MINES Saint-Étienne

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PrediSurge

CHU Saint-Étienne

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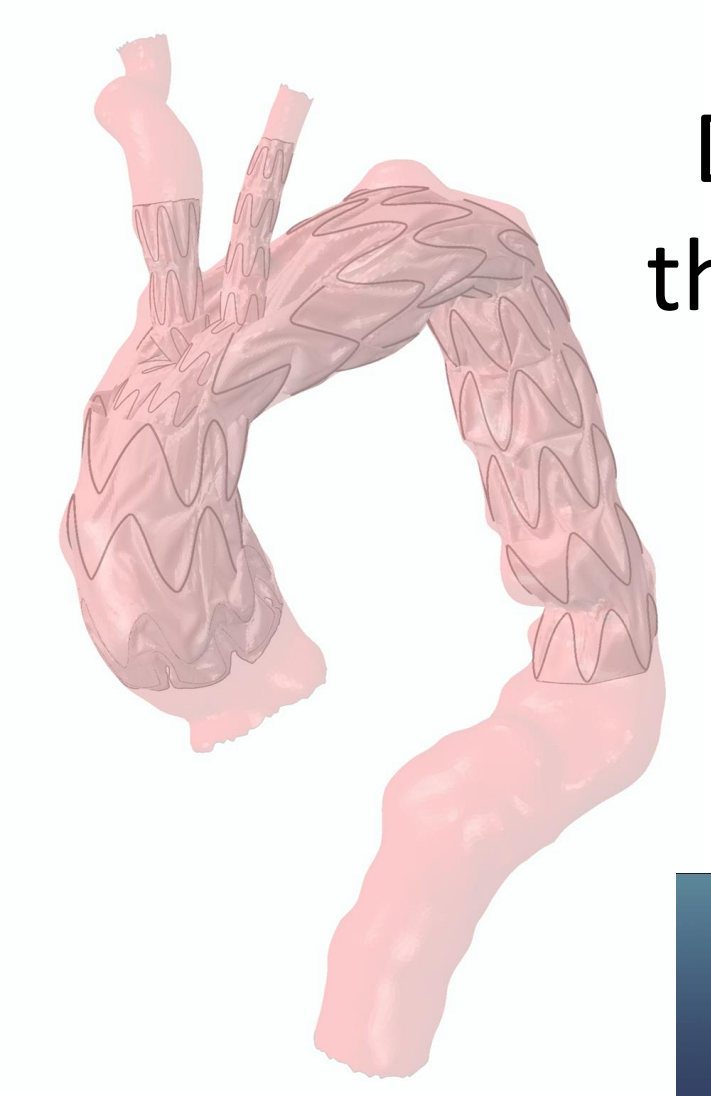

Digital twin of the thoracic aorta: from bench to bedside

Prof Stéphane Avril

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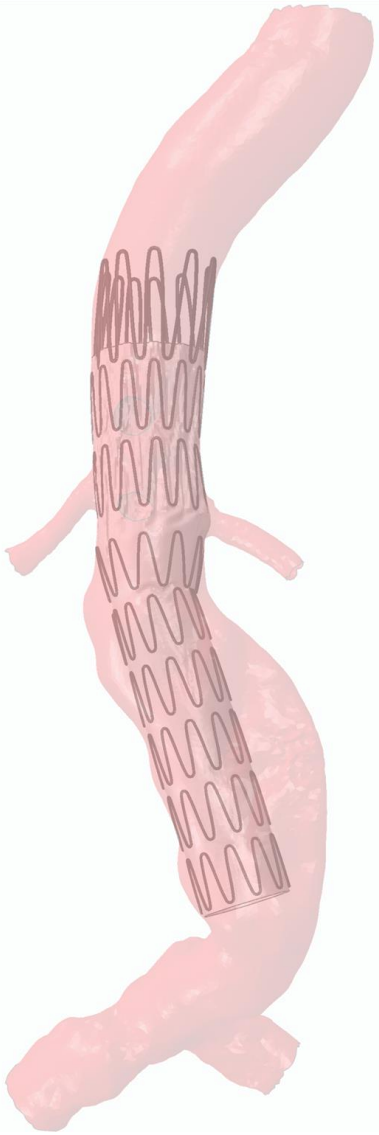

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NOVEMBER 21/22 2019
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Disclosures

S. Avril is cofounder of the company Predisurge SAS.

The bench side

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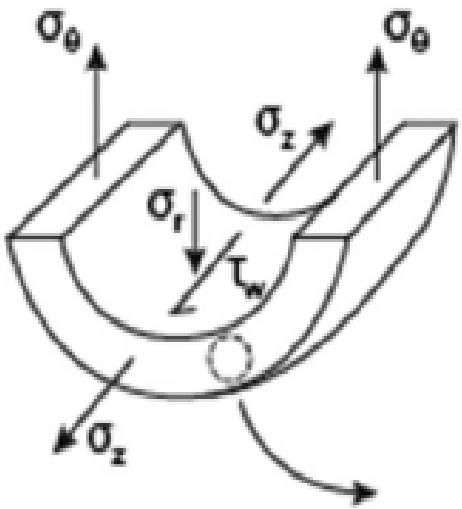
Basics of arterial mechanics

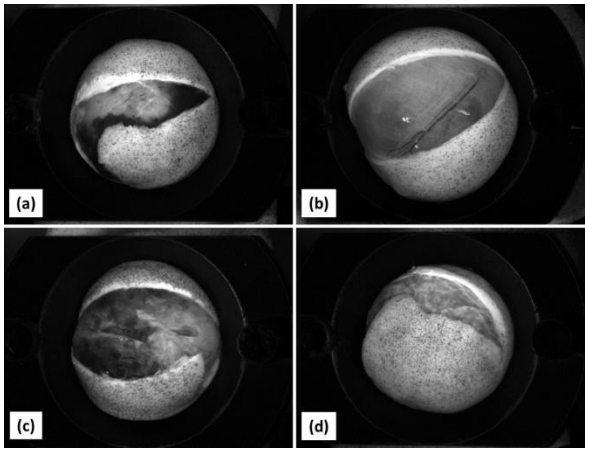


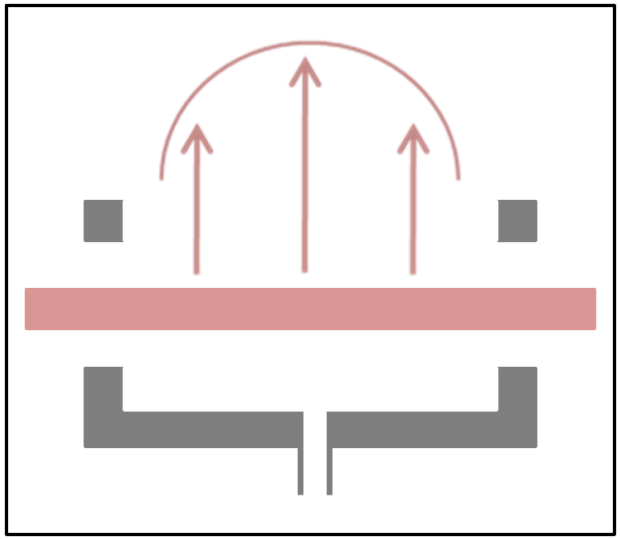
$$\tau_w = \frac{4\mu Q}{\pi a^3}, \qquad \sigma_\theta = \frac{P a}{h}$$

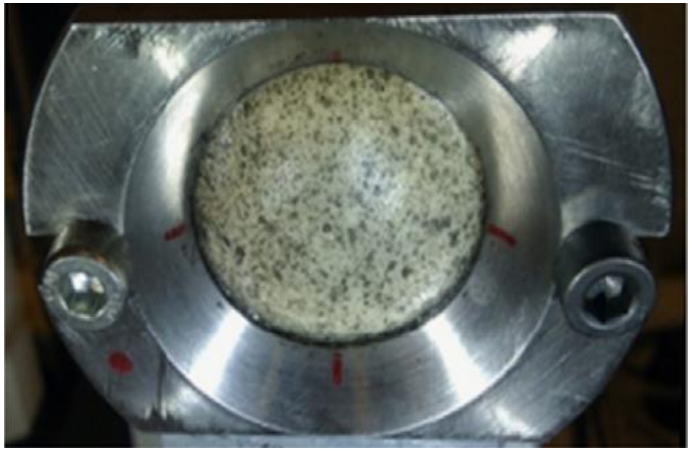
Humphrey JD (2002) *Cardiovascular Solid Mechanics: Cells, Tissues, and Organs*, Springer-Verlag, NY

Characterizing thoracic aortas with an appropriate bench test

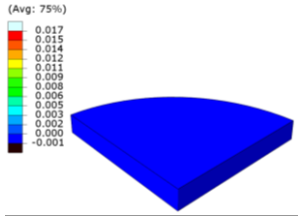
Romo et al. Journal of Biomechanics - 2014

