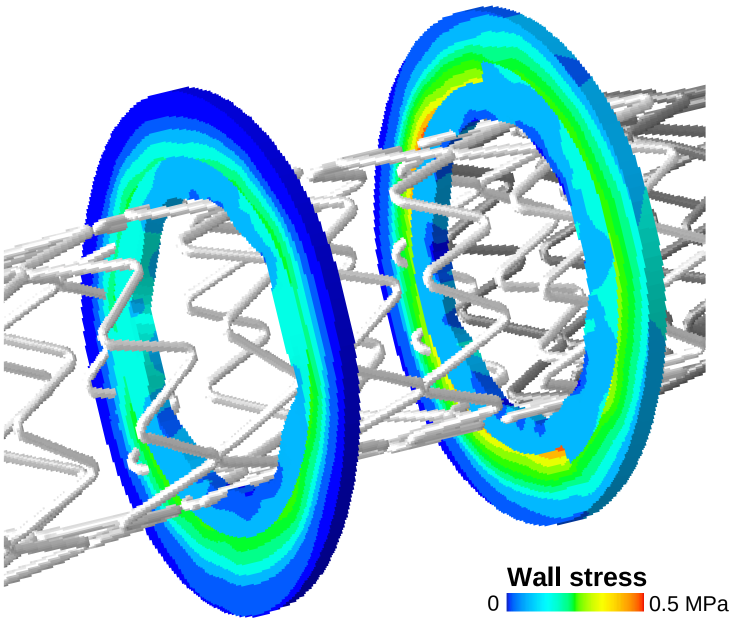
Biomechanical impact of stenting

SOLID MECHANICS



- Vessel wall damage
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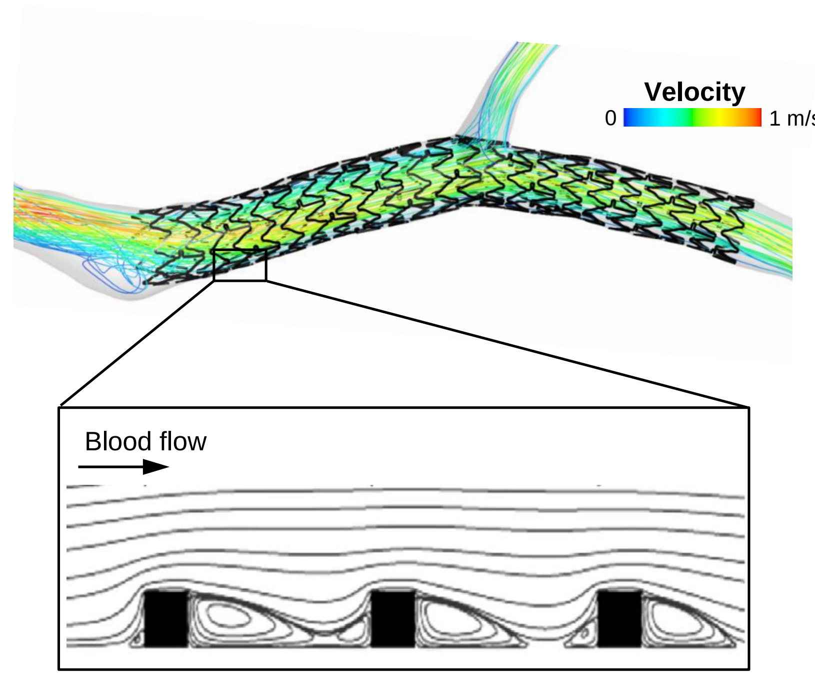
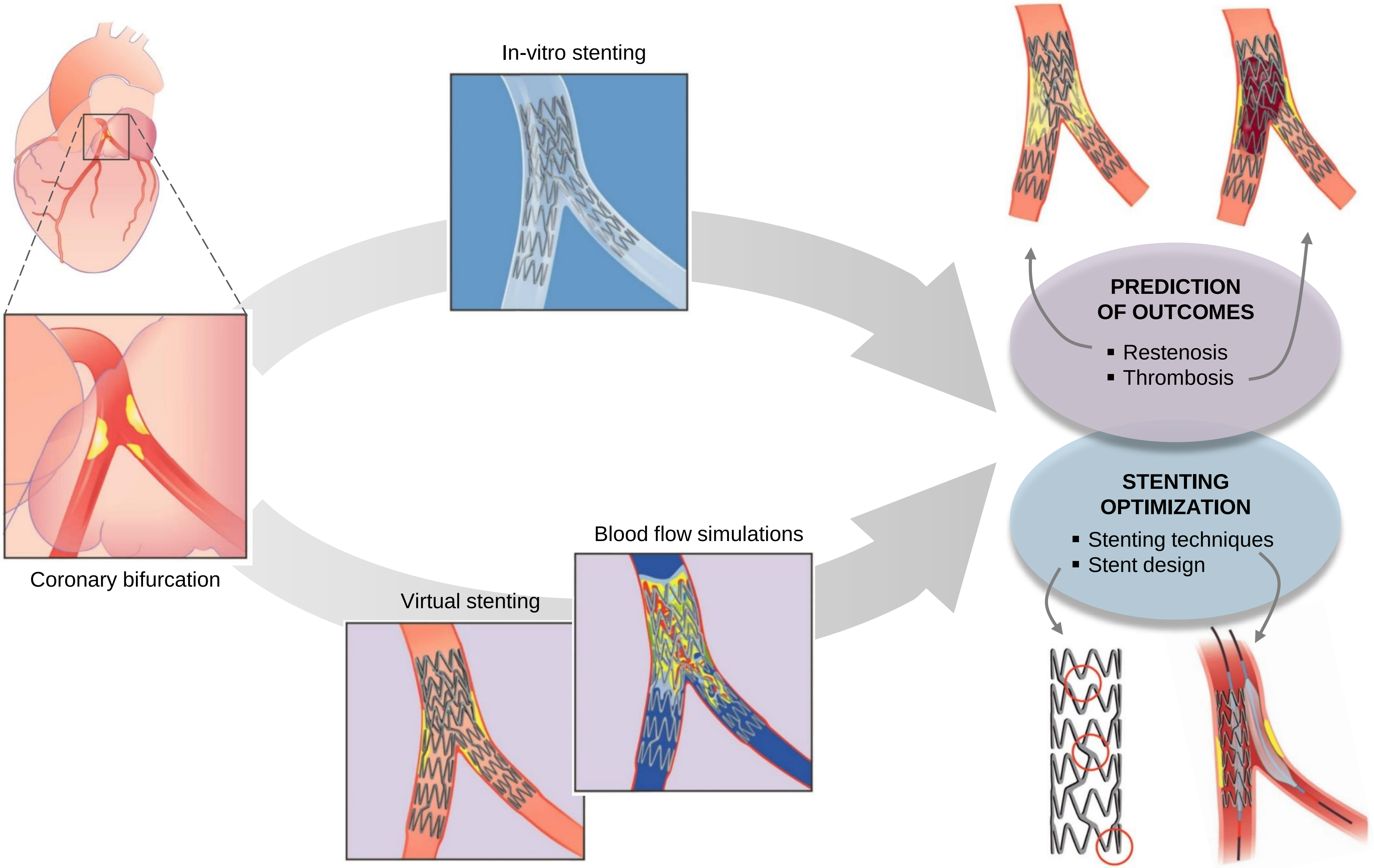


- Influence on tissue regrowth

Biomechanical analysis of coronary stents



Antoniadis et al. *J Am Coll Cardiol Interv*, 2015

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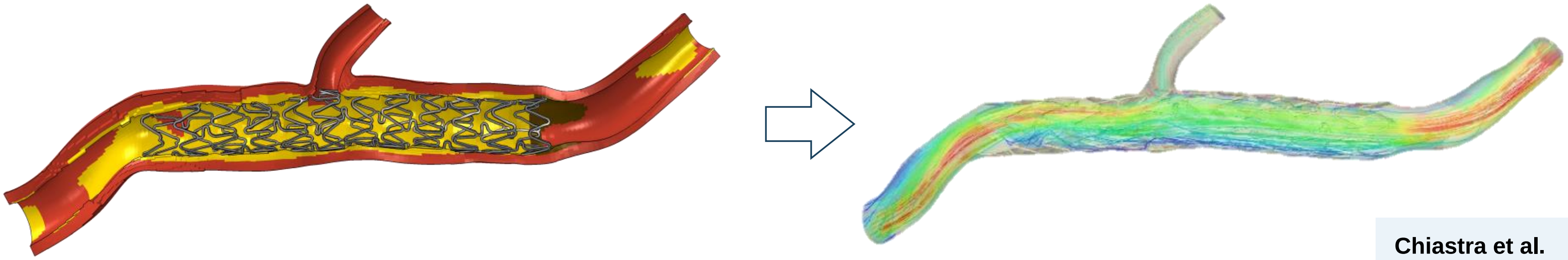
Idealized and patient-specific studies

- **Side branch compromise after main vessel stenting** (study 1)

Iannaccone, Chiastra et al. *EuroInterv*, 2017

- **Computational replication of stenting procedure for the treatment of two real clinical cases** (study 2)



Chiastra et al. *J Biomech*, 2016

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Research group

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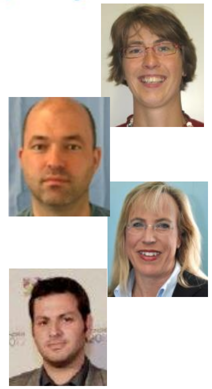

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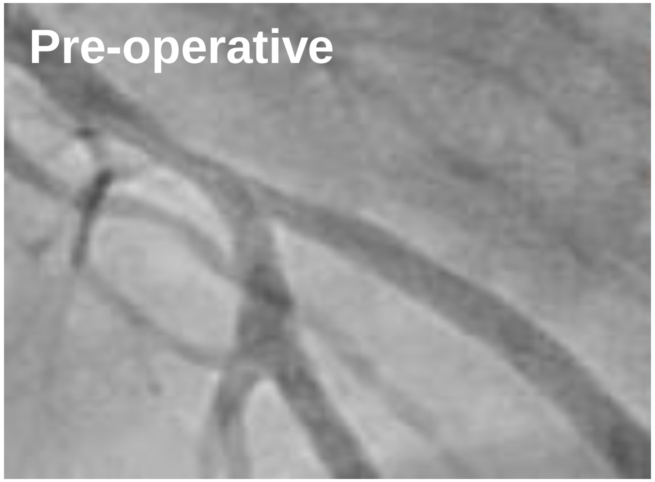
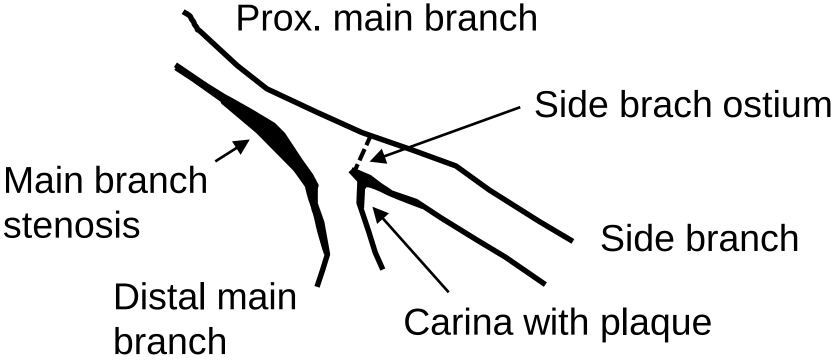
Clinical problem: plaque / carina shift

Lateral dislocation of plaque/carina during stent implantation

⇩

Possible occlusion of the side branch





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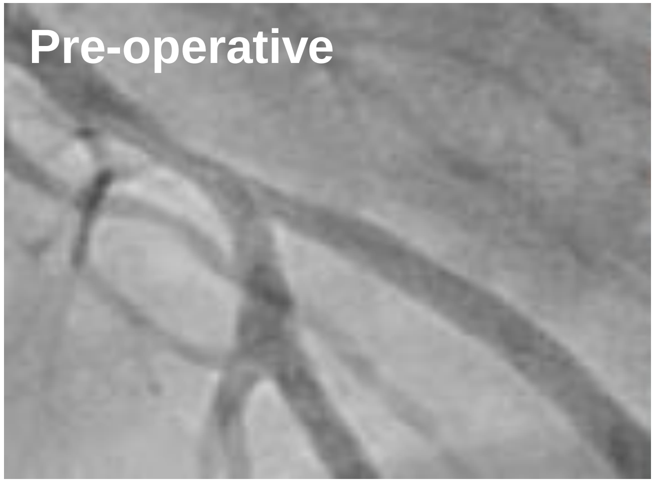

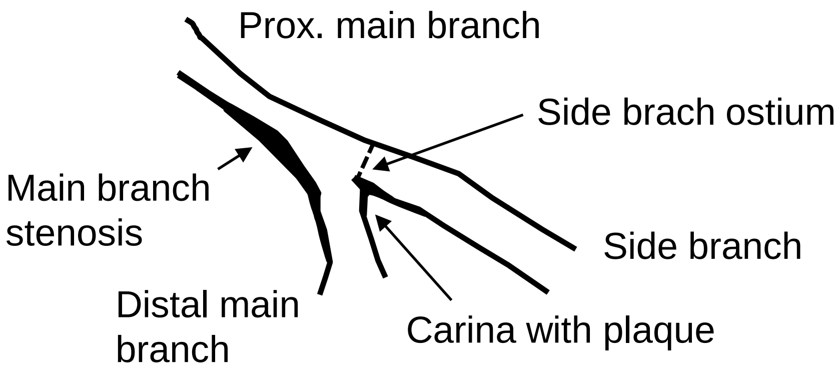

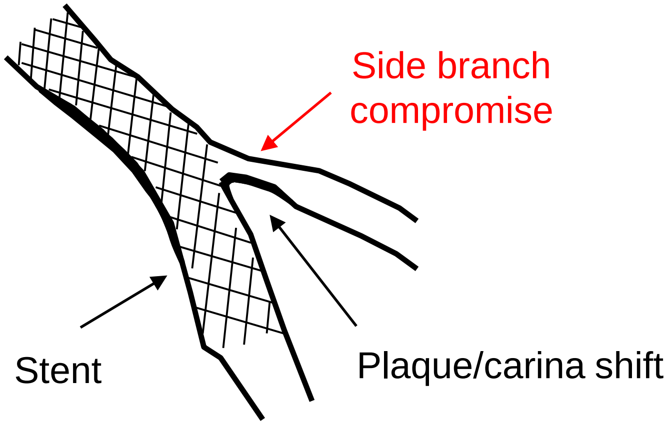

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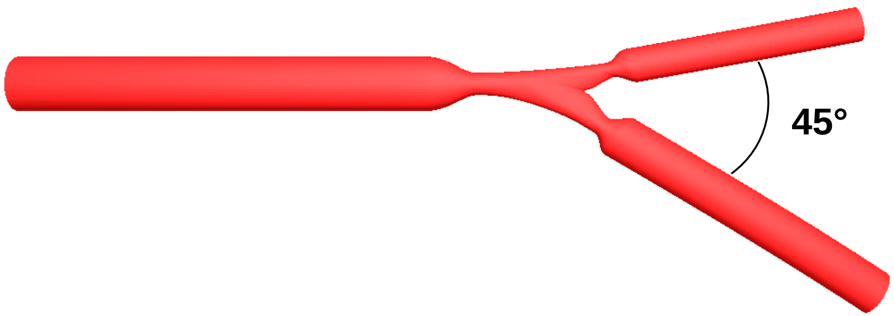
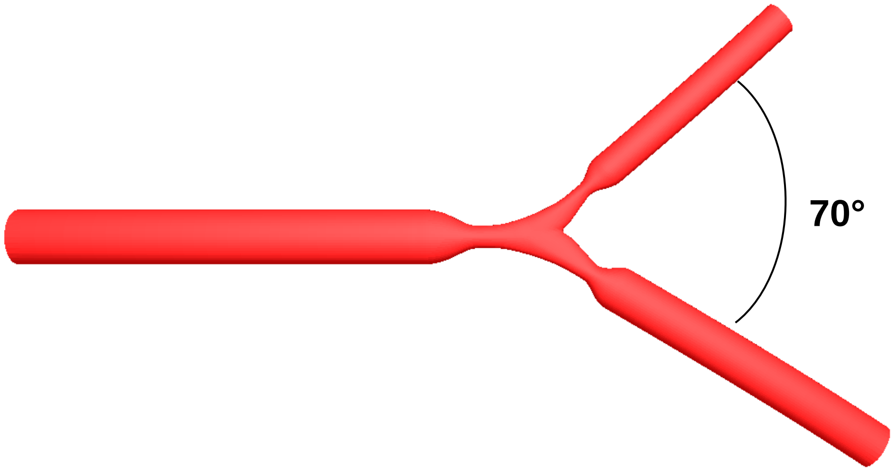
Aim

To investigate the **influence of <u>distal angle / plaque composition</u> on side branch compromise** because of **main branch stenting**

⇨ 2 bifurcation geometries with **different distal angles*** are investigated

⇨ different types of plaques





* ***Distal angle = 57.3° ± 10.0°*** *calculated on LAD, RCA, LCX (mainly LAD, 92.2%) (n = 153 patients) by Elsaban et al. 2013*
Elsaban et al. J Invasive Cardiol 2013

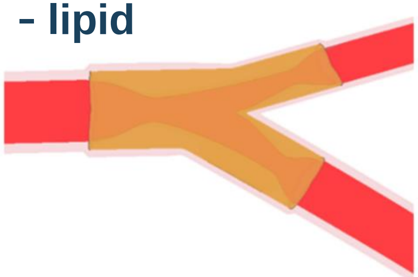
Aim

To investigate the **influence of distal angle / plaque composition on side branch compromise** because of **main branch stenting**

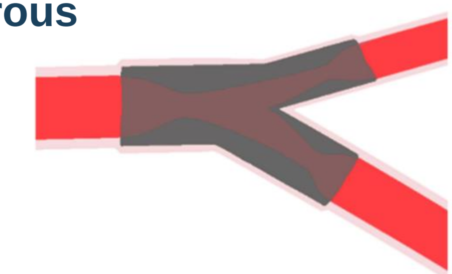
⇨ 2 bifurcation geometries with **different distal angles*** are investigated

⇨ different types of plaques

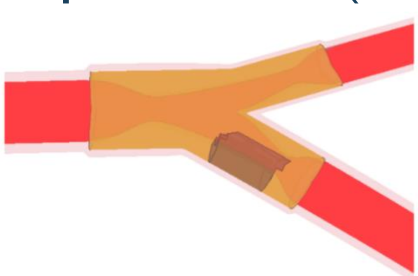
- lipid



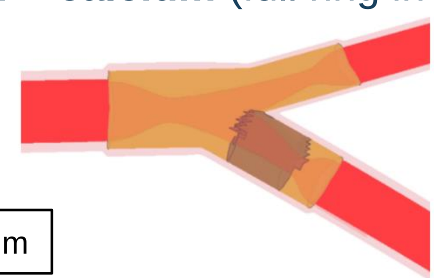
- fibrous



- lipid + calcium (half ring in the DMB)



- lipid + calcium (full ring in the DMB)



■ Lipid ■ Fibrous ■ Calcium

■ LAD / D1 bifurcation parametric model (Chiastra et al. 2016)

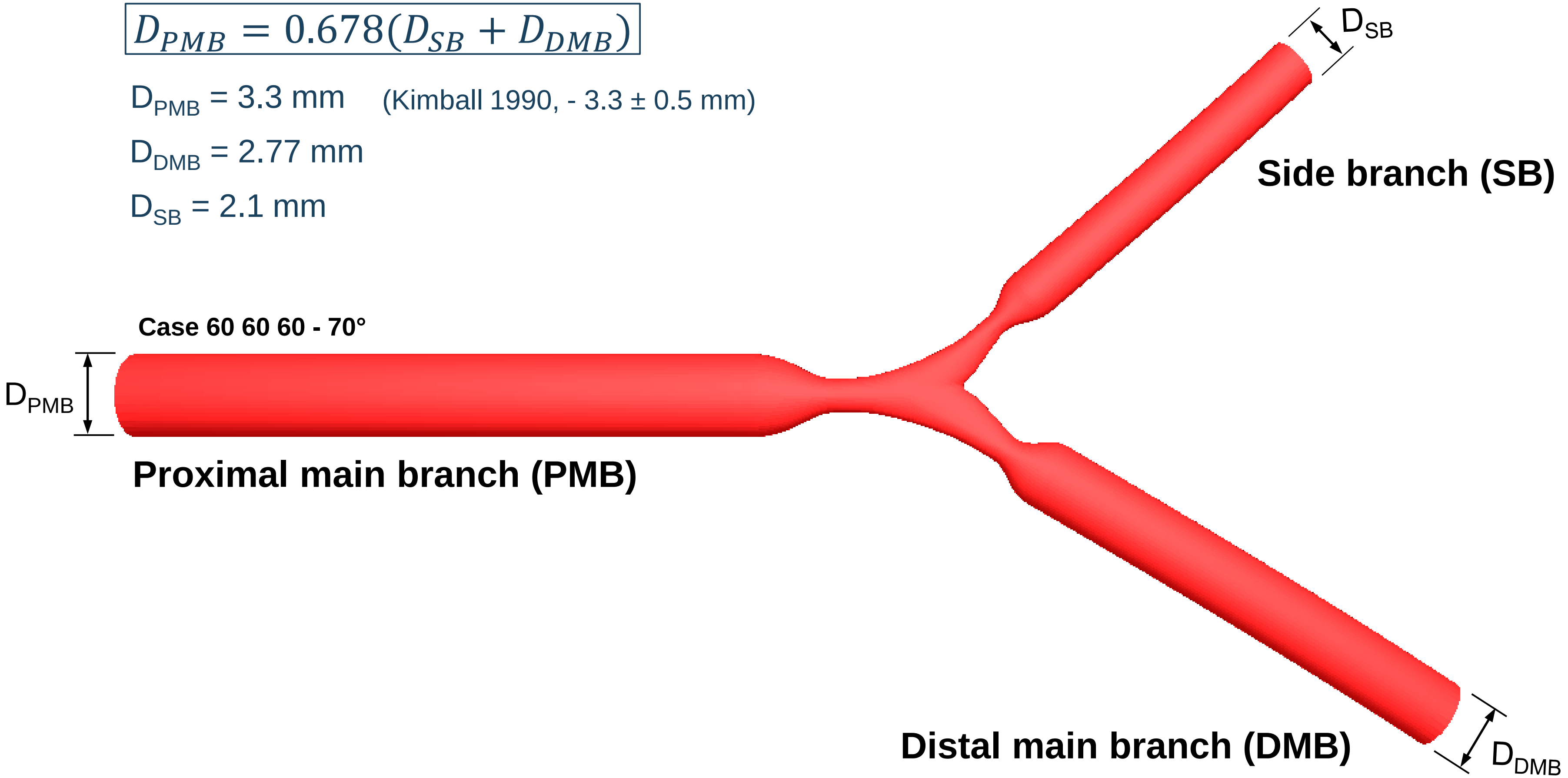
- **Diameters** defined according to **Finet's law**:

$$D_{PMB} = 0.678(D_{SB} + D_{DMB})$$

D_{PMB} = 3.3 mm (Kimball 1990, - 3.3 ± 0.5 mm)

