Computational Mechanics and Advanced Materials Group
University of Pavia, Italy
XXXI ciclo

ADVANCED PATIENT-SPECIFIC MODELING AND ANALYSIS OF COMPLEX AORTIC STRUCTURES BY MEANS OF ISOGEOMETRIC ANALYSIS

Margherita Coda

11/02/2019

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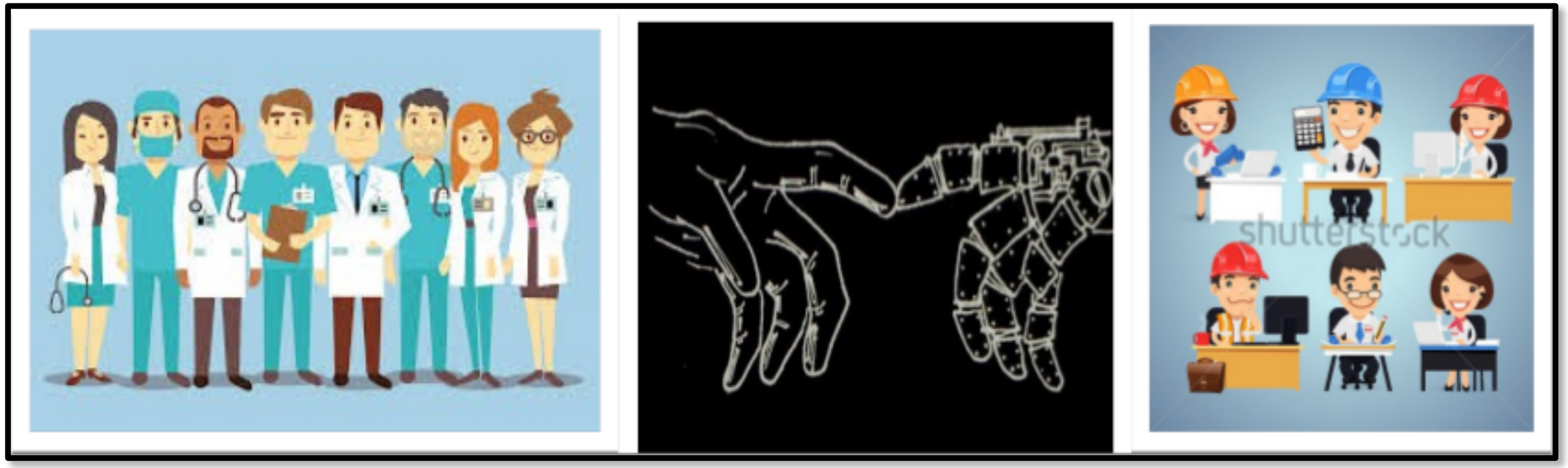
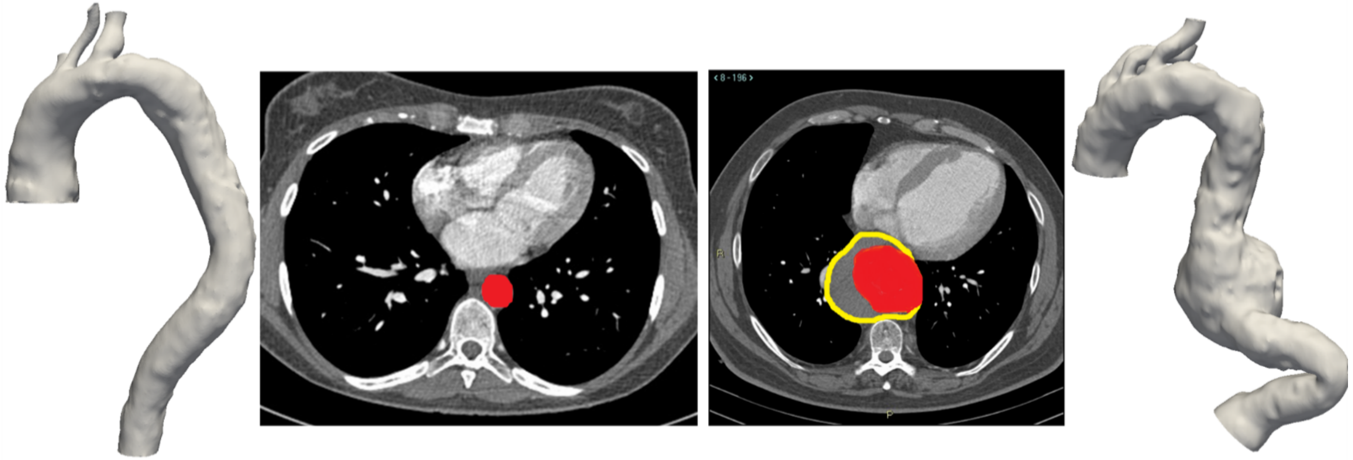
Prof. Ferdinando Auricchio
Coadvisors: Prof. Robert L. Taylor
Prof. Santi Trimarchi

Ultimate goal: creation of a set of computational tools to provide support and "predictive medicine" to vascular surgeons during the pre-operative planning phase.

- **Study 0:** Development and testing of analysis-suitable isogeometric unclamped knot vectors in FEAP.
- **Study 1:** Patient-specific isogeometric geometrical modeling of Thoracic Aortic Aneurysms by means of unclamped knot vectors.
- **Study 2:** Patient-specific isogeometric modeling of bifurcated geometries by means of T-splines.
- **Study 3:** Towards an accurate simulation of complex contact interactions in biomechanics problems using Isogeometric Analysis.

AN ENGINEERING SUPPORT TO MEDICINE





A B

A: CT scan of an healthy aorta.
B: CT scan of a TAA.

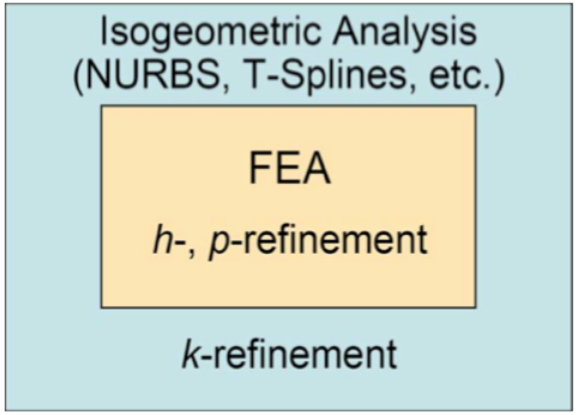
Goal:

Provide physicians an opportunity to simulate the best combination of procedure strategies and medical devices prior to surgical intervention, given a **patient-specific** morphology.

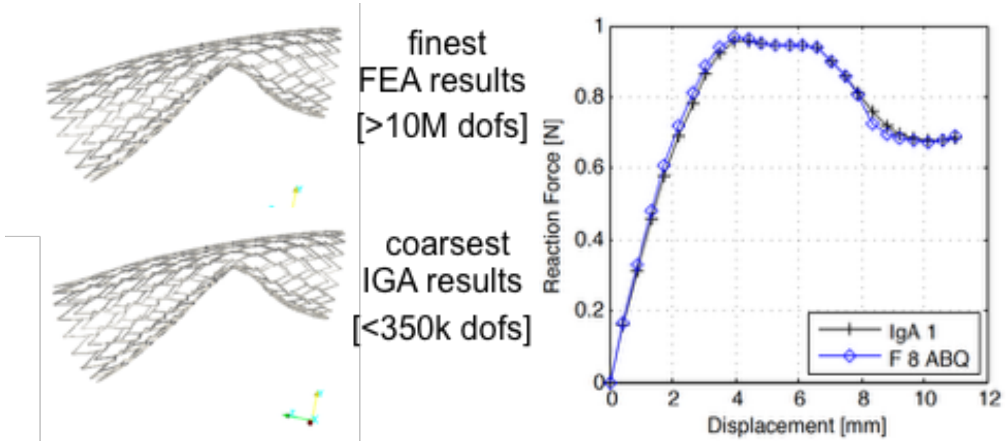
ISOGEOMETRIC ANALYSIS (IgA, Hughes et al., 2005)

Cost-effective alternative to FE analysis (based, e.g., on NURBS), ***including FEA as a special case***, but offering other possibilities:

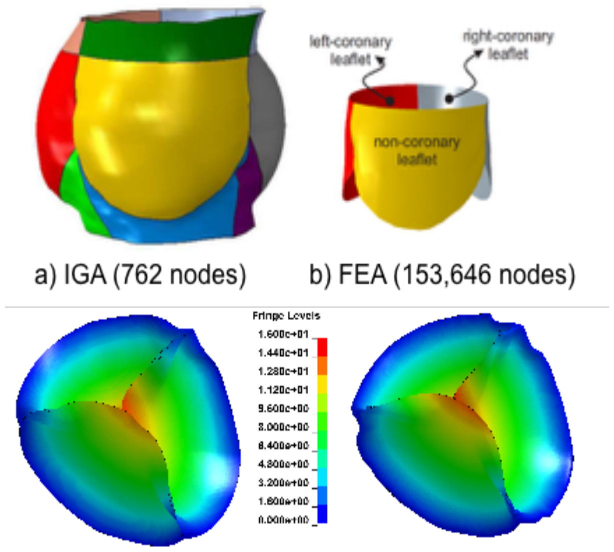
- **Improved** accessibility with CAD;
- **Patient-specific** geometries described in a very precise way with a low number of d.o.f.'s;
- **High-continuity** of the stress field;
- **Simplified** mesh refinement;
- **Better** performance over FEM:
  - **Highly** accurate result;
  - **Reduced** computational costs.



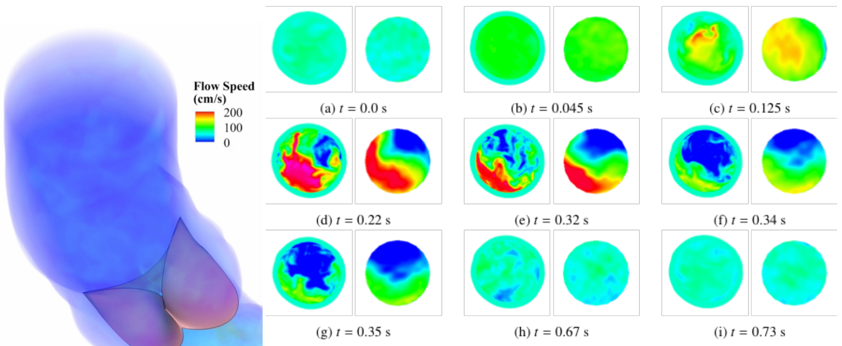
IgA and biomechanics



Auricchio et al., CMAME 2015



Morganti et al., CMAME 2015

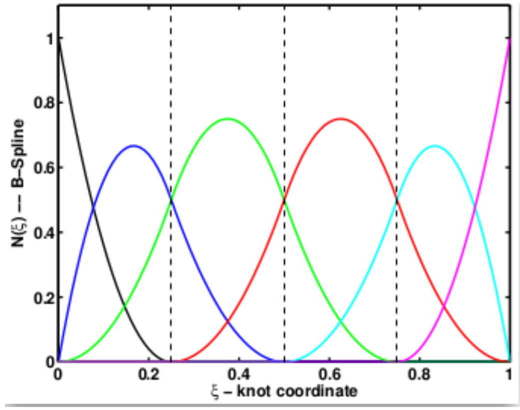


Left: numerical results
Right: medical image data (phase contrast MRI)

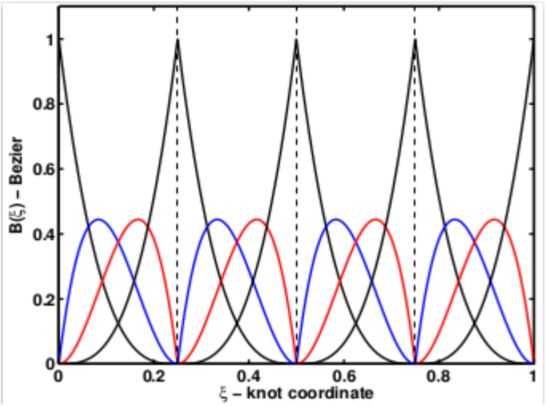
Xu et al., IJNMBE 2018

ISOGEOMETRIC ANALYSIS (IgA, Hughes et al., 2005)

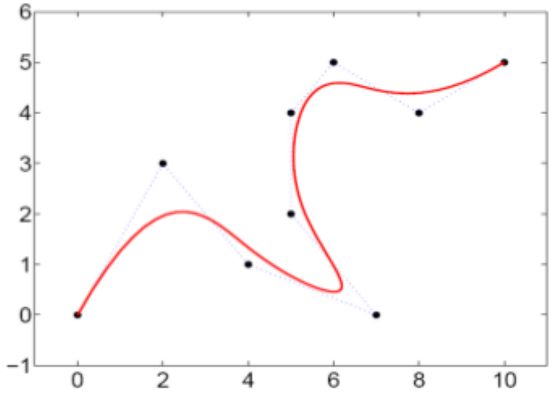
- Knot vector : set of coordinate in the curve parametric space used to evaluate the basis functions.
- Given the **open knot vector** {0 0 0 0 0.2 0.4 0.6 0.8 1 1 1 1}



Cubic basis functions



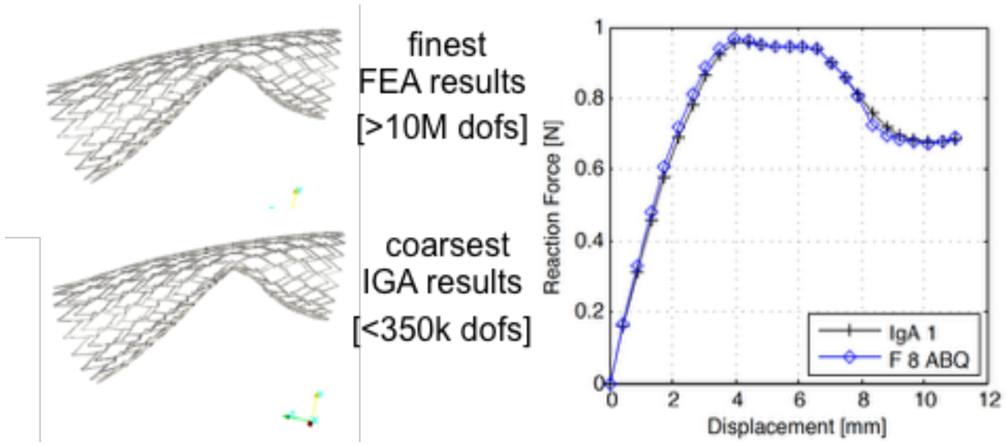
Bézier basis functions



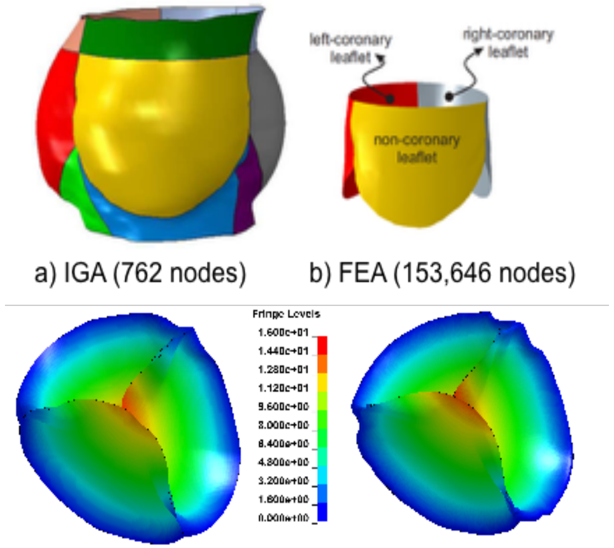
Control Polygon

Properites:

- Non-negativity
- Partition of unity
- C^{p-m} continuity



Auricchio et al., CMAME 2015



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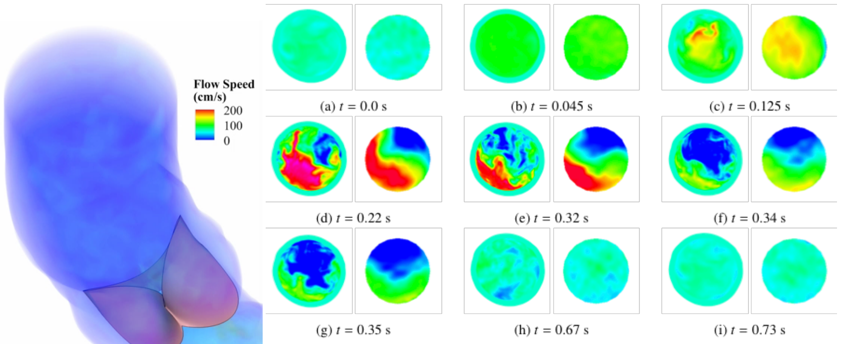
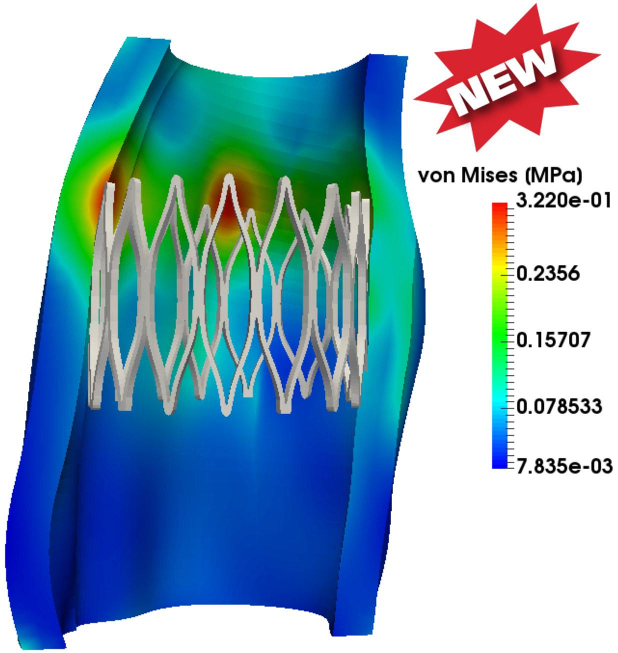


