LABORATORY OF BIOLOGICAL STRUCTURE MECHANICS

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WHICH IS THE ROLE OF MYOCARDIAL TRABECULAE?

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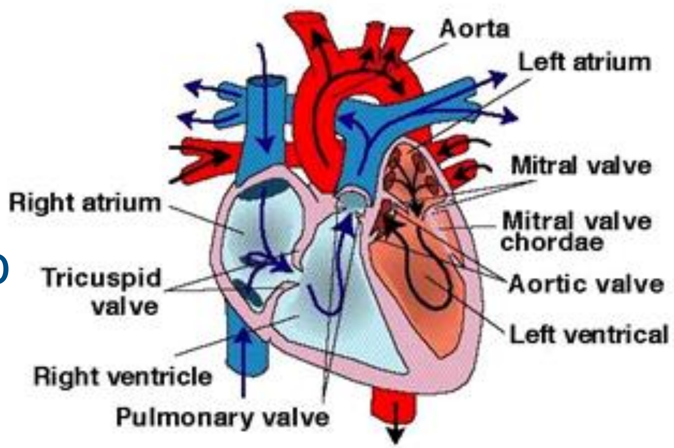
Scientific and Technological Advancements in Cardiac and Vascular Surgery

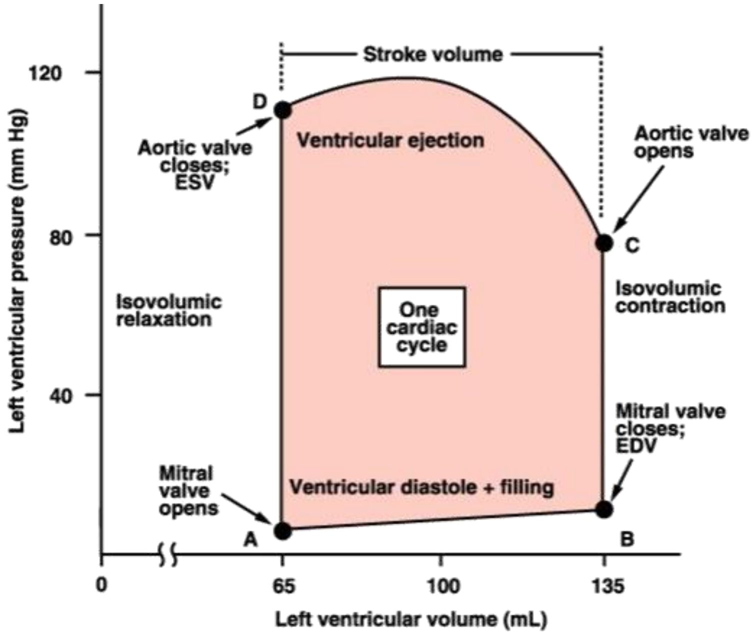
Erice, May 3rd 2015

INTRODUCTION

The HEART pumps blood both into the systemic and pulmonary circulations

- Right and left atria: receive blood from veins
- Right and left ventricles: pump blood into arteries





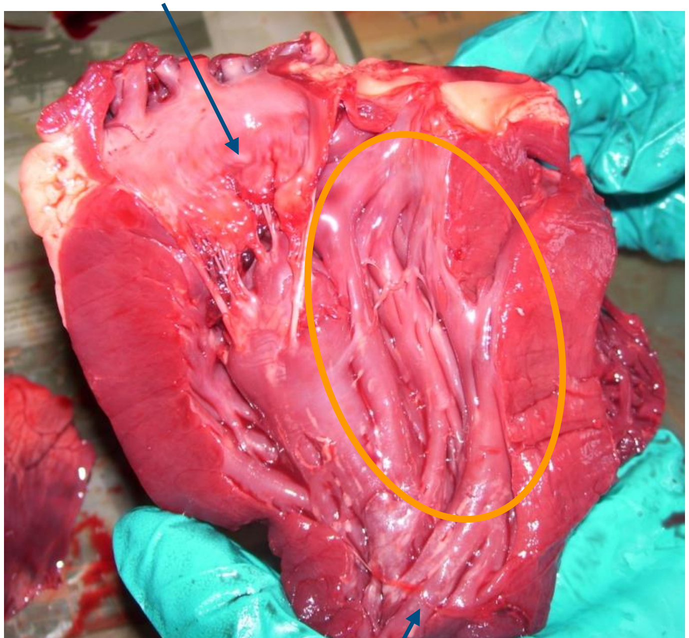
Cardiac cycle

- passive filling (diastolic phase)
- active contraction (systolic phase)

In literature studies some features of the cardiac structure are surprisingly disregarded

CARDIAC TRABECULAE

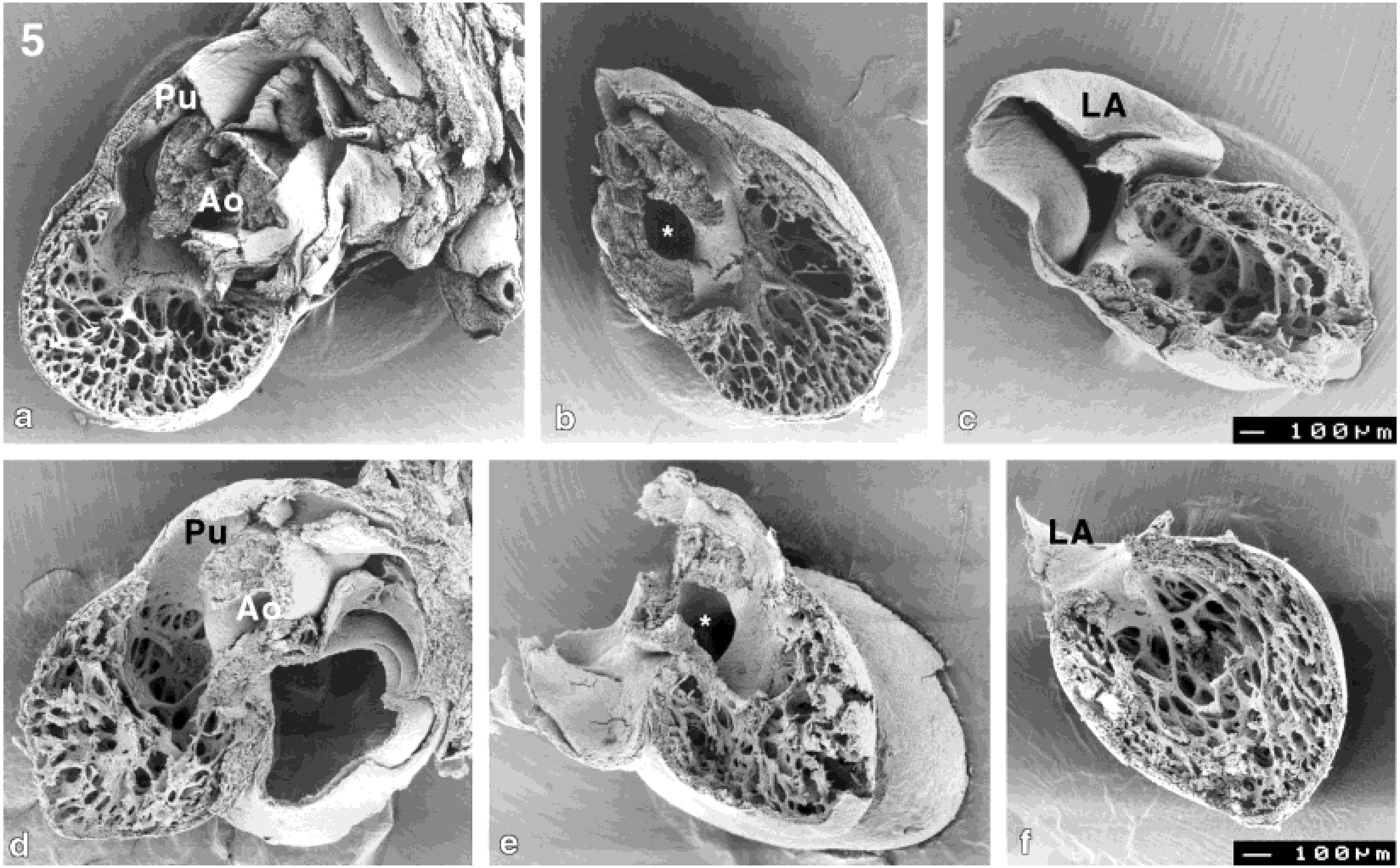
- **“strands” of axially arranged cardiac tissue**
- arise from the apex, and insert into the atrio-ventricular ring
- ventricle- and species-specific



- Emergence of trabeculation during the embryonic development enables the myocardium to increase its mass also in the absence of coronary circulation.

[Jacquier A, Thuny F *et al,* European Heart Journal 2010].

MYOCARDIAL MORPHOGENESIS



Sagittal dissection of trabeculated **chick** (a–c, 6th day/stage 29) and **human** (d–f, 41 days, Carnegie stage 18) hearts.

[Sedemera et al. The Anatomical Record 258:319–337 (2000)]

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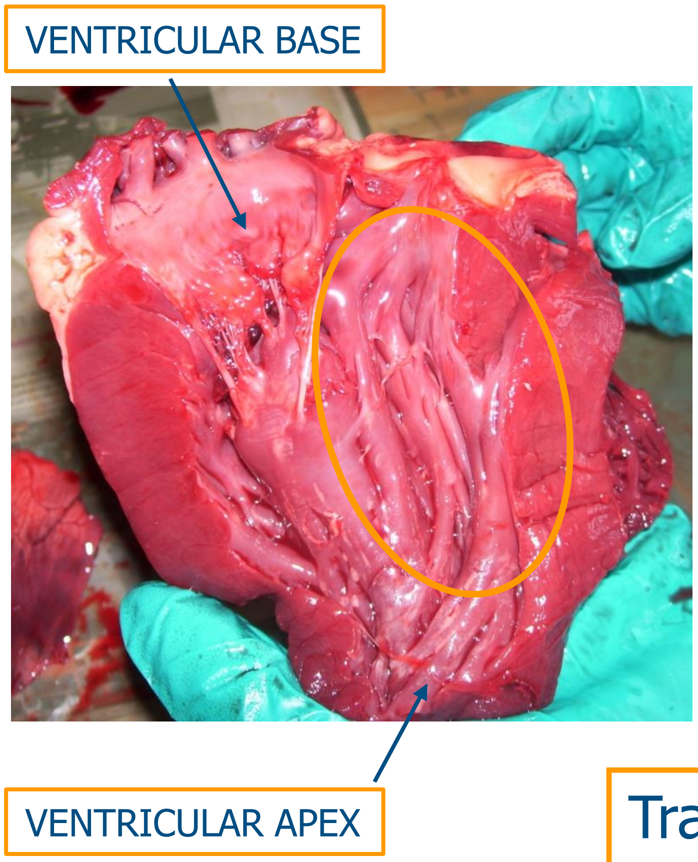

- Emergence of trabeculation during the embryonic development enables the myocardium to increase its mass also in the absence of coronary circulation.

