How do the mechanics and structure of the heart matter in regard to patient-specific cardiac modelling?

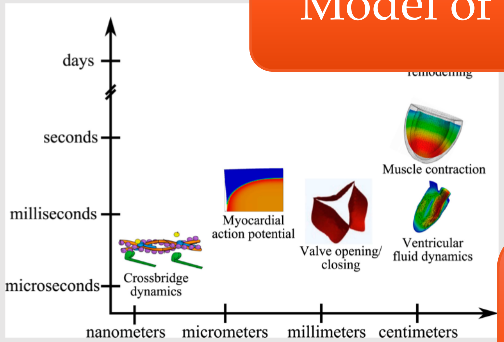
Trial lecture

17.01.2018

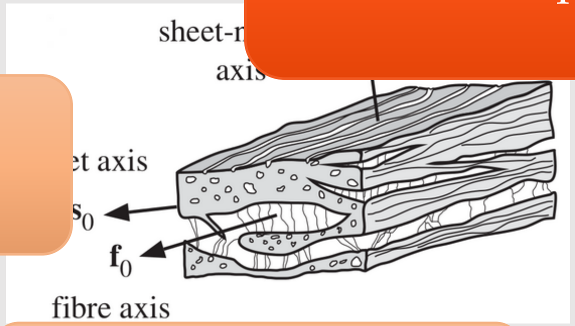
Henrik Nicolay Topnes Finsberg

simula

The heart



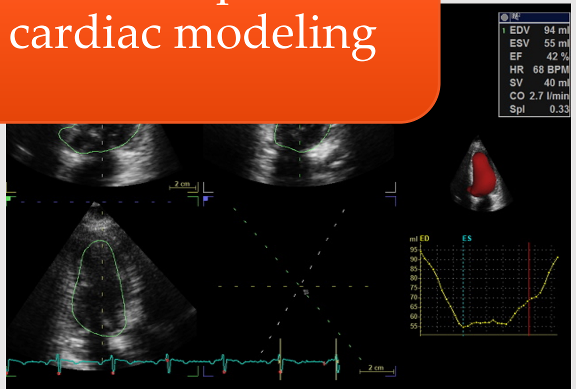
Model of the heart



Mechanics and structure of the heart

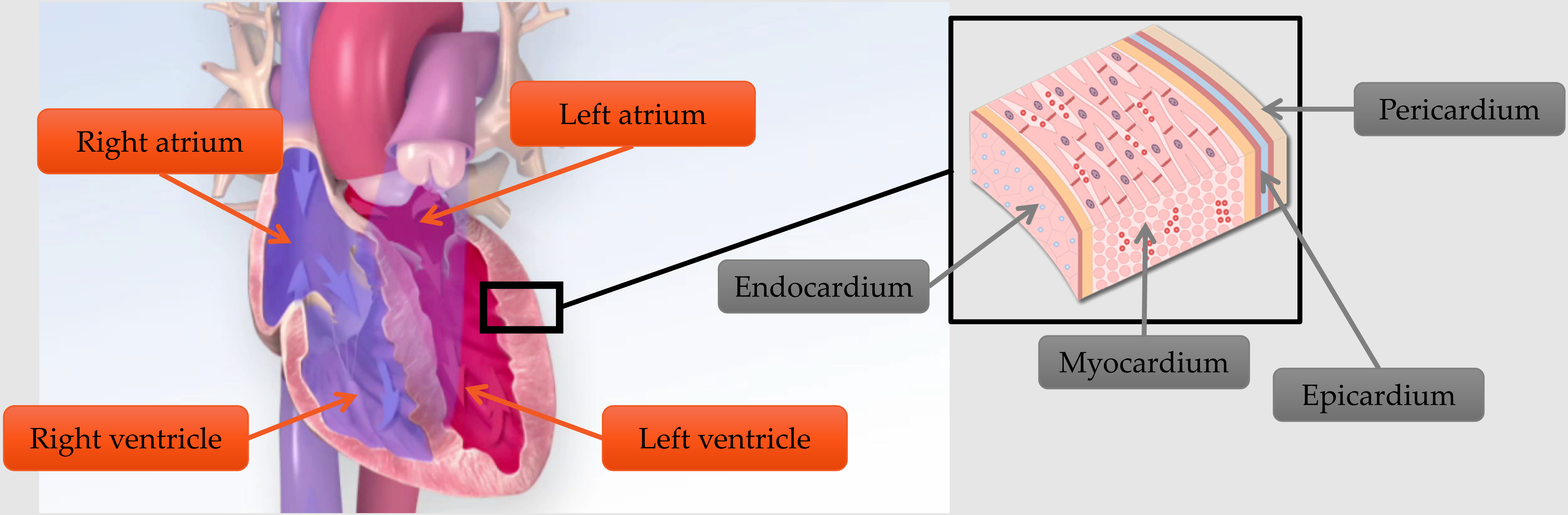
Assumptions?

Importance?



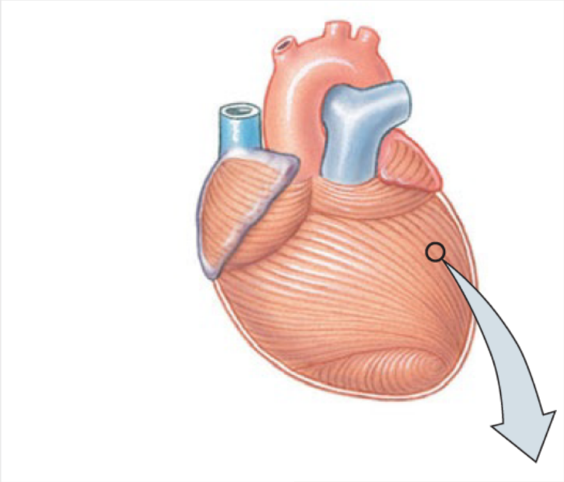
Patient-specific cardiac modeling

The heart is the muscular organ responsible for circulating blood throughout the body

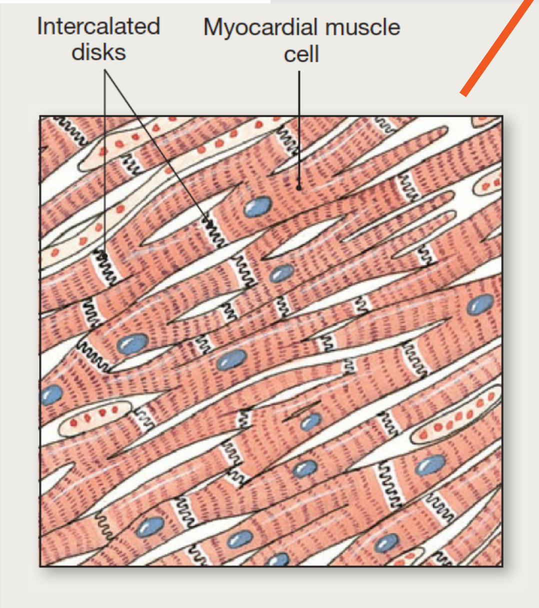


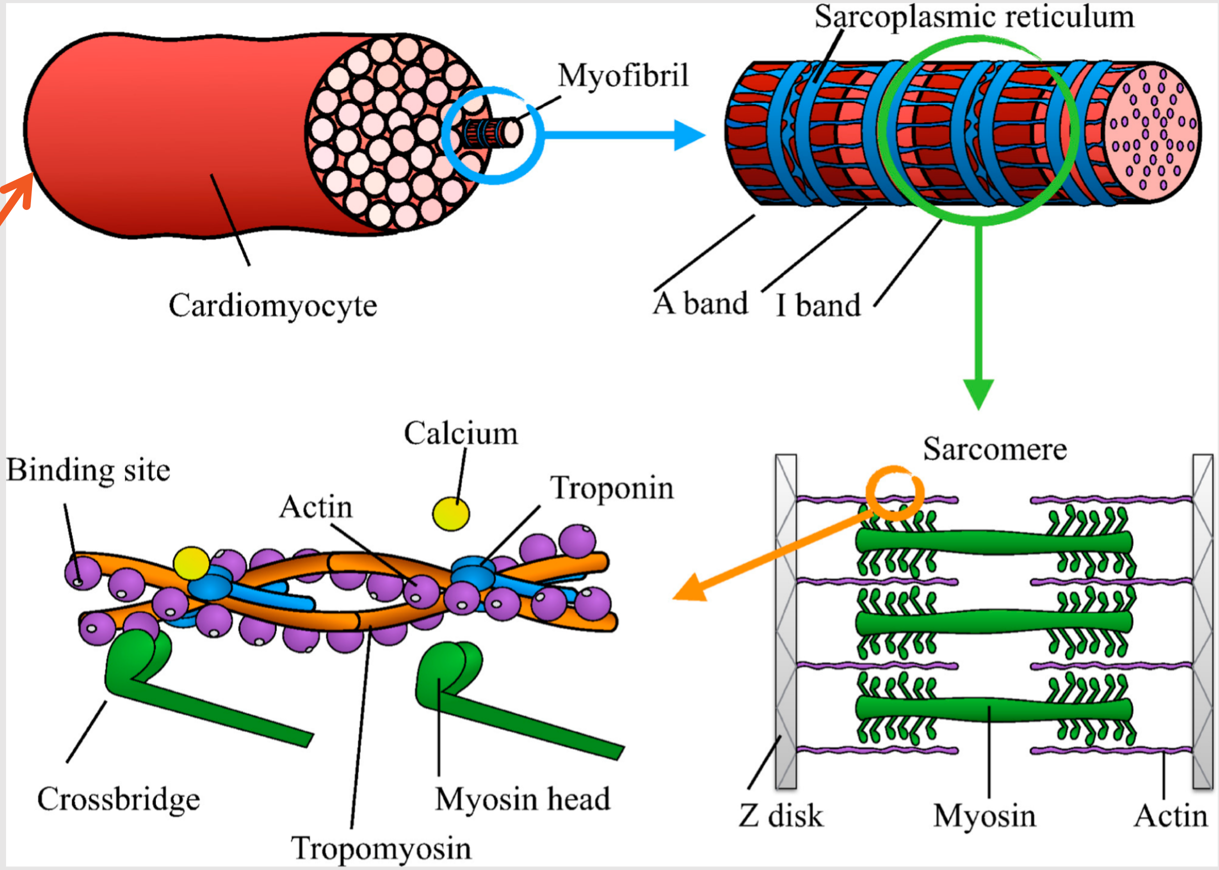
Source: American Heart Association

The myocardium is made up by muscle fibers which form a complicated fibrous network



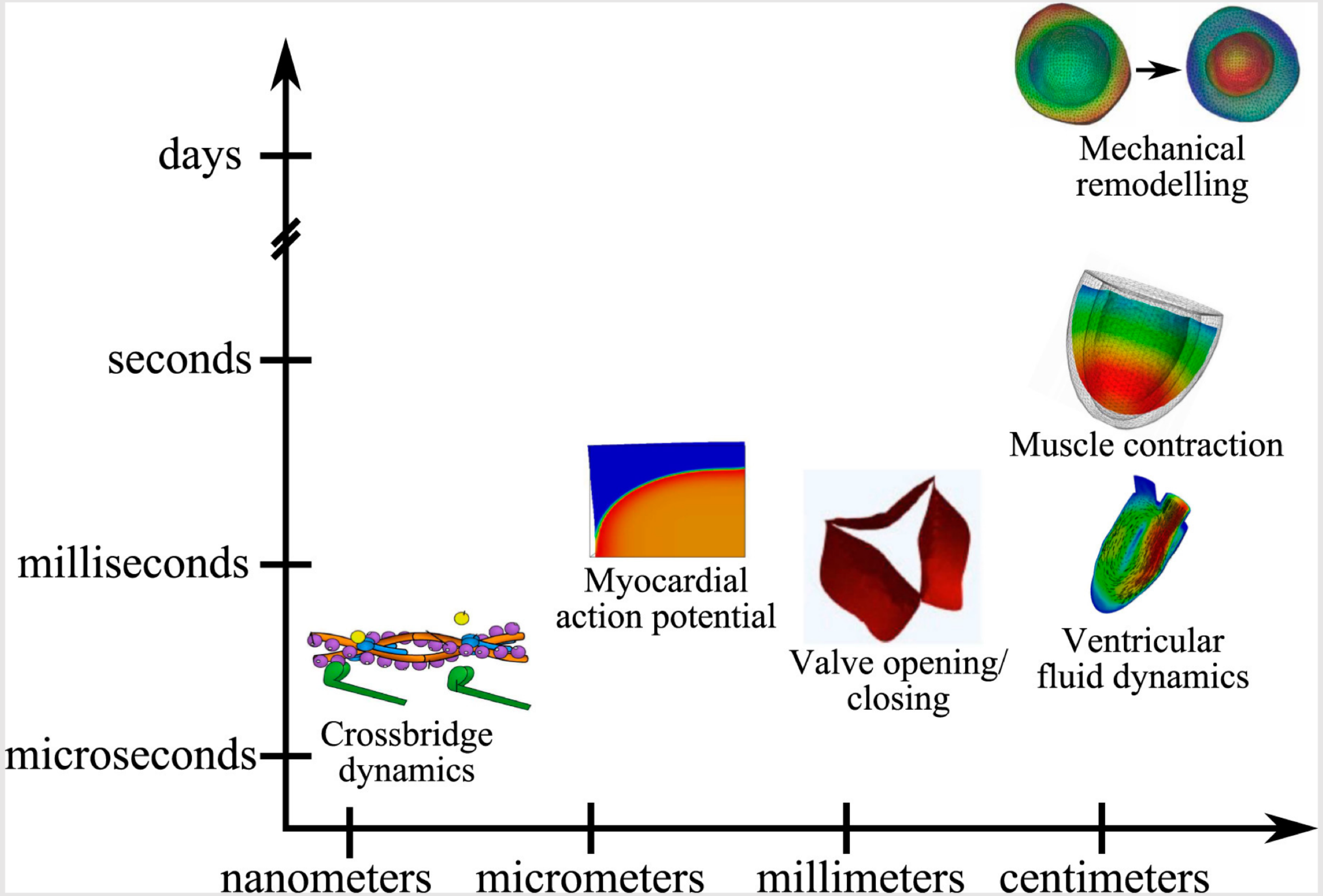
Silverthorn (2010)