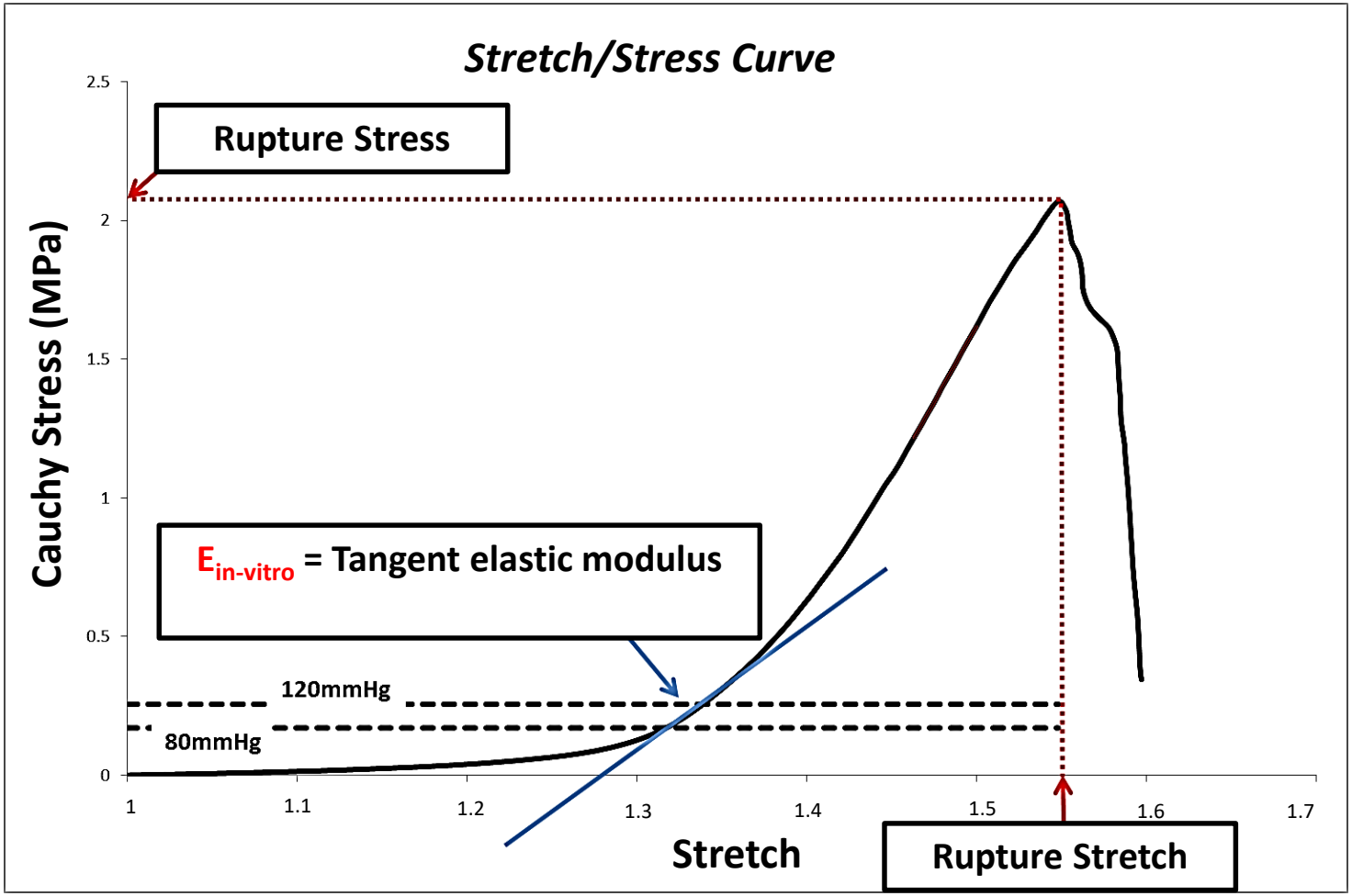






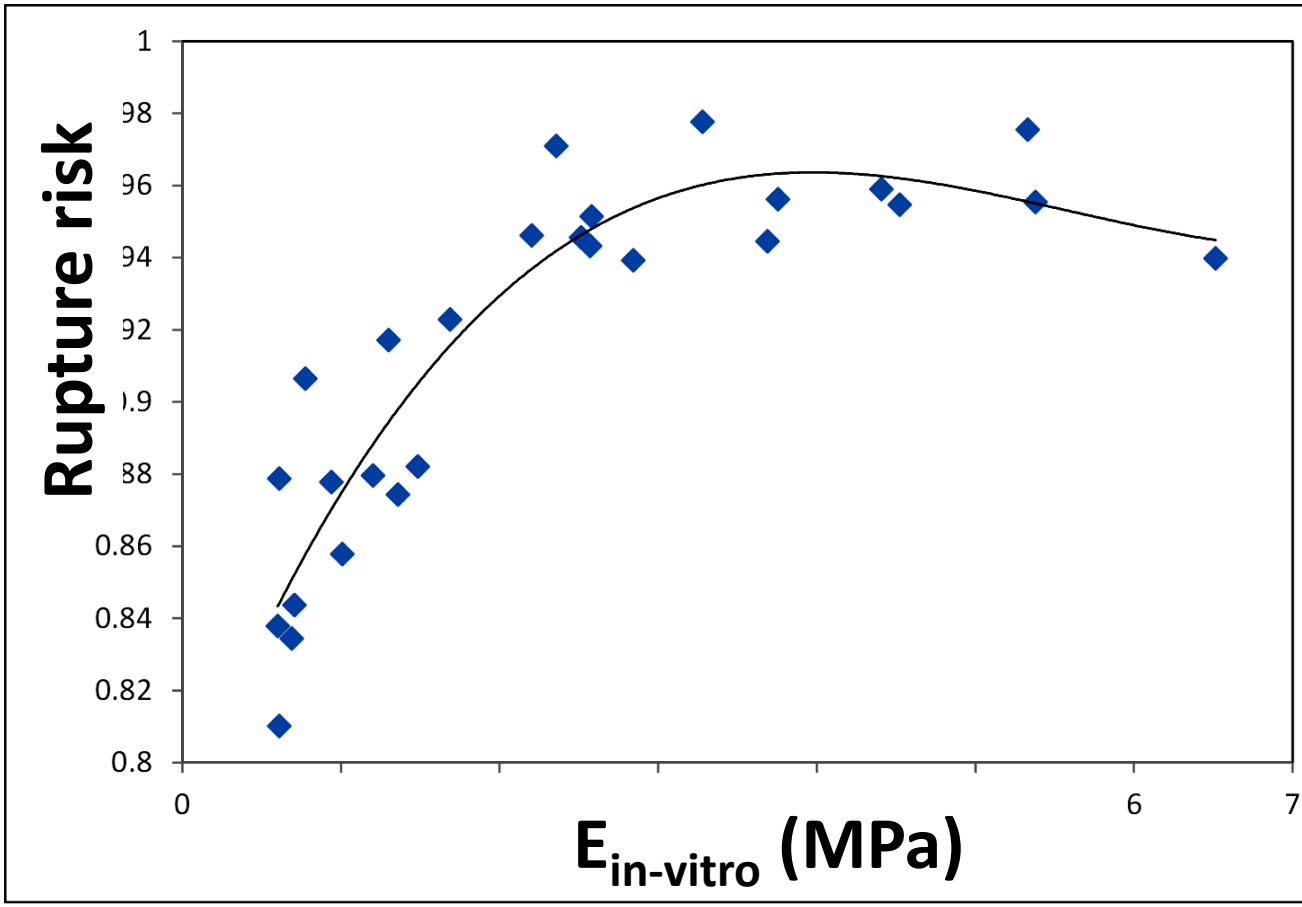
Rupture risk estimation





Correlation between the stretch-based rupture risk and the tangent elastic modulus

Duprey A, et al. Biaxial rupture properties of ascending thoracic aortic aneurysms. ***Acta Biomaterialia 2016.***



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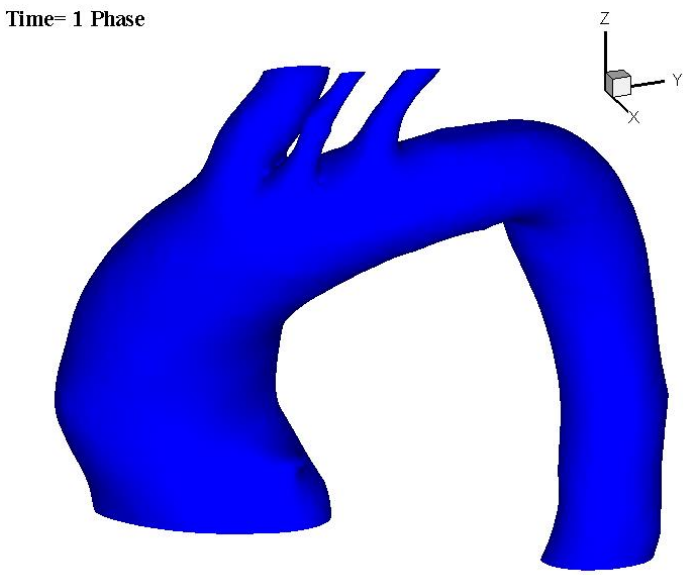
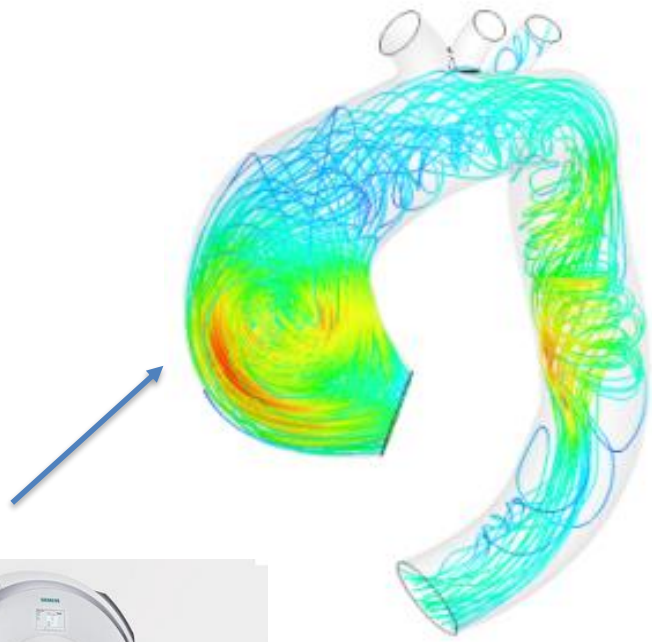
Relationship with aortic stiffness?

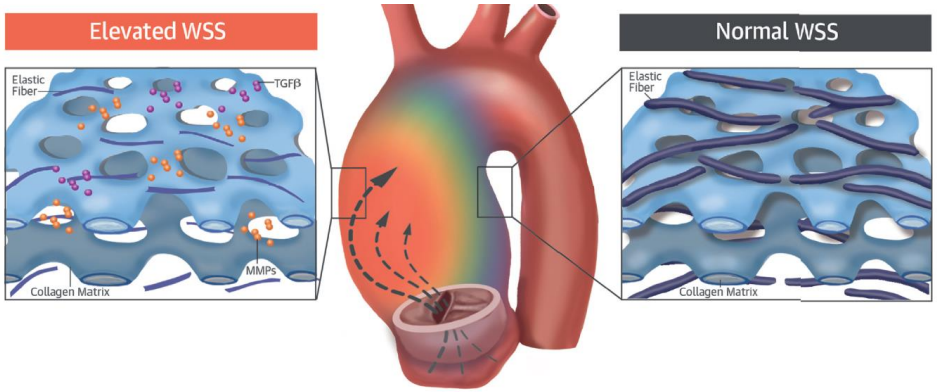
The stretch based rupture risk criterion correlates with the aortic stiffness measured by multiphase CT imaging.

Olfa Trabelsi, Miguel A Gutierrez Cambron, Solmaz Farzaneh, Ambroise Duprey, Stéphane Avril. A non-invasive methodology for ATAA rupture risk estimation. ***Journal of Biomechanics 2017.***



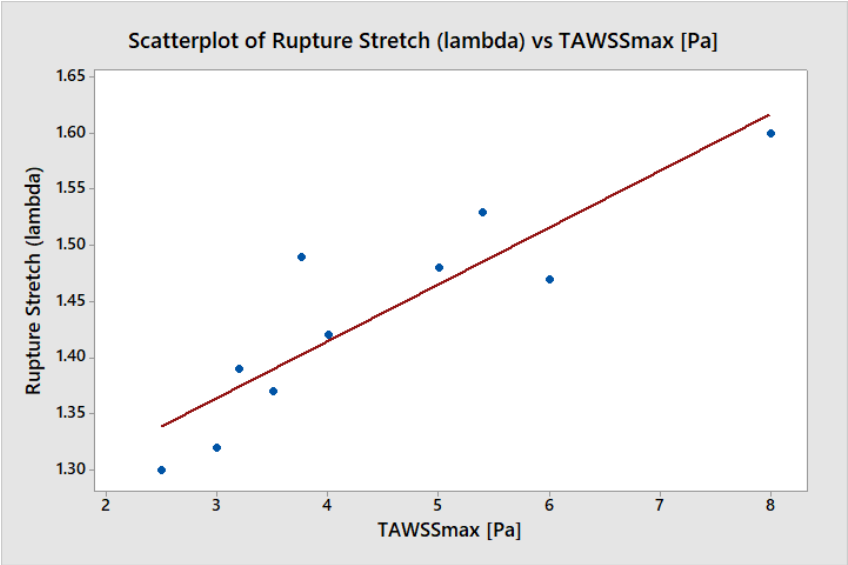
Relationship with hemodynamics





Guzzardi, D.G. et al. J Am Coll Cardiol. 2015; 66(8):892-900.