- In subsequent development, there is a compaction of these structures, **but an inner layer of trabecular tissue still remains**.

Trabecular mass is the ~ **12%** - **17%** of ventricular mass in adult healthy subjects

[Jacquier A, Thuny F *et al,* European Heart Journal 2010].

CARDIAC TRABECULAE

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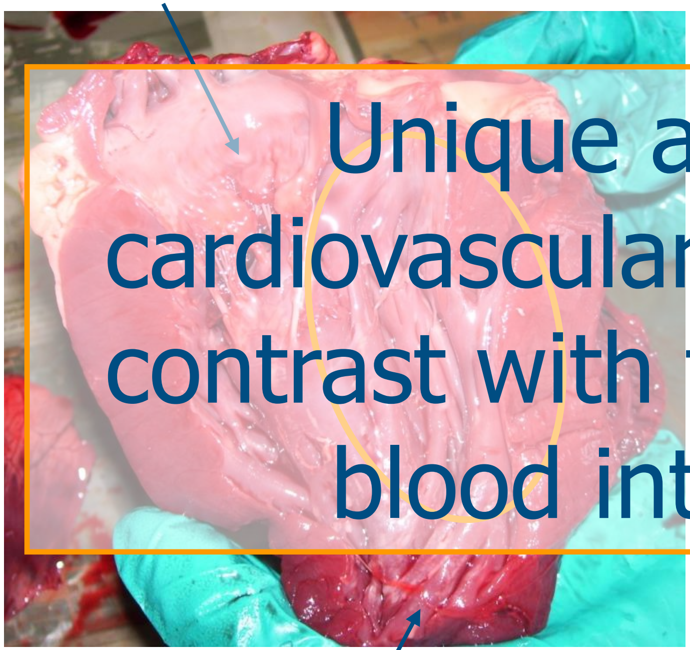
VENTRICULAR BASE



Unique architecture in the cardiovascular system, apparently in contrast with the typical structure of blood interacting surfaces

VENTRICULAR APEX

Trabecular mass is the ~ **12%** - **17%** of ventricular mass in adult healthy subjects

[Jacquier A, Thuny F *et al,* European Heart Journal 2010].

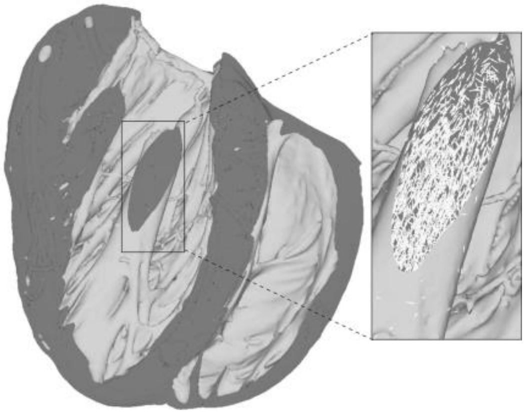
STATE OF ART

QUALITATIVE HYPOTESES ON TRABECULAE

- promote the loss of kinetic energy of blood during diastole,
- reduce the wrinkling of the sub-endocardial layer during systole, avoiding wall injuries,
- reduce the flow turbulence during the systolic phase,
- help the closure of the atrio-ventricular valves.

QUANTITATIVE STUDIES

- fluid dynamic modelling: the blood "entrapped" into the inter-trabecular spaces is expelled by the contraction of the trabeculae, avoiding stagnation,
- electro-mechanical modelling: in simulation of cardiac arrhythmias, the excitation wavefront is not significantly affected by the trabeculated layer.



[Bishop JB, Planck G *et al*, The Journal of Physiology 2012]

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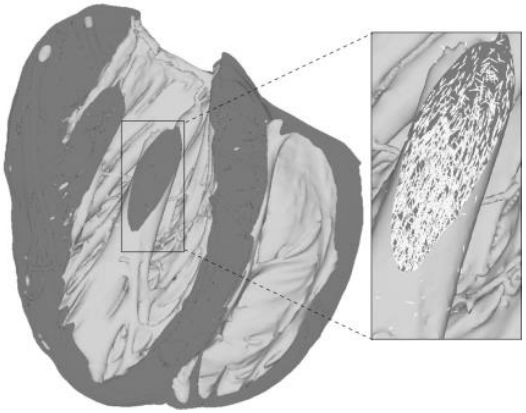
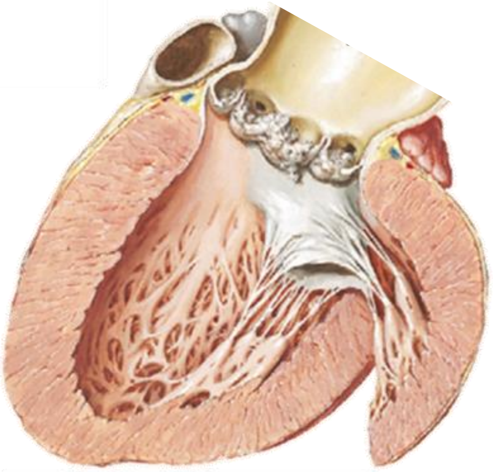


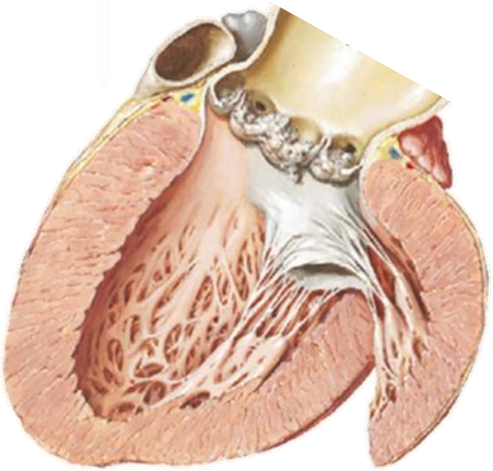
- **NO SPECIFIC MECHANICAL STUDIES**

[Bishop JB, Planck G *et al*, The Journal of Physiology 2012]

WHY DO TRABECULAE EXIST?



WHY DO TRABECULAE EXIST?



Study the influence of cardiac trabeculae on ventricular mechanics through the comparison of a trabeculated and a non-trabeculated ventricle (smooth ventricle)

METHODS

- Finite element structural models (Abaqus®) of the left ventricle keeping constant
  - **total ventricular muscular mass**
  - **intra-ventricular volume**

both **in the presence (trabeculated model) and the absence of trabecular mass (smooth model)**

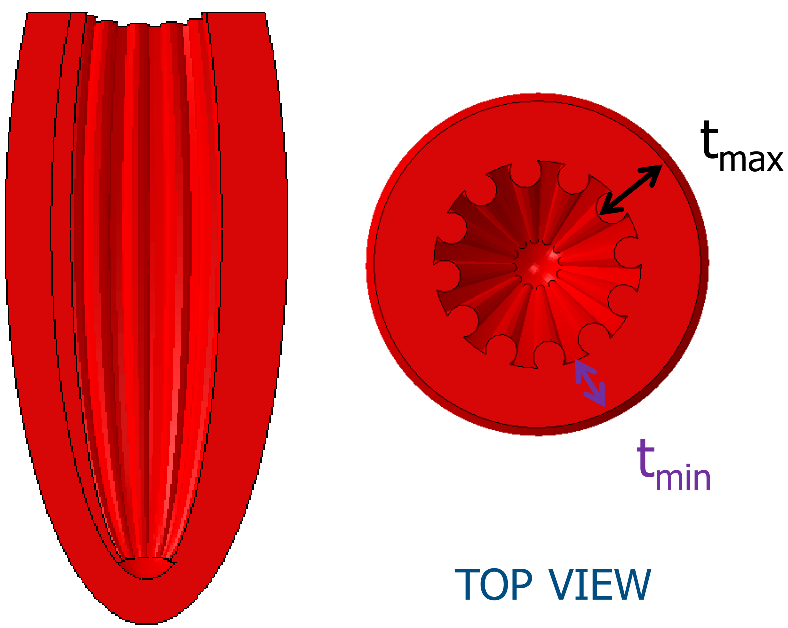
- Influence of some parameters characterising the trabecular layer
  - **trabecular mass**
  - **trabeculae diameter**
  - **trabecular orientation**

METHODS: Geometrical models

- Left ventricle simplified as a truncated ellipsoid in the reference, stress free configuration. **Intra-ventricular volume: 43 ml**

- **TRABECULATED MODEL:** 15% of the compact layer converted into trabeculae (physiological average value)

