Ansys
Virtual
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Symposium
Spring 2025

RBF Morph

Accelerating cardiovascular pre-operative planning and building large cohort of patient realistic modeling: the mesh morphing solution

Marco Evangelos Biancolini
Company founder @RBF
Associate Professor @UTV

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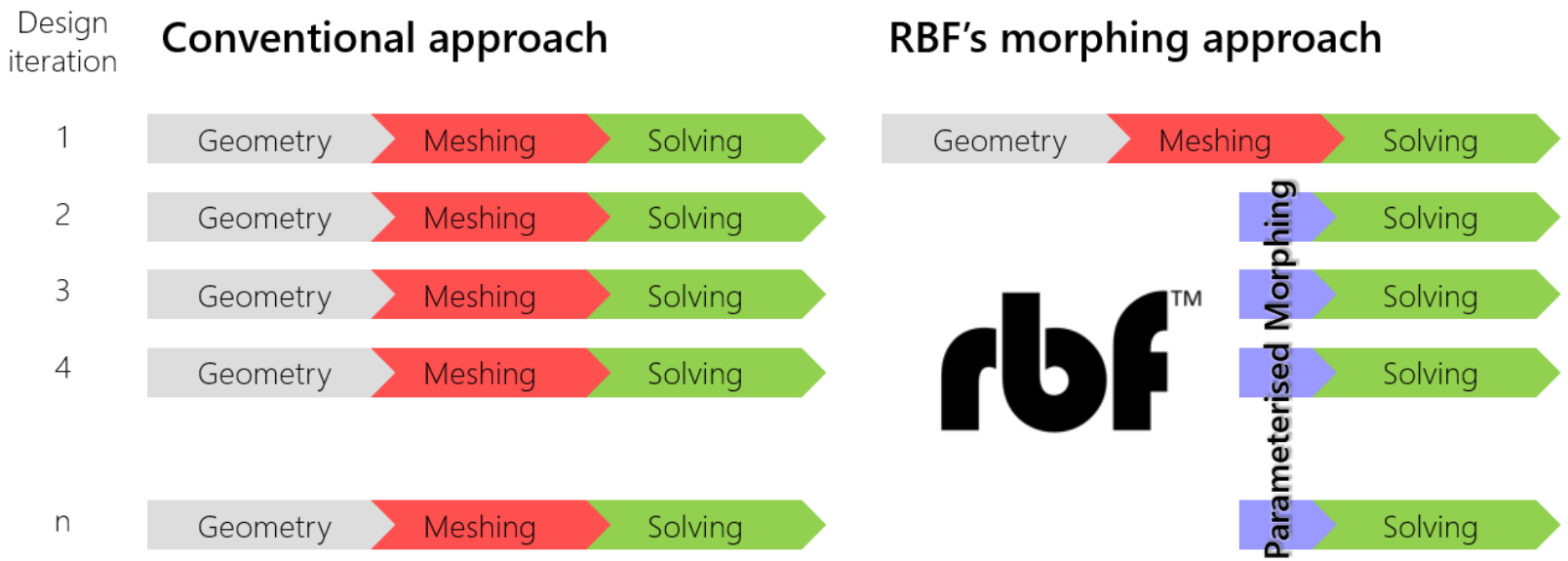
TOR VERGATA
UNIVERSITÀ DEGLI STUDI DI ROMA

Medical Digital Twins Challenges

- In silico **simulation technologies are mature**, but significant challenges remain for widespread adoption in clinical practice.
- There is a need for **user-friendly tools** that can integrate seamlessly with hospital workflows and existing data infrastructures.
- Technological barriers must be overcome to make **patient-specific** modeling fast, reliable, and intuitive enough for use by medical staff.
- **Automation and standardization** are essential to reduce the effort and expertise required to generate and validate patient-specific models.
- **Regulatory hurdles** remain a major obstacle: digital twins must meet strict certification standards to be used in medical decision-making.

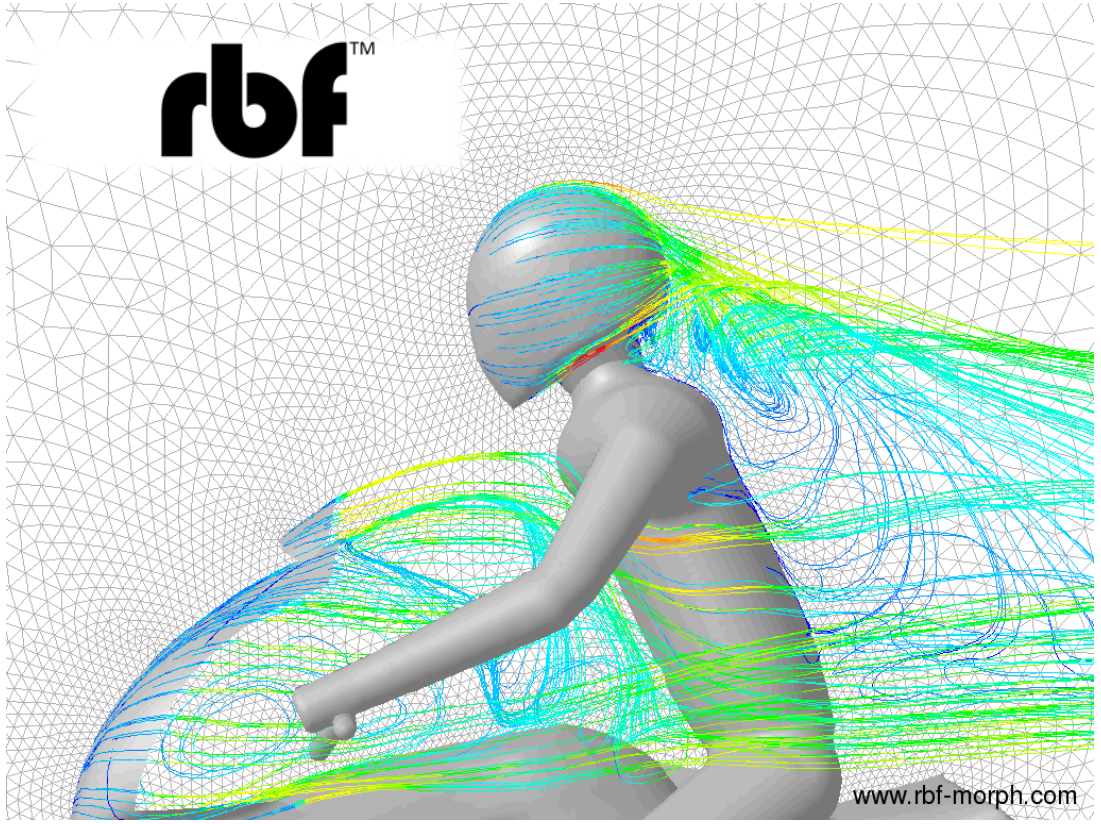
Mesh morphing makes CAE models parametric

- RBF Morph makes the CAE model **parametric**
- Shape parameters are driven by **an orchestrator**
- Shape parameters can be used to generate snapshots for real time Digital Twins (**ROM/AI**)



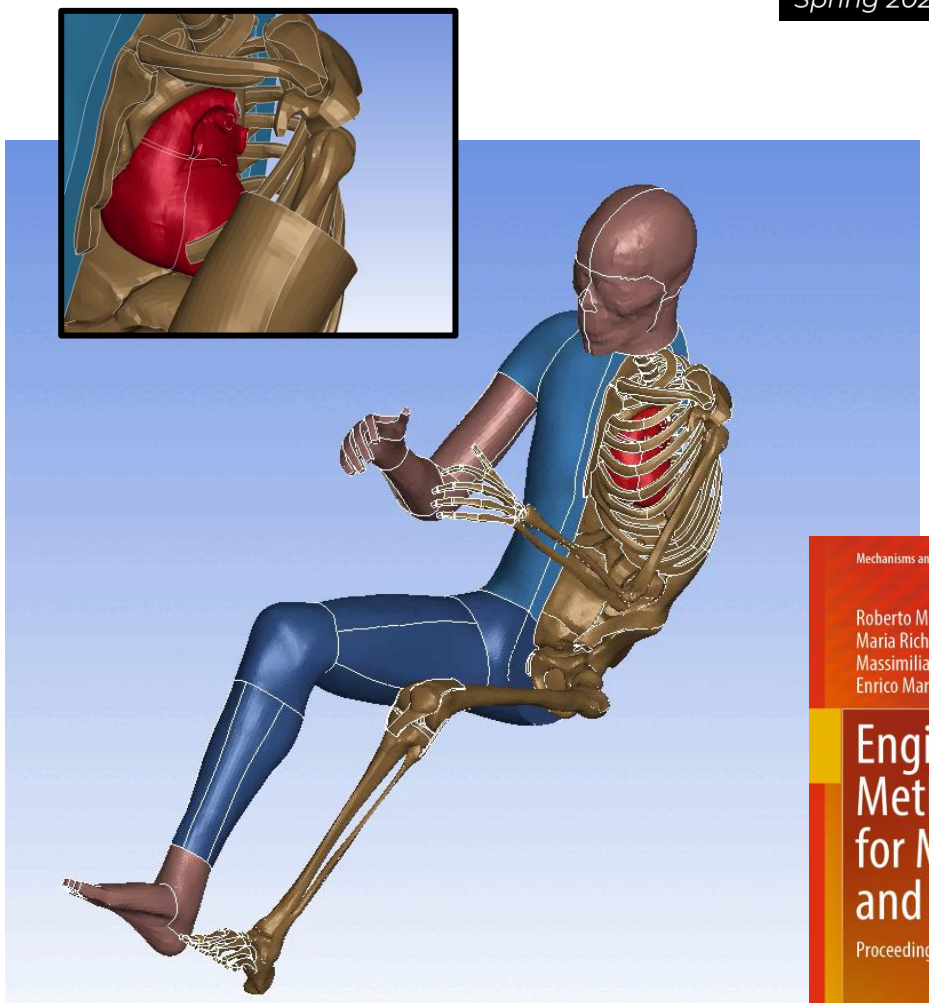
Radial Basis Functions mesh Morphing

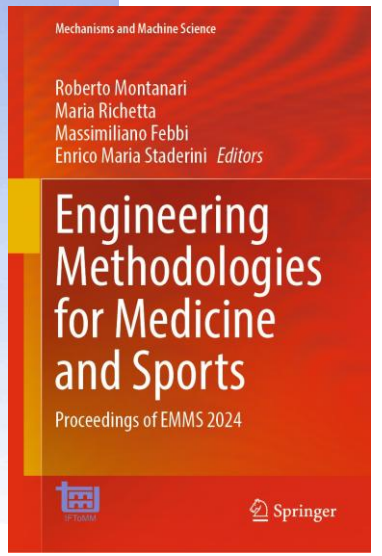
- Geometric control by **R**adial **B**asis **F**unctions mesh **Morph**ing
  - Surface shape changes
  - Volume mesh adaption
- A **new shape** of the CAE model **ready to run**
  - for structures in the FEA solver
  - for flows in the CFD solver
  - for FSI and multi-physics



Parametric THUMS

- Total HUman Model for Safety (**THUMS**) https://www.toyota.co.jp/thums/
- We can adapt the shape to be occupant specific
- **Patient specific**? Occupant specific?
- THUMS is a standard for crashworthiness and is emerging in **Sports Engineering**





https://link.springer.com/book/10.1007/978-3-031-63755-1

Radial Basis Functions mesh Morphing

- We offer **Radial Basis Functions** (RBF) to drive mesh morphing (smoothing) from a list of source points and their displacements

$$\begin{cases} s_x(\boldsymbol{x}) = \sum_{i=1}^{N} \gamma_i^x \varphi(\|\boldsymbol{x} - \boldsymbol{x_{s_i}}\|) + \beta_1^x + \beta_2^x x + \beta_3^x y + \beta_4^x z \\ s_y(\boldsymbol{x}) = \sum_{i=1}^{N} \gamma_i^y \varphi(\|\boldsymbol{x} - \boldsymbol{x_{s_i}}\|) + \beta_1^y + \beta_2^y x + \beta_3^y y + \beta_4^y z \\ s_z(\boldsymbol{x}) = \sum_{i=1}^{N} \gamma_i^z \varphi(\|\boldsymbol{x} - \boldsymbol{x_{s_i}}\|) + \beta_1^z + \beta_2^z x + \beta_3^z y + \beta_4^z z \end{cases}$$