Left: numerical results
Right: medical image data (phase contrast MRI)

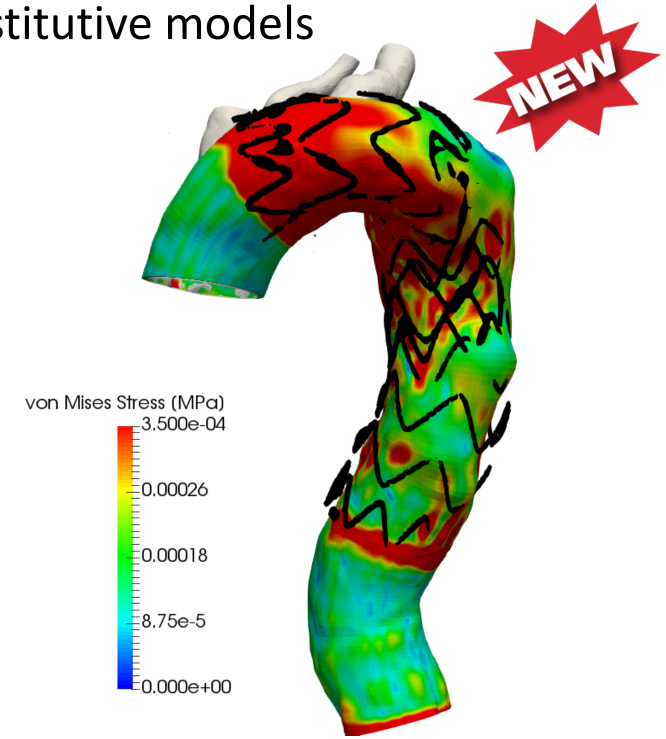
Xu et al., IJNMBE 2018

ISOGEOMETRIC ANALYSIS in FEAP

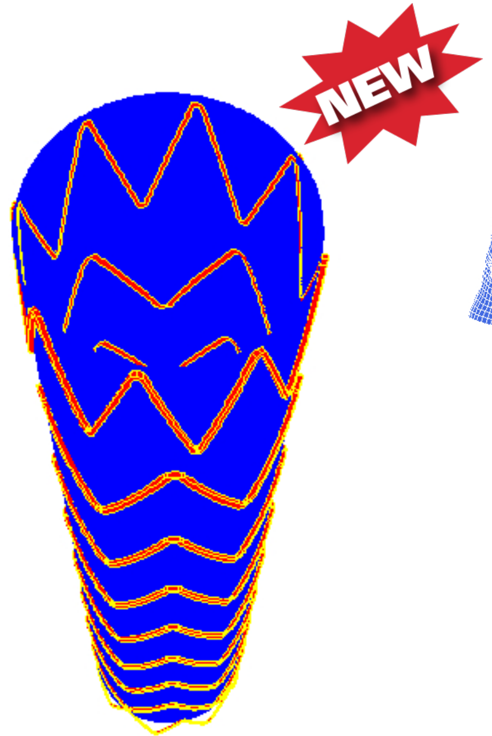
- **FEAP**: **F**inite **E**lement **A**nalysis **P**rogram
  - Primarily for research & educational
  - Based on the Finite Element Method
- **FEAP Isogeometric** package for **B-splines** (clamped/unclamped), tensor product, multi-patch **NURBS**, or **T-splines**.
  - Geometric linear and non-linear problems
  - Static and transient analysis
  - Solid (displacement based and mixed) + shell (Kiendl, et al., 2009)
  - Linear and non-linear constitutive models



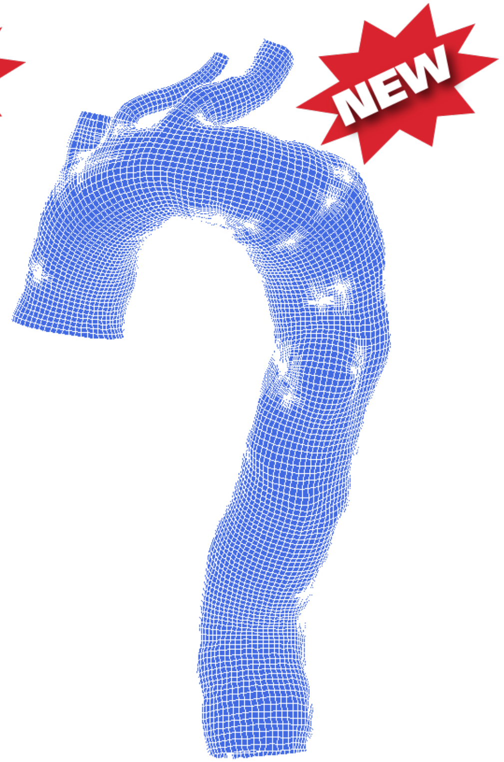
Deployment simulation between a patient-specific NURBS aortic vessel and a multi-patch NURBS stent



Patient-specific stress analysis on an unclamped model of thoracic aorta, employing a non linear membrane model for the stent, with properties obtained from an RVE.



Compatibility with CAD software, e.g., Abaqus



Compatibility with CAD software, e.g., Rhinoceros

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Study 0:
Development and testing of analysis-suitable isogeometric unclamped knot vectors in FEAP.

Collaboration with:
Prof. Robert L. Taylor, University of California, Berkeley

Study 0:

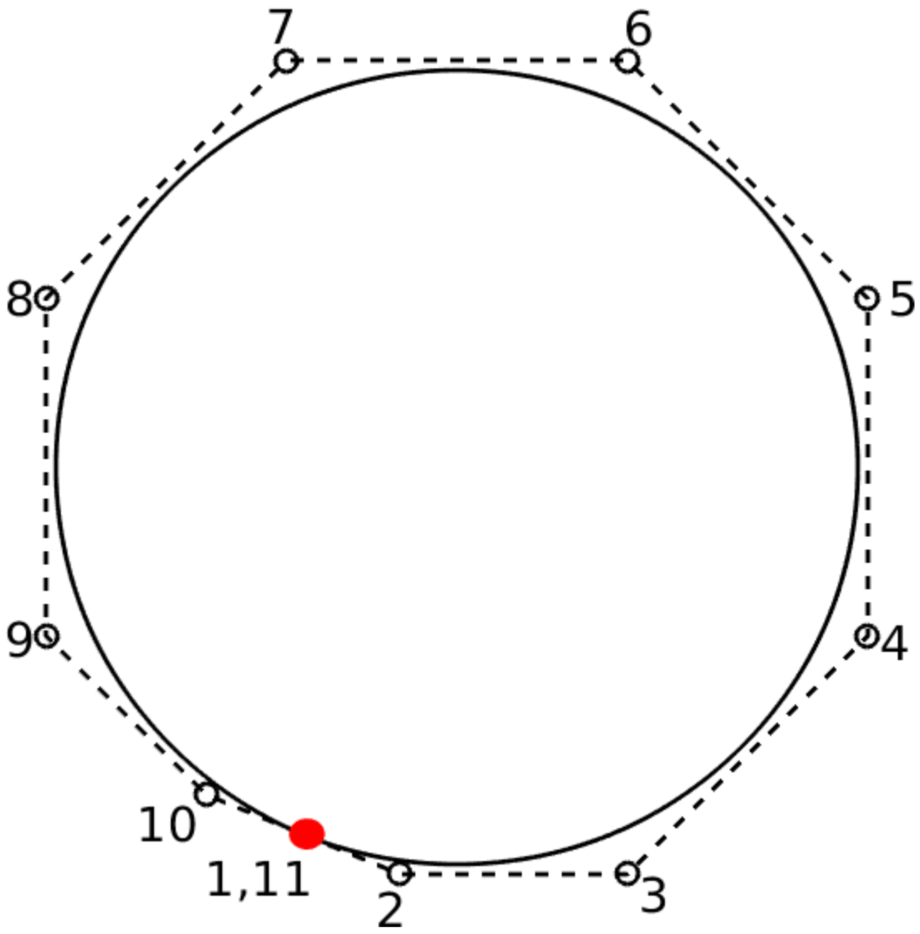
Development and testing of analysis-suitable isogeometric unclamped knot vectors in FEAP.

FINAL GOAL: **EXPLOIT UNCLAMPED KNOT VECTORS CAPABILITIES FOR THE CREATION OF PERIODIC STRUCTURES AND APPLY THEM TO THE STUDY OF PATIENT-SPECIFIC MORPHOLOGIES.**

KEYWORD: **UNCLAMPED KNOT VECTORS.**

WHAT DOES IT *ACTUALLY* MEAN USING *UNCLAMPED KNOT VECTORS*?

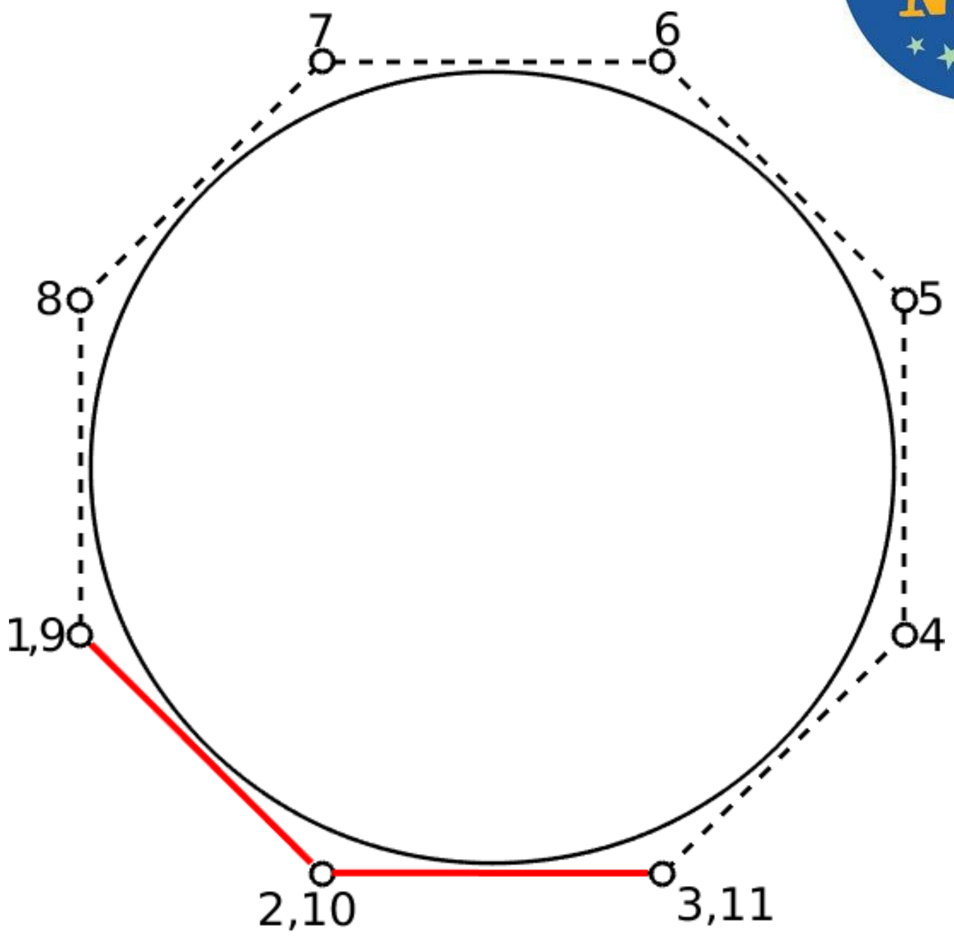
BRAND NEW!



CLAMPED RING

Knot vector: [**3 3 3 3** 4 5 6 7 8 9 10 **11 11 11 11**]

p = 3, num. CPs = 11

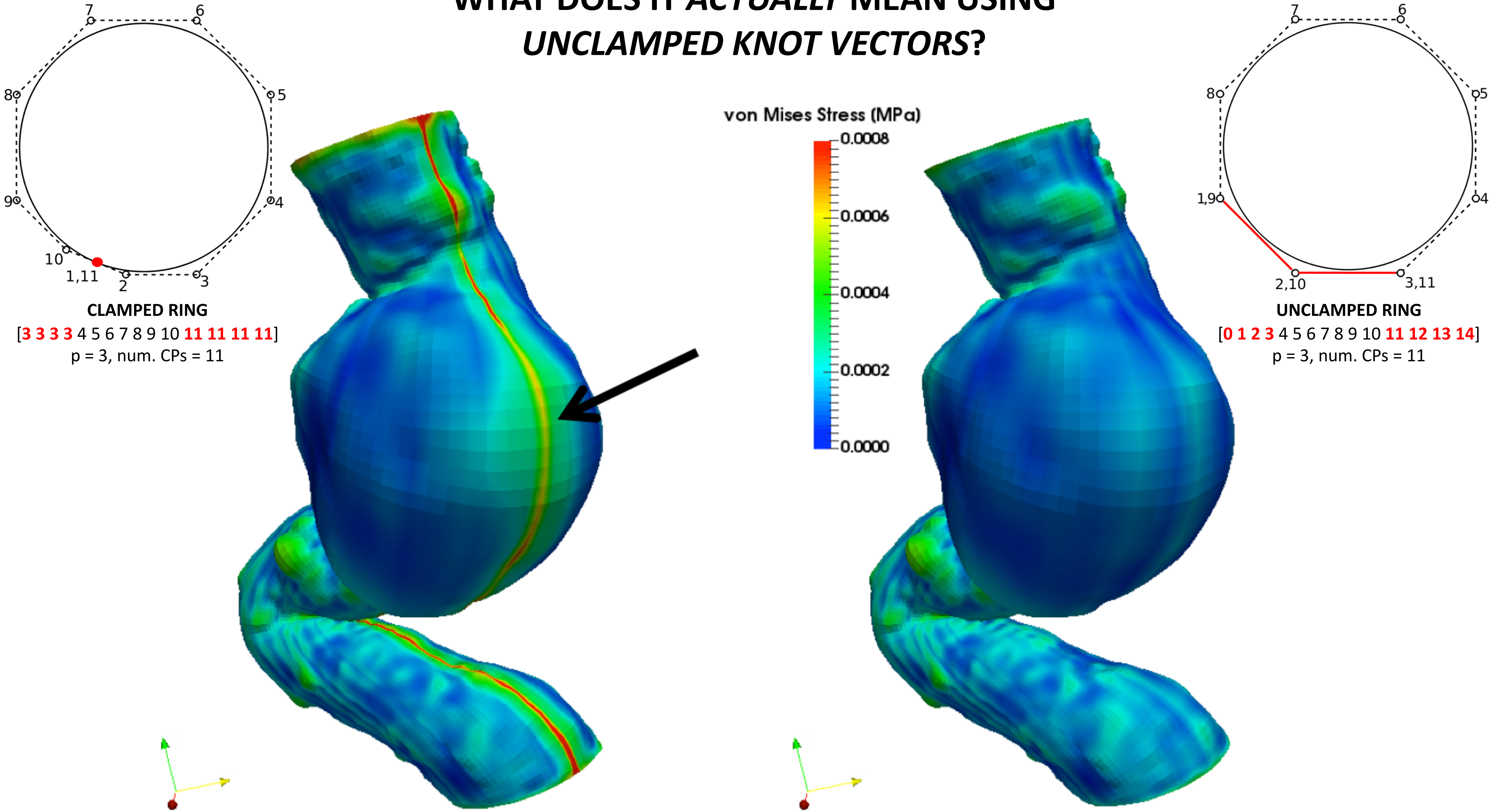


UNCLAMPED RING

Knot vector: [**0 1 2 3** 4 5 6 7 8 9 10 **11 12 13 14**]

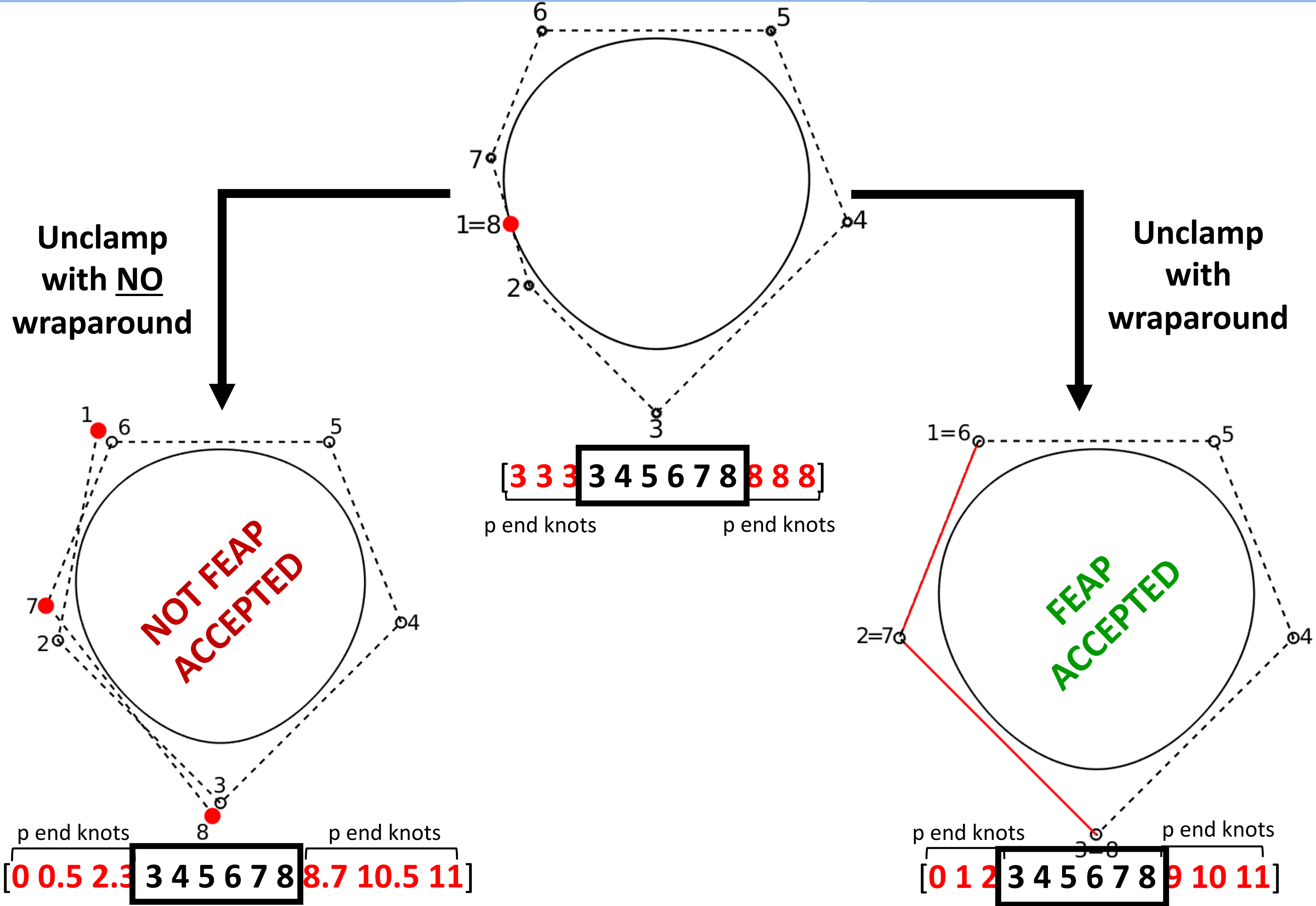
p = 3, num. CPs = 11

WHAT DOES IT *ACTUALLY* MEAN USING *UNCLAMPED KNOT VECTORS*?