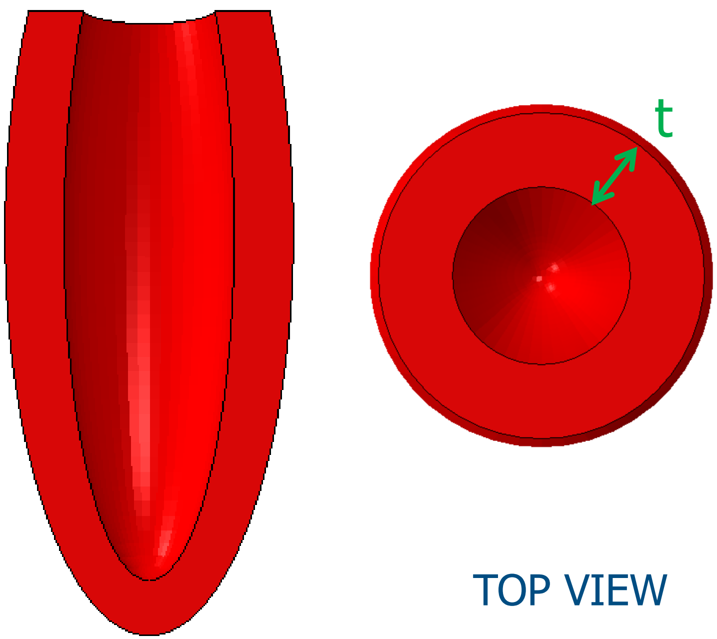
- **SMOOTH MODEL:** NO trabeculae



AXIAL SECTION

TOP VIEW

t_{min} = 7.2 mm; t_{max} =10.3 mm; D_t=4mm



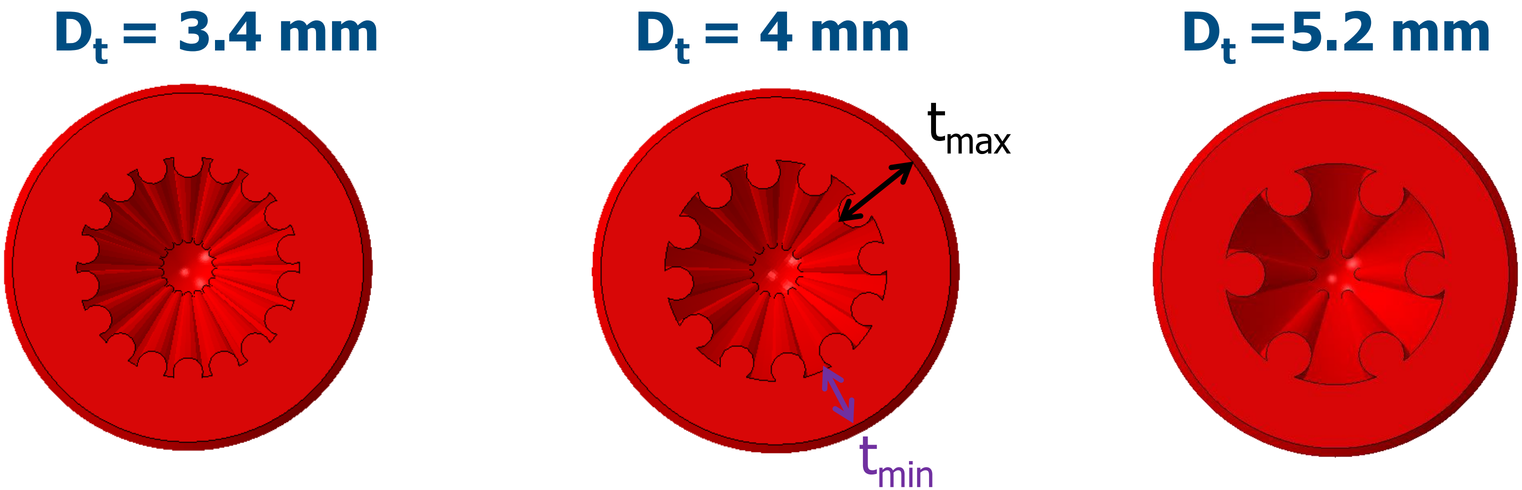
AXIAL SECTION

TOP VIEW

t = 9 mm

METHODS: Geometrical models

- Different **trabeculated layer diameter (D_t)** (Constant thickness of the compact layer t_{min})
  - Trabeculated layer mass = 15%

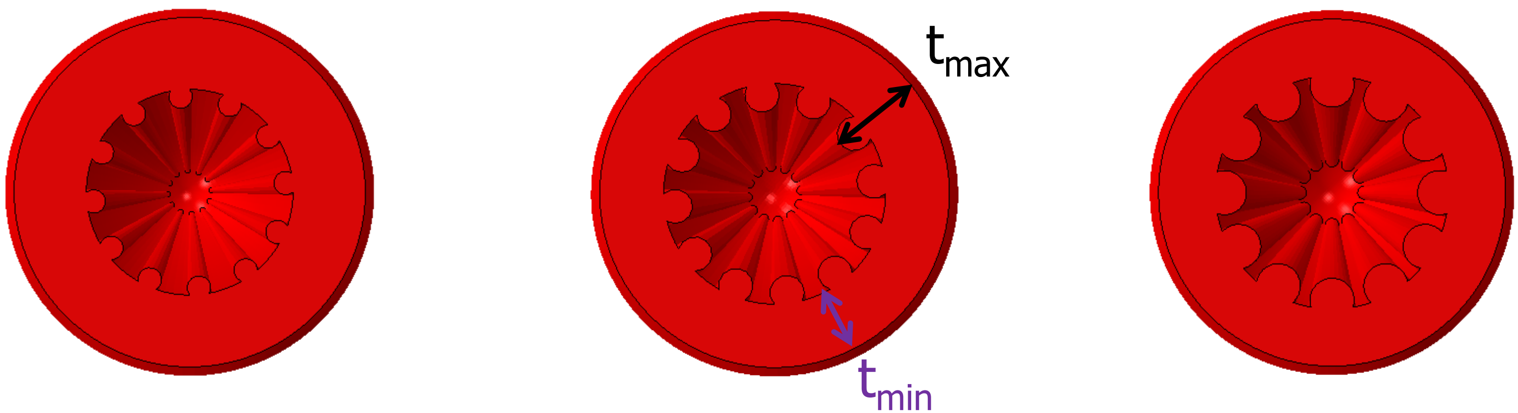


	D_t =5.2 mm	D_t =4 mm	D_t =3.4 mm
t_{min} [mm]	7.25	7.25	7.25
t_{max} [mm]	9.6	10.45	11.85

METHODS: Geometrical models

- Different **trabeculated layer mass (M_t)**

M_t = 7% | M_t = 15% | M_t = 22%



	Smooth	M_t =7%	M_t =15%	M_t =22%
t_{min} [mm]	9	8.2	7.2	6.5
t_{max} [mm]	9	10.3	10.4	10.1

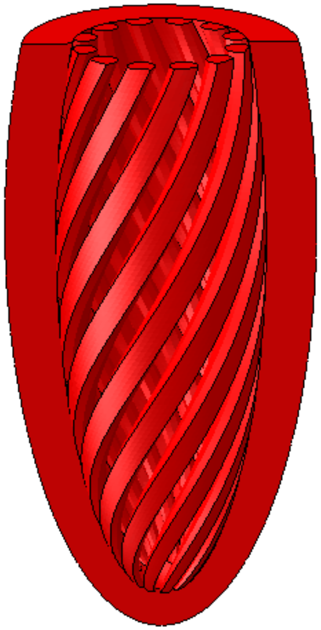
METHODS: Geometrical models

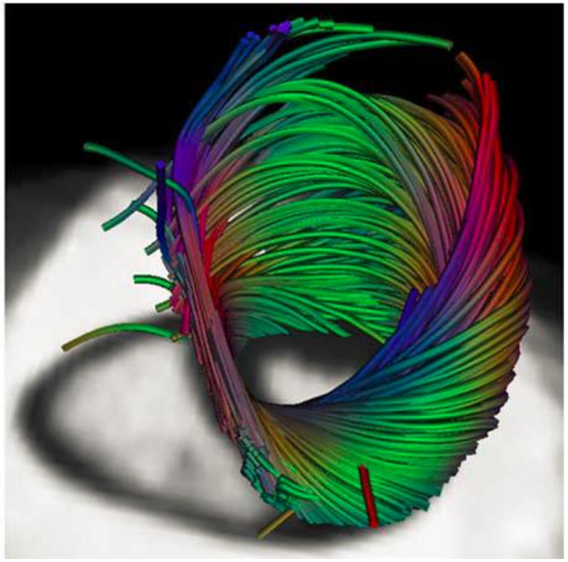
- Different **orientation** of the trabecular structures

  ➡ Trabeculae oriented at +60° with respect to the circumferential direction, as suggested by experimental findings

  - Trabeculated mass = 15%
  - Trabeculae diameter = 4 mm

Ventricular cavity reconstruction obtained by laser technique (Mechanical Engineering Depart. and LaBS, Politecnico di Milano)





Spiral fibres architecture in the left human ventricle [Lombaert et al. IEEE Transactions on Medical Imaging 2012]

METHODS: Cardiac tissue modeling

- MATERIAL CONSTITUTIVE LAW
- MUSCLE FIBER DISTRIBUTION

METHODS: Cardiac tissue modeling

MATERIAL CONSTITUTIVE LAW: passive behaviour

MUSCLE FIBER DISTRIBUTION

Strain energy potential [Holzapfel et al.]:

$$\Psi = \underbrace{C_{10}(\bar{I}_1 - 3)}_{\text{MATRIX}} + \underbrace{\frac{k_1}{2k_2}(\exp(k_2(\bar{I}_4 - 1)^2) - 1)}_{\text{FIBRES}}$$

$$\overline{I_1} = tr(\overline{\boldsymbol{C}}) \qquad \overline{I_4} = \boldsymbol{A}_\alpha \cdot \overline{\boldsymbol{C}} \cdot \boldsymbol{A}_\alpha$$

- Incompressible material
- One family of perfectly aligned fibers
- $\boldsymbol{A}_\alpha$ is a unit vector which defines the fiber direction

METHODS: Cardiac tissue modeling

- **MATERIAL CONSTITUTIVE LAW: passive behaviour**
- **MUSCLE FIBER DISTRIBUTION**

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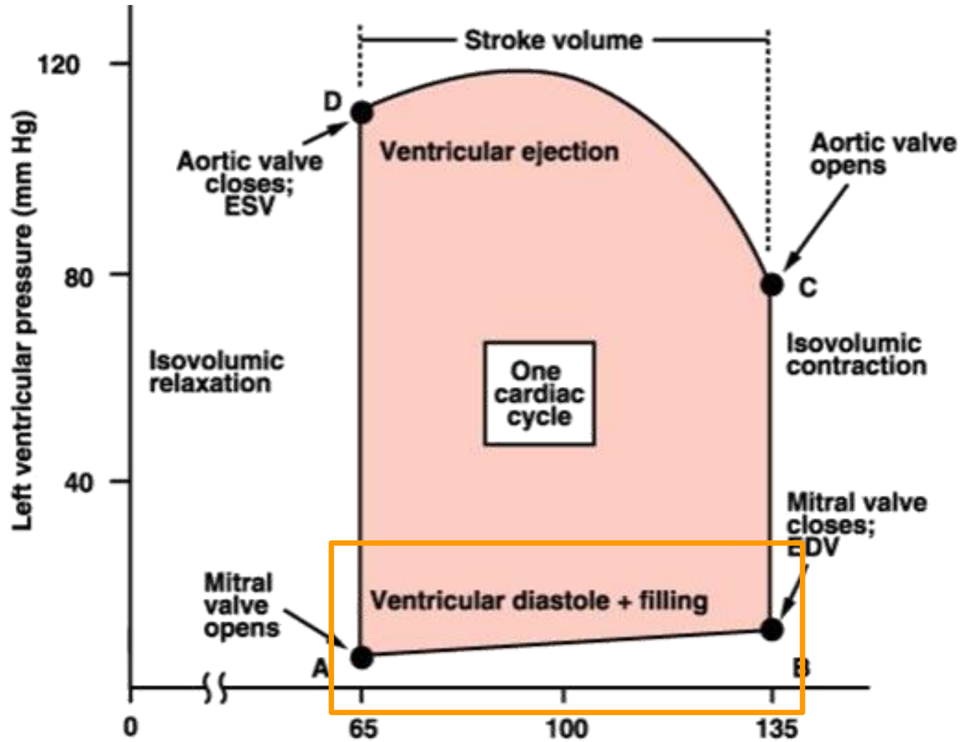
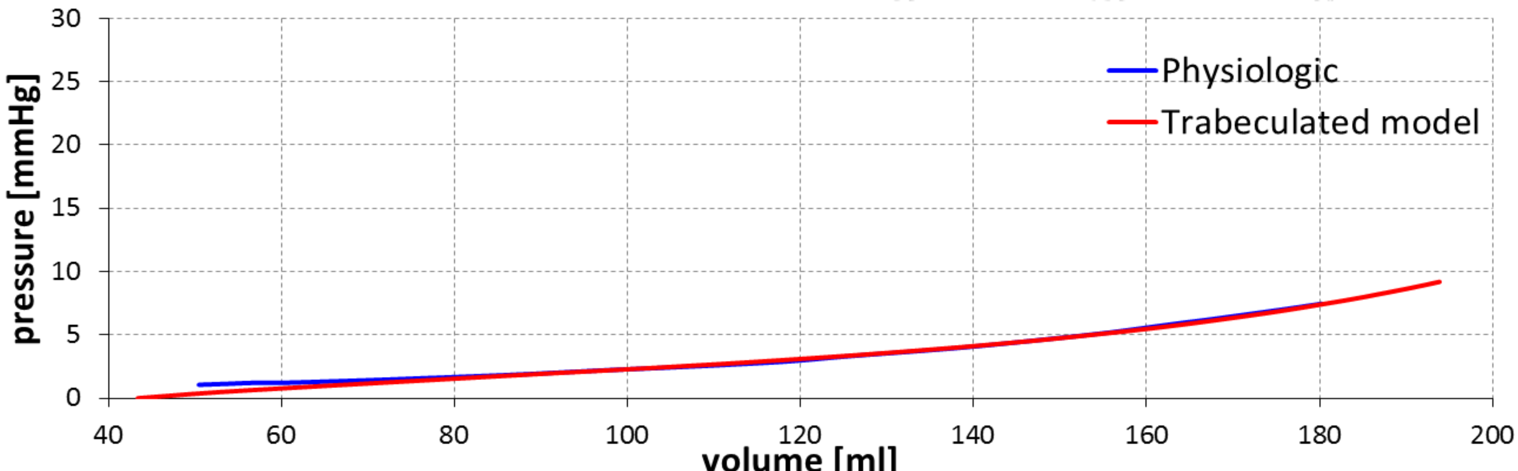
- PARAMETERS ESTIMATION (C_{10}, k_1, k_2) by fitting a physiologic pressure-volume relationship during ventricular filling of the trabeculated model