D_{DMB} = 2.77 mm

D_{SB} = 2.1 mm



Chiastra et al. *Biomed Eng Online*, 2016
Finet et al. *EuroIntervention*, 2007
Kimball et al. *J Cardiol,* 1990

■ LAD / D1 bifurcation parametric model (Chiastra et al. 2016)

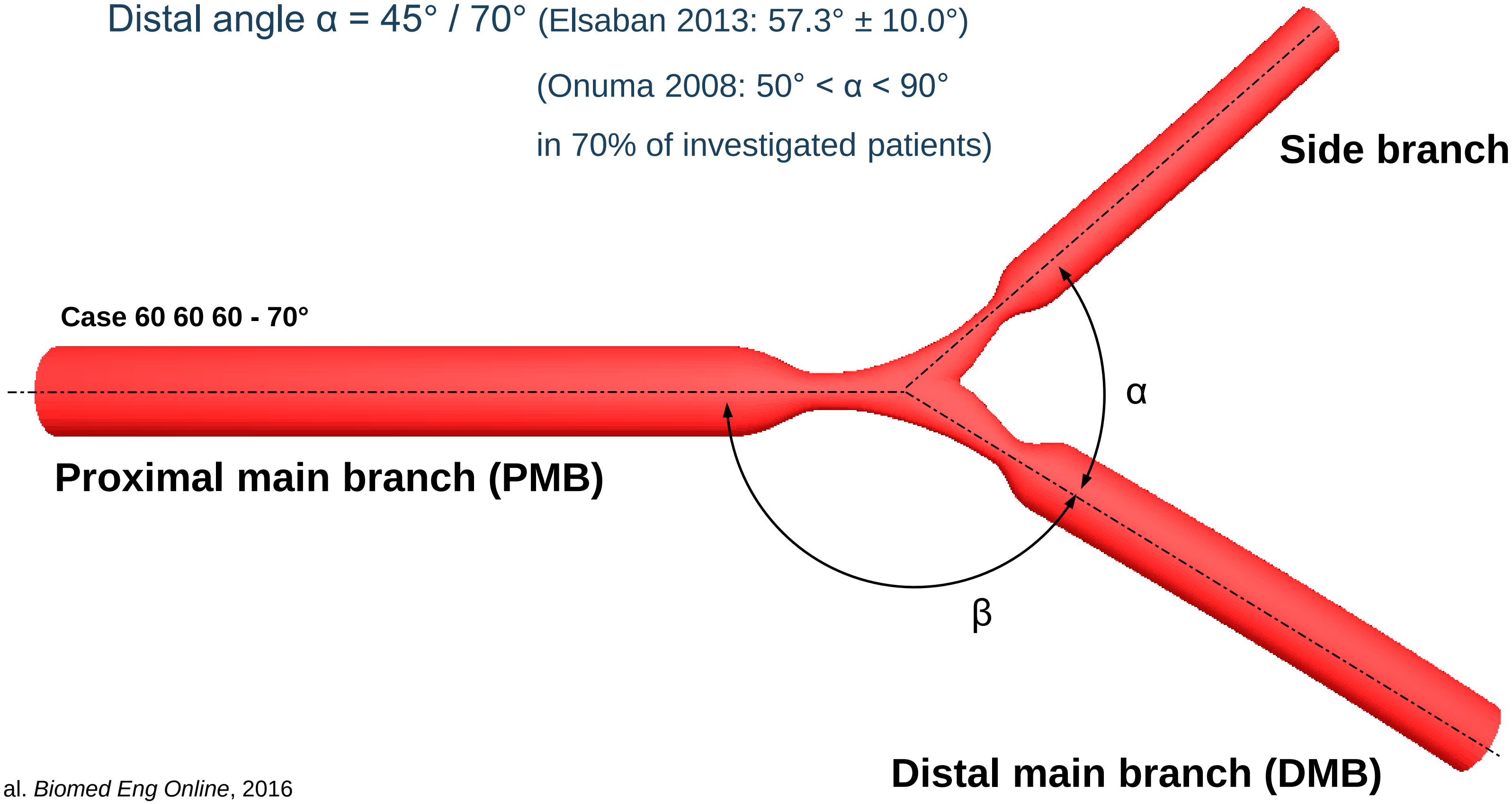
- **Angles:**

Main branch angle β = 150° (Godino 2010: 156°± 19°)

Distal angle α = 45° / 70° (Elsaban 2013: 57.3° ± 10.0°)

(Onuma 2008: 50° < α < 90°

in 70% of investigated patients)



Chiastra et al. *Biomed Eng Online*, 2016
Godino et al. *J Interv Cardiol*, 2010
Onuma et al. *EuroIntervention*, 2008
Elsaban et al. *J Invasive Cardiol*, 2013

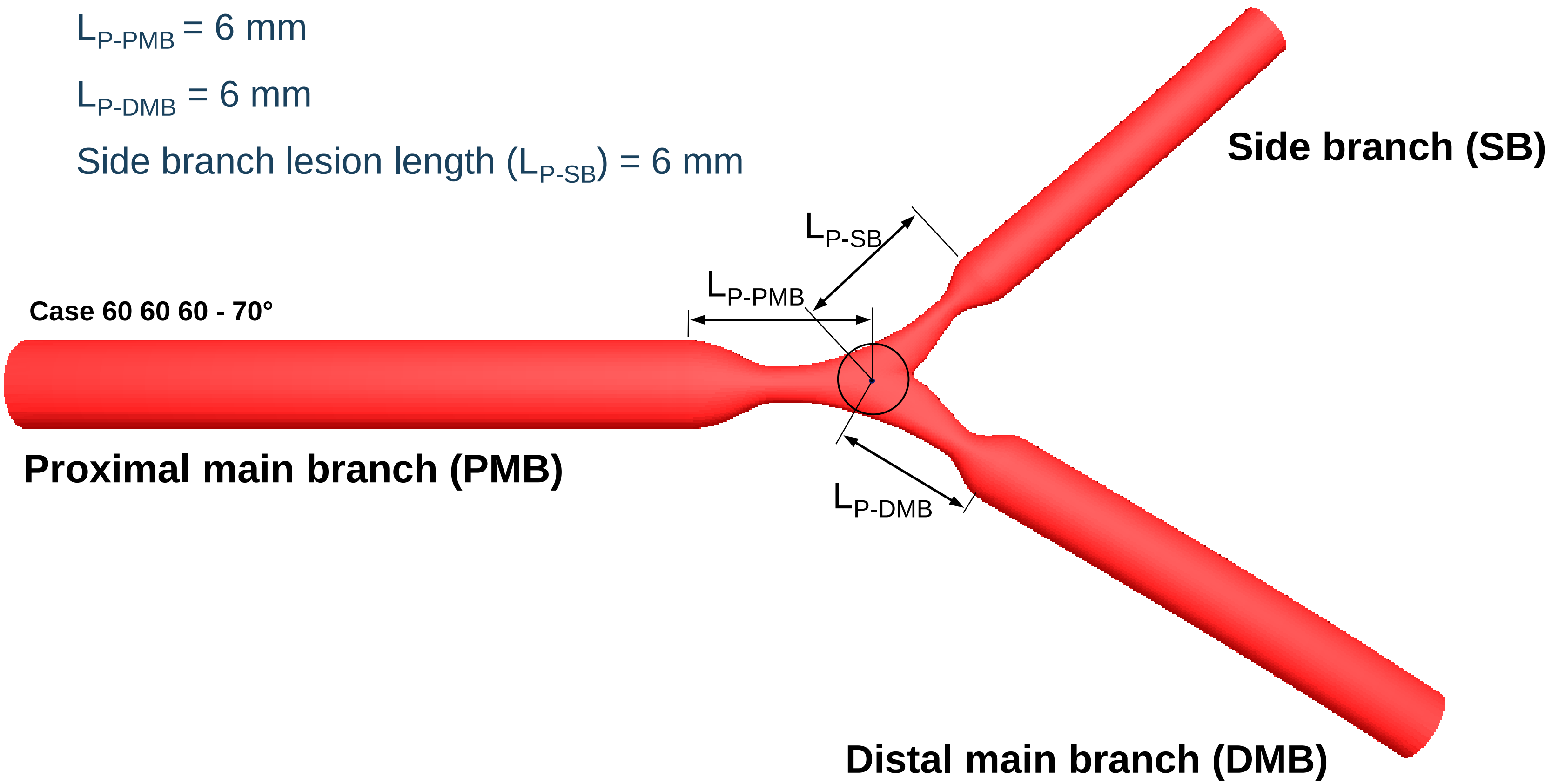
Methods: geometry

- **LAD / D1 bifurcation parametric model** (Chiastra et al. 2016)
  - **Stenosis:** PMB 60% - DMB 60% - SB 60%
  - **Plaque length:**

$L_{P\text{-}PMB}$ = 6 mm

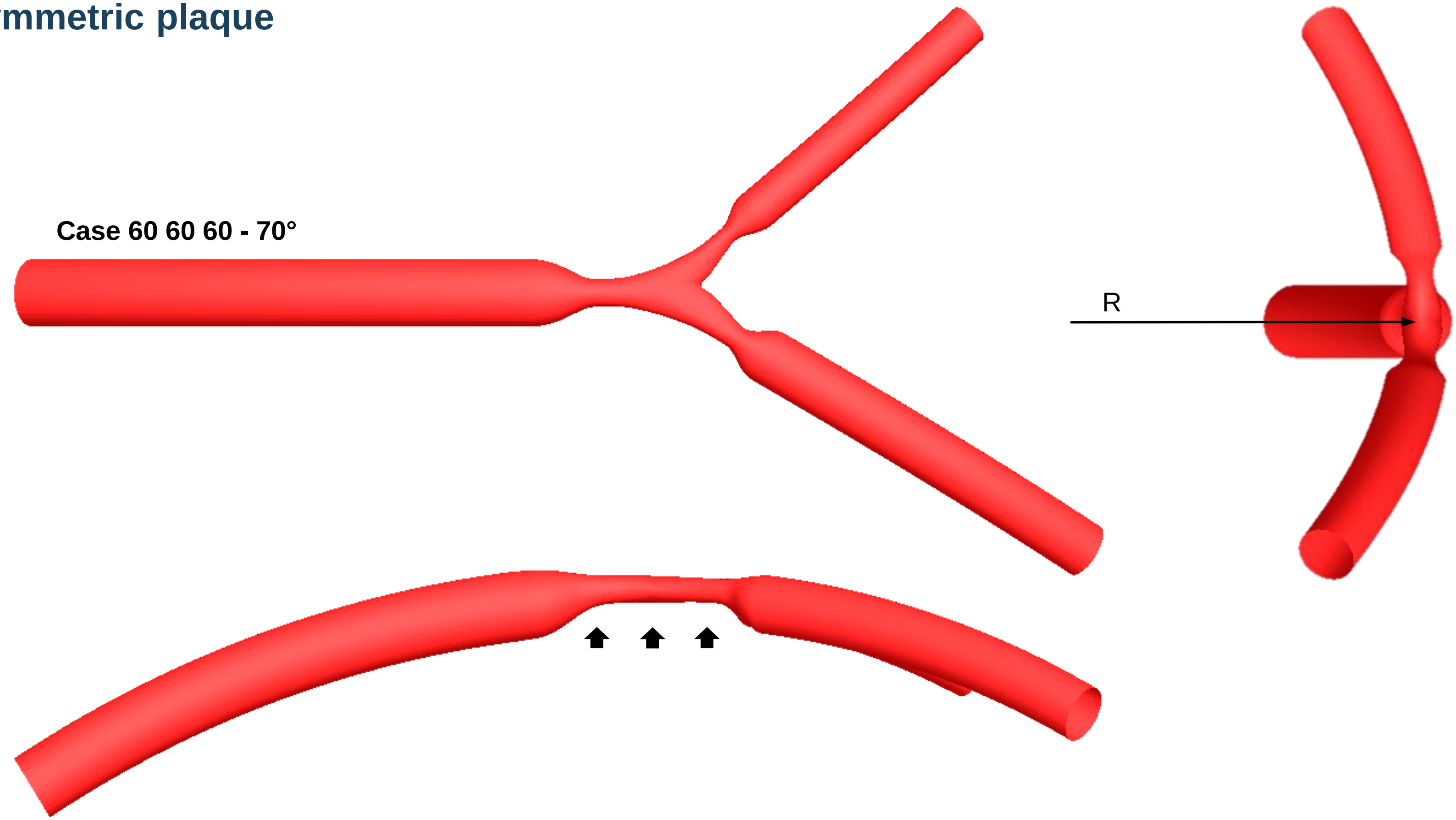
$L_{P\text{-}DMB}$ = 6 mm

Side branch lesion length ($L_{P\text{-}SB}$) = 6 mm



Chiastra et al. *Biomed Eng Online*, 2016

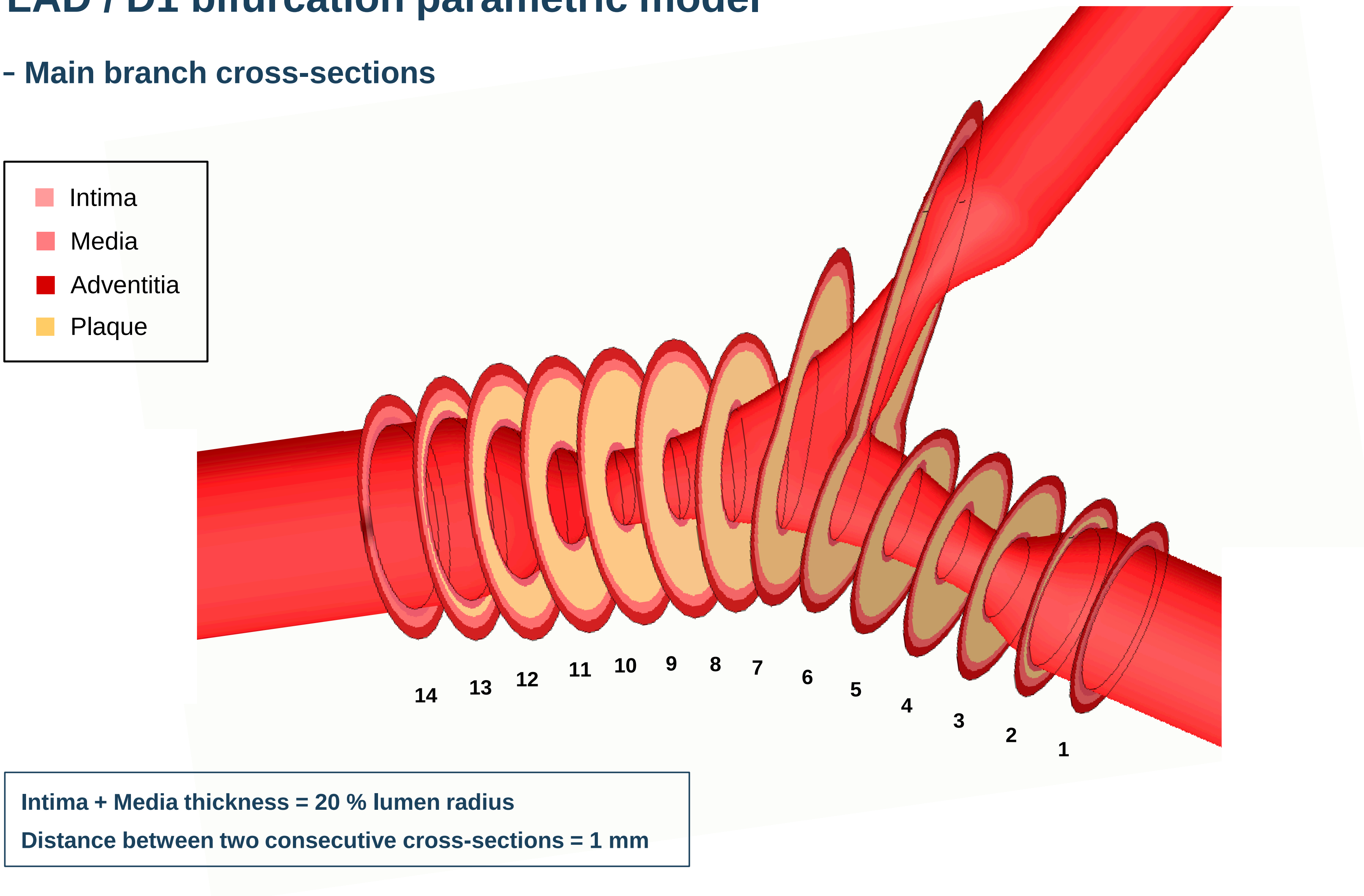
- **LAD / D1 bifurcation parametric model** (Chiastra et al. 2016)
  - **Curvature:** bifurcation placed on a sphere with radius R representing the heart, R= 56.25 (Pvikin 2005)
  - **Asymmetric plaque**



Chiastra et al. *Biomed Eng Online*, 2016
Pvikin et al. *J Biomech*, 2005

LAD / D1 bifurcation parametric model

- Main branch cross-sections



Intima + Media thickness = 20 % lumen radius

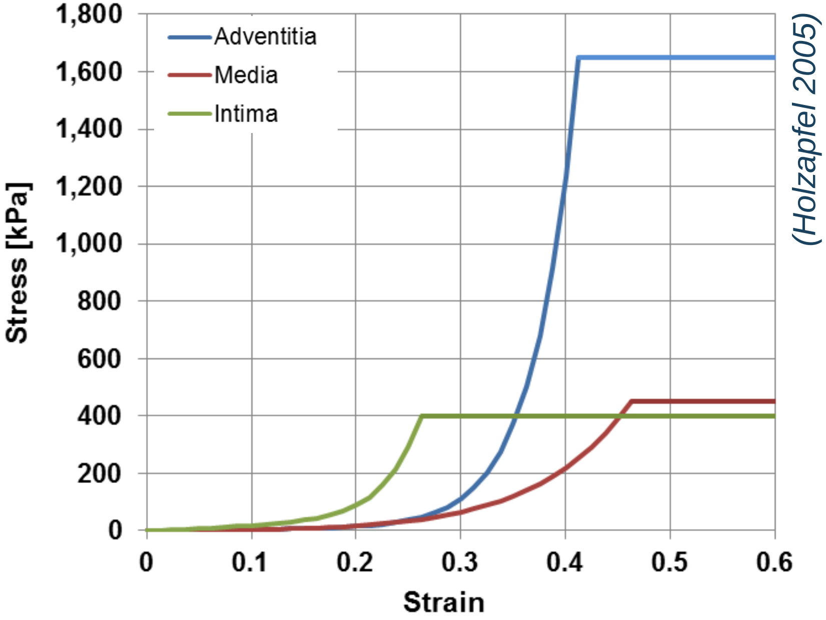
Distance between two consecutive cross-sections = 1 mm

Methods: vessel material properties

■ Arterial wall

Isotropic hyperelastic behavior with ideal plasticity to mimic vessel damage

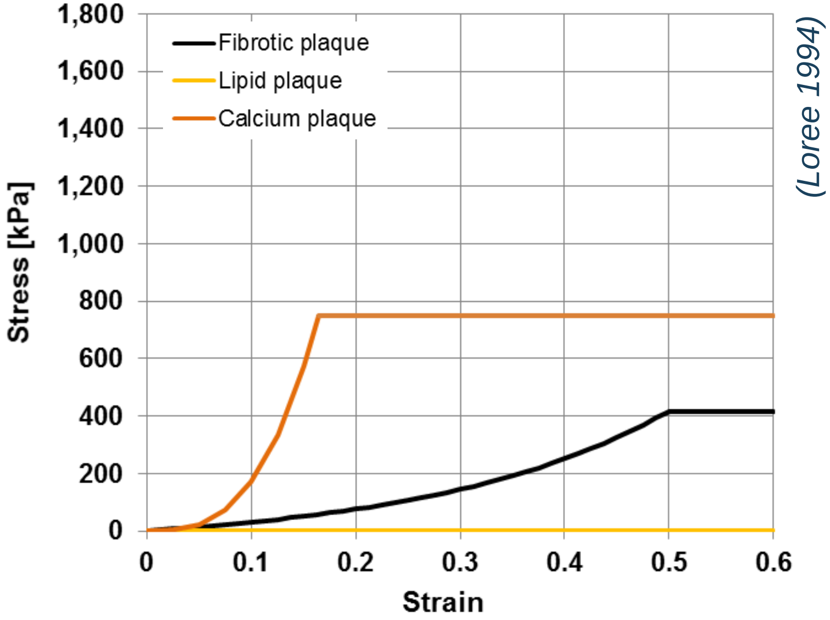
⇩



■ Fibrous / lipid / calcium plaque

Isotropic hyperelastic behavior with ideal plasticity to mimic plaque rupture

⇩



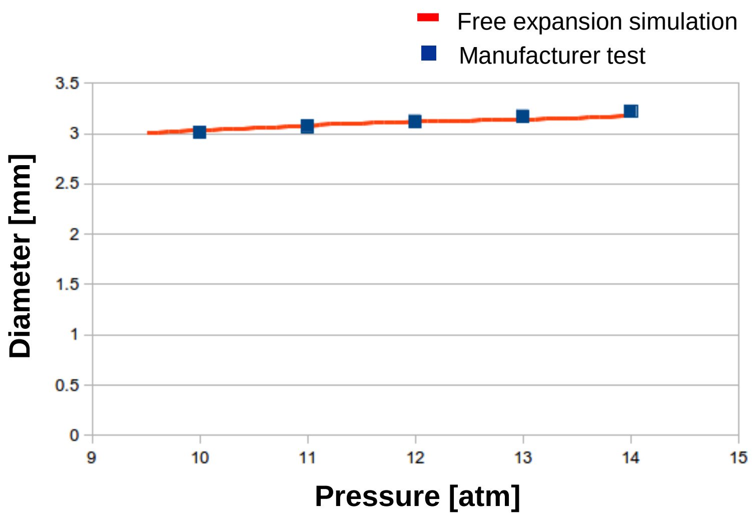
Loree et al. *J Biomech*, 1994

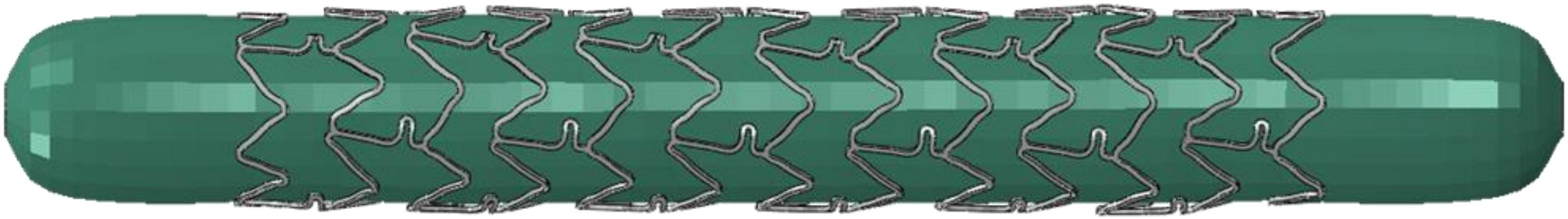
Holzapfel et al. *Am J Physiol Heart Circ Physiol*, 2005

