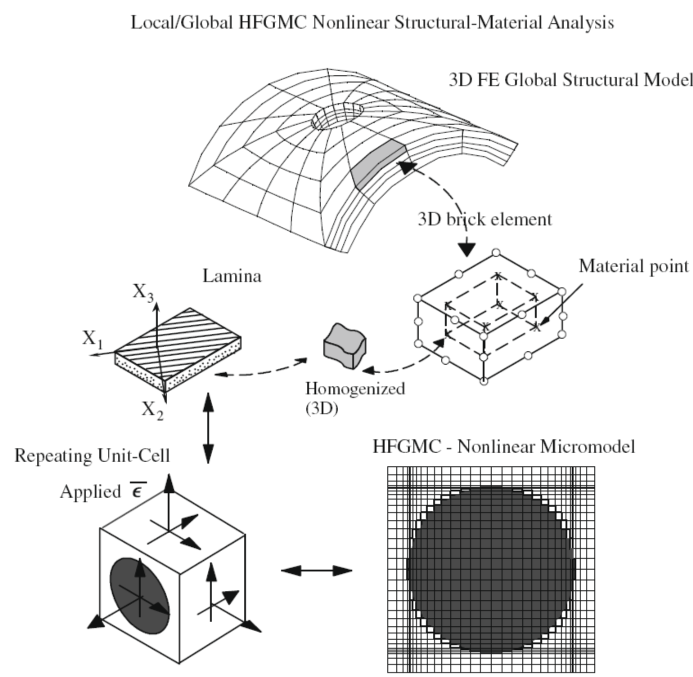
1. FINAL PUBLISHABLE SUMMARY REPORT

Aortic valve (AV) disease expressed by tissue inflammation and calcification is one of the major causes for cardiac related deaths in the world. Calcific stenosis leads to dramatic increase in leaflet stiffness and thus abnormal mechanical-structural performance of the AV which includes larger stiffness and stress concentration in the tissue and structure. This project deals with the analytical and computational mechanical modelling of native and prosthetic AV systems. Different aspects of the analytical and numerical work must be carried out and are part of this project in order to ultimately generate realistic overall AV models for both normal and abnormal (pathology) native AVs. The first major aspect is to generate nonlinear micromechanical models for the tissue material. Towards that goal, an effort to formulate and generate analytical nonlinear modelling of multi-phase periodic composite materials is carried out. The second major aspect deals with integrating the nonlinear micromechanical models into a multi-scale finite-element (FE) analysis framework for generating the overall mechanical response and behaviour of the AVs subject to in-vitro and in-vivo loadings. The third major research thrust includes experimental verification of several aspects of the AV system. Towards that goal, digital image correlation techniques are being investigated in the dynamic measurement of AV tissue deformation under in-vitro settings. The last thrust area is to introduce pathology in a previously verified AV model. The pathology that will be considered includes (but not limited to): moderate and severe calcification of the AV leaflets and their effect on the overall mechanical behaviour, simulation of different AV correction surgery such as leaflet corrections, AV root aneurysms, and re-implantation or remodelling procedures. The final goal of this project deals with a new parametric AV mathematical model that can realistically describe AV geometry with and without pathology with minimal number of parameters. In addition, a new Fluid-Structure Interaction (FSI) modelling approach has been developed to simulate the multi-physics and multi-scale mechanical behaviour of native and prosthetic AVs.