ANALYSIS SUITABLE UNCLAMPED KNOT VECTORS IN FEAP

One is free to choose the **2p** new end knots rather arbitrarily and the position of the control points depends on the knots. Unclamping with ***no*** wraparound of the control points is also possible but is ***not*** accepted by FEAP.



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Study 1:

Patient-specific Isogeometric Geometrical Modeling Of Thoracic Aortic Aneurysms by Means Of Unclamped Knot Vectors.

Collaboration with:
Elena Faggiano, Ph.D
Prof. Santi Trimarchi, Università degli Studi di Milano
Prof. Robert L. Taylor, University of California, Berkeley

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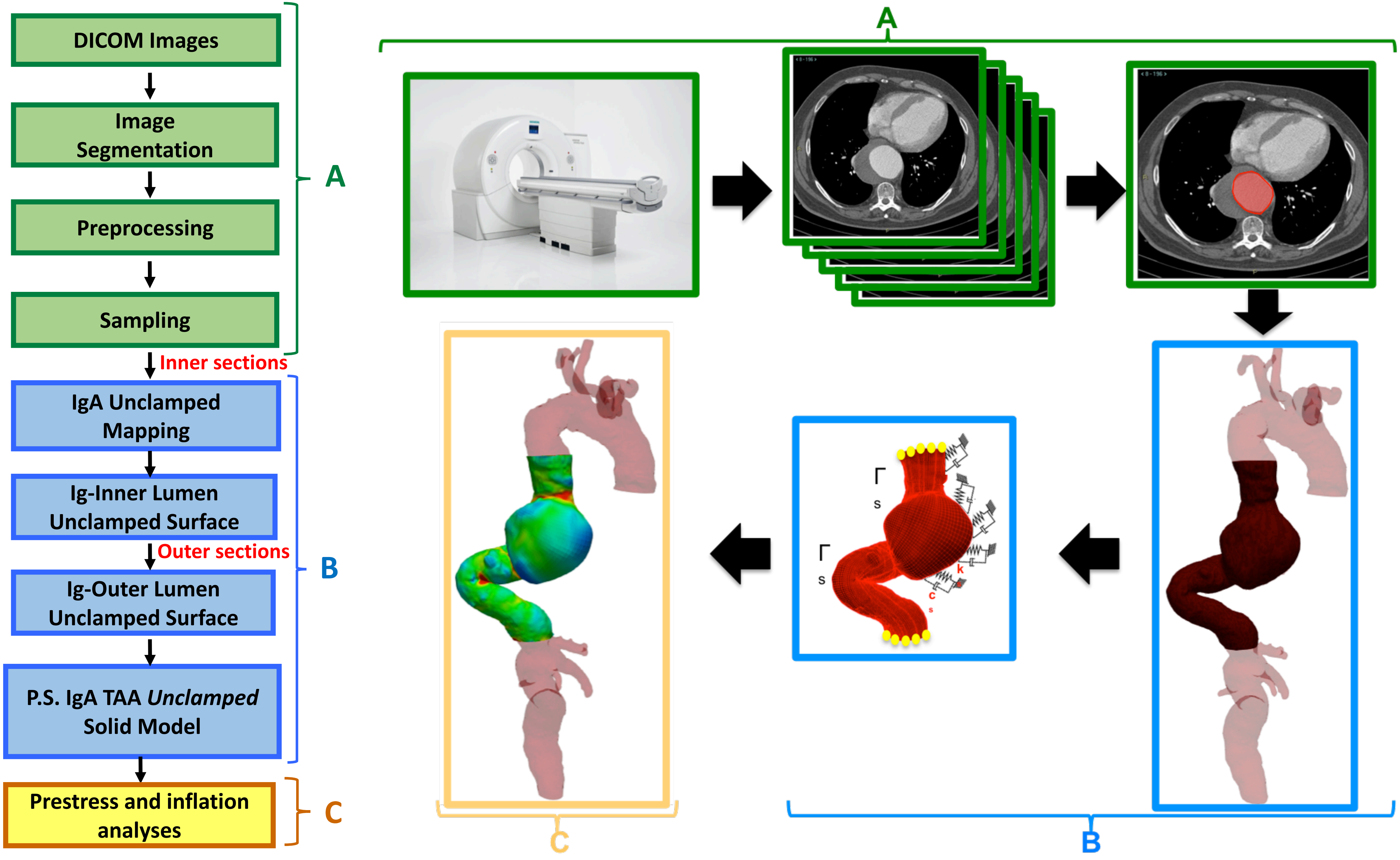
Study 1:

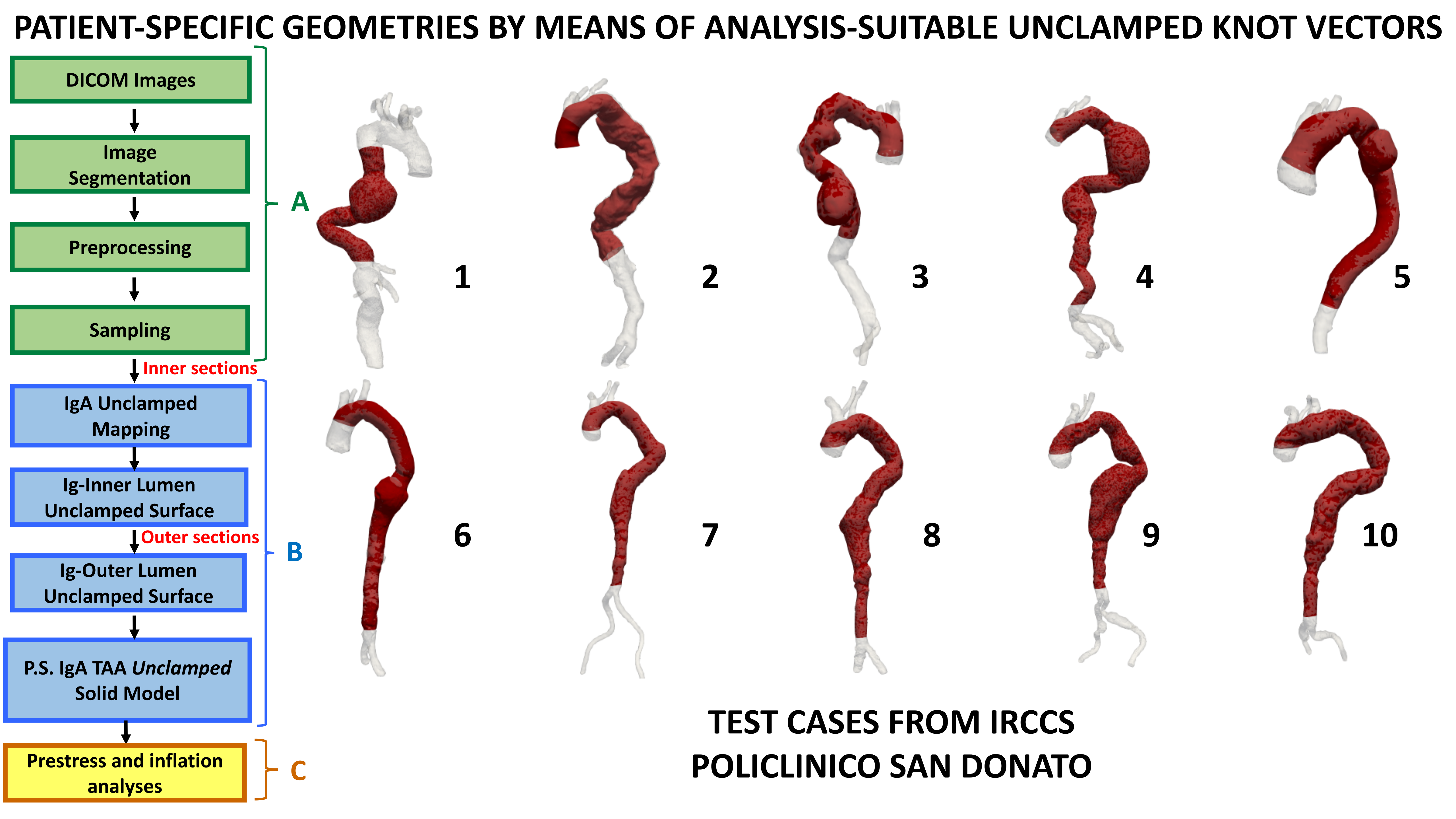
Patient-specific Isogeometric Geometrical Modeling Of Thoracic Aortic Aneurysms by Means Of Unclamped Knot Vectors.

FINAL GOAL: DEMONSTRATE HOW THE CREATION OF P.S. IGA SUITABLE MODEL OF TAA CAN BE DONE QUASI AUTOMATICALLY BY MEANS OF A LIMITED NUMBER OF EASY STEPS.

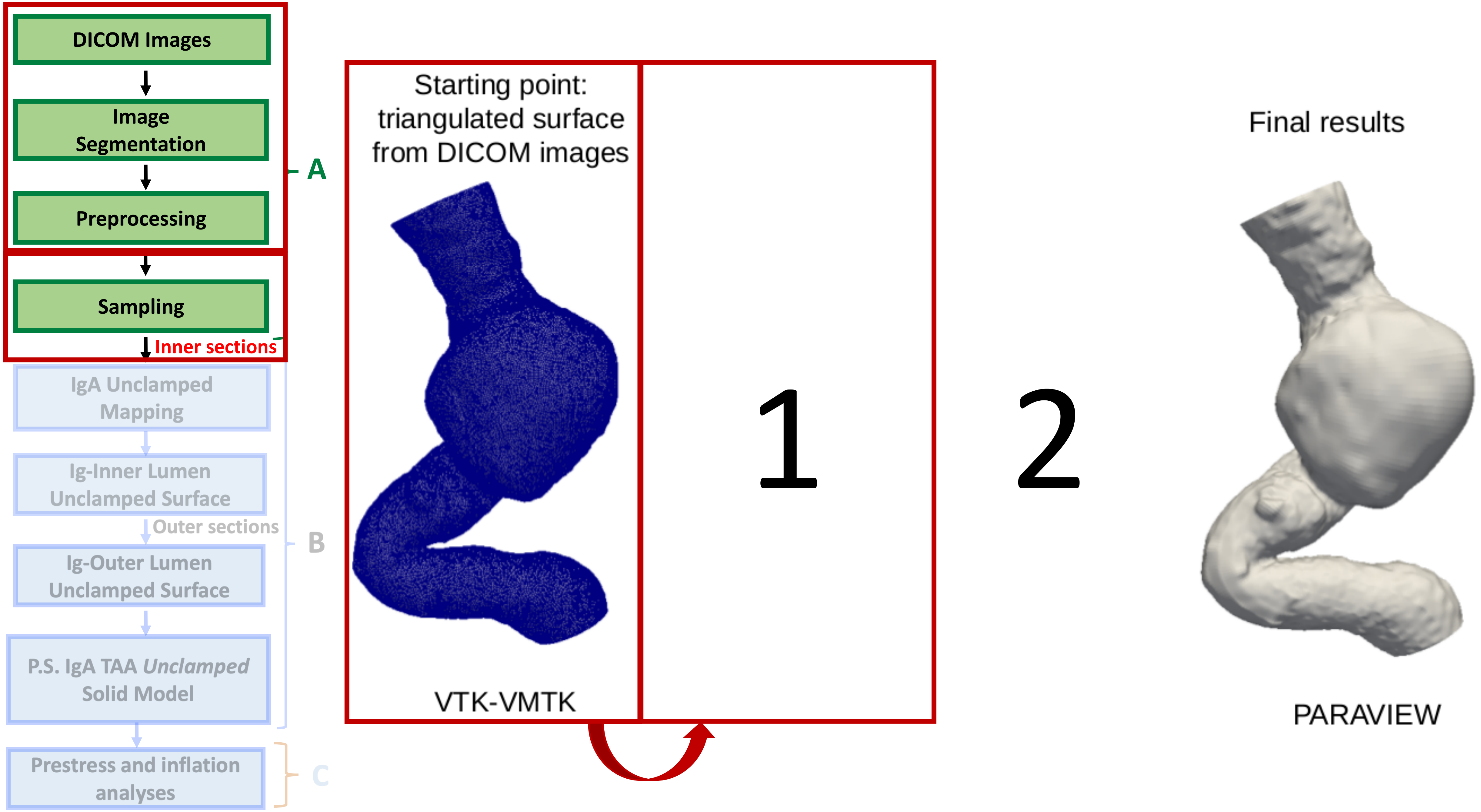
KEYWORD: UNCLAMPED B-SPLINE

PATIENT-SPECIFIC GEOMETRIES BY MEANS OF ANALYSIS-SUITABLE UNCLAMPED KNOT VECTORS



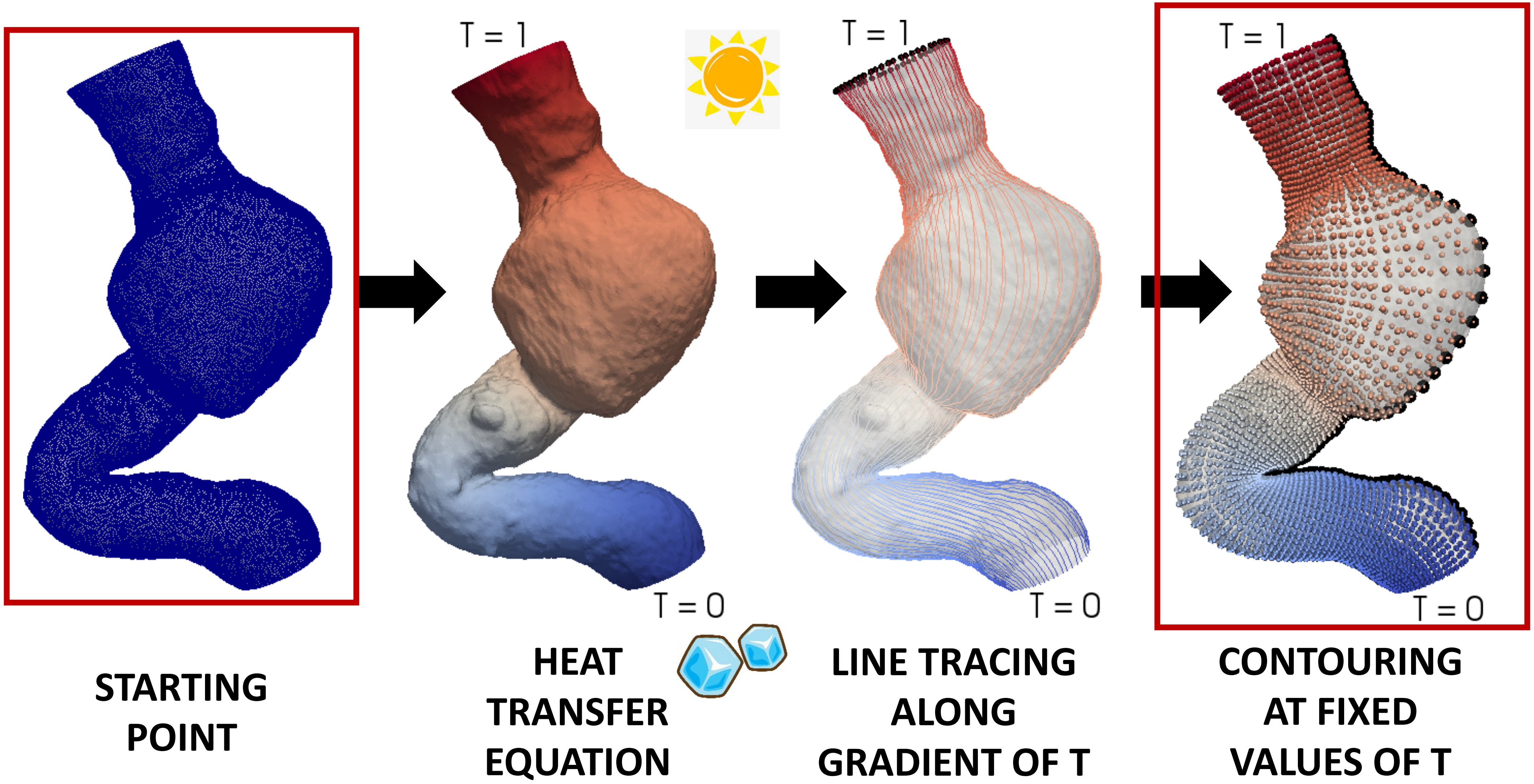

PATIENT-SPECIFIC GEOMETRIES BY MEANS OF ANALYSIS-SUITABLE UNCLAMPED KNOT VECTORS
DICOM Images
Image Segmentation
Preprocessing
Sampling
A
Inner sections
IgA Unclamped Mapping
Ig-Inner Lumen Unclamped Surface
Outer sections
Ig-Outer Lumen Unclamped Surface
P.S. IgA TAA *Unclamped* Solid Model
B
Prestress and inflation analyses
C
1
2
3
4
5
6
7
8
9
10
TEST CASES FROM IRCCS POLICLINICO SAN DONATO

