Evaluation of the principal strain lines for assessment of the Left Ventricular Function

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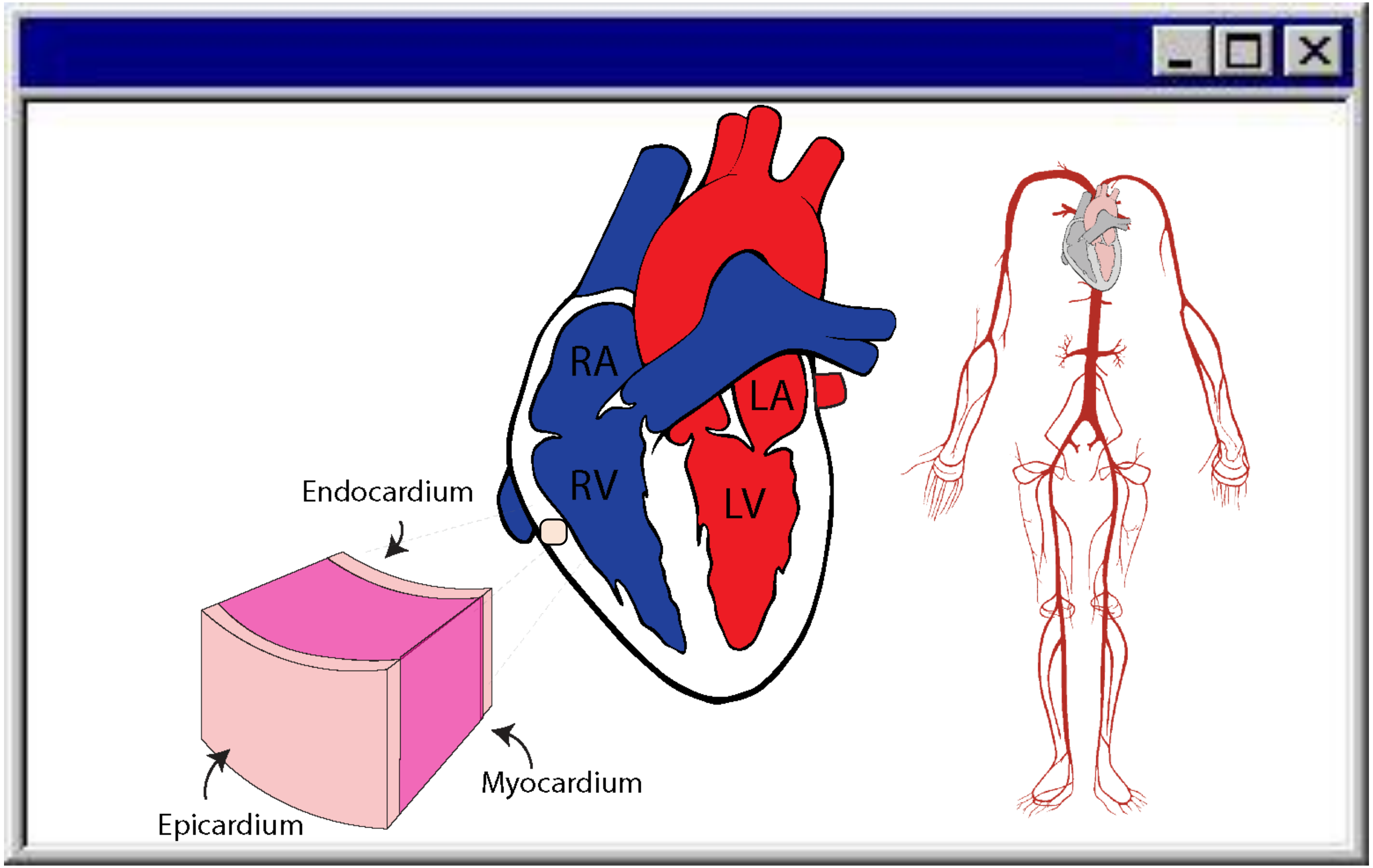
The left ventricle (LV) is the thickest of the heart's chambers and is responsible for pumping oxygenated blood to tissues all over the body



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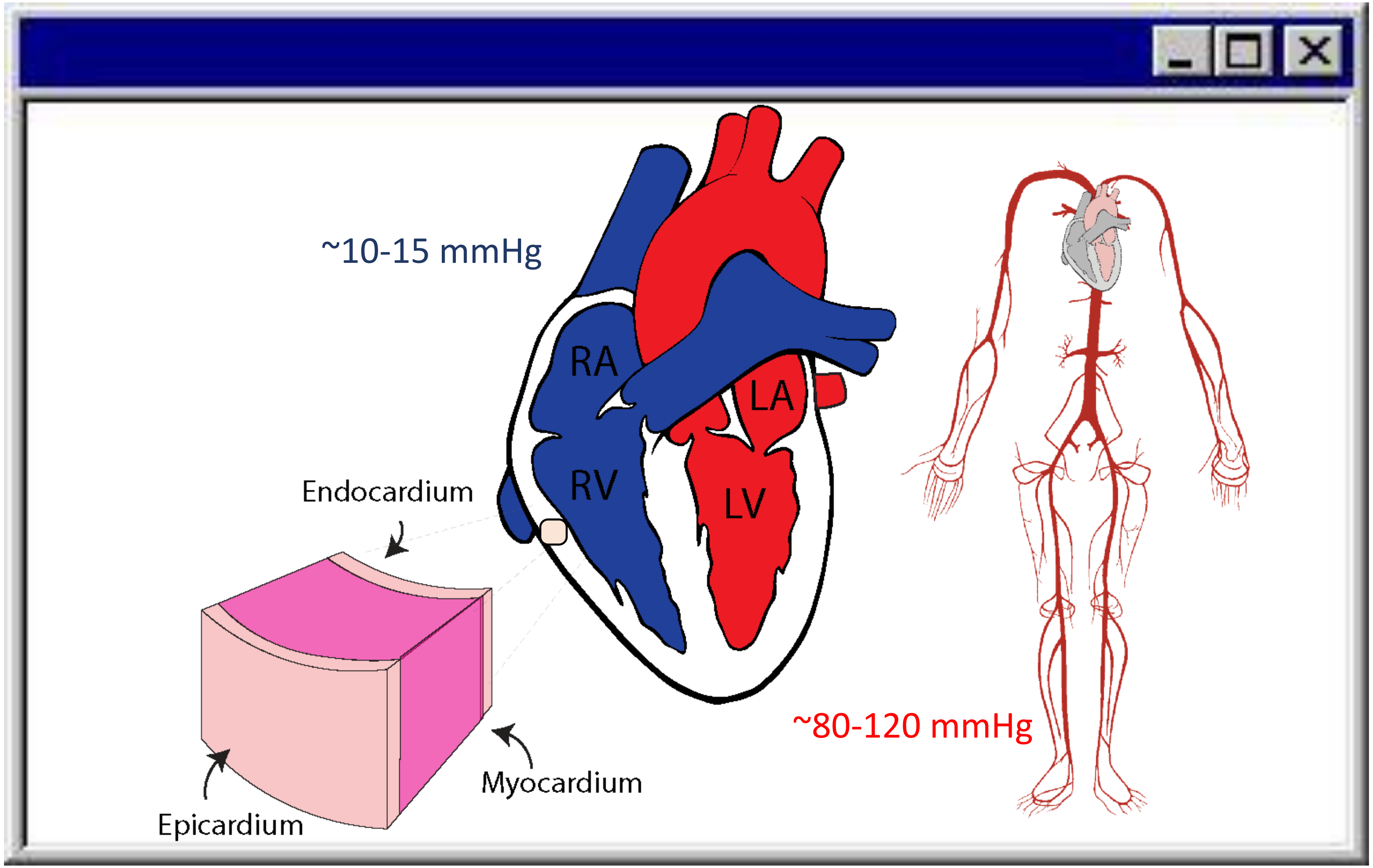


The fibrous composition of the myocardium is well recognized; nevertheless, a detailed description of the fibers arrangement is unknown.

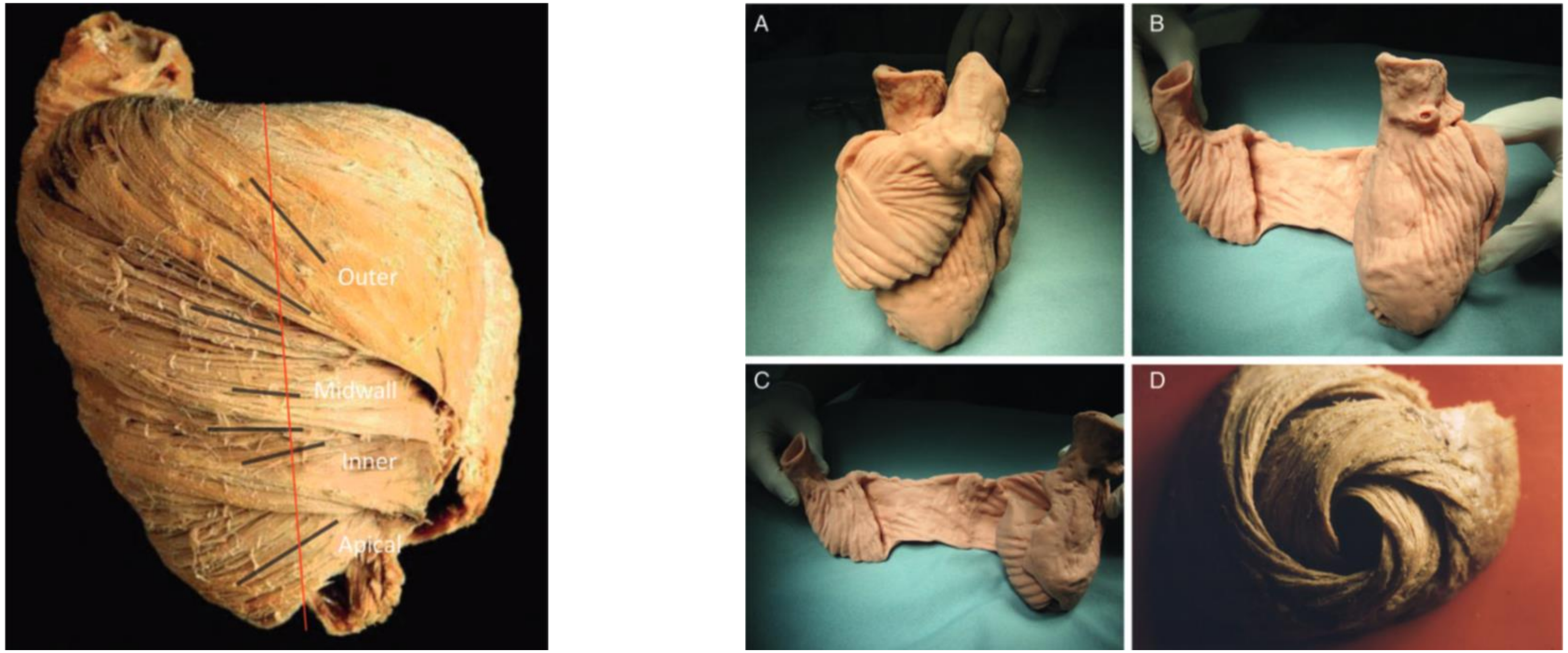
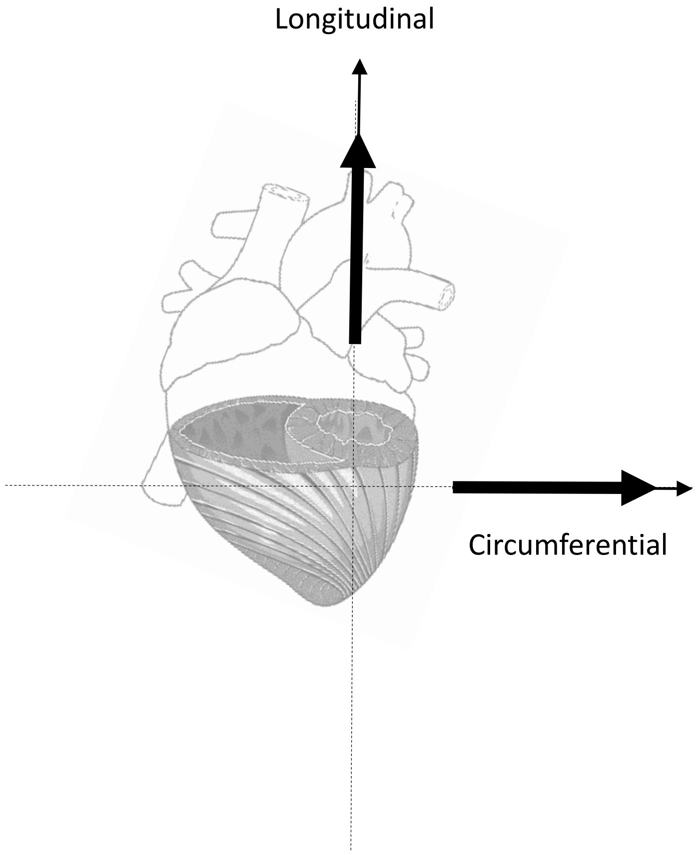