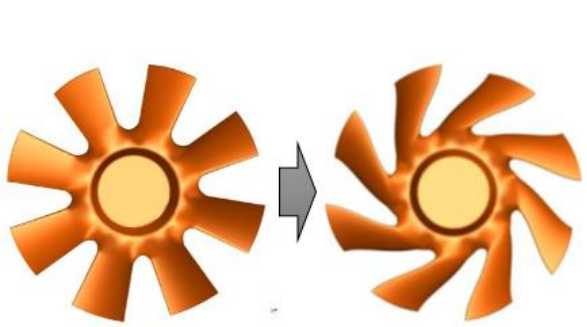
- RBF are recognized to be one of the **best mathematical tool** for mesh morphing

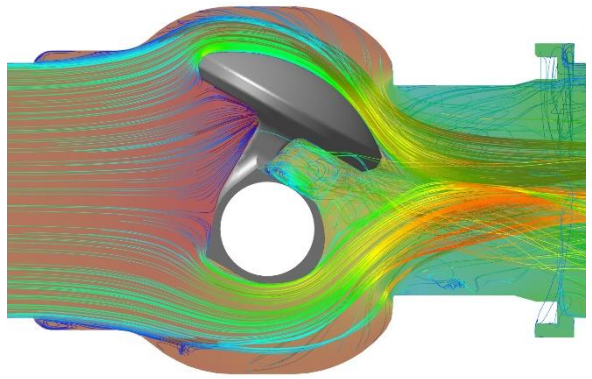
https://link.springer.com/book/10.1007/978-3-319-75011-8

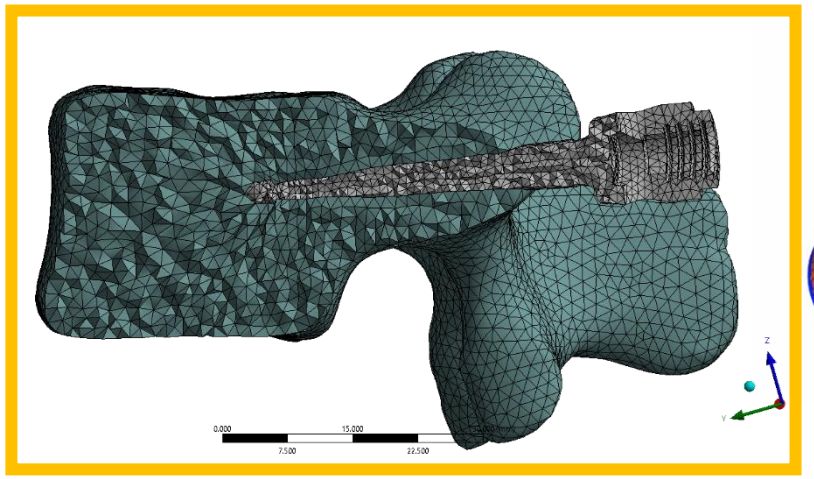
Main uses of mesh morphing

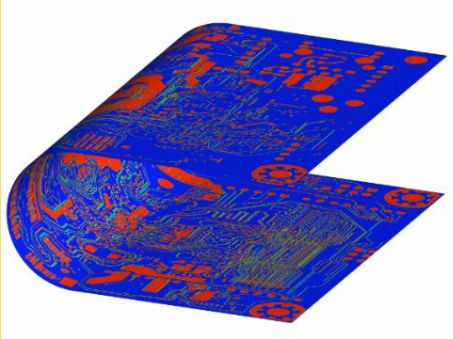
Usage	Mechanical	Fluent	optiSLang	Twin Builder
Automated and quick variable design space exploration.	✓	✓		
Optimization (Single physics or multi-physics). Shape optimization for stress reduction, mass reduction, fluid-structure interaction	✓	✓	✓	
Digital twin development (static ROMs)	✓	✓	✓	✓
Lifing applications Simulate defects such as corrosion pits, spalling of material, erosion, chips, etc.	✓	✓		
Examine the effects of non-conformance and manufacturing variability	✓	✓		
Robust Design	✓	✓	✓	

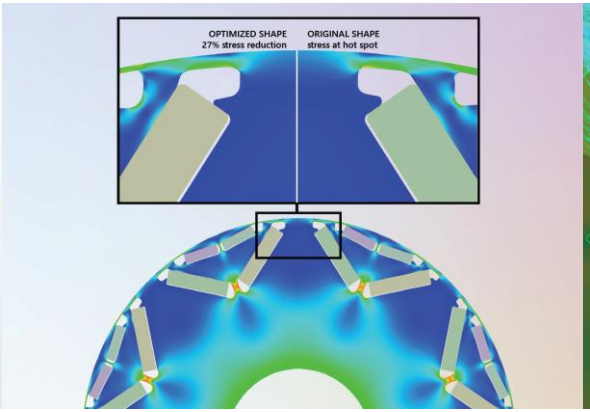
Applications

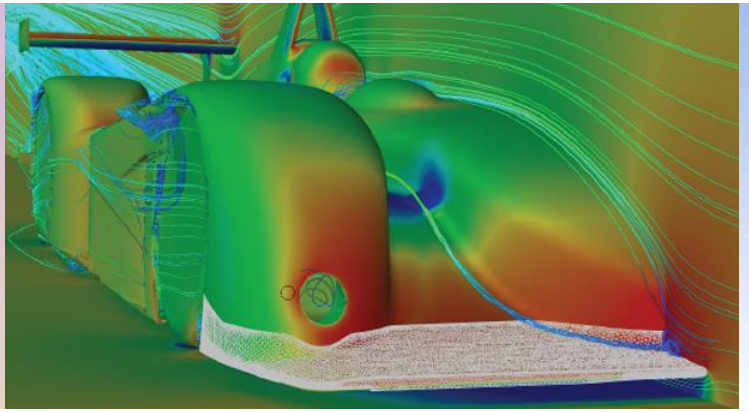


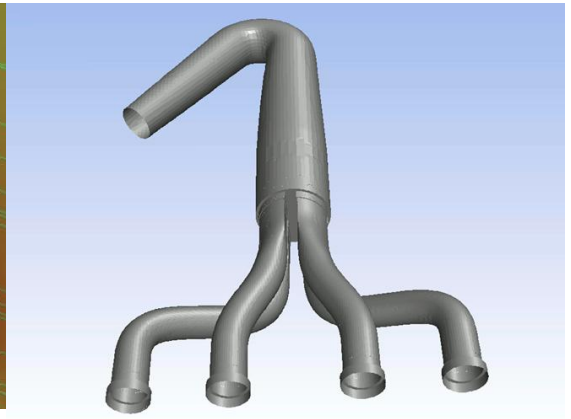








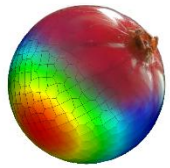




EU-funded research projects

RBF4AERO

FORTISSIMO



RIBES

Cloudi Facturing

EUROfusion

spinner
next generation spine experts

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4 EuroHPC

FORTISSIMO
PLUS

Medical Digital Twins Challenges for mesh morphing

- Parameterization of the treatment – **device patient-specific anatomy matching**. Virtual surgery as a decision support tool.
- Parametric patient anatomy. **SSM vs parametric models**.
- **Augmenting images** with simulations. Advanced App? On imaging devices?
- **Virtual cohorts** can be created to augment existing data. More data to train AI based models.

The Medical Digital Twin for Aneurysm Prevention and Treatment

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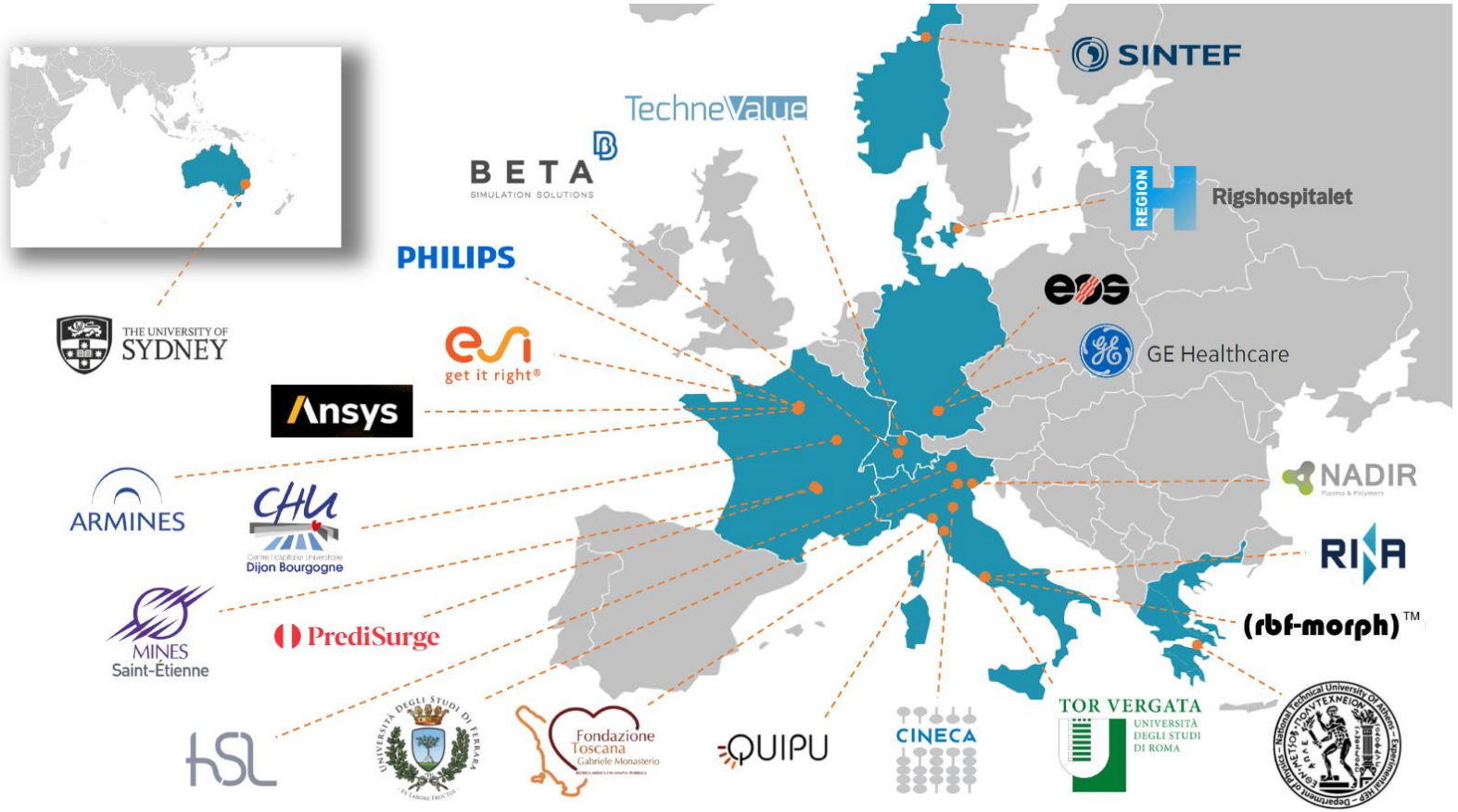