Methods: stent and balloon

- **<u>Multi-Link 8</u>** (Abbott Laboratories, Abbott Park, IL, USA)
  - Bare-metal stent, Co-Cr alloy
  - Size: 3x18 mm

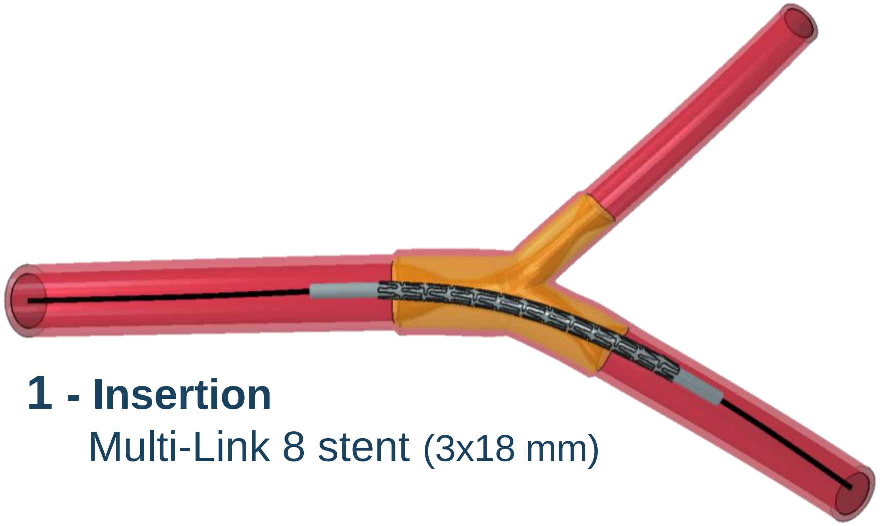
- **Balloon:**
  - Modeled as a straight tube using a simplified approach*
  - Calibrated using the manufacturer compliance chart from 10 atm to 14 atm
    (nominal pressure = 10 atm, burst pressure = 18 atm)





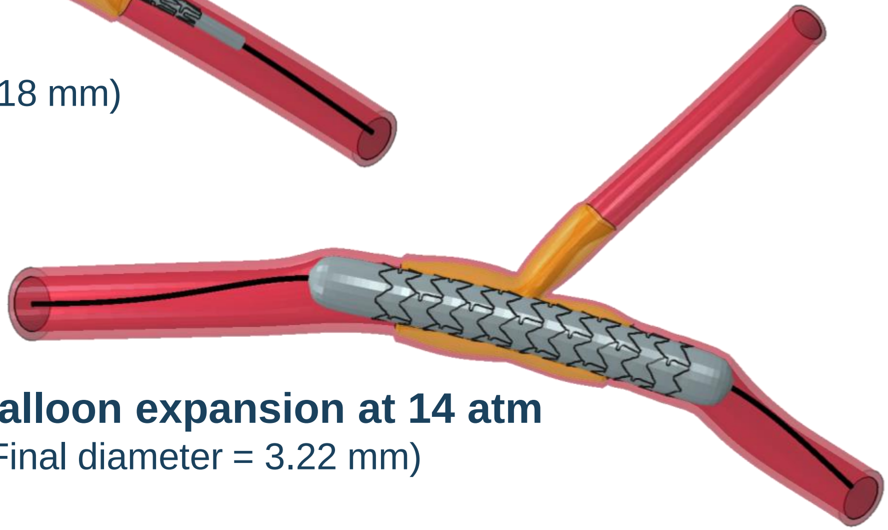
Kiousis et al. *Int J Num Methods Eng*, 2008

Provisional side branch stenting



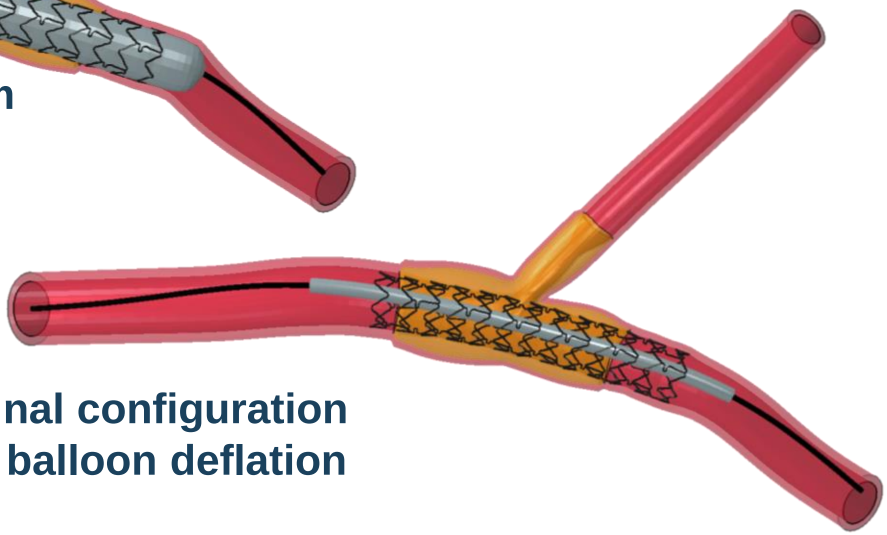
1 - Insertion

Multi-Link 8 stent (3x18 mm)



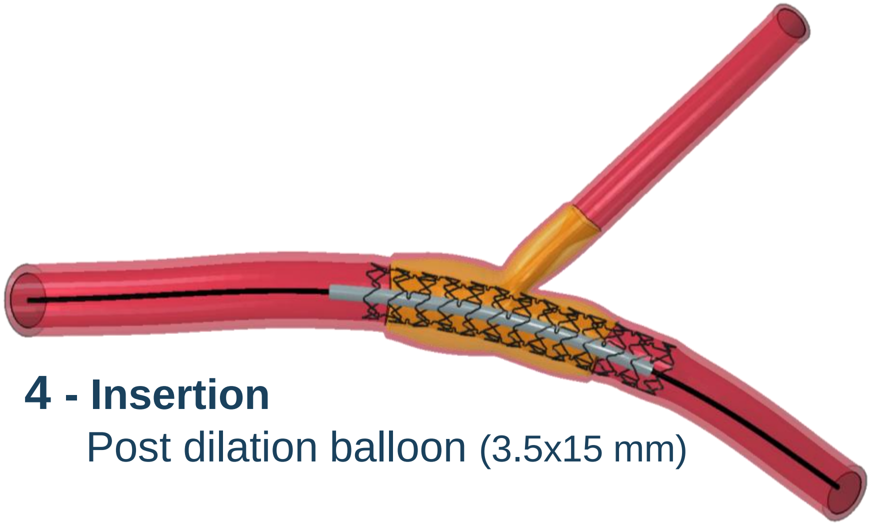
2 - Balloon expansion at 14 atm

(Final diameter = 3.22 mm)

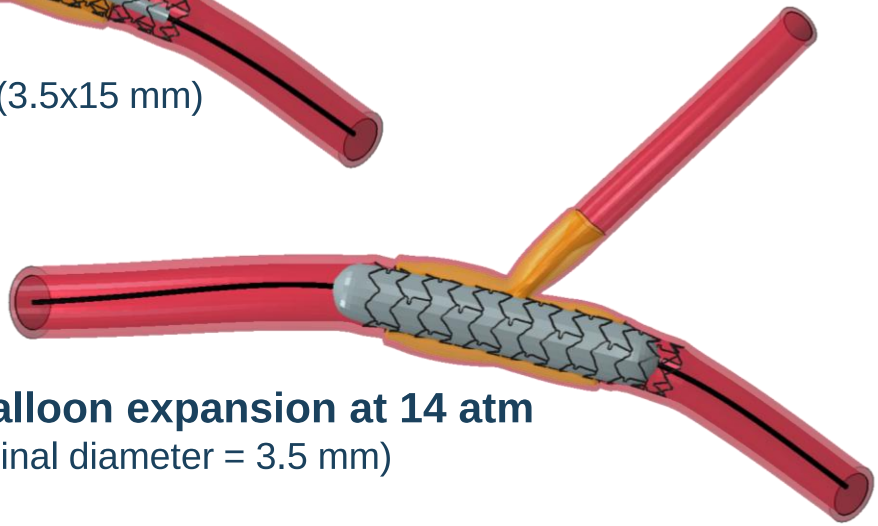


3 - Final configuration after balloon deflation

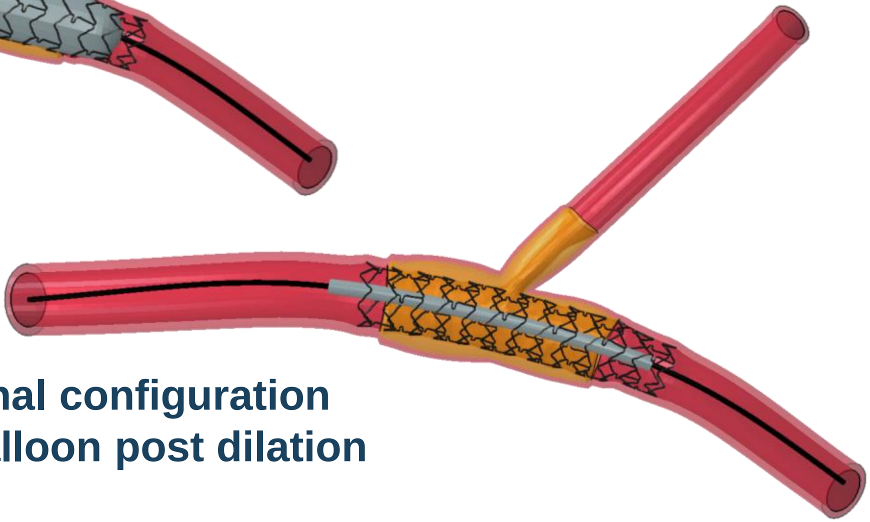
Provisional side branch stenting



4 - Insertion
Post dilation balloon (3.5x15 mm)



5 - Balloon expansion at 14 atm
(Final diameter = 3.5 mm)



6 - Final configuration after balloon post dilation

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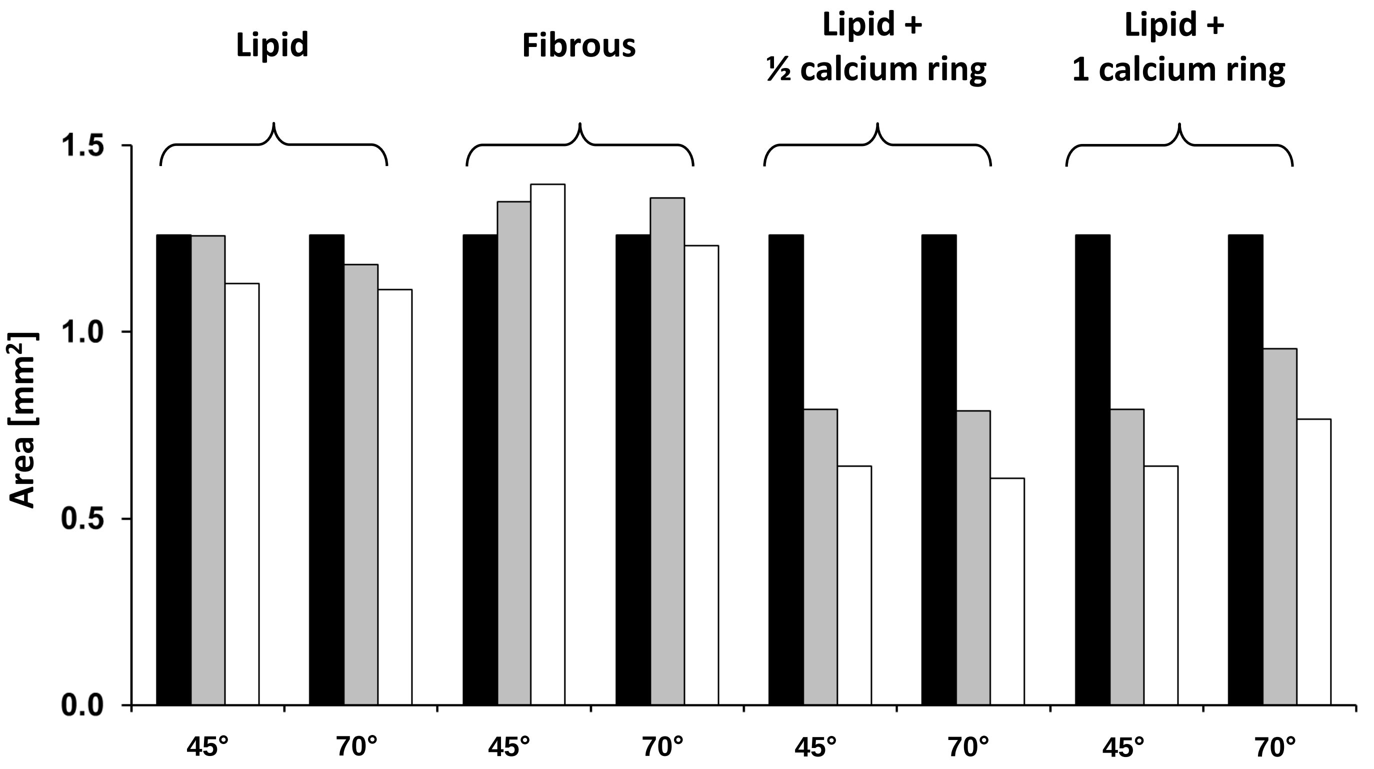
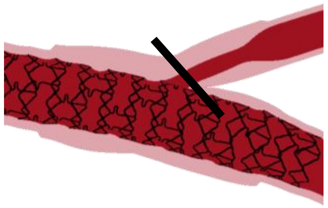
Results: Side branch lumen area





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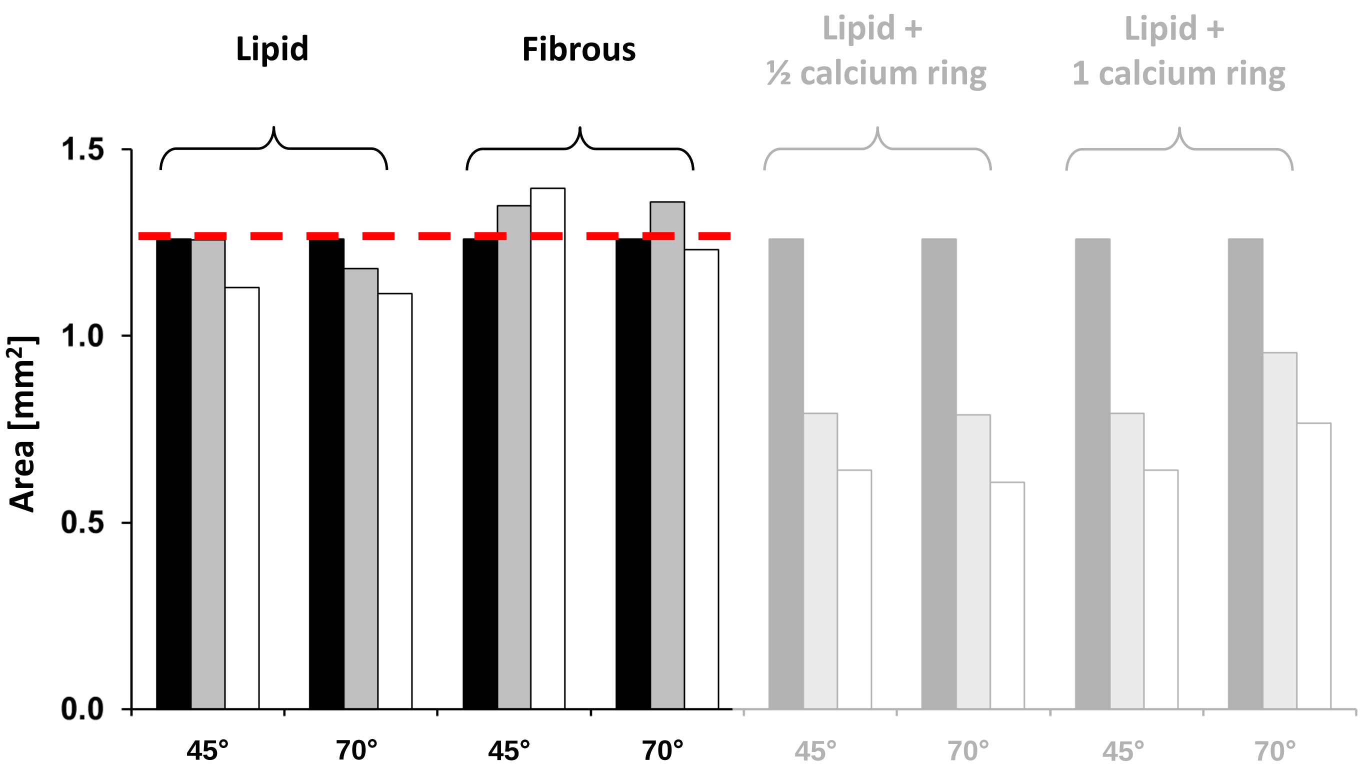
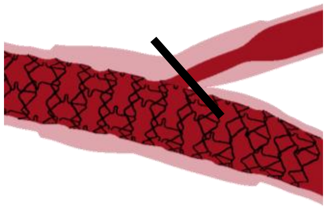
Results: Side branch lumen area

- **Marginal change for <u>lipid</u> and <u>fibrous</u> cases**
  - ⇨ more influence on lumen shape





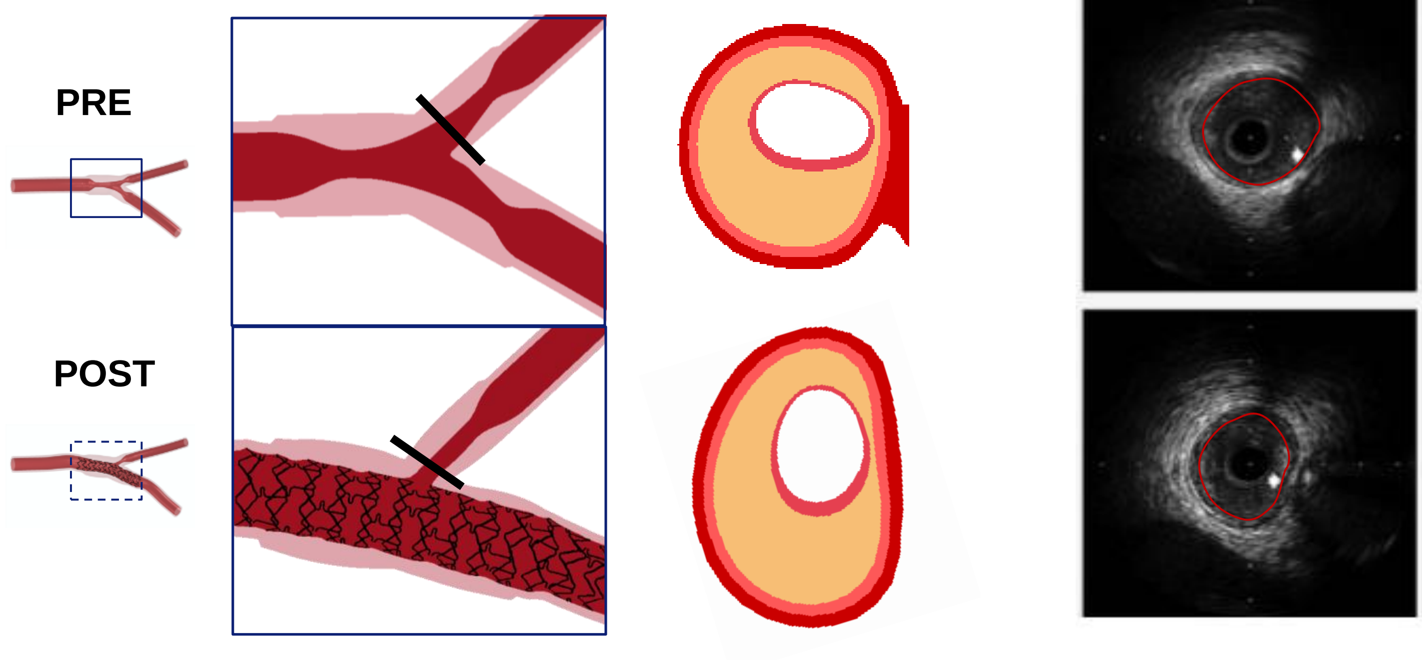
Results: Side branch lumen area

- **Marginal change for <u>lipid</u> and <u>fibrous</u> cases**
  ⇨ more influence on lumen shape