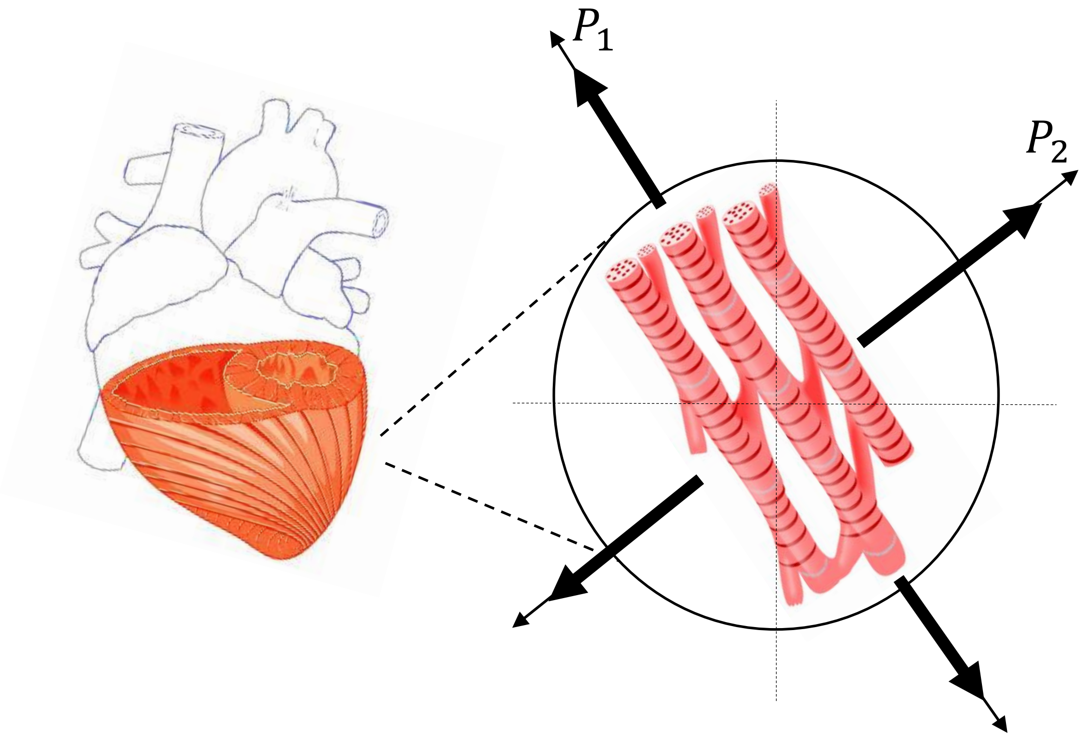
Fig. 1: (Left) Blunt dissection of the heart shows the gradual transition of the helical angle of the inner, the mid-wall and the outer zones [1]. (Right) Demonstration of the construction of the right ventricle [2].

[1] The end of the unique myocardial band: Part I. Anatomical considerations

[2] Ventricular structure-function relations in health and disease: part II. Clinical considerations

The architecture suggests that muscular fibers are a major constituents of myocardial wall and that strains should be oriented in the same direction as the fibers.

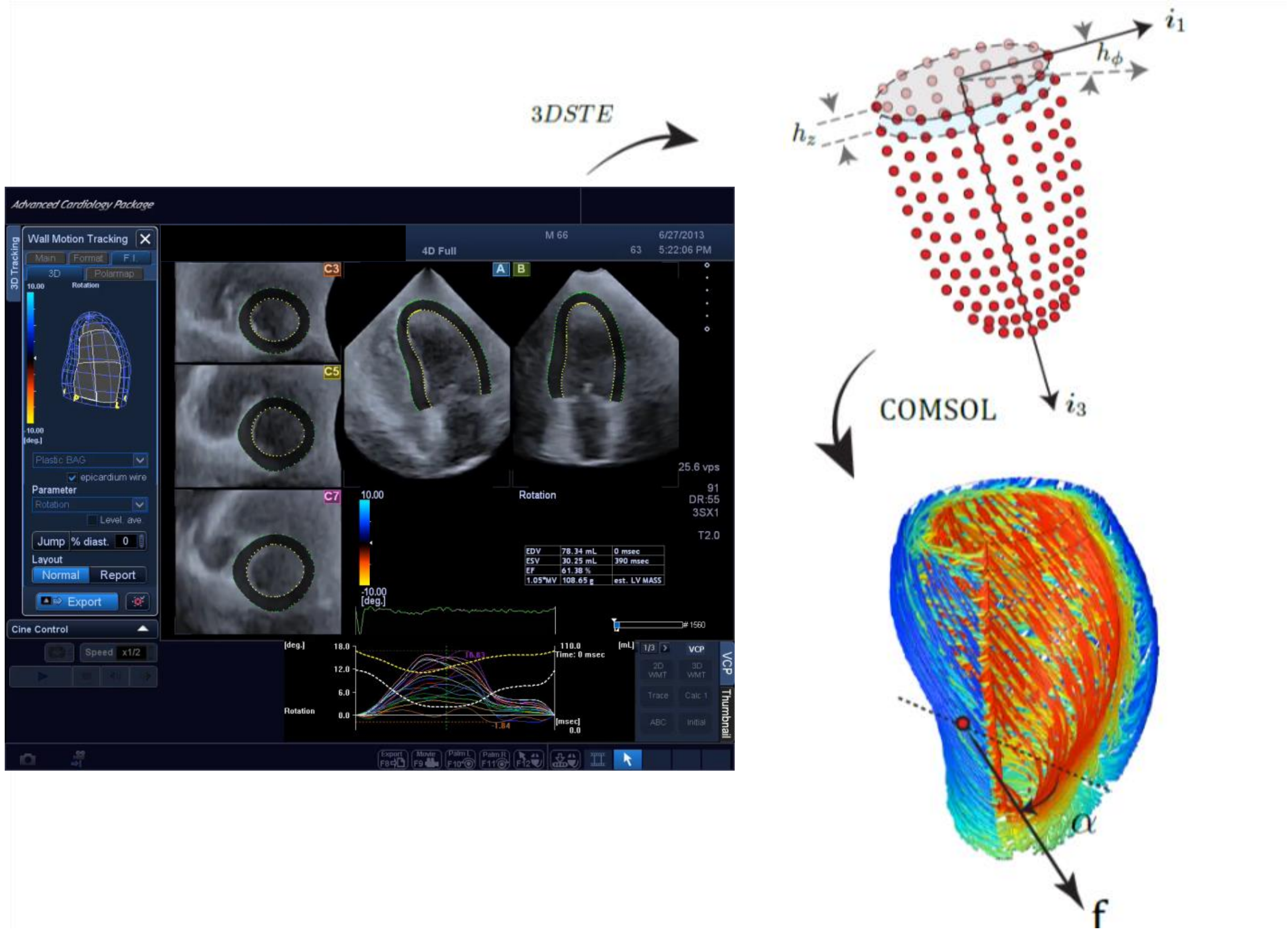




We present a framework for the study of patient-specific cardiac motion.

- Confront numerical simulations with real data acquired by echocardiography.
- Determine the clinical importance of the LV strains pattern and to investigate its relationship with the arrangement of myocardial fibers.

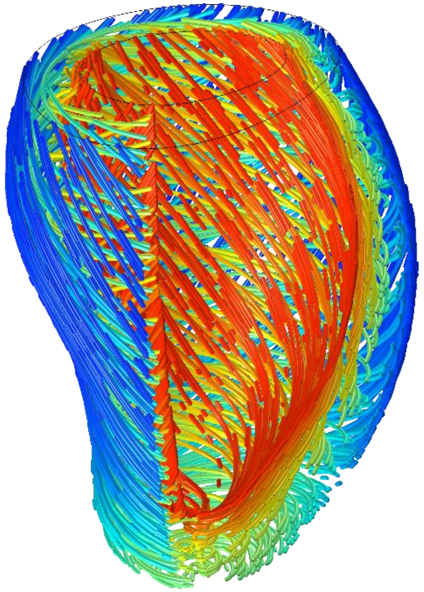
Geometrical Model

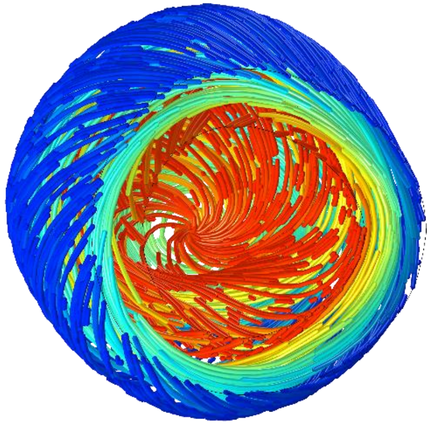


- Geometry
  - Real LV geometry, post-processing of 3DSTE measurements.
- Fibers
  - The structure of model is defined by the architecture of the muscle fibers.
  - The orientation muscle fiber is quantified by the helix fiber angle which is assumed to vary linearly in the wall layers (endocardium 60°, epicardium -60°) [3].

