Mathematical modeling for aortic valve replacement

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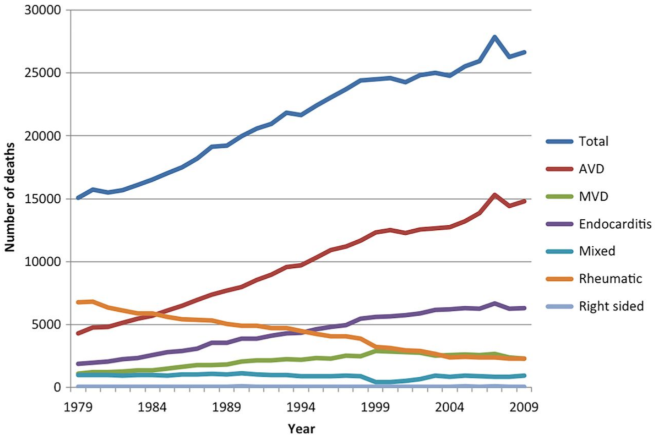
Aortic valve replacement

Heart valve diseases: statistics

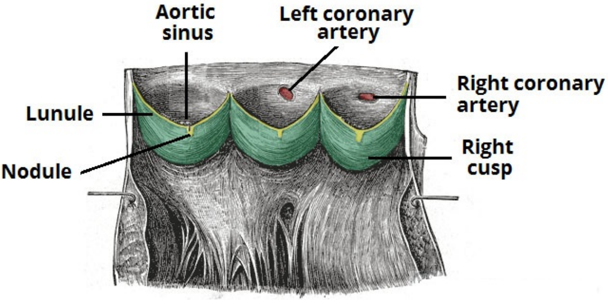
Coffey S. et al. The modern epidemiology of heart valve disease. Heart, 2016.

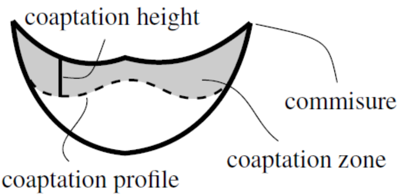


- Heart valve disease as the ‘next cardiac epidemic’
- Aortic valve disease (AVD) accounts for 45% of deaths from heart valve diseases

Aortic valve replacement

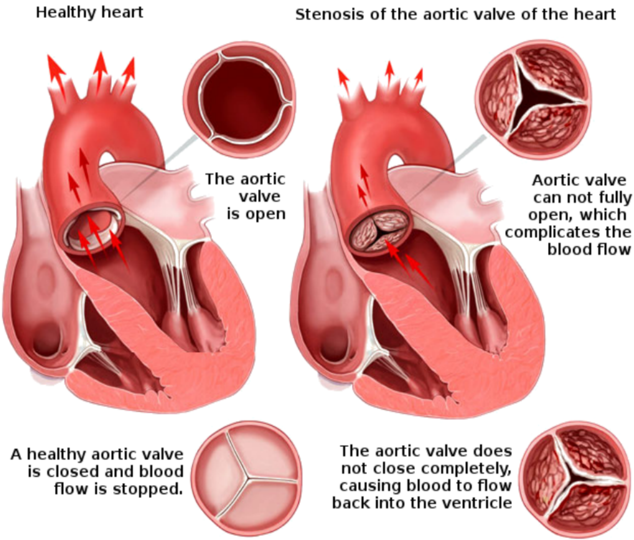
Aortic valve (AV)





Aortic valve replacement

Aortic valve disease (AVD)

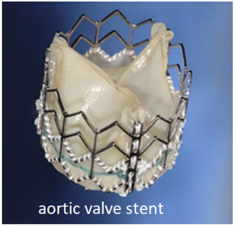


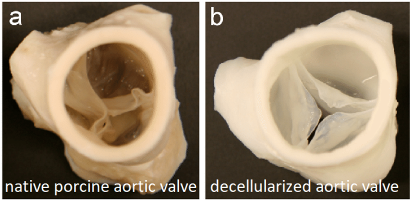
Aortic valve replacement

Aortic valve disease: treatment

Surgical treatment of AVD:

- AV replacement using mechanical/biological aortic valve (decellularized aortic homografts)