Siemens 3T Prisma



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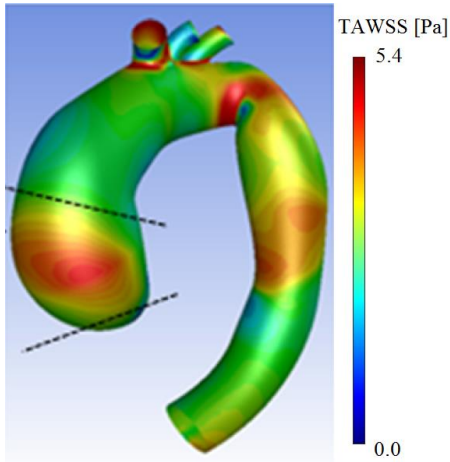
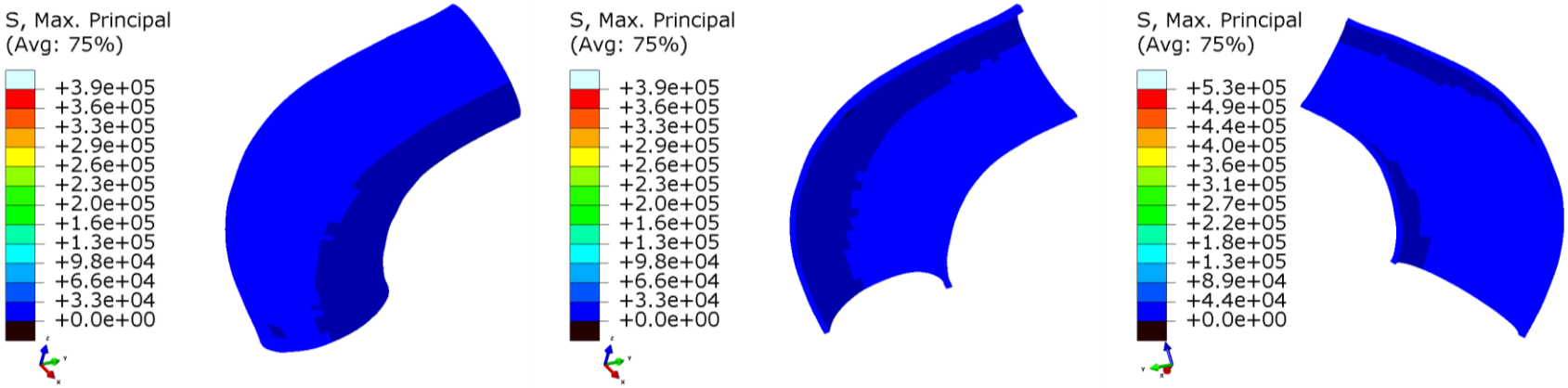
Computational mechanobiology



Growth and remodeling of a two–layer patient–specific human ATAAs due to elastin loss

Mousavi et al, BMMB 2019

Small growth parameter



Maximum Principal stress

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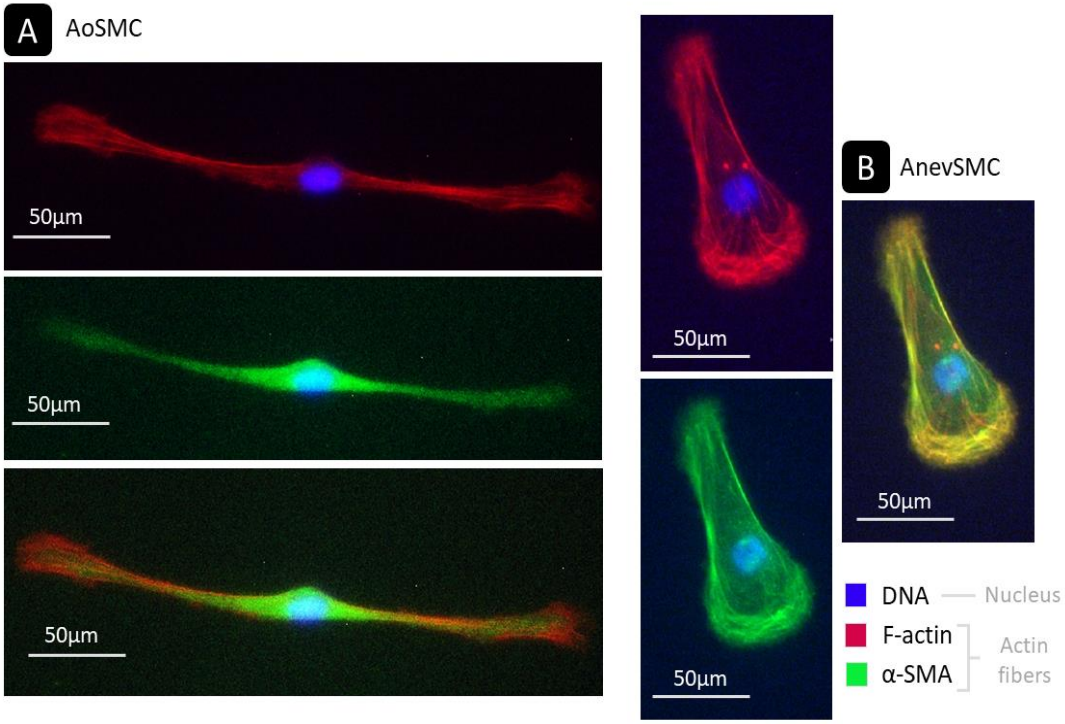
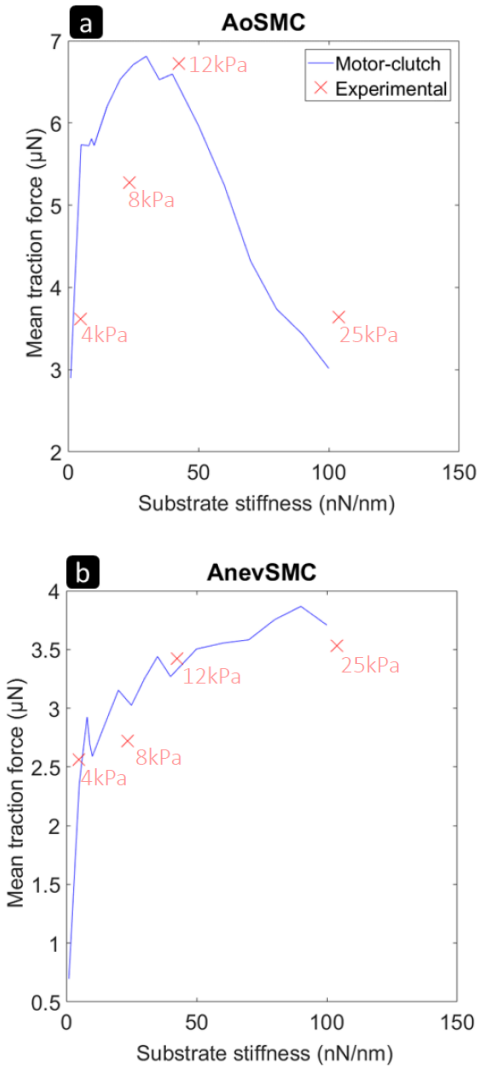
Experimental mechanobiology

Smooth muscle cells in aortic aneurysms missense their mechanical environment.





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The bed side

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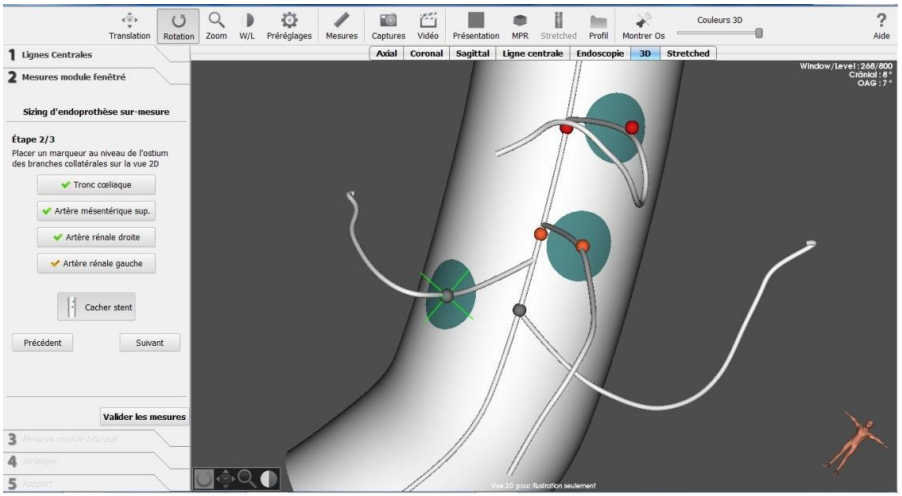
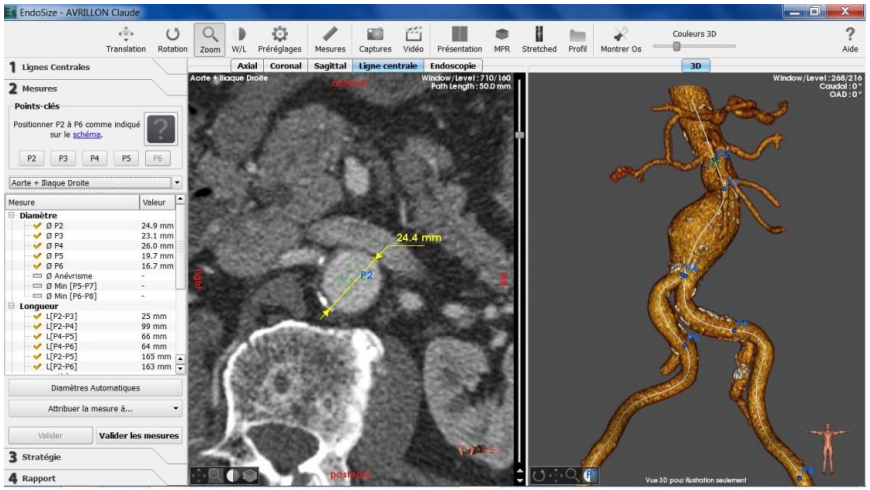
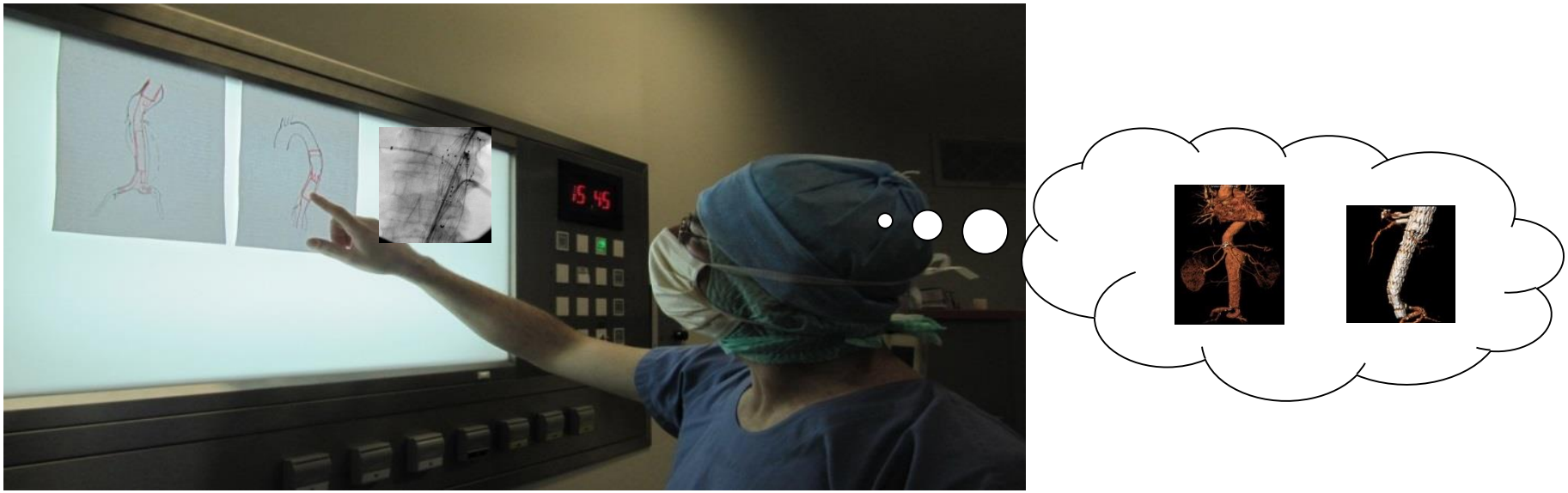
Planification / sizing of fenestrated stent grafts in EVAR procedures







Current limitations of planification / sizing

- Intra-operative difficulties induced by inappropriate pre-operative planification.