METHODS: Cardiac tissue modeling

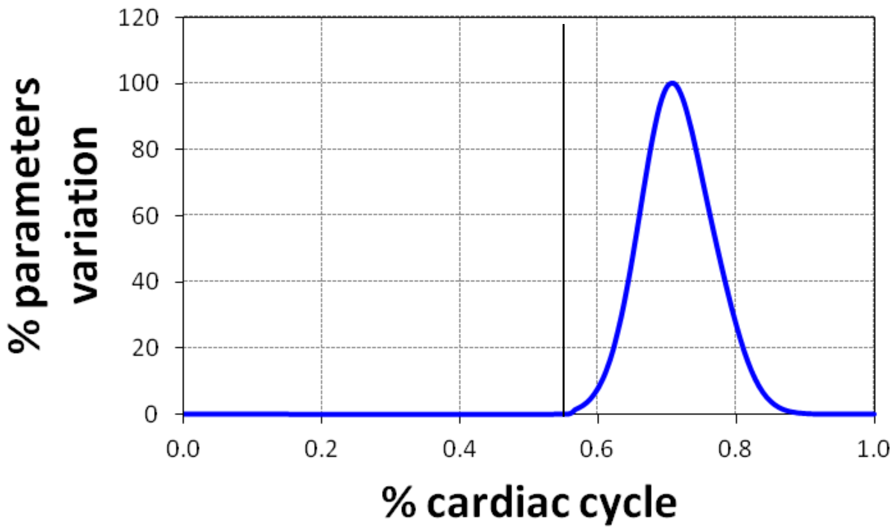
- **PARAMETERS ESTIMATION** (C_{10}, k_1, k_2) by fitting a physiologic pressure-volume relationship during ventricular filling of the trabeculated model





- **MATERIAL CONSTITUTIVE LAW: active behaviour**
- **MUSCLE FIBER DISTRIBUTION**

- Myocytes contraction obtained by changing material parameters C_{10}, k_1, k_2 during the cardiac systole



Parameter	Diastolic value	Systolic maximum value
C_{10}	0.2 kPa	6 kPa
k_1	1 kPa	150 kPa
k_2	2	20

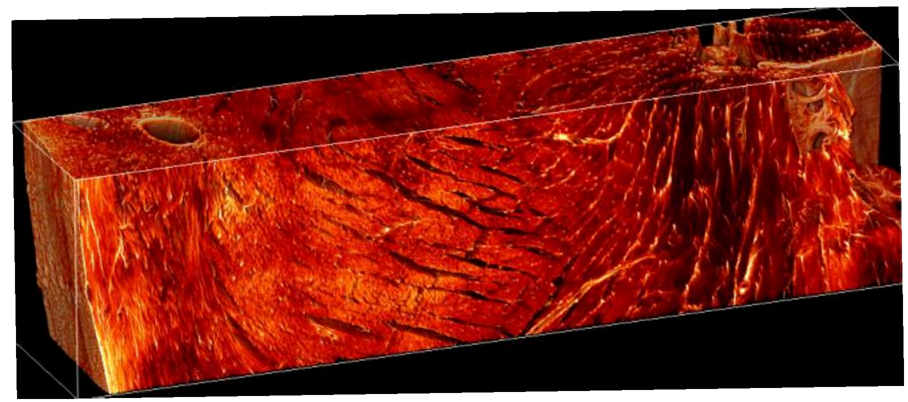
- force generated by the muscle fiber secondary to an intracellular calcium variation

METHODS: Cardiac tissue modeling

MATERIAL CONSTITUTIVE LAW

MUSCLE FIBER DISTRIBUTION

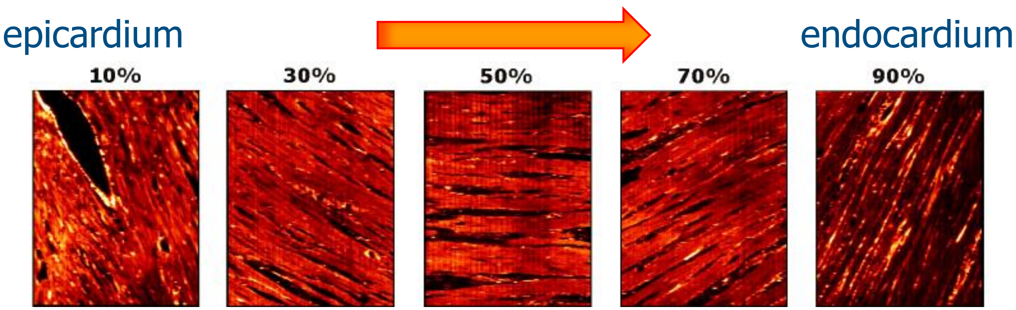
Ventricular wall = series of discrete layers of parallel myocytes



- The orientation of muscle fibers changes across the compact ventricular wall

  (- 80° at the epicardium;
  0° at the midwall;
  +80° at the endocardium)

- Fibers are arranged **axially in the trabeculae**



[Sands GB, Dane A et al. *Microscopy research and technique* 2005]

METHODS: Cardiac tissue modeling

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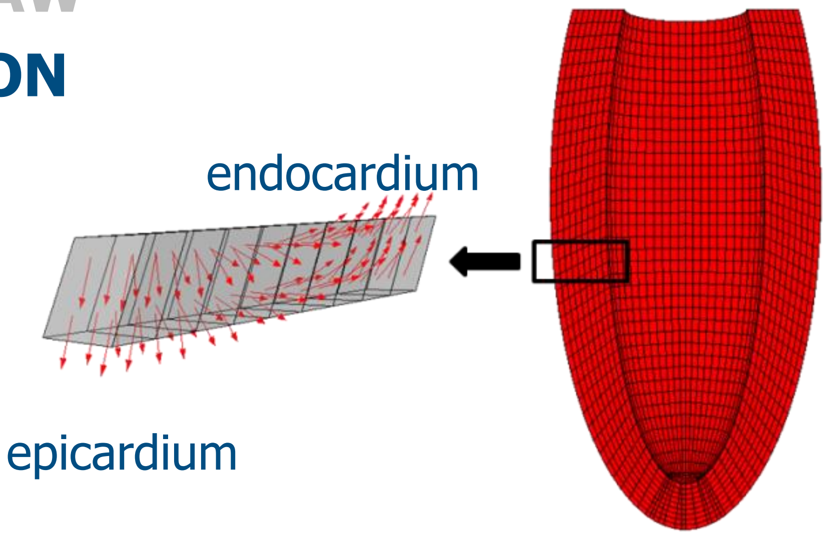
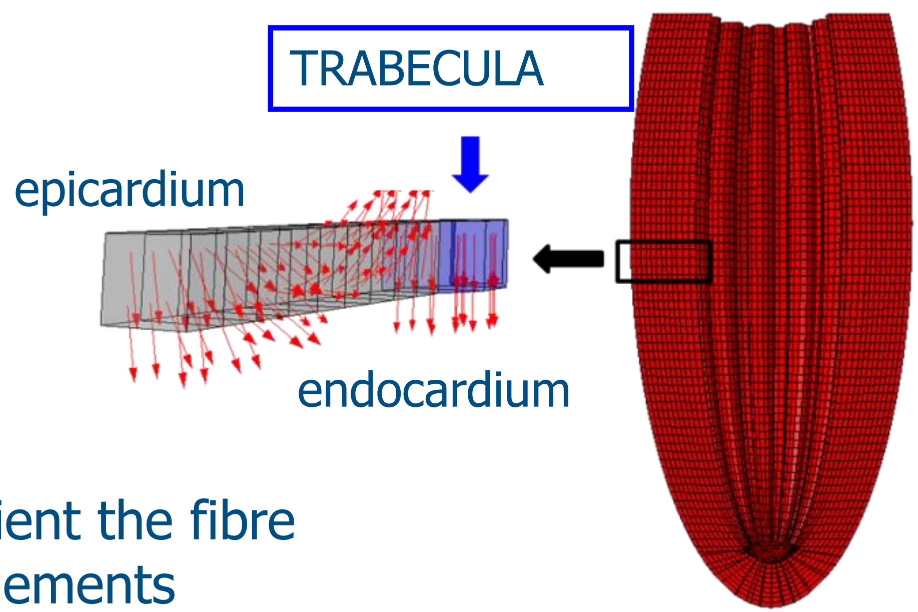
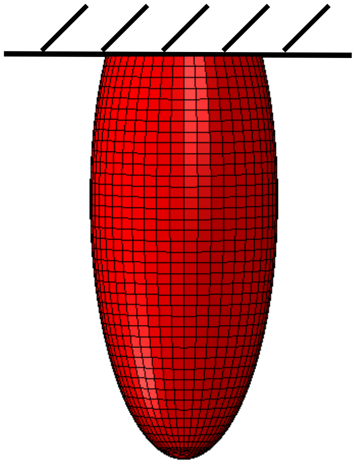
  Software routines to orient the fibre direction in the mesh elements





METHODS: Boundary conditions

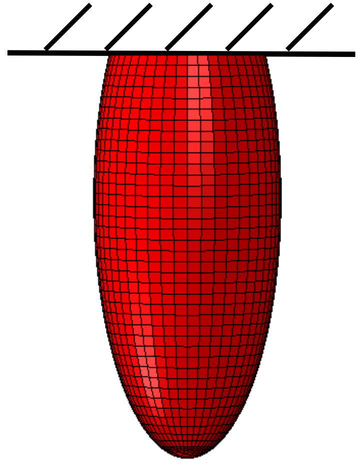
KINEMATIC CONSTRAINTS



Displacements of the ventricular base were prevented.

