Моделирование диастолического состояния клапана в задаче реконструкции аортального клапана по методу Озаки

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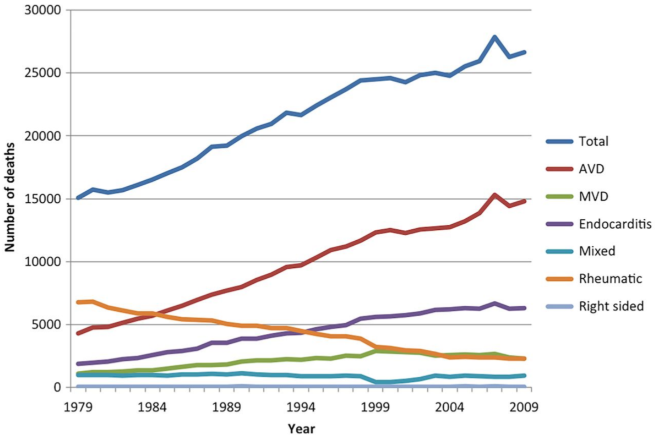
3 ноября 2020, XII конференция по математическим моделям и численным методов в биоматематике, Москва

Aortic valve replacement

Heart valve diseases: statistics

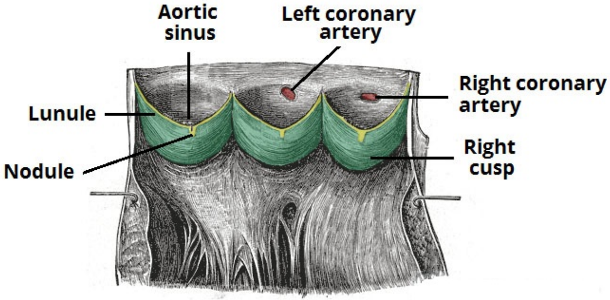
Coffey S. et al. The modern epidemiology of heart valve disease. Heart, 2016.

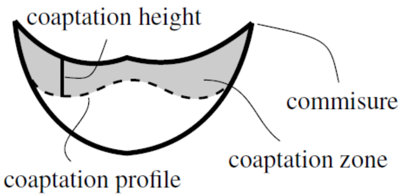


- Heart valve disease as the ‘next cardiac epidemic’
- Aortic valve disease (AVD) accounts for 45% of deaths from heart valve diseases

Aortic valve replacement

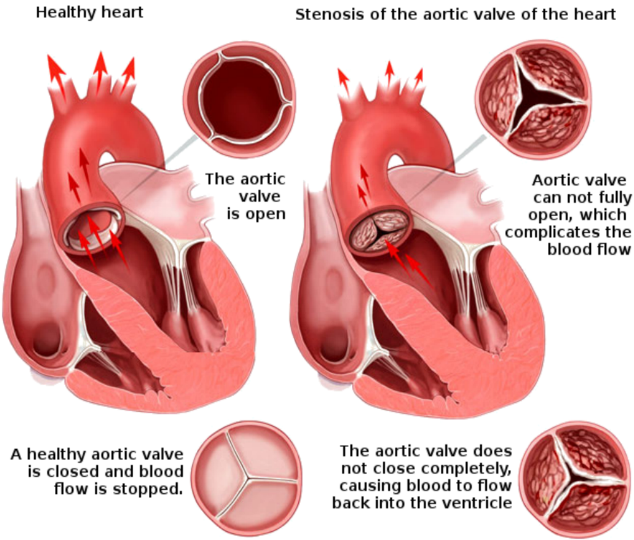
Aortic valve (AV)





Aortic valve replacement

Aortic valve disease (AVD)

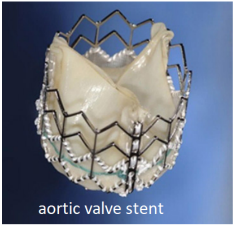


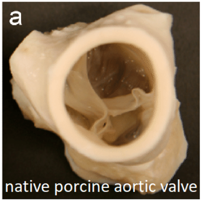
Aortic valve replacement

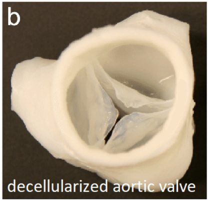
Aortic valve disease: treatment

Surgical treatment of AVD:

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







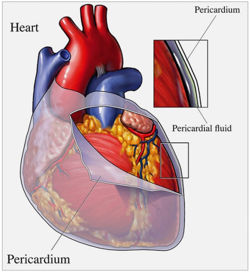
durability; problem of clotting; cost; problem of rejection

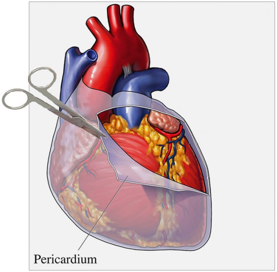
- AV cusps replacement by leaflets cut from auto-pericardium
  - no immune response
  - efficient, low-cost
  - all measurements and cuttings are made during operation

Aortic valve replacement

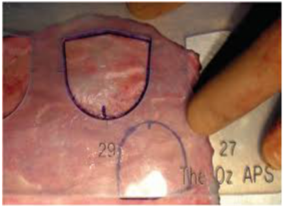
Auto-Pericardium. Ozaki procedure.

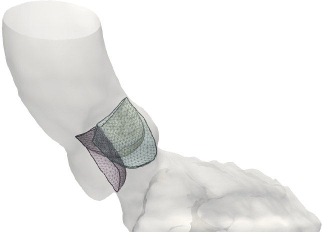
The pericardium is a fluid filled sack that surrounds the heart and the roots of the great vessels.





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

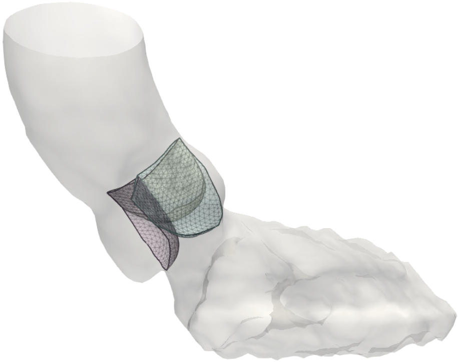


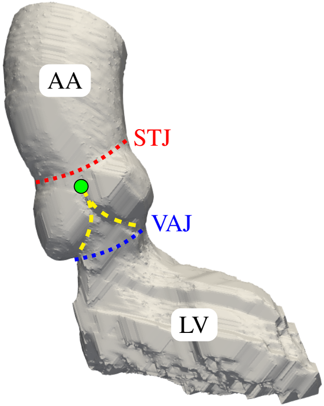


Mathematical modeling of AV replacement

Objectives of modeling:

- degree of regurgitation
- coaptation zone (heights) [demand on computation time for real-time surgical planning system: the results within a few minutes on a personal computer.]

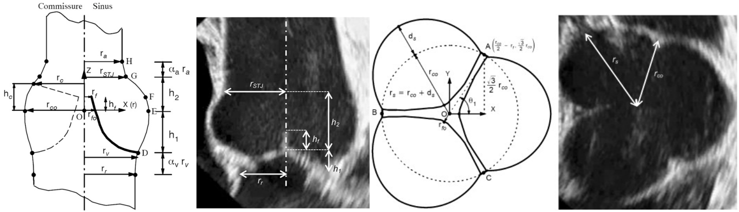




Mathematical modeling of AV replacement

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

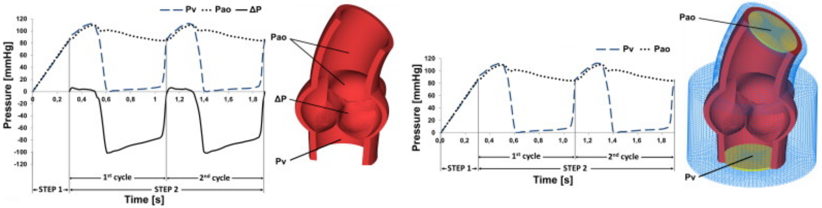
[2] Haj-Ali R. et al. A general three-dimensional parametric geometry of the native aortic valve and root for biomechanical modeling. Journal of biomechanics, 2012

[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]

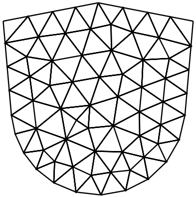
[1] Sturla F. Impact of modeling fluid-structure interaction in the computational analysis of aortic root biomechanics. Medical Engrg.&Physics, 2013

[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.