- Variability of fenestration positions depending on operators.

- Extended delivery times.

- Use of in vitro validation test with plastic replica for Terumo Anaconda®.

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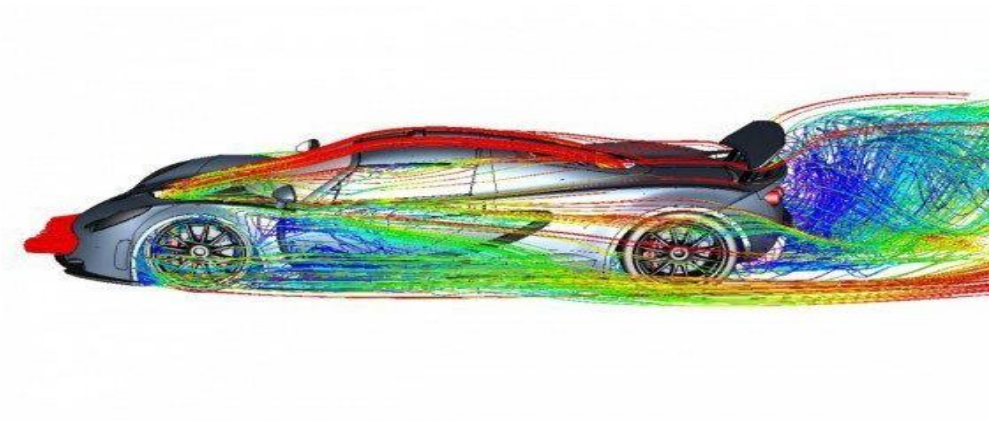
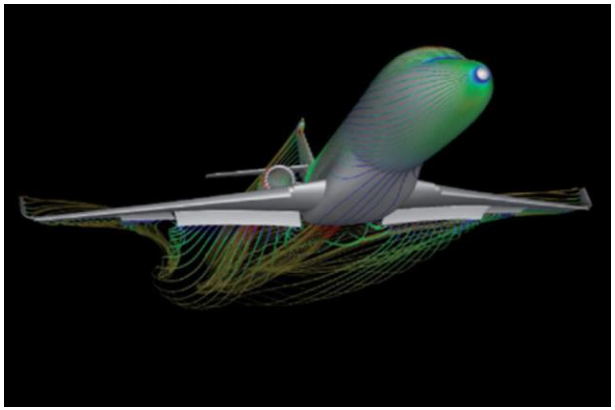
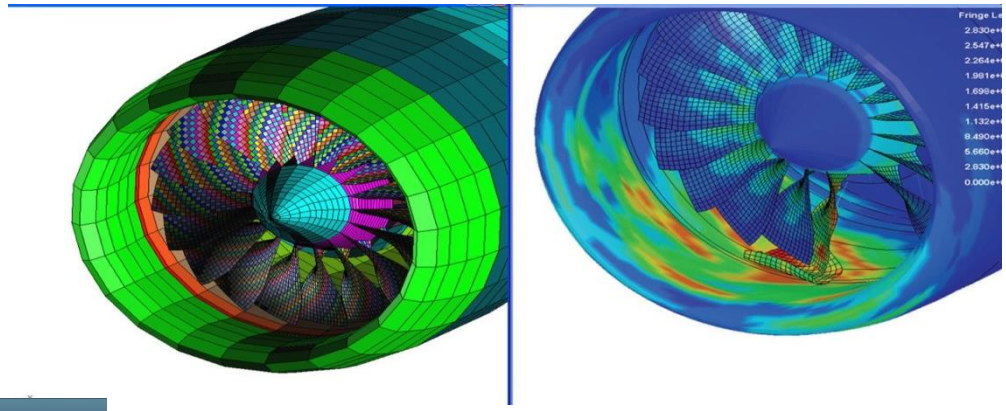
Numerical simulation is commonplace in automotive and aeronautics industry







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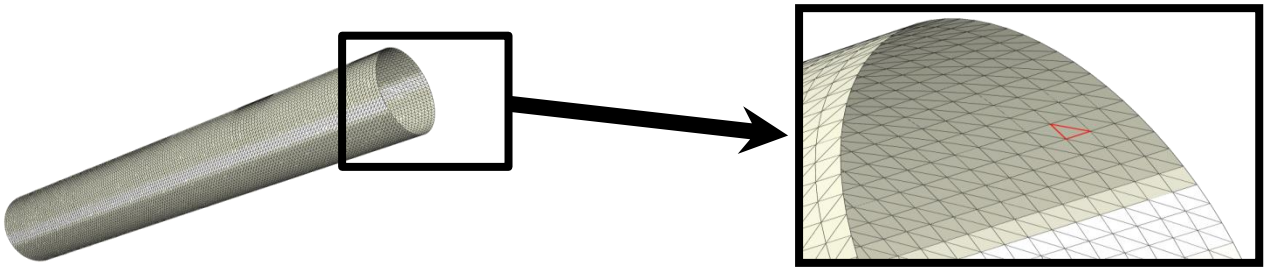
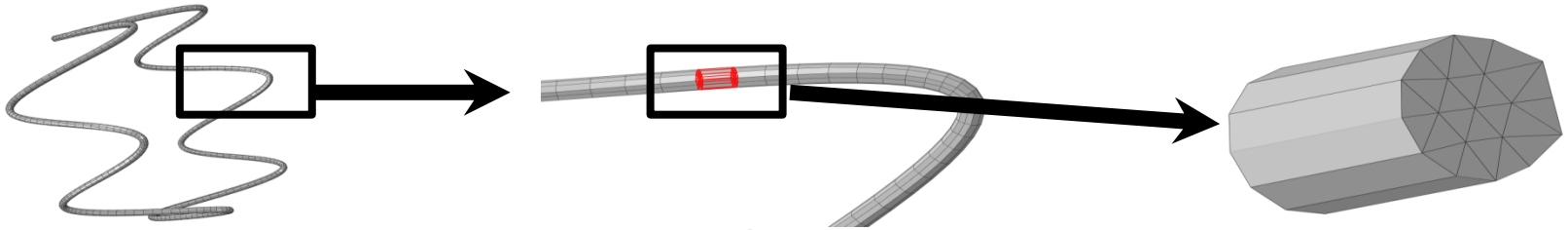
Finite element simulations of stent grafts



$$\begin{pmatrix} \varepsilon_{LL} \\ \varepsilon_{CC} \\ 2\varepsilon_{LC} \end{pmatrix} = \begin{pmatrix} 1/E_L & -\frac{\upsilon_{LC}}{E_L} & 0 \\ -\frac{\upsilon_{CL}}{E_C} & 1/E_C & 0 \\ 0 & 0 & 1/G_{LC} \end{pmatrix} \begin{pmatrix} \sigma_{LL} \\ \sigma_{CC} \\ \sigma_{LC} \end{pmatrix}$$



$$\frac{1}{E_\theta} = \frac{\cos^4\theta}{E_L} + \frac{\sin^4\theta}{E_C} + \frac{1}{4}\left(\frac{1}{G_{LC}} - \frac{2\upsilon_{LC}}{E_L}\right)\sin^2(2\theta).$$

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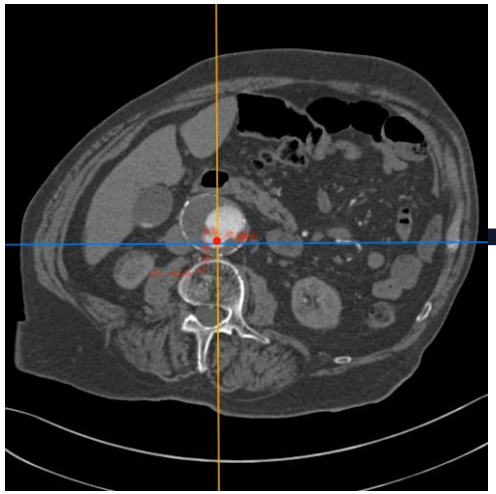
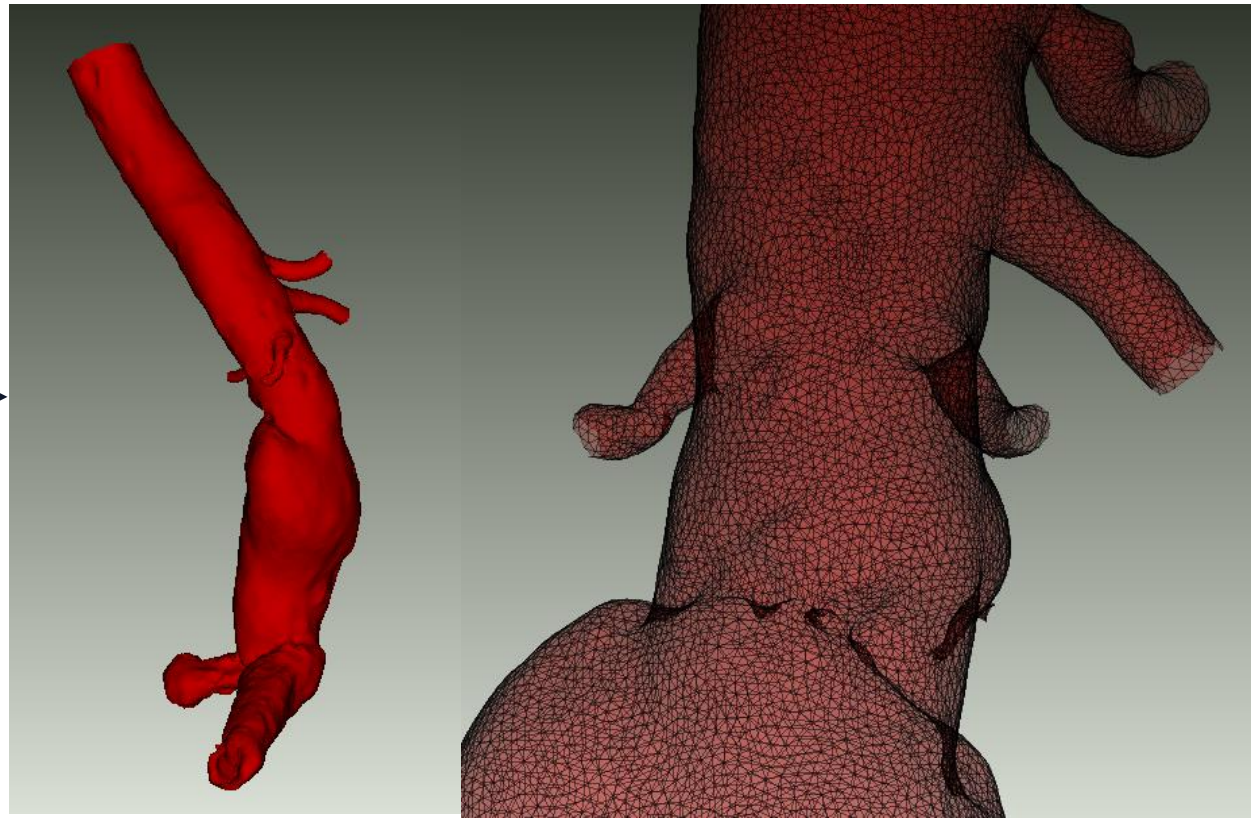
Patient-specific model of the aorta