METHODS: Boundary conditions

KINEMATIC CONSTRAINTS



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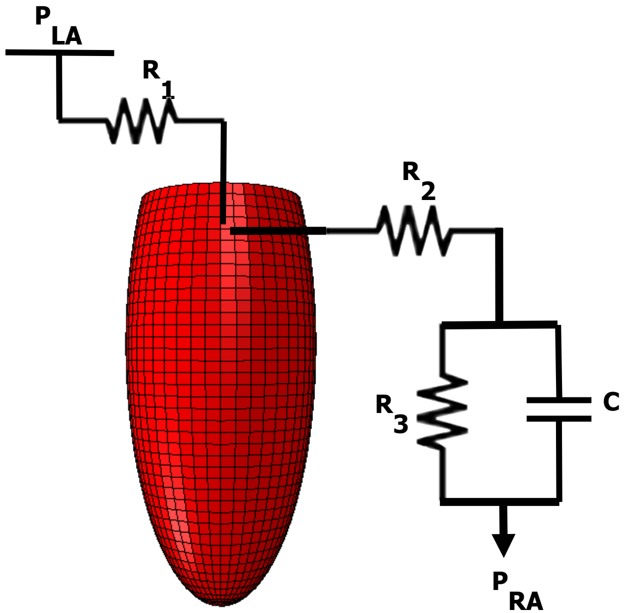
PRELOAD AND AFTERLOAD CIRCUITS



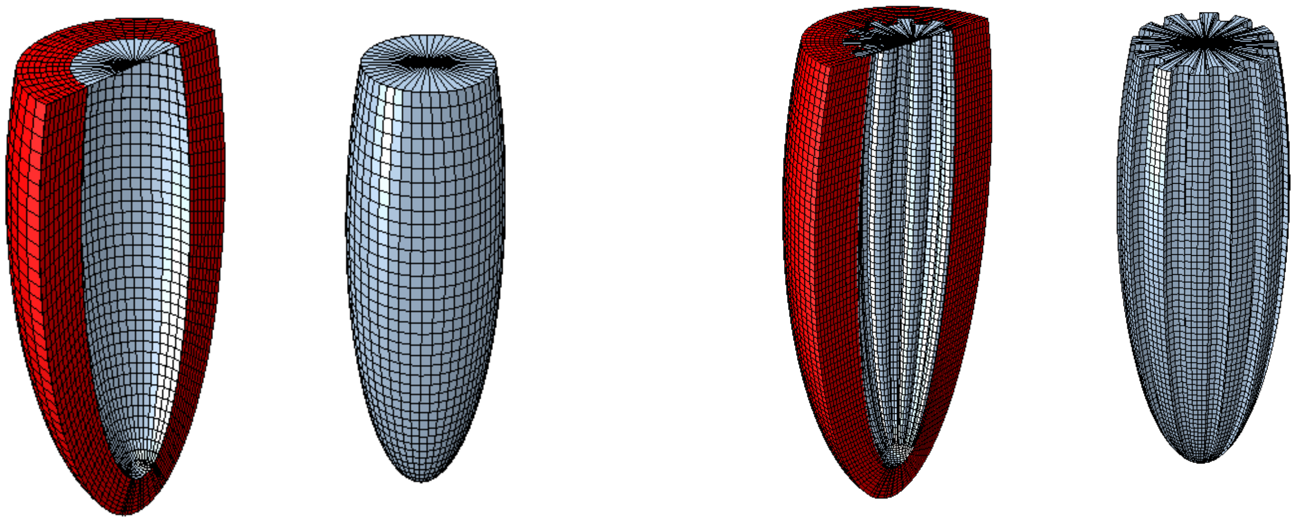
Physiological atrial pressure was set during the diastole to simulate the ventricular filling (preload).

A RCR model was coupled to the ventricle to simulate the systemic circulation (afterload).

METHODS: Boundary conditions

PRELOAD AND AFTERLOAD CIRCUITS

- Hydrostatic fluid elements
- Surface elements which share the nodes with the structural elements, if present
- Closed cavities



- coupling between the deformation of the fluid-filled cavity and the pressure exerted by the fluid (uniform pressure, no gradient)
- simulation of blood inflow and outflow

METHODS: Other simulation conditions

- **Quasi-static** approach
- A minimum of **five cycles** were simulated for each model to reach the steady state of the system
- Standard heart rate = **75 bpm**

↓

Other heart rates were simulated by changing the diastolic (T_D) and systolic duration (T_s)

$$T_S = \sqrt{kT}$$

$$T_D = T - T_S$$

k = 0.096 s

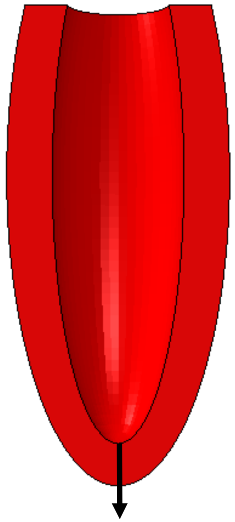
[Katz LN and Feil HS, 1932]

Simulated heart rates = 10, 30, 60, 75, 110, 180 bpm

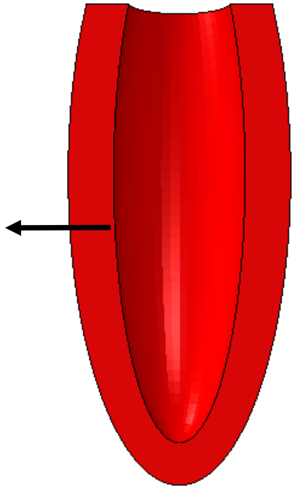
RESULTS: Trabeculated VS Smooth Ventricle