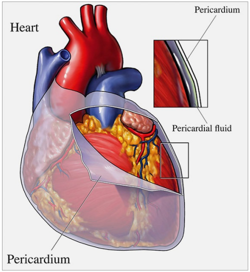
durability; problem of clotting; cost; problem of rejection

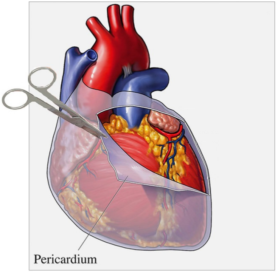
- AV cusps replacement by leaflets cut from auto-pericardium
  - no immune response
  - efficient, low-cost
  - all measurements and cuttings are made during operation

Aortic valve replacement

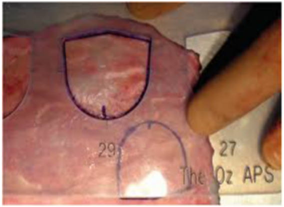
Auto-Pericardium

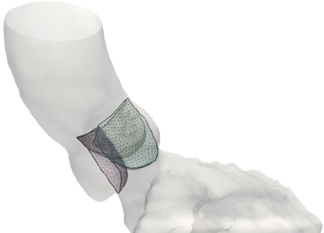
The pericardium is a fluid filled sack that surrounds the heart and the roots of the great vessels.





'Future' leaflets are cut from chemically treated auto-pericardium

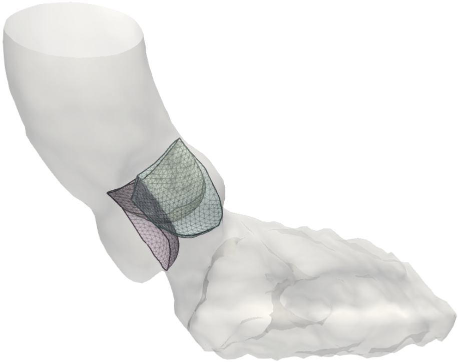


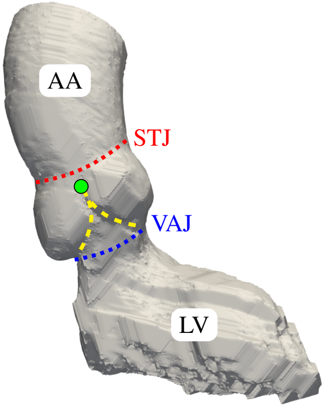


Mathematical modeling of AV replacement

Objectives of modeling:

- degree of regurgitation
- coaptation zone (heights)

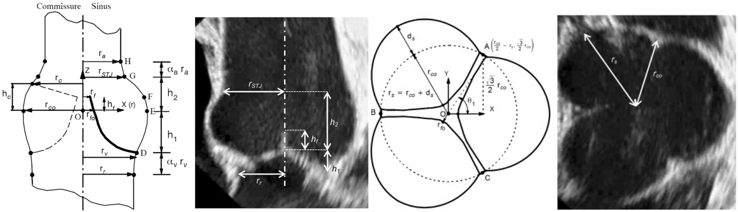




Mathematical modeling of AV replacement

Different approaches

- Geometric models
  - parametric geometry of the AV [1] [2] [3]



  - no personalization, 'ideal geometry'
  - no taking into account mechanical properties of AV leaflets

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[1] Thubrikar M. The aortic valve. 1996

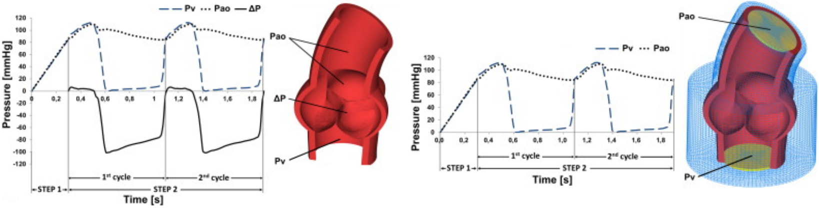
[2] Haj-Ali R. et al. A general three-dimensional parametric geometry of the native aortic valve and root for biomechanical modeling. Journal of biomechanics, 2012

[3] LabrosseM. R., et al. Geometric modeling of functional trileaflet aortic valves: development and clinical applications. Journal of biomechanics, 2006

Mathematical modeling of AV replacement

Different approaches

- Structural finite element models (FEM)
- Fluid-structure interaction simulation