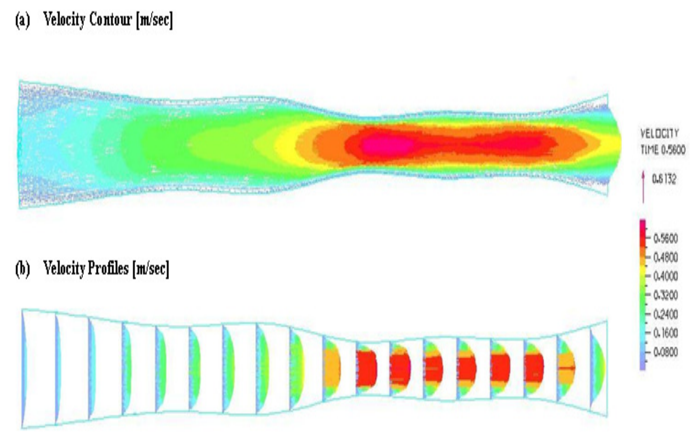
The following are select short summaries of different aspects of the above research thrusts that was and still ongoing within the proposed research activities.



1. Nonlinear Micromechanical Formulations

The recent High Fidelity Generalized Method of Cells (HFGMC) micromechnical modeling framework of multiphase composites is formulated in a new form which facilitates its computational efficiency that allows an effective multiscale material–structural analysis. Towards this goal, incremental and total formulations of the governing equations are derived. A new stress update computational method is established to solve for the nonlinear material constituents along with the micromechanical equations. The method is well-suited for multiaxial finite increments of applied average stress or strain fields. The new formulation of the HFGMC is used to generate a nested local-global nonlinear finite element analysis of composite materials and structures.

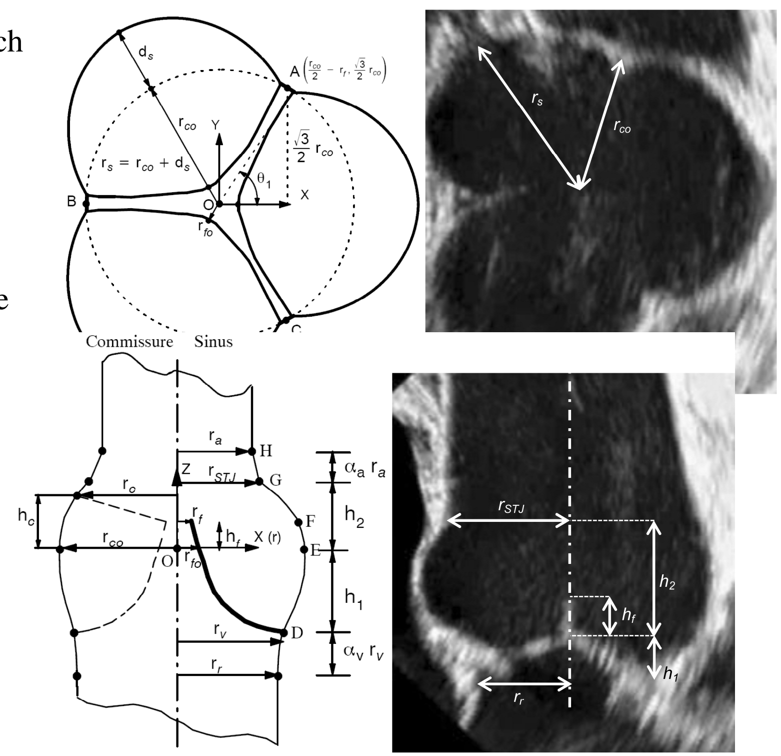
2. Stress Concentrations of Vulnerable Plaques



Simulations were conducted using 3D FSI models to generate the flow velocity in a stenosed left coronary artery (LCA) with a necrotic tissue located 100 µm from the lumen. Large changes in the stress distributions are evident by examining the effective stresses at different sections of the LCA wall, higher stress are shown at the LCA opening due to the relative higher pressure. Examining the critical section, it is shown clearly that there is a stress concentration at the cap layer with higher gradients, even though the absolute values of the stress are small at the necrotic (or plaque) core.

The method of computational micromechanical models has never been applied to FSI simulations of coronary arteries with vulnerable atherosclerotic plaques, which often are not homogenous and constitute of a variety of tissues with different material properties.