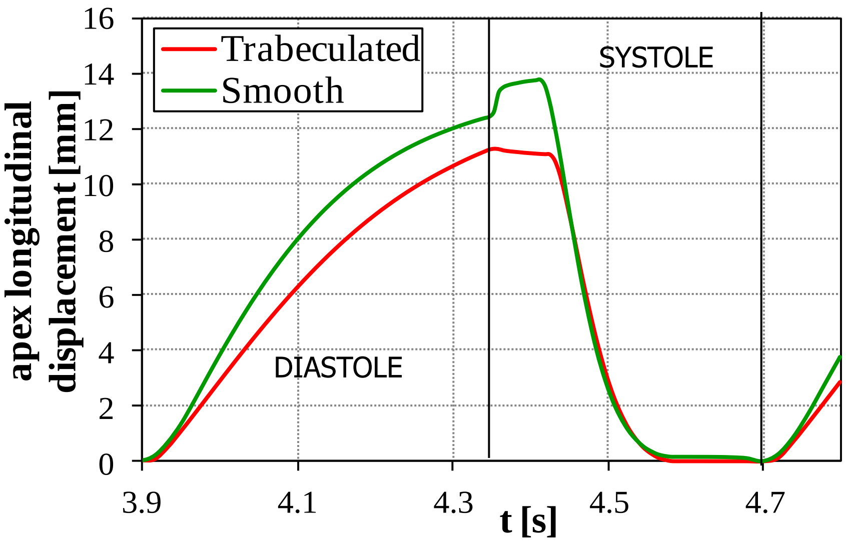
Kinematic behaviour

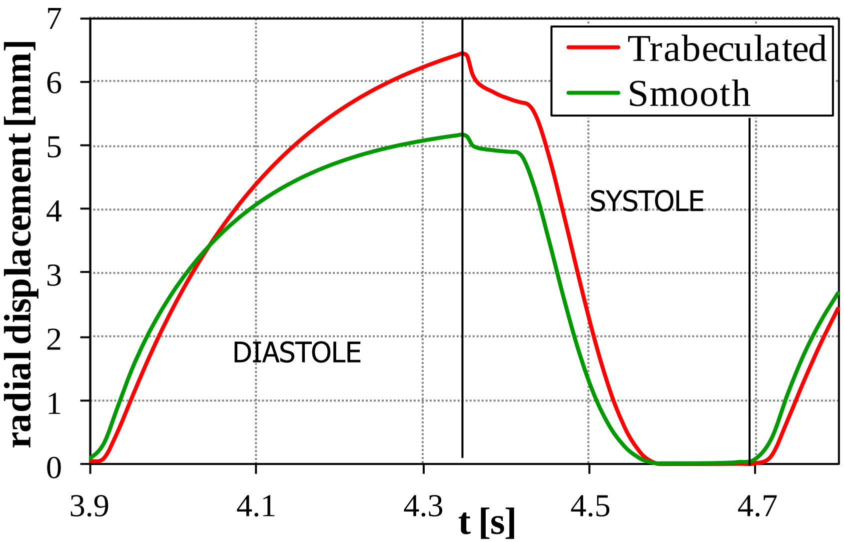
Apex longitudinal displacement



Mid-axis radial displacement

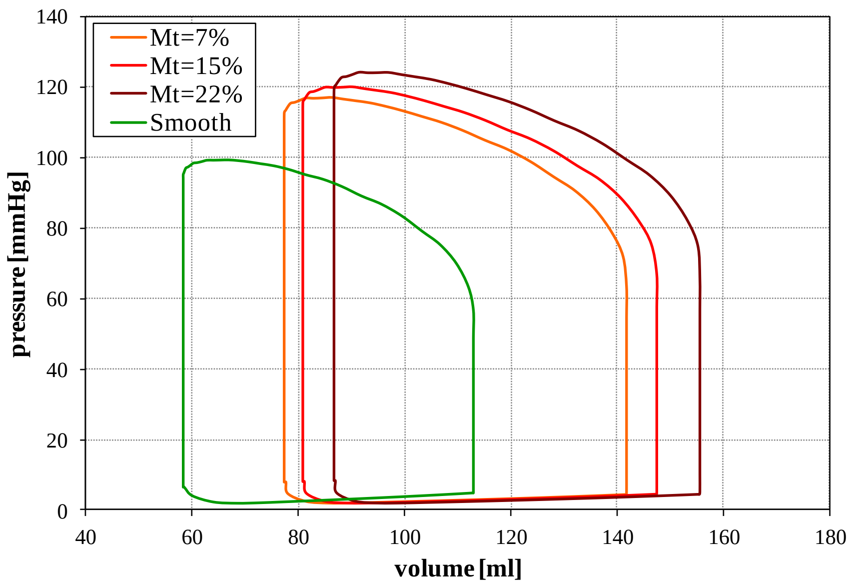


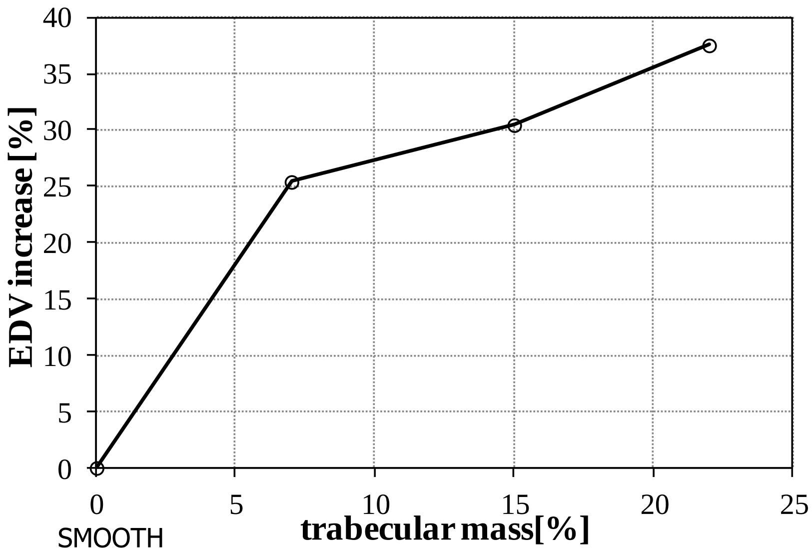


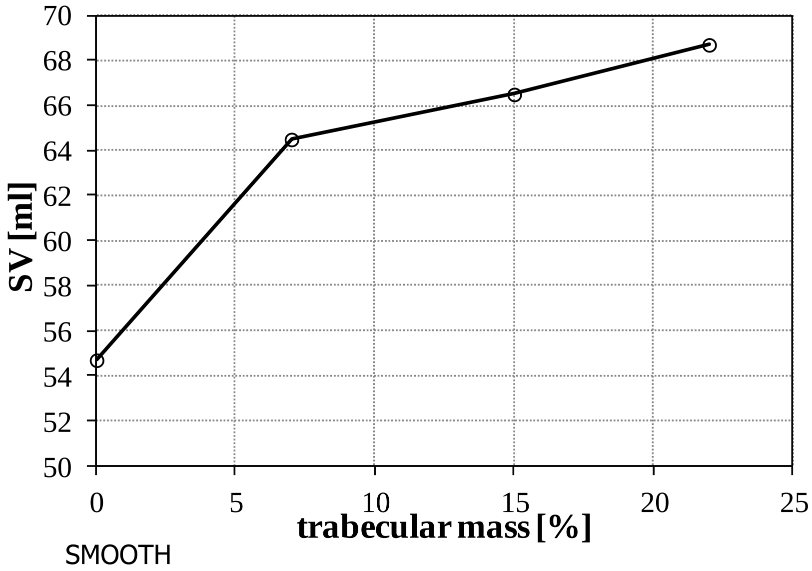


RESULTS: Influence of trabeculated mass

PV loop



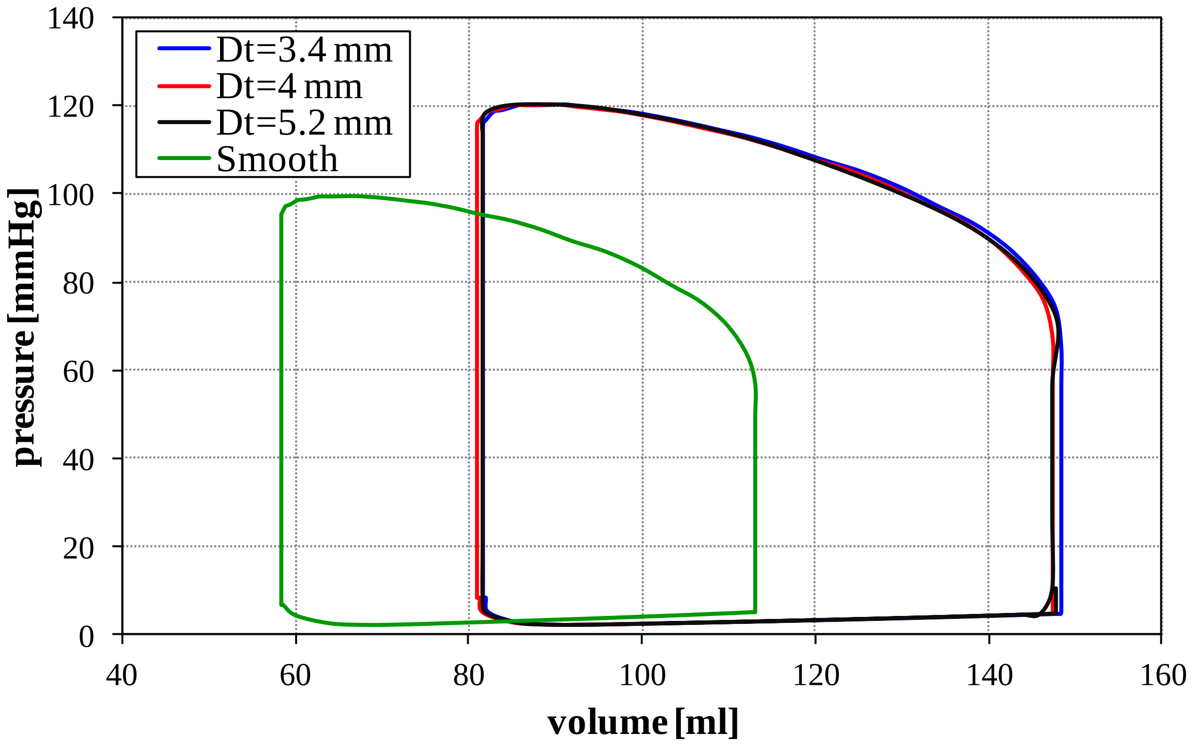




- A larger trabecular mass is responsible for a **non-linear increase of the EDV** and, consequently, of the SV

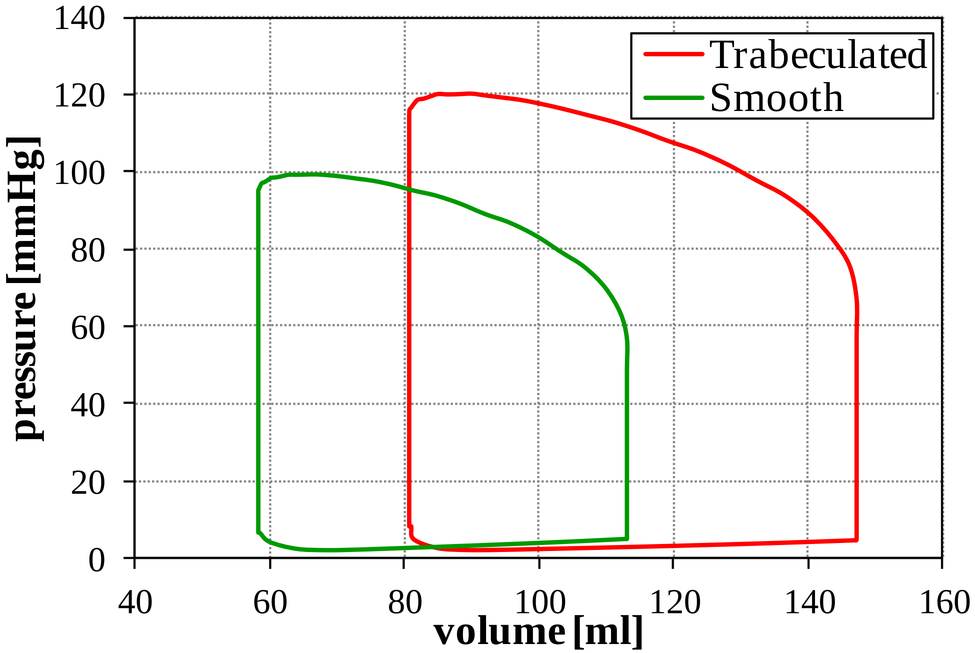
RESULTS: Influence of trabeculae diameter

