Advanced Theoretical Modelling and Fluid-Structure Interaction Analysis of Patient-Specific Cardiovascular Haemodynamics

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Introduction

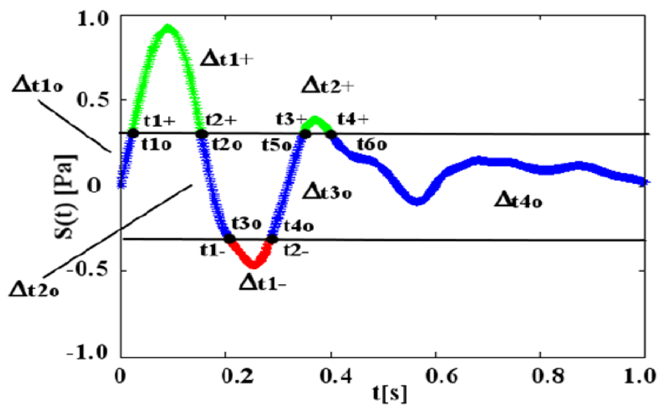
Mathematical and numerical models for the cardiovascular system have the potential to deliver a **concrete aid in diagnosis and therapy in health-care.**
This study focuses in this direction, by producing **several novel outcomes**.

- ✓ The **first contribution** consists in a deep **investigation into the role of the Wall Shear Stress (WSS)** in the development of abdominal aortic aneurysms and in the deposition of an **intraluminal thrombus in the aneurysm sac**.
- ✓ The **second contribution** consists in the **comparison** of the **performances of the stented and the stentless bioprostheses** employed to substitute a diseased aortic valve.

Materials and methods

In this study, **geometrical mutiscale** (3D-0D) **patient-specific fluid-structure interaction** simulations are performed [1][2].

❖ For the **first topic**, two geometries representing **a healthy abdominal aorta and an abdominal aortic aneurysm (AAA)** are considered. These two geometries derive from CT scans and are reconstructed using VMTK tools. The arterial wall is obtained via extrusion, and a **boundary layer fluid mesh** is adopted to provide **an accurate WSS analysis.** Two novel risk predictors are introduced using the information contained in the **Three Band Decomposition (TBD)** technique [3]. The **TBD analysis** consists in **dividing** a **signal into a set of three functions** via a control running threshold, σ, as combination of Heaviside step functions.



$$S^{0,\mp}(t) \equiv S(t)H^{\mp,0}(\sigma)$$

$$\begin{cases} H^{-}(\sigma) = 1 & \text{if} \quad S(t) < -\sigma \quad \text{and} \quad 0 \quad \text{otherwise} \\ H^{+}(\sigma) = 1 & \text{if} \quad S(t) > \sigma \quad \text{and} \quad 0 \quad \text{otherwise} \\ H^{0}(\sigma) = 1 & \text{if} \quad -\sigma \leq S(t) \leq \sigma \quad \text{and} \quad 0 \quad \text{otherwise.} \end{cases}$$

For each value of the threshold σ**, the TBD analysis permits to evaluate the number N(σ)** of the crossing intervals and their individual extent Δt_j The **rich information** contained in the WSS structure **is condensed in the following novel synthetic risk indicators** [4]:

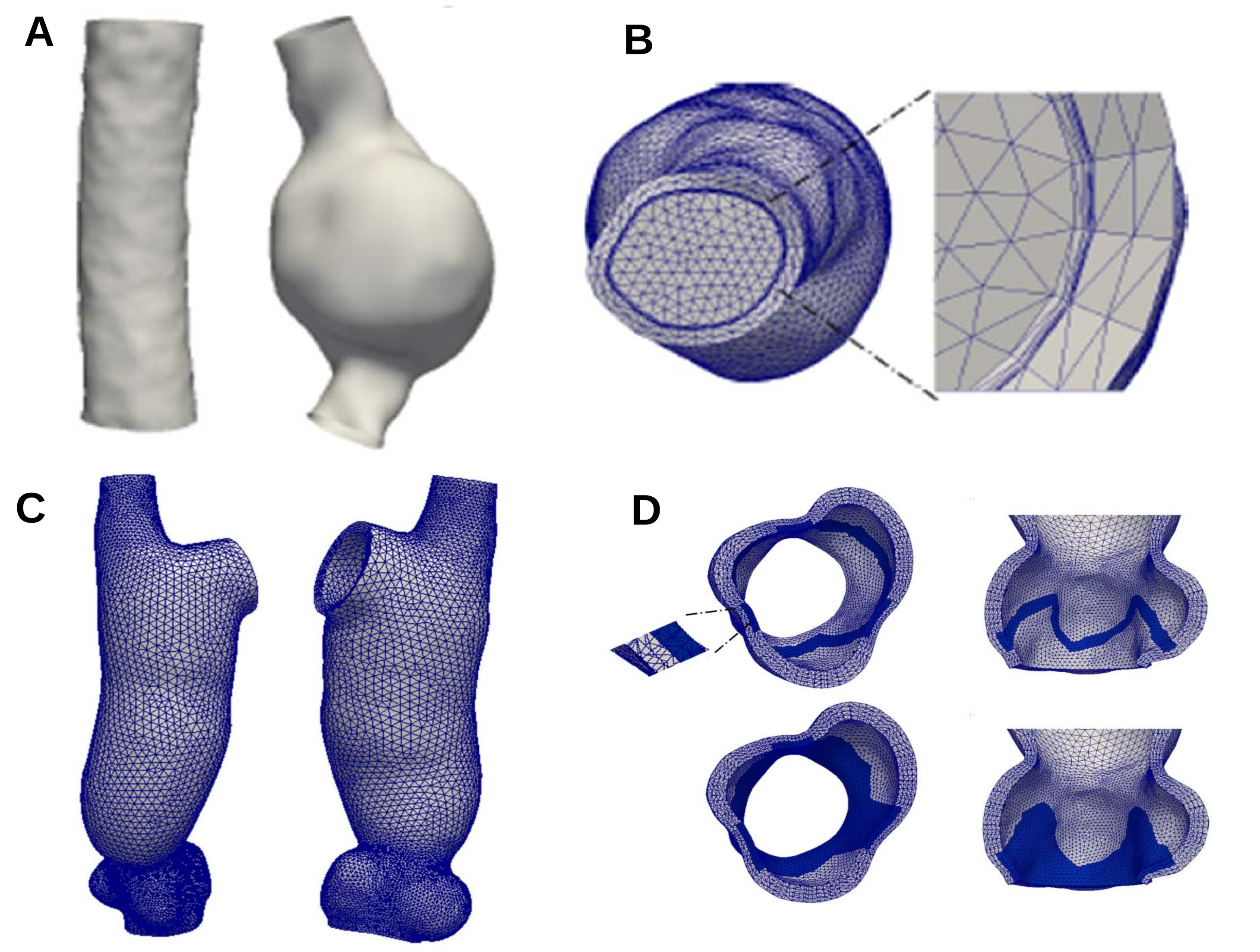
$$\mathrm{TBD_N} = \frac{\sum_{k=0}^{K} \sigma_k N_k^{-}}{\sum_{k=0}^{K} \sigma_k \left(N_k^{+} + N_k^{-} + N_k^{0}\right)}$$

$$\mathrm{TBD_{\Delta T}} = \frac{\sum_{k=0}^{K} \sigma_k T_k^{-}}{\sum_{k=0}^{K} \sigma_k \left(T_k^{+} + T_k^{-} + T_k^{0}\right)}.$$

$$T^{0,\mp} \equiv \sum_{j=1}^{N^{0,\mp}} \left(t_{2j}^{0,\mp} - t_{2j-1}^{0,\mp}\right) = \sum_{j=1}^{N^{0,\mp}} \Delta t_j^{0,\mp}$$

