NUMERICAL PREDICTION OF CALCIFIC REGIONS IN BIOPROSTHETIC HEART VALVES: CORRELATING IMAGING AND SIMULATION DATA

Pascal Corso (1), Elena Tsolaki (2, 3), Robert Zboray (4), Dominik Obrist (1), Inge K. Herrmann (2, 3)

1. University of Bern, Switzerland; 2. Laboratory for Particles-Biology Interactions, Swiss Federal Laboratories for Materials Science and Technology (Empa), Switzerland; 3. ETH Zurich, Switzerland; 4. Center for X-ray Analytics, Empa, Switzerland.

Introduction

Calcification of bioprosthetic heart valves (BHV) represents a major concern since calcific aortic stenosis affects 12% of the population over age 75 and calcification limits BHV durability [1]. Calcification consists of the irregular deposition of mineralised crystals that change both the micro- and macro-scale architecture of the pre-treated biological tissues of BHV [2]. We thus intend to elucidate the mechanisms pertaining to the interaction of blood and valve motion that are correlated to calcification in BHV leaflets.

Methods

The study relies on both numerical simulations of the coupled blood and valve motion and on micro X-ray computed tomography (CT) measurements. The numerical simulation of a BHV model (Fig. 1B) is based upon (i) a finite-element formulation to solve the elastodynamics equation at a spatial resolution of about 500 µm [3], (ii) a high-order finite-difference formulation to solve the Navier-Stokes equations at a spatial resolution of about 100 µm [4], (iii) a variational approach for the transfer of information between the fluid and the structure [5]. The leaflets' constitutive relation is the Holzapfel-Gasser-Ogden model fitted to match tensile test data on pre-treated bovine pericardium [6]. The simulation data are validated against *in vitro* measurements [7]. The microCT measurements use a cone-beam RX Solutions Easy Tom XL microCT system, with a flat panel Varian PaxScan detector operated at an accelerating voltage of 140 kV with a tube current of 180 µA. The voxel size of the microCT scans is around 20 µm.

Results

Four relevant metrics obtained from the displacement and velocity fields at the interface between the leaflets and the blood are calculated (Fig. 1D). These indicators are the oscillatory shear index (OSI), relative residence time (RRT), topological shear variation index (TSVI) and the scalar strain (SS). A minimisation problem is then formulated in order to correlate the insightfully chosen indicators to the distribution of large-sale calcific structures measured from microCT. The resolution of the least-square minimisation problem provides an equation convincingly correlating the observed calcification-prone intensity from microCT to the reconstructed one, the latter depending on the evaluated indicators (Fig 1E). Finally, a novel method based on the computation of finite-time Lyapunov exponents (FTLE) from the leaflets' strain tensor (Fig. 1D) is devised to bring insights as to the leaflet motion at peak systole explaining the trustworthy observed correlation.

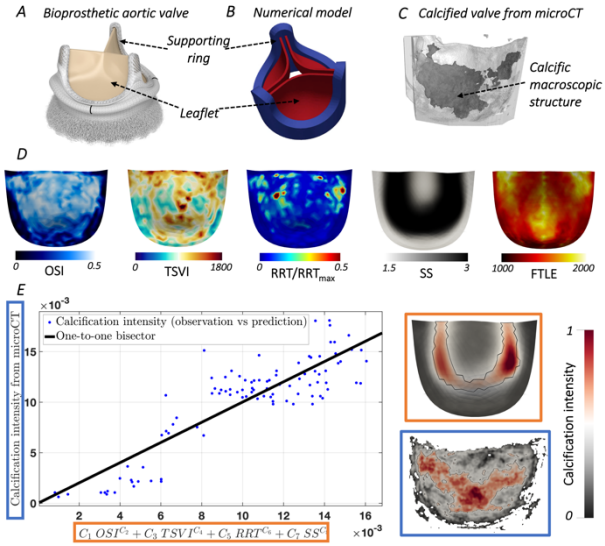

Figure 1: A. Tissue valve manufactured by Edwards. B. Corresponding computer model. C. Calcific crystals characterised through the microCT measurements. D. Four indicators and FTLE evaluated from the simulation data. E. Correlation (R^2 = 0.77) of the calcification intensity predicted from the simulations and that observed from the microCT measurements [8].

Discussion and Conclusion

The present study provides an equation to reliably predict from the four indicators calculated out of high-fidelity simulations of the coupled blood-valve system the regions on BHV leaflets where minerals tend to accumulate. We also observe that unstable motions of BHV leaflets at peak systole leading to high values of time-averaged FTLE are connected to calcification owing to the repeated strain exerted on the leaflets.

References

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