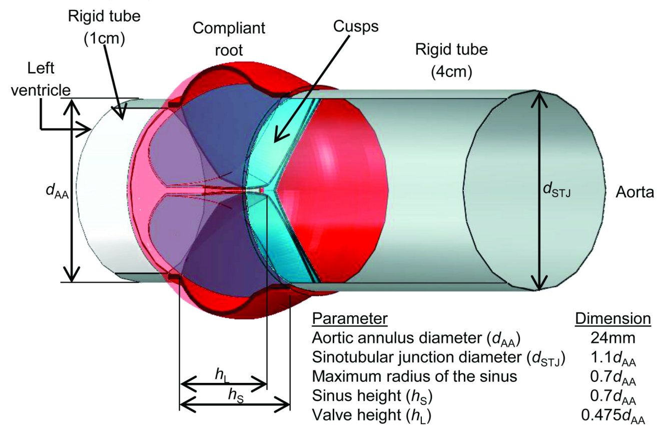
3. A General Three-Dimensional Parametric Geometry of the Native Aortic Valve and Root for Biomechanical Modeling



The complex three-dimensional (3D) geometry of the native tricuspid aortic valve (AV) is represented by select parametric curves allowing for a general construction and representation of the 3D-AV structure including the cusps, commissures and sinuses. The proposed general mathematical description is performed by using three independent parametric curves, two for the cusp and one for the sinuses. These curves are used to generate different surfaces that form the structure of the AV. Additional dependent curves are also generated and utilized in this process, such as the joint curve between the cusps and the sinuses. The model's feasibility to generate patient-specific parametric geometry is examined against 3D-transesophageal echocardiogram (3D-TEE) measurements from a non-pathological AV.

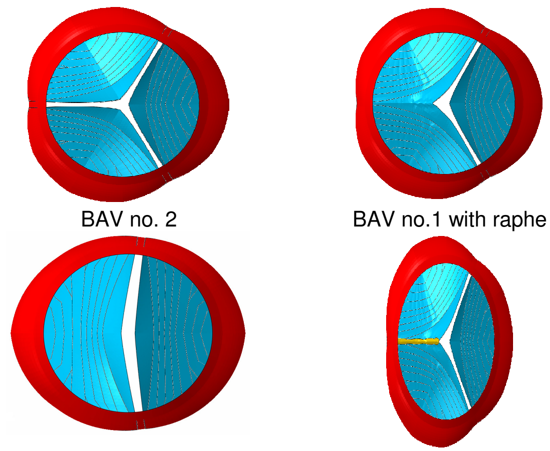
4. Hemodynamics in Fluid-Structure Interaction Model of Tricuspid and Bicuspid Aortic Valves

The bicuspid aortic valve (BAV) is a congenital cardiac disorder where the valve consists of only two cusps instead of three in a normal tricuspid valve (TAV). Although 97% of BAVs include asymmetric cusps, little or no prior studies investigated the flow through physiological three-dimensional BAV and root. This study presents a comparison between four full fluid-structure interaction (FSI) models, including native TAV, asymmetric BAV with or without a raphe and an almost symmetric BAV. The FSI simulations are based on coupled structural and fluid dynamics solvers that allow accurate modeling of the pressure load on both the root and the cusps. The partitioned solver has non-conformal meshes and the flow is modeled employing the Eulerian approach. The cusps tissue model recognizes the hyperelastic collagen fiber network embedded in the elastin matrix. The tissues of aortic sinuses are also deformable and have hyperelastic behavior. The coaptation is modeled with master-slave contact algorithm. A full cardiac cycle is modeled by imposing physiological blood pressure at the upstream and downstream boundaries. All the BAV models had significantly smaller opening area of the valve than found in the TAV. Larger stress values were also found in the cusps of the BAV models with fused cusps, both at the systolic and diastolic phases. The asymmetric geometry cause asymmetric vortices and much larger wall shear stress on the cusps, which is a potential cause for valvular calcification.