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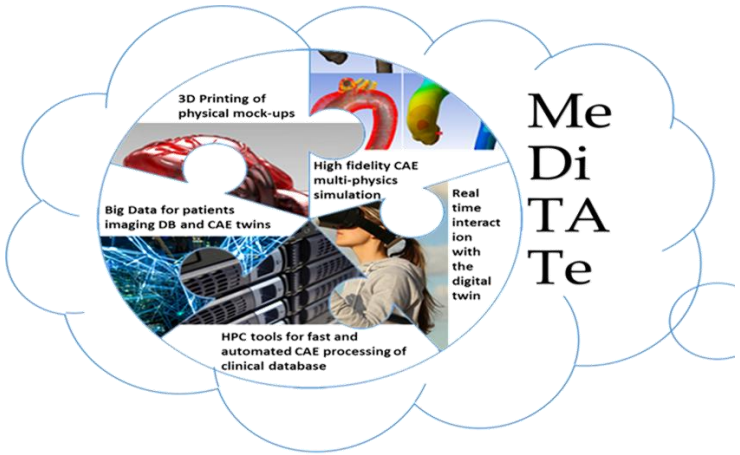

https://meditate-project.eu/

The Medical Digital Twin for Aneurysm Prevention and Treatment

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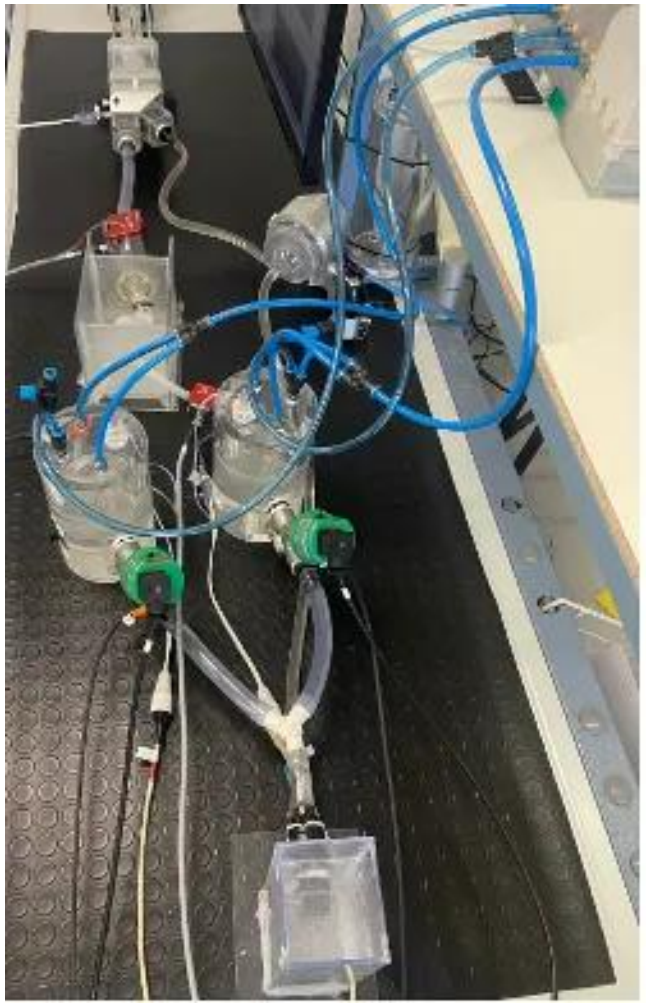

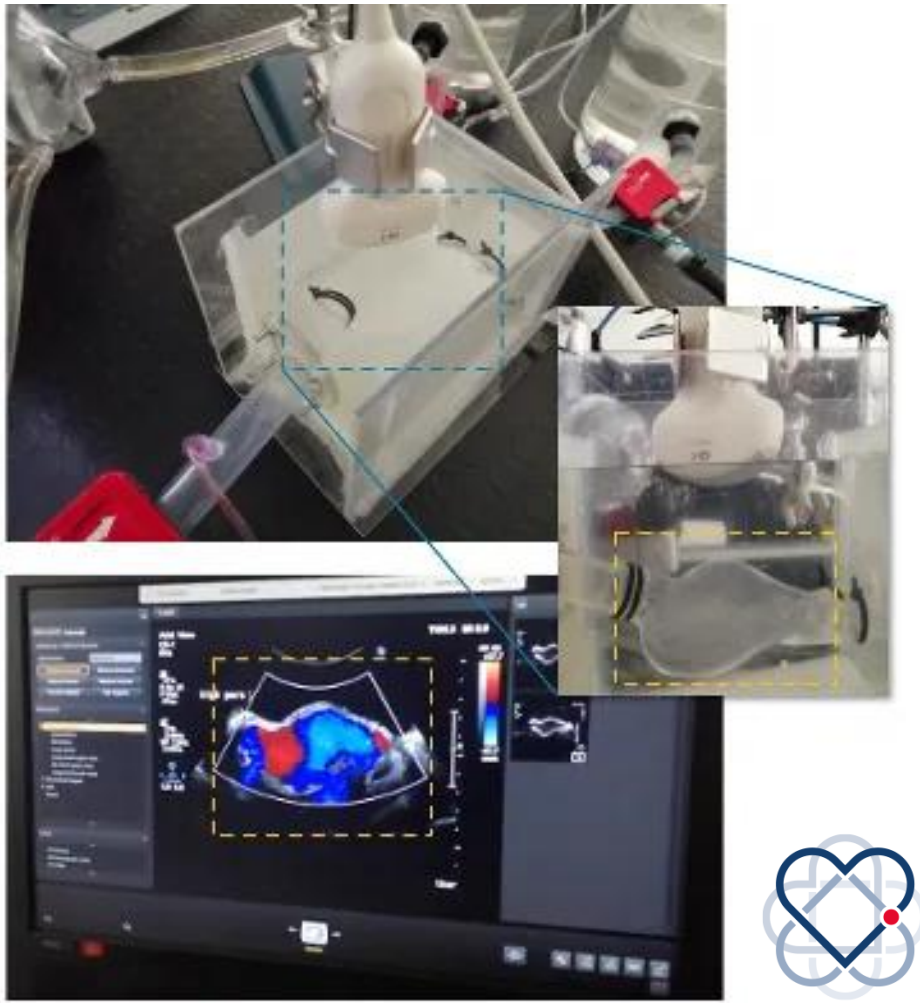

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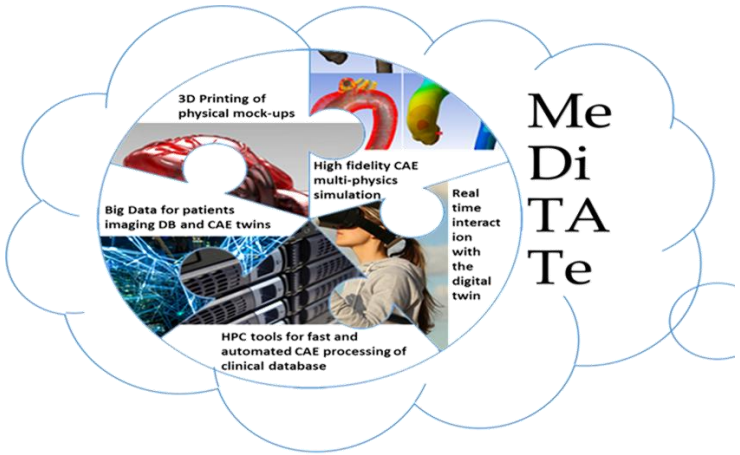

Monasterio
la ricerca che cura

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MeDiTATe Endovascular Abdominal Aneurysm Repair

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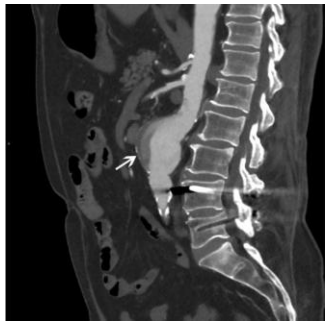
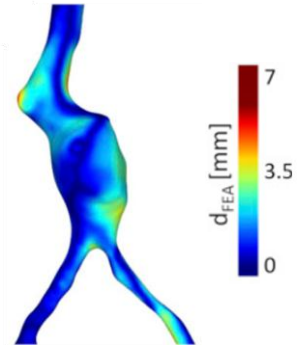
AAA patient case

ST. OLAVS HOSPITAL UNIVERSITETSSYKEHUSET I TRONDHEIM



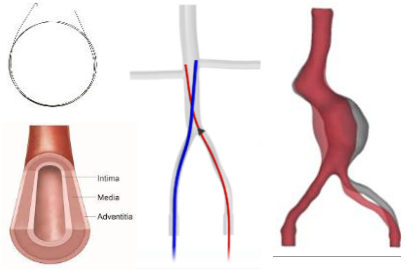
CT scan segmentation

3DSlicer



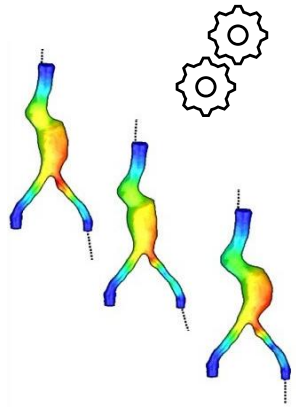
Baseline Finite Element case

Ansys LS - DYNA



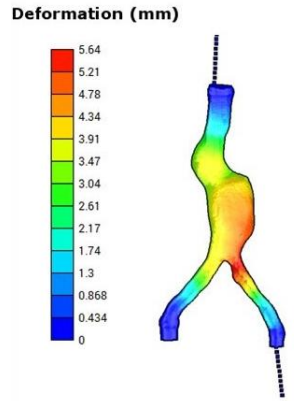
Morphological, clinical, mechanical parameterization