- personalization; mechanical properties of soft tissues
- computationally expensive (dynamic: FSI = 195 h, FEM = 19 h; static: FEM = 98 min)[1] [2]
- FSI model recovers AV transient motion and blood dynamics
- AV diastolic coaptation characteristics were almost the same for FEM and FSI[1]

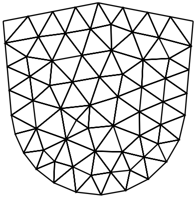
[1] Sturla F. Impact of modeling fluid-structure interaction in the computational analysis of aortic root biomechanics. Medical Engrg.&Physics, 2013

[2] Pappalardo O. Mass-spring models for the simulation of mitral valve function: Looking for a trade-off between reliability and time-eﬂciency. Med. Eng. Phys., 2017

Mathematical modeling of AV replacement

Different approaches

- Finding diastolic state of AV using simplified models



- leaflet is an oriented triangulated surface
- each node has a point mass at which forces due to pressure, elasticity and contacs are applied
- we search static equilibrium
- personalization, real-time simulation, mechanical prop.

$\mathbf{F}_i^e$ elastic force:

1. Mass-spring model (each edge is a spring with given stiffness)

$$\mathbf{F}_i^e = \sum_{e_{ij}} \mathbf{F}_{ij}, \ \mathbf{F}_{ij} = k_{ij}(\|\mathbf{r}_j - \mathbf{r}_i\| - L_{ij}) \frac{\mathbf{r}_j - \mathbf{r}_i}{\|\mathbf{r}_j - \mathbf{r}_i\|}, \quad k_{ij} = \frac{E(\varepsilon, \alpha_0) H A_{ij}}{L_{ij}^2}$$

2. Hyperelastic nodal force (HNF)

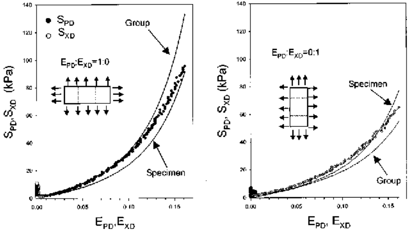
$$\mathbf{F}_i^e = \sum_{T_P \in S_i} \mathbf{F}_i(T_P), \ \mathbf{F}_i(T) = -A_T \frac{\partial U_d(\mathbf{r}_i, \mathbf{r}_j, \mathbf{r}_k)}{\partial \mathbf{r}_i},$$

where the discretized counterpart $U_d(\mathbf{r}_i, \mathbf{r}_j, \mathbf{r}_k)$ of the elastic potential U

Mathematical modeling of AV replacement

Mechanical properties of pericardium

- Animal pericardium
  - Anisotropic (orthotropic)

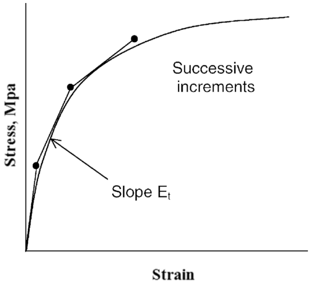


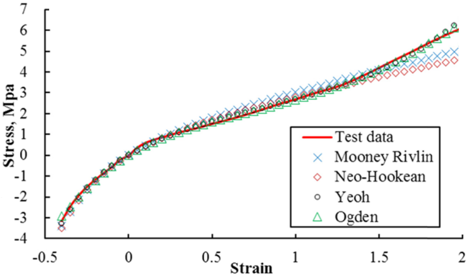
  - Treated pericardium is more stiffer than fresh one and is also anisotropic.

- Human pericardium
  - Is thought to be isotropic. Only one work is arguing anisotropic property.
  - Treated pericardium is more stiffer than fresh (isotropic vs. anisotropic = ?)
  - Need more experimental data on mechanical properties of human pericardium

Mathematical modeling of AV replacement

Mechanical properties is taken into account via incremental elastic modulus (MSM) or elastic potentials (hyperelasticity)





Mathematical modeling of AV replacement

The next talk by Liogkiy A.

- technology for patient-specific modeling of aortic valve closure (diastolic state) at the preoperative stage
- simplifed models (MSM, HNF)
- chosen elastic potentials with minimal number of material parameters
- varied elastic modulus and models