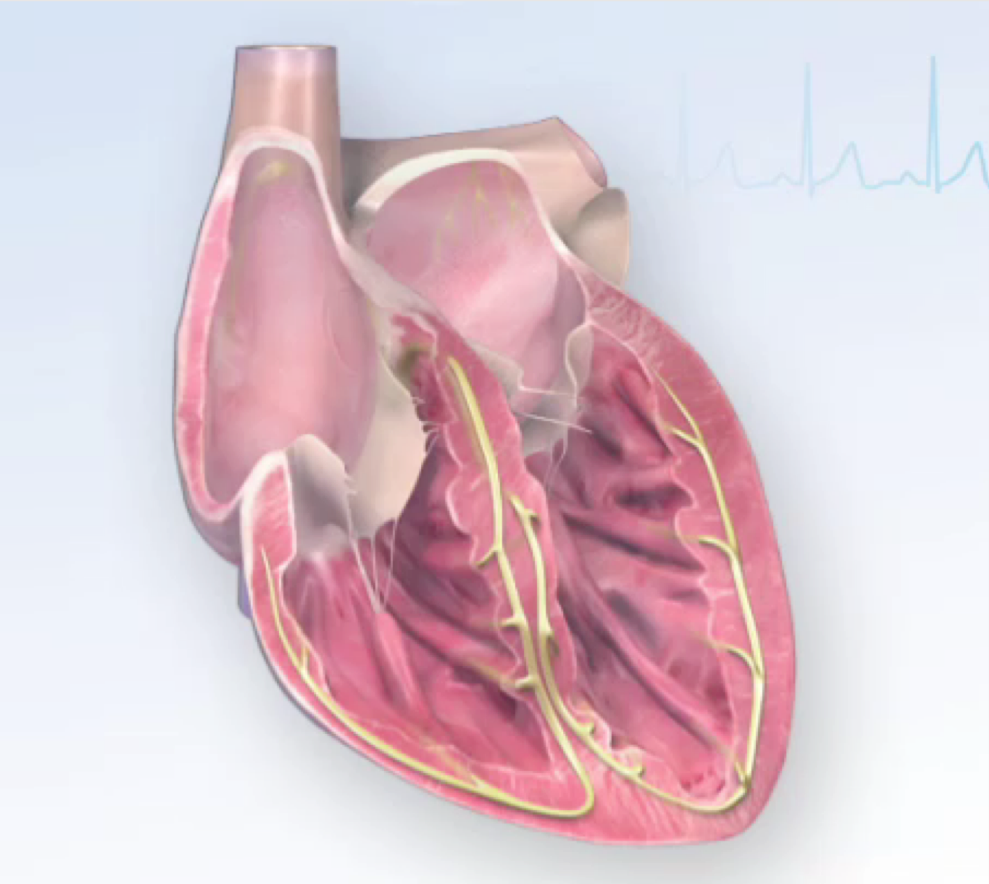
Quarteroni, A., Lassila, T., Rossi, S. and Ruiz-Baier, R., 2017. Integrated Heart—Coupling multiscale and multiphysics models for the simulation of the cardiac function. Computer Methods in Applied Mechanics and Engineering, 314, pp.345-407.

Cardiac modeling is the field of describing the heart function through mathematics



Quarteroni, A., Lassila, T., Rossi, S. and Ruiz-Baier, R., 2017. Integrated Heart—Coupling multiscale and multiphysics models for the simulation of the cardiac function. Computer Methods in Applied Mechanics and Engineering, 314, pp.345-407.

Models of cardiac electro-mechanics integrate the coupling between electrophysiology and mechanics



Source: *American Heart Association*

Source: *https://www.youtube.com/watch?v=YBswOmm999U*

How do the mechanics and structure of the heart matter in regard to patient-specific cardiac modelling?

Mechanics is the study of motion and forces

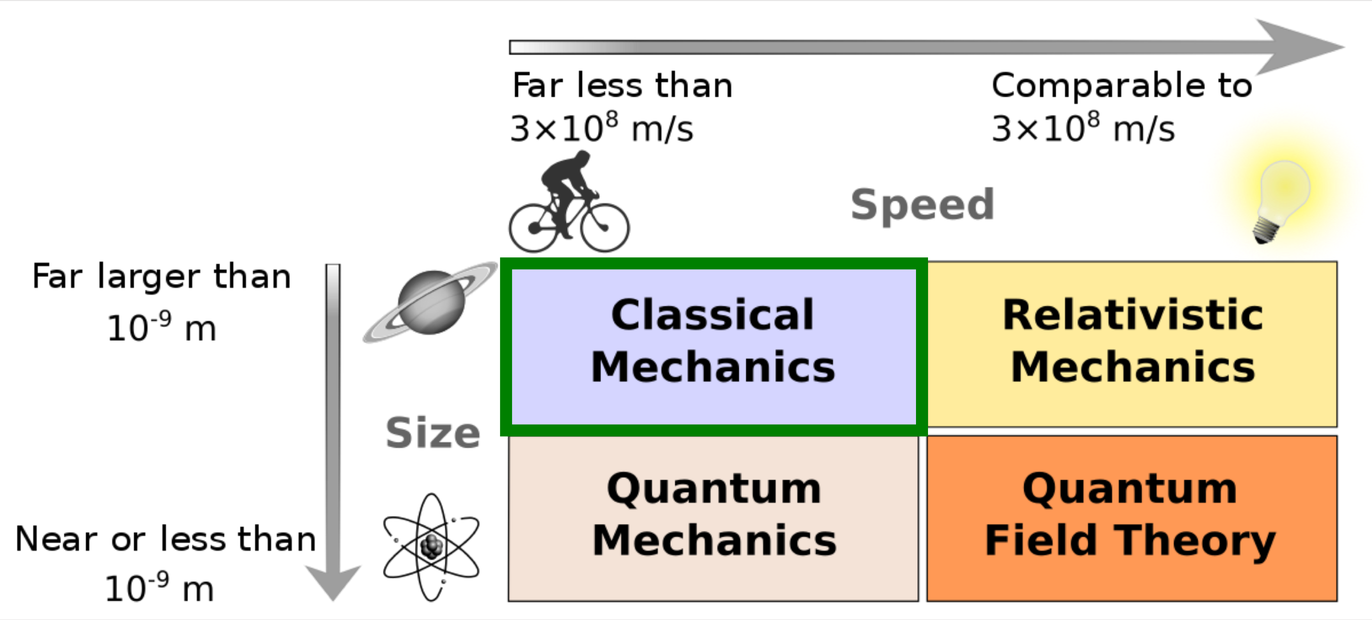


Image source: Wikipedia:Classical_physics

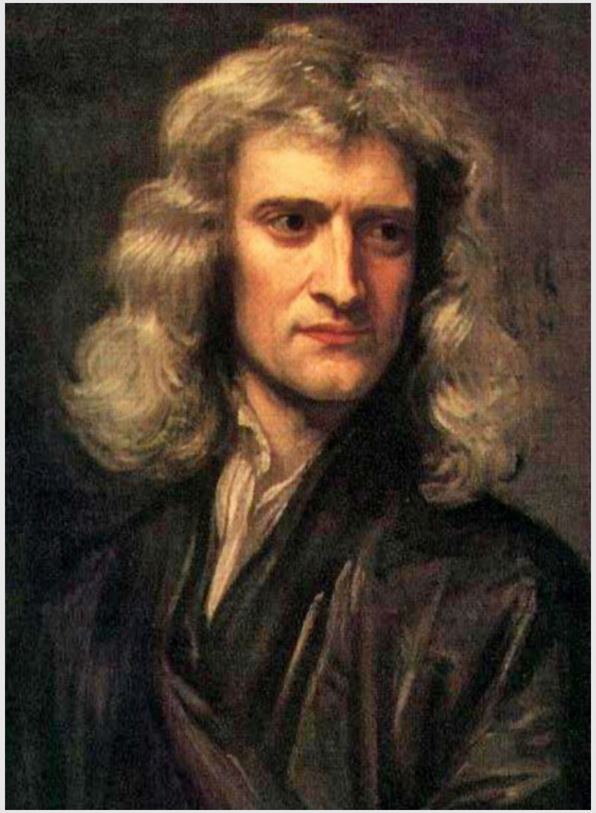
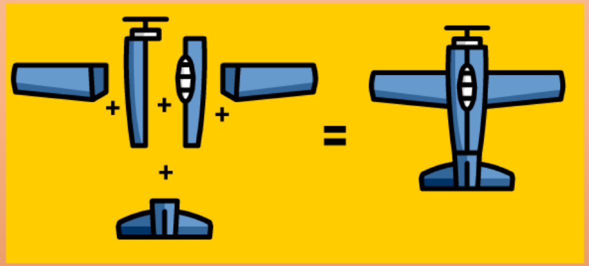


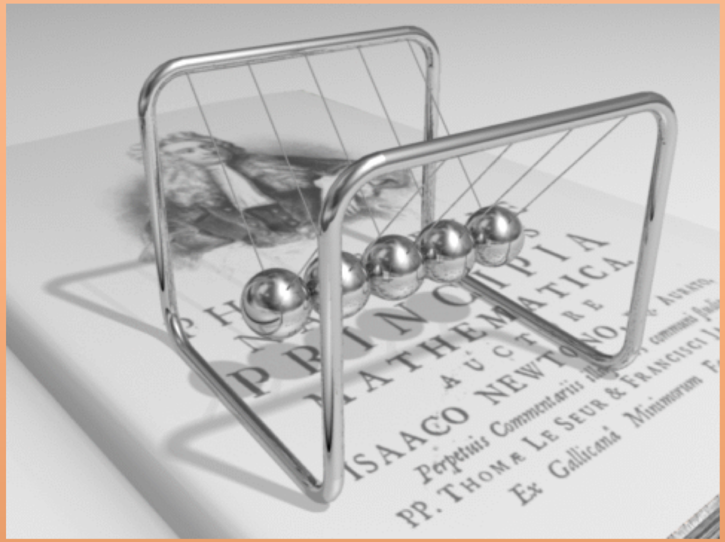
Image source: Wikipedia:Isaac_Newton

The physical laws in classical mechanics are based on principles of conservation

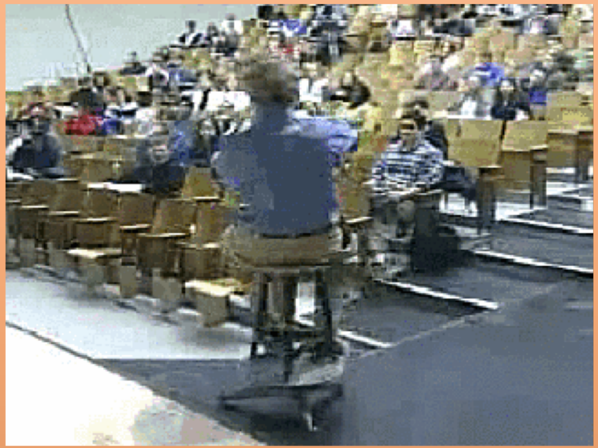
Conservation of mass



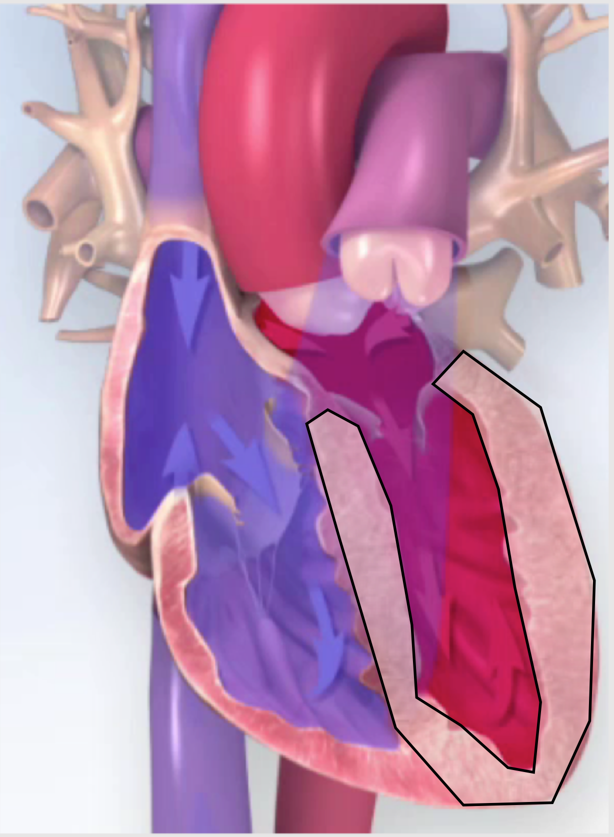
Conservation of linear momentum



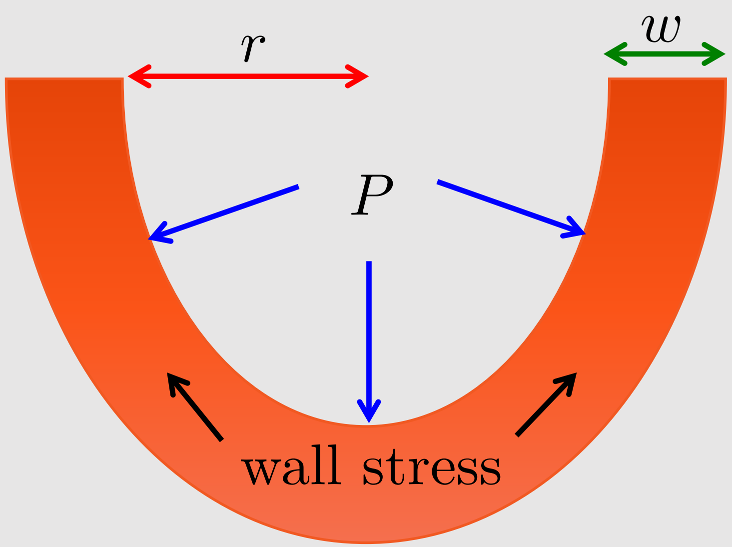
Conservation of angular momentum



Simple geometric models provide intuition about how structure alters mechanics



$\approx$



Law of Laplace (Woods 1892)

$$\text{wall stress} = \frac{P \times r}{2 \times w}$$

P : pressure

r : radius

w : wall thickness

Normal

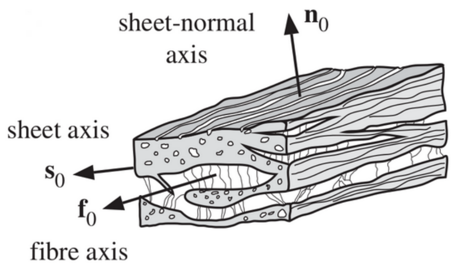
$r \uparrow \implies$ wall stress $\uparrow$

$w \downarrow \implies$ wall stress $\uparrow$

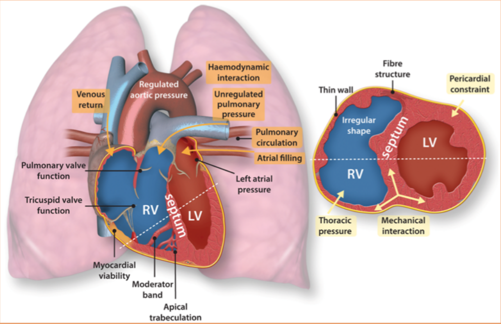
$r \downarrow \implies$ wall stress $\downarrow$

time

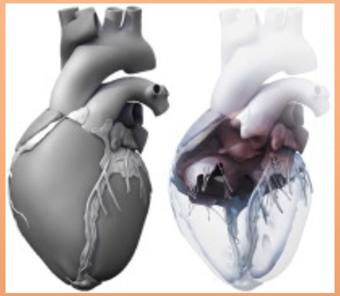
Material properties



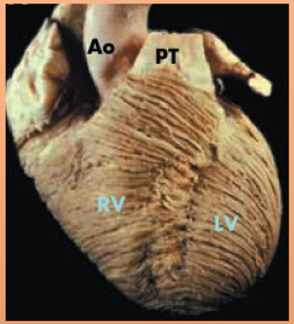
Boundary conditions



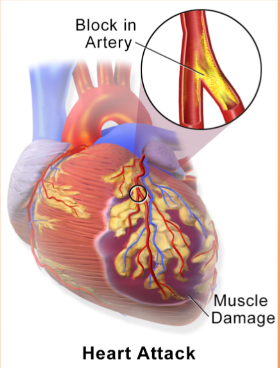
Geometry

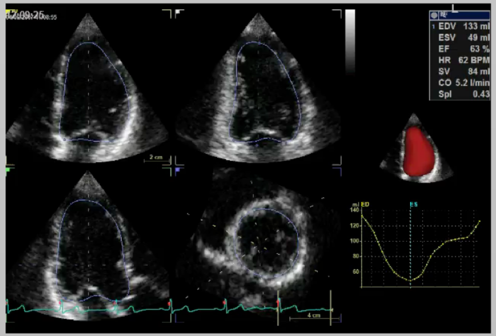


Microstructural architechture



Pathology





Patient specific modeling

Model

Patien t data → Model personali zation black box → Patient-specific model

How do the mechanics and structure of the heart matter in regard to patient-specific cardiac modeling?