PATIENT-SPECIFIC GEOMETRIES BY MEANS OF ANALYSIS-SUITABLE UNCLAMPED KNOT VECTORS



Sampling method to get cross sections of points that satisfy:

- Two cross-sections of points cannot intersect;
- Each cross-section of points is orthogonal to the vessel wall.
- ***No centerline involved!***



Sampling method to get cross sections of points that satisfy:

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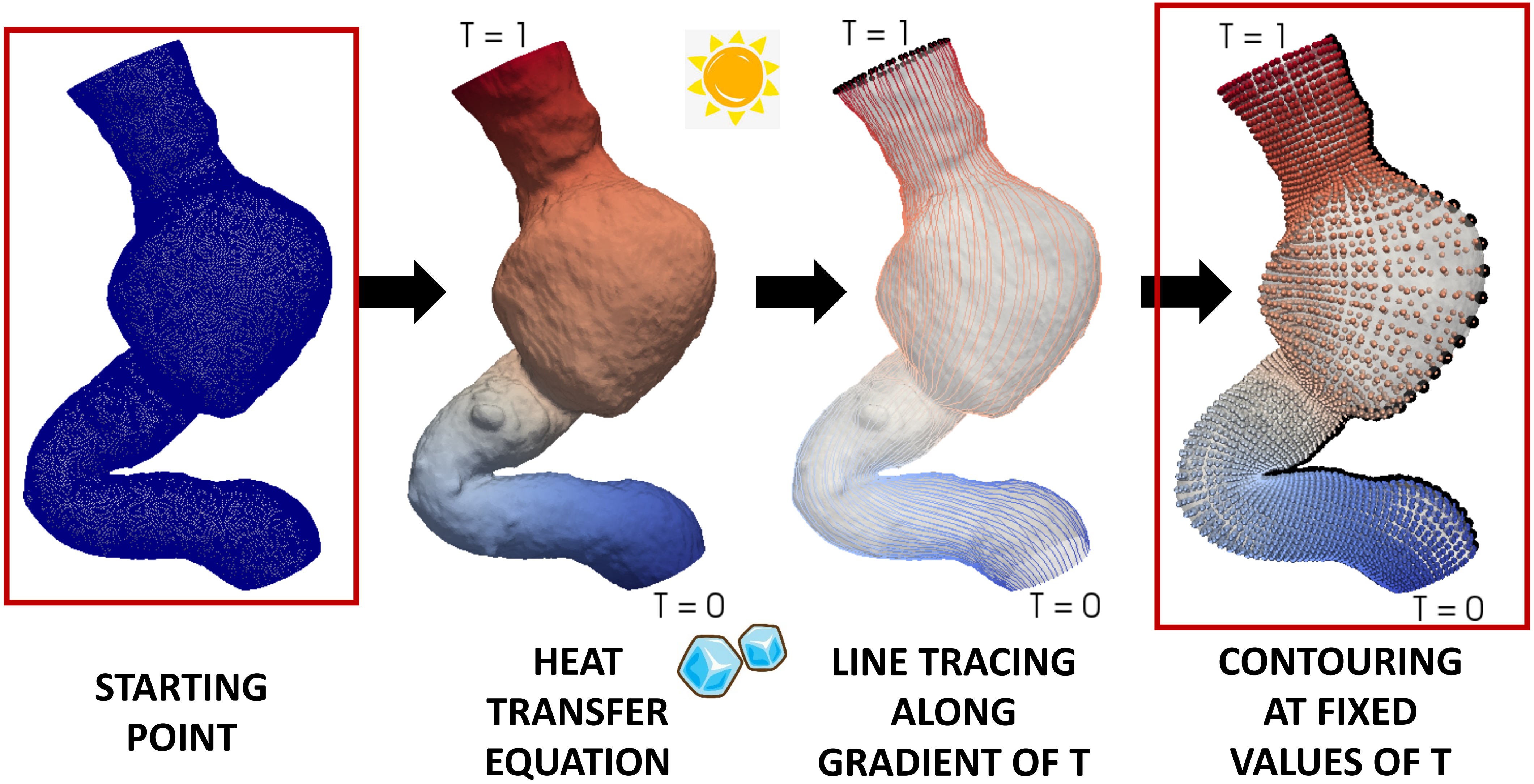
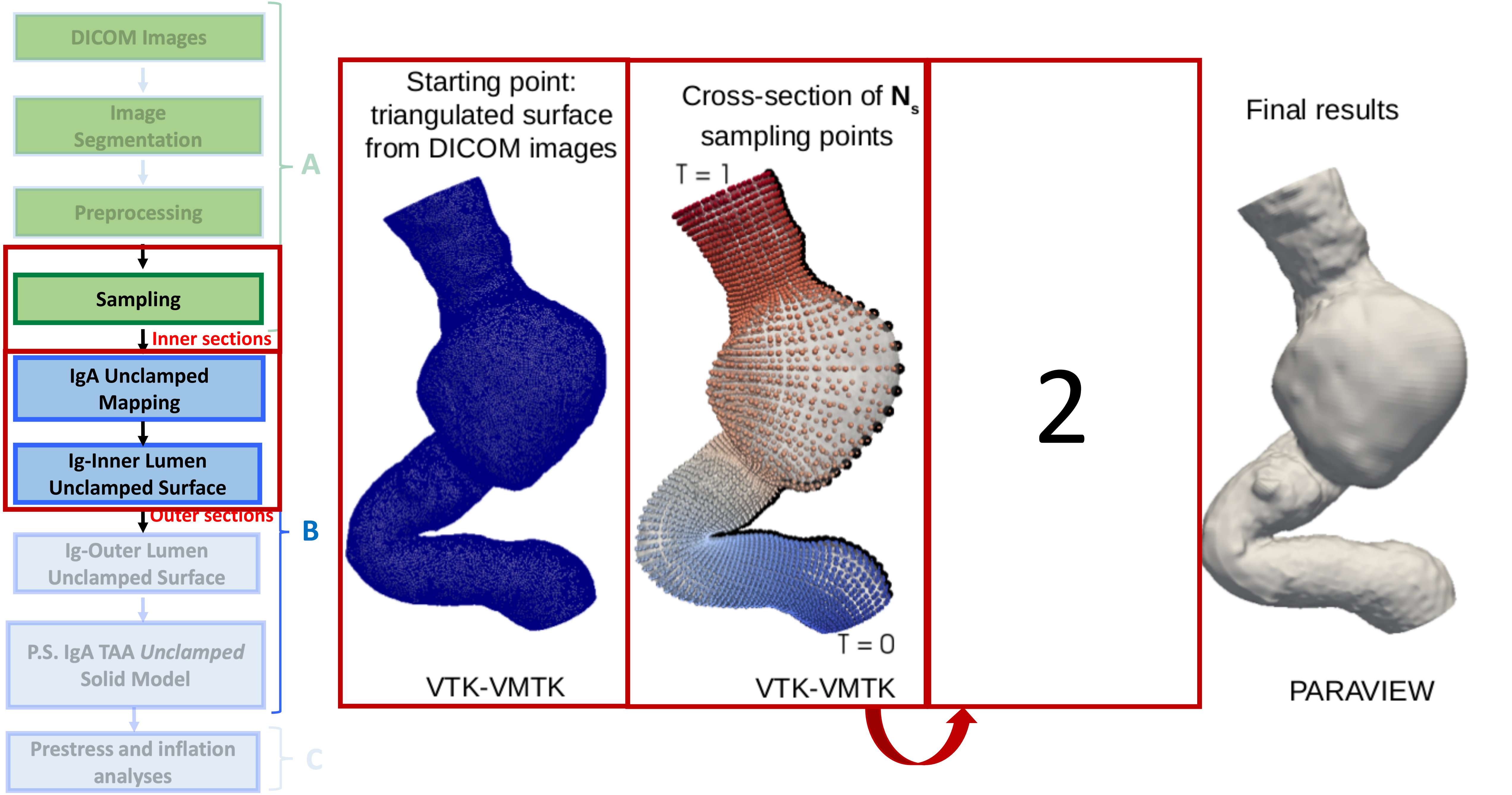
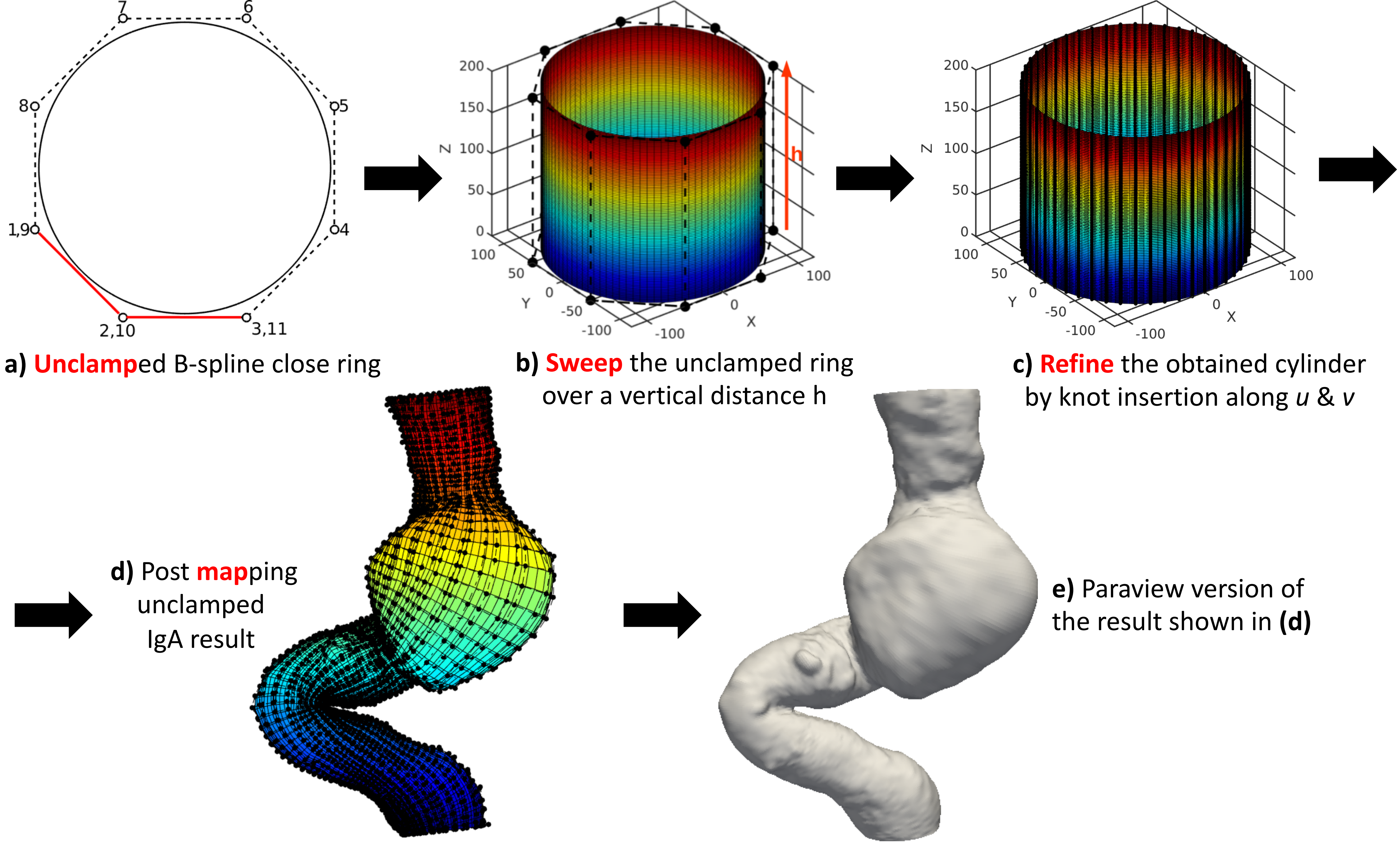
TIME: 3.2 ± 2.0 mins



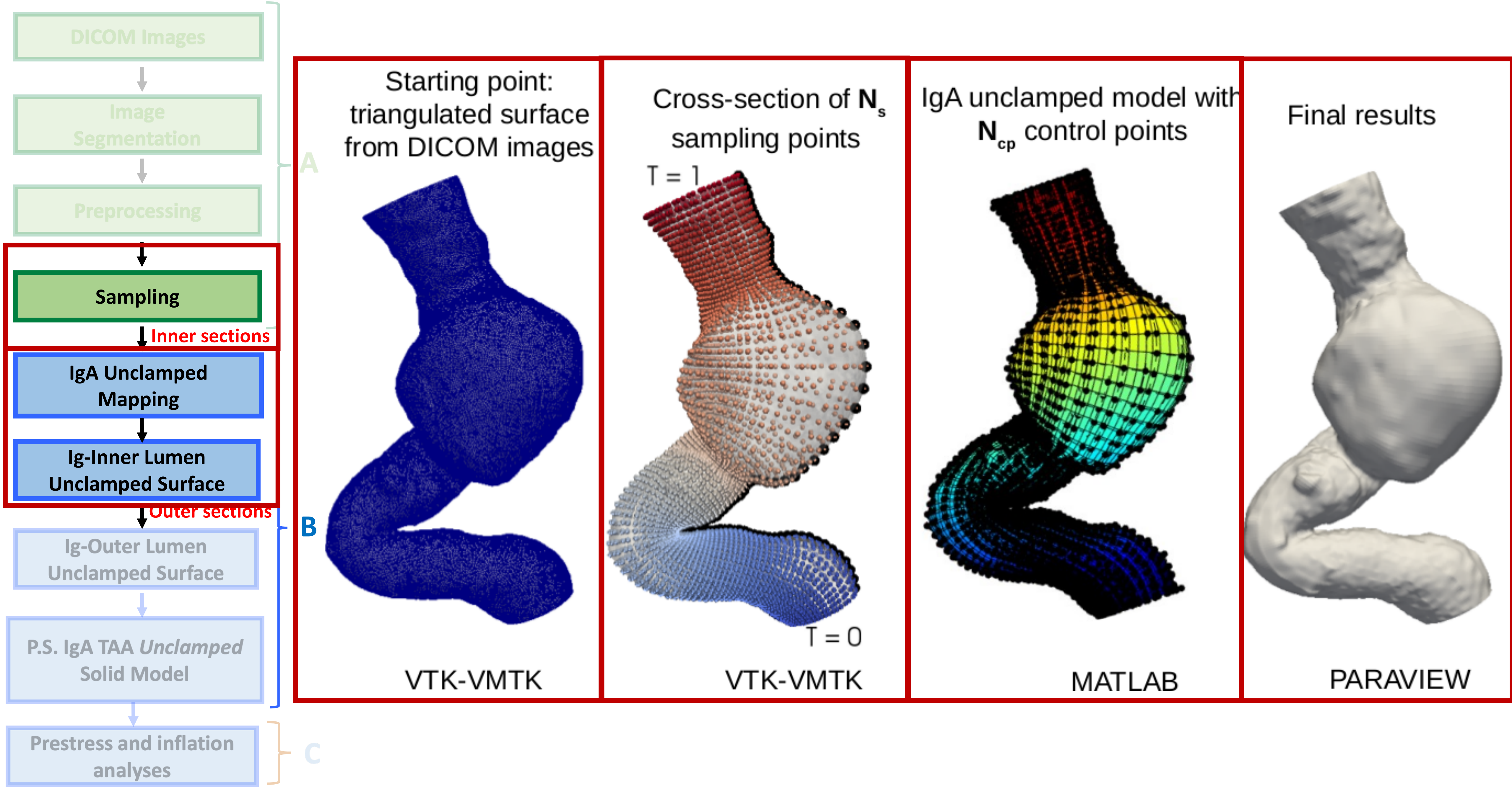
PATIENT-SPECIFIC GEOMETRIES BY MEANS OF ANALYSIS-SUITABLE UNCLAMPED KNOT VECTORS