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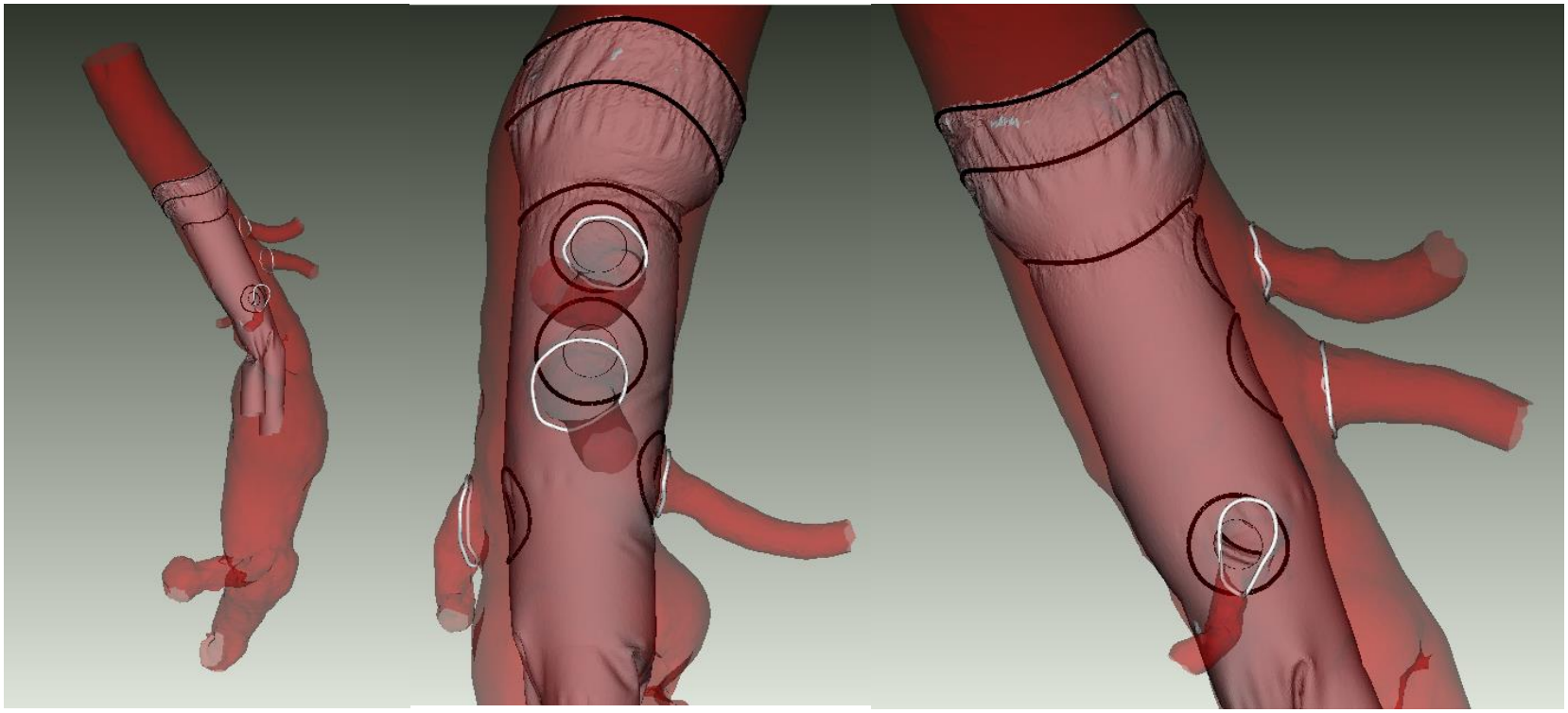
Patient-specific prediction of the deployed stent-graft in the aorta – Example with Terumo Anaconda®



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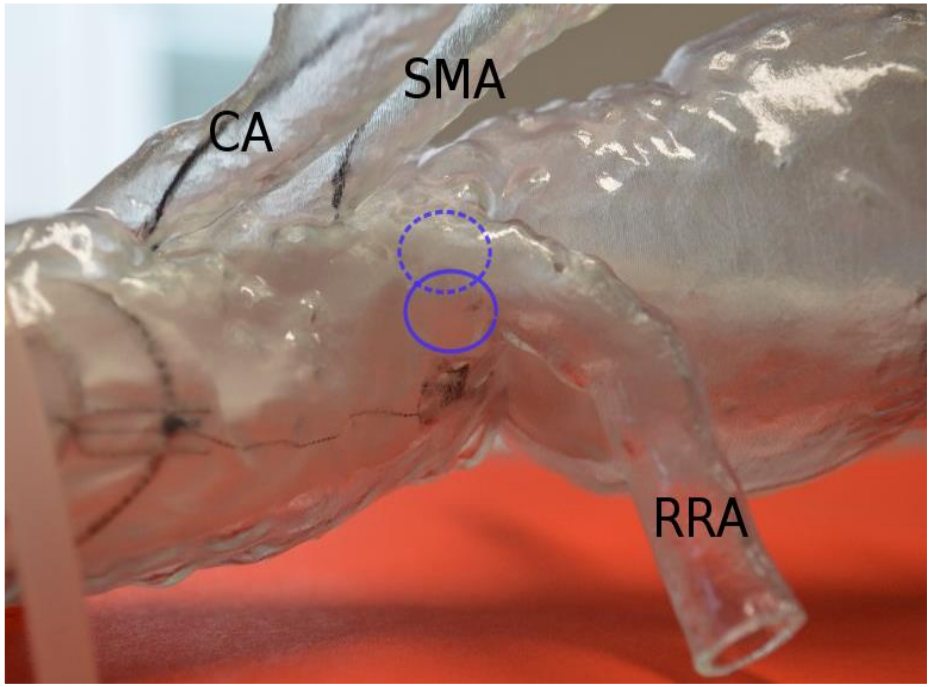
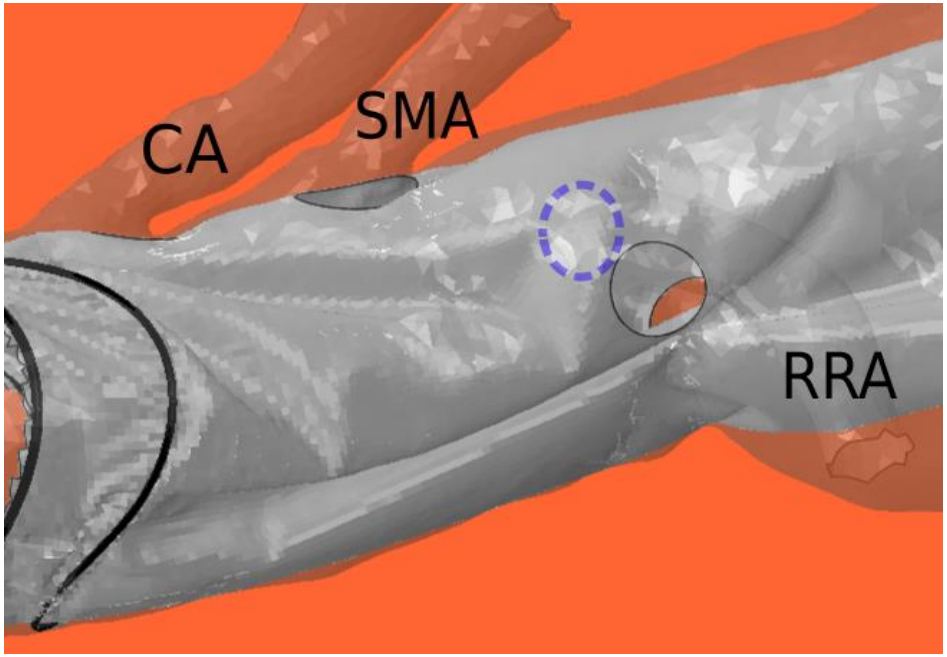
Digital model of in vitro validations for Terumo Anaconda® fenestrated stent-grafts