- **Angiographic pictures depending on the angle can mislead interpretation of the outcomes** ⇨ good FFR values even when the angiographic result is not optimal

Simulation
(fibrous plaque - 70°)

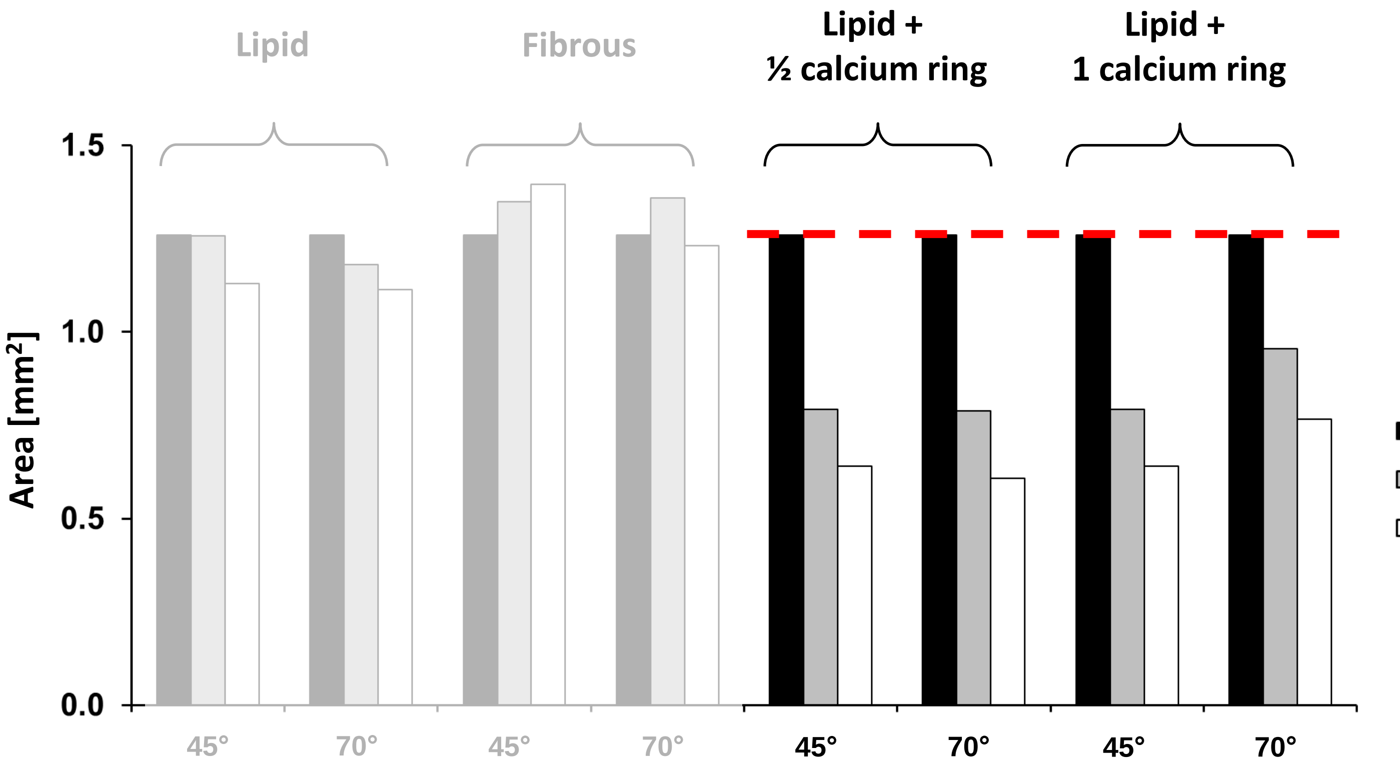
Xu et al. 2012

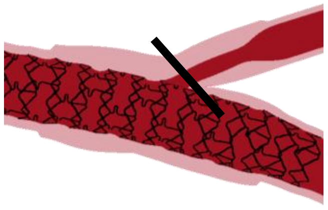


Xu et al. *Circ Cardiovasc Interv*, 2012

Results: Side branch lumen area

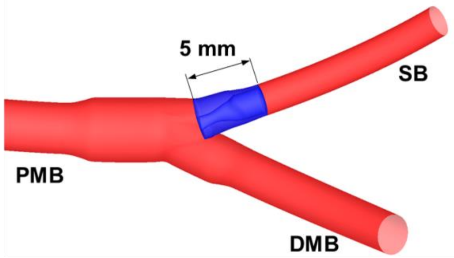
- Significant change for cases with <u>calcium plaques</u>

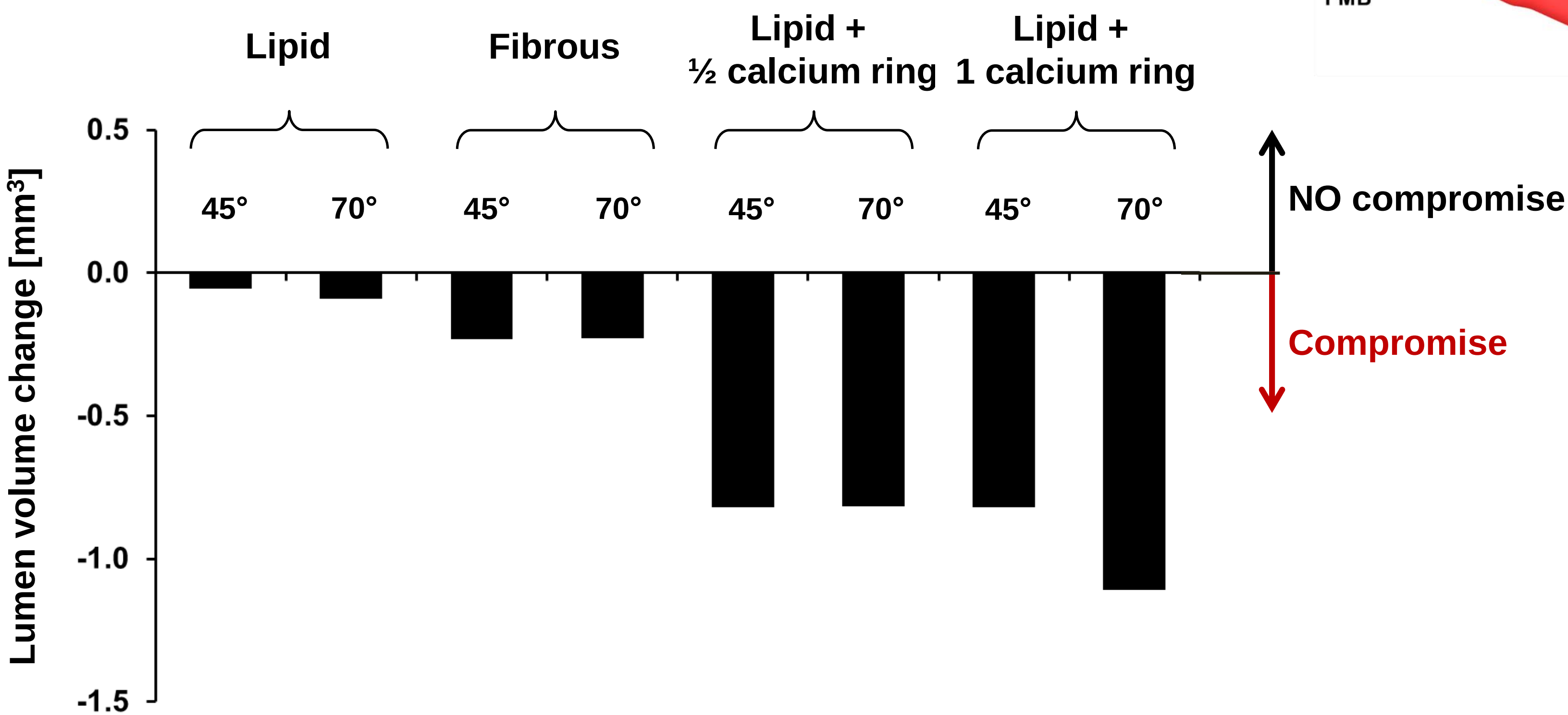




Results: Side branch compromise

- Volumetric analysis





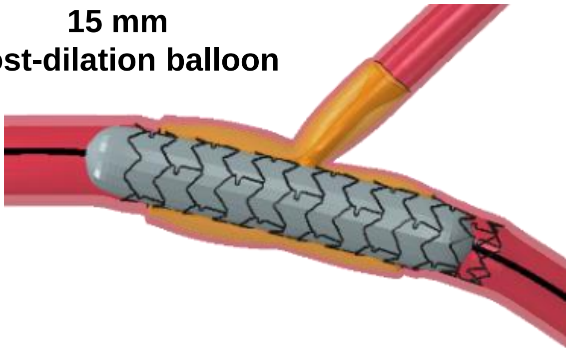
SB compromise* = lumen volume decrease in the SB segment after MB stenting

* Xu et al. *Circ Cardiovasc Interv*, 2012

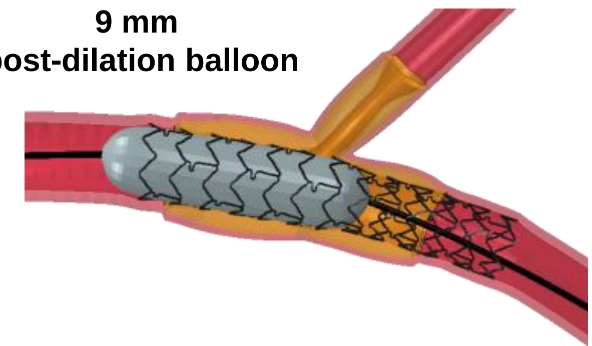
Results: Side branch compromise

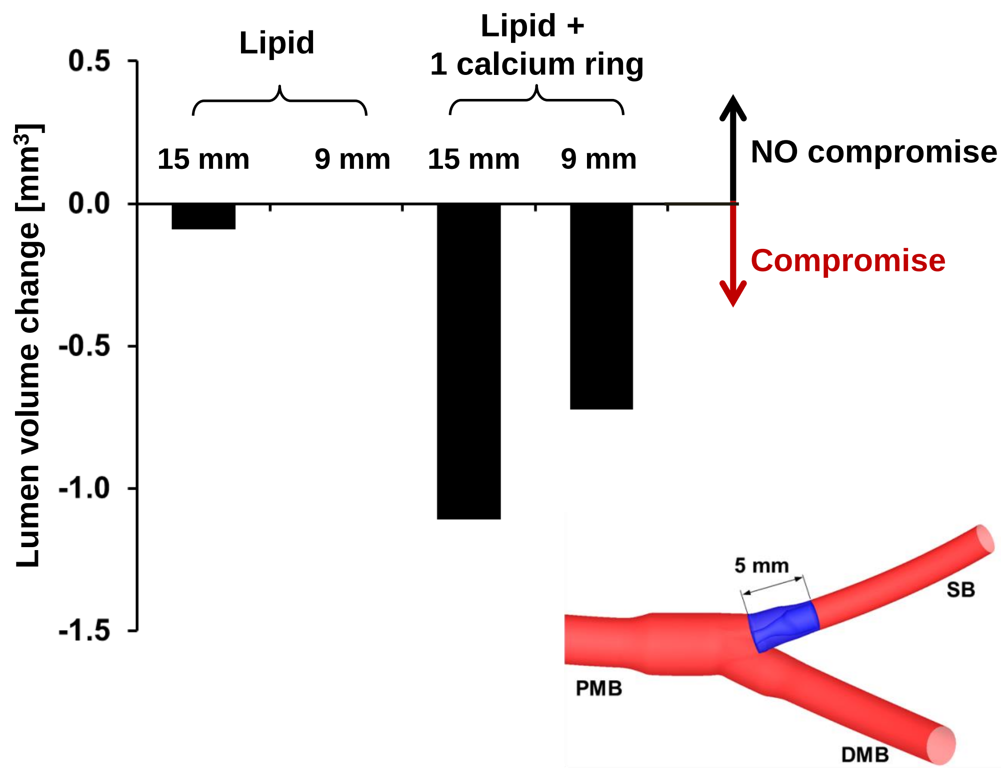
- Volumetric analysis: <u>15 versus 9 mm long post-dilation balloon</u>

**15 mm
post-dilation balloon**



**9 mm
post-dilation balloon**





SB compromise* = lumen volume decrease in the SB segment after MB stenting

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Conclusions (study 1)

- **Development of a parametric model of a coronary bifurcation to investigate side branch compromise after main branch stenting**

CLINICAL CONCLUSIONS

- **Change in side branch ostium shape after stenting but its area remains similar for lipid and fibrous cases**
  - possible misleading interpretation of the outcomes from angiography

- **Side branch compromise depends mainly on plaque composition**

- **Side branch compromise is reduced if a shorter post-dilation balloon is used**

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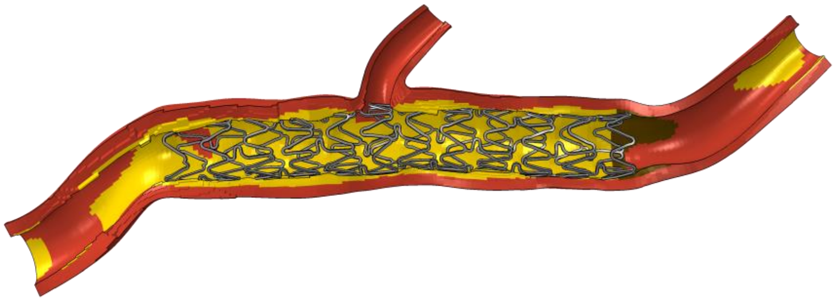
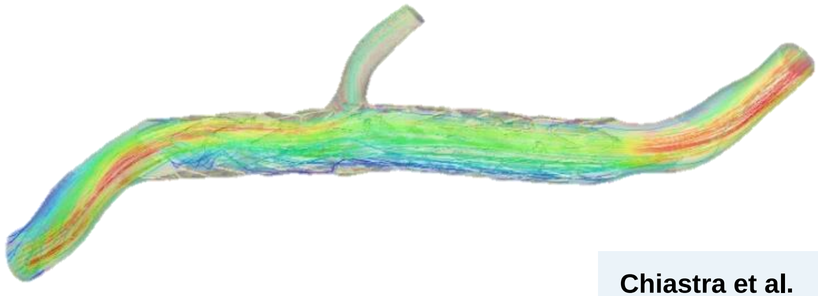
Idealized and patient-specific studies

- Side branch compromise after main vessel stenting (study 1)

Iannaccone, Chiastra et al.
EuroInterv, 2017

- **Computational replication of stenting procedure for the treatment of two real clinical cases** (study 2)





Chiastra et al.
***J Biomech*, 2016**

Research group

POLIMI
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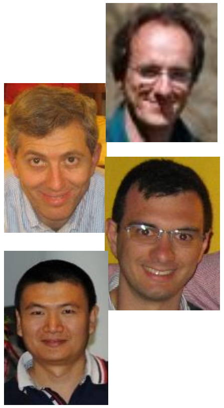
Prof. Francesco Migliavacca

Prof. Gabriele Dubini

Claudio Chiastra, PhD

Wei Wu, PhD



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Ali Aleiou

Benjamin Dickerhoff

Kobe University Graduate School of Medicine
(Kobe, Japan)

Hiromasa Otake, MD

Aims

Patient-specific virtual stenting

of coronary bifurcation models from OCT and CT images

⇩

Replicate the **complete procedure** followed by clinicians

to treat coronary bifurcations

1. Investigation of the **reliability of finite element analyses** in predicting post-operative geometry

2. **Pre-operative virtual planning** to test:

- different stent designs
- different stent positioning

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Aims

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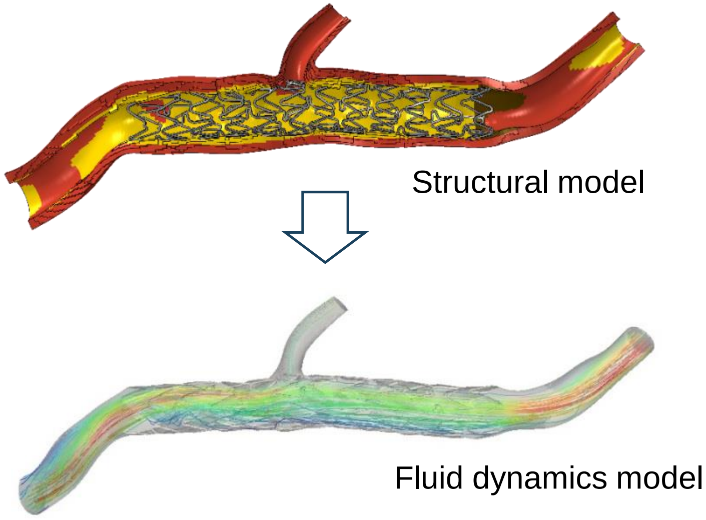
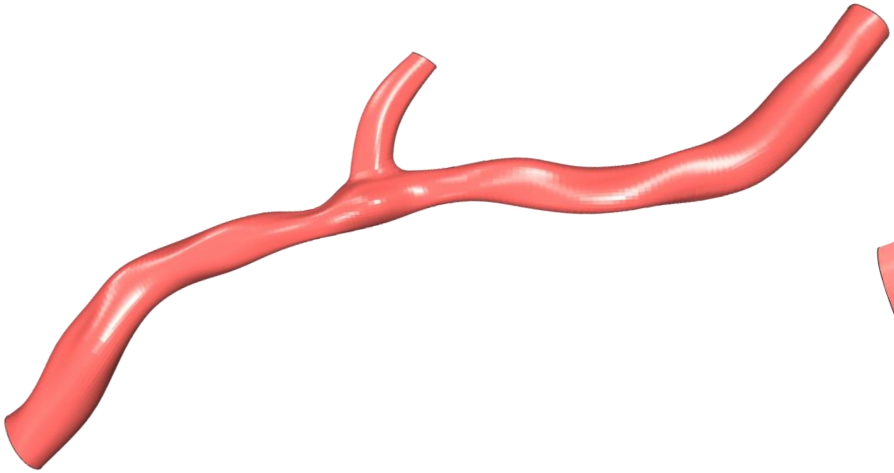


Investigated cases

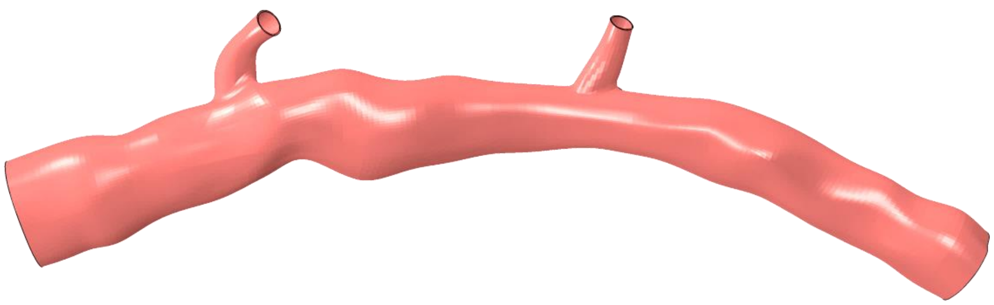
- **Pre / post operative data:**
  - Angiography
  - Computed tomography (CT)
  - Optical coherence tomography (OCT)

Kobe University Graduate School of Medicine (Kobe, Japan)

Case 1
Left anterior descending / diagonal (LAD/D1) bifurcation



Case 2
Left circumflex artery with two branches



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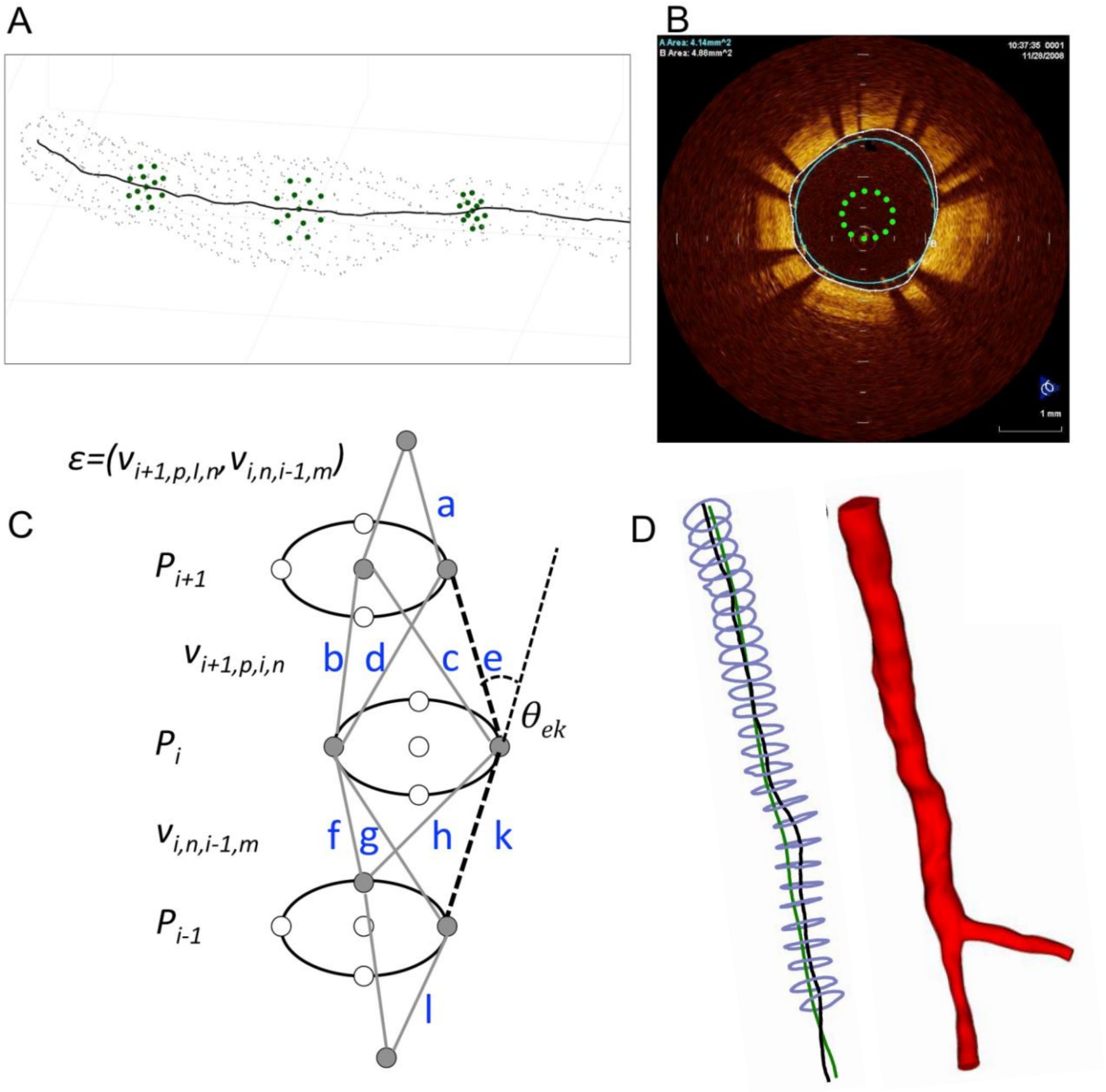
Methods: Vessel lumen model