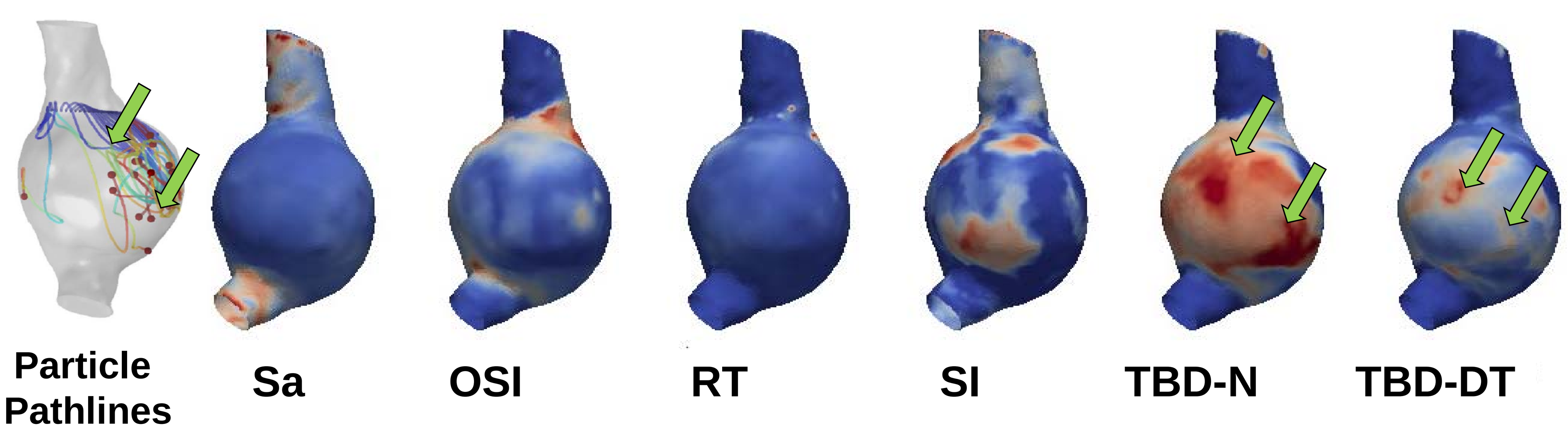
These two predictors are **compared with** the **risk indices existing in the literature:** the **time-averaged magnitude of WSS** (**Sa**), the **Oscillatory Shear Index** (**OSI**), the **Residence Time** (**RT**) and **Stagnation Index** (**SI**) .

❖ For the **second topic, three geometries of aortic roots are reconstructed**. In particular, **the stentless, the stented, and the healthy scenario** are considered for each patient by reproducing the **profiles of both the stented and the stentless prostheses in agreement with biomedical images**.



A. Lumen boundary surfaces of the healthy abdominal aorta (left) and the AAA model (right).
B. Fluid and Solid mesh of the AAA model (the zoomed region refers to the boundary layer introduced into the fluid grid) .
C. Fluid and Solid mesh for the geometry of aortic root and ascending aorta of patient 1.
D. Detail of the stentless (right, up) and stented (right, bottom) configurations. In blue, the regions reproducing the prostheses profile.