rbf™ python™



ROM Build-up

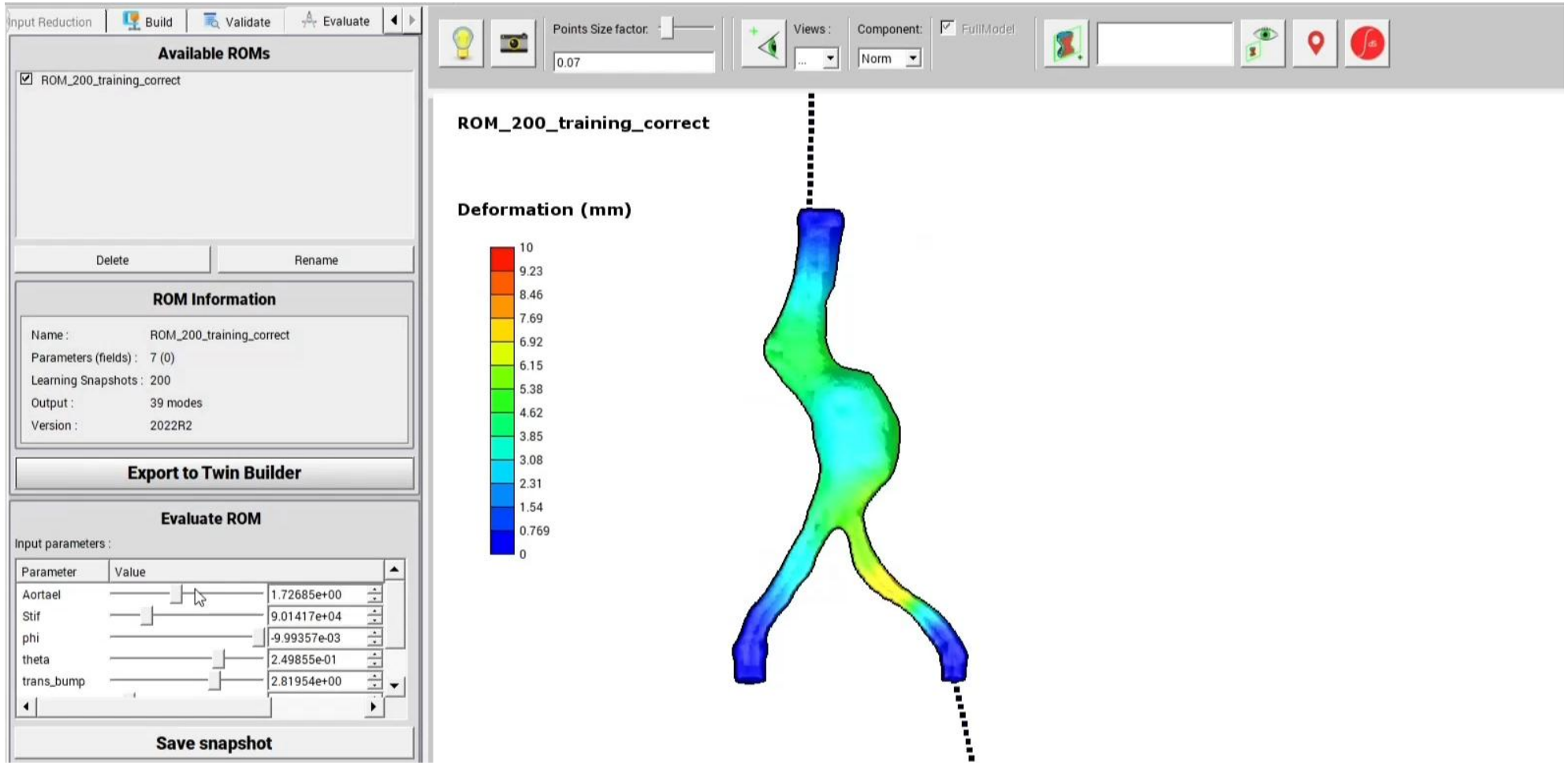
Ansys TWIN BUILDER



ROM exploitation

Ansys TWIN BUILDER

MeDiTATe Endovascular Abdominal Aneurysm Repair



Medical Digital Twin Copernicus

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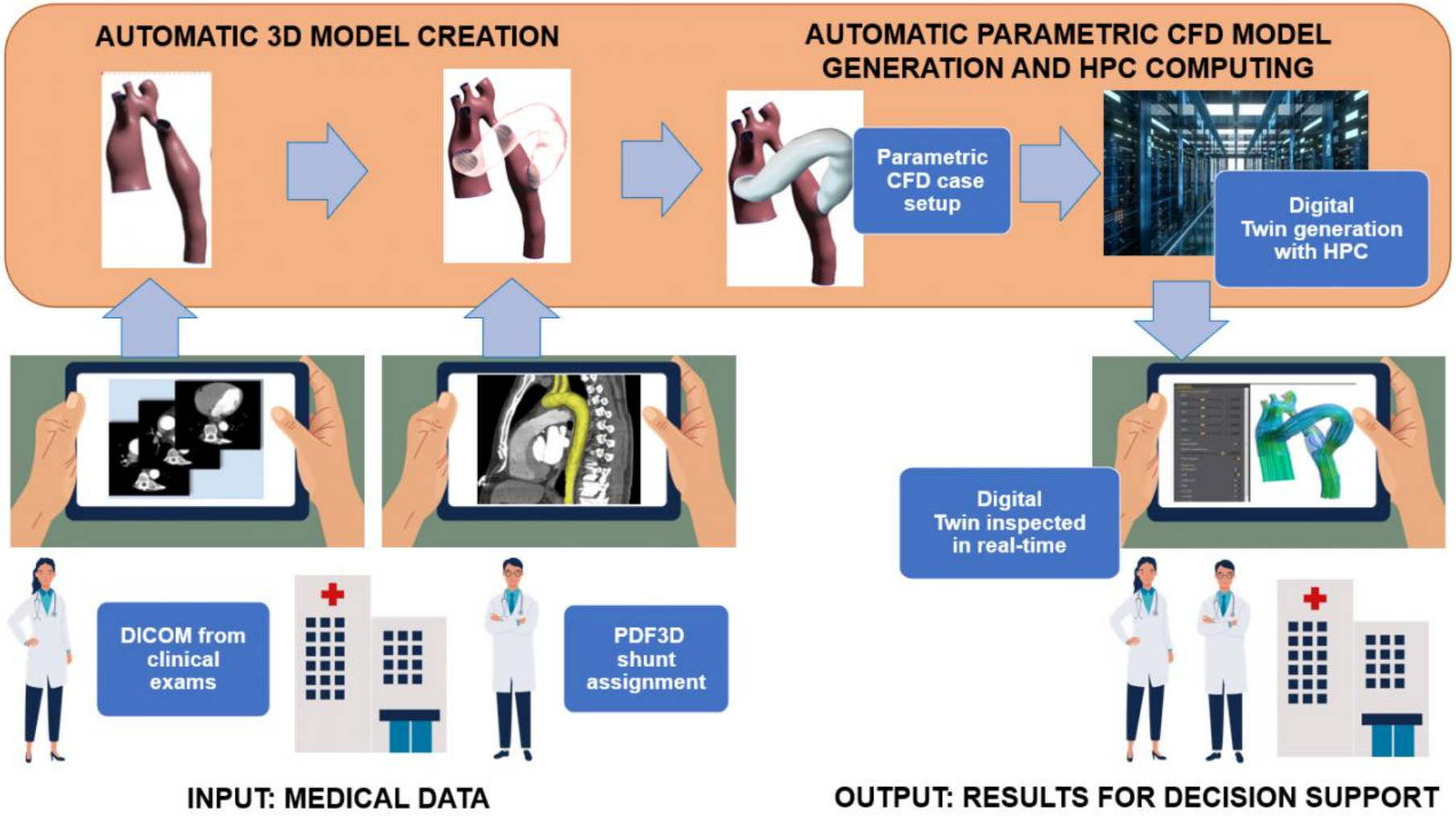
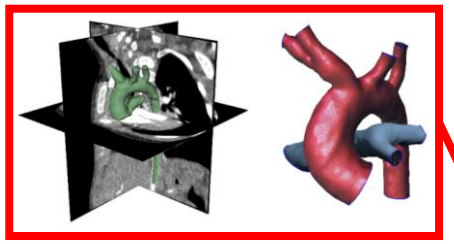
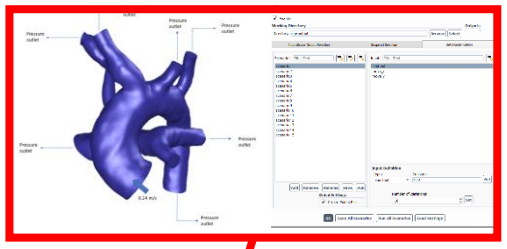


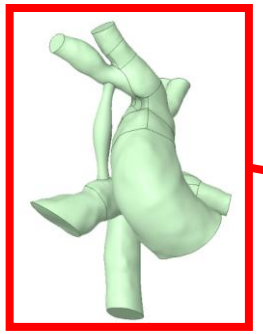
ff4EuroHPC

https://www.ff4eurohpc.eu/en/experiments/2021070910512579/cloudbased_hpc_platform_to_support_systemicpulmonary_shunting_procedures

Medical Digital Twin Copernicus







CT Image Segmentation (Python Code)

CAD Reconstruction + Shunt creation (SpaceCaliam)

Surface and volume Mesh generation (Fluent – Watertight)

Ansys FLUENT

CFD and Snapshot set-up (Fluent – RBP)

RBF Shape modifiers set-up (Fluent – RBF Morph)

Ansys FLUENT rbf™

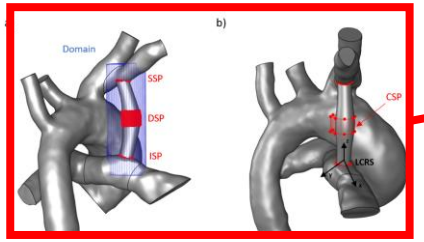
HPC for Snapshot generation (Fluent – RBF Morph)

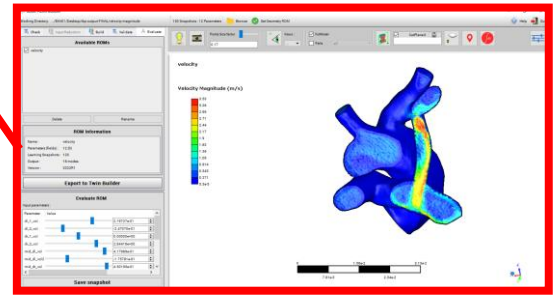
Ansys TWIN BUILDER

ROM Generation (Twin Builder)

ROM Evaluation (Twin Builder)

Ansys TWIN BUILDER





Copernicus Pre-Processing

Copernicus Computing

Copernicus Post-Processing

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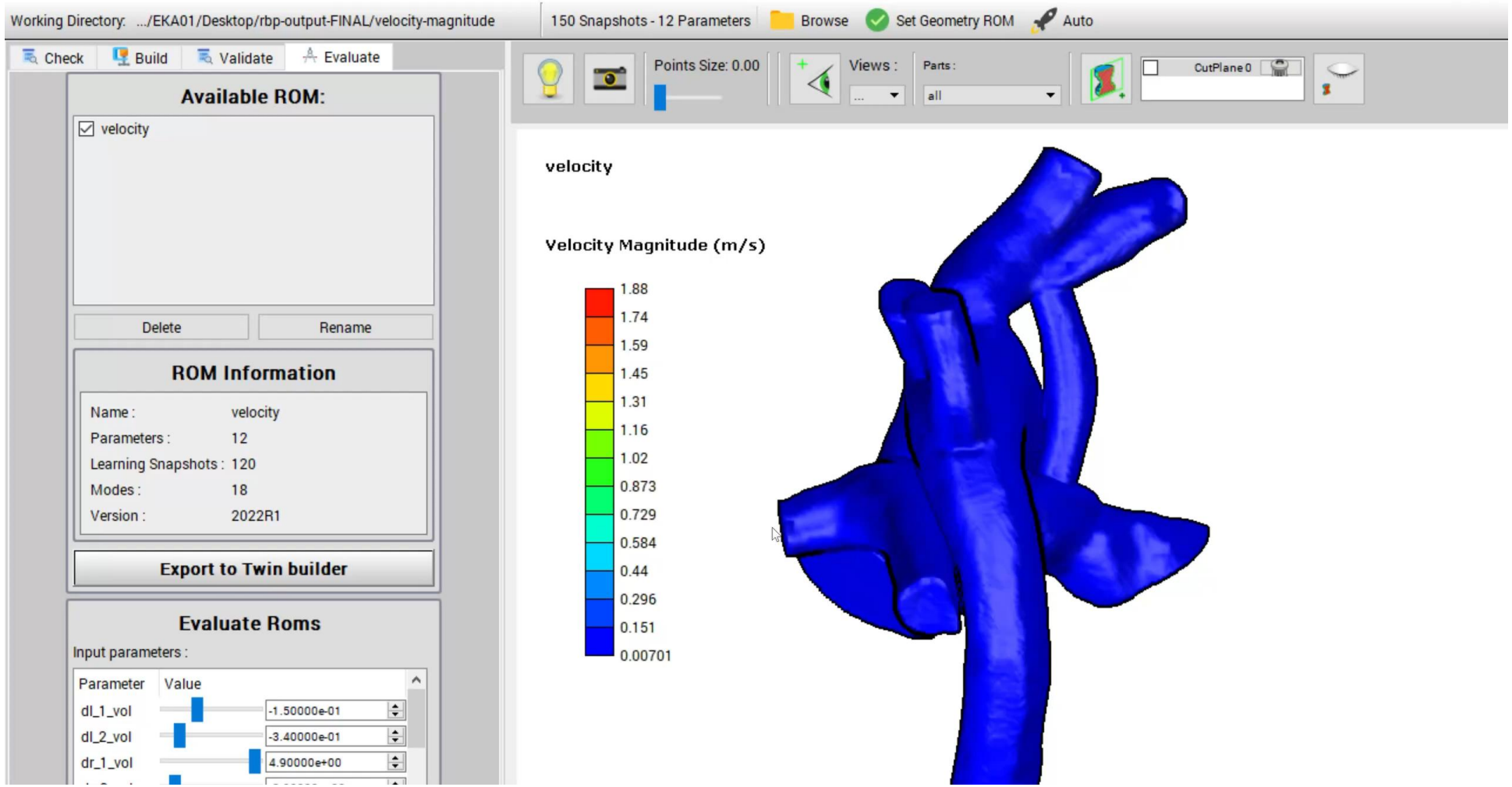
Medical Digital Twin Copernicus