■ Locating OCT pullback path and reconstructing pre-stenting geometry



A. Position orthogonal sets of coplanar transducer candidate points within coarse volume from CT

B. Segment OCT images into lumen (white) contours containing candidate points (green)

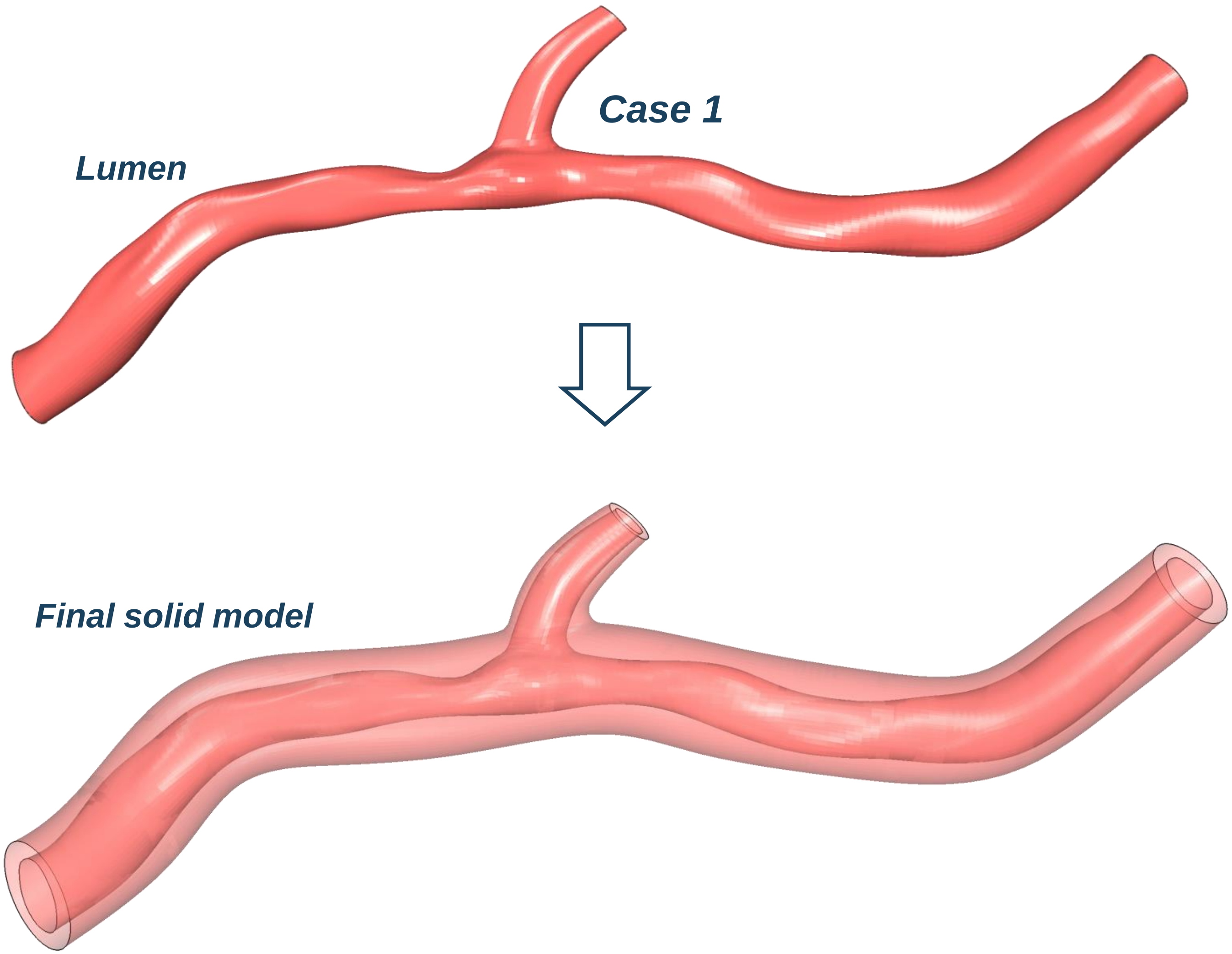
C. Create spatial diagram of a vessel and its graph diagram. Determine the wire pathway with minimum bending energy

D. Register OCT segments (purple) in 3D space and create the vessel lumen model

Ellwein et al. *Cardiovasc Eng Tech*. 2011

Methods: Vessel solid model

- Wall thickness defined according to ex vivo measurements *

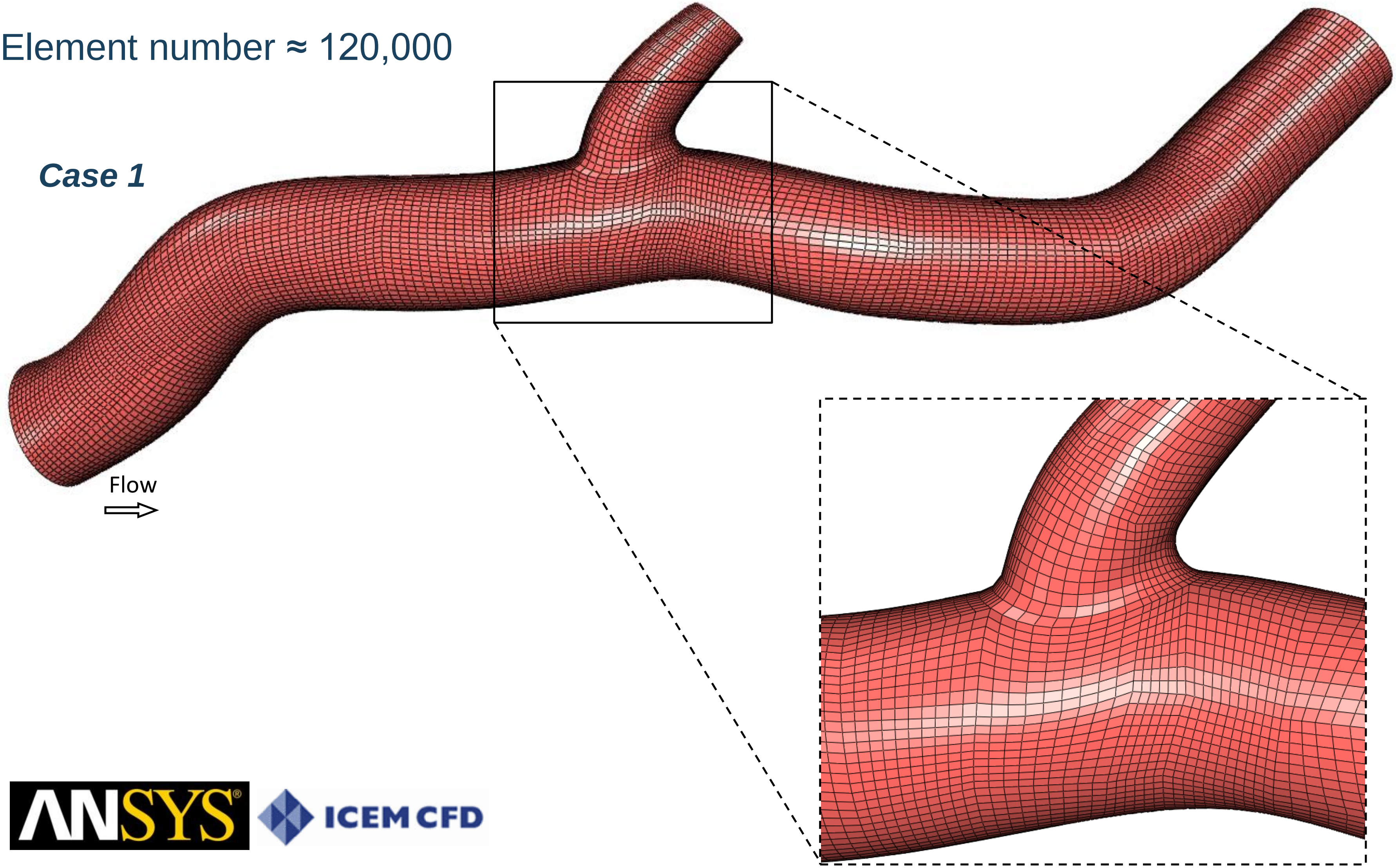


* Holzapfel et al. *Am J Physiol Heart Circ Physiol*, 2005

Methods: Vessel solid model mesh

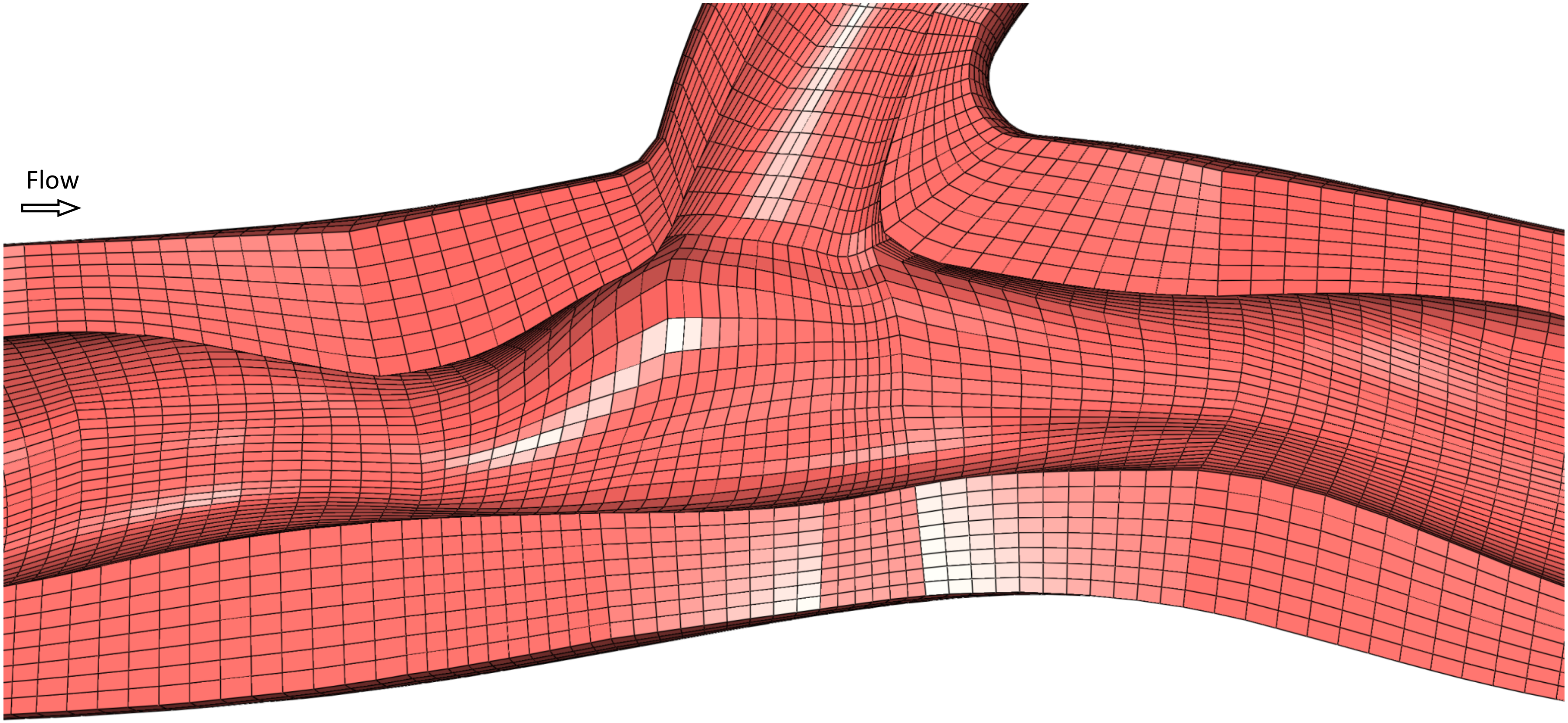
- Hexahedral elements C3D8R
- Element number ≈ 120,000

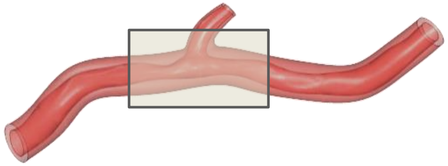
Case 1



Methods: Plaque identification

- Method by Morlacchi et al. (2013)*





* Morlacchi et al. Med Eng Phys, 2013

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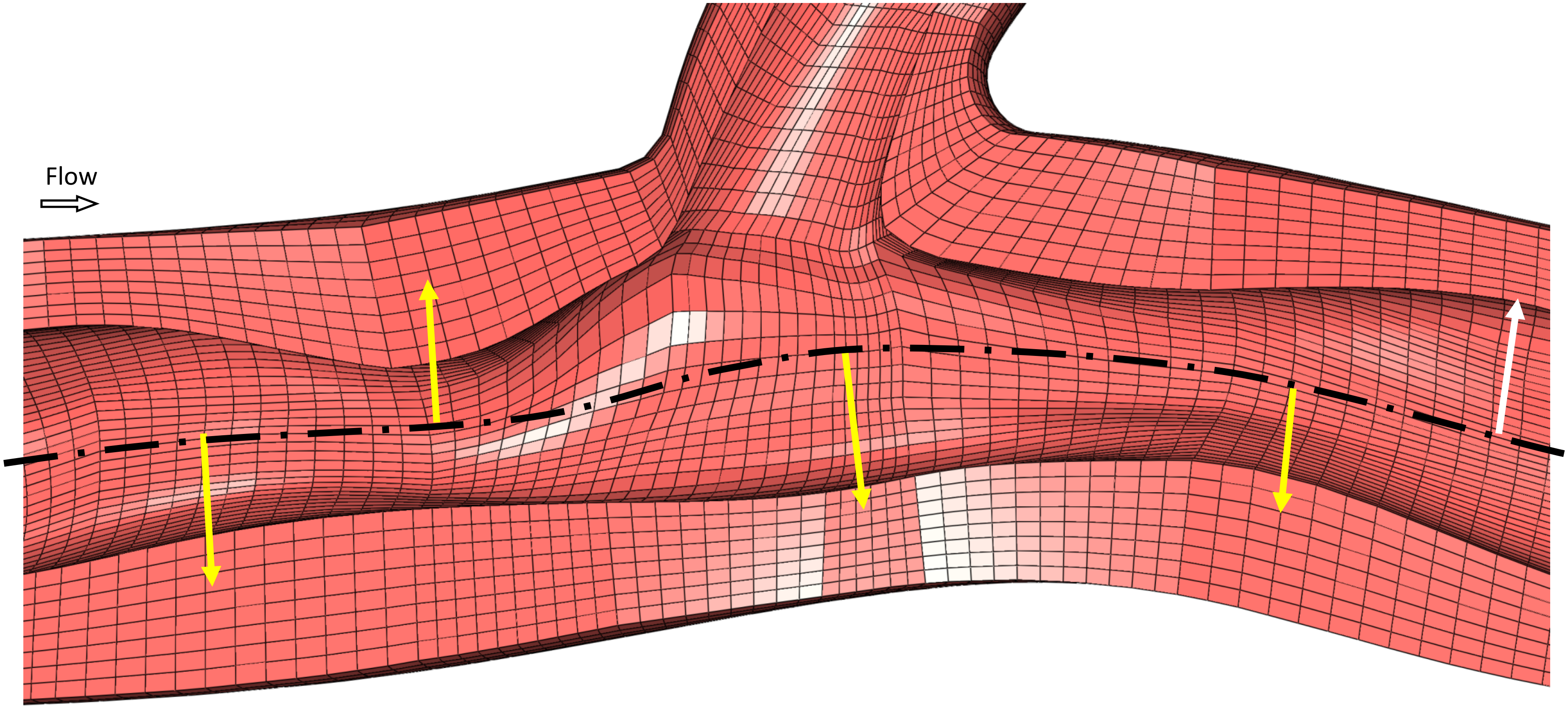

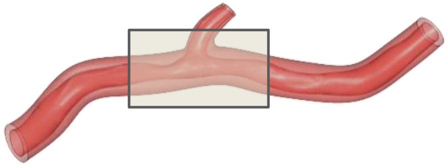

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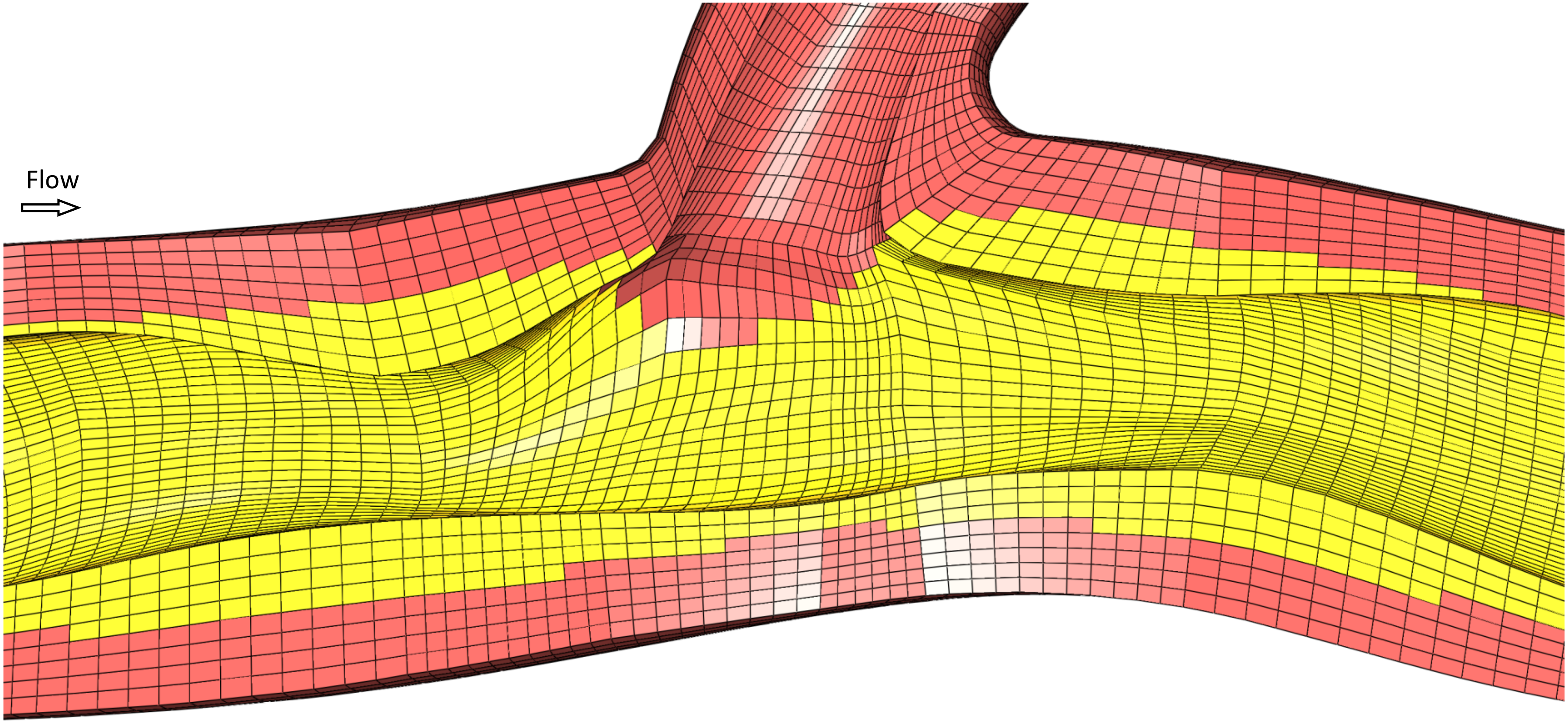
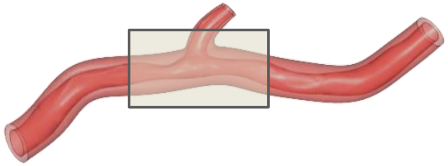
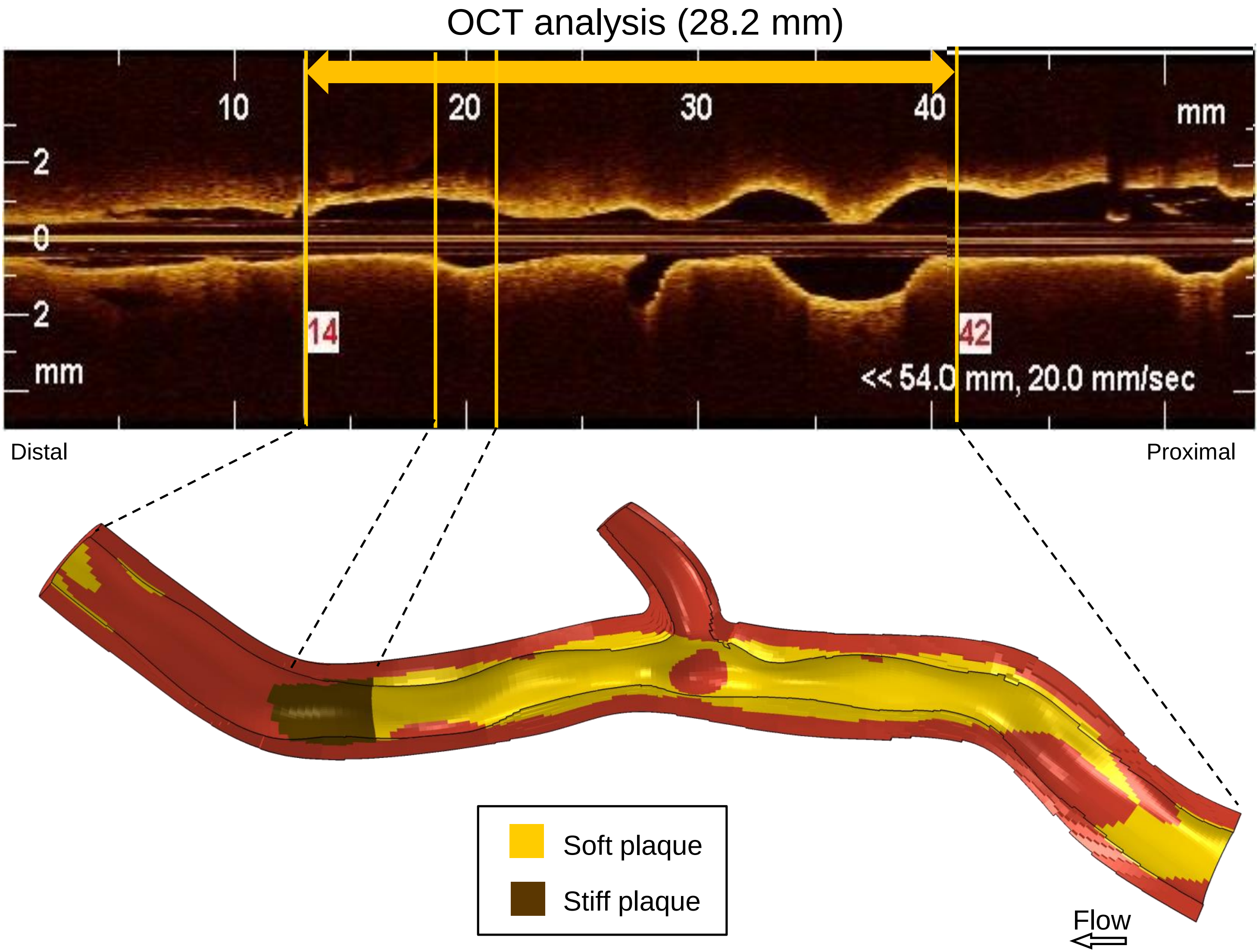