[3] Biomedical Engineering Fundamentals Andrew D. McCulloch

Material Model





- Matrix Fibered: heterogeneous, transversely isotropic, nearly incompressible [4,5].

$$\psi(F_e) = \psi_{sf} + \varphi_v$$

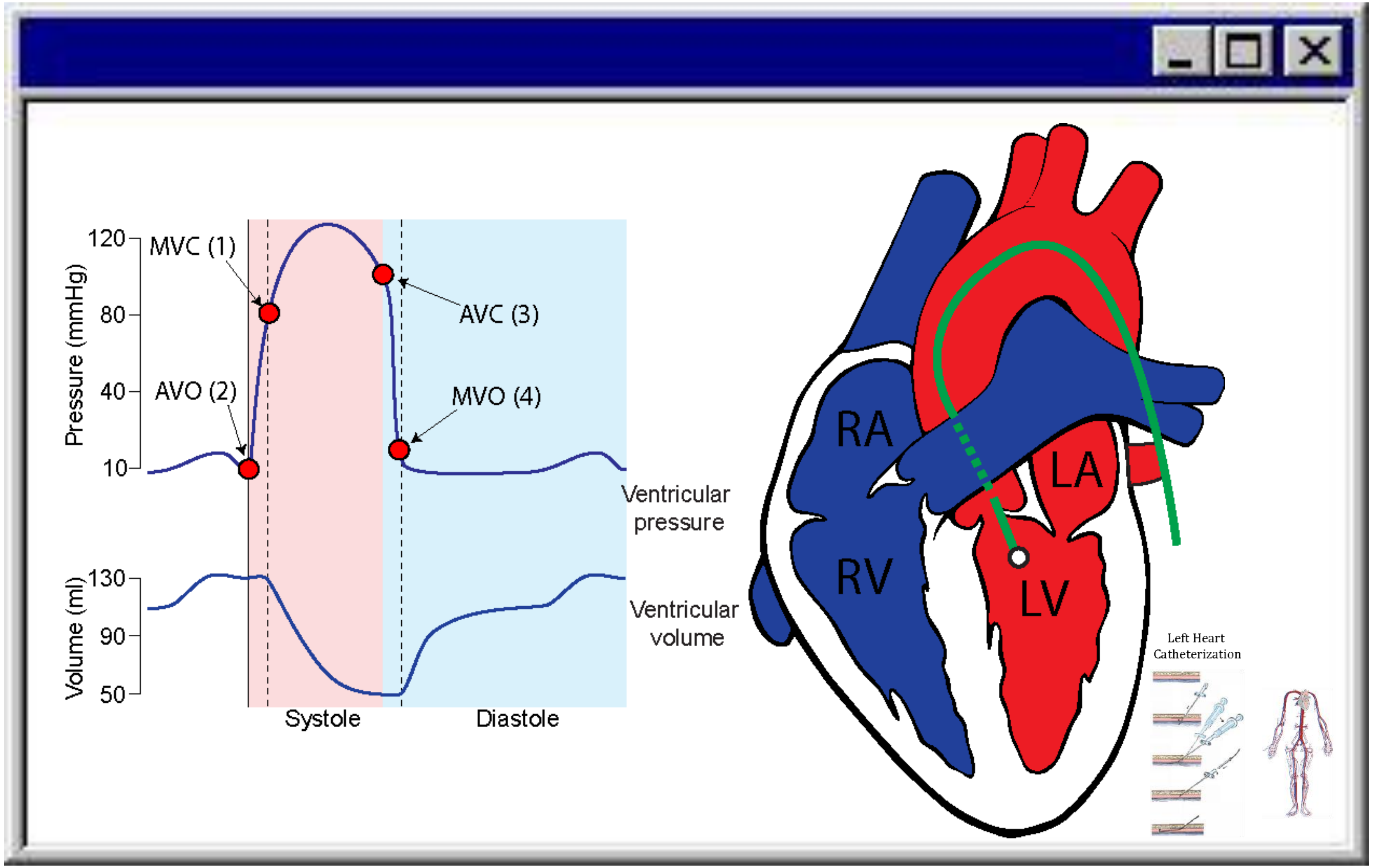
- Fibers: Active component. The deformation gradient is split into a passive and an active component [4,5].

$$F = F_e F_o$$

[4] J.I. Colorado-Cervantes, L. Teresi, P. Piras, P. Nardinocchi, V. Sansalone, C. Torromeo, G. Esposito, V. Varano, P.E. Puddu., 2020, Assesment of the strain lines pattern in the human left ventricle, Royal Society Open Science. (*Pre–print*)

[5] J.I. Colorado-Cervantes, V. Sansalone, L. Teresi, Patient-specific Analysis of Left Ventricle Motion, COMSOL Conference Europe 2020, 14-15 October 2020.

A Pressure-volume (PV) loop plots the changes in ventricular pressure associated with the changes in volume which occur during the cardiac cycle.



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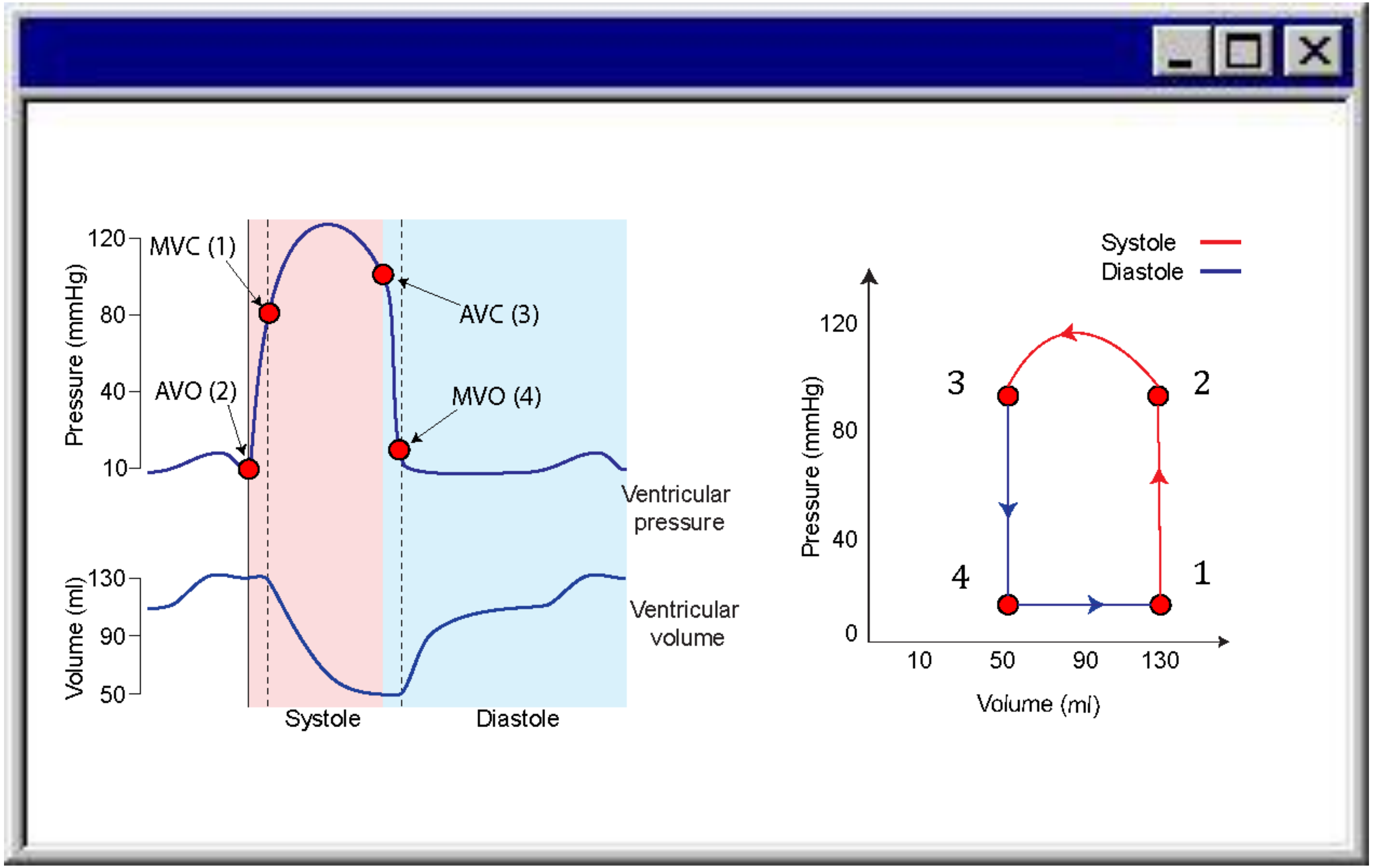
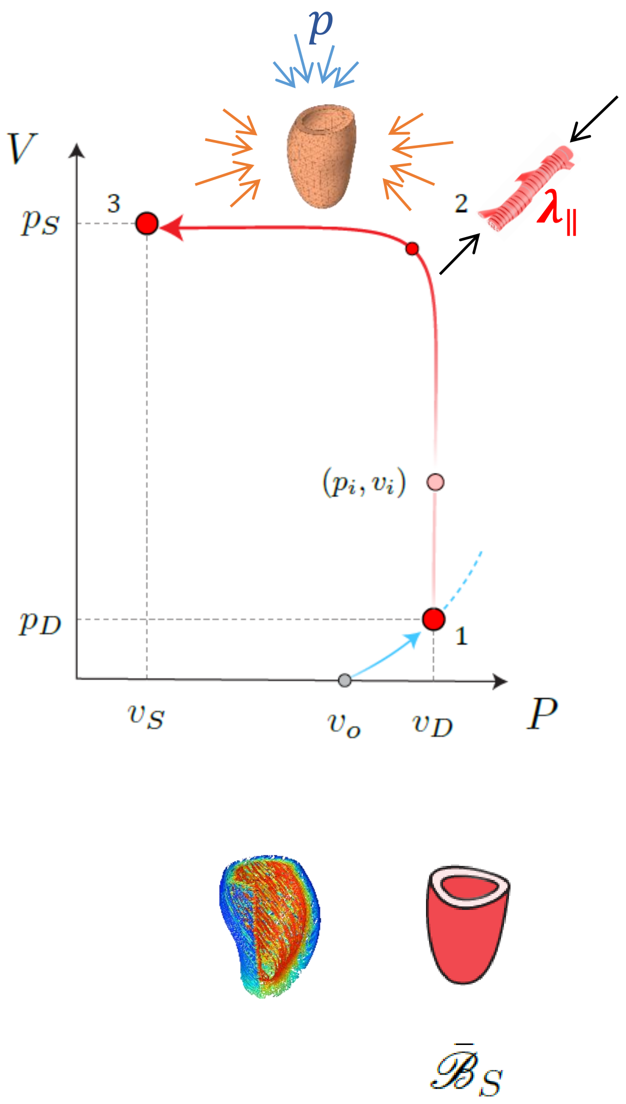
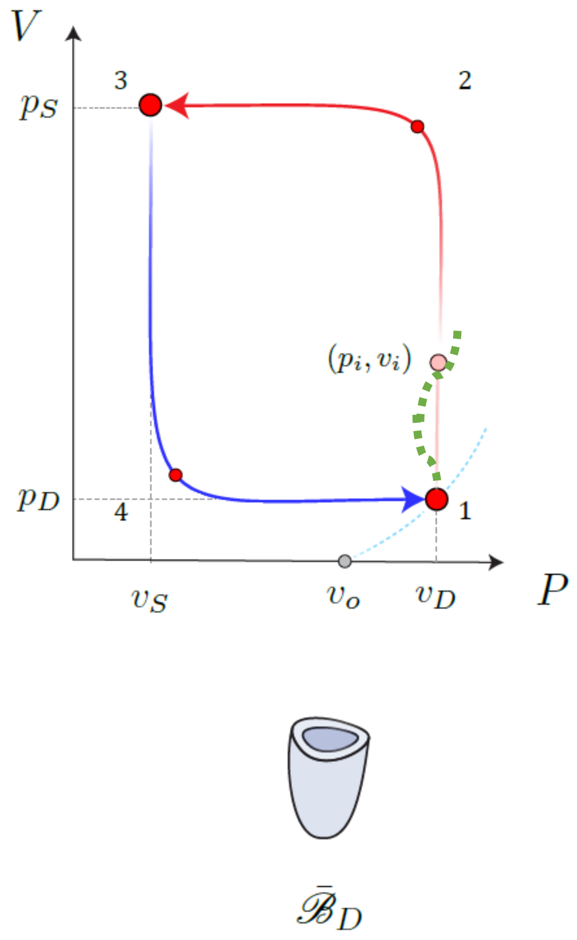