https://www.mdpi.com/2079-9292/11/13/1930

Medical Digital Twin DiTAiD

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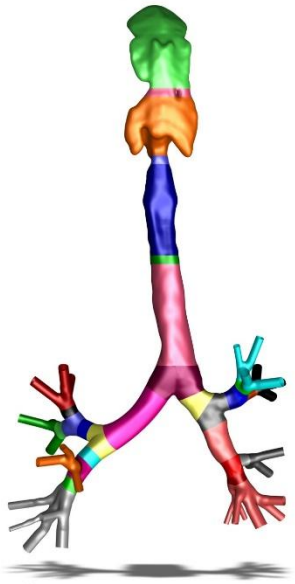
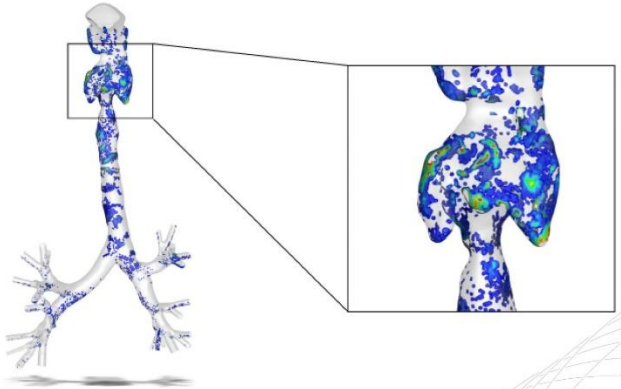
From lung scan to medical use

1) Scan of lungs



2) Extraction of lung shape parameters

3) Digital twin



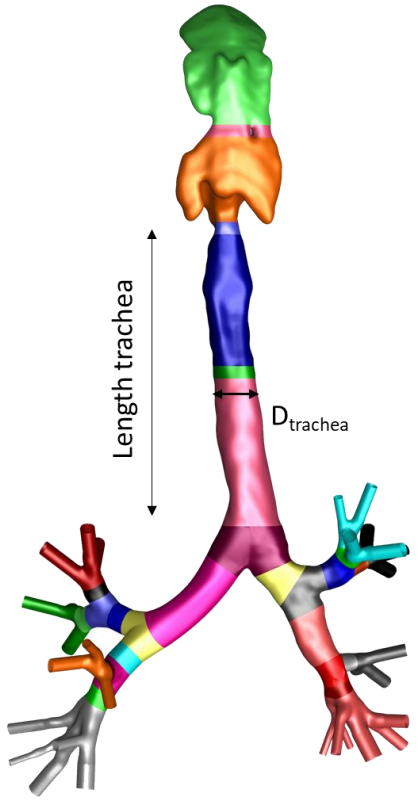
4) Visualization and interpretation for medical use

ff4EuroHPC

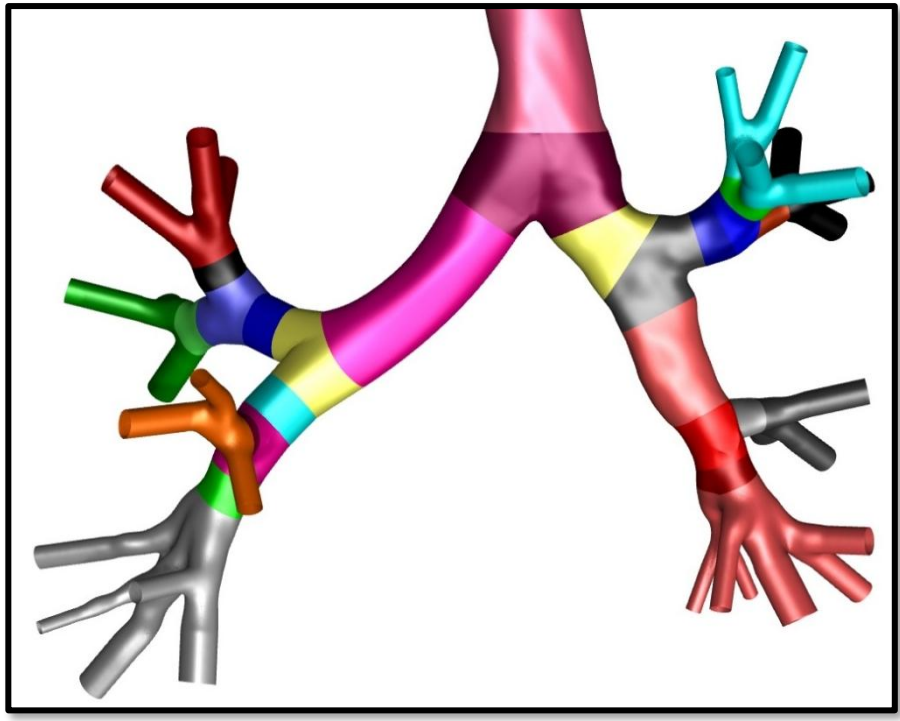
https://www.ff4eurohpc.eu/en/experiments/2022031514424665/digitaltwin_for_airflow_and_drug_delivery_in_human_airways

Medical Digital Twin DiTAiD

- Potentially a huge amount of shape parameters!
- Amount of input parameters is limited by assuming:
  - ✓ Circularity is kept constant
  - ✓ Only considered angle is the branching angle
  - ✓ Diameter follows a fixed ratio6 of h=0.79
- Mouth-throat part: 3 parameters
- Lower airways: 23 parameters
  - ✓ Generation 0 (trachea): 1L, 1D, 1A
  - ✓ Generation 1: 2L, 2A
  - ✓ Generation 2: 4L, 4A
  - ✓ Generation 3: 8L



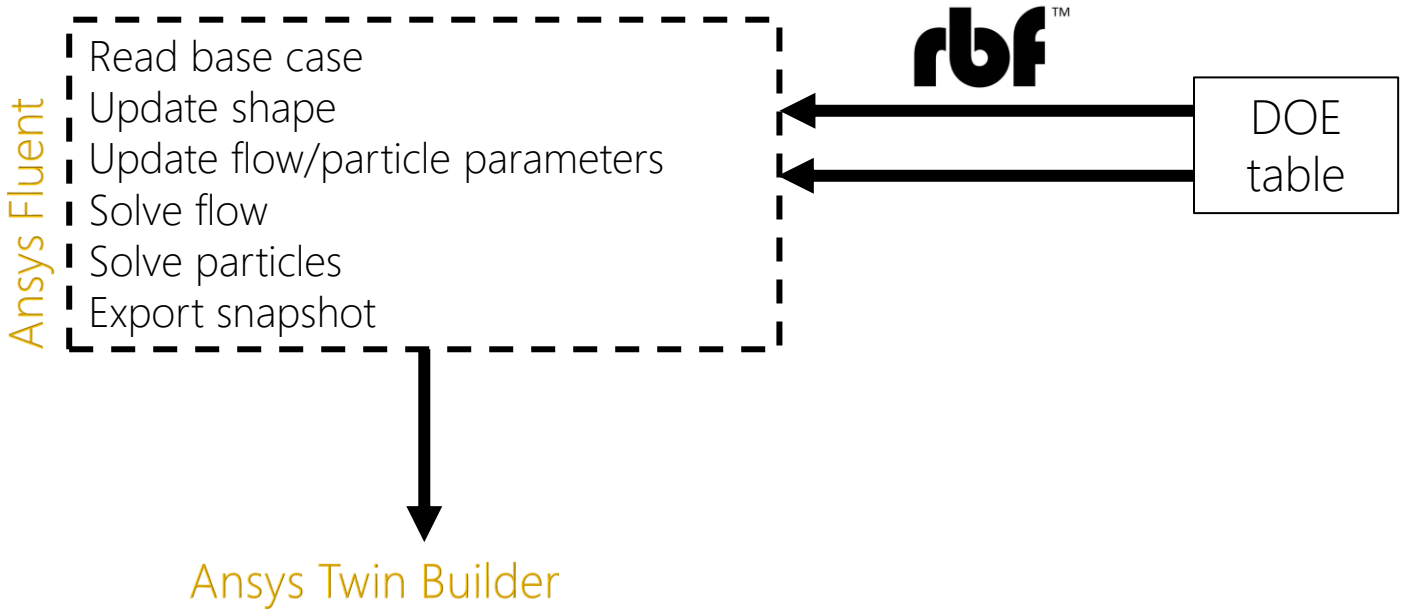
T. Van de Moortele et al.; *"Morphological and functional properties of the conducting human airways investigated by in vivo computed tomography and in vitro MRI"*



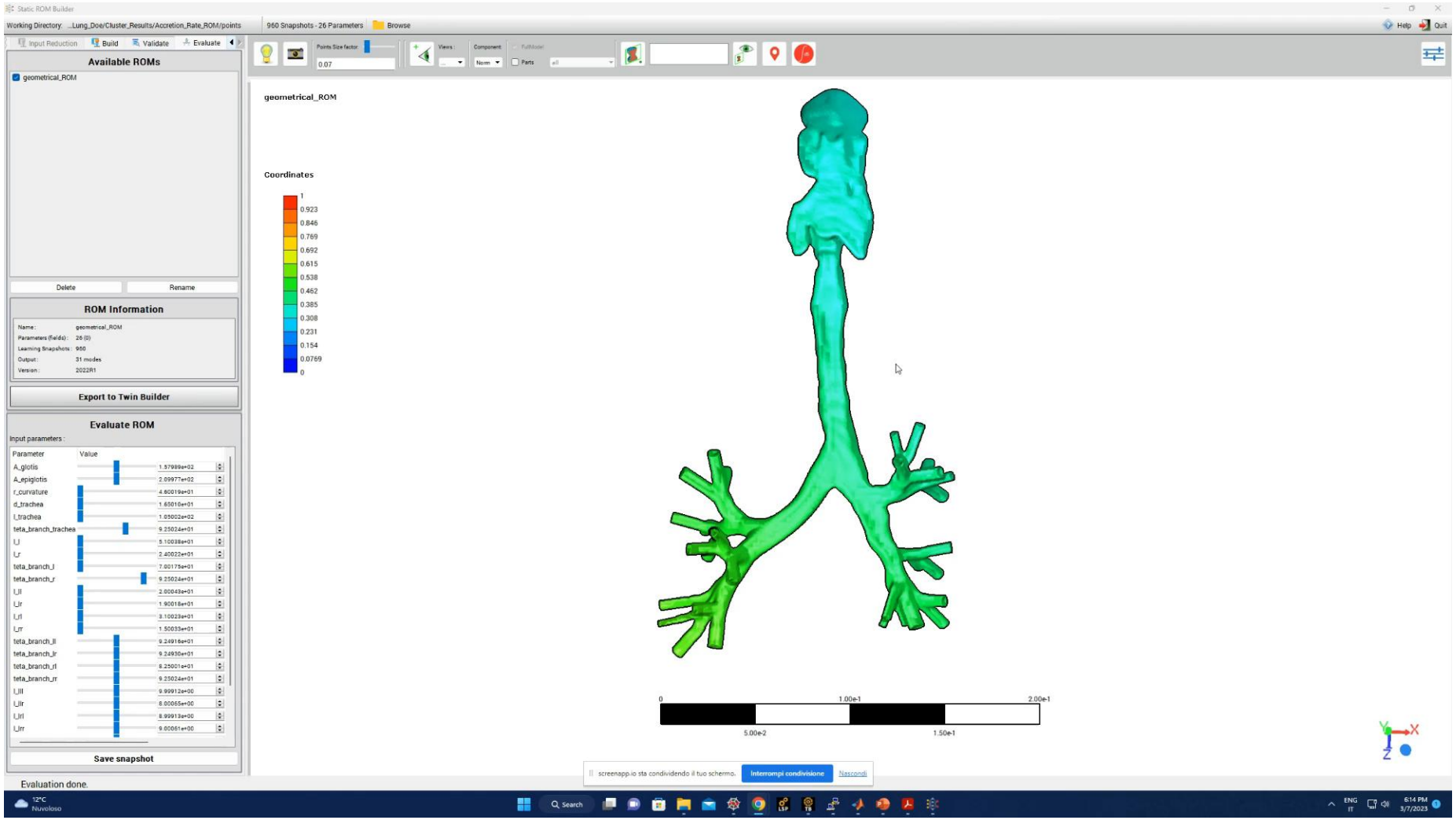
Generation	Diameter [mm]	Length [mm] Left	Length [mm] Right	Branching angle [deg]
0 (Trachea)	15 - 20	100 - 120		80 - 95
1		51 - 57	24 - 28	75 - 90
2		12 - 16	15 - 28	65 - 95
3		7 - 10	7 - 10	55 - 70