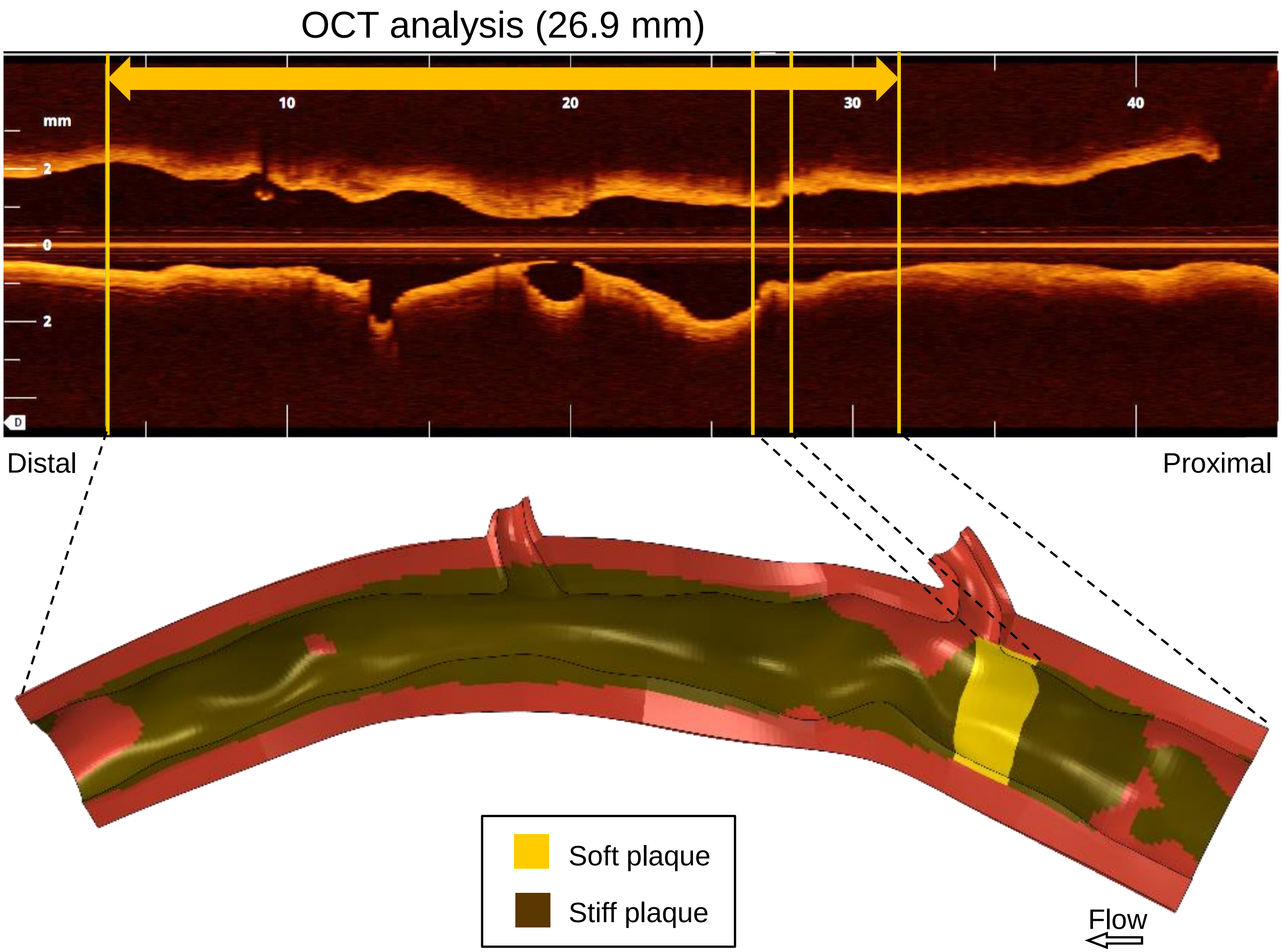
* Morlacchi et al. Med Eng Phys, 2013

- **Physician-guided delineation of plaque components**



Methods: Plaque identification (Case 2)

- **Physician-guided delineation of plaque components**

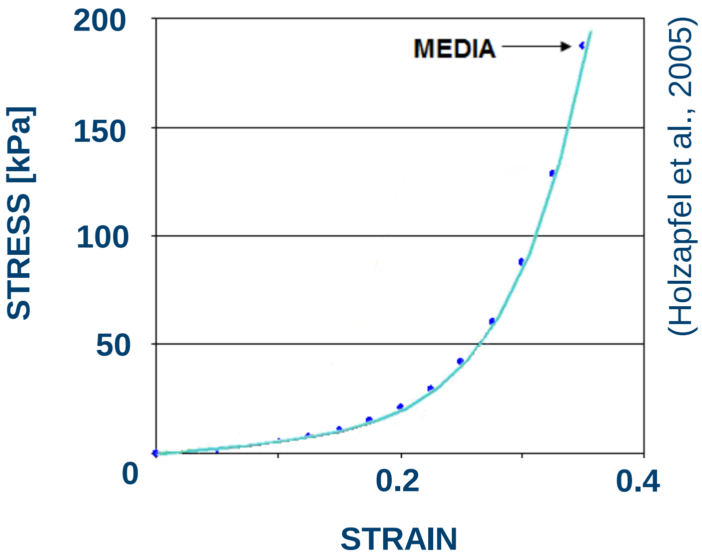


Methods: Material properties

■ Arterial wall

Isotropic hyperelastic constitutive law based on a sixth order polynomial strain energy density function

⇩

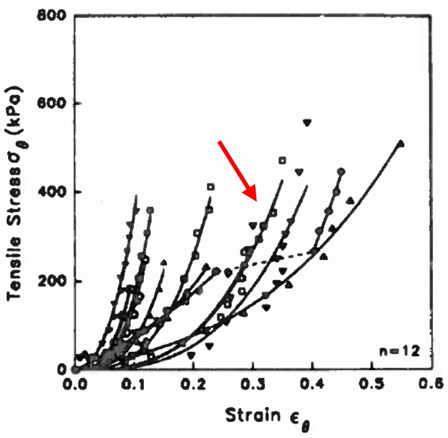


■ Soft / stiff plaque

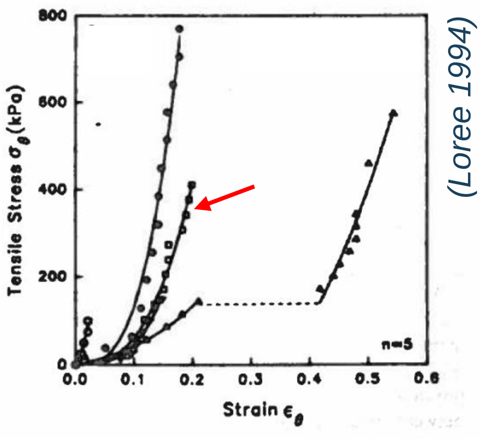
Isotropic hyperelastic behavior with ideal plasticity at mean value of plaque rupture

⇩

Soft plaque



Stiff plaque



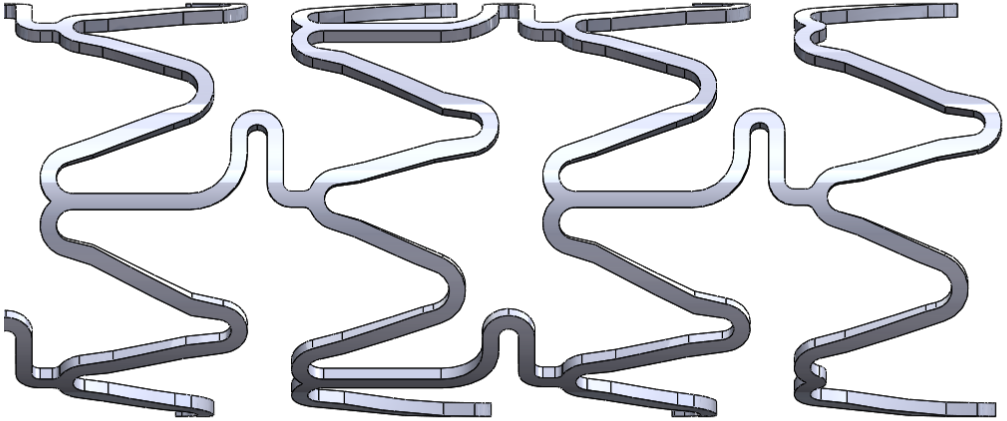
Loree et al. *J Biomech*, 1994
Holzapfel et al. *Am J Physiol Heart Circ Physiol*, 2005

Methods: Stent

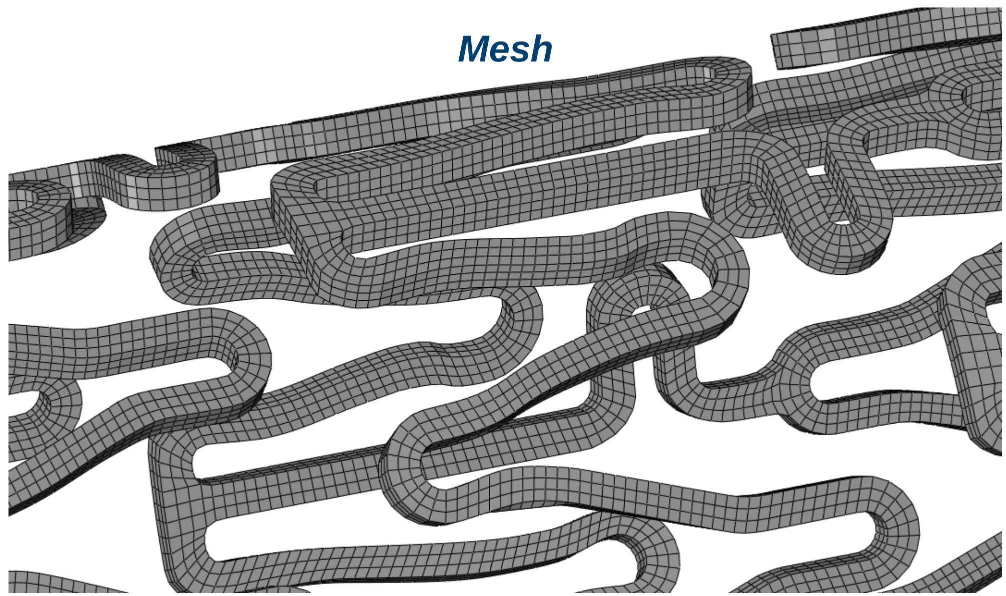
■ **XIENCE PRIME®** (Abbott Vascular, USA)

Length = 18 mm
Diameter = 2.5 mm (Case 1)
= 3.5 mm (Case 2)
Strut thickness = **81 µm**

CAD model



Mesh



Material: L-605 Co-Cr alloy elasto-plastic with kinematic hardening

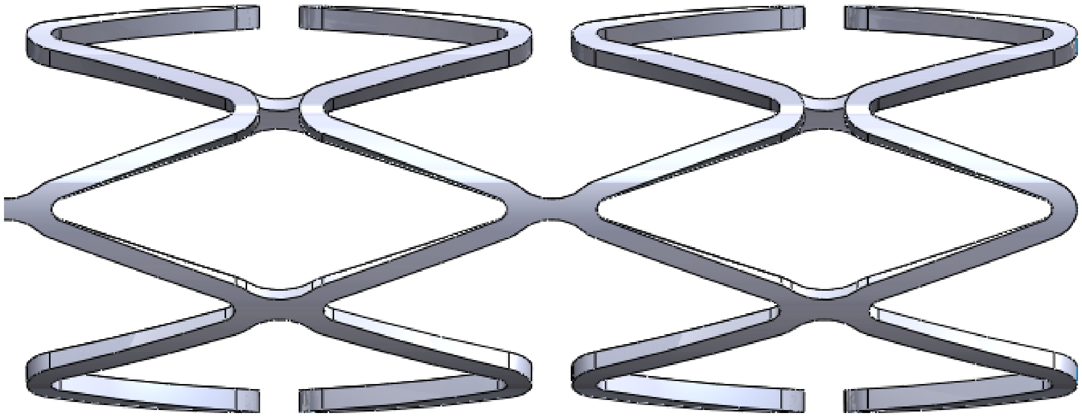
Mesh: highly regular hexahedral mesh, ≈100,000 volume C3D8R elements

Methods: Stent

- **NOBORI®** (Terumo, Japan)

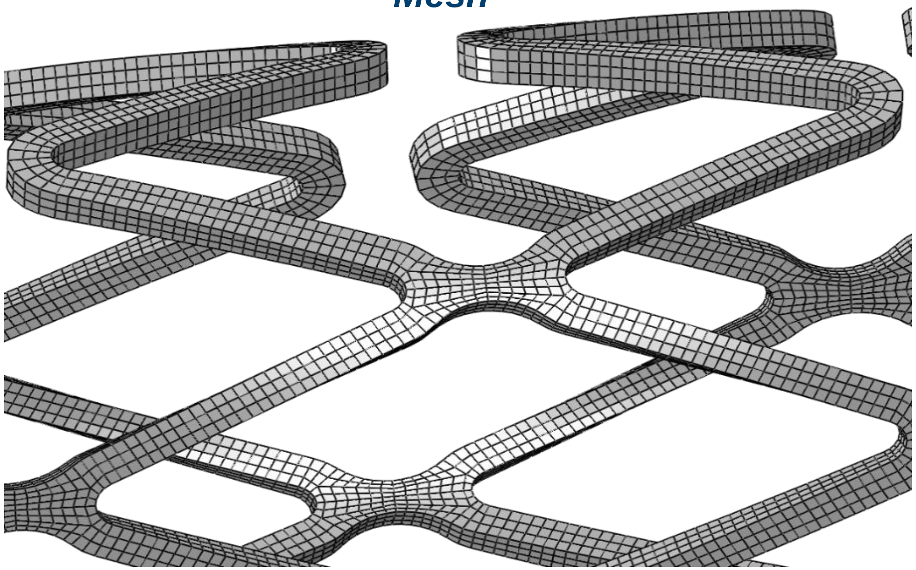
Length = 18 mm
Diameter = 2.5 mm (Case 1)
= 3.5 mm (Case 2)
Strut thickness = **125 µm**

CAD model



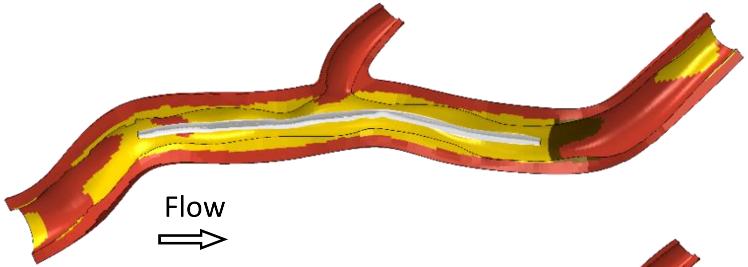
Material: L-605 Co-Cr alloy elasto-plastic with kinematic hardening

Mesh

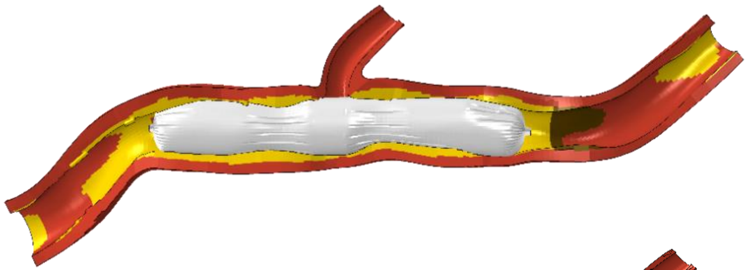


Mesh: highly regular hexahedral mesh, ≈100,000 volume C3D8R elements

Stenting procedure (Case 1)

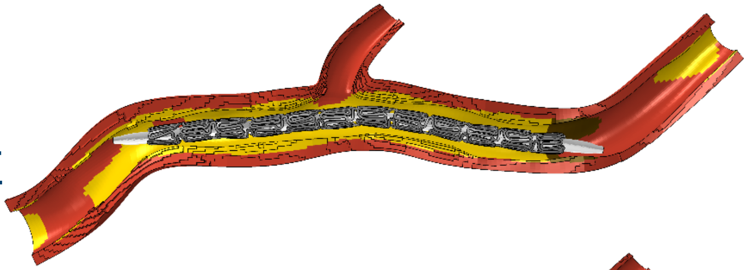


1. Angioplasty
(2.5x18 mm balloon positioning)

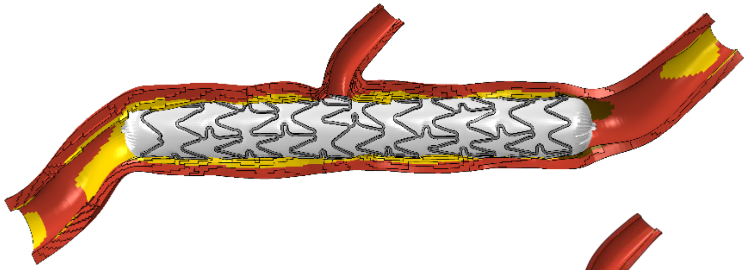


2. Angioplasty (balloon expansion)

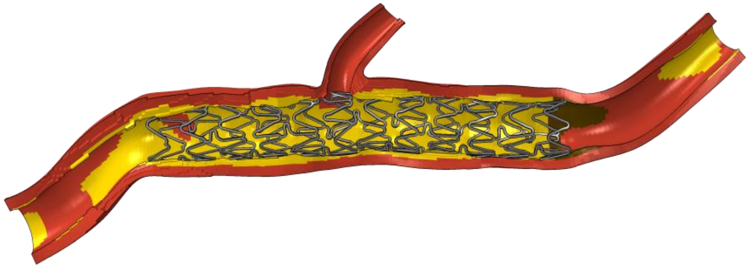
3. Provisional technique
(2.5x18 mm XIENCE PRIME stent insertion)



4. Provisional technique
(stent expansion)



5. Provisional technique
(stent release)



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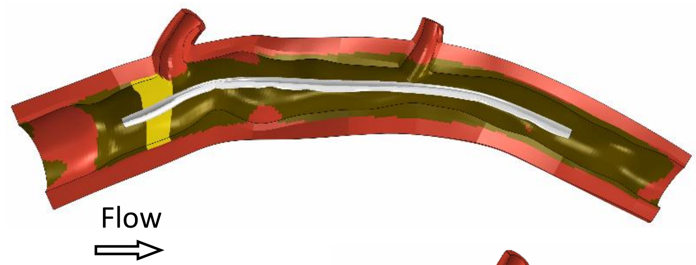
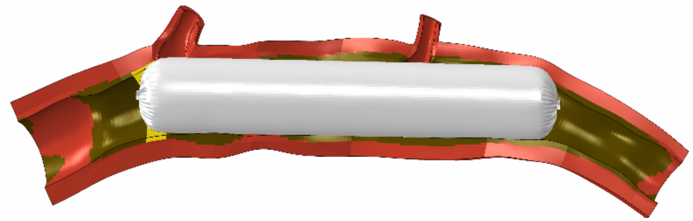
Stenting procedure (Case 2)