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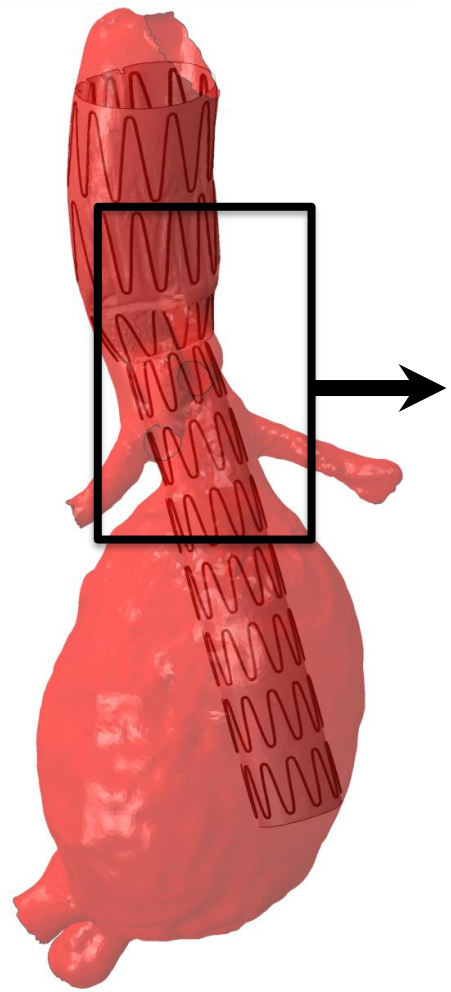
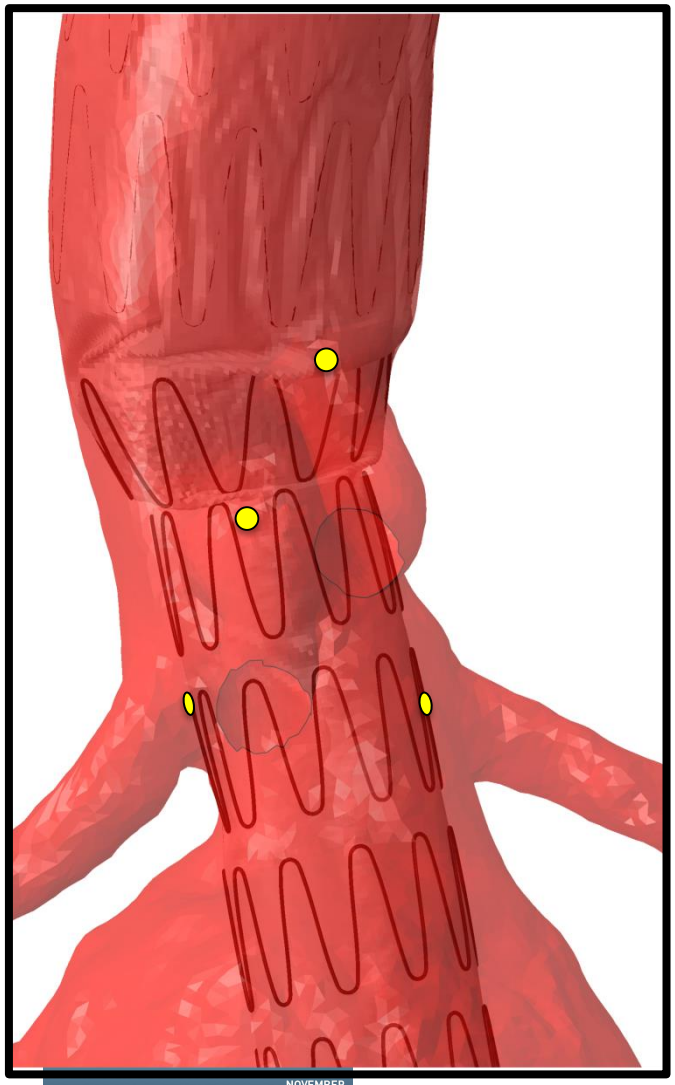
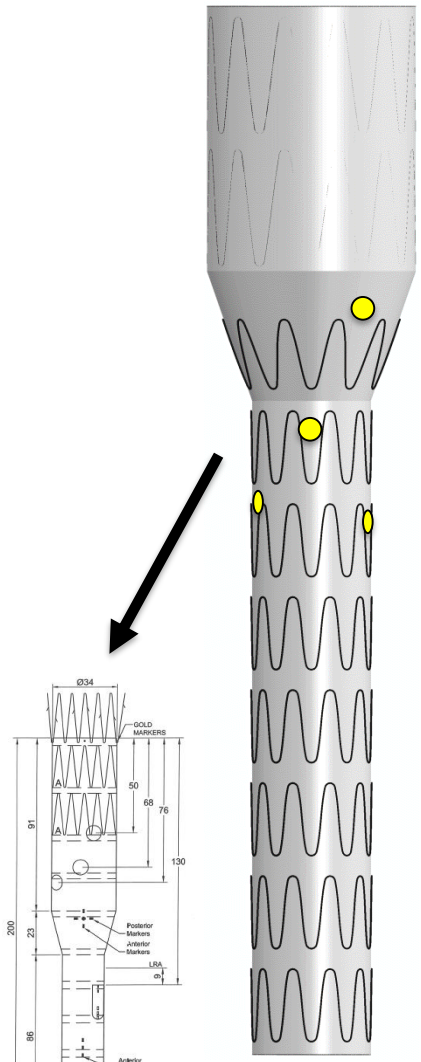
Fast and repeatable approach for FEVAR Zenith® Cook Medical



Position of ostias



Position of fenestrations



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Clinical validation for fenestrated Terumo Anaconda®
6 centers – 70 patients
Prospective study (on going)
PI: Bertrand Chavent (Saint-Etienne, France)

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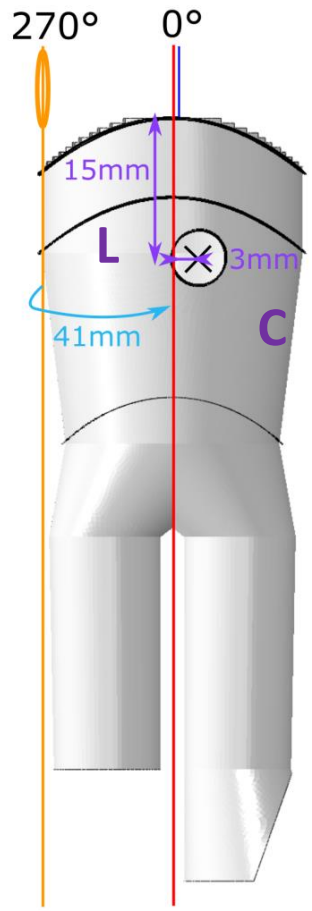
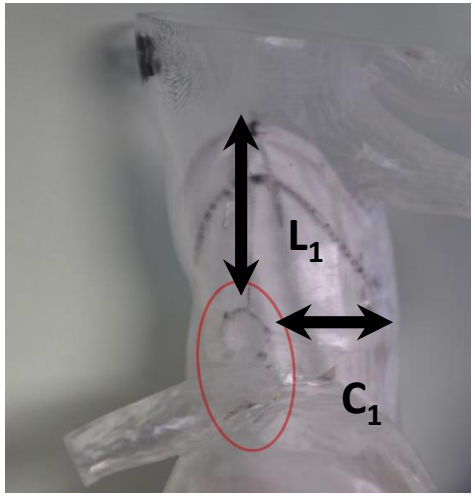
Assessment criteria

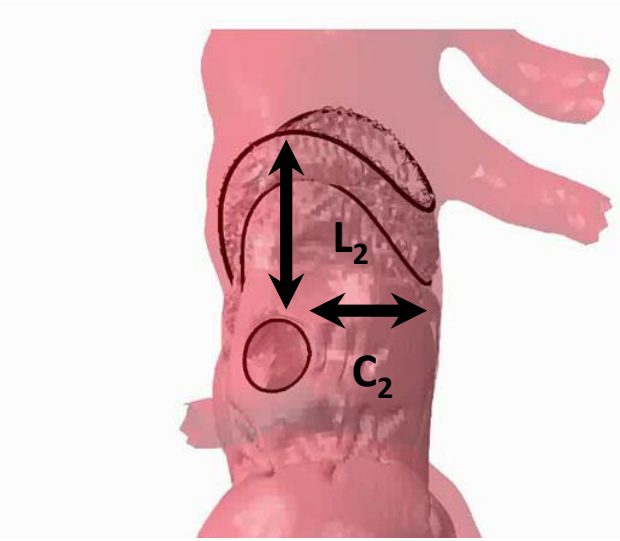
$\Delta L = |L1 - L2|$

$\Delta C = |C1 - C2|$

ΔL et $\Delta C \leq 2.5$ mm for more than 80%







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Results

Average difference:

- longitudinal **L1-L2** **1.5mm**
- circulferential **C1-C2** **1.2mm**

Position difference < 2.5mm

- **longitudinal** **96%**
- **circumferential** **97%**

Process duration:

- in vitro test 17 days
- numerical simulation 1.8 days

p<0.001

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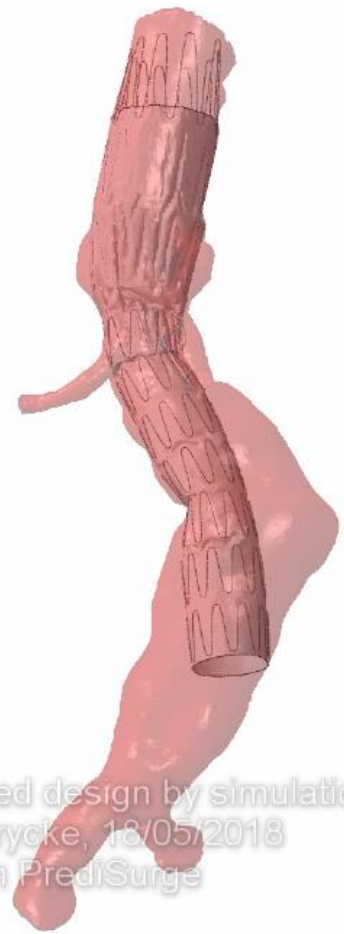
Clinical validation for FEVAR Zenith® Cook Medical
51patients- 180 fenestrations – 18 scallops
Retrospective study 2016-2018
PI: Stephan Haulon (Paris)



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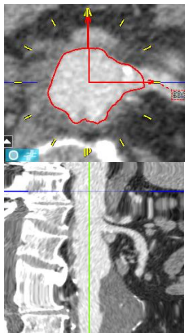
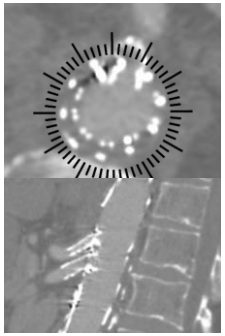
Results

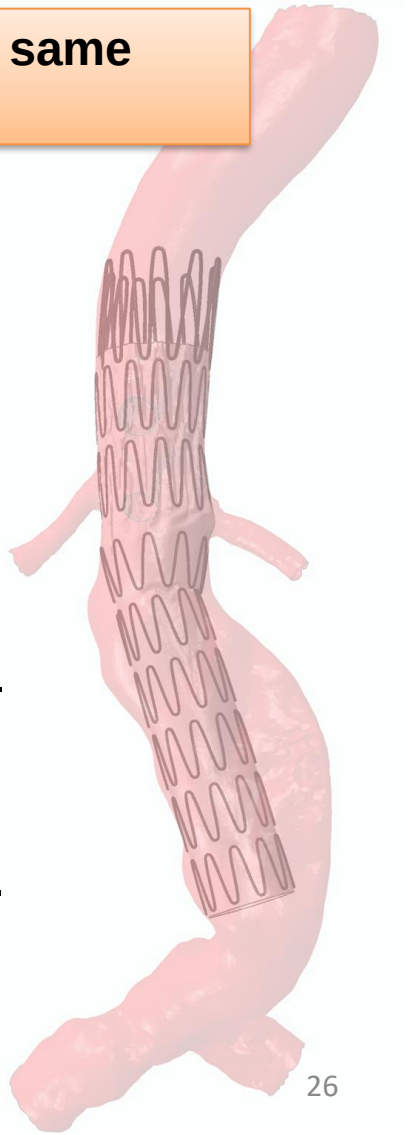
Measurements: longitudional and circumferential				
Longitudinal position, mm				
	Pre-op sizing		**Post-op sizing**	
	Median ± SD [Min-Max]	**N ≤ 3 mm %**	**Median ± SD [Min-Max]**	**N ≤ 3 mm %**
Simulation	1.0 ± 1.1 [-5.9, 6.0]	95	0.96 ± 0.97 [-4.6, 5.0]	98
Pre-op sizing	0.8 ± 0.8 [-4.0, 4.0]	97		
Circonferential position, °				
	Pre-op sizing		**Post-op sizing**	
	Median ± SD [Min-Max]	**N ≤ 15 ° %**	**Median ± SD [Min-Max]**	**N ≤ 15 ° %**
Simulation	6.9 ± 6.1 [-44.3, 25.1]	96	4.8 ± 3.6 [-21.8, 19.3]	99
Pre-op sizing	5.1 ± 5.0 [-37.1, 18.4]	98		





Conclusions

Numerical simulation can position fenestrations with the same precision as the standard approach

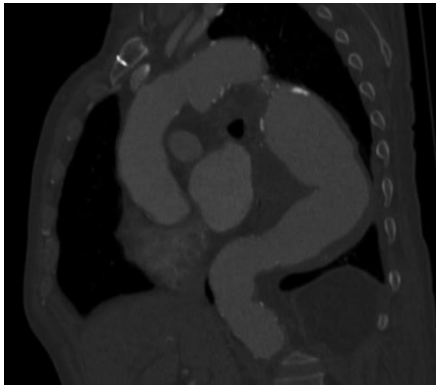


Potential advantages are:

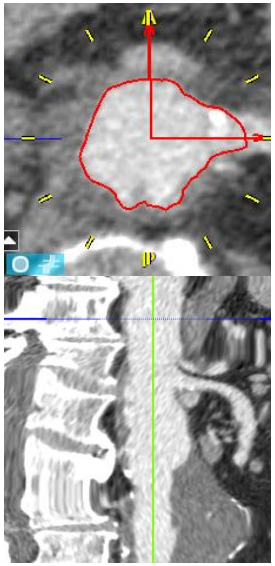
- Reduce inter- and intra-operator variability.
- Give quantitative information about the deployend stent-graft in the aorta (mechanics).
- Decrease the incidence of post-operative complications.