Medical Digital Twin DiTAiD

- Design Of Experiments (DOE) table is generated:
  - ✓ For the 29 input parameters
  - ✓ Using the Latin Hypercube Sampling for optimal spacing
  - ✓ Creating 1000 design points
- Fluent settings validated in literature
  - ✓ Steady state
  - ✓ RANS, transitional SST (4eq)
  - ✓ Particles are one-way coupled



Medical Digital Twin DiTAiD



https://www.mdpi.com/2311-5521/9/1/27

Hemodynamic prediction based on surrogate modeling

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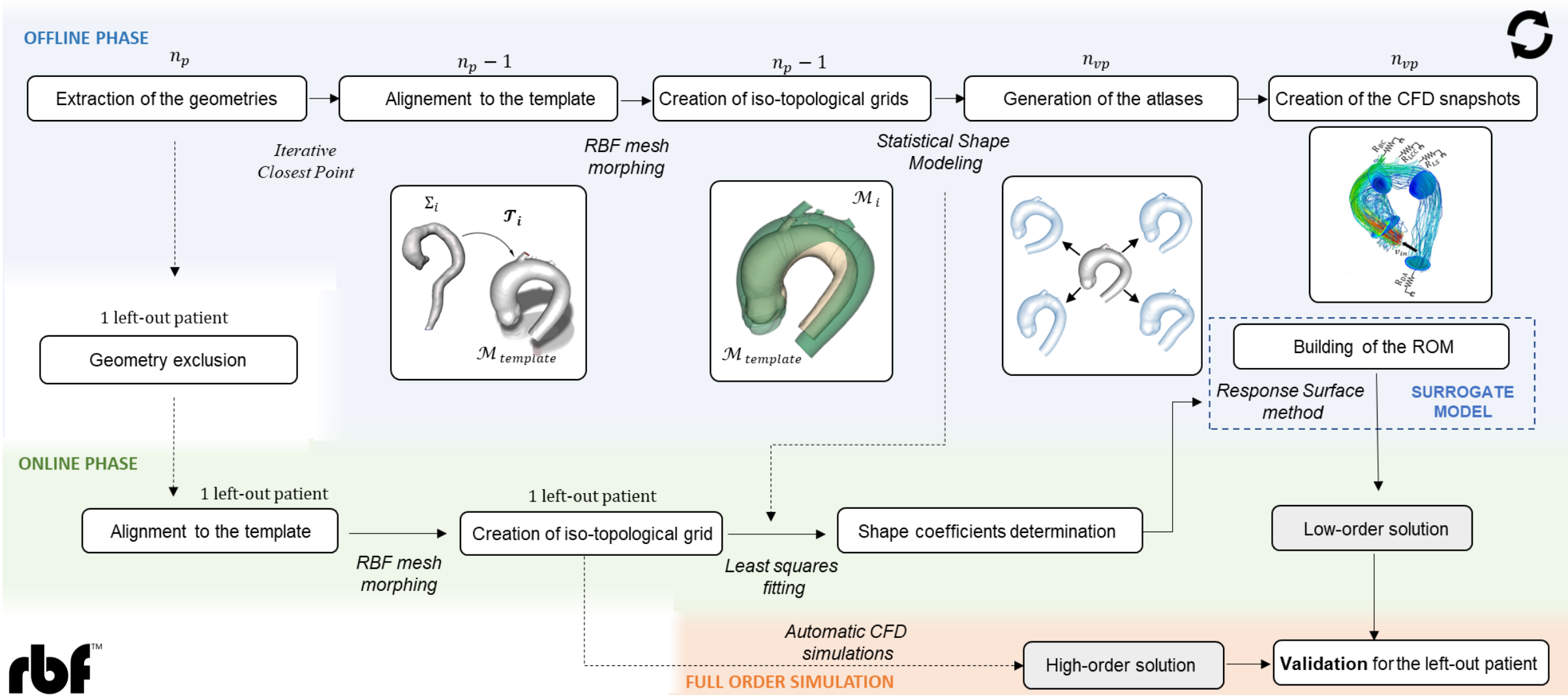

The offline phase

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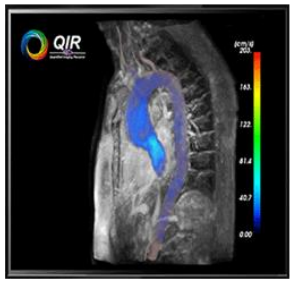
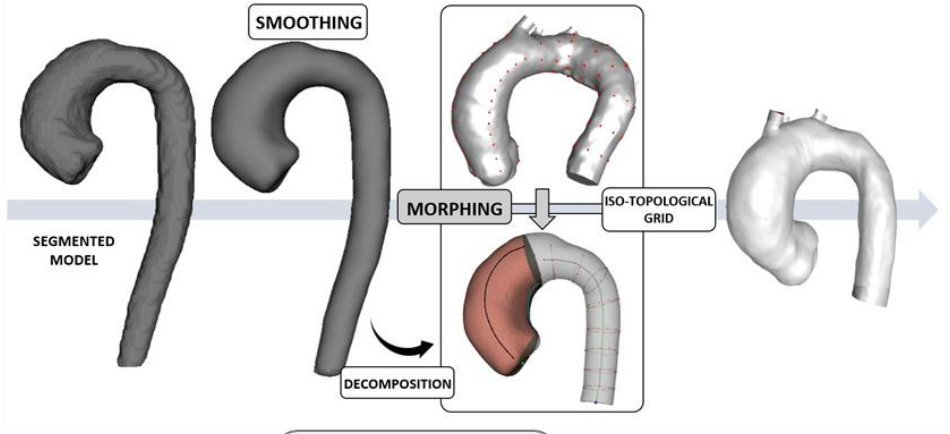
MRI 4D Flow



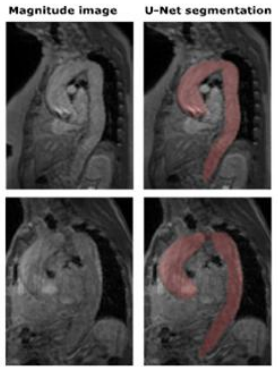


Based on principal component analysis (**PCA**)

Each shape $\widetilde{M_S}^i$ can be built combining n_{SM} eigenvalues λ_j and n_{SM} eigenvectors $\boldsymbol{W_j}$

$$\widetilde{M_S}^i = M_{S_{mean}} + \sum_{j=1}^{n_{SM}} c_j^i \sqrt{\lambda_j} W_j$$

Automatic (3D U-net) segmentation methods developed by Marin-Castrillon et al. [11] → **3D model** → **RBF Mesh Morphing** → **Iso-topological grid** → **Statistical Shape Modeling** → **Parametric 3D model**



$$s(\mathbf{x}) = \sum_{i=1}^{N} \gamma_i \varphi\left(\left\|\mathbf{x} - \mathbf{x}_{s_i}\right\|\right) + h(\mathbf{x})$$

In the 3D space:

$$\mathbf{x}_{\mathbf{node}_{\mathbf{new}}} = \mathbf{x}_{\mathbf{node}} + \begin{bmatrix} s_x(\mathbf{x}_{\mathbf{node}}) \\ s_y(\mathbf{x}_{\mathbf{node}}) \\ s_z(\mathbf{x}_{\mathbf{node}}) \end{bmatrix}$$

[11] Marin-Castrillon et al. *Magnetic Resonance Materials in Physics, Biology and Medicine* (2023): 1-14.

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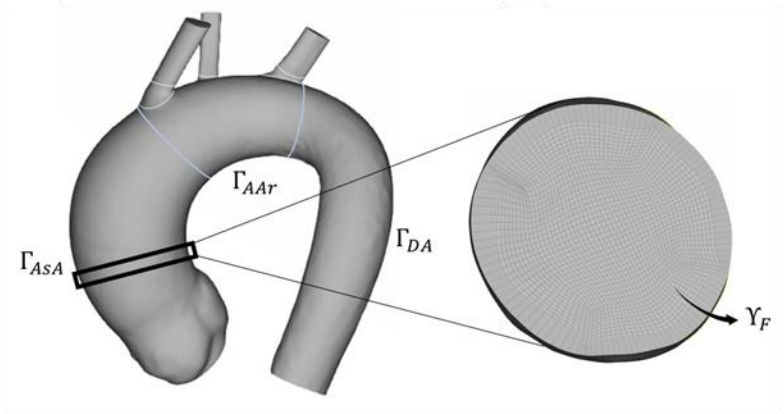
The offline phase

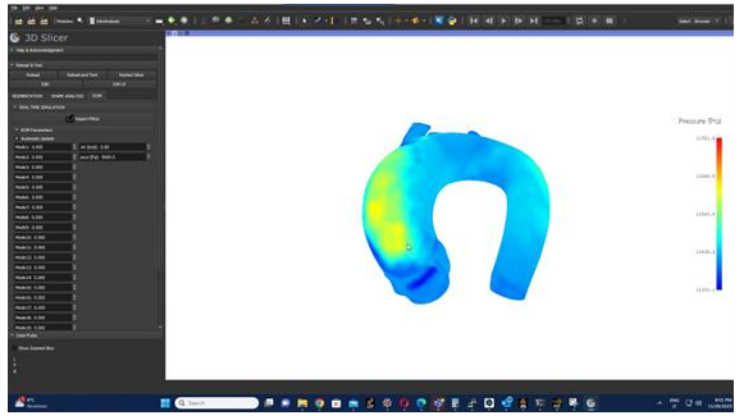


1) DECOMPOSITION

Proper orthogonal decomposition (**POD**) techniques:

$$\boldsymbol{\Omega} = \boldsymbol{U\Sigma V^T}$$

$$\min_{\boldsymbol{\Phi}} \left\| \boldsymbol{\Omega} - \boldsymbol{\Phi\Phi^T} \right\|^2$$



CFD Simulation using the synthetic data created through SSM → **Set of learning snapshots (Wall pressure)** → **Model order reduction techniques** → **Surrogate Model** → **Surrogate model deployment**

Navier-Stokes equations:

$$\mathbf{u} \cdot \nabla \mathbf{u} = -\frac{1}{\rho} \nabla p + \nu \nabla^2 \mathbf{u}, \text{in } \Upsilon_F$$