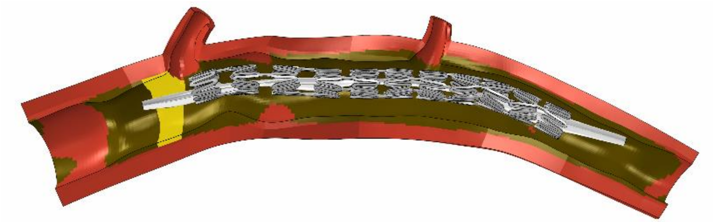


1. Angioplasty
(3.5x18 mm balloon positioning)

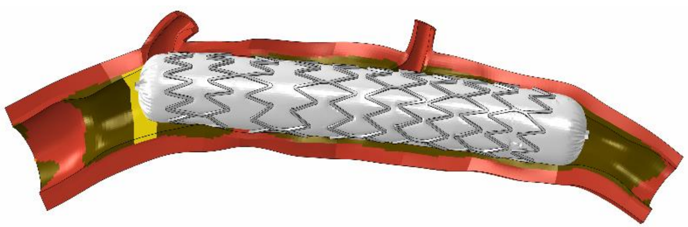


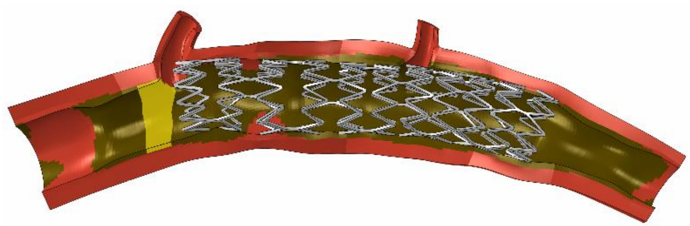
2. Angioplasty (balloon expansion)

3. Provisional technique
(3.5x18 mm NOBORI stent insertion)



4. Provisional technique
(stent expansion)





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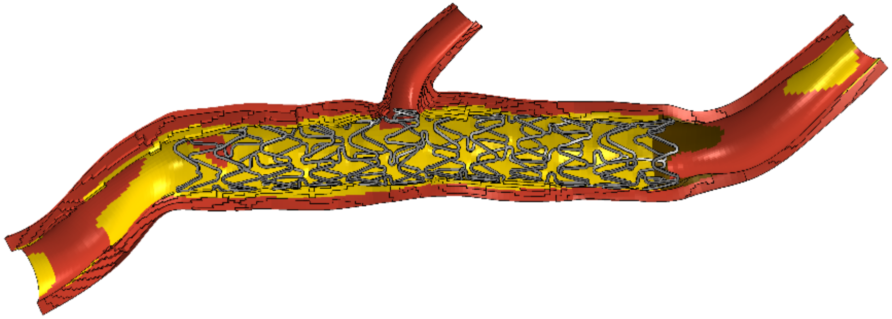
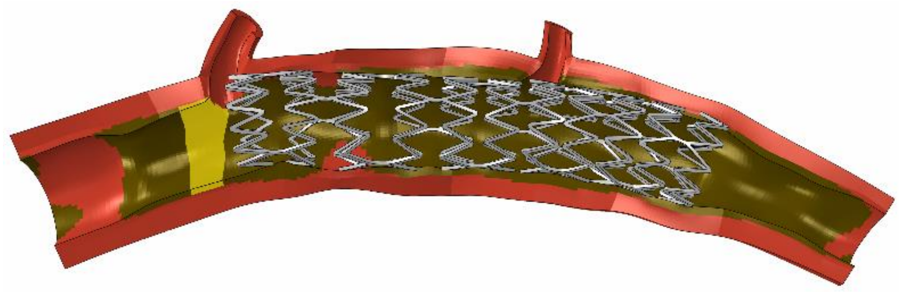
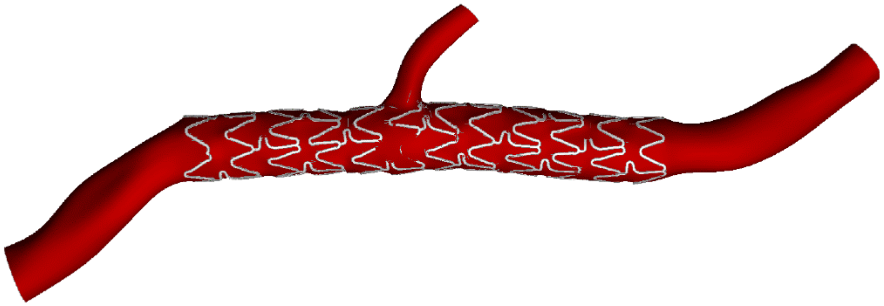
From structural to fluid dynamics simulations

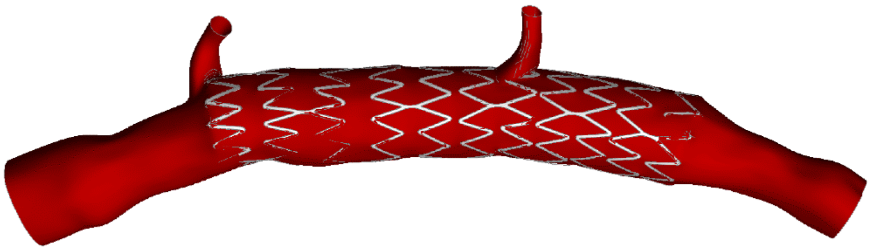
Case 1

Case 2





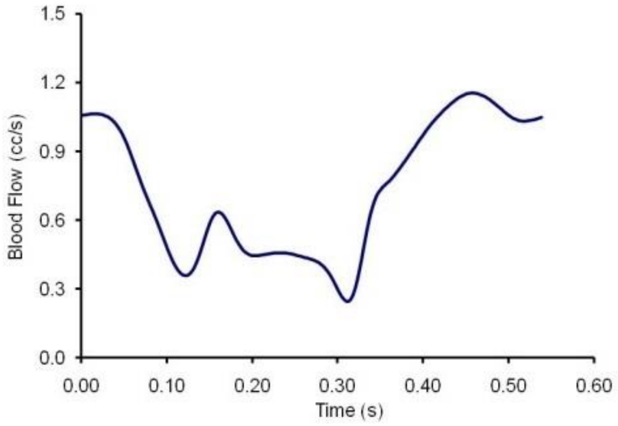




Fluid dynamics methods

- **Inflow waveforms*** and estimates of **downstream vascular resistances** implemented from previous studies**

Inlet



Aimed Pressure [mmHg]

Systolic - 77
Mean - 68
Diastolic - 59

Additional details:

- μ = 4.0 cP
  ρ = 1.06 g/cm^3
- Vessel walls assumed to be rigid after stenting*

	Case 1	
	MV	SB
Q (mL/sec)	1.32	0.24
R_c (dyn·s·cm^{-5})	16,400	46,600
C (cm^5/dyn)	9.0E-07	5.5E-07
R_d (dyn·s·cm^{-5})	43,600	292,000

*LaDisa et al. *J Appl Physiol*, 2002 **Van Huis et al. *AJP - Heart*, 1987

Fluid dynamics methods

- **Inflow waveforms*** and estimates of **downstream vascular resistances** implemented from previous studies**

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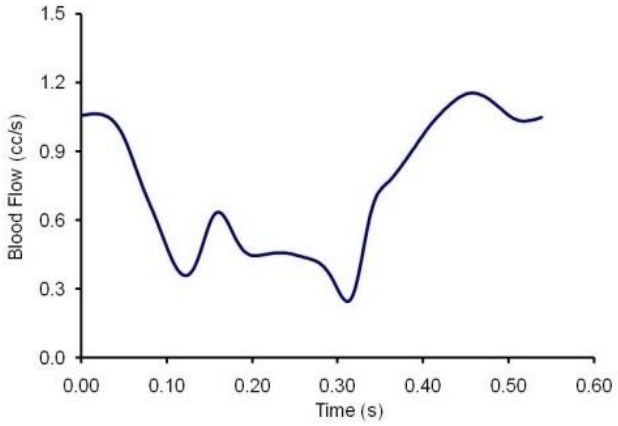

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Diastolic - 59

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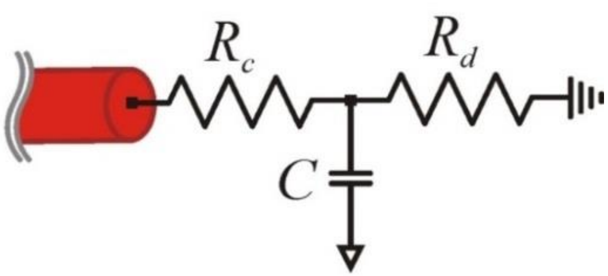
  ρ = 1.06 g/cm^3
- Vessel walls assumed to be rigid after stenting*

Outlets



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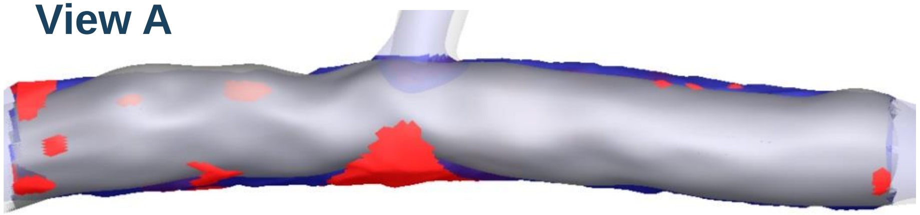
Validation of the structural model

- From patient images
- Simulation
- Distance > 0.25 mm

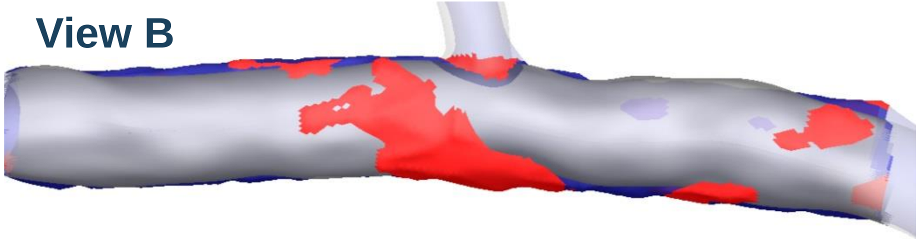
Case 1

View A



Flow

View B



Flow

Perc. diff = 14.8 %

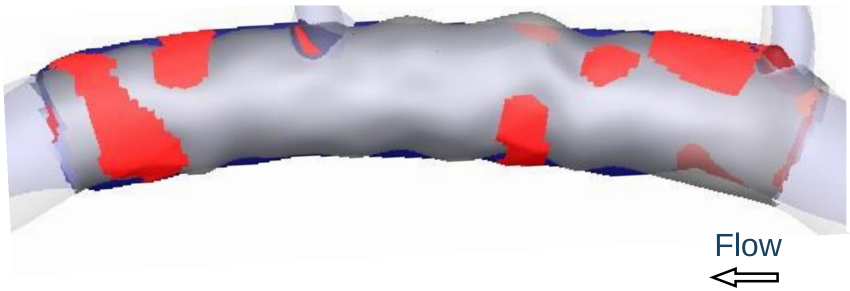
(threshold = 0.25 mm)

Case 2

View A

Flow

View B



Flow

Perc. diff = 20.3 %

(threshold = 0.25 mm)

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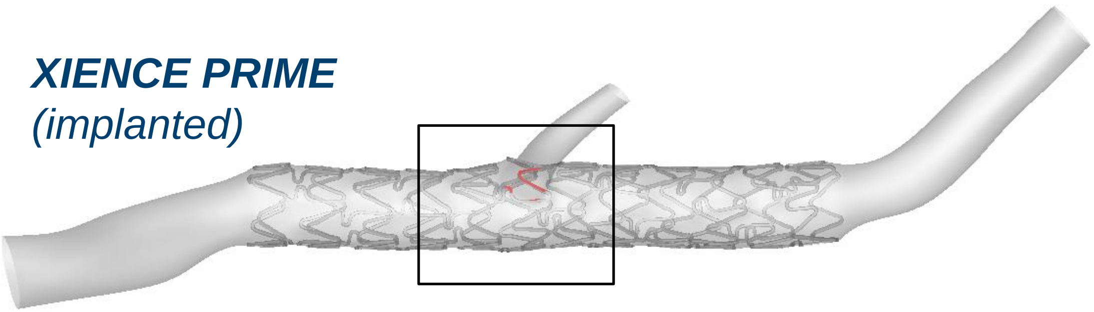
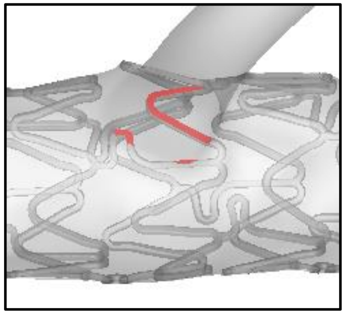
■ Malapposition

Flow ⇦

XIENCE PRIME (implanted)



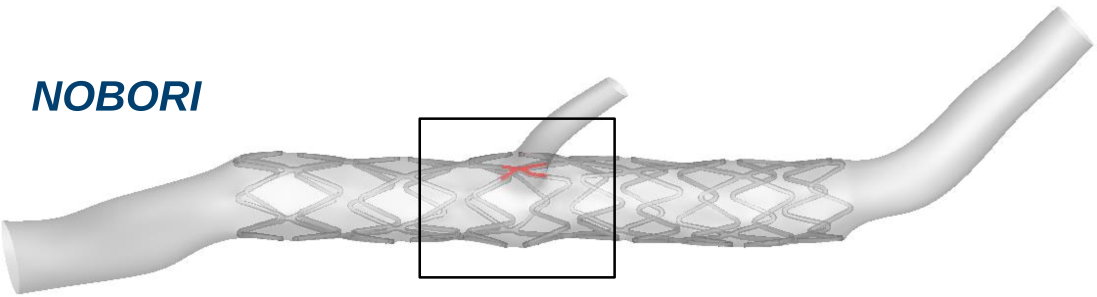
Flow ⇨

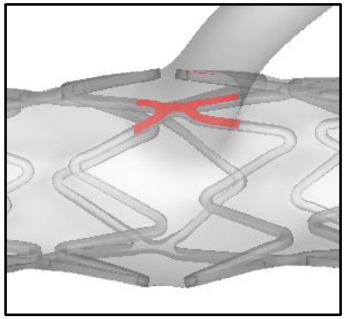


Malapp. = 0.9 %

- Malapposed
- Well-apposed

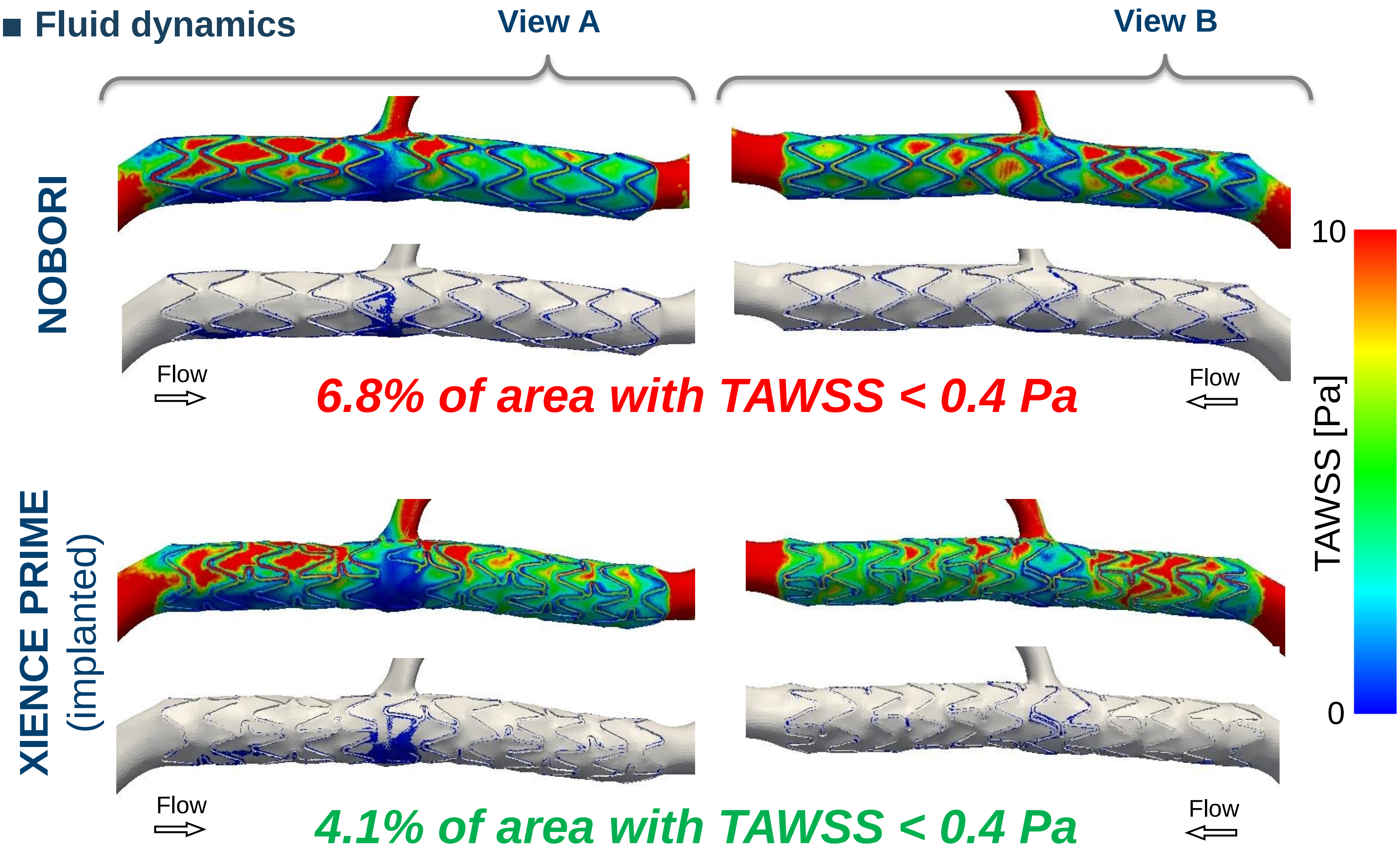
NOBORI





Malapp. = 1.5 %

- **Fluid dynamics**



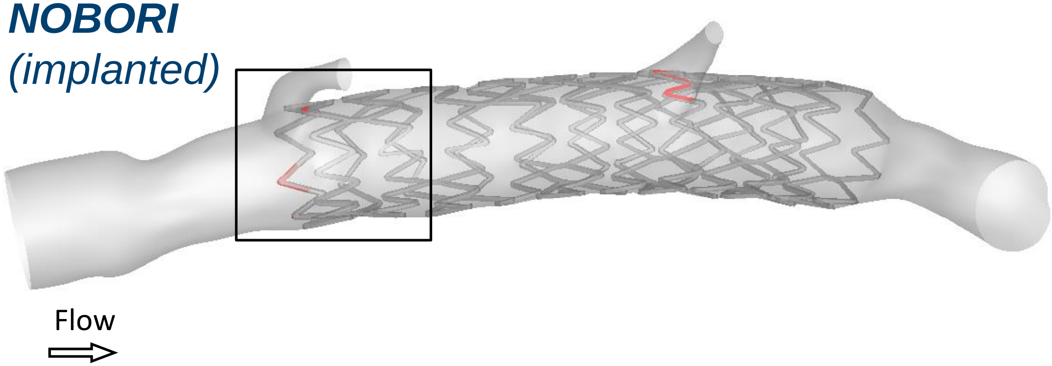
6.8% of area with TAWSS < 0.4 Pa

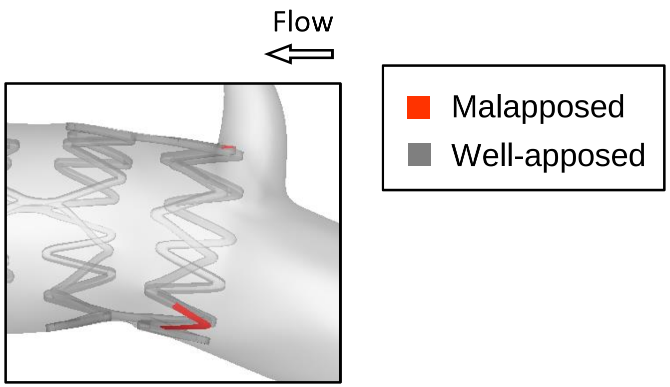
4.1% of area with TAWSS < 0.4 Pa

Pre-clinical planning: optimal stent choice (Case 2)

- **Malapposition**

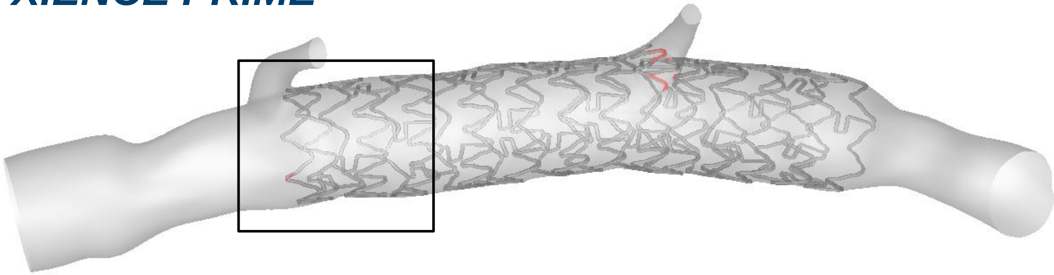
NOBORI
(implanted)