To reproduce the LV function, we construct a sequence of elastic problems parametrized by the contraction $\boldsymbol{\lambda}_{\parallel}$ and the inflating pressure $\boldsymbol{p}$.





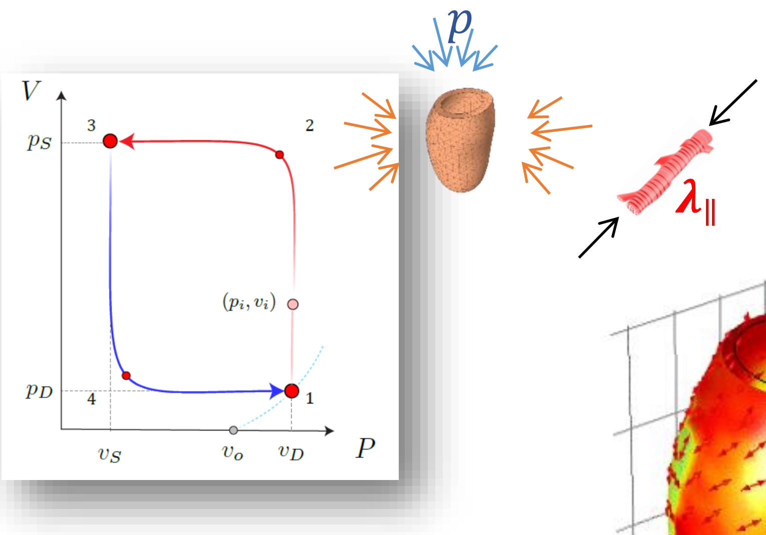
We define a distortion F_o field sharing the same directions with the fiber.

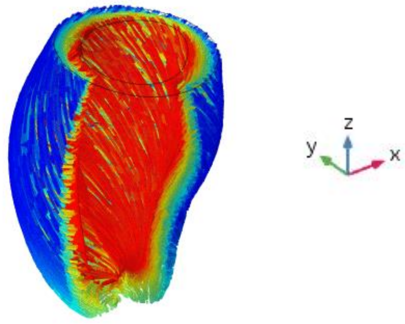
$$F_o = \boldsymbol{\lambda}_{\parallel}\, e \otimes e + \lambda_{\perp}(I - e \otimes e)$$

Tune the contraction $\boldsymbol{\lambda}_{\parallel}$ to find the desired volume v_i at p_i

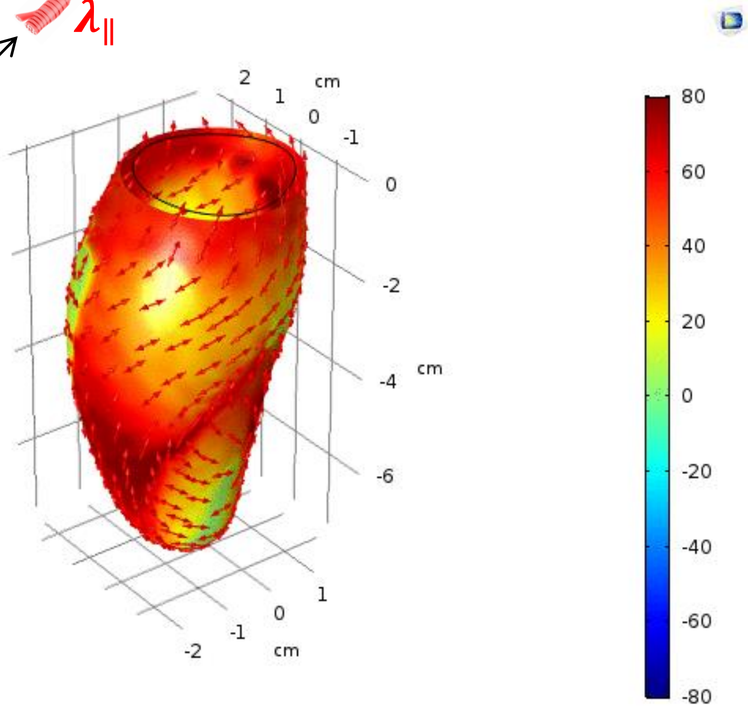
p_i: intracavitary pressure

Simulation of the left ventricle function

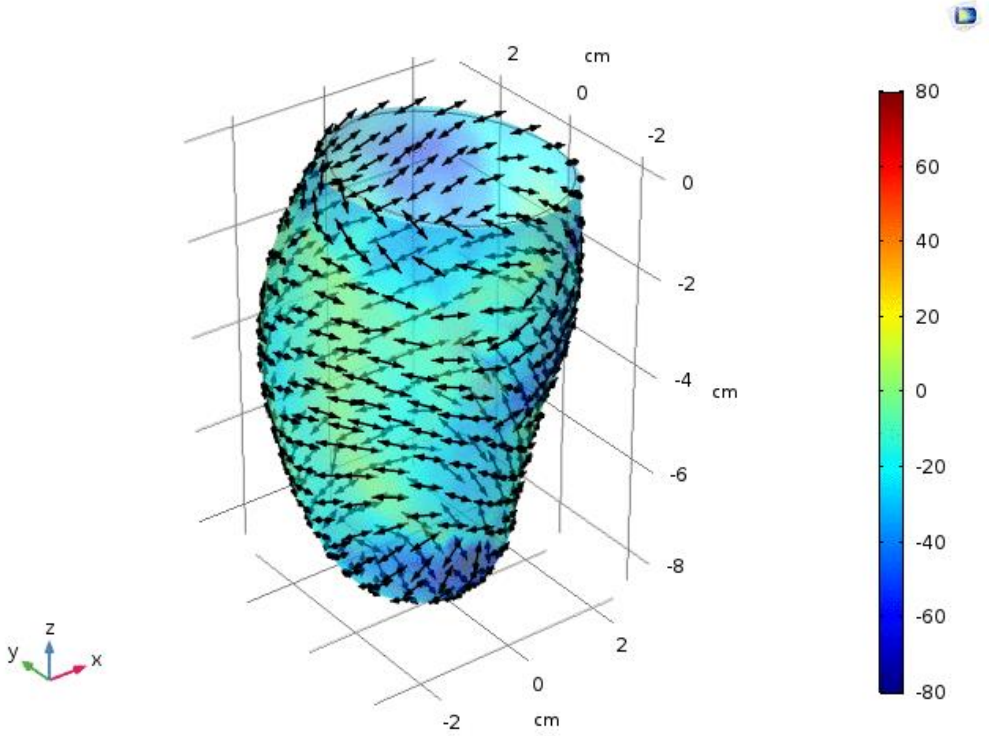




LV

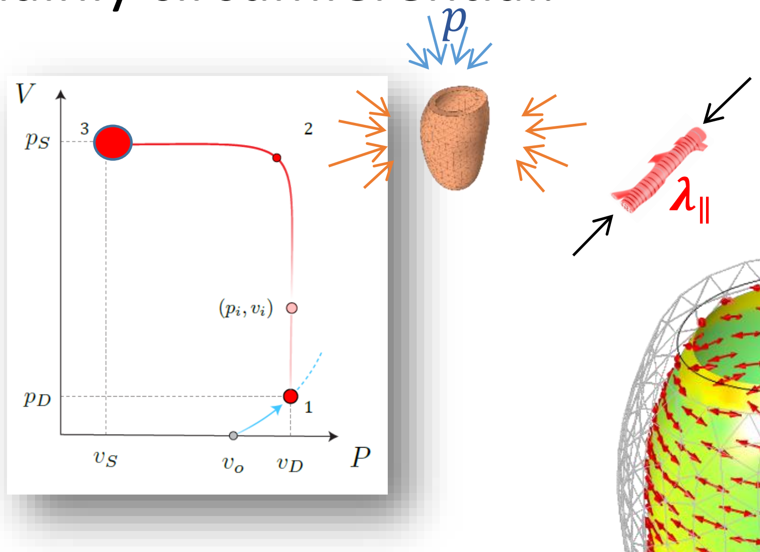


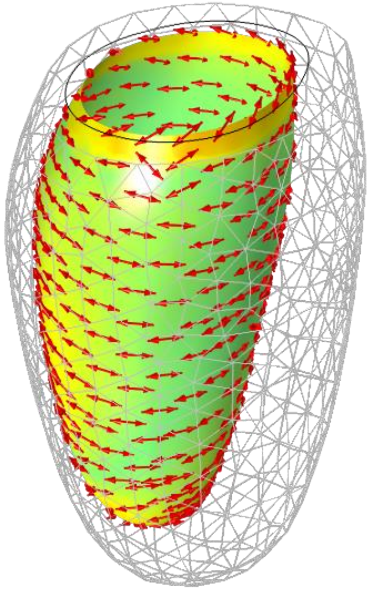
Endocardium



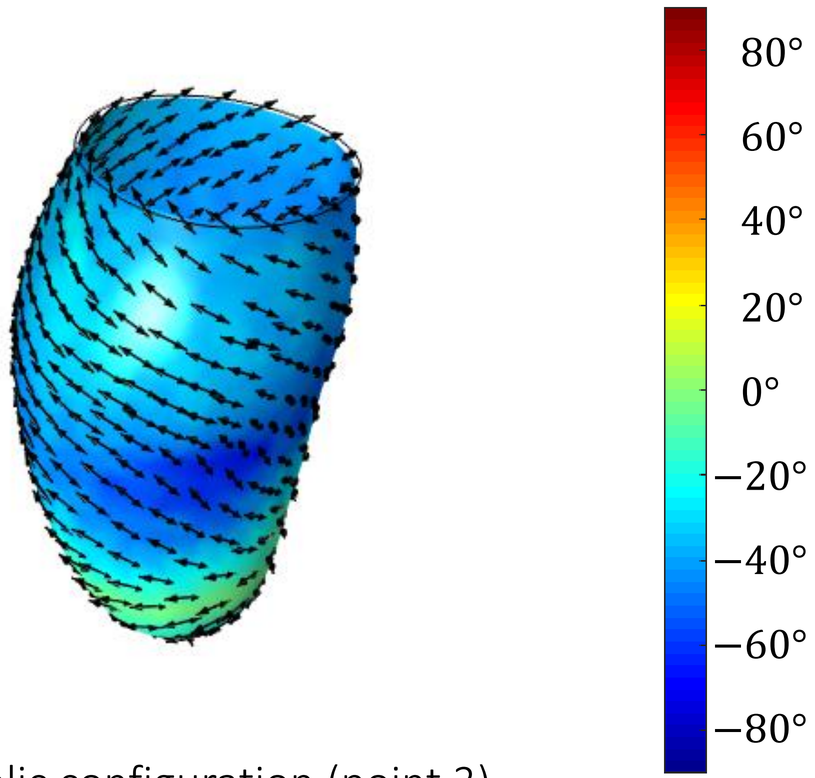
Epicardium

Principal strain lines at epicardium closely follows the fiber orientation while at endocardium are mainly circumferential.