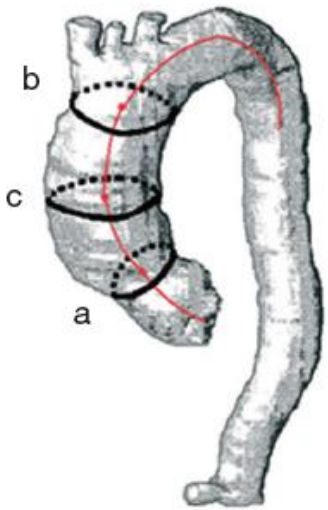
Current developments

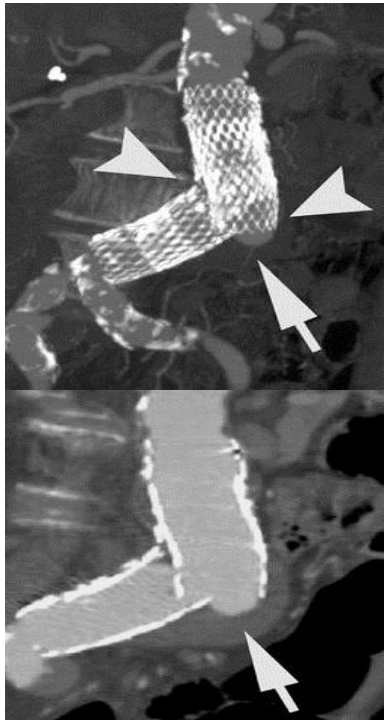
Patient specific FE model of double branch Bolton® device deployment in aortic arch aneurysm



Endovascular Aortic Arch Challenges







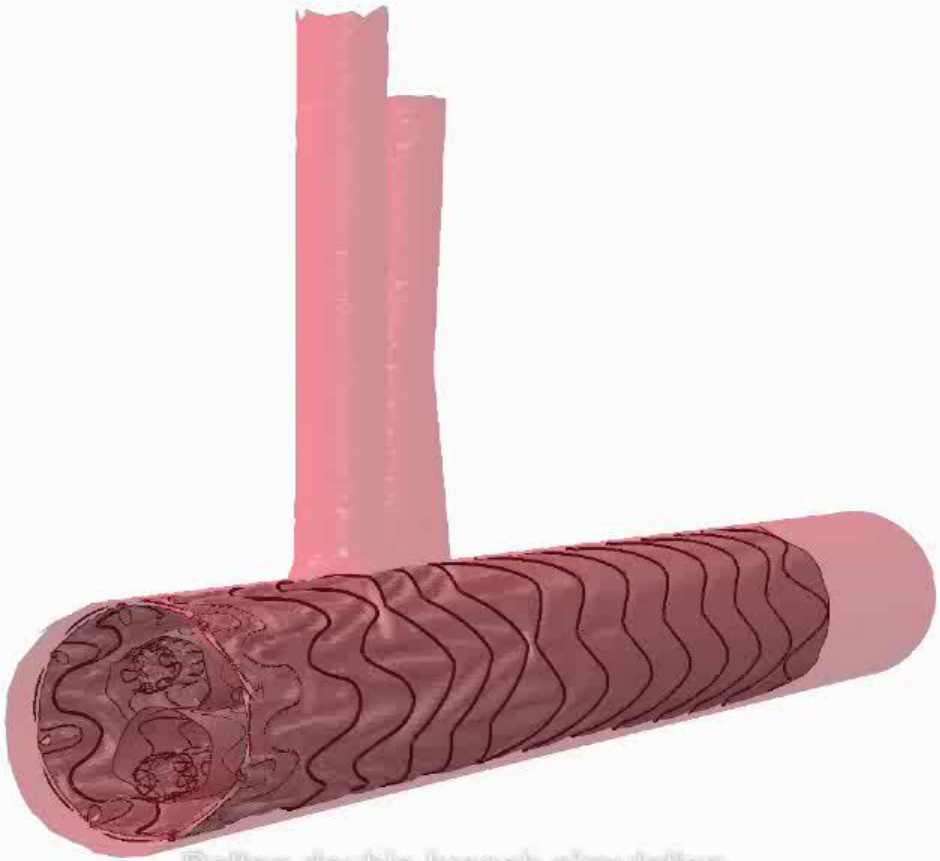
Custom-made device
Measures on preop CT

Device alignment
Secure device

Device durability
New set of physiological loads

Numerical simulation can assist at the planification stage and can be helpful to improve device properties

Current developments



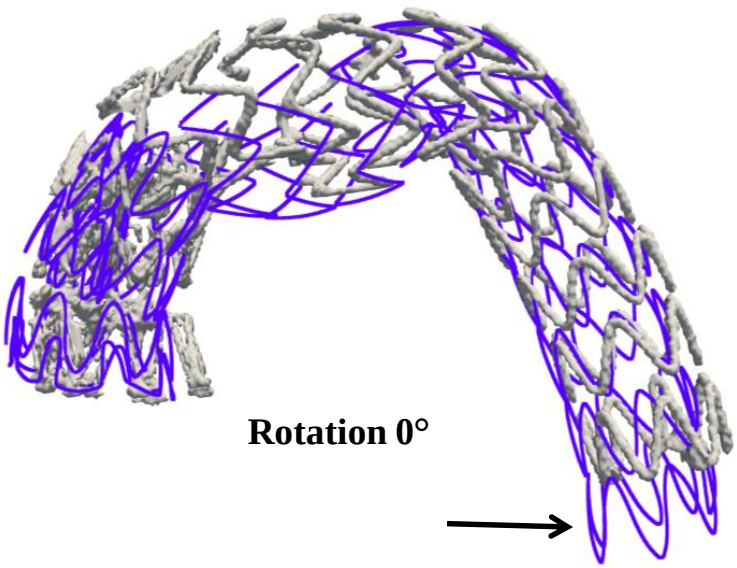
Bolton double branch simulation
03/09/2018
Lucie Derycke, with PrediSurge

Current developments

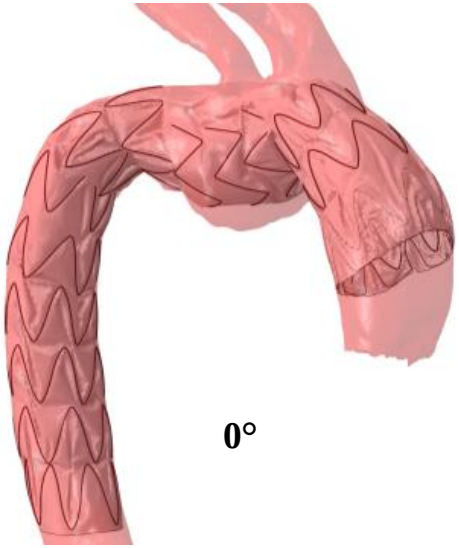
Bolton double branch simulation
03/09/2018
Lucie Deryckè, with PrediSurge