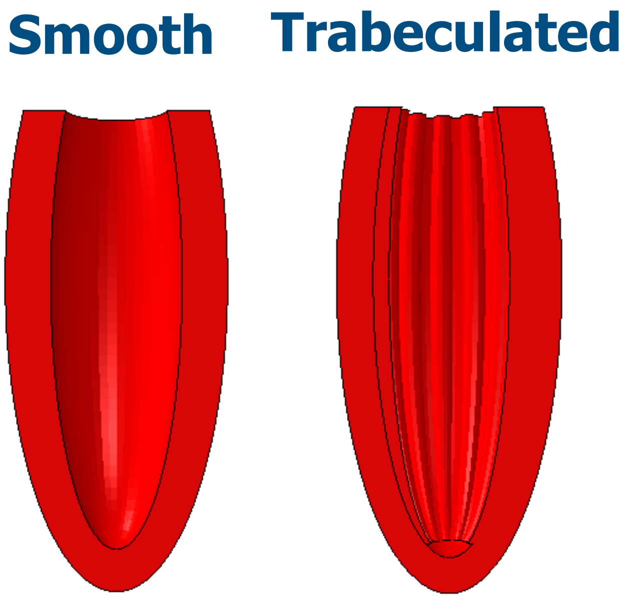
PV loop



RESULTS: Trabeculated VS Smooth Ventricle

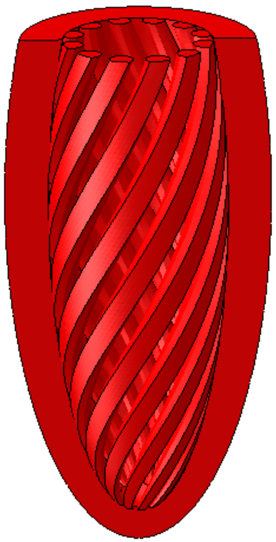
PV loop

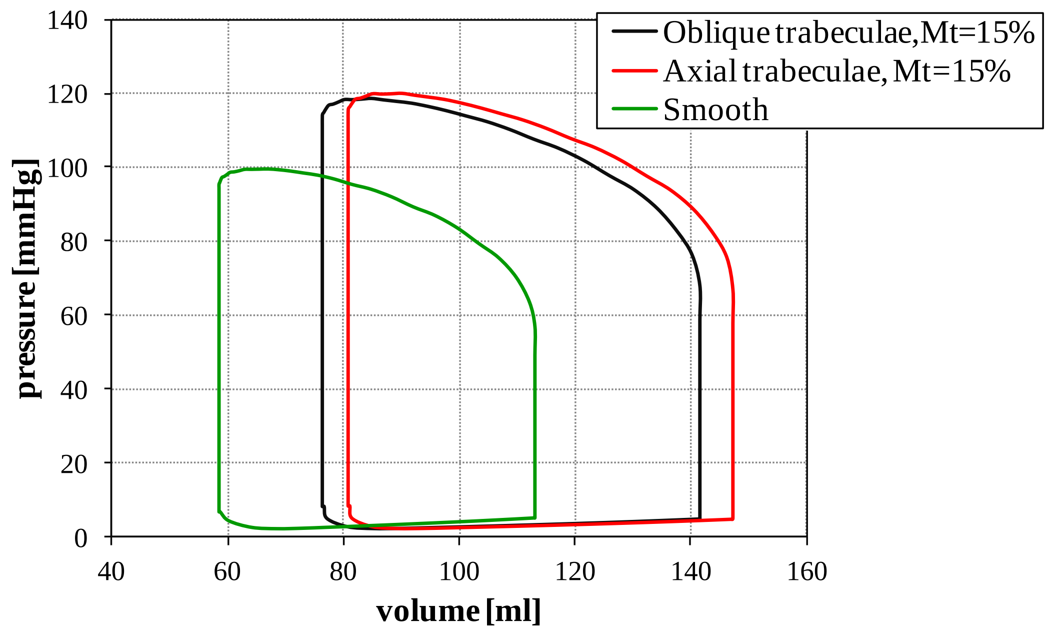


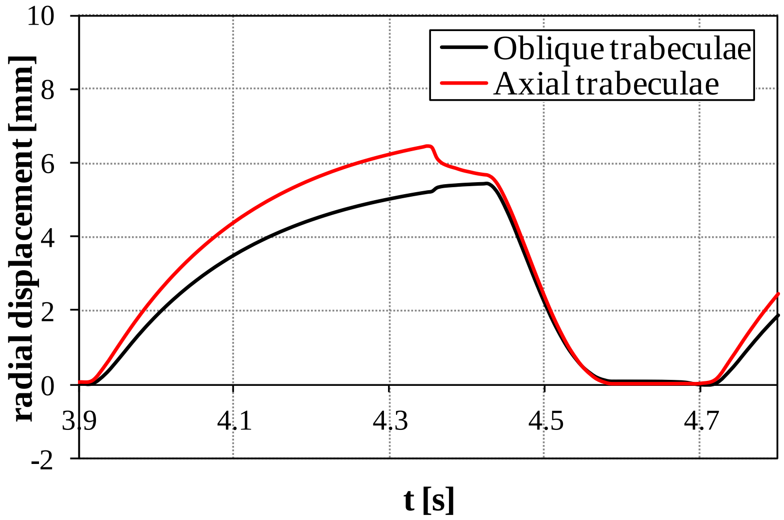


RESULTS: Influence of trabeculae orientation

PV loop

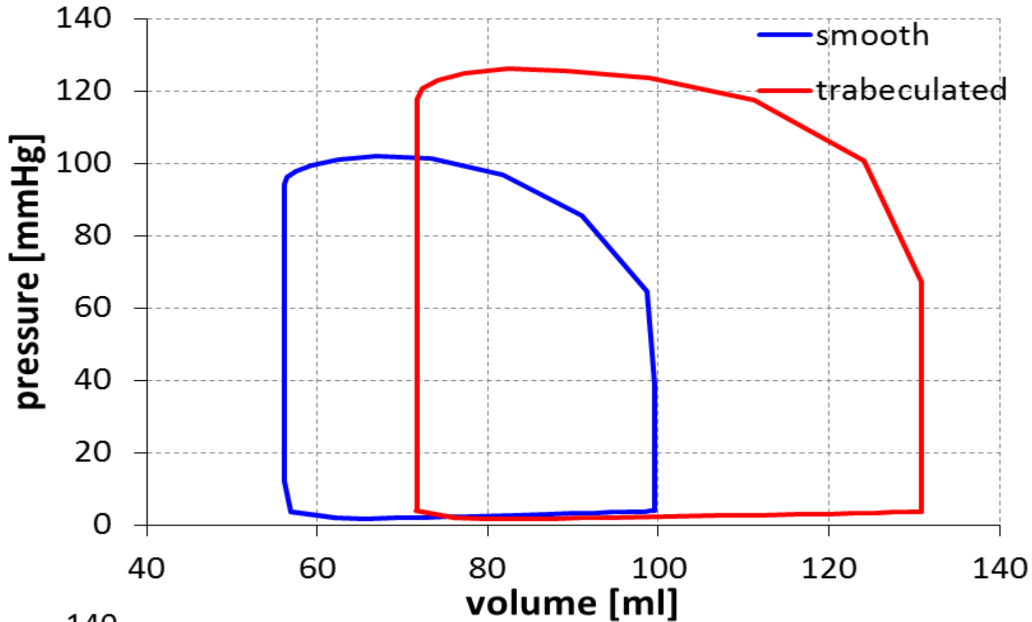






- The trabecular orientation contributes to a decrease of the EDV, due to a smaller radial displacement