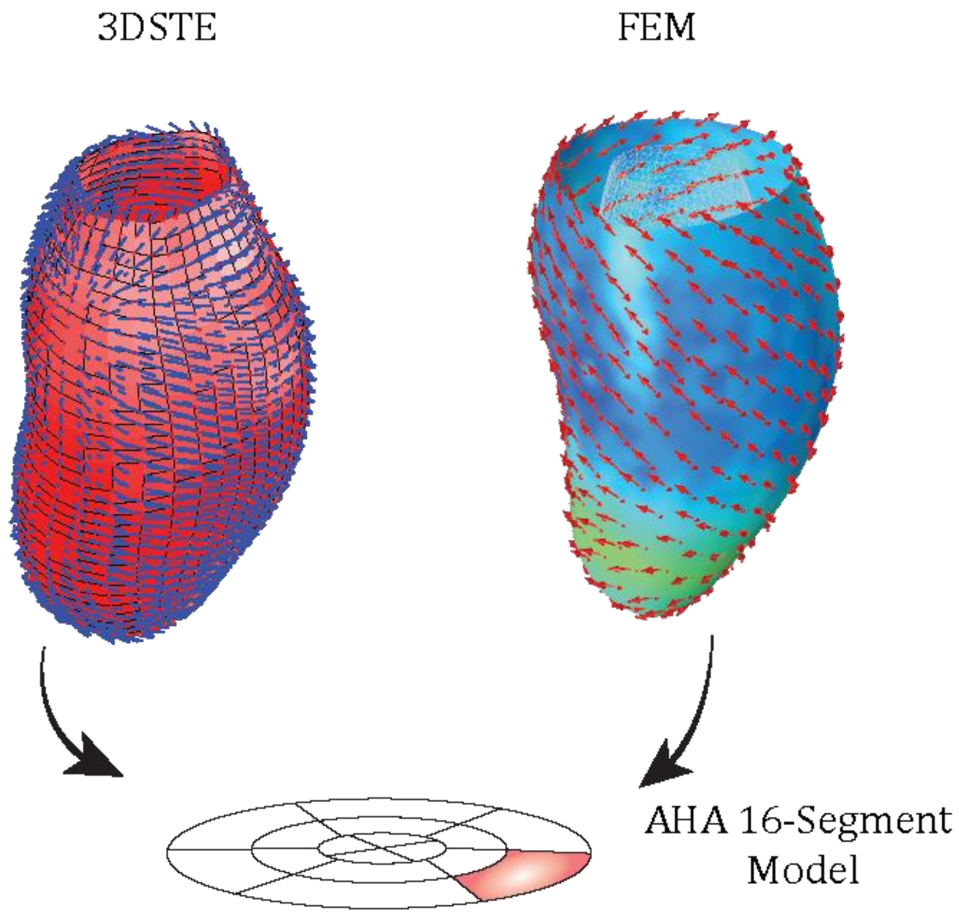


End-Systolic configuration (point 3)
Endocardium



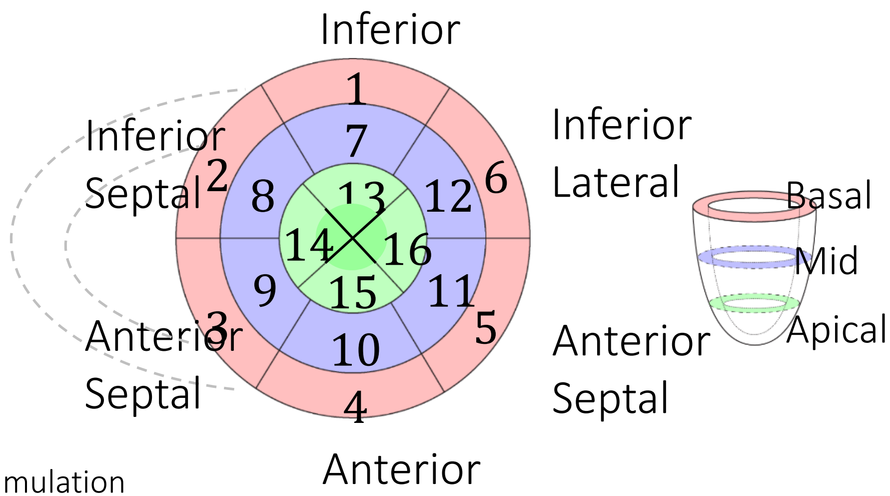
End-Systolic configuration (point 3)
Epicardium

We perform a **landmark-wise** comparison between **real 3DSTE** and **FEM simulation** using the same strain analysis protocol [5].



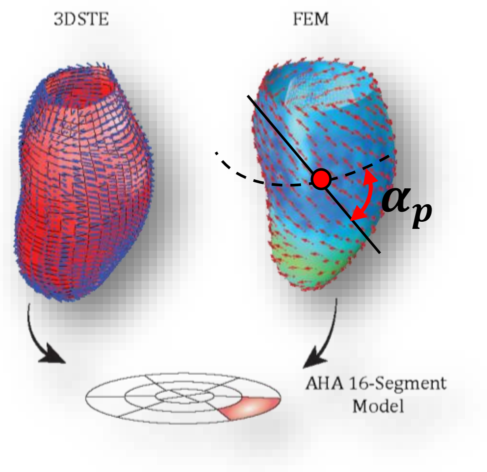
- Evaluate surface strain $\hat{\mathbf{C}} = \mathbf{P}\,\mathbf{C}\,\mathbf{P}\ \ ;\ \ \mathbf{P} = \mathbf{I} - \mathbf{n} \otimes \mathbf{n}$
- Eigen-analysis on $\hat{\mathbf{C}}$ to obtain $(\gamma_\alpha, \boldsymbol{c}_\alpha)$; with $\alpha = 1,2$

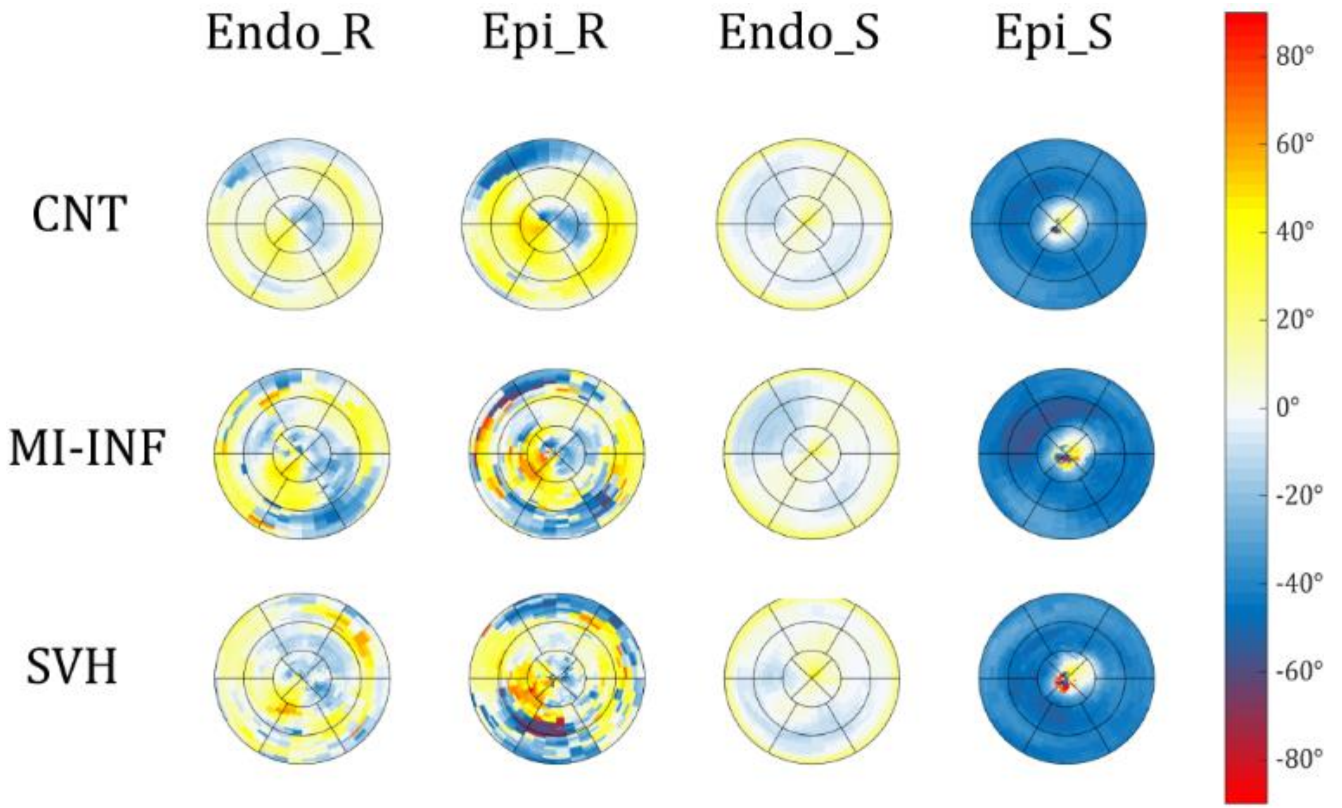
γ_α= eigenvalue
$\boldsymbol{c}_\alpha$= eigenvector



[6] Gabriele, S., Nardinocchi, P., & Varano, V. (2015). Evaluation of the strain-line patterns in a human left ventricle: a simulation study. *Computer methods in biomechanics and biomedical engineering*, *18*(7), 790-798.