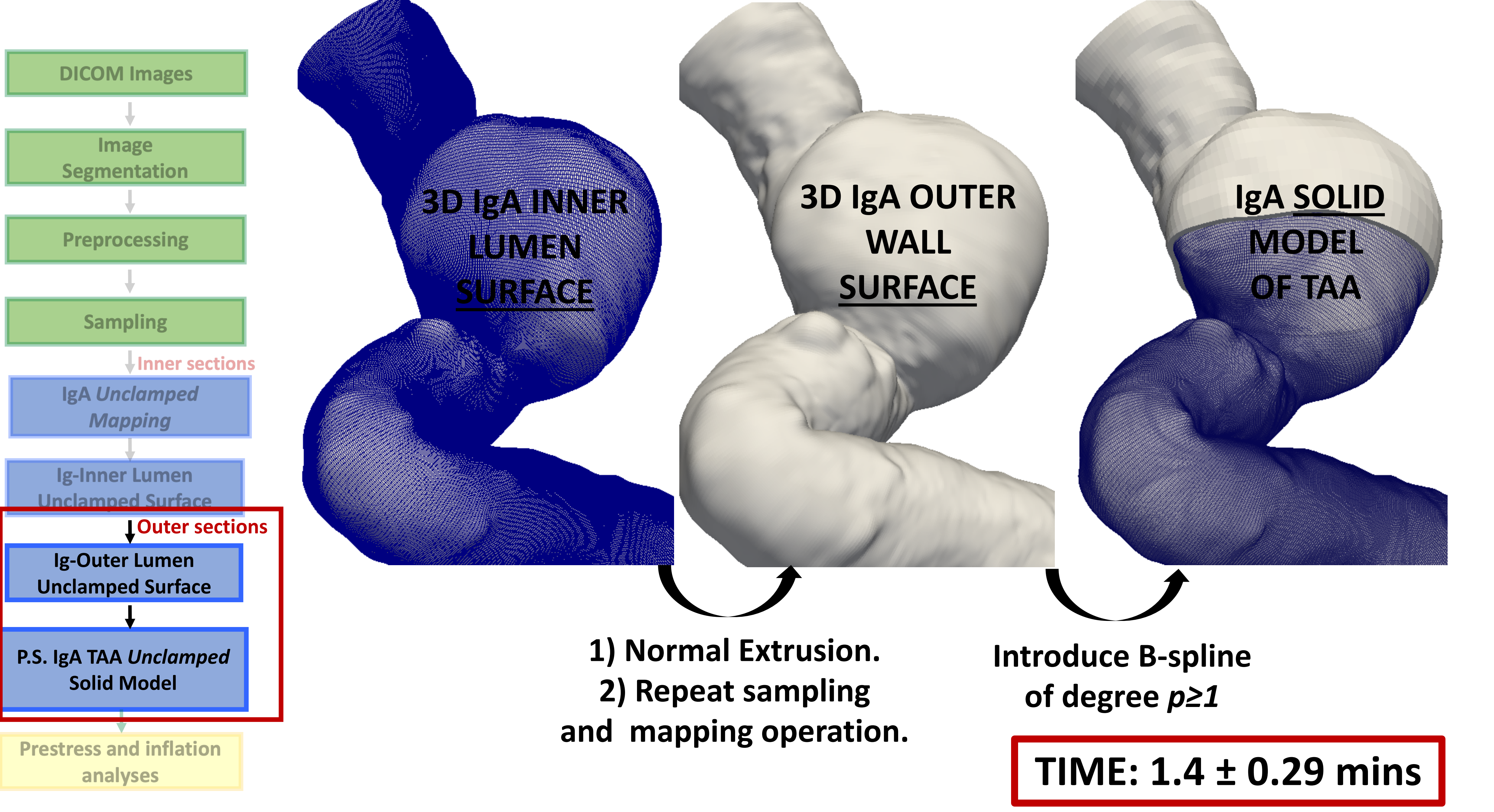




7
6
8
5
1,9
4
2,10
3,11
a) Unclamped B-spline close ring
200
150
100
50
0
Z
h
100
50
0
-50
-100
Y
-100
0
100
X
b) Sweep the unclamped ring over a vertical distance h
c) Refine the obtained cylinder by knot insertion along u & v
d) Post mapping unclamped IgA result
e) Paraview version of the result shown in (d)

PATIENT-SPECIFIC GEOMETRIES BY MEANS OF ANALYSIS-SUITABLE UNCLAMPED KNOT VECTORS




DICOM Images
Image Segmentation
Preprocessing
Sampling
Inner sections
IgA *Unclamped* *Mapping*
Ig-Inner Lumen Unclamped Surface
Outer sections
Ig-Outer Lumen Unclamped Surface
P.S. IgA TAA *Unclamped* Solid Model
Prestress and inflation analyses
3D IgA INNER LUMEN SURFACE
3D IgA OUTER WALL SURFACE
IgA SOLID MODEL OF TAA
1) Normal Extrusion.
2) Repeat sampling and mapping operation.
Introduce B-spline of degree *p≥1*
TIME: 1.4 ± 0.29 mins

DICOM Images

↓

Image Segmentation

↓

Preprocessing

↓

Sampling

↓ Inner sections

IgA *Unclamped Mapping*

↓

Ig-Inner Lumen Unclamped Surface

↓ Outer sections

Ig-Outer Lumen Unclamped Surface

↓

P.S. IgA TAA *Unclamped* Solid Model

↓

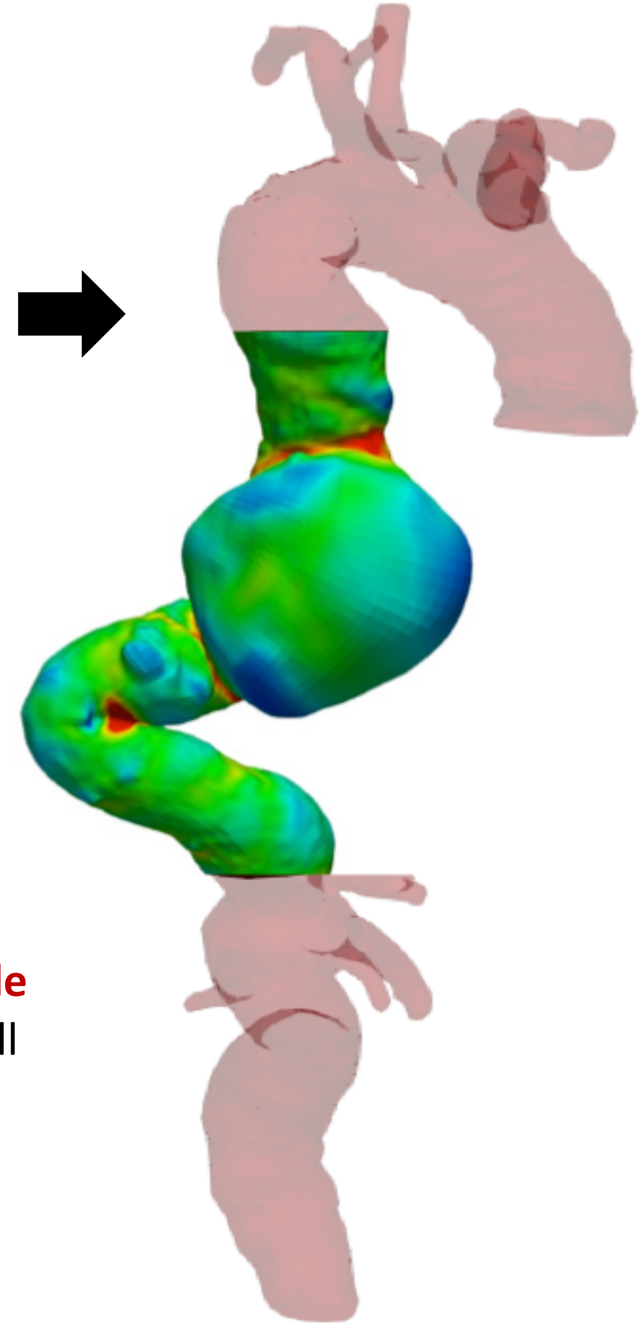
Prestress and inflation analyses

B-Spline Geometry

Zero-pressure B-spline unclamped geometries (Bols Y, *et al*, 2013)

Constitutive Description

Non-linear, hyperelastic, isotropic, nearly-incompressible formulation for the arterial wall (Raghavan and Vorp, 2000)

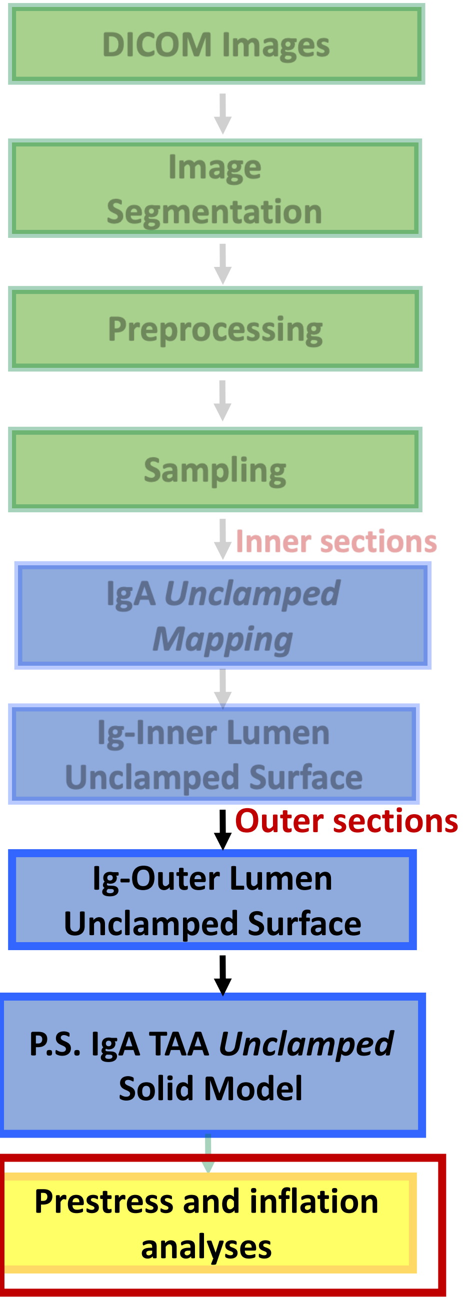


Blood pressure

Patient-specific MAP pressure from CFD analyses (Romarowski, *et al*. 2018)

Boundary Conditions

Robin B.C. to simulate the surrounding organs (Moireau, *et al.*, 2011)



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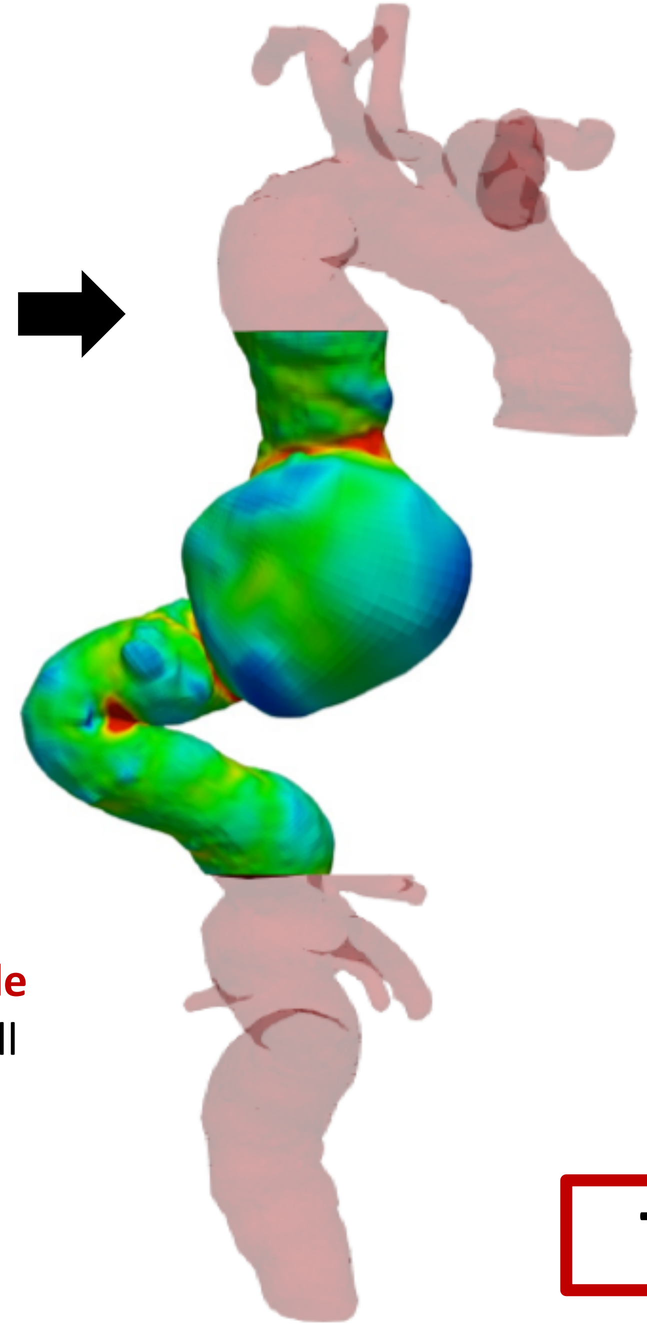


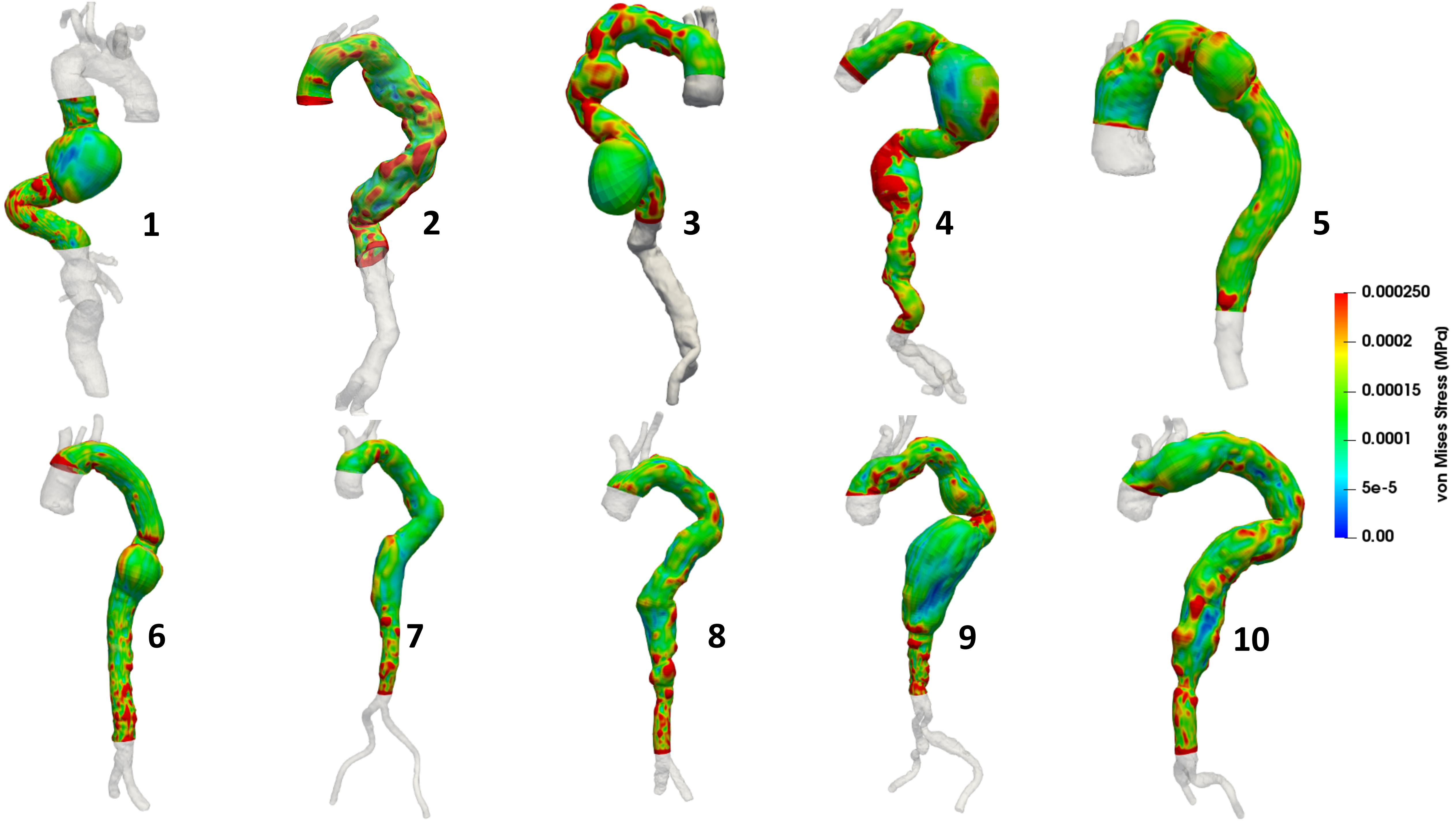
Blood pressure

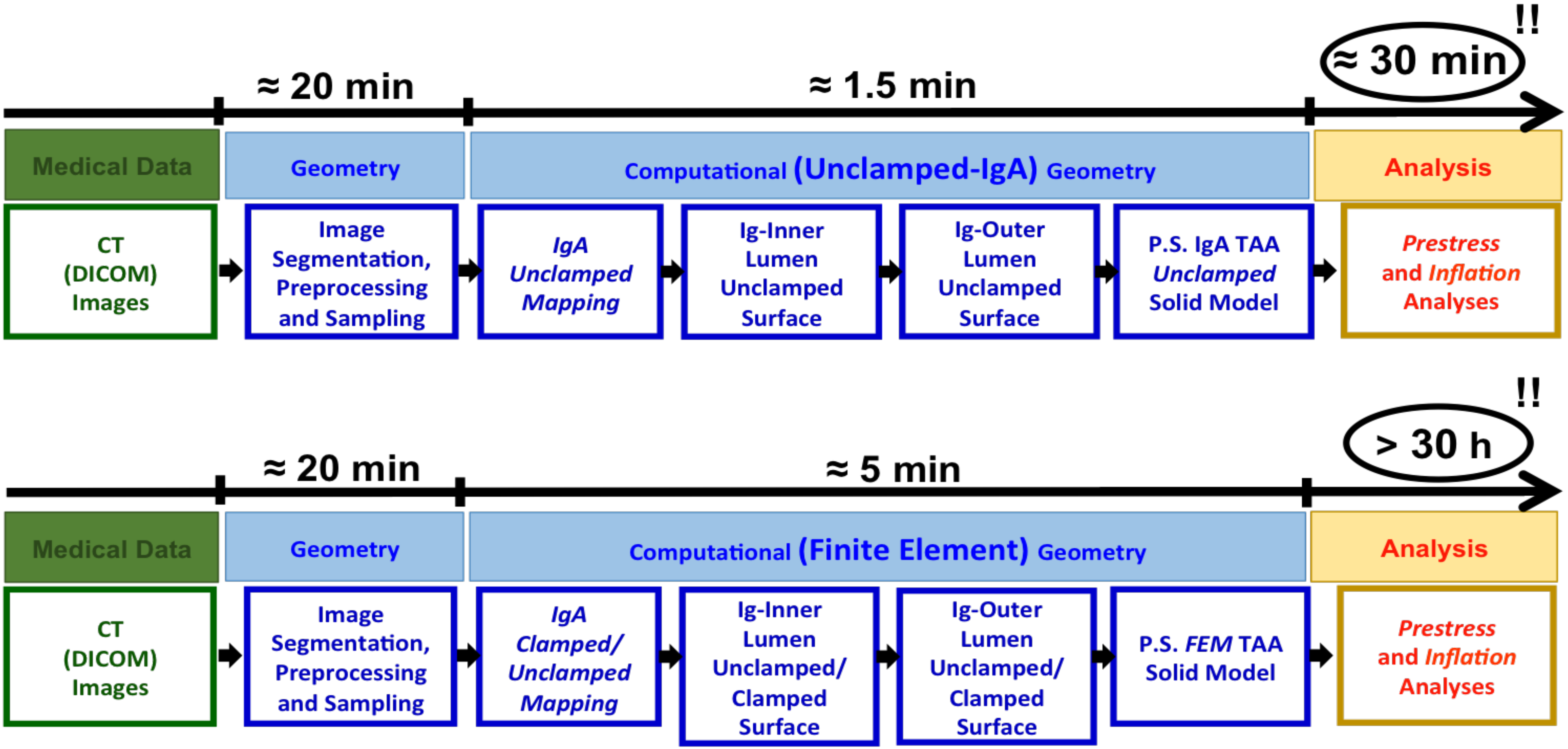
Patient-specific MAP pressure from CFD analyses (Romarowski, *et al*. 2018)

Boundary Conditions

Robin B.C. to simulate the surrounding organs (Moireau, *et al.*, 2011)

TIME: 35 ± 11 mins


1
2
3
4
5
6
7
8
9
10
0.000250
0.0002
0.00015
0.0001
5e-5
0.00
von Mises Stress (MPa)



!!
≈ 30 min
≈ 20 min
≈ 1.5 min
Medical Data
Geometry
Computational (Unclamped-IgA) Geometry
Analysis
CT (DICOM) Images
Image Segmentation, Preprocessing and Sampling
IgA Unclamped Mapping
Ig-Inner Lumen Unclamped Surface
Ig-Outer Lumen Unclamped Surface
P.S. IgA TAA Unclamped Solid Model
Prestress and Inflation Analyses
!!
> 30 h
≈ 20 min
≈ 5 min
Medical Data
Geometry
Computational (Finite Element) Geometry
Analysis
CT (DICOM) Images
Image Segmentation, Preprocessing and Sampling
IgA Clamped/ Unclamped Mapping
Ig-Inner Lumen Unclamped/ Clamped Surface
Ig-Outer Lumen Unclamped/ Clamped Surface
P.S. FEM TAA Solid Model
Prestress and Inflation Analyses

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Take home messages:

- Creating a p.s. IgA suitable model of TAA can be done **almost automatically** by performing a limited number of relatively easy steps

- Simulations model and analysis settings represent a good compromise between computational time and accuracy.