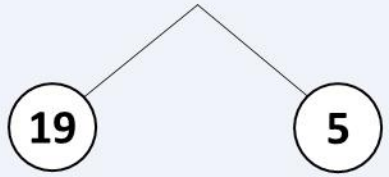
$$\nabla \cdot \mathbf{u} = 0, \text{in } \Upsilon_F$$

SIMPLE pressure-velocity coupling

Parameteric velocity **inlet** – pressure **outlet** BCs

2) INTERPOLATION

Genetic Aggregation Response Surface (**GARS**) technique for the ROM interpolation



Geometrical parameters Physical parameters

FMU DEPLOYMENT
Model Exchange 2.0

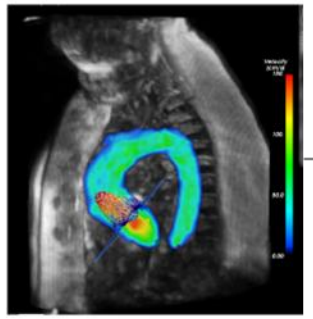
The online phase

Excluded patient

Automatic (3D U-net) segmentation

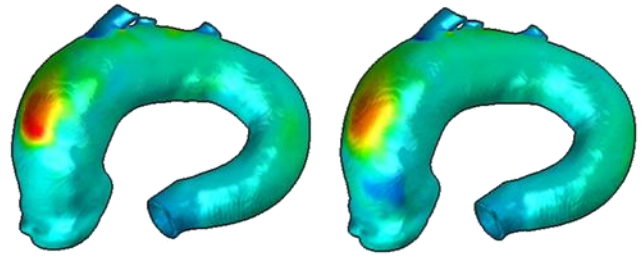
3D model

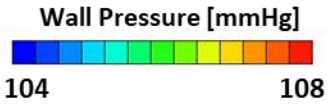
RBF Mesh Morphing



Inlet BC velocity value from the images

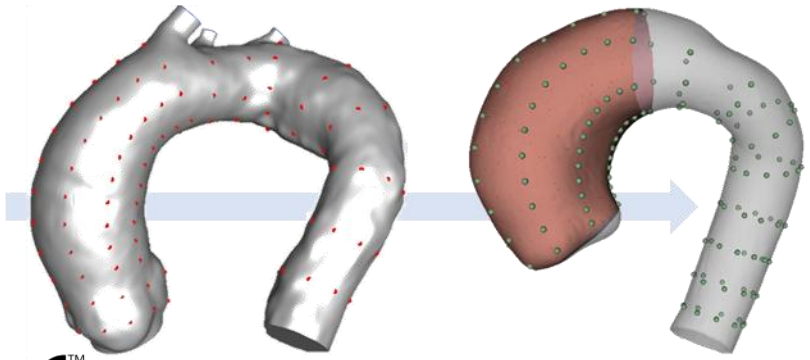
Full order model | Low order model

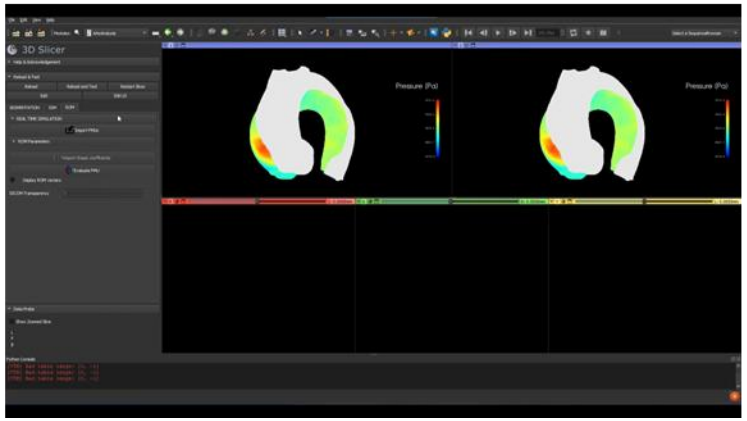




$$\boldsymbol{\omega}^{\mathrm{FOM}}(\boldsymbol{\alpha},\boldsymbol{\beta}) \approx \boldsymbol{\omega}^{\mathrm{ROM}}(\boldsymbol{\alpha},\boldsymbol{\beta}) = \sum_{i=1}^{N_{POD}} w_i \sqrt{\sigma_i(\boldsymbol{\alpha},\boldsymbol{\beta})}\,\boldsymbol{\phi}_i(\boldsymbol{\alpha},\boldsymbol{\beta})$$

Iso-topological grid → Shape representation using lest squares fitting + ROM interpolation → Reduced order results → Comparison full order vs reduced order simulation

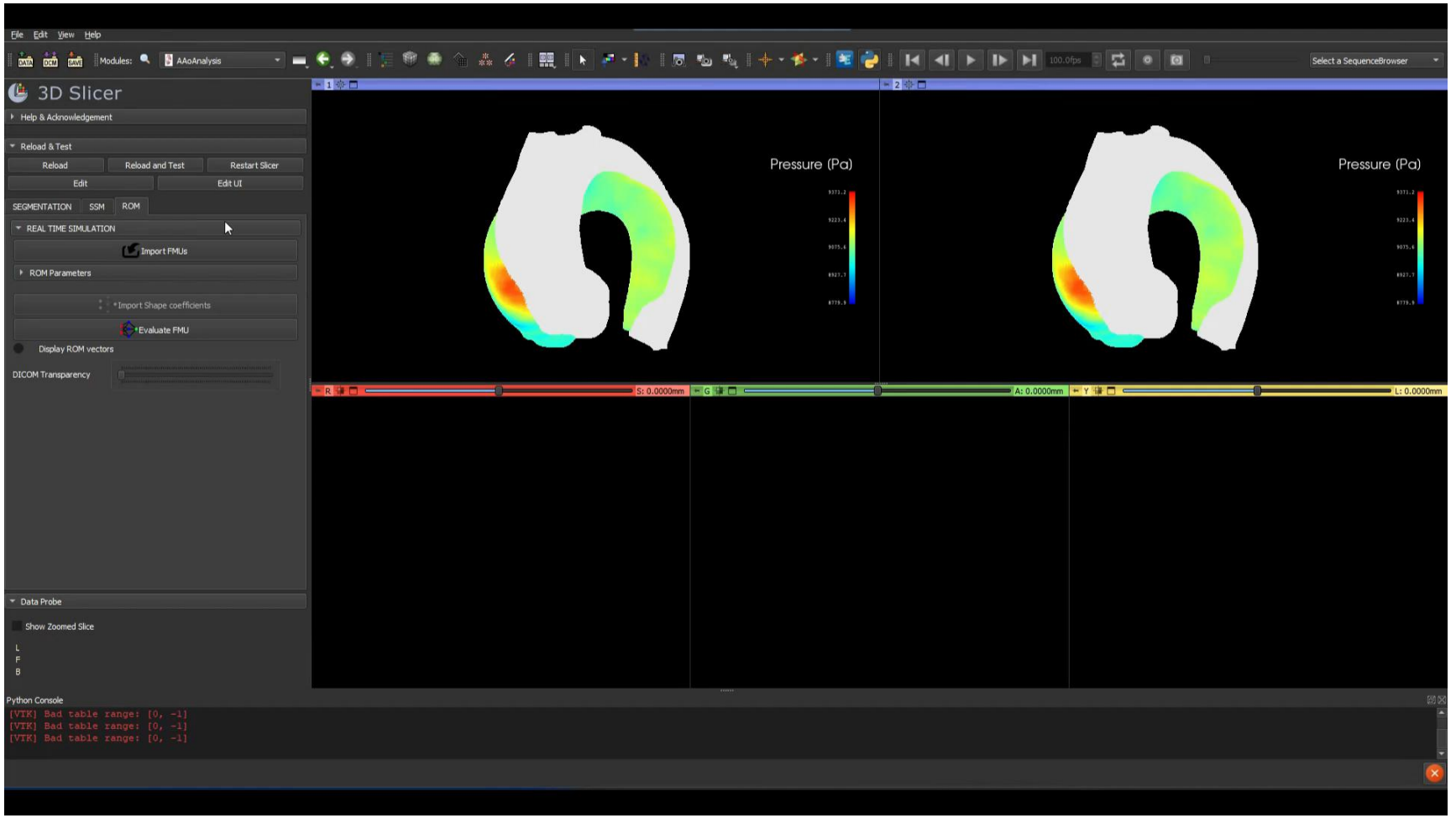




$$e_{ROM}^{rel,i-out} = \frac{\left\|\boldsymbol{\omega}_{i-out}^{FOM} - \boldsymbol{\omega}_{i-out}^{ROM}\right\|}{\left\|\boldsymbol{\omega}_{i-out}^{ROM}\right\|}$$

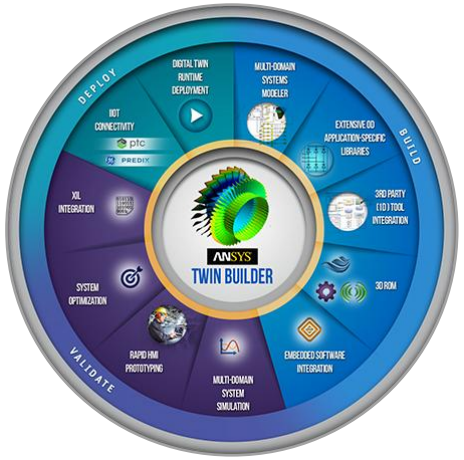
$$e_{ROM}^{abs,i-out} = \max\left(\left\|\boldsymbol{\omega}_{i-out}^{FOM} - \boldsymbol{\omega}_{i-out}^{ROM}\right\|\right)$$

The online phase

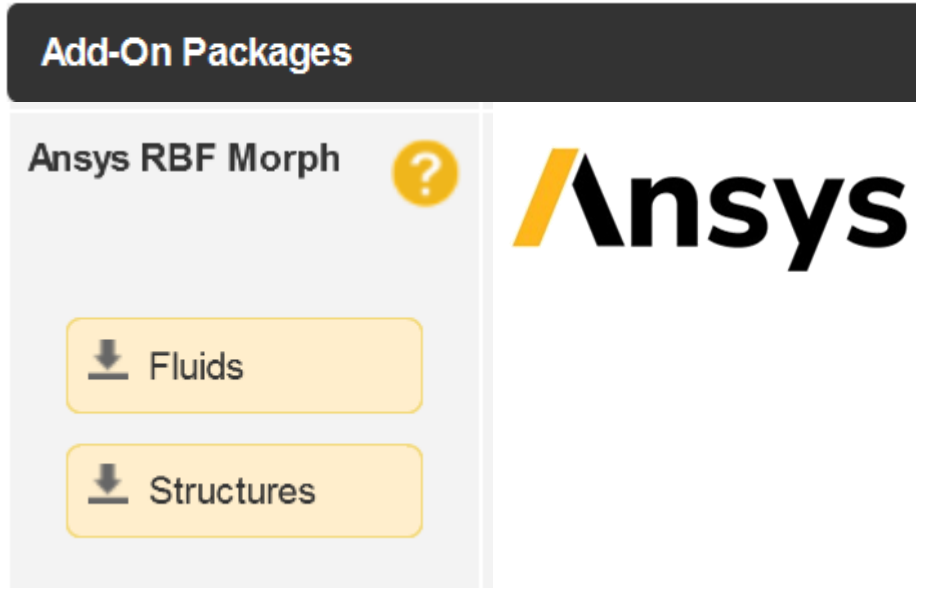


Ansys RBF Morph products

- An RBF mesh morphing solution fully embedded in Ansys
  - **RBF Morph Fluids** – an Add On for Fluent
  - **RBF Morph Structures** – an ACT App for Mechanical
- Full integration with **optiSLang** and **Twin Builder**
- Support for **LS-DYNA** and **APDL**