Median value of orientation of the PSLs α_p for Control (CNT, 82), Myocardial Infarction on Inferior Wall (MI-IW, 4) and Secondary Ventricular Hypertrophy (SVH, 7) subjects.





Per-category **median value of orientation of the PSLs** measured by the angle α_p with respect to the horizontal in the endocardial (Endo) and epicardial (Epi) surfaces, for both real (_R) and simulated (_S) data at the end of the systole. Control (CNT), Myocardial Infarction on Inferior wall (MI-IW), Secondary Ventricular Hypertrophy (SVH)

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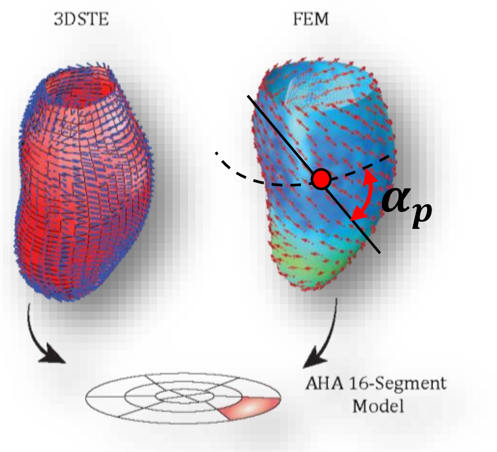

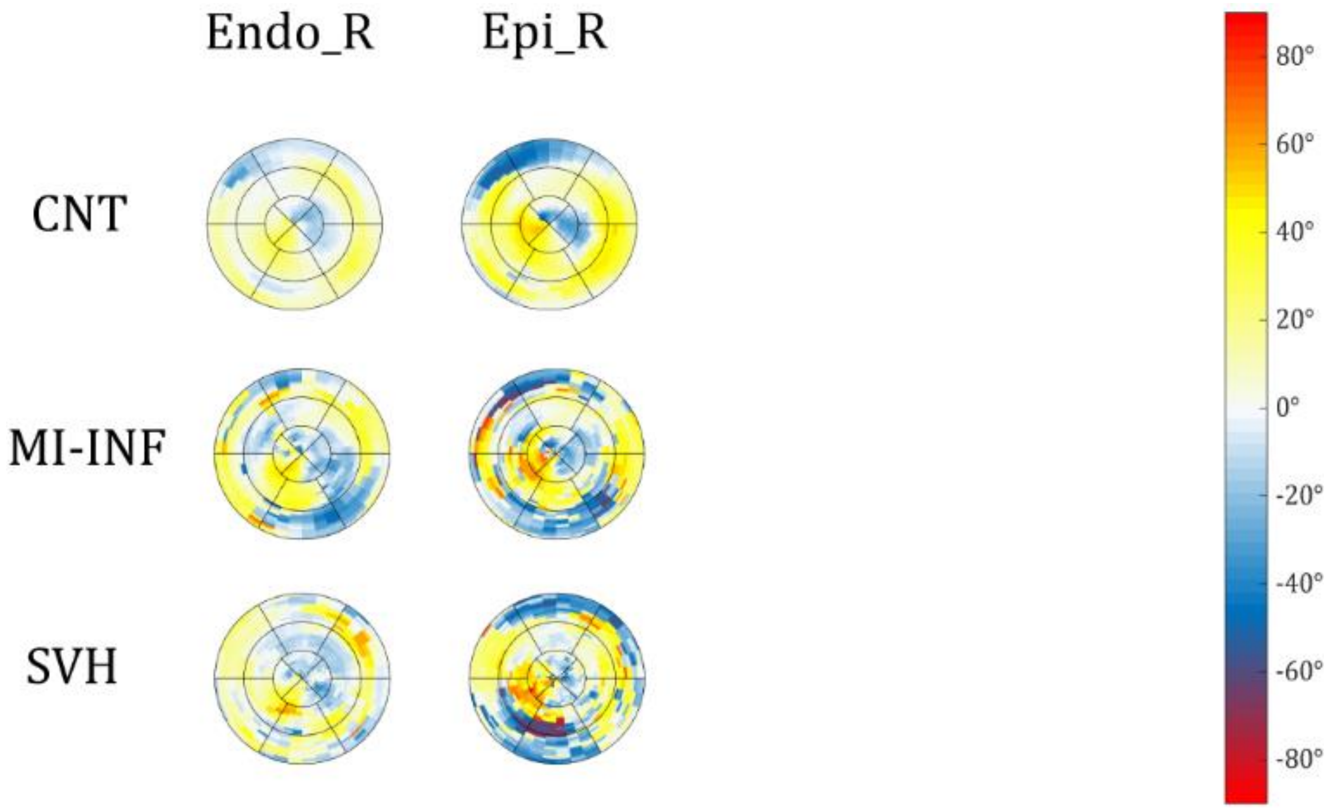

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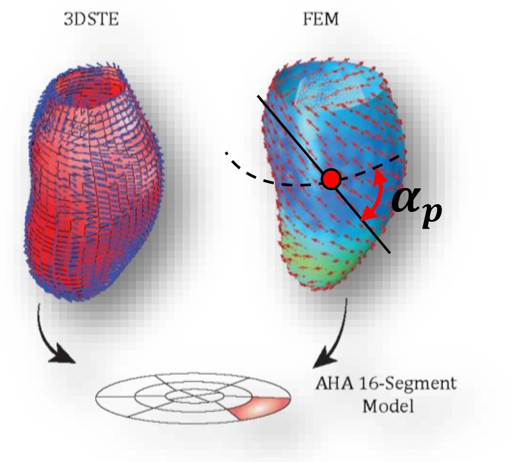

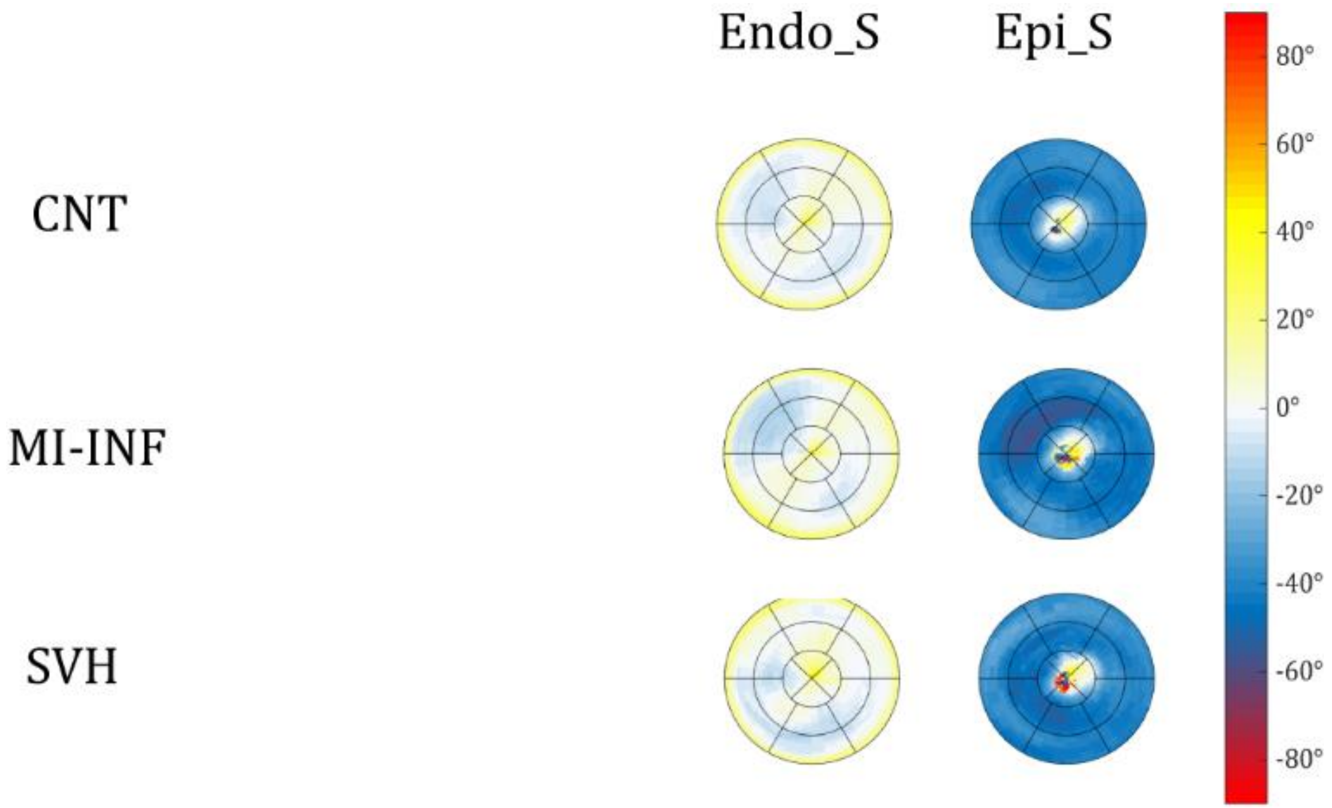

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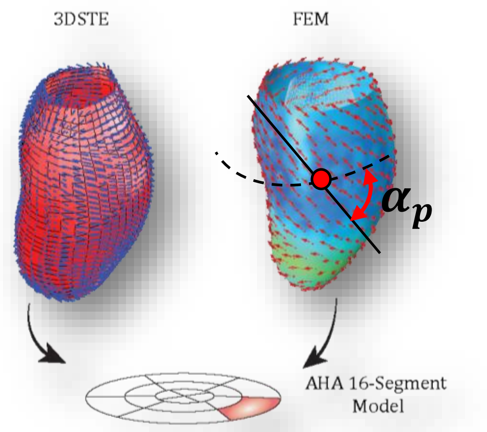