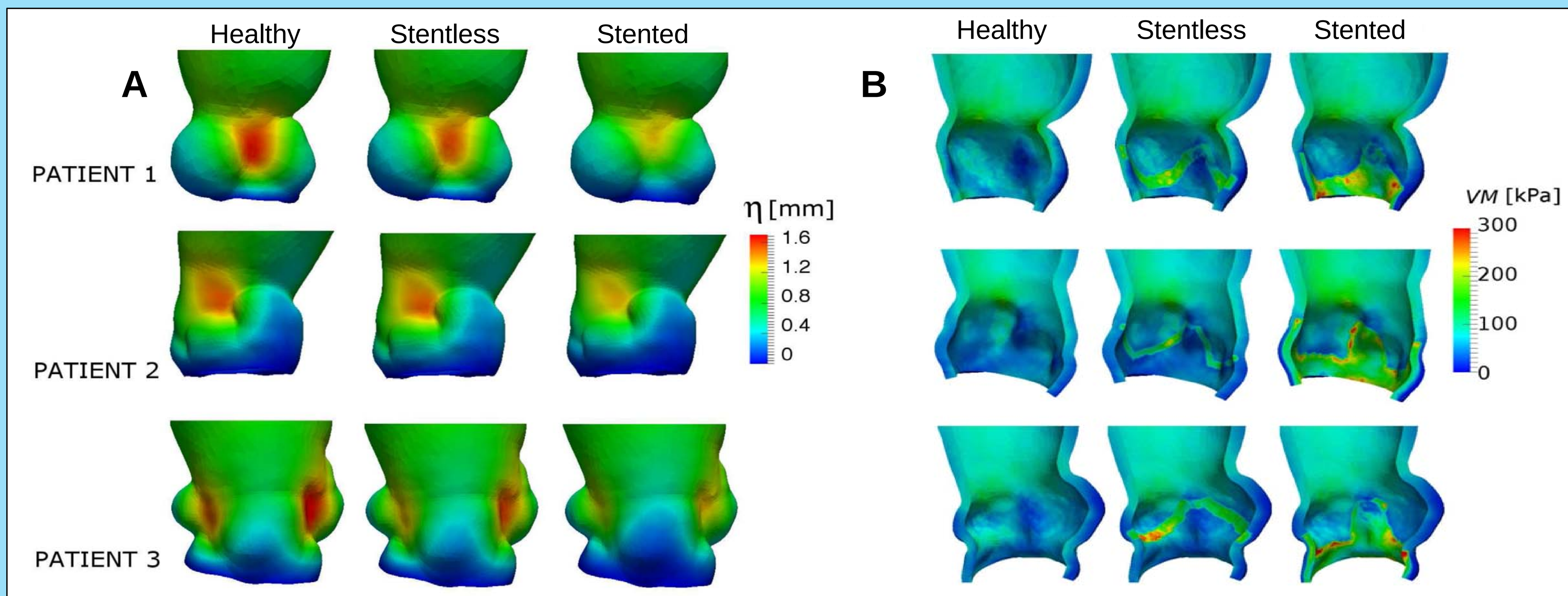
Results (1)



Representation of the particles pathlines after six periods of pulsatile flow and spatial distribution of the risk indices in the AAA.

- ❑ A schematic view of the **particles tracking,** detecting and quantifying the site of platelets deposition within the aneurysm bulge, show that **particles entrapped in the central and distal region of the aneurysm sac tend to deposit in the sites predicted by the two novel TBD indicators.**
- ❑ **The other risk indices do not capture such a risk condition**.
- ❑ It is worth pointing out that these **results are also in good agreement with clinical observations concerning the site of thrombus deposition** [5-6].

Results (2)



Aortic root displacements (A) and Von Mises stresses (B).

- ❑ The obtained results highlight that **the presence of the rigid frame in the stented scenarios causes a reduction** of about 20% in the values **of** the **aortic root displacements with respect to the healthy** situation [7].
- ❑ **Negligible differences** are observed **between the stentless and the healthy configurations**.
- ❑ Such a trend is also confirmed by computing the Von Mises Stresses. **Very high stress values** are found **in all the stented configurations with respect to the** corresponding **healthy scenario**. Again, **negligible differences** are observed **between the stentless and the healthy scenarios** [7].

Conclusions

As a first immediate clinical implication of these results, it is worth to point out that:

- ➢ The **WSS analysis** highlights **the predictivity performance of the two novel risk indicators as compared with the existing in the literature**.
- ➢ The **stentless bioprostheses allow the aortic root to recover a more physiological dynamics,** thus improving the mechanical performance with respect to the stented ones.

Bibliography

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