Current developments

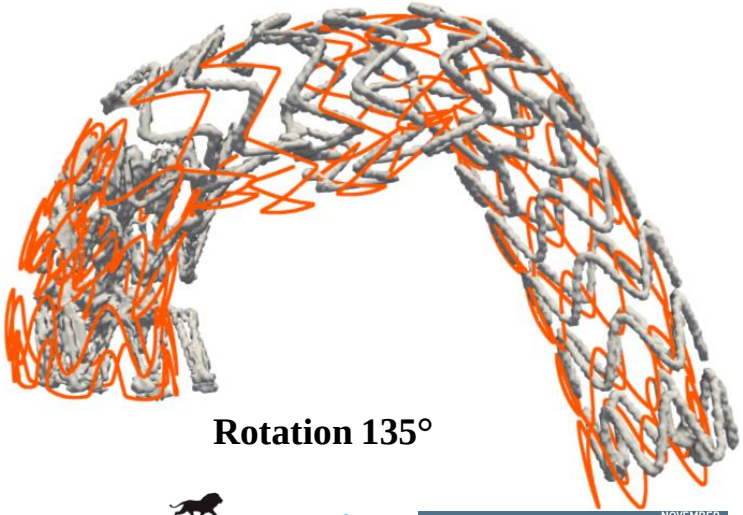
TORSION EFFECTS



Rotation 0°



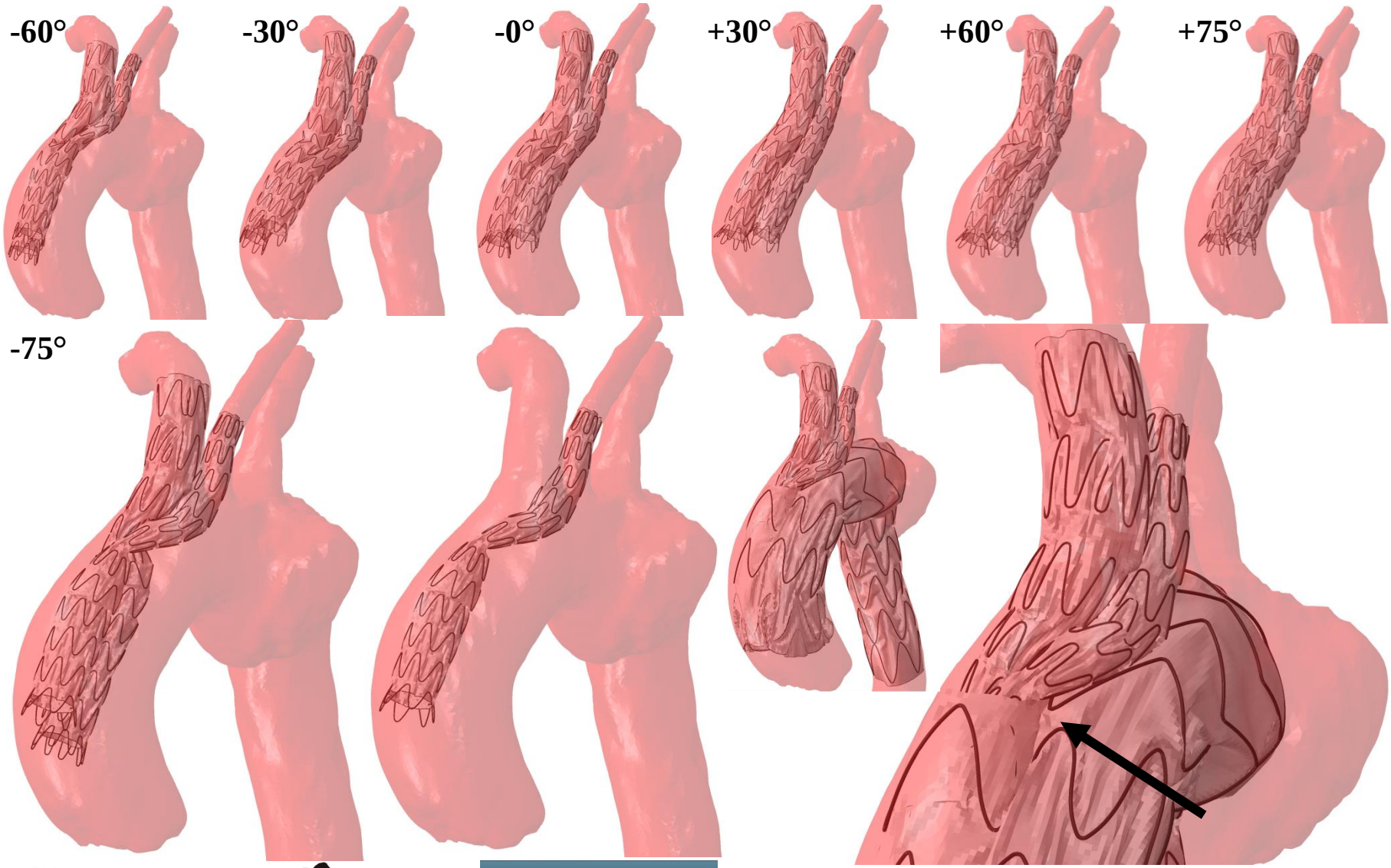
0°



Rotation 135°

135°

Current developments



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Summary

PrediSurge www.predisurge.com

Software solutions assisted by numerical simulation

Optimize design, preoperative planning and implantation of medical devices

- Company founded in May 2017
- Focus on endovascular repair (EVAR) of aortic aneurysms
- Graphical user interface
- On-going CE and FDA approval

The digital twin

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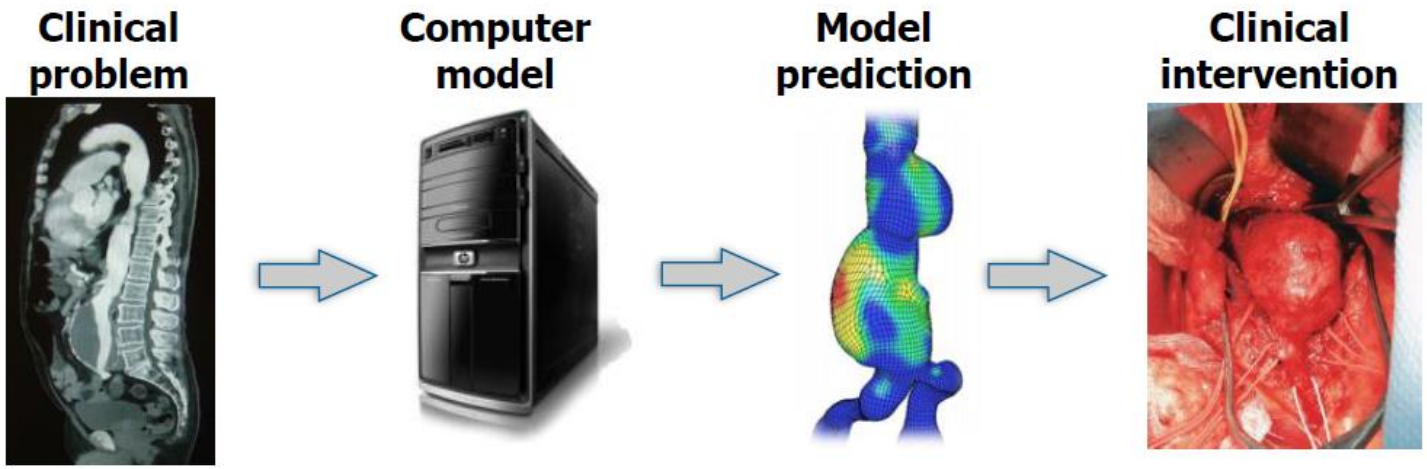
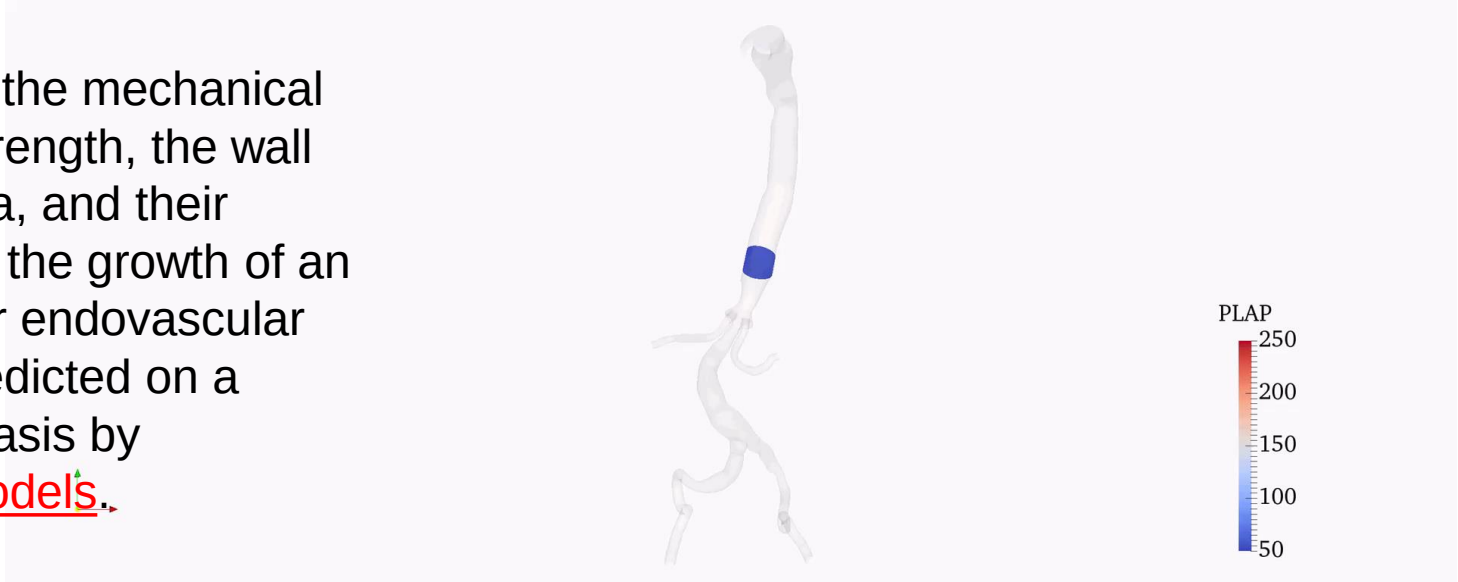
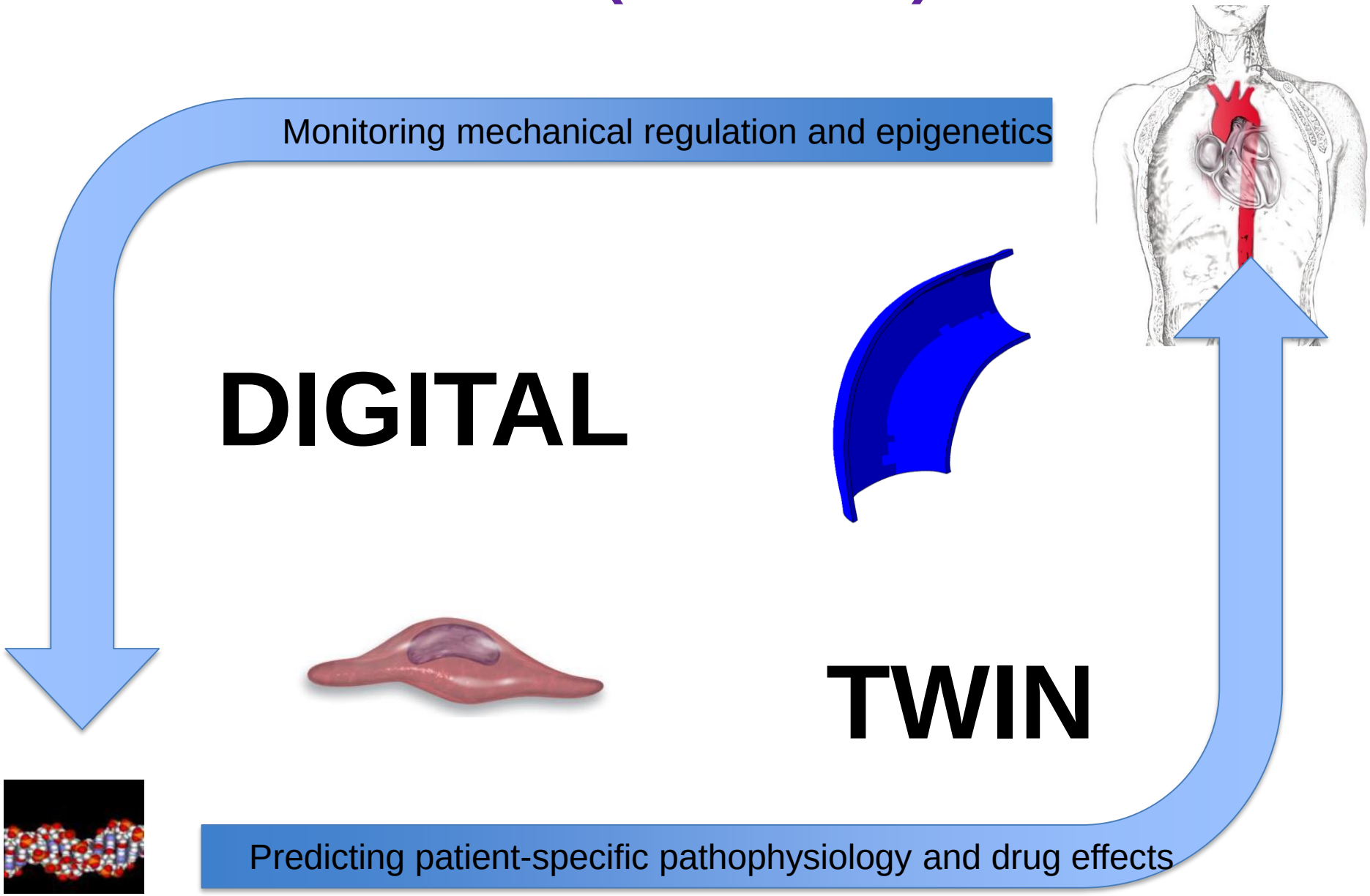
The virtual patient



Our vision is that the mechanical properties, the strength, the wall stress of the aorta, and their evolutions during the growth of an aneurysm or after endovascular repair, can be predicted on a patient-specific basis by computational models.



Ambition (or dream!)



MERCI!

S Ben Ahmed, B Chavent, A Millon, P Feugier, M Reijnen, JW Lardenoije, A Assadian, J Falkensammer, M Kliewer, N Frisch, C Muller, D Midy, F Cochennec, J Senemaud, JP Favre, L Derycke, D Perrin, JN Albertini, S Haulon…

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