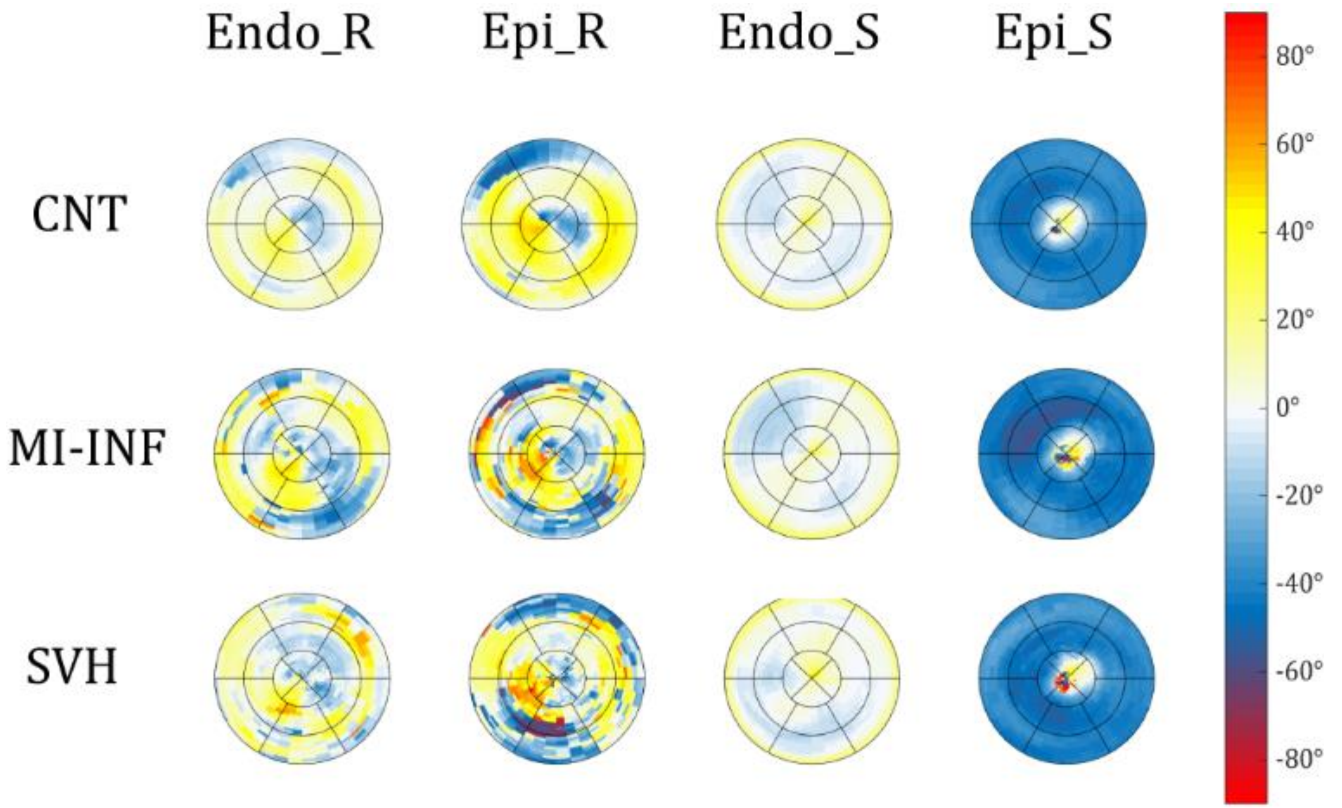

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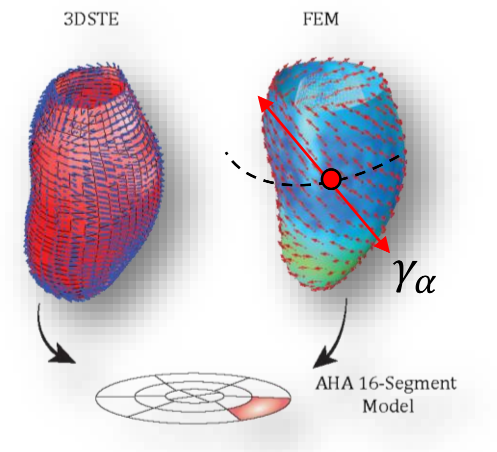

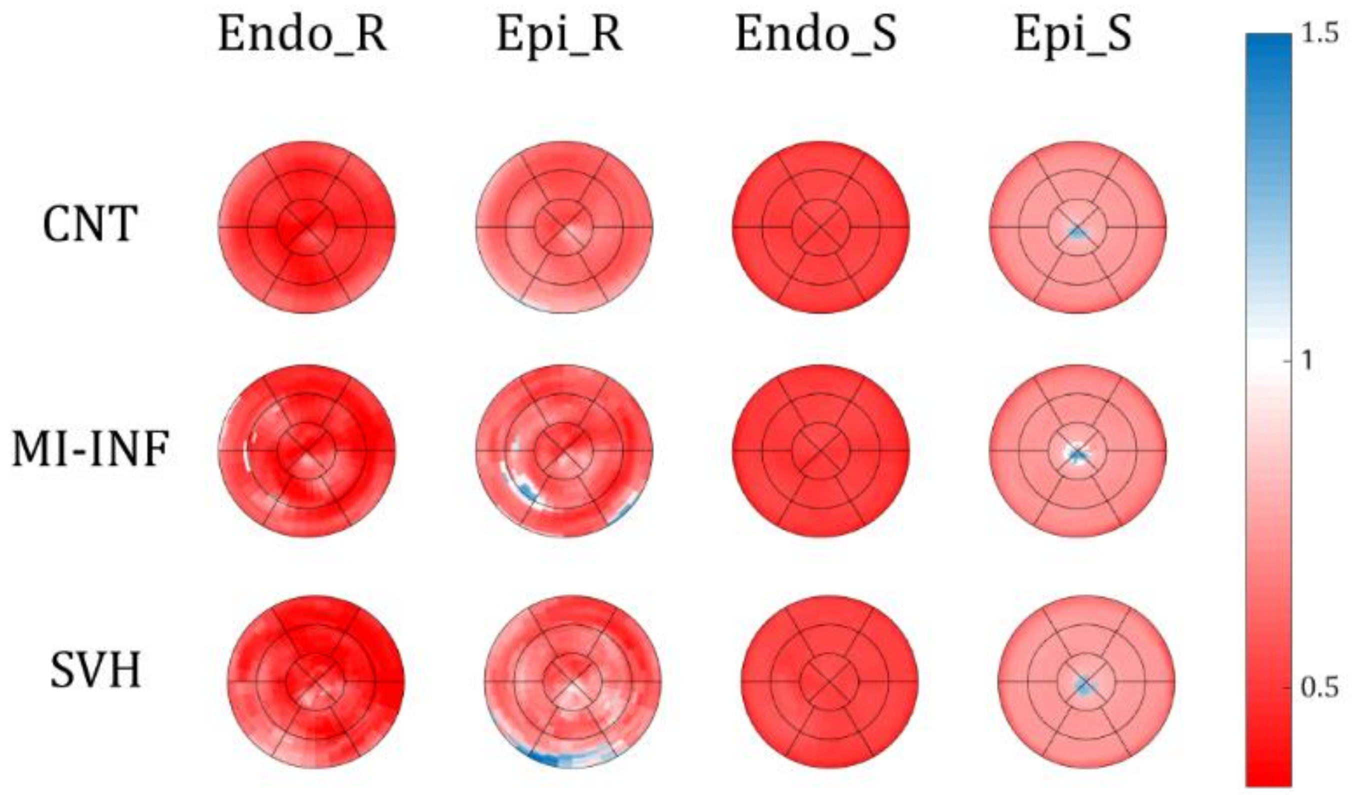

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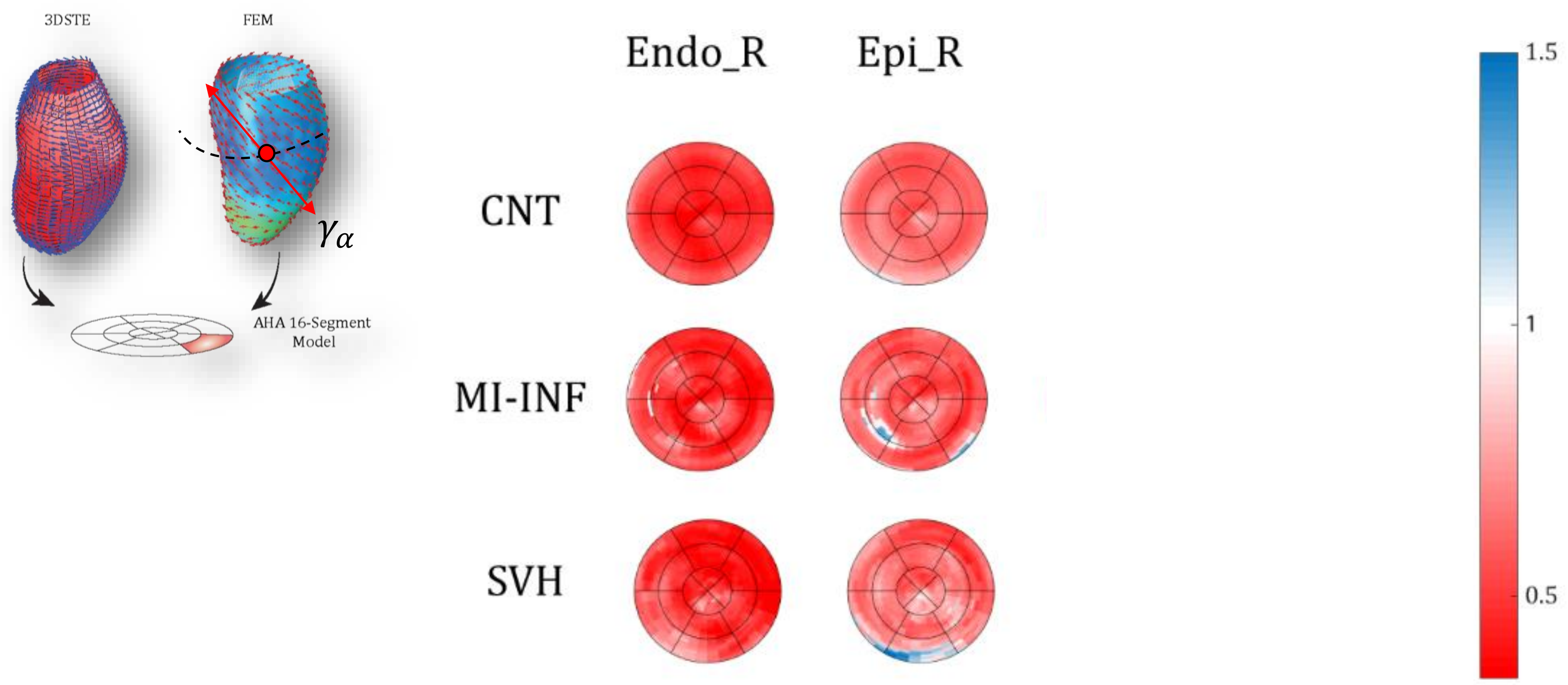

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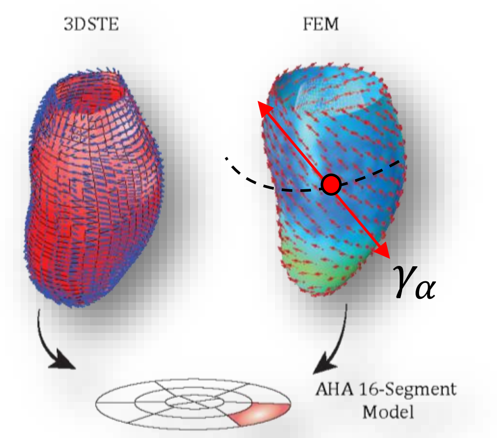