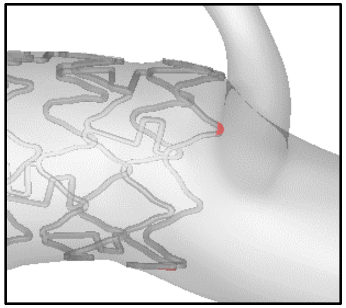




Malapp. = 2.4 %

XIENCE PRIME

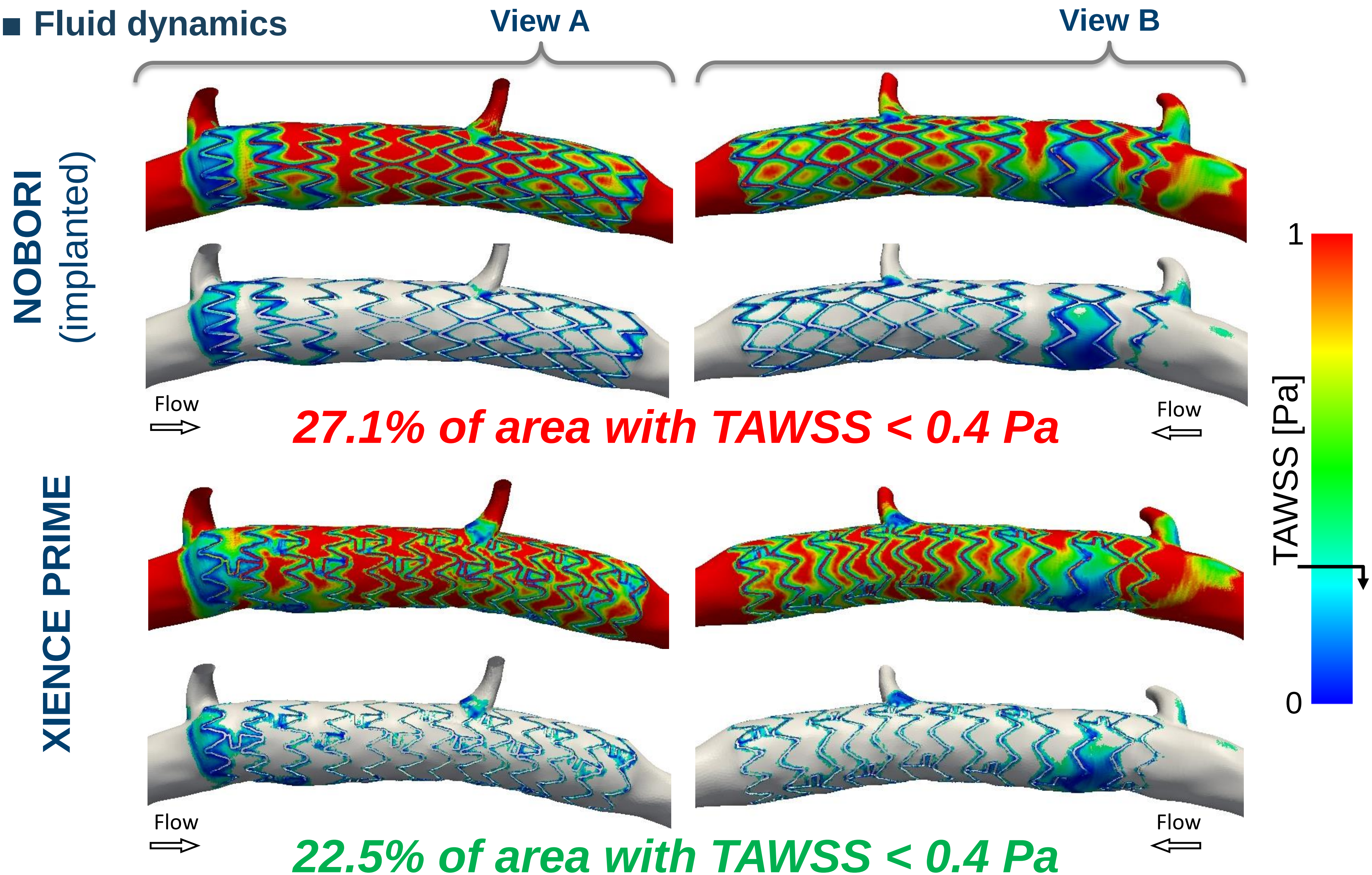




Malapp. = 0.9 %

Pre-clinical planning: optimal stent choice (Case 2)

- **Fluid dynamics**



27.1% of area with TAWSS < 0.4 Pa

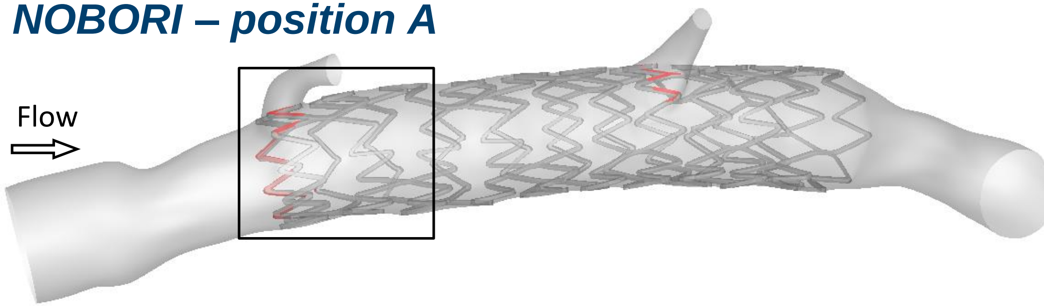
22.5% of area with TAWSS < 0.4 Pa

Pre-clinical planning: stent positioning (Case 2)

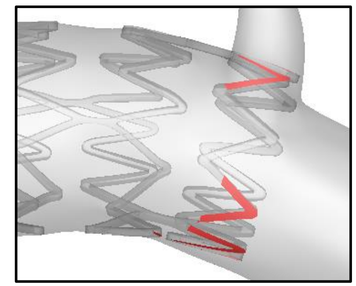
■ Malapposition

NOBORI – position A

Flow



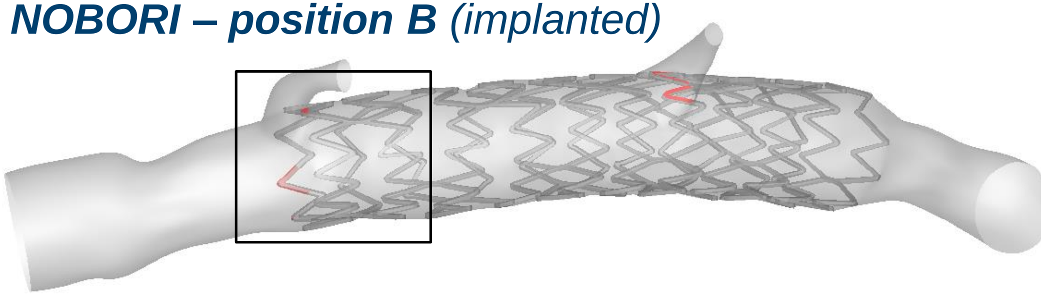
Flow

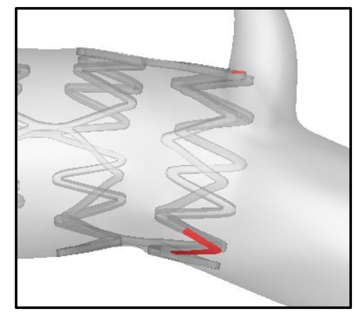


Malapp. = 4.9 %

- Malapposed
- Well-apposed

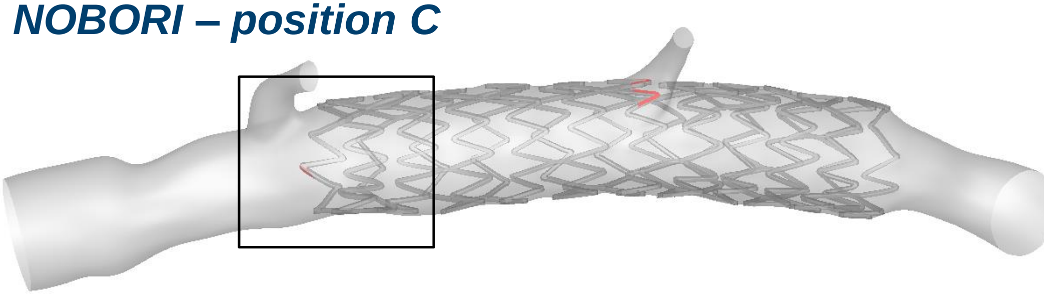
NOBORI – position B (implanted)

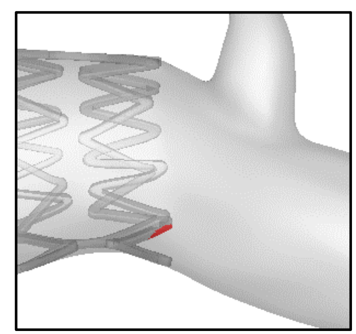




Malapp. = 2.4 %

NOBORI – position C





Malapp. = 1.3 %

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Conclusions (study 2)

- Creation of **coronary bifurcation models from CT** and **OCT**, including **plaque composition**

- **Virtual stenting methodology** able to replicate **real clinical cases**

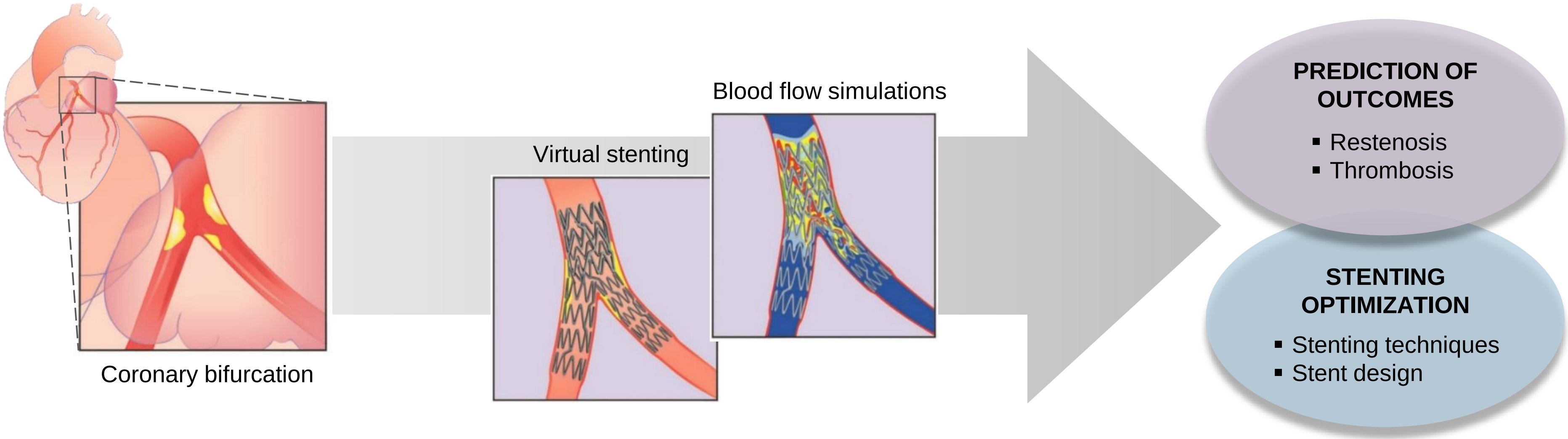
- **Reasonable agreement** between the **post-operative geometry** obtained after **virtual expansion** and the one created from **patient images**

- **Pre-clinical planning** using a sequential method (mechanical + fluid dynamics simulations) to find
  - the best stent design
  - the best stent position
  - the best stenting technique

Overall conclusions

- **Computer simulations** (mechanical + fluid dynamics analyses)

  ⇨ **powerful tool for investigating coronary stents**



- **High-performance computing fundamental** for running those simulations efficiently, reliably and fast

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Thank you for your attention

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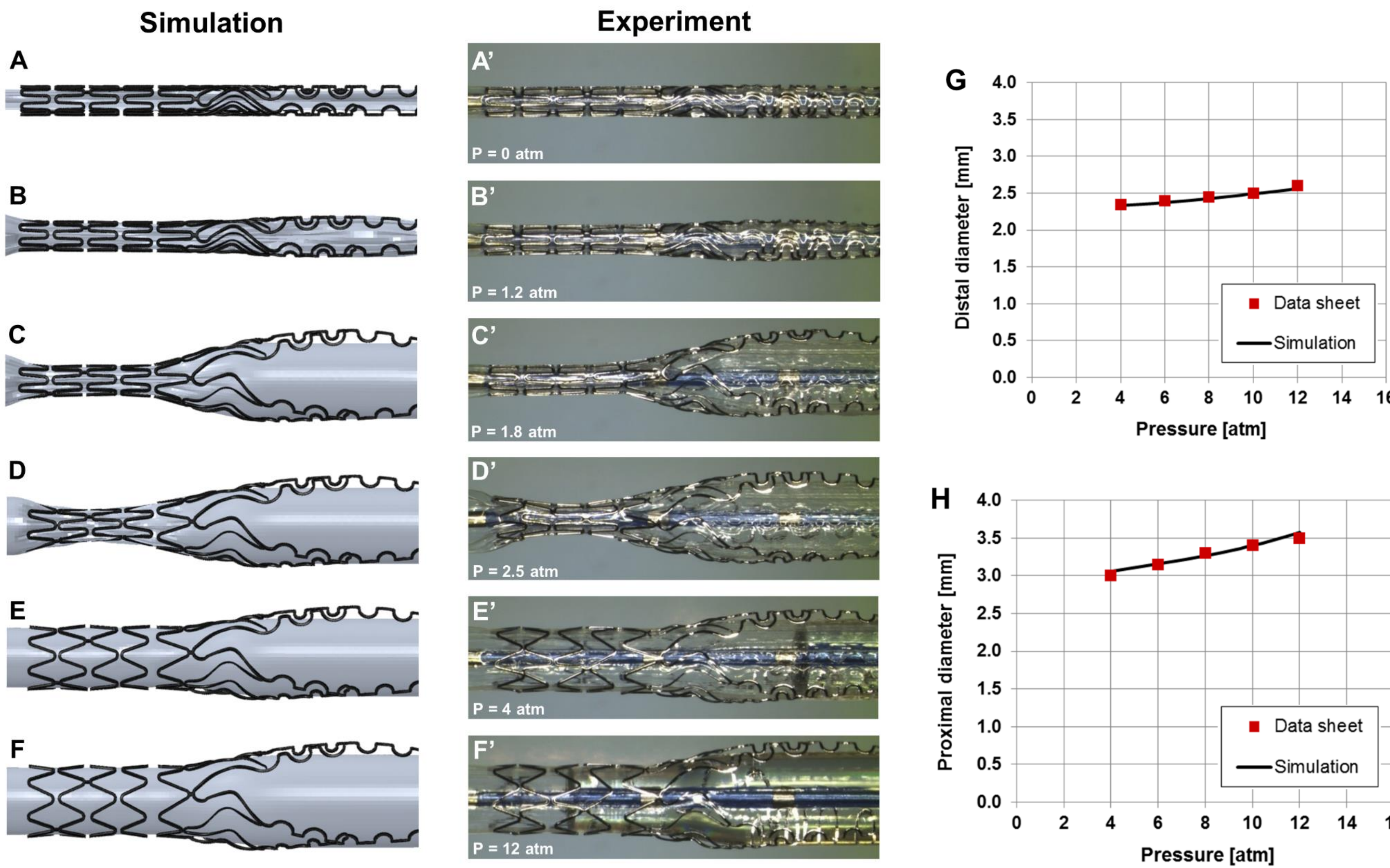
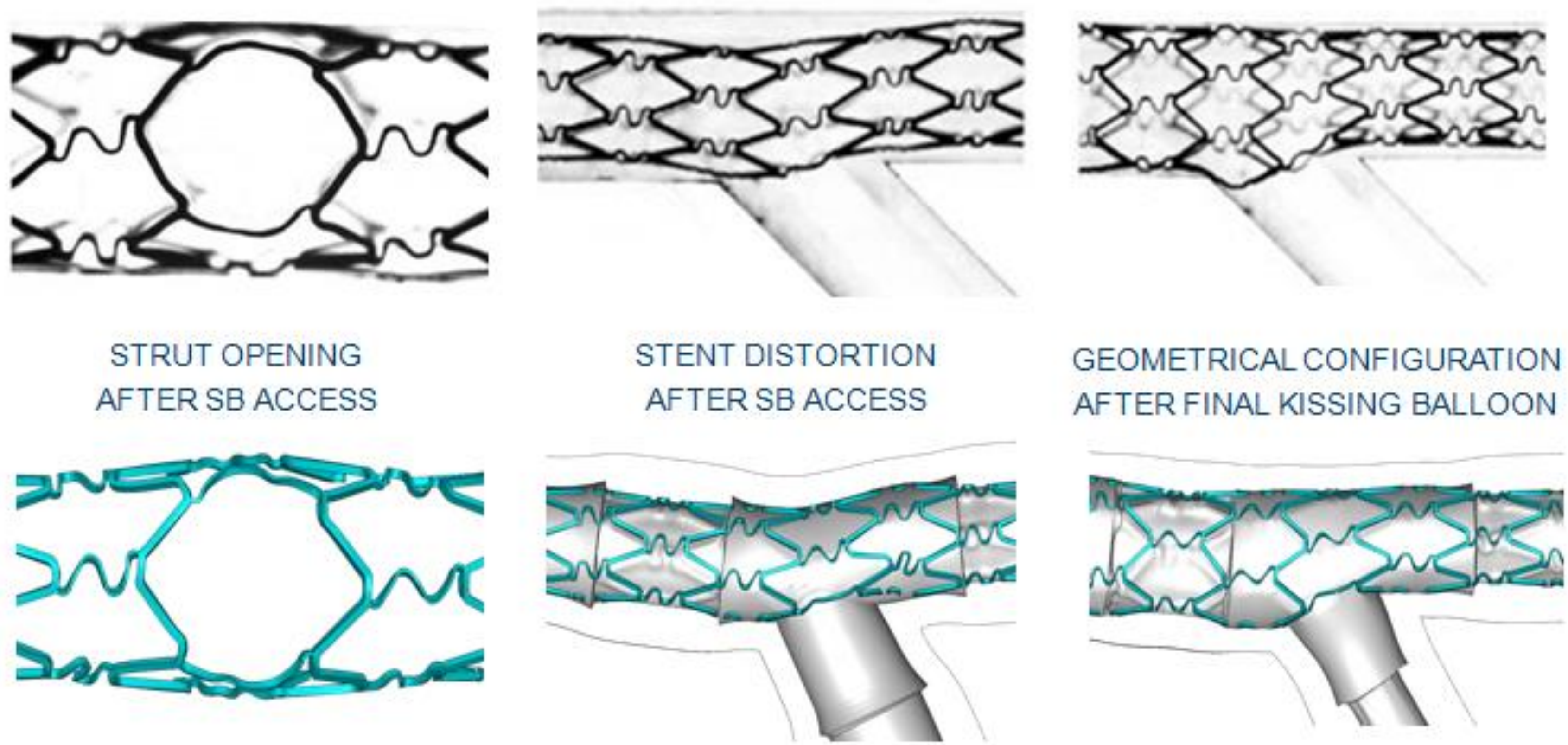
Validation of numerical simulations



Chiastra et al. *Eurointervention*, 2015

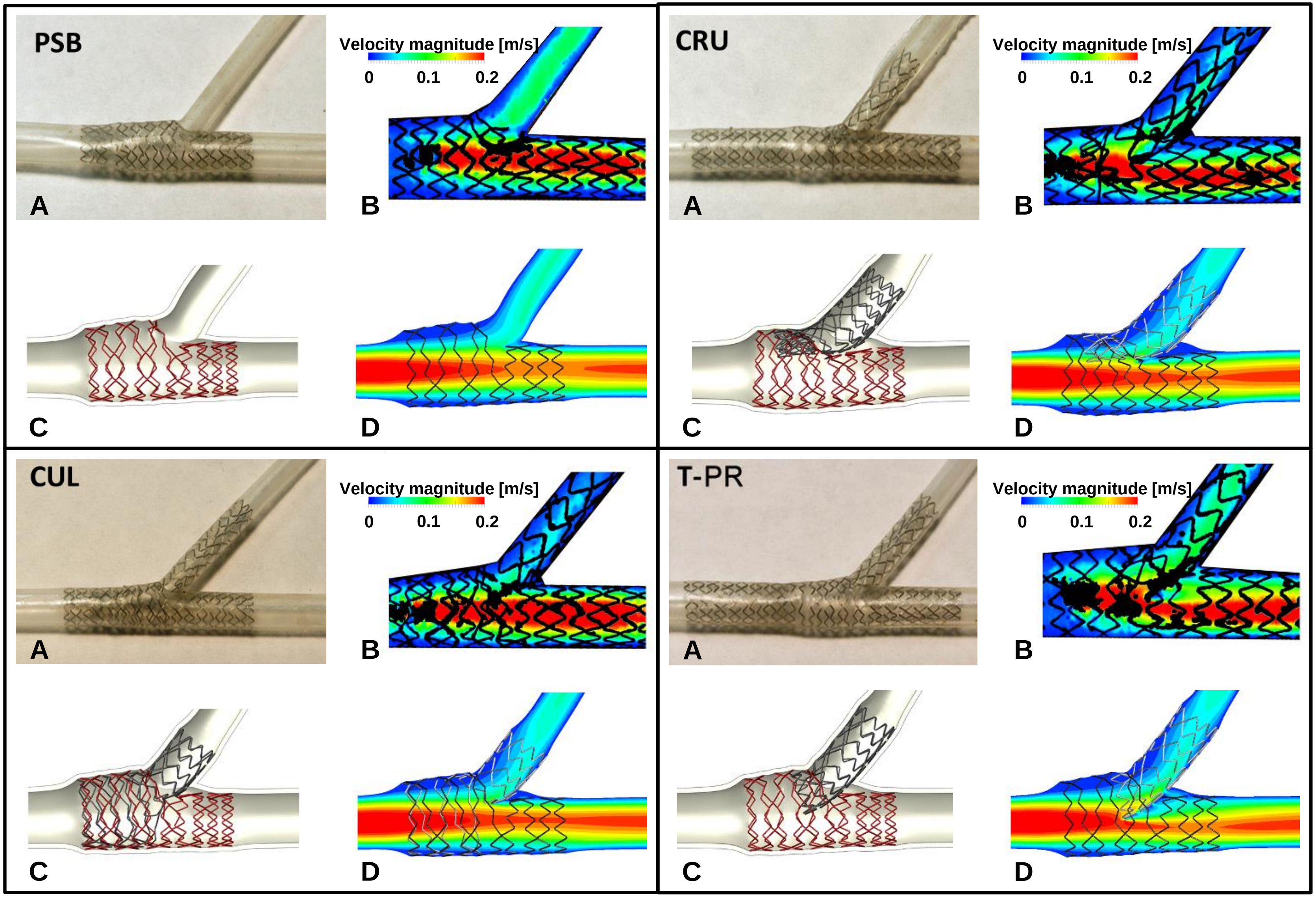
Validation of numerical simulations

- Comparison between the geometrical results of the experimental data and of the structural analysis



Morlacchi et al. *Biomech Model Mechanobiol*, 2010

Validation of numerical simulations



Raben et al. *J Appl Biomater Funct Mater*, 2014