Moving from idealized geometries to patient specific geometries

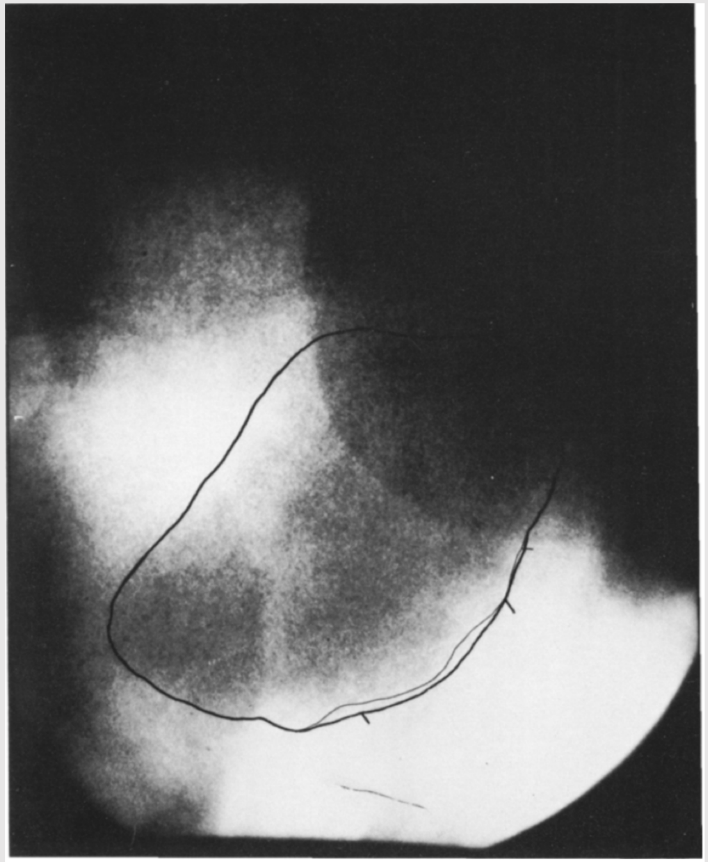


Fig. 1. An X-ray film of the left ventricle in anteroposterior projection.

Peak stress

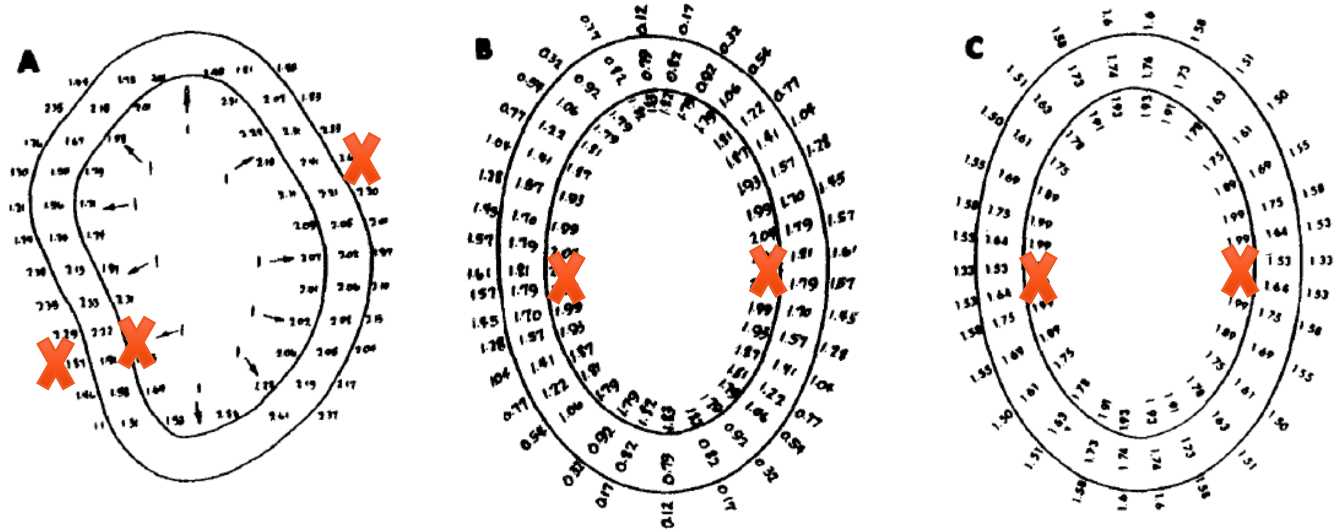
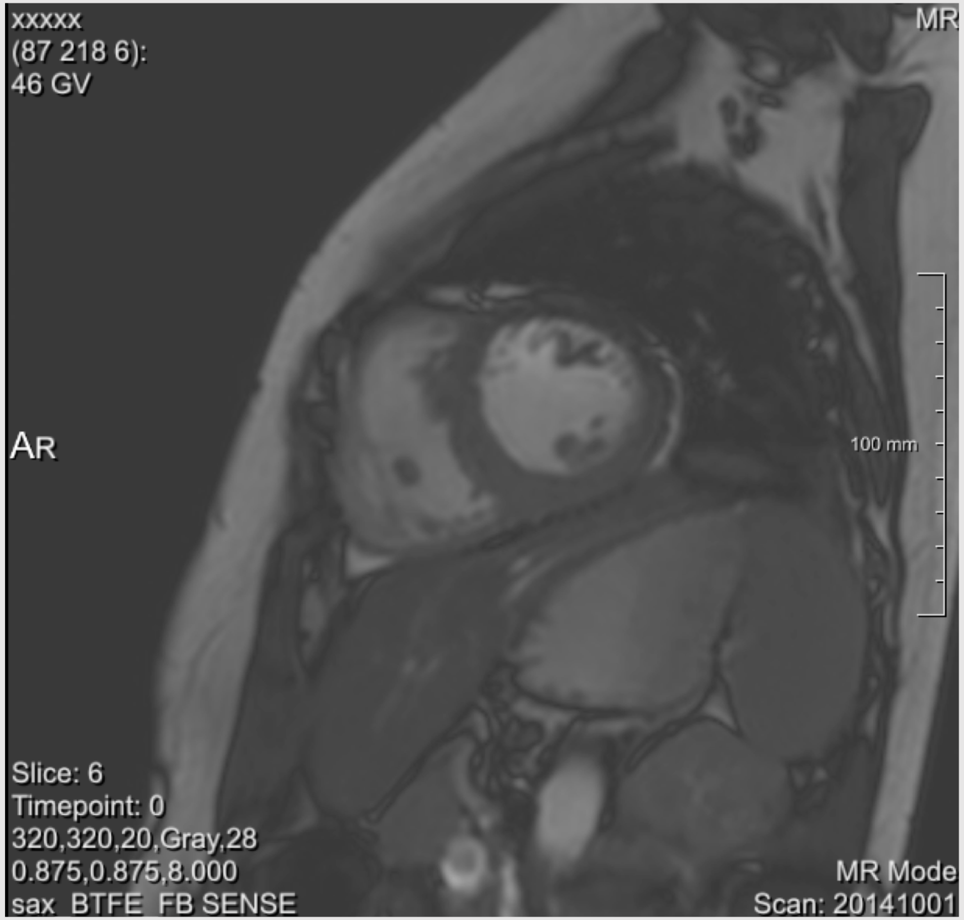
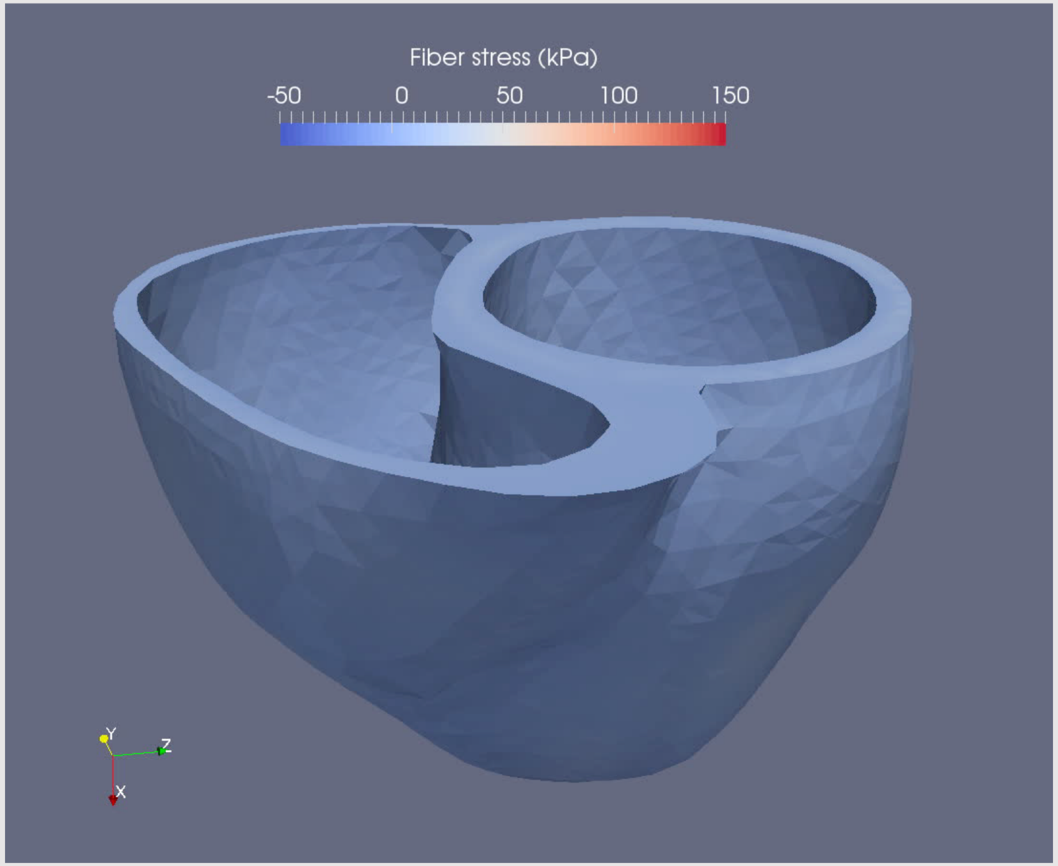


Fig. 9. Comparison of circumferential stress distribution
(A) Finite element model
(B) Mirsky Model
(C) Ghista Model.

Gould, P., Ghista, D., Brombolich, L. and Mirsky, I., 1972. In vivo stresses in the human left ventricular wall: analysis accounting for the irregular 3-dimensional geometry and comparison with idealised geometry analyses. Journal of biomechanics, 5(5), pp.521IN13523-522539.