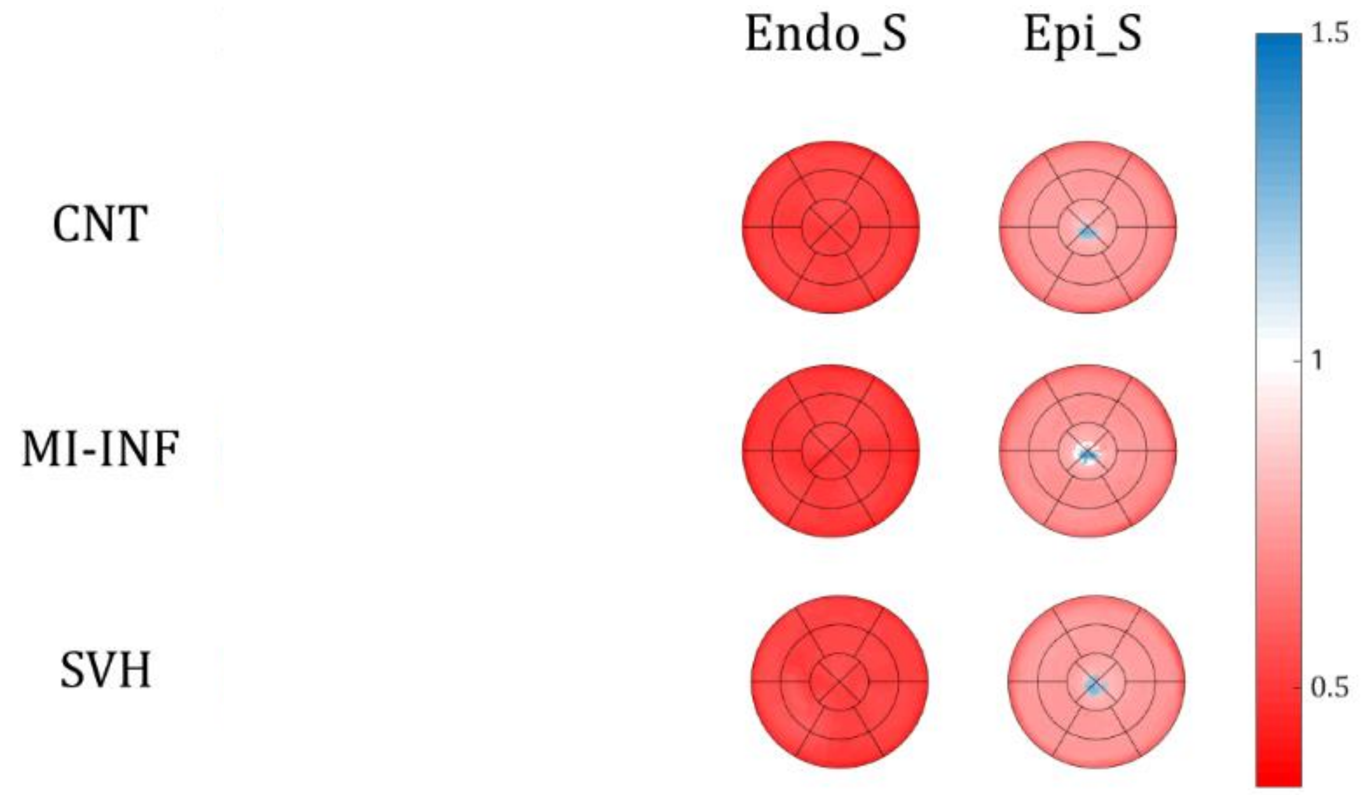

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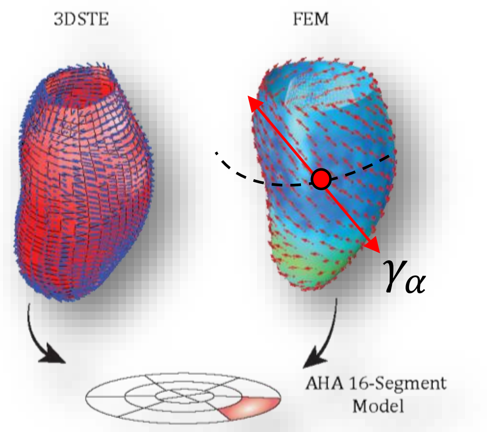

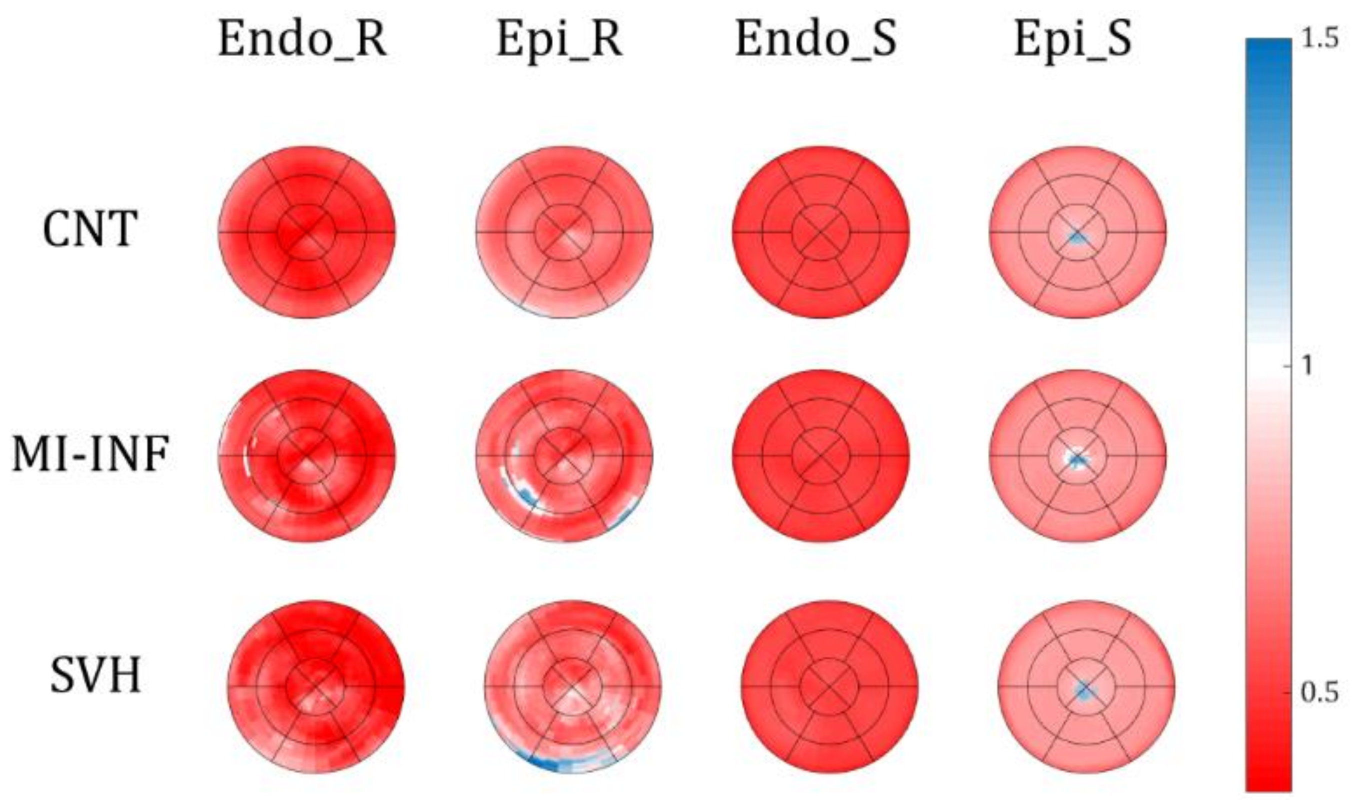

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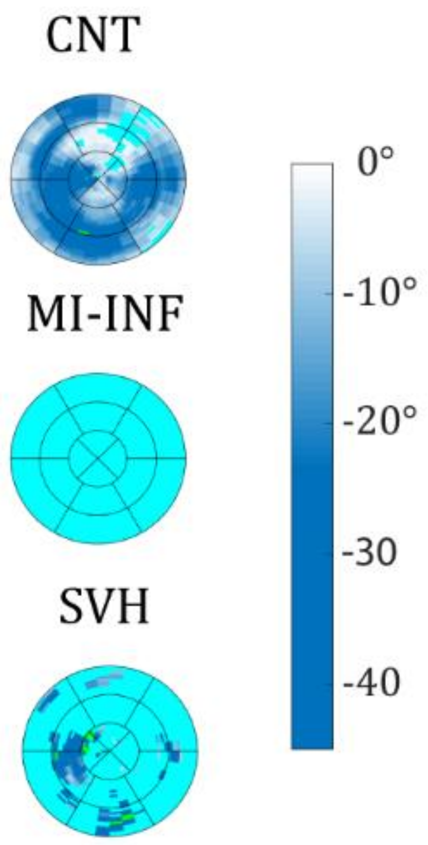
Difference between absolute value of PSL angle $\Delta_k = \alpha_{p,ENDO} - \alpha_{p,EPI}$ for **REAL** data.

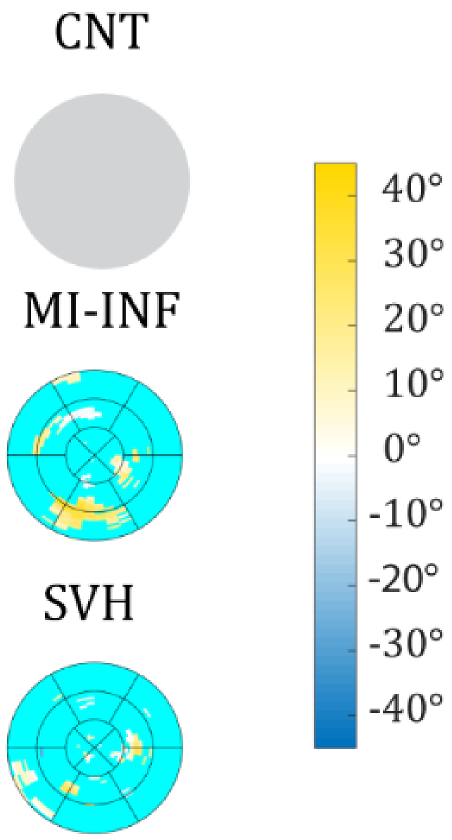


Green for $\Delta_k > 0$

Cyan Δ_k<0 and not significant Wilcoxon test

Per-category median value Δ_k, measuring the difference between the absolute value of PSL angle at endocardium and at epicardium. For each category, all landmarks locations were subjected to the paired nonparametric test

Difference between Control (CNT) and other categories for **REAL** data.



$$\Delta_{k,CNT} - \Delta_{k,MI-INF}$$

$$\Delta_{k,CNT} - \Delta_{k,SVH}$$

Cyan: not significant
Wilcoxon test

Differences $\Delta_{k,CNT} - \Delta_{k,OTHER}$ between the $\Delta_{k,}$values of control group and other categories.

Conclusions

- We present a framework for the study of patient-specific cardiac motion.
- Our results agree with previous reports, PSL's at the endocardium are oriented in circumferential manner while at epicardium are closely oriented in anatomical manner.
- PSL's are not result of a preferred orientation of myocytes lying in the cardiac walls, but reflect the overall performance within the myocardium.
- Statistical analysis did not show relevant differences between healthy and pathological subjects.