F_i^e elastic force:

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

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

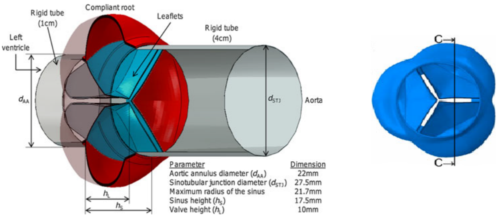
2. Hyperelastic nodal force (HNF)

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

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

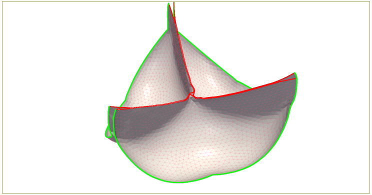
Mathematical modeling of AV replacement

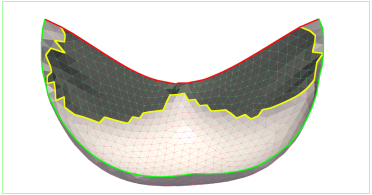
G. Marom et al. J. Thorac. Cardiovasc. Surg. 145 (2013) [FSI+lin.elasticity]



Parameter	Dimension
Aortic annulus diameter (d_{AA})	22mm
Sinotubular junction diameter (d_{STJ})	27.5mm
Maximum radius of the sinus	21.7mm
Sinus height (h_S)	17.5mm
Valve height (h_L)	10mm

Calculated coaptation characteristics: h_E, h_{C-C}, h_{avr}, NCCA.
h_E = valve height at pressure of 3 mm Hg.
h_{C-C} = coaptation height measured in the $C - C$ plane (distanced by 5 mm).
h_{avr}= of the coaptation area / the free-edge length.
NCCA = the coaptation area / the total cusp surface area.

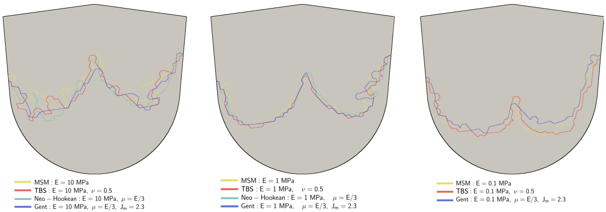


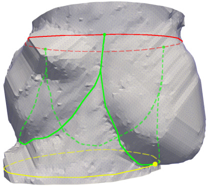


Model	h_E, mm	h_{C-C}, mm	h_{avr}, mm	NCCA, %	CPU time, s
FSI, lin.el.	10.5	1.5	2.7	21	n/a
MSM	10.8	3.8	3.3	25	44
St-V-K (TBS)	10.8	3.1	2.9	24	58
neo-Hookean	10.4	3.0	2.5	21	136
Gent	10.8	3.4	3.1	24	203

Coaptation profiles for different elastic models

Models and elastic modulus were varied.





Conclusions

- Coaptation profile is insensitive to the elasticity models with the same elastic modulus.
- The variations of the coaptation heights may achieve 3–10 mm for different modulii and models; and 2-4 mm for different models with the same elastic modulus.
- The sensitivity to anisotropy of the pericardium was assessed for the mass-spring model: the variations of the heights are about 1 mm.
- Future plans: sensitivity to anisotropy with hyperelastic models, validation for real surgery cases, optimization of leaflets design, obtain more experimental data on mechanical properties for fresh and treated human pericardium, adding bending stiffness, algorithms of attachment lines and anatomical landmarks segmentation.

Thank you for your attention!