- The framework can be a promising starting point for the development of a decision making tool to be used **real-time** by physicians to decide whether is worth operating or not.

- **BUT, we are neglecting the presence of supra-aortic branches**, that may impact the computation of the von Mises stress at the vessel wall.

Study 2:

Patient-specific Isogeometric Modeling Of Bifurcated Geometries By Means Of T-splines.

Collaboration with:
John Eric Dofour, Ph.D
Prof. Robert L. Taylor, University of California, Berkeley

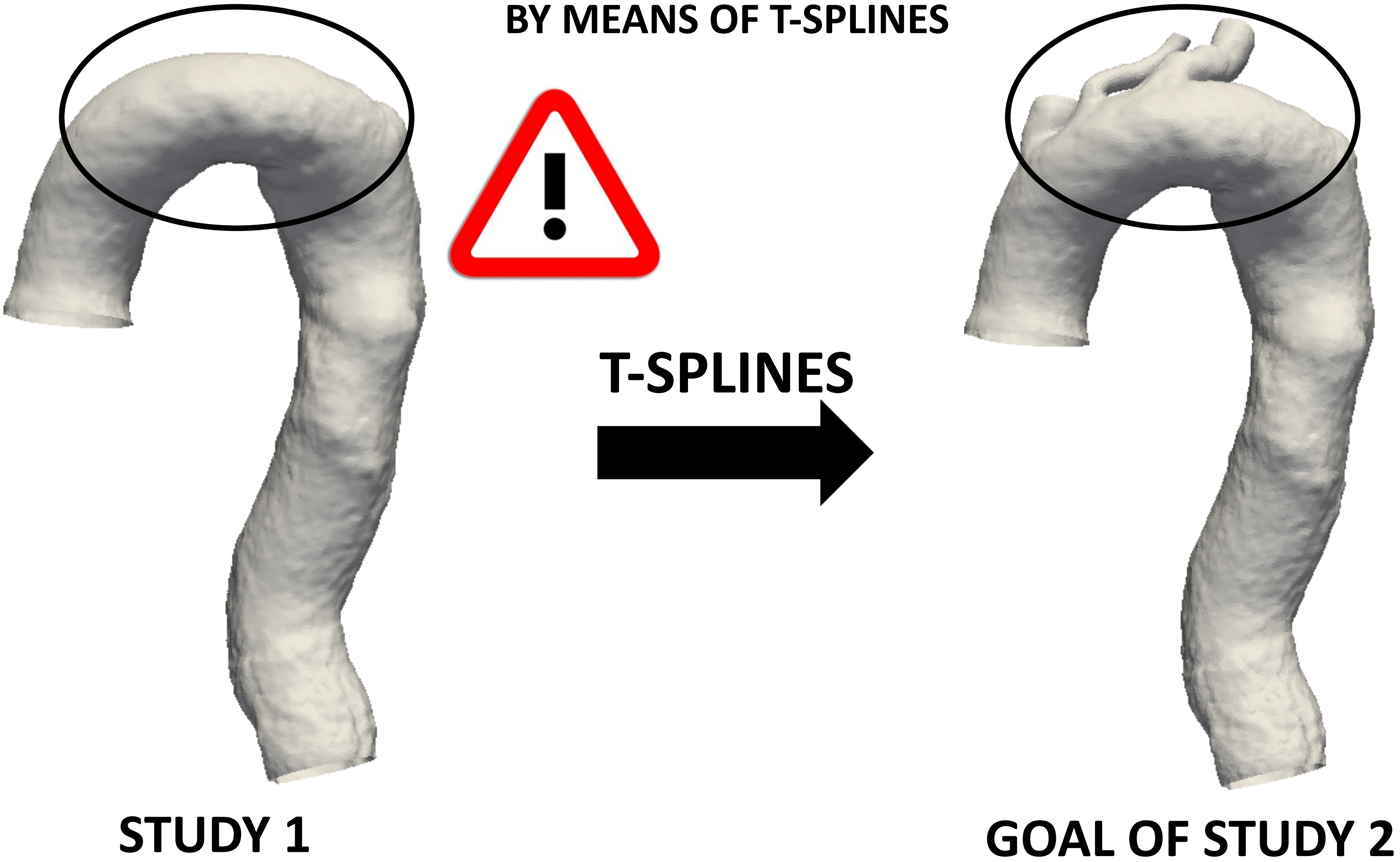
Study 2:

Patient-specific Isogeometric Modeling Of Bifurcated Geometries By Means Of T-splines.

FINAL GOAL: **DEMONSTRATE HOW THE CREATION OF *BRANCHED* P.S. IGA SUITABLE MODELS CAN BE DONE QUASI AUTOMATICALLY BY MEANS OF A LIMITED NUMBER OF EASY STEPS**

KEYWORD: **T-SPLINES**

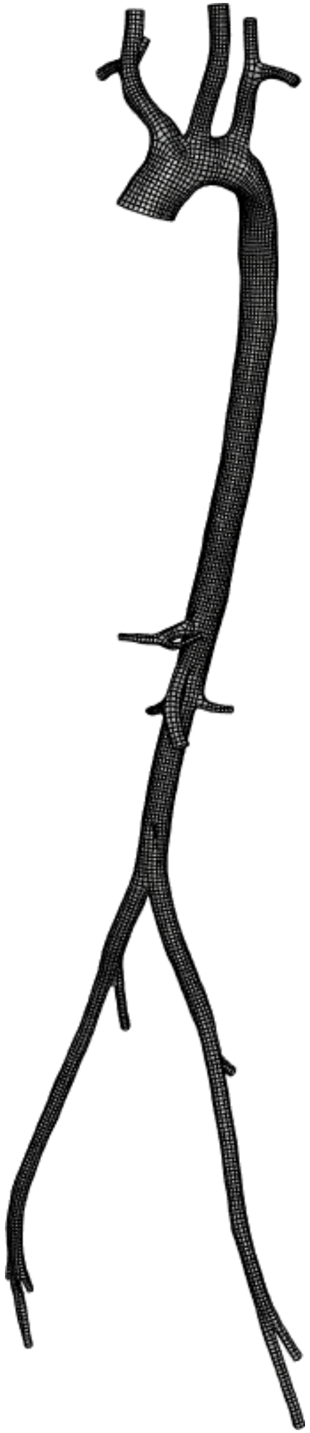
PATIENT-SPECIFIC ISOGEOMETRIC MODELING OF BIFURCATED GEOMETRIES BY MEANS OF T-SPLINES



PATIENT-SPECIFIC ISOGEOMETRIC MODELING OF BIFURCATED GEOMETRIES BY MEANS OF T-SPLINES

Isogeometric T-spline meshing in FEAP

- T-spline meshing using Rhino Autodesk plugin;
- Creates many extraordinary points;
- Note fine mesh locations;
- Required definition of extraction operator;
- Mostly for surfaces.



Courtesy of Prof. A. Kamenskiy,
University of Nebraska

Courtesy of
IRCCS Policlinico San Donato

PATIENT-SPECIFIC ISOGEOMETRIC MODELING OF BIFURCATED GEOMETRIES BY MEANS OF T-SPLINES

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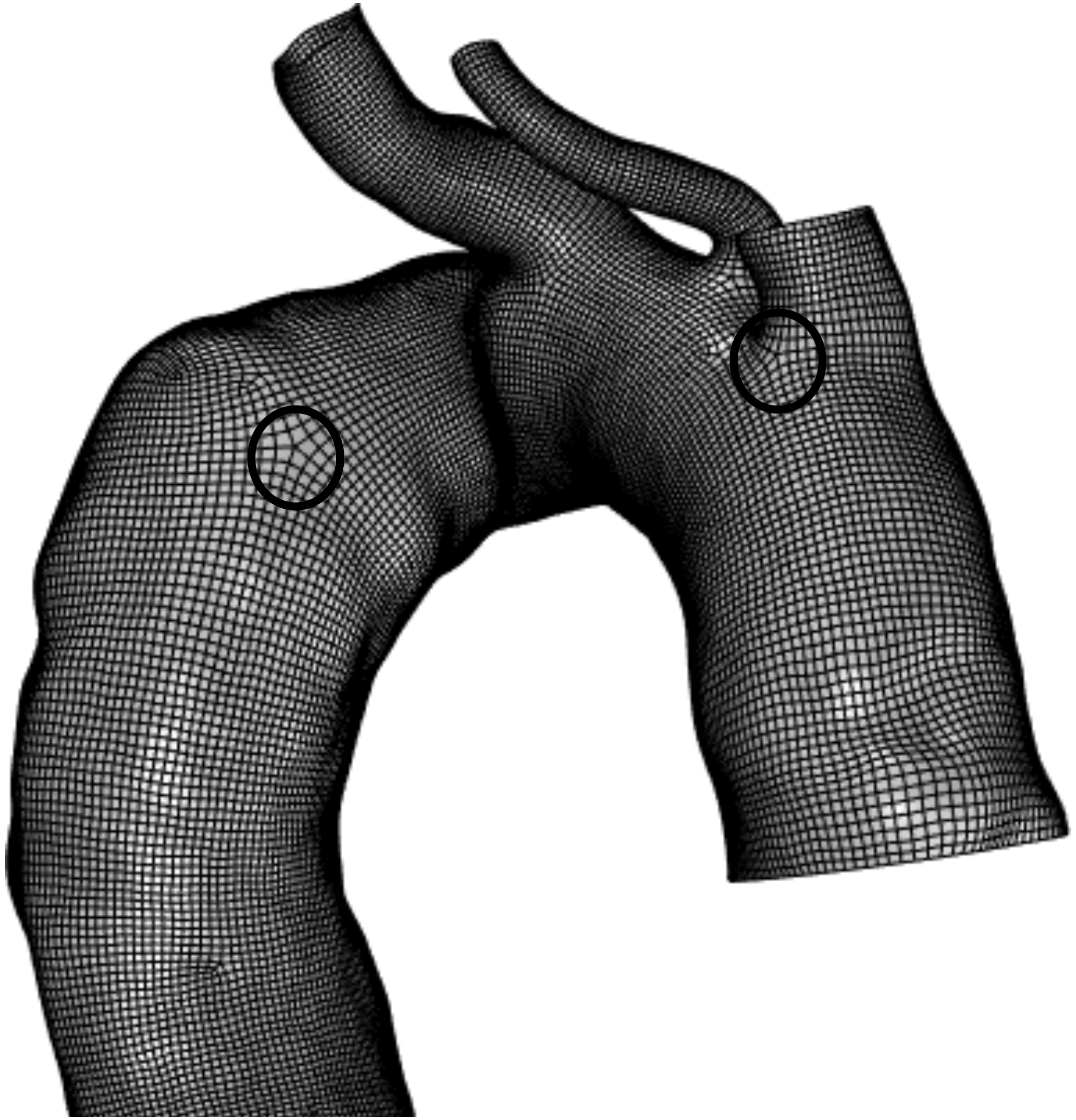

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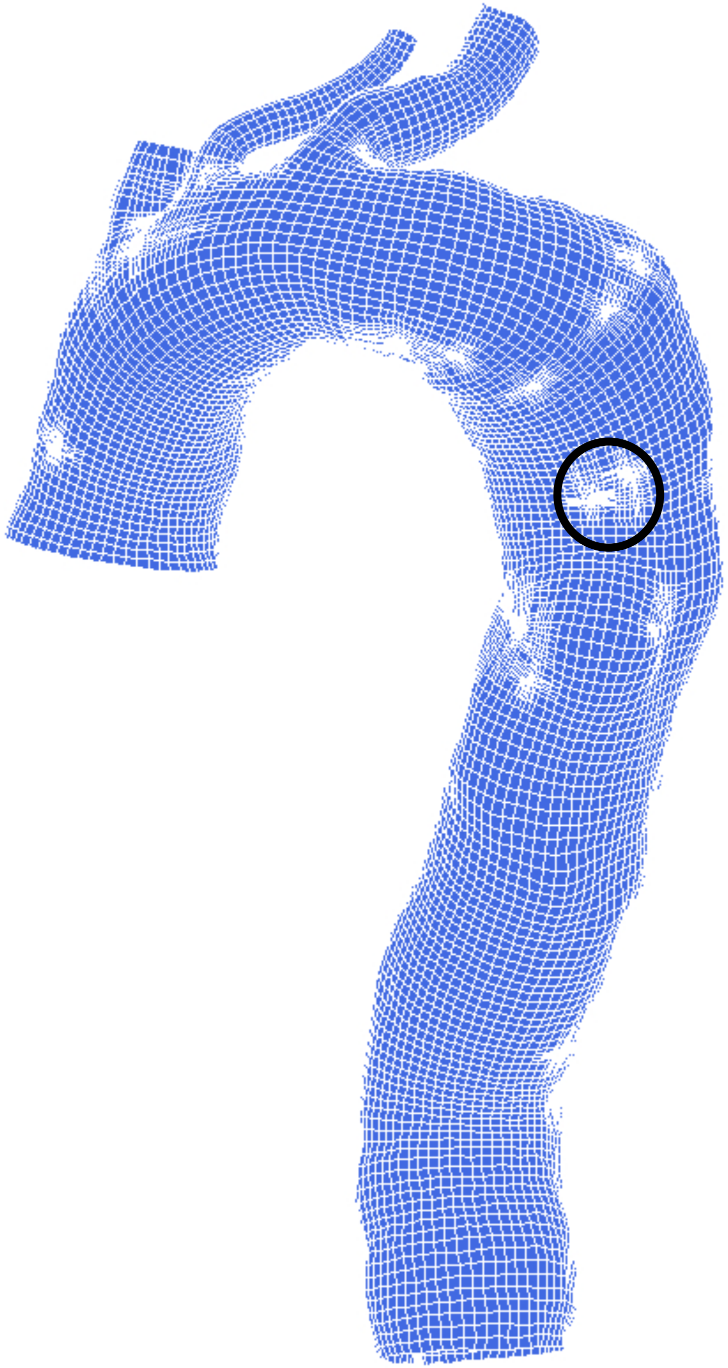
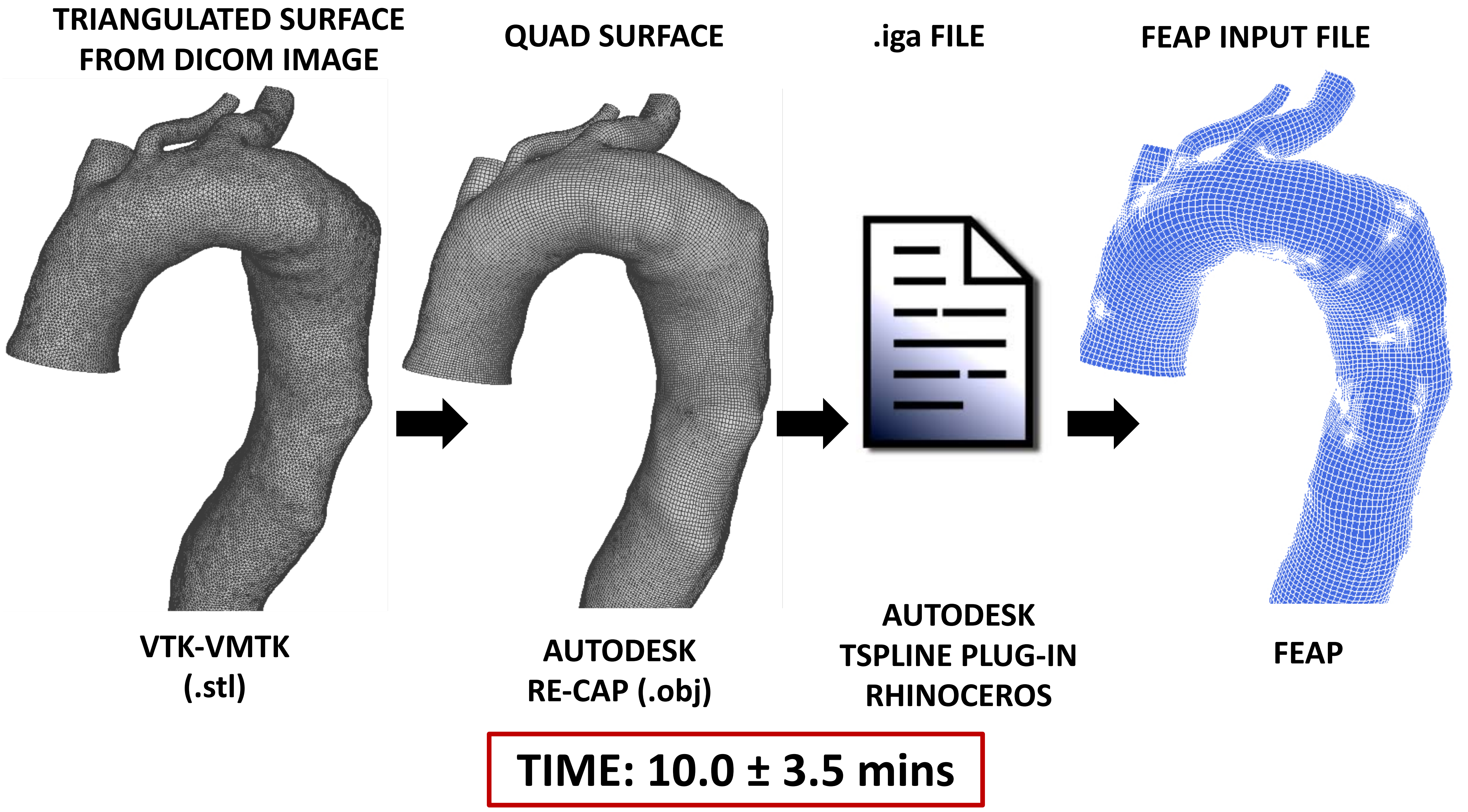
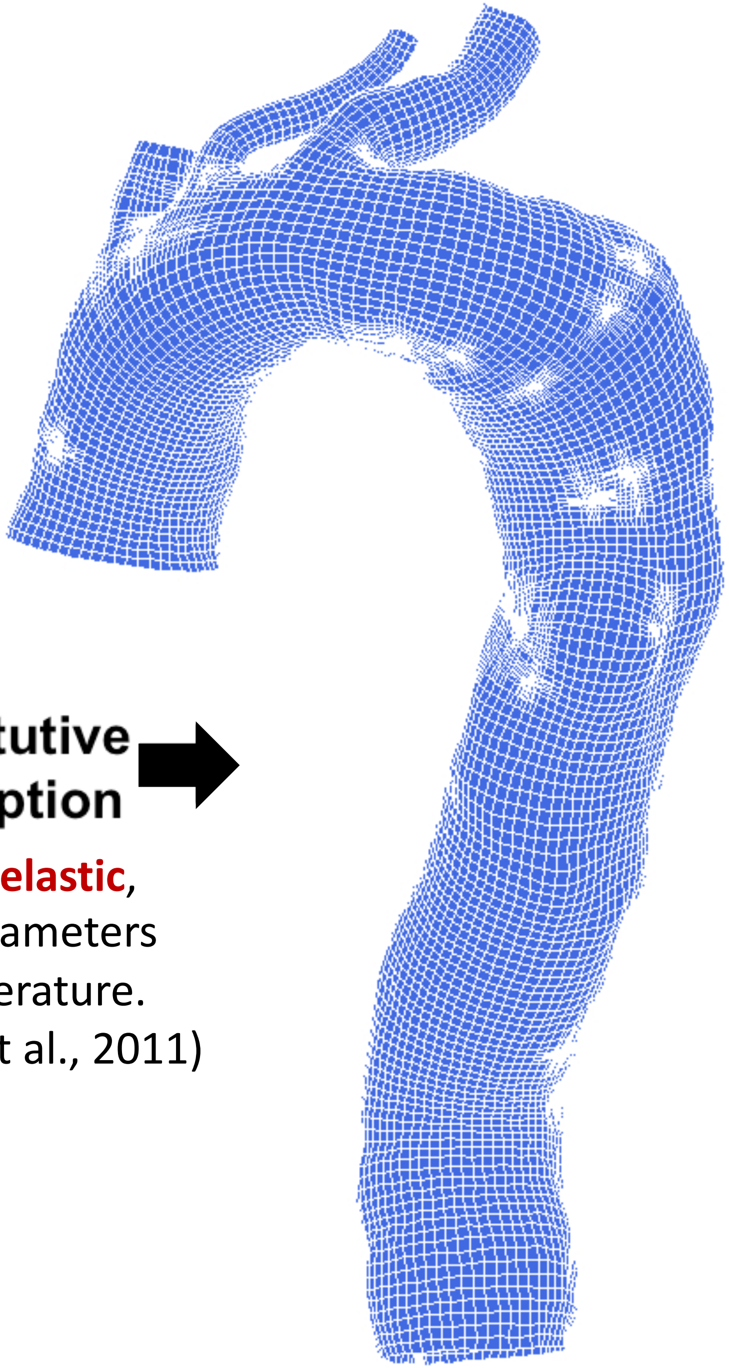