Today, advanced imaging techniques provide us with detailed anatomical structure





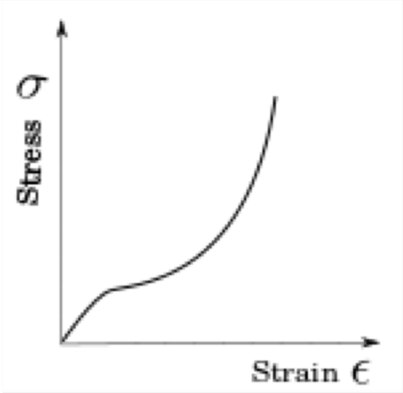
The UT-Heart

https://www.youtube.com/watch?v=2LPboySOSvo

Stress in a material is related to the deformation through constitutive laws

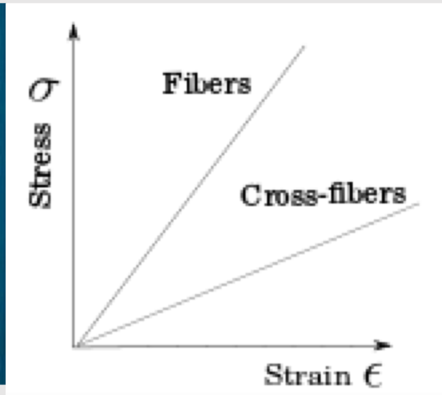
Rubber

Nonlinear isotropic



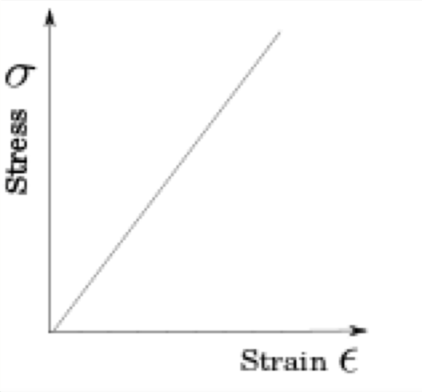
Fiber reinforced concrete

Linear anisotropic



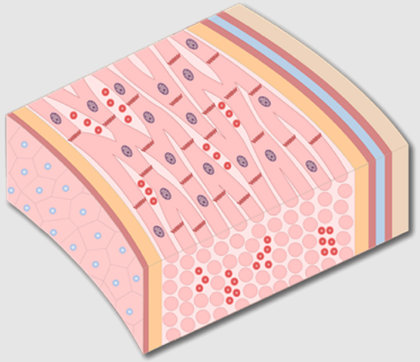
Steel

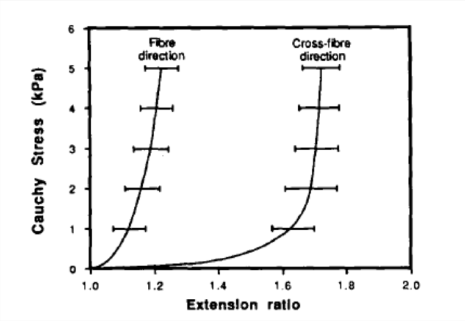
Linear isotropic



Myocardium

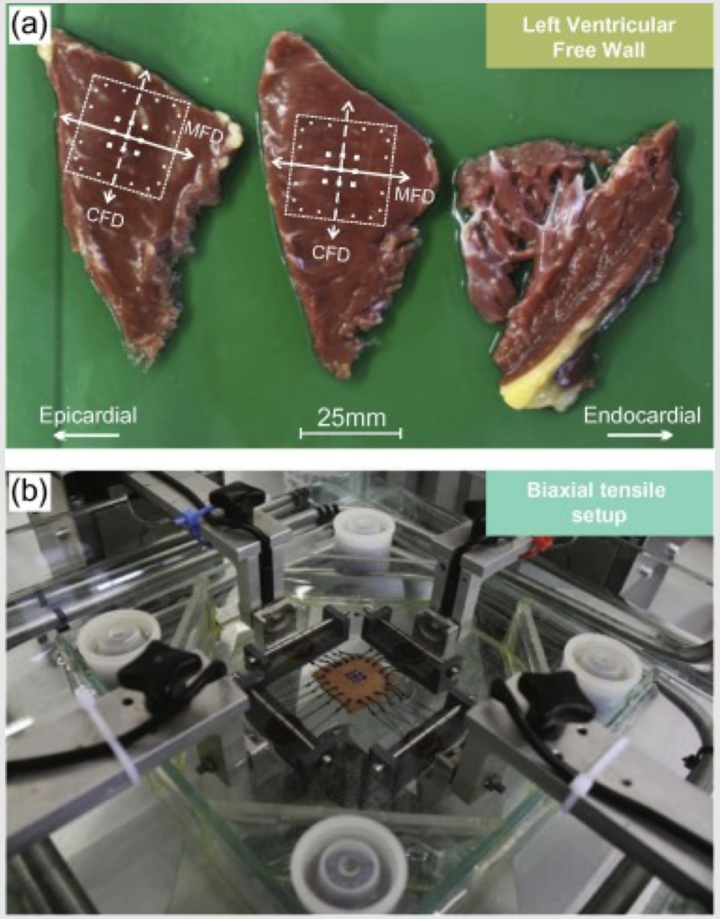
Nonlinear anisotropic

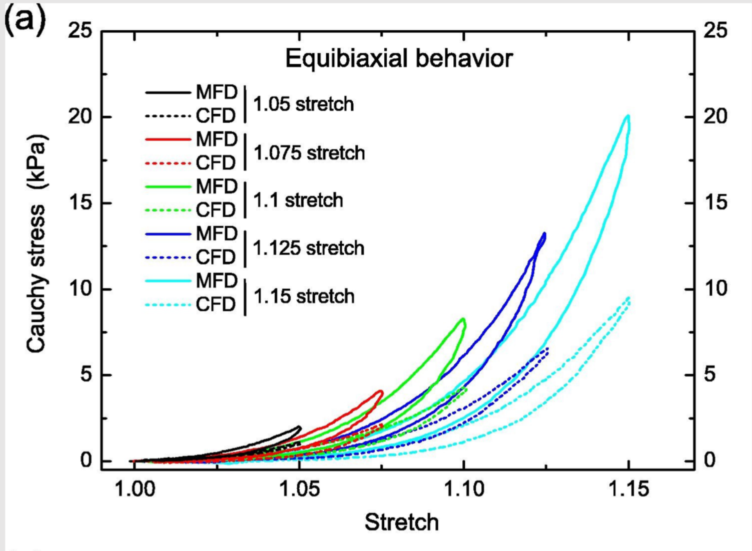


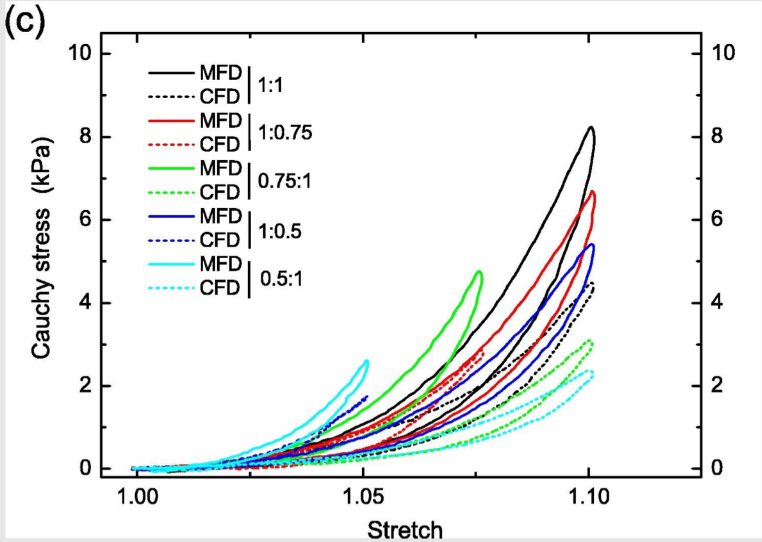


Hunter, P.J. and Smaill, B.H., 1988. The analysis of cardiac function: a continuum approach. Progress in biophysics and molecular biology, 52(2), pp.101-164.a

Material properties can be assessed through biaxial experiments

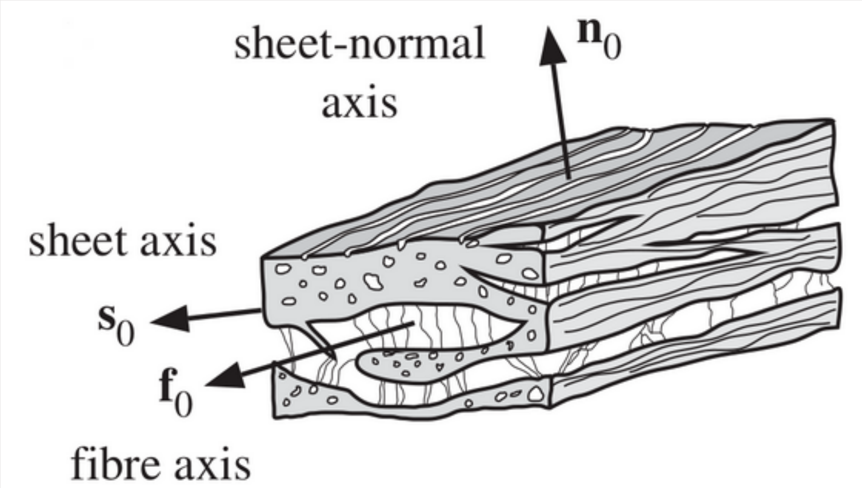




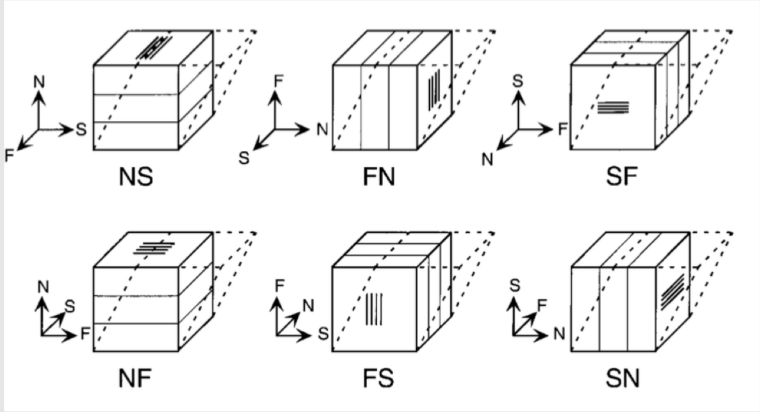


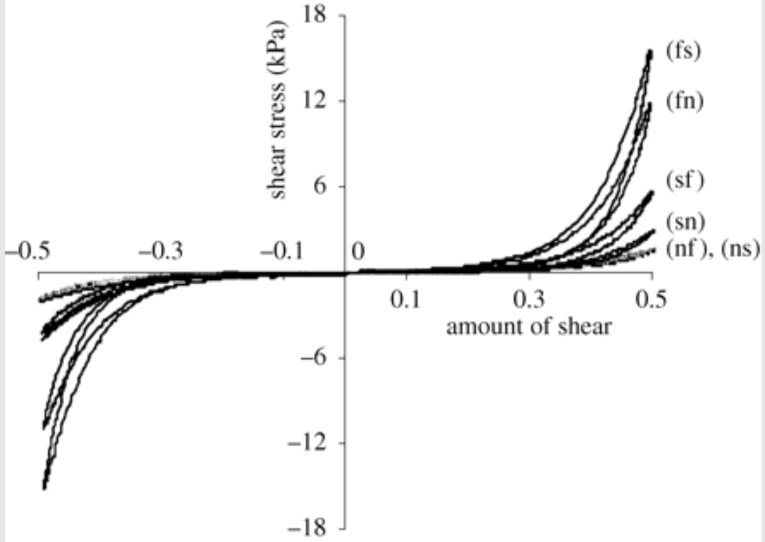
Sommer, G., Schriefl, A.J., Andrä, M., Sacherer, M., Viertler, C., Wolinski, H. and Holzapfel, G.A., 2015. Biomechanical properties and microstructure of human ventricular myocardium. Acta biomaterialia, 24, pp.172-192.

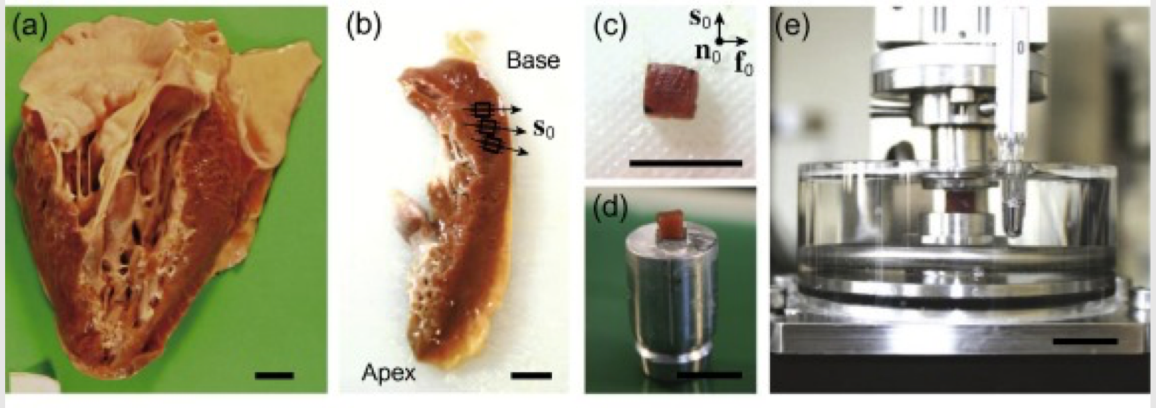
Today experimental data suggests that the myocardium is orthotropic



Holzapfel, G.A. and Ogden, R.W., 2009. Constitutive modelling of passive myocardium: a structurally based framework for material characterization. Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences, 367(1902), pp.3445-3475.



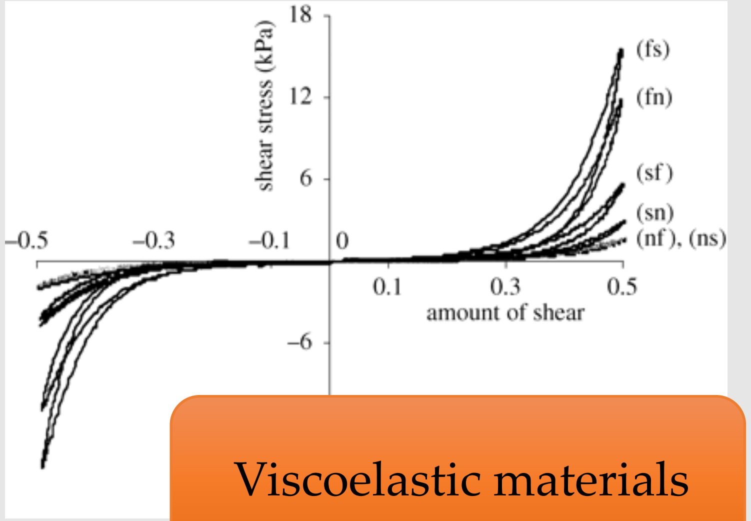




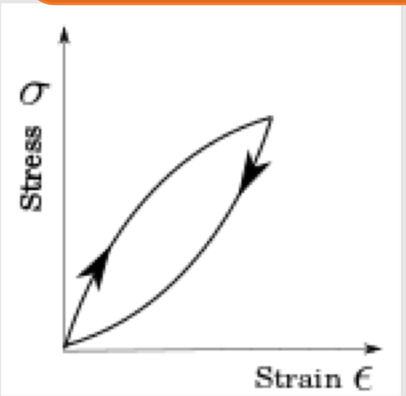
Sommer, G. et. al, 2015. Biomechanical properties and microstructure of human ventricular myocardium. Acta biomaterialia, 24, pp.172-192.