RESULTS: Trabeculated vs Smooth Ventricle

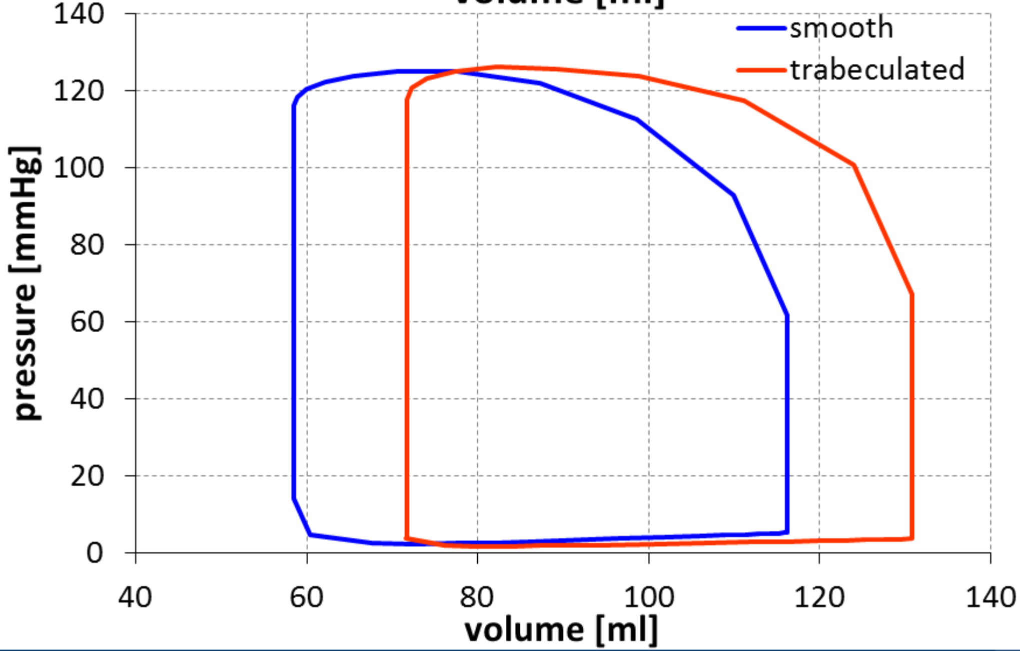


Atrial pressure = 4 mmHg

Different Stroke Volume

Smooth model = 43 ml

Trabeculated model = 60 ml



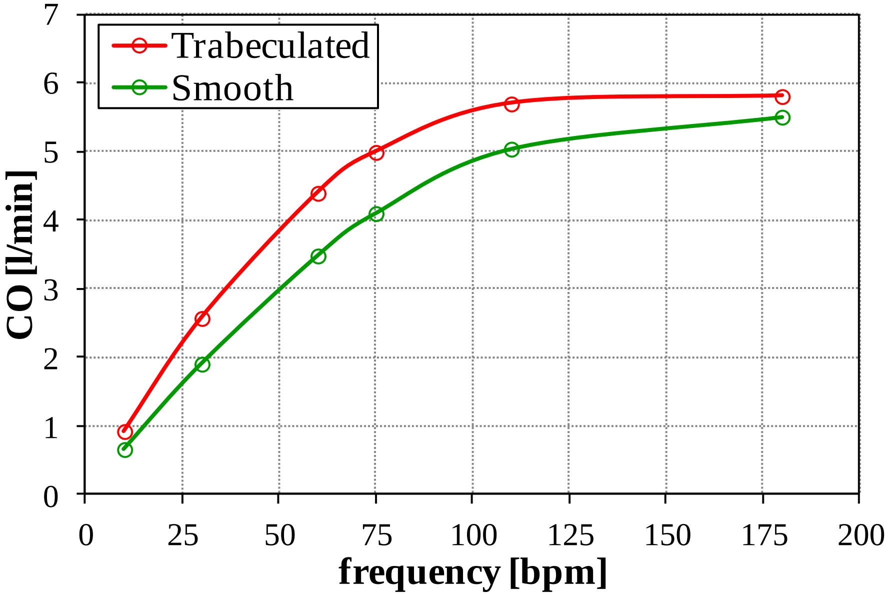
Stroke volume = 60 ml

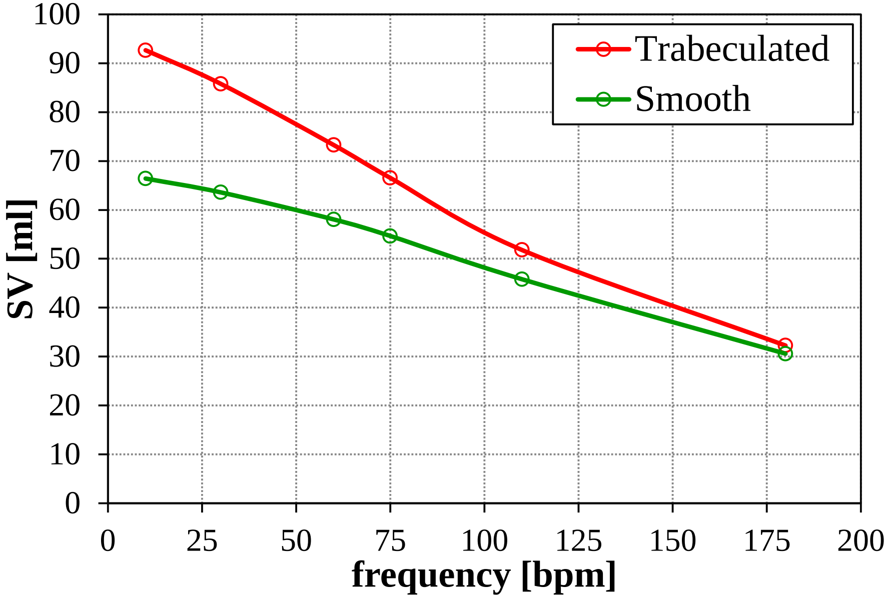
Different Atrial pressure

- Smooth model = 5.1 mmHg
- Trabeculated model = 4 mmHg

RESULTS: Influence on heart physiology

Effect of cardiac frequency





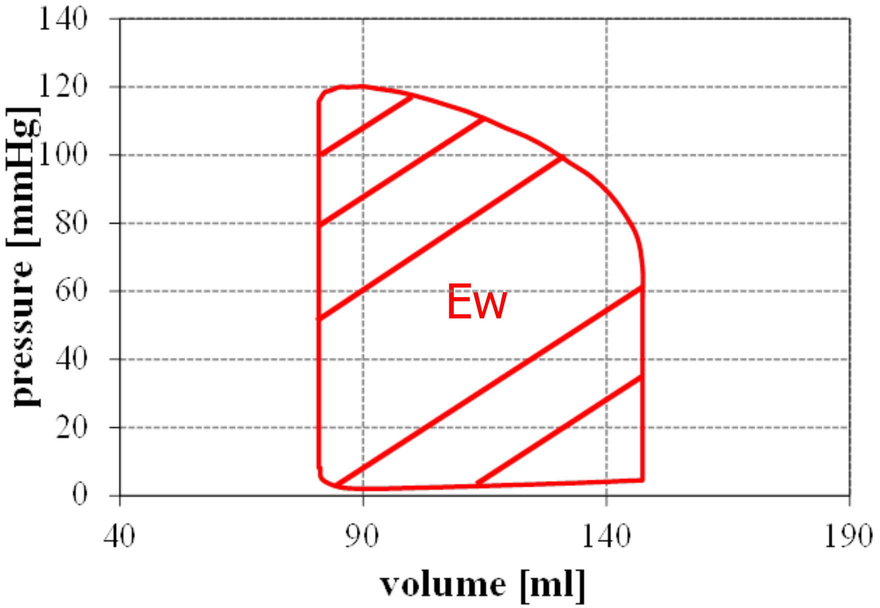
CO = Heart rate* SV

- The trabeculated model generates larger CO at each heart rate, than the smooth model
- The SV is higher too, especially at low heart rates.

Ventricular efficiency

$$\eta = \frac{E_w}{E_{tot}} = \frac{\oint p dV}{E_{tot}}$$

Physiological value $\eta = 10\%\text{-}20\%$

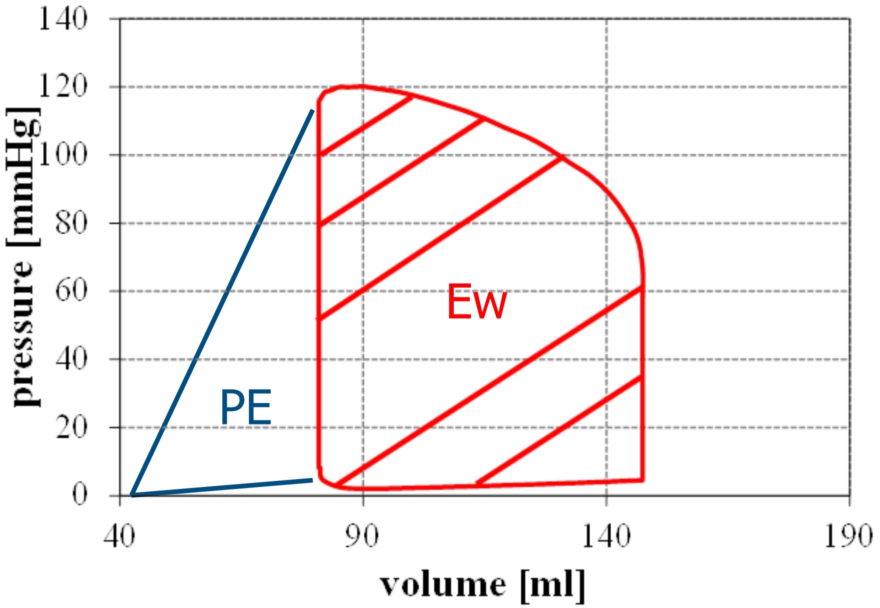


RESULTS: Influence on heart physiology

Ventricular efficiency

$$\eta = \frac{E_w}{E_{tot}} = \frac{\oint p dV}{\boxed{MV_{O2}}} = \frac{\oint p dV}{\oint p dV + TTI}$$

Different literature methods for the oxygen consumption estimation

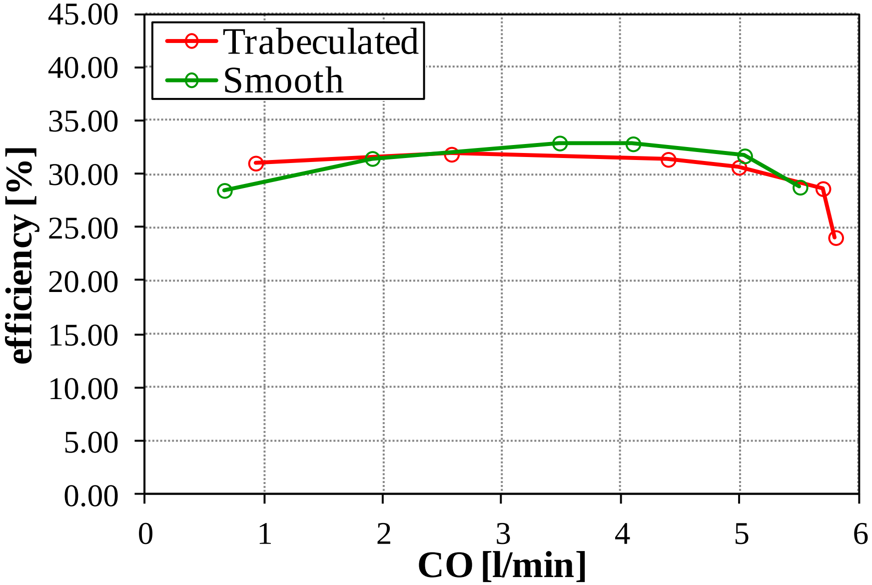


1. **Experimental** linear relationship between MV_{O2} and PVA (PVA=Ew+PE) [Loiselle DS, Crampin EJ et al. *Progress in biophysics and molecular biology* 2008]
2. **Experimental** piecewise linear relation between MV_{O2} and cardiac frequency [Nelson RR, Gobel FL et al., *Circulation.* 1974]
3. **Estimation** of the tension-time index (TTI) by the ventricular fibre stress [A.C. *Physiology and biophisics of the circulation* 1972]

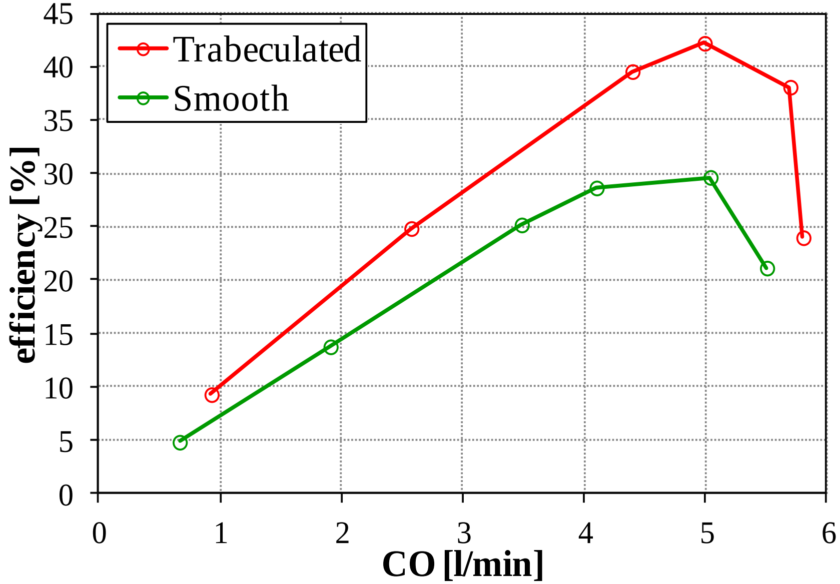
RESULTS: Influence on heart physiology

Ventricular efficiency (Physiological range η = 10%-20%)

1. MV_{O2}(PVA)



2. MV_{O2}(heart rate)



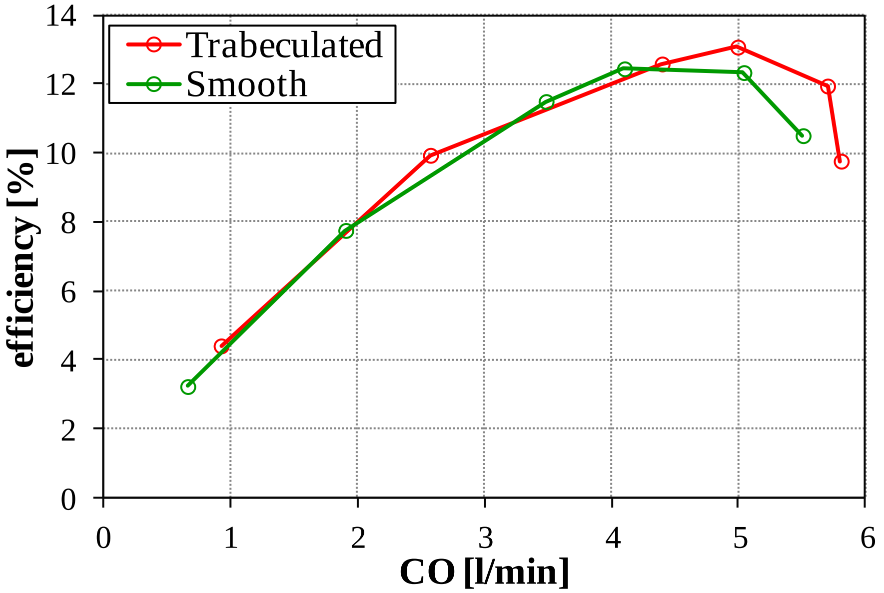
- Predicted efficiency above the physiological range
- No efficiency variation with CO not in agreement with physiology
- No significant differences between models

- Predicted efficiency above the physiological range
- Efficiency-CO relationship in good agreement with the physiological one
- The trabeculated model shows a remarkable higher efficiency

RESULTS: Influence on heart physiology

- **Ventricular efficiency** (Physiological range $\eta = 10\%\text{-}20\%$)

3. $MV_{O2}(TTI)$



$$TTI = a \int_{t_s} T dt$$

$$T = \int_V \sigma_f dV$$

$$T = fibre\ tension$$

$$t_s = systolic\ period$$

$$a = 9\ [1/s]$$

- Realistic efficiency values
- Efficiency-CO relationship in good agreement with the physiologic one
- No significant differences between models

CONCLUSIONS

The presence of the cardiac trabeculae significantly influences the mechanical behaviour of the left ventricle

- **Higher ventricular compliance in the presence of trabeculae** → **Enhanced ventricular filling**; **Higher stroke volume**; **Higher CO at the same heart rate**
- **Trabeculae diameter** → **Influences the wall stress distribution**
- **Trabecular mass** → **non-linear increase of the EDV and of the SV against the trabecular mass**
- **Trabeculae orientation** → **The ventricular compliance decreases if the trabeculae are not axially oriented**
- **Efficiency?**

Thank you for your attention

This work was performed with the help of Marta Serrani PhD and Massimiliano Mariani