Ansys
OPTISLANG

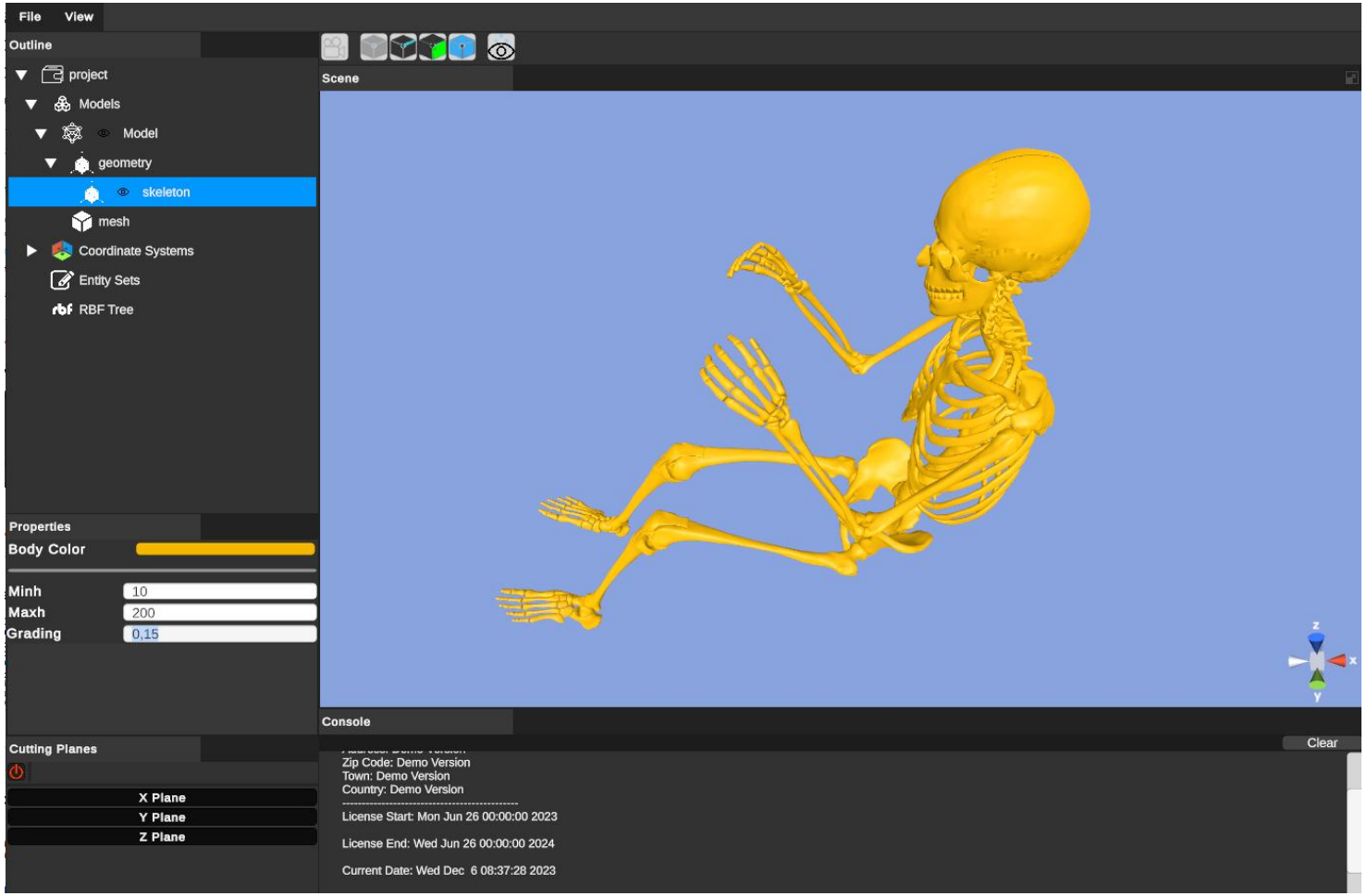


Ansys

https://www.rbf-morph.com/wp-content/uploads/2023/05/RBFMorph_Brochure.pdf

rbf™

The new rbfCAE platform



- Released in 2024
- Read in **STL, STEP**
- **Unity - OpenCascade**
- Solver independent process that supports **many mesh formats**
- **Scriptable** via python

Next step?
A complete solution to deliver interactive digital twins with AR/VR custom UI

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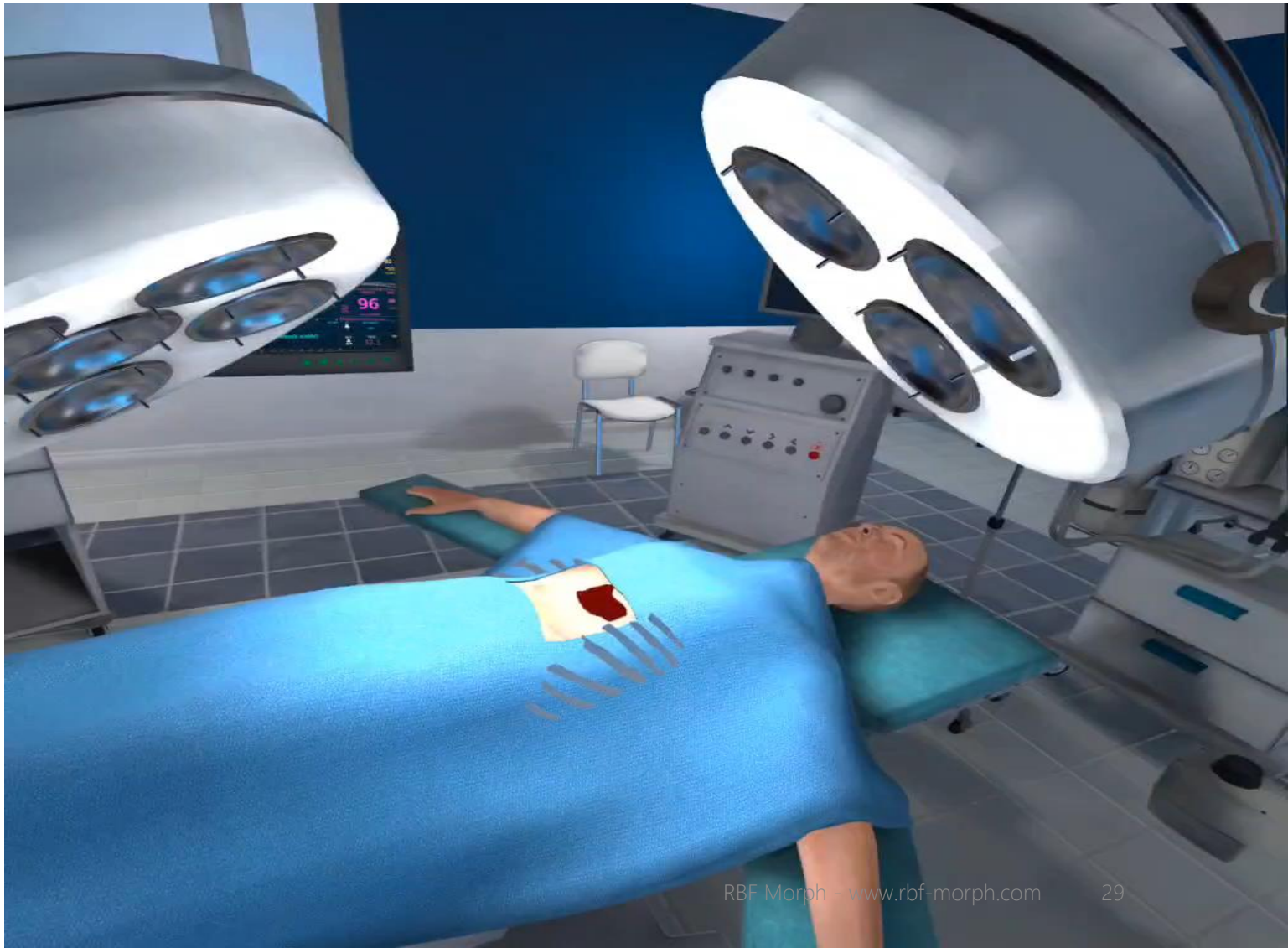
- FMU are translated to ARM
- Meta Quest 3
- Apple Vision Pro (very soon!)
- Input parameters are controlled by hands



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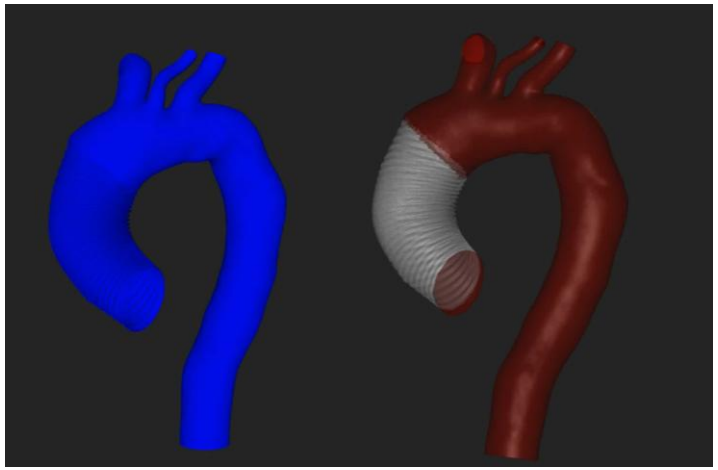
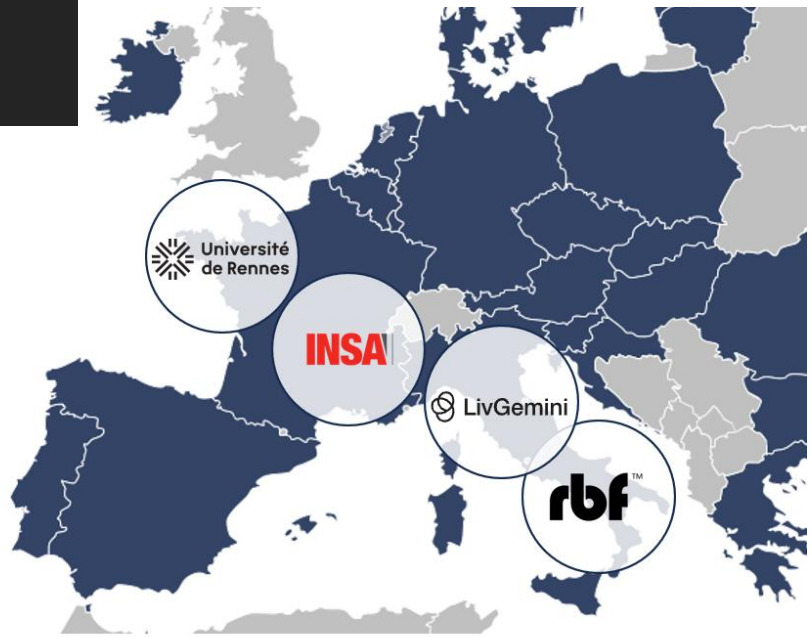
Next step?
Fortissimo Plus Business Case - PANDORA

FORTISSIMO
PLUS



PANDORA

Pre-operative AssistaNt based on Data-driven apprOaches for vasculaR grAft surgery



Conclusions

- Medical Digital Twins are feasible today!
- The **In Silico** path, i.e. MDT driven by high fidelity simulations, is ready and requires
  - Patient specific data (from images)
  - State of the art multi-physics simulation
  - Reduced order models and advanced mesh morphing
- A clear **business model** is required
  - Public funds are today the major resource
  - Certification is complex
- We are moving in the right direction and there is **mainstream focus** on Medical Digital Twins

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Thank you!

marco.biancolini@rbf-morph.com

linkedin.com/company/rbf-morph

youtube.com/user/RbfMorph

rbf-morph.com