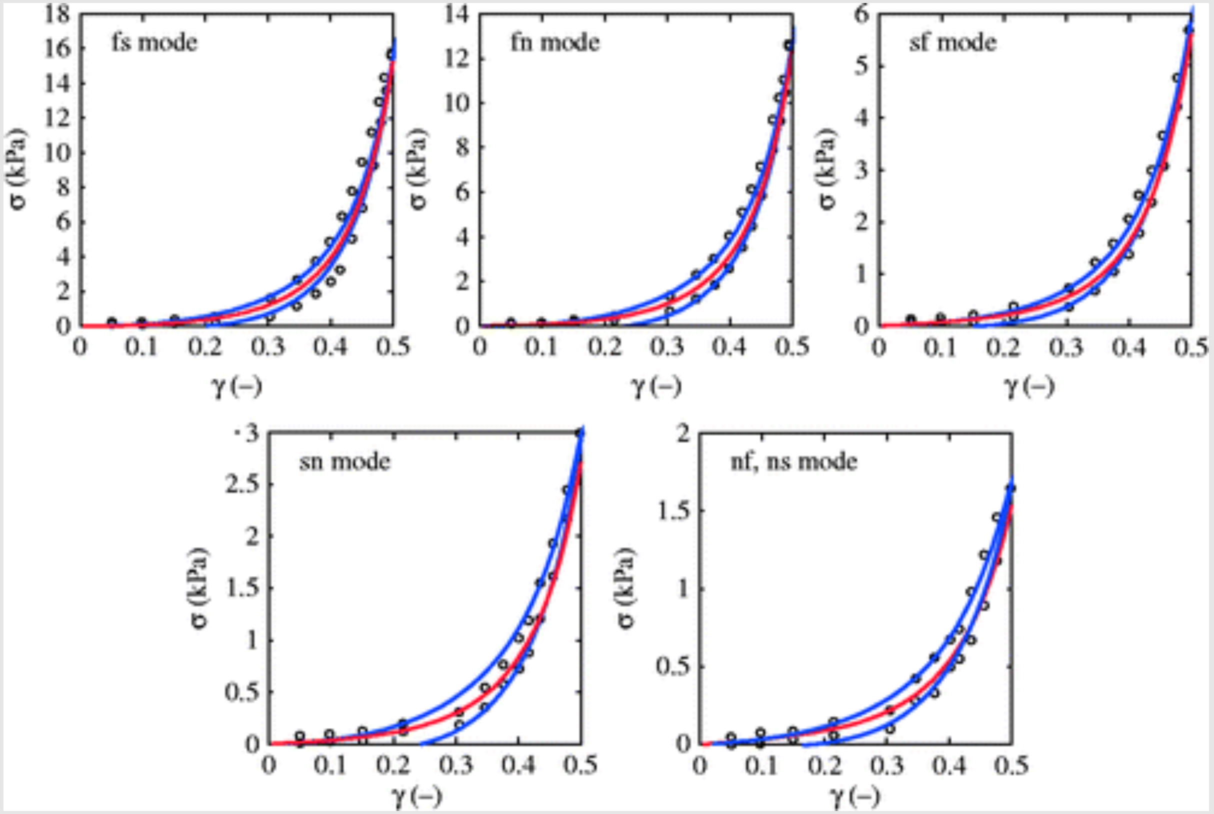
Dokos, S. et. al, 2002. Shear properties of passive ventricular myocardium. American Journal of Physiology-Heart and Circulatory Physiology, 283(6), pp.H2650-H2659.

Hysteresis can be captured with a viscoelastic model



Viscoelastic materials





Cansız, F.B.C., Dal, H. and Kaliske, M., 2015. An orthotropic viscoelastic material model for passive myocardium: theory and algorithmic treatment. Computer methods in biomechanics and biomedical engineering, 18(11), pp.1160-1172.

How important is the acceleration?

Newton's law of motion $\Sigma F = ma$

$a = 0$

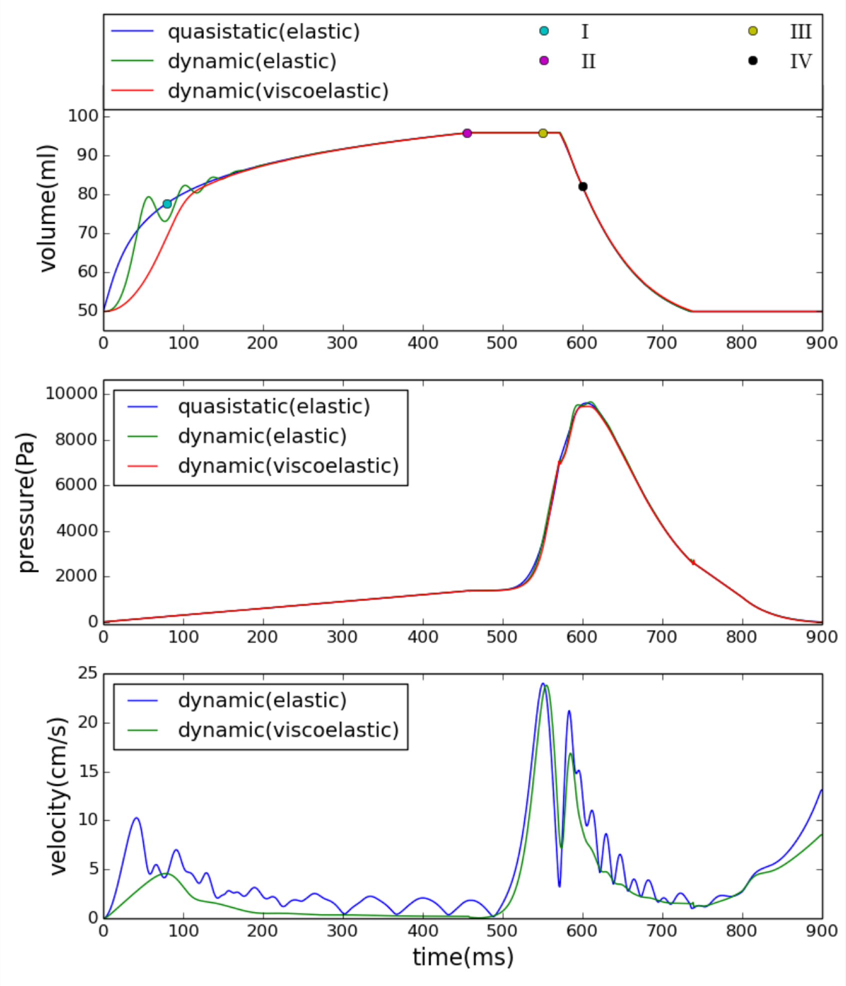
Static

$a \neq 0$

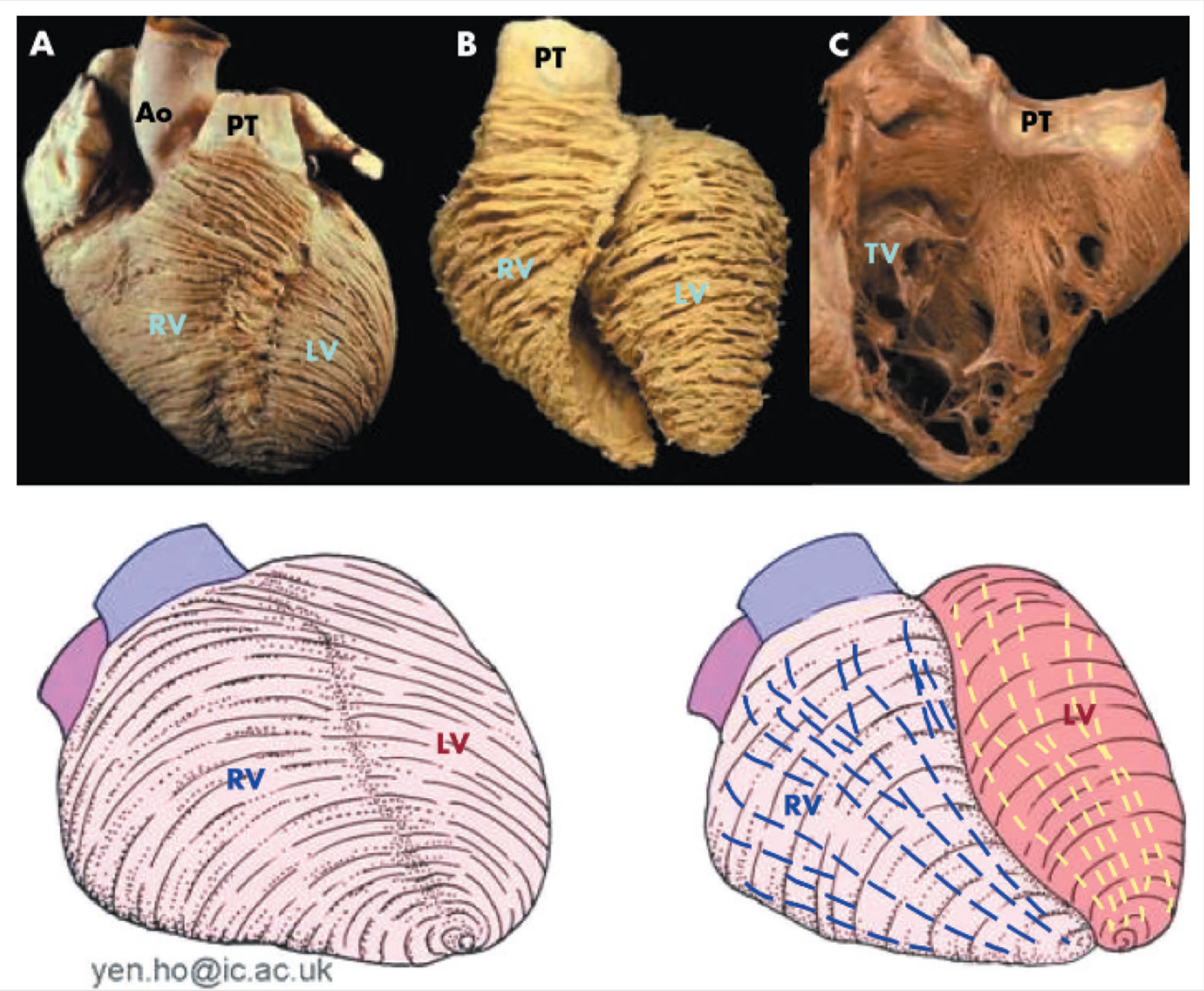
Dynamic

$a \approx 0$

Quasi – Static



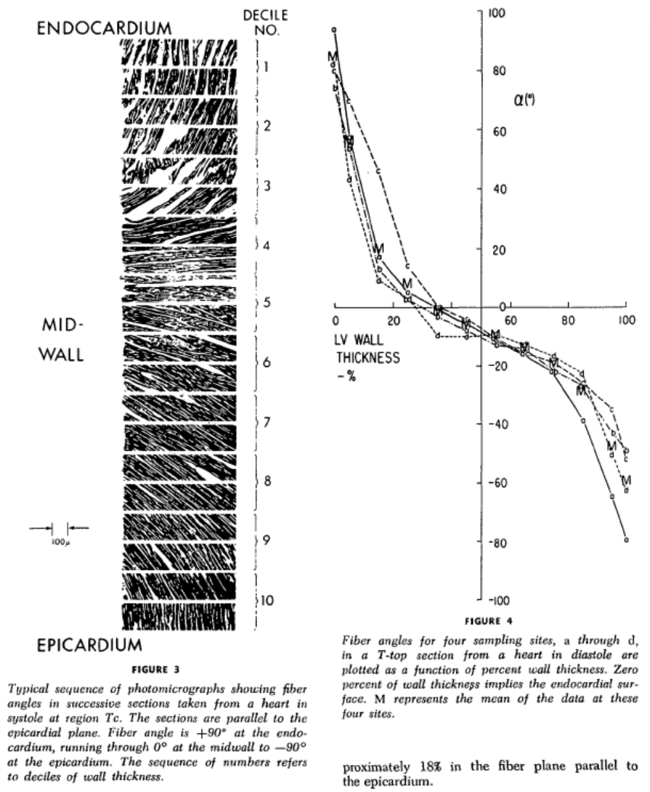
Karlsen, 2017, Effects of Inertia in Modeling of Left Ventricular Mechanics (Master thesis)



Ho, S.Y. and Nihoyannopoulos, P., 2006. Anatomy, echocardiography, and normal right ventricular dimensions. Heart, 92(suppl 1), pp.i2-i13.

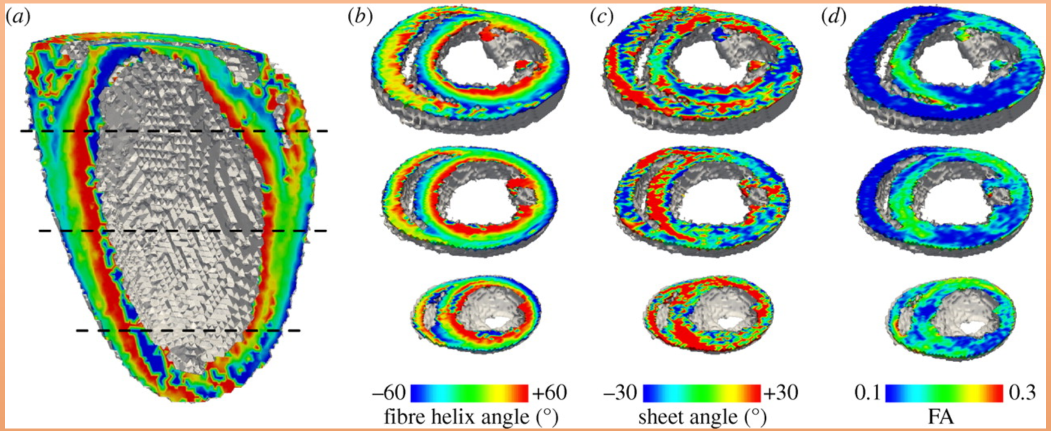
Cardiac microstructural architecture can be incorporated using different techniques

Histological studies



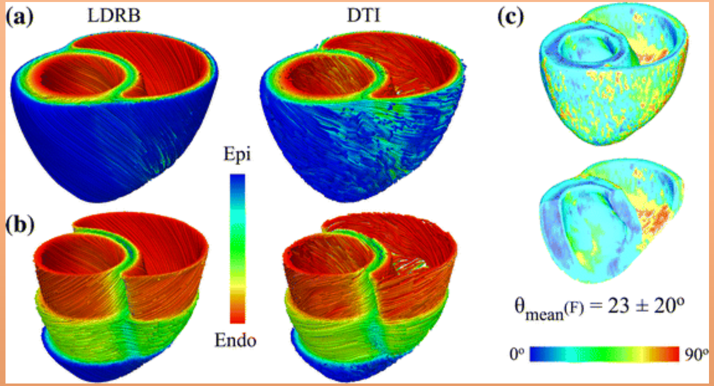
Streeter et. al. "Fiber orientation in the canine left ventricle during diastole and systole." Circulation research 24, no. 3 (1969): 339-347.

Diffusion Tensor MRI



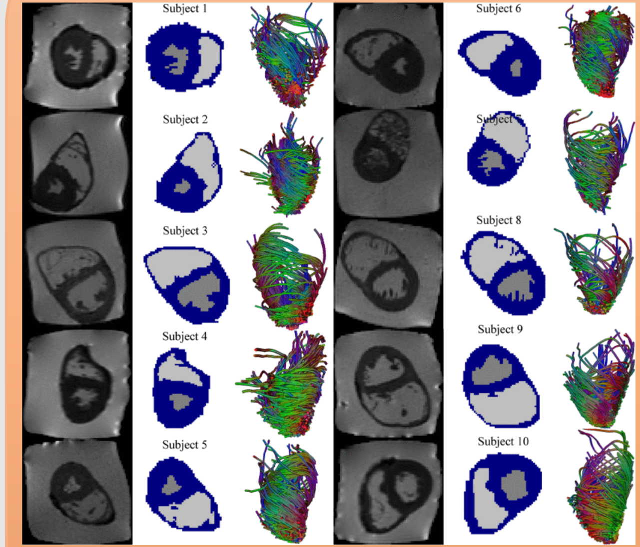
Benson et. al, 2010. Construction and validation of anisotropic and orthotropic ventricular geometries for quantitative predictive cardiac electrophysiology. Interface focus, p.rsfs20100005

Rule-based methods



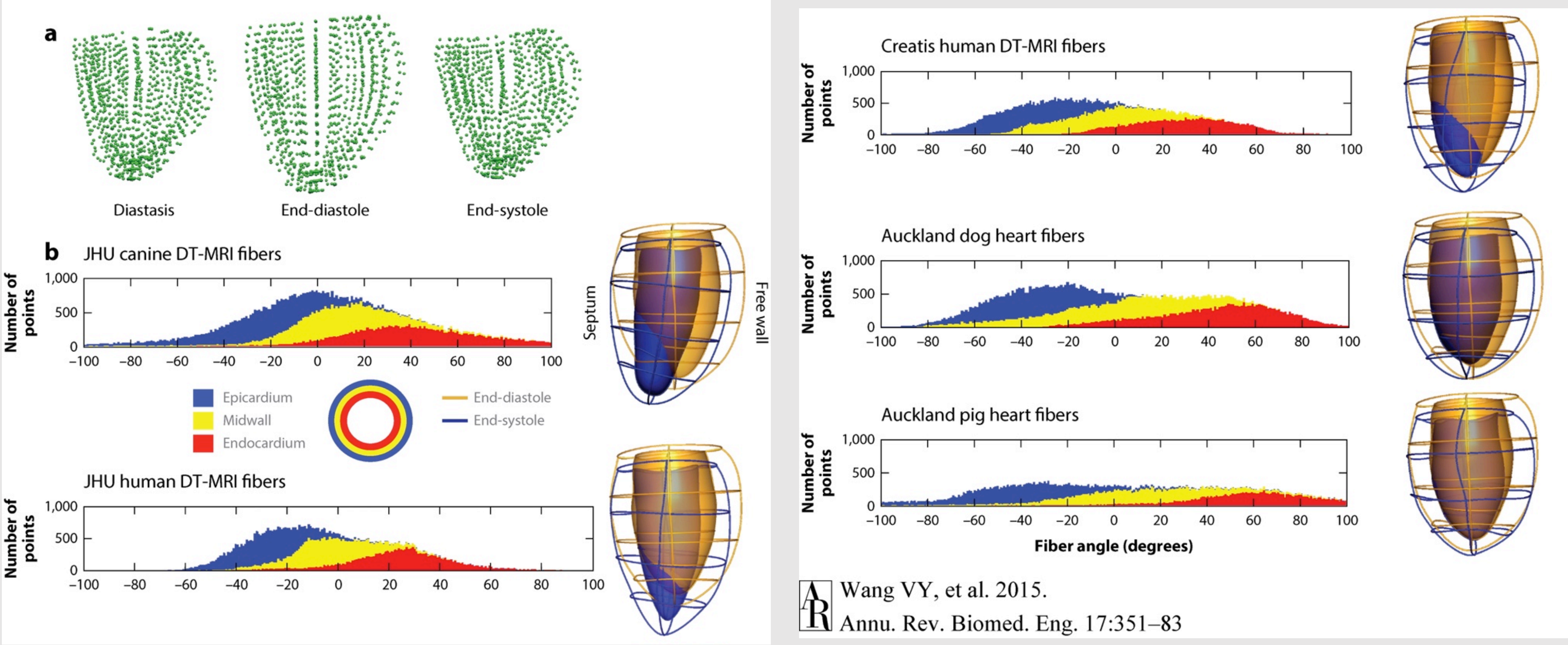
Bayer et. al, 2012. A novel rule-based algorithm for assigning myocardial fiber orientation to computational heart models. Annals of biomedical engineering, 40(10), pp.2243-2254.

Cardiac Atlases



Lombaert et. al, 2012. Human atlas of the cardiac fiber architecture: study on a healthy population. IEEE transactions on medical imaging, 31(7), pp.1436-1447.

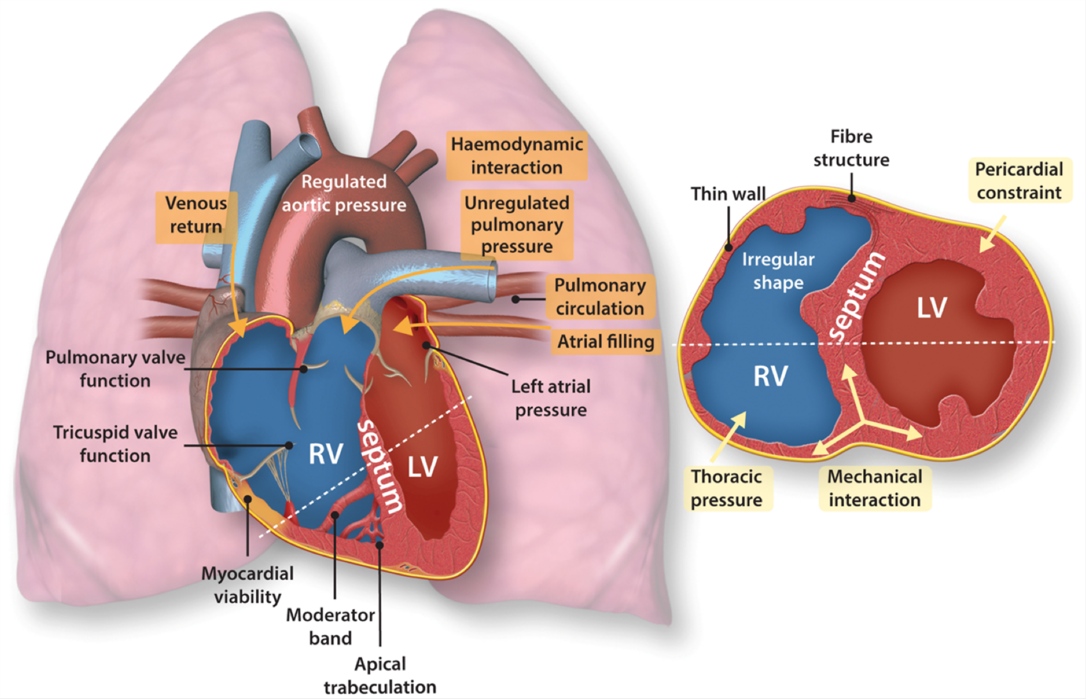
A model with more vertically oriented fibers would predict greater long-axis shortening during contraction



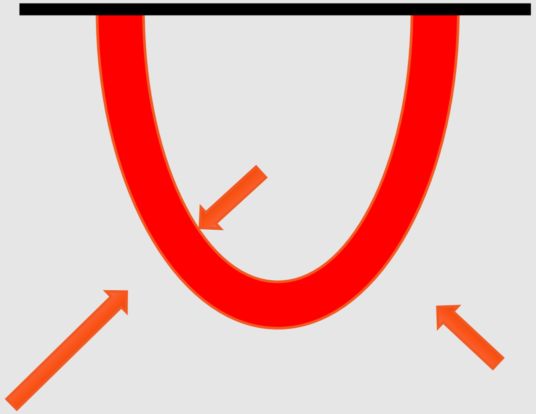
(a) Experimental data at diastasis, end-diastole, and end-systole

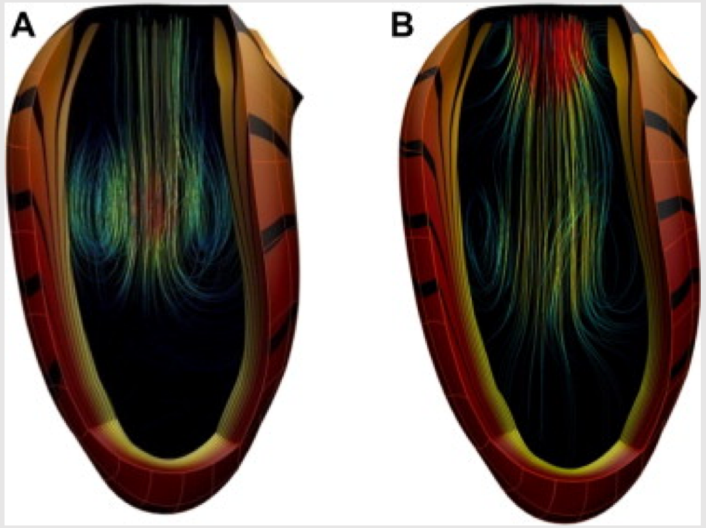
(b) (*Left*) Comparison of fiber-angle histograms for three diffusion tensor MRI (DT-MRI) and two histologically measured data sets. (*Right*) The associated predictions for LV mechanics at end-diastole (*gold*) and end-systole (*blue*)

Boundary conditions should reflect what is observed clinically

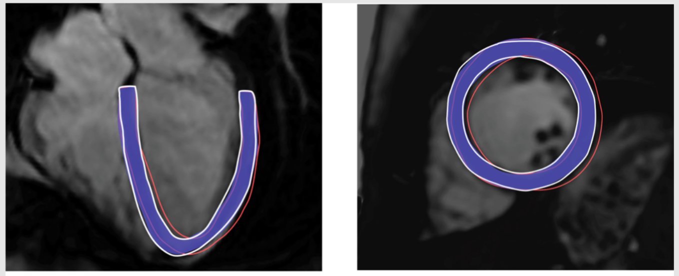


Walmsley et. al, , 2017. Combining computer modelling and cardiac imaging to understand right ventricular pump function. Cardiovascular research, 113(12), pp.1486-1498.





Nordsletten et. al, 2011. Coupling multi-physics models to cardiac mechanics. Progress in biophysics and molecular biology, 104(1), pp.77-88.



Asner, et. al, 2017. Patient-specific modeling for left ventricular mechanics using data-driven boundary energies. Computer Methods in Applied Mechanics and Engineering, 314, pp.269-295.

Heart diseases can change the properties of the myocardium

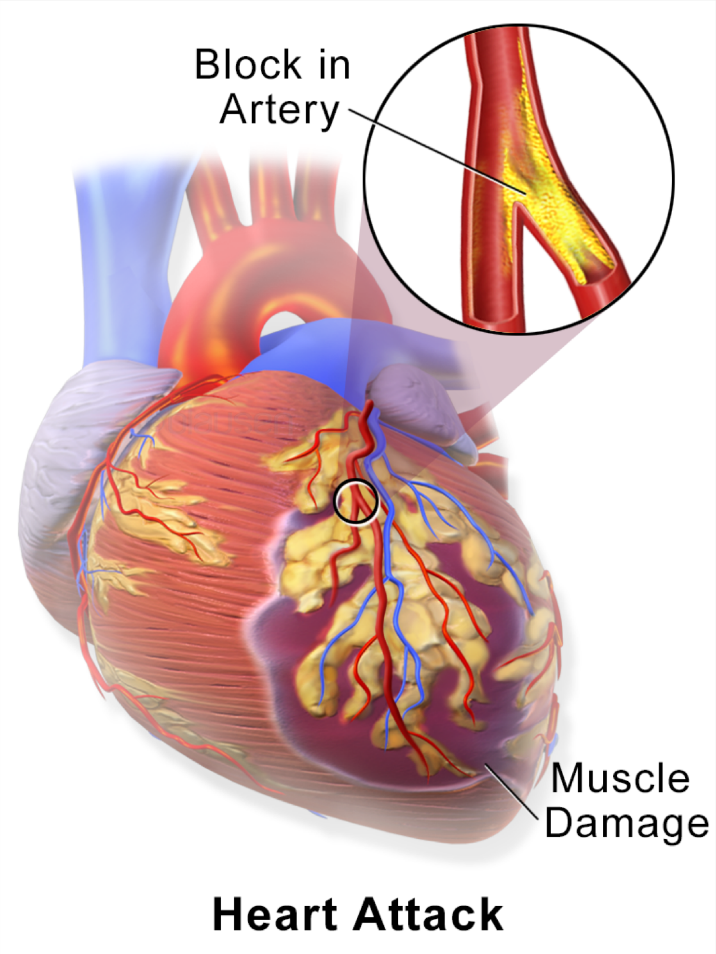
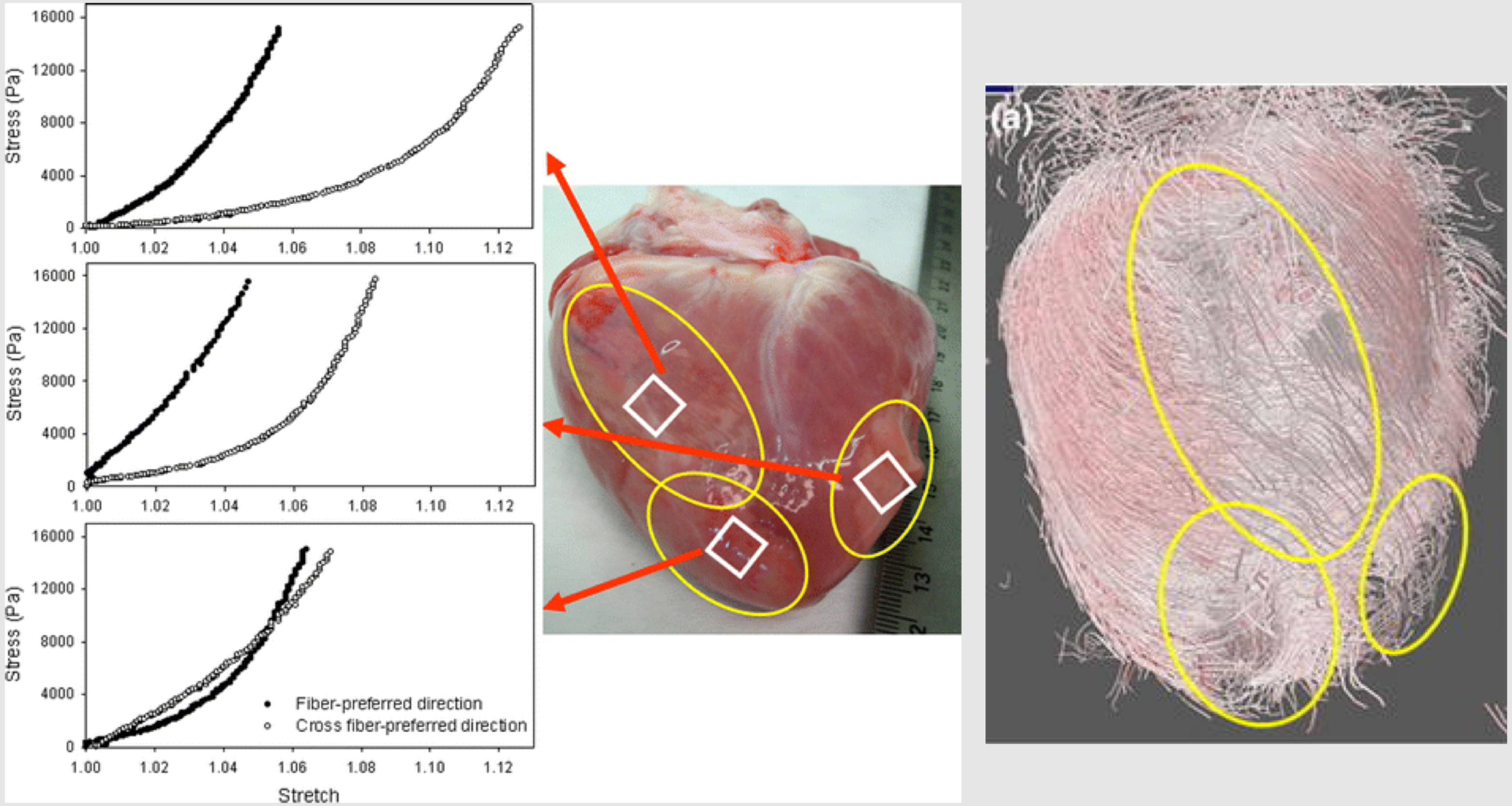
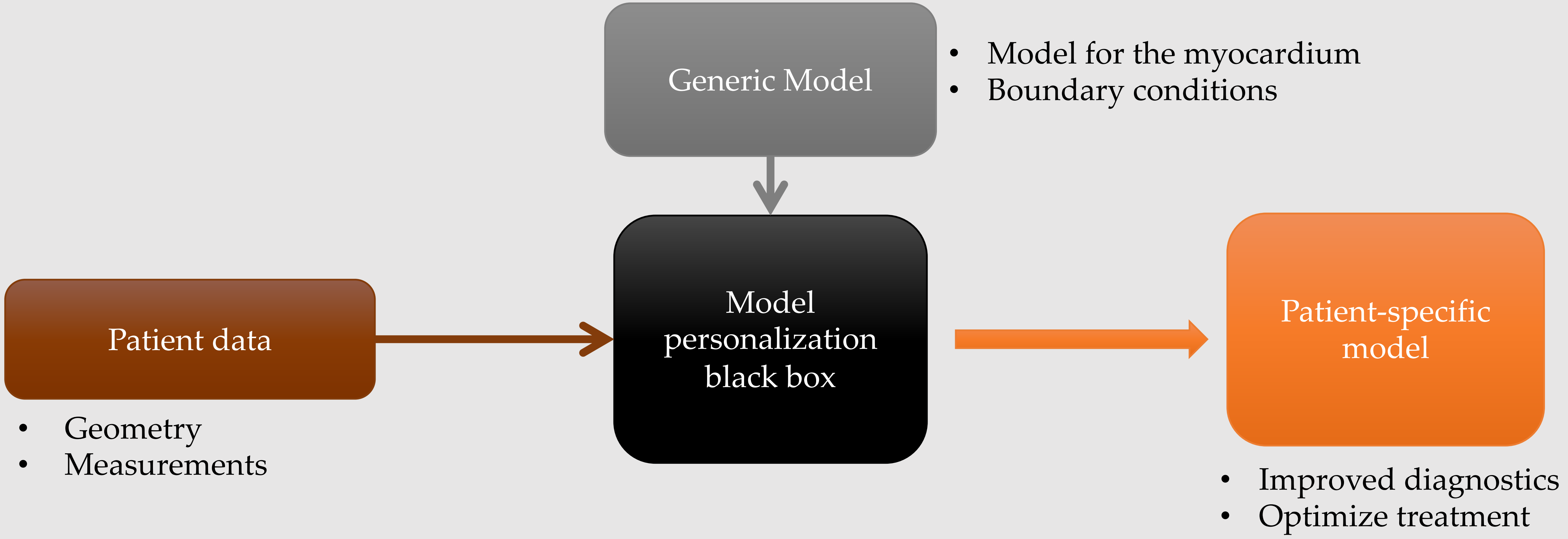


Image source: Wikipedia:Myocardial_infarction

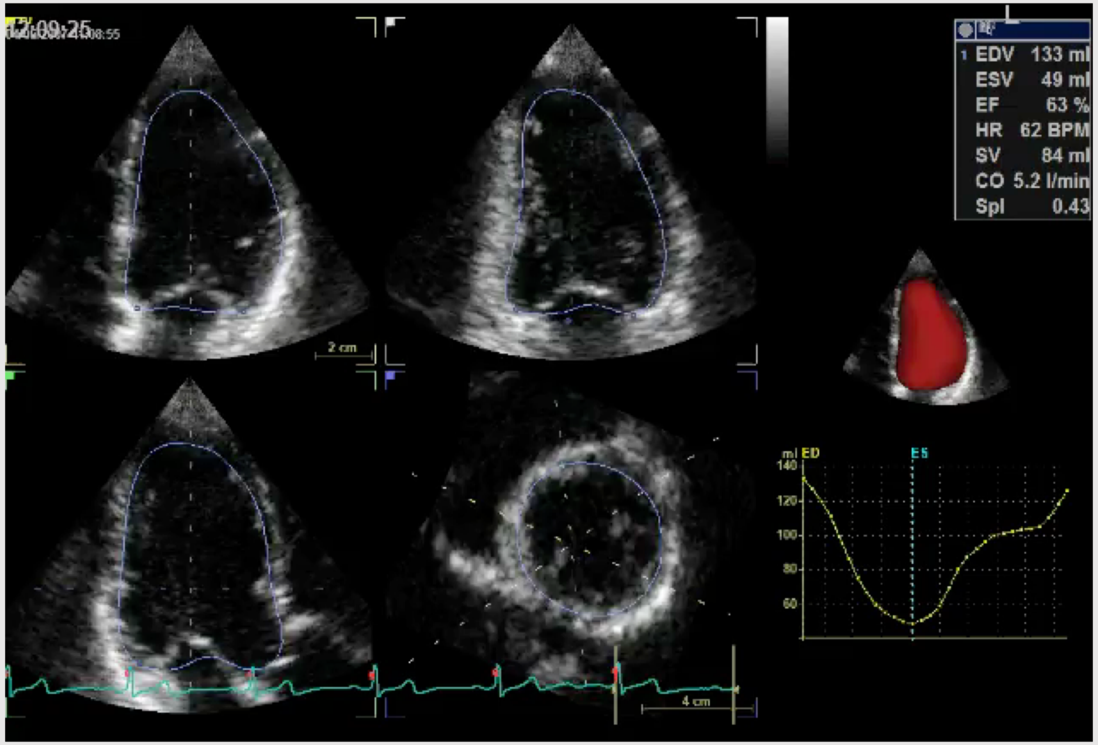


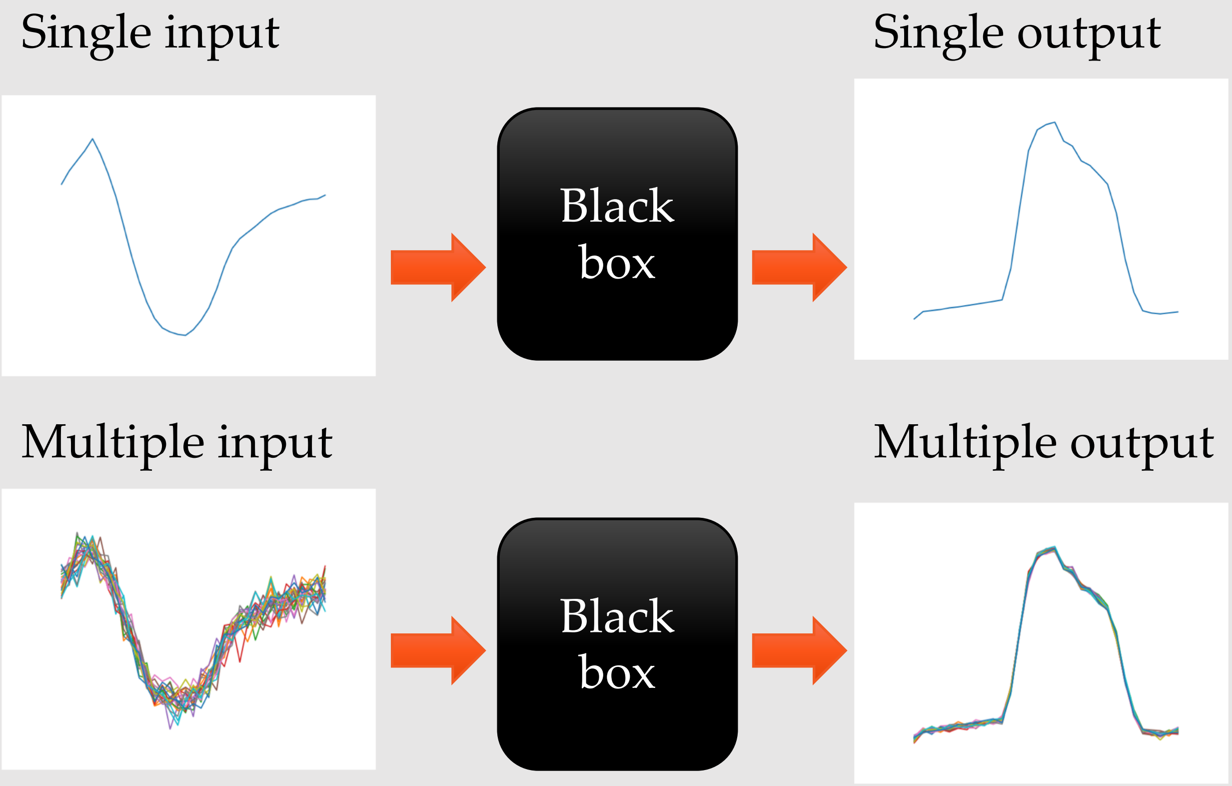
Zhang, , 2010. The correlation of 3D DT-MRI fiber disruption with structural and mechanical degeneration in porcine myocardium. Annals of biomedical engineering, 38(10), pp.3084-3095.

Patient-specific modeling is the development of computational models that are individualized to patient-specific data



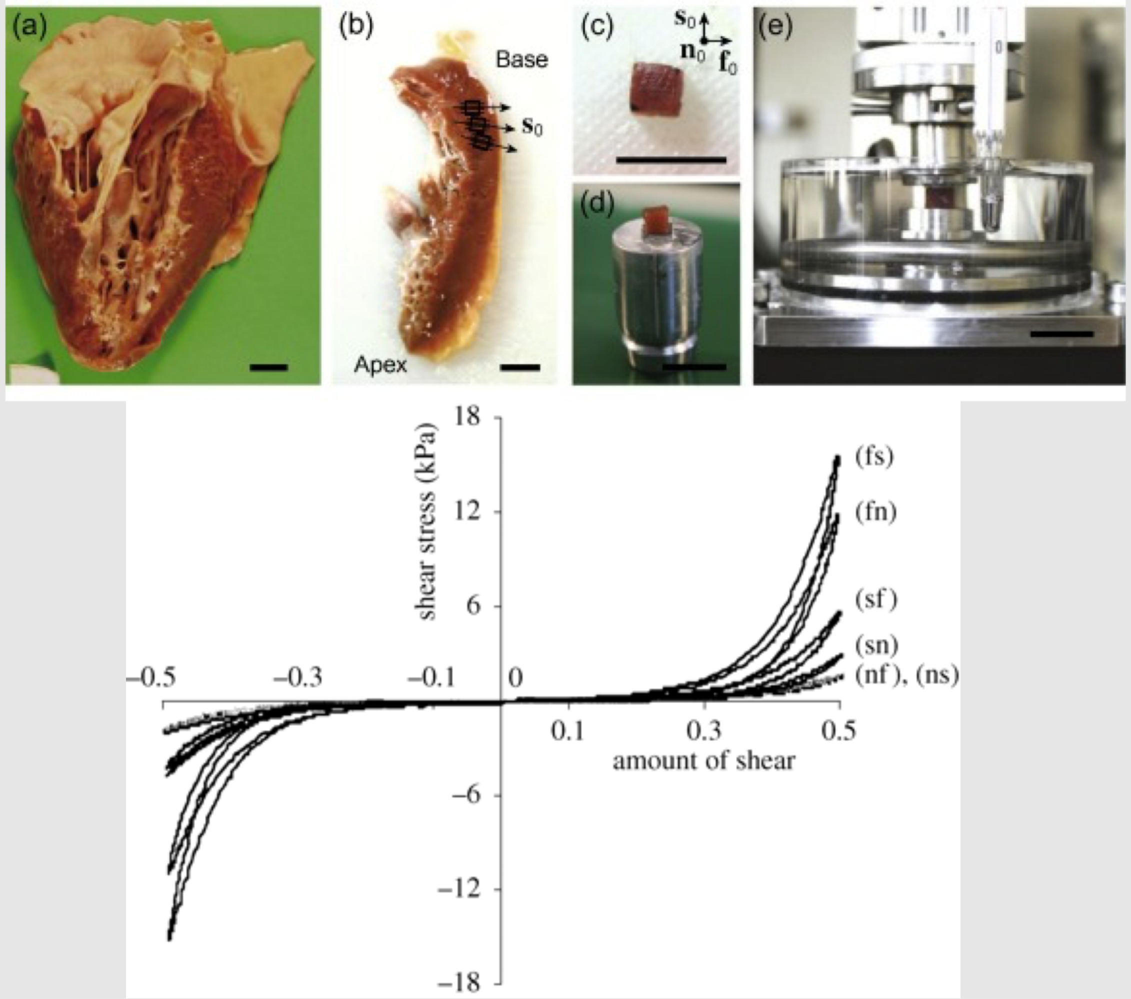
Patient data contains uncertainty

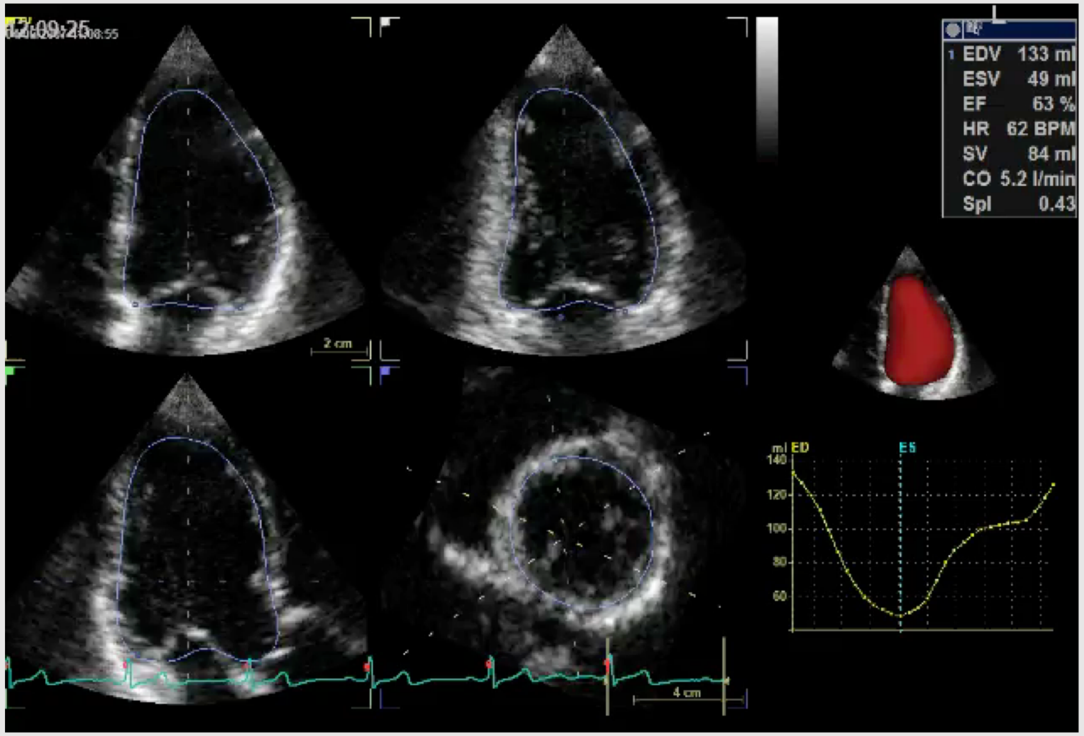




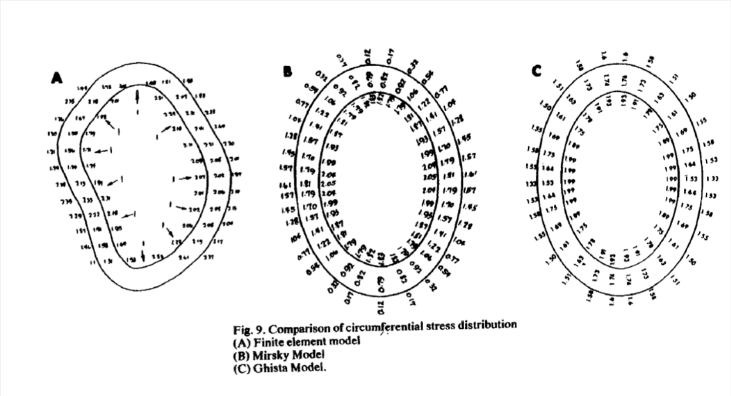
How do the mechanics and structure of the heart matter in regard to patient-specific cardiac modelling?

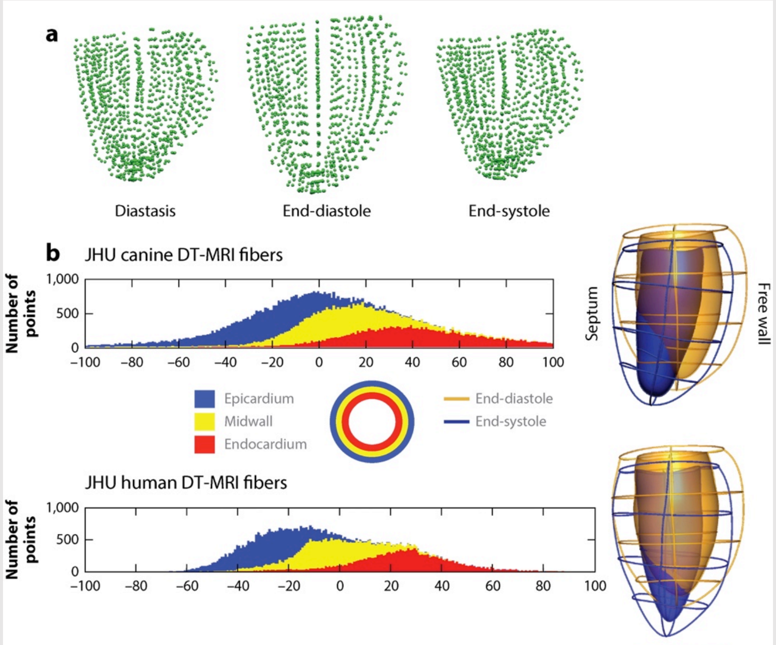
How the mechanics and structure of the heart matter depends on the data that you have





How the mechanics and structure of the heart matter depends on the questions you want to ask

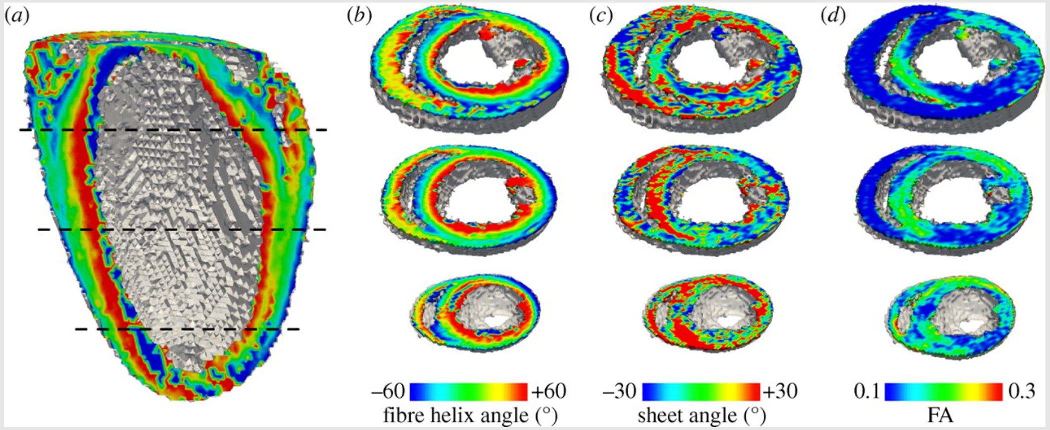




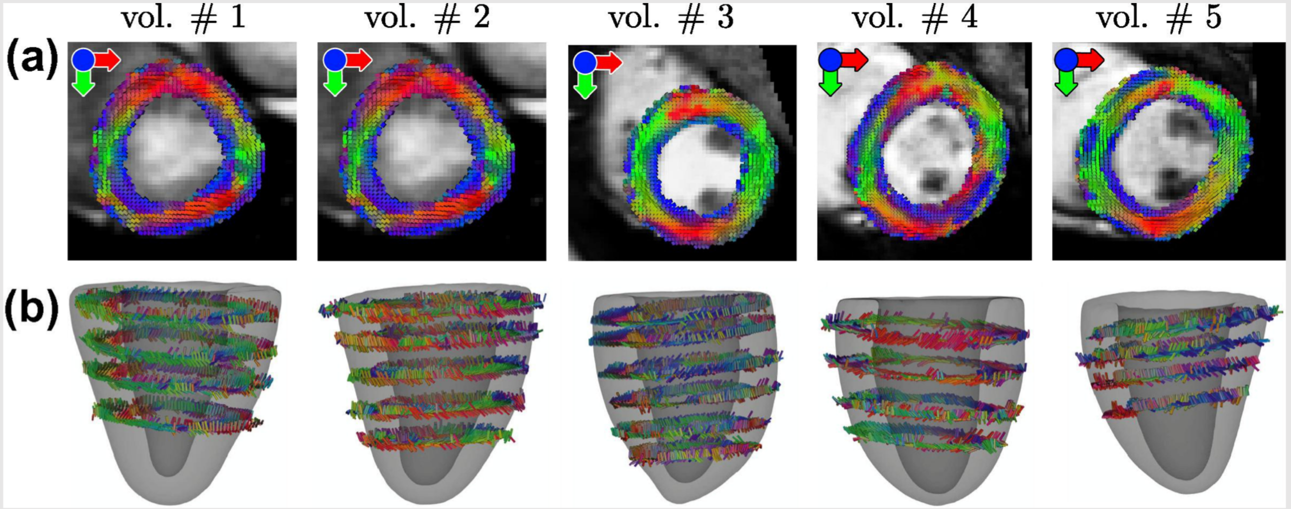
Single input

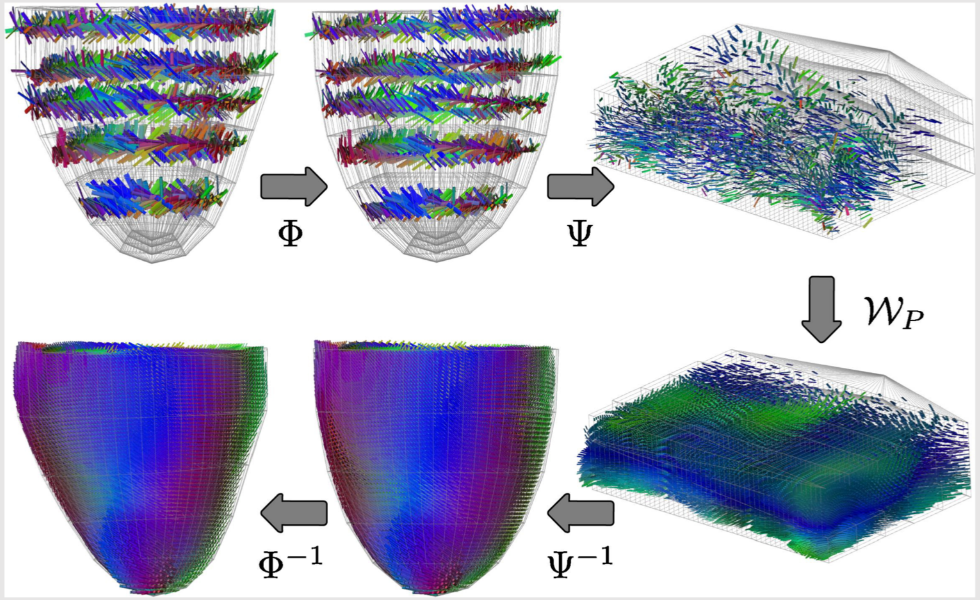
Multiple input

Measuring the cardiac microstructural architecture using imaging techniques



Benson et. al, 2010. Construction and validation of anisotropic and orthotropic ventricular geometries for quantitative predictive cardiac electrophysiology. Interface focus, p.rsfs20100005

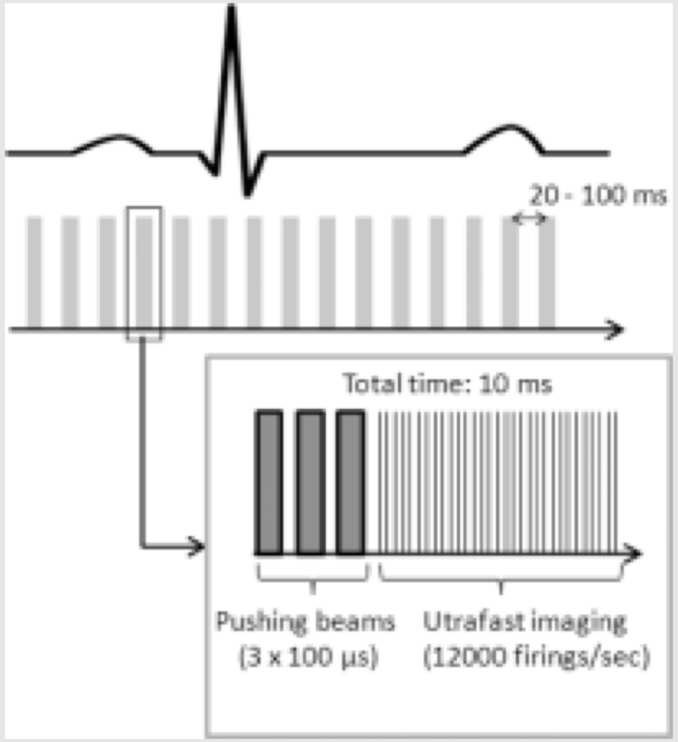




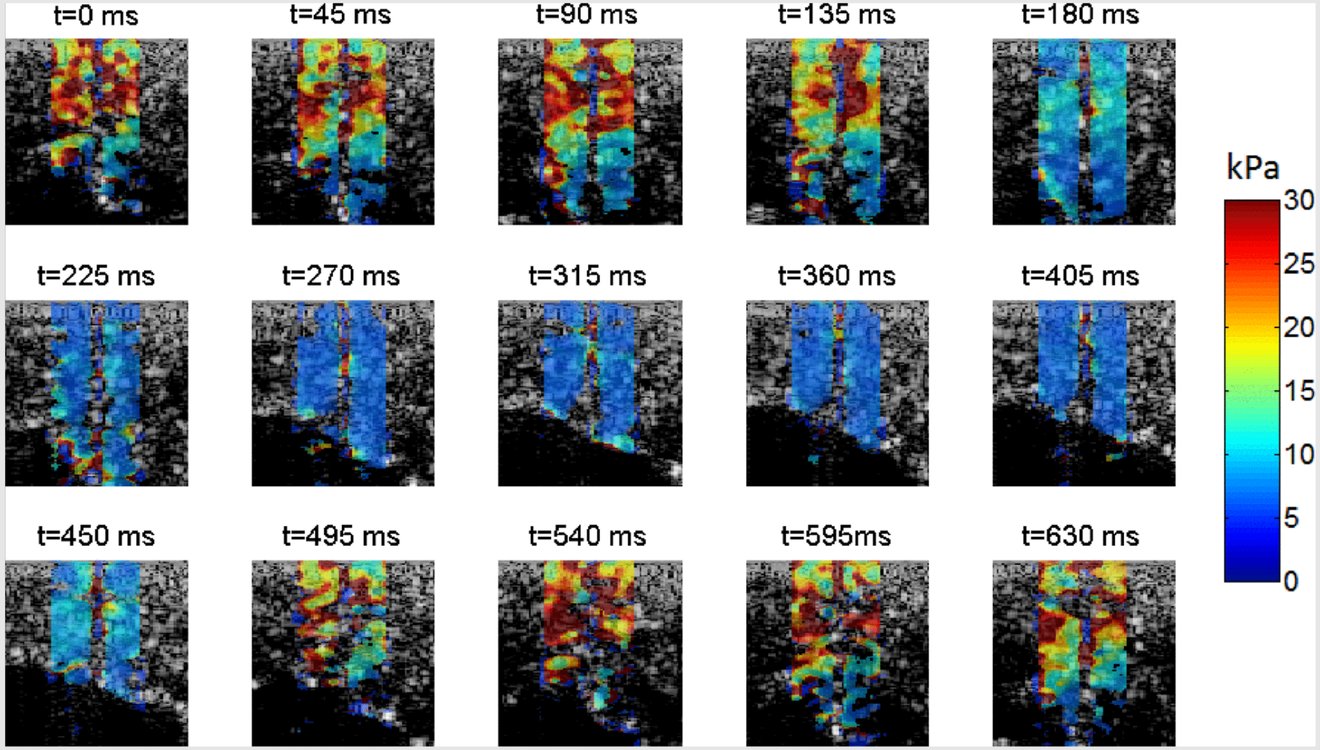
Toussaint, N. et. al, 2013. In vivo human cardiac fibre architecture estimation using shape-based diffusion tensor processing. Medical image analysis, 17(8), pp.1243-1255.

Assessment of viscoelastic and anisotropic properties from medical images

Ultrafast imaging detects shear waves