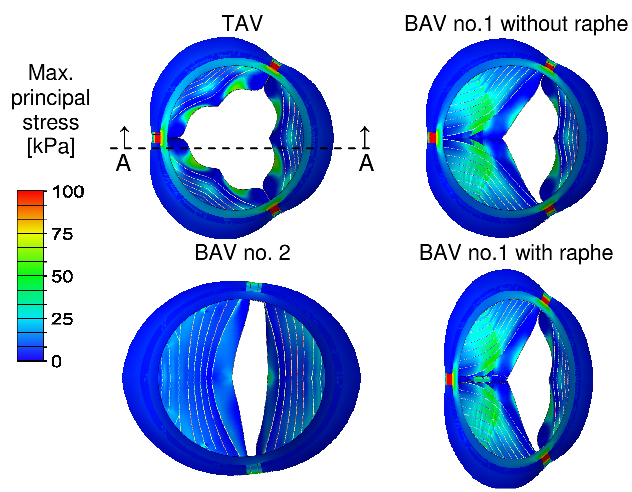


A schematic view of the tricuspid valve (TAV) model with compliant region and rigid tubes.

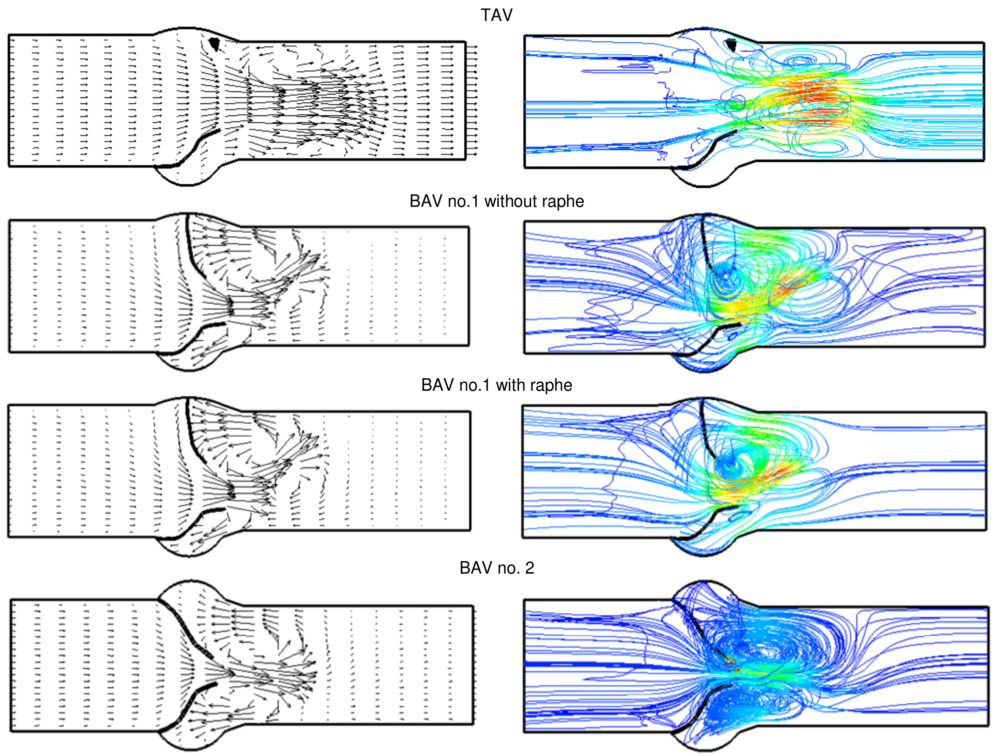
TAV BAV no.1 without raphe



Four types of initial geometries of tricuspid (TAV) and bicuspid (BAV) aortic valves.



Maximum principal stress distribution on the four types of aortic valves during peak systole.



Velocity vectors on A-A section and streamlines during peak systole for the four types of aortic valves.