TRIANGULATED SURFACE FROM DICOM IMAGE
QUAD SURFACE
.iga FILE
FEAP INPUT FILE
VTK-VMTK (.stl)
AUTODESK RE-CAP (.obj)
AUTODESK TSPLINE PLUG-IN RHINOCEROS
FEAP
TIME: 10.0 ± 3.5 mins

Element Type

Kirchhoff-Love thin shell elements are used.
(Kiendl, 2009)



Blood pressure

Patient-specific MAP pressure from CFD analyses
(Romarowski, *et al*. 2018)

Constitutive Description

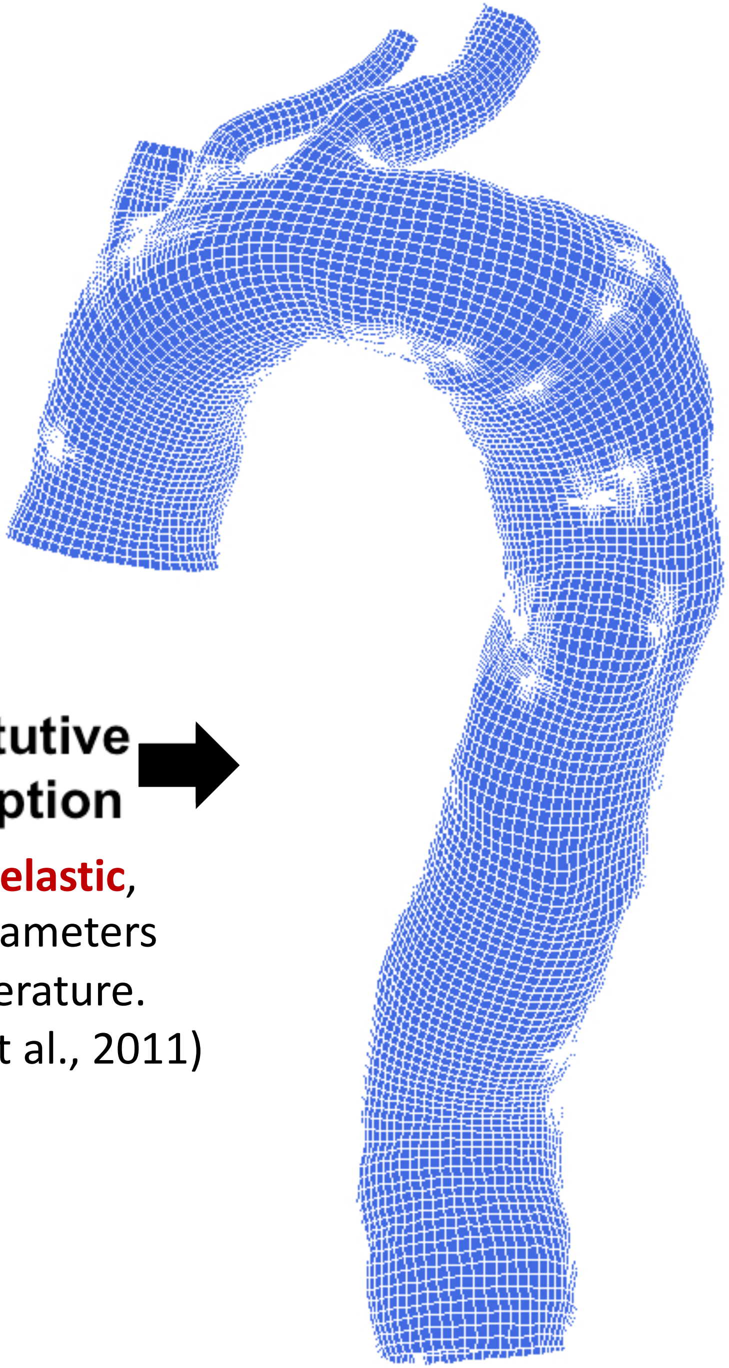
Linear, elastic, with parameters from literature.
(Nathan, et al., 2011)

Boundary Conditions

Robin B.C. to simulate the surrounding organs
(Moireau, *et al.*, 2011)

Element Type

Kirchhoff-Love thin shell elements are used.
(Kiendl, 2009)



Blood pressure

Patient-specific MAP pressure from CFD analyses
(Romarowski, *et al*. 2018)

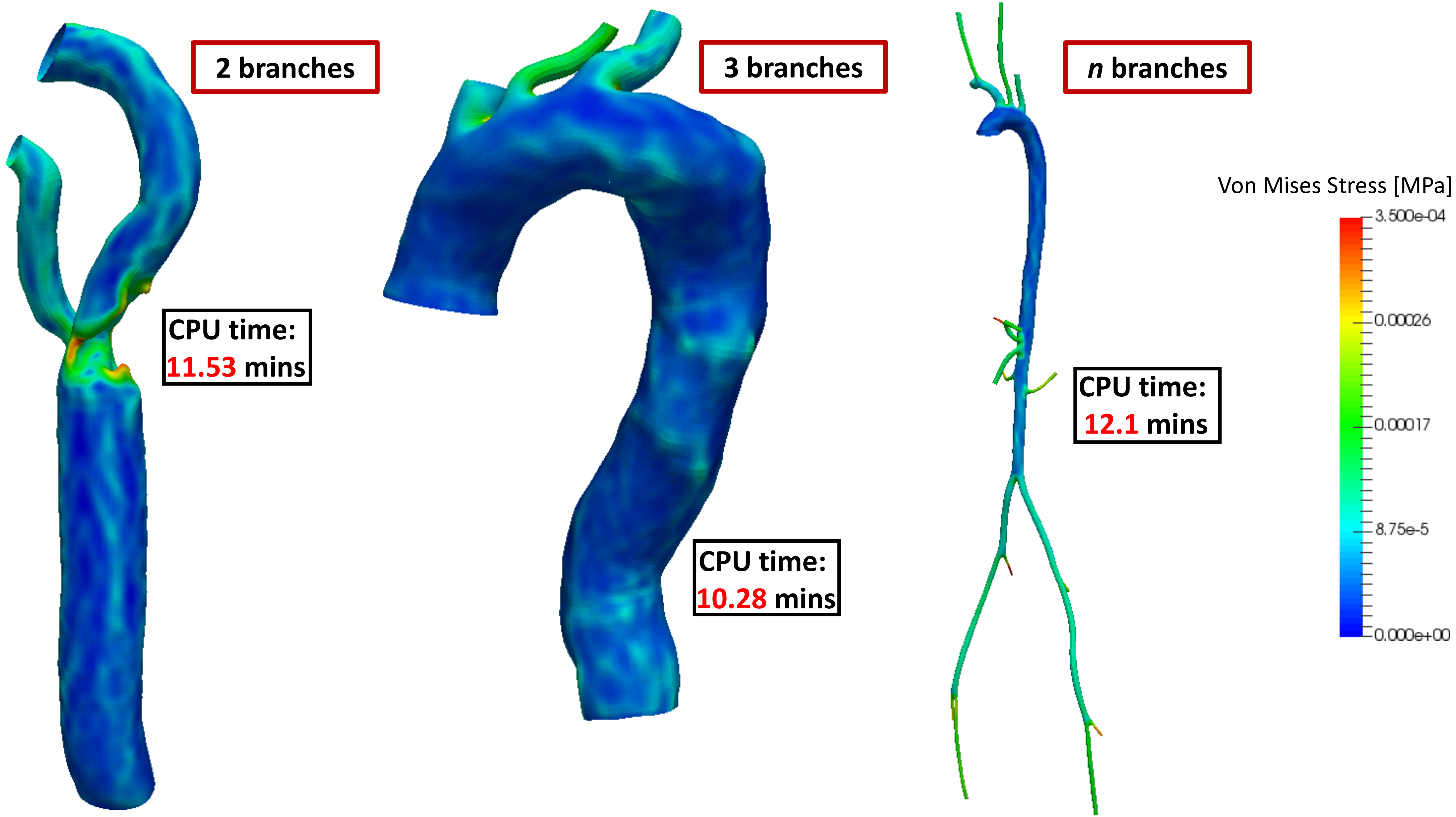
Constitutive Description

Linear, elastic, with parameters from literature.
(Nathan, et al., 2011)

Boundary Conditions

Robin B.C. to simulate the surrounding organs
(Moireau, *et al*., 2011)

TIME: 10.20 ± 2.5 mins


2 branches
CPU time:
11.53 mins
3 branches
CPU time:
10.28 mins
n branches
CPU time:
12.1 mins
Von Mises Stress [MPa]
3.500e-04
0.00026
0.00017
8.75e-5
0.000e+00

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Take home messages:

- Creating a p.s. branched IgA suitable model can be done **almost automatically** by performing a limited number of relatively easy steps.
- Simulations model and analysis settings represent a good compromise between computational time and accuracy.
- The framework can be a promising starting point for the development of a decision making tool to be used **real-time** by physicians.
- **BUT,** more addition to the pipeline have to be done.

Study 3:

Towards An Accurate Simulation Of Complex Contact Interactions In Biomechanics Problems Using Isogeometric Analysis.

Collaboration with:
Mauro Ferraro, Ph.D
Prof. Robert L. Taylor, University of California, Berkeley

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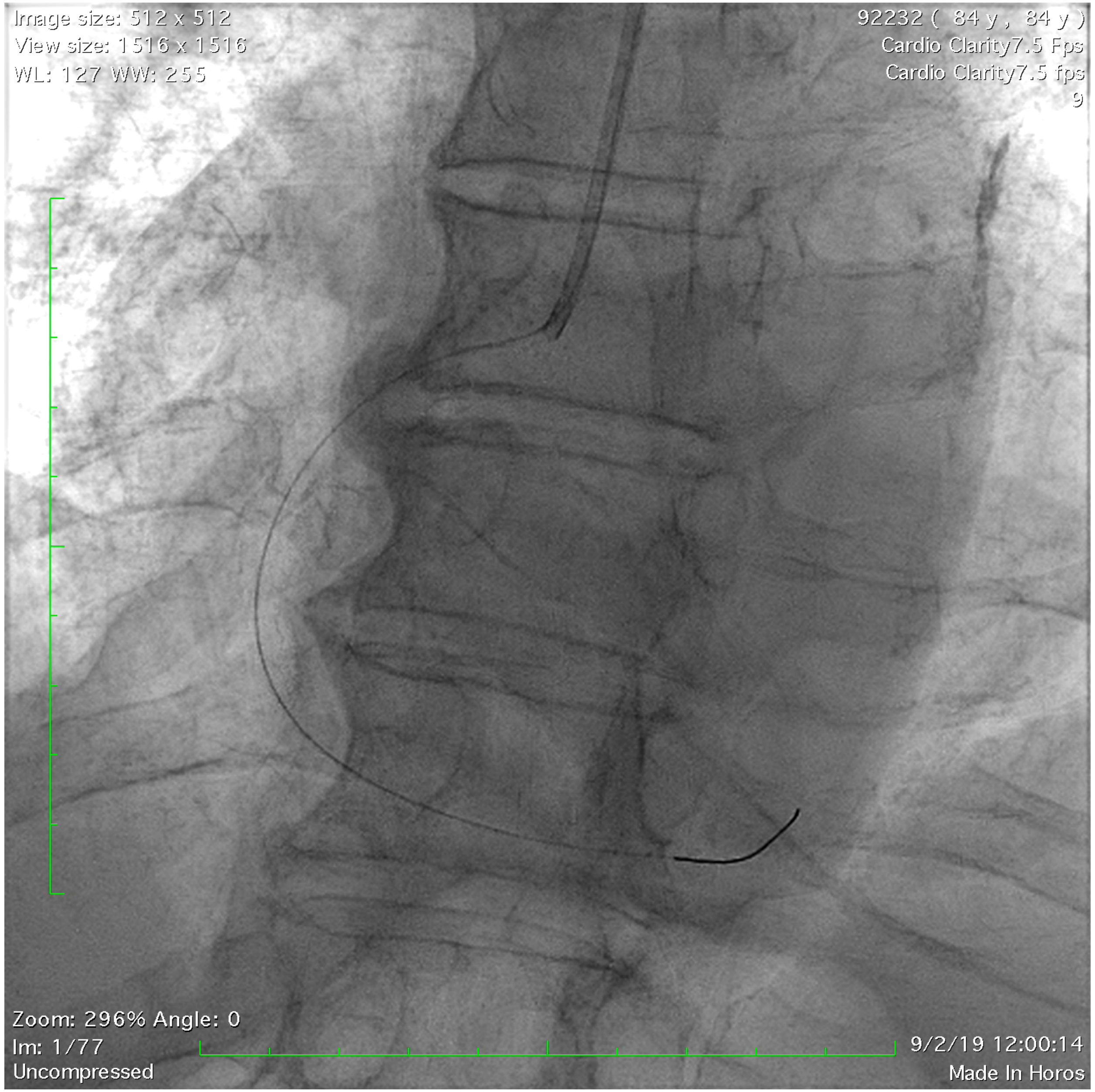
Study 3:

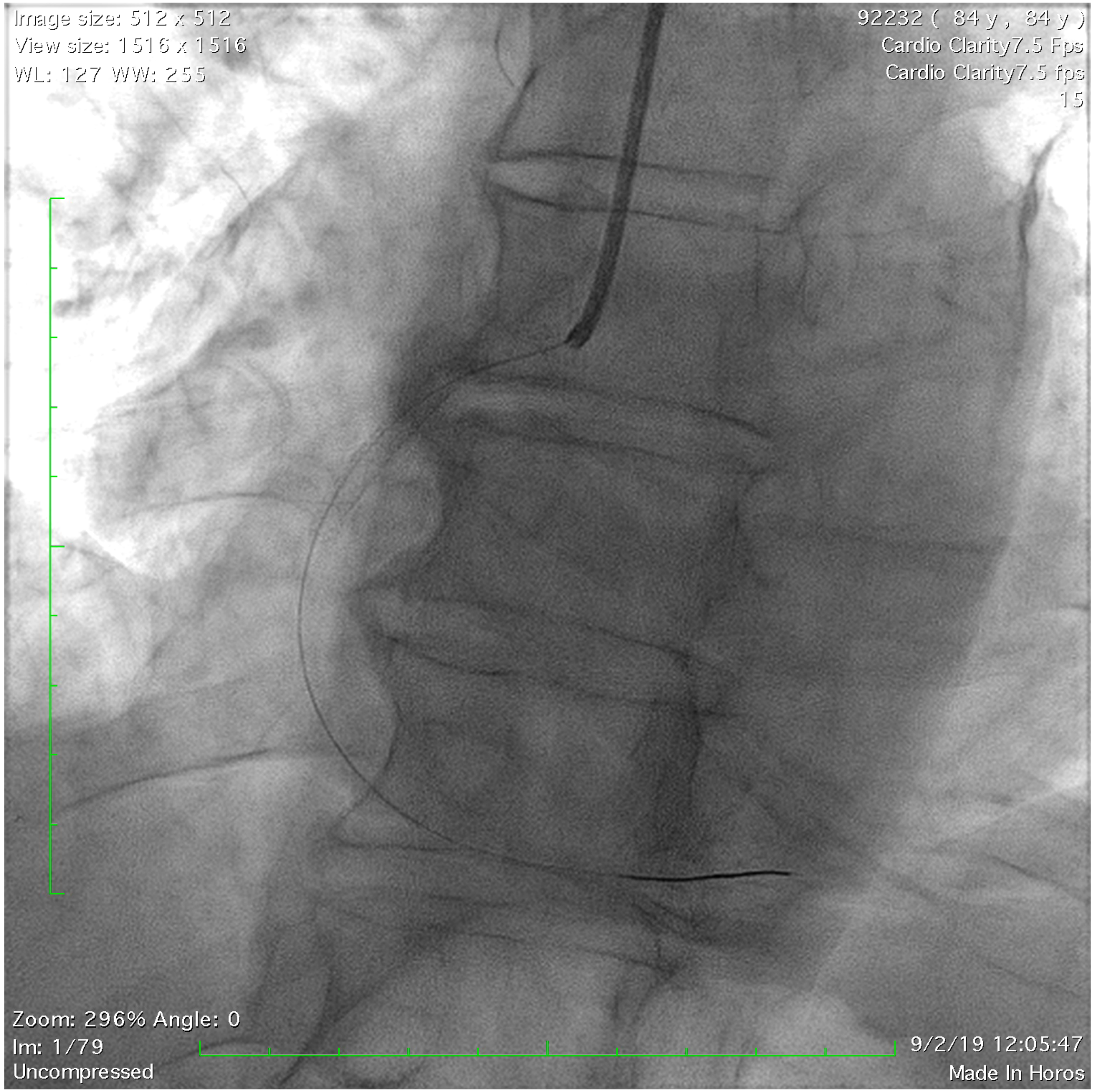
Towards An Accurate Simulation Of Complex Contact Interactions In Biomechanics Problems Using Isogeometric Analysis.

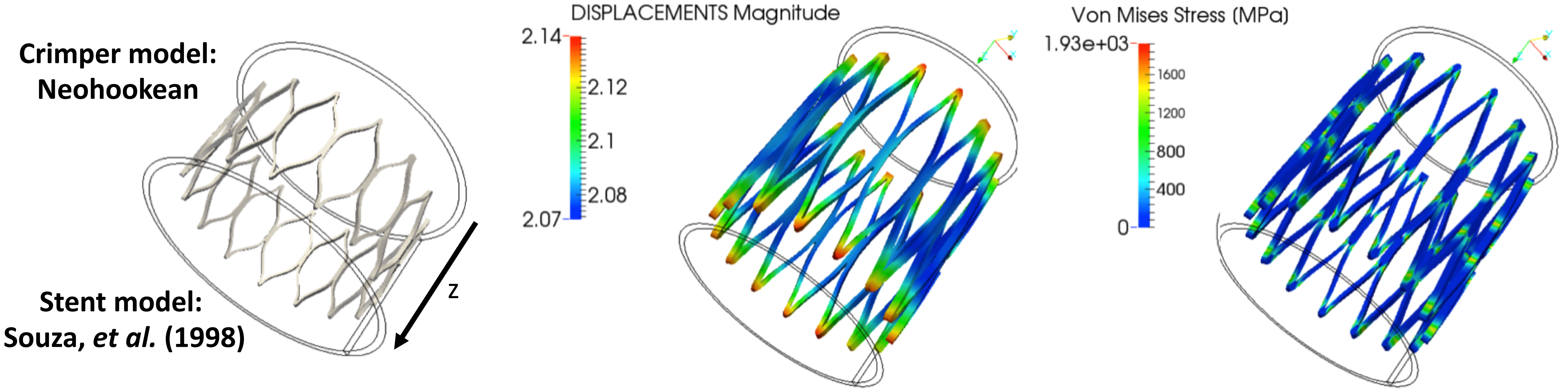
***FINAL GOAL*: EXPLOIT IgA TO SOLVE NONLINEAR CONTACT PROBLEM**
***KEYWORD*: SINGLE AND MULTI-PATCH NURBS**

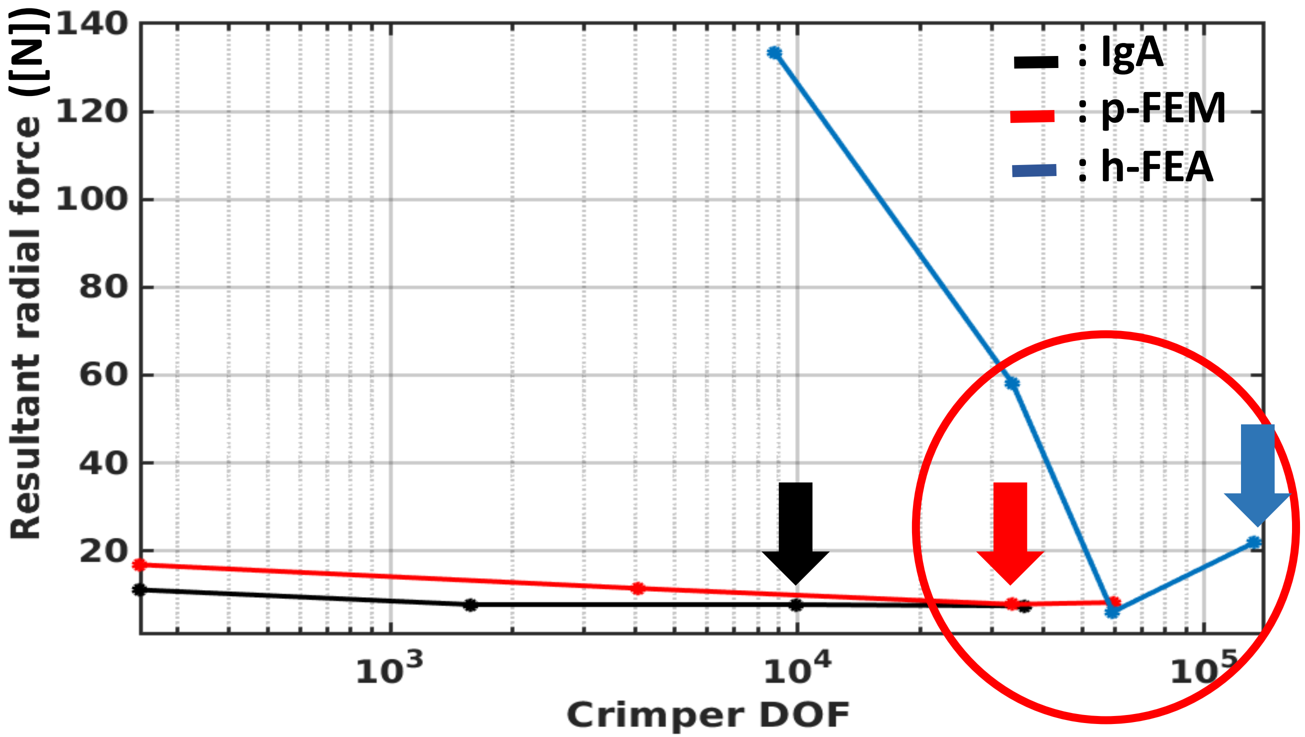
STENOSIS CASE



REFLOW AFTER DEPLOYMENT





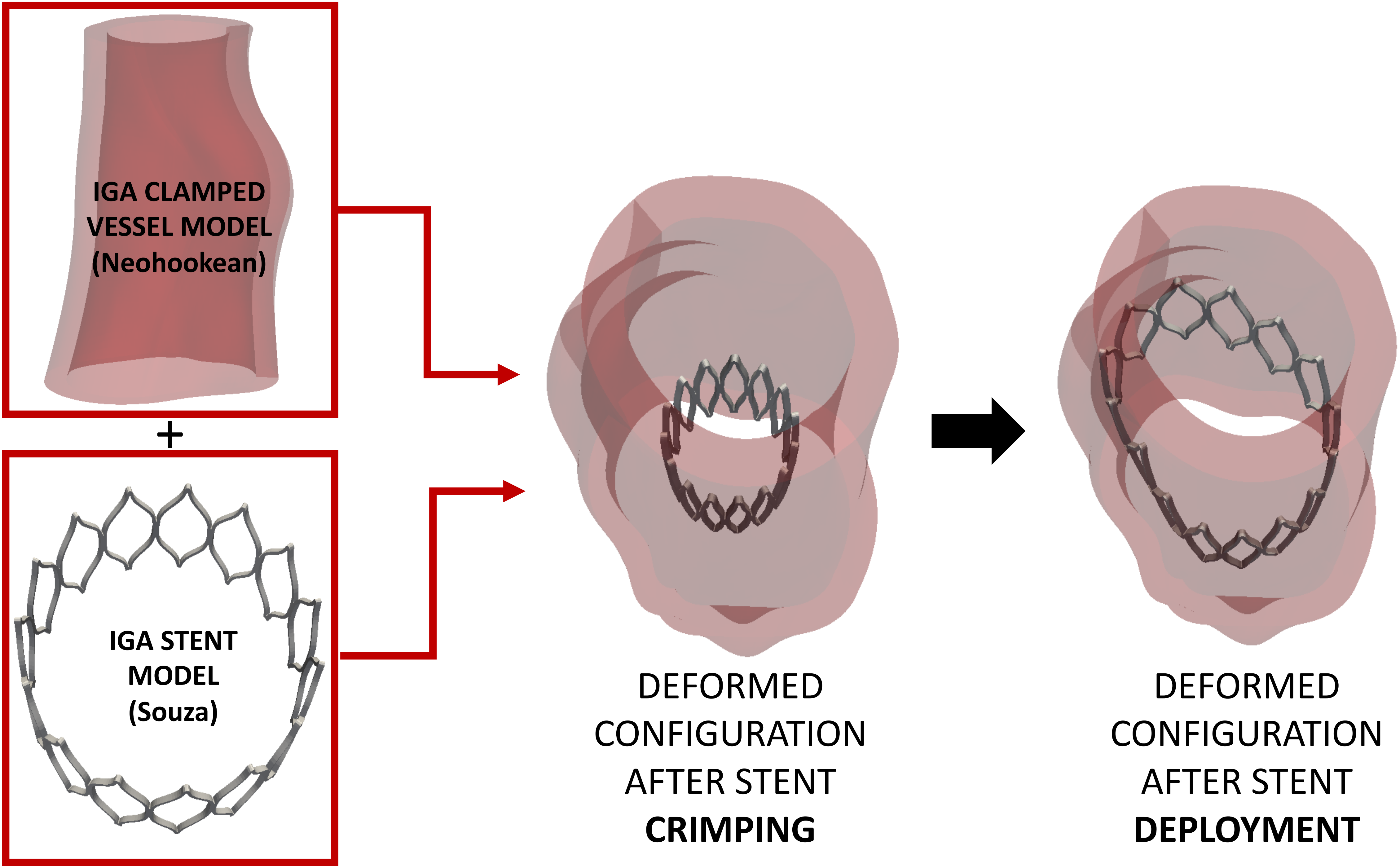


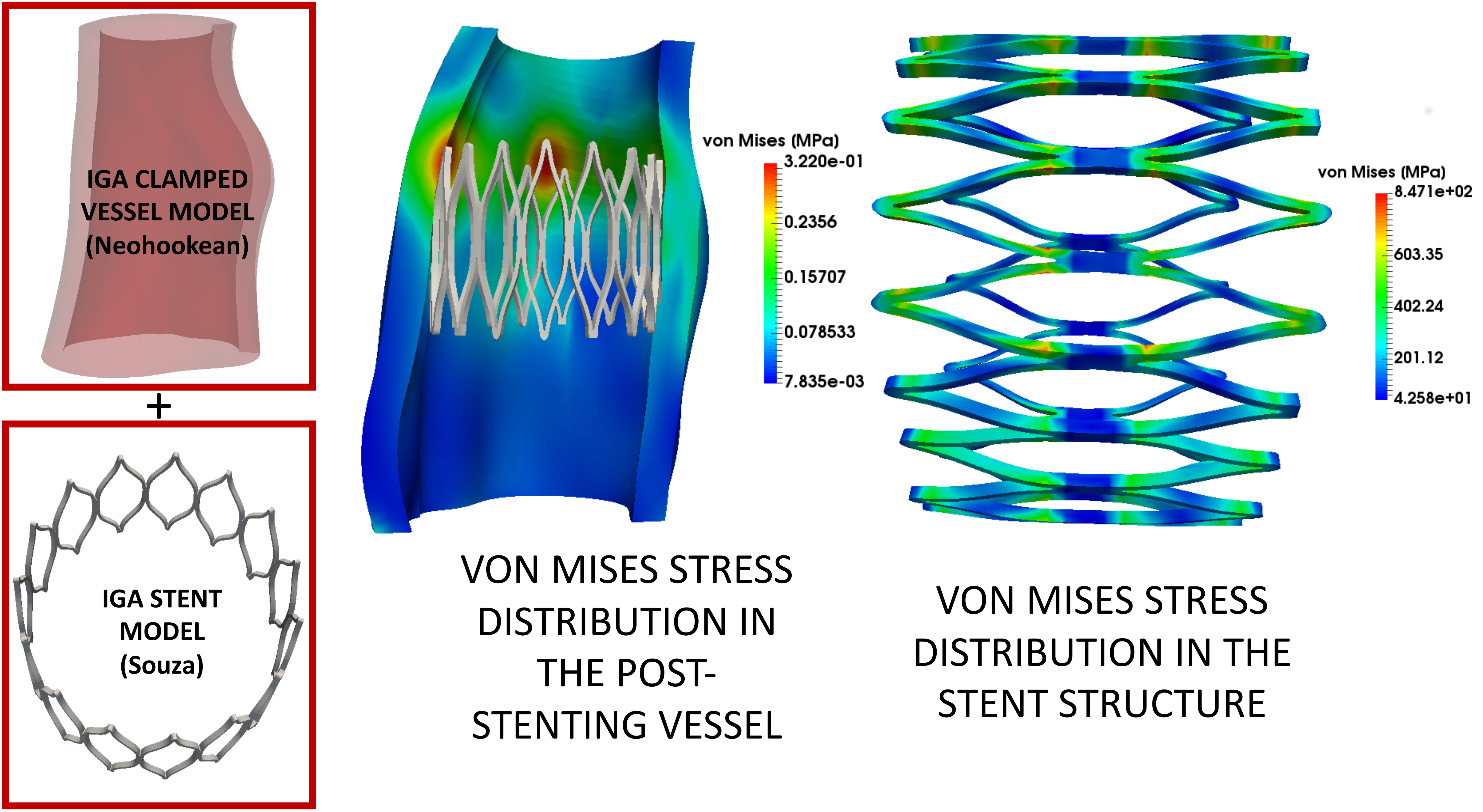
CPU time < 2 mins!

IgA DOFs: 9,945 ✓

p-FEM DOFs: 33,759 ✓

h-FEM DOFs: 132,309 ✗


IGA CLAMPED VESSEL MODEL (Neohookean)
+
IGA STENT MODEL (Souza)
DEFORMED CONFIGURATION AFTER STENT CRIMPING
DEFORMED CONFIGURATION AFTER STENT DEPLOYMENT


IGA CLAMPED VESSEL MODEL (Neohookean)
+
IGA STENT MODEL (Souza)
von Mises (MPa)
3.220e-01
0.2356
0.15707
0.078533
7.835e-03
von Mises (MPa)
8.471e+02
603.35
402.24
201.12
4.258e+01
VON MISES STRESS DISTRIBUTION IN THE POST-STENTING VESSEL
VON MISES STRESS DISTRIBUTION IN THE STENT STRUCTURE

Take home messages:

❖ IgA is able to accurately represent the computational domain.

❖ IgA allows to get better approximation of the solution with a widely reduced number of DOF with respect to traditional and high-order FEA.

❖ Implant simulations showe very promising results in terms of accuracy and computational efficiency

❖ Let's try to extend the framework to other anatomical districts

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ADVANCED PATIENT-SPECIFIC MODELING AND ANALYSIS OF COMPLEX AORTIC STRUCTURES BY MEANS OF ISOGEOMETRIC ANALYSIS

THANKS FOR YOUR ATTENTION!

Margherita Coda
11/02/2019

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Prof. Ferdinando Auricchio
Coadvisors: Prof. Robert L. Taylor
Prof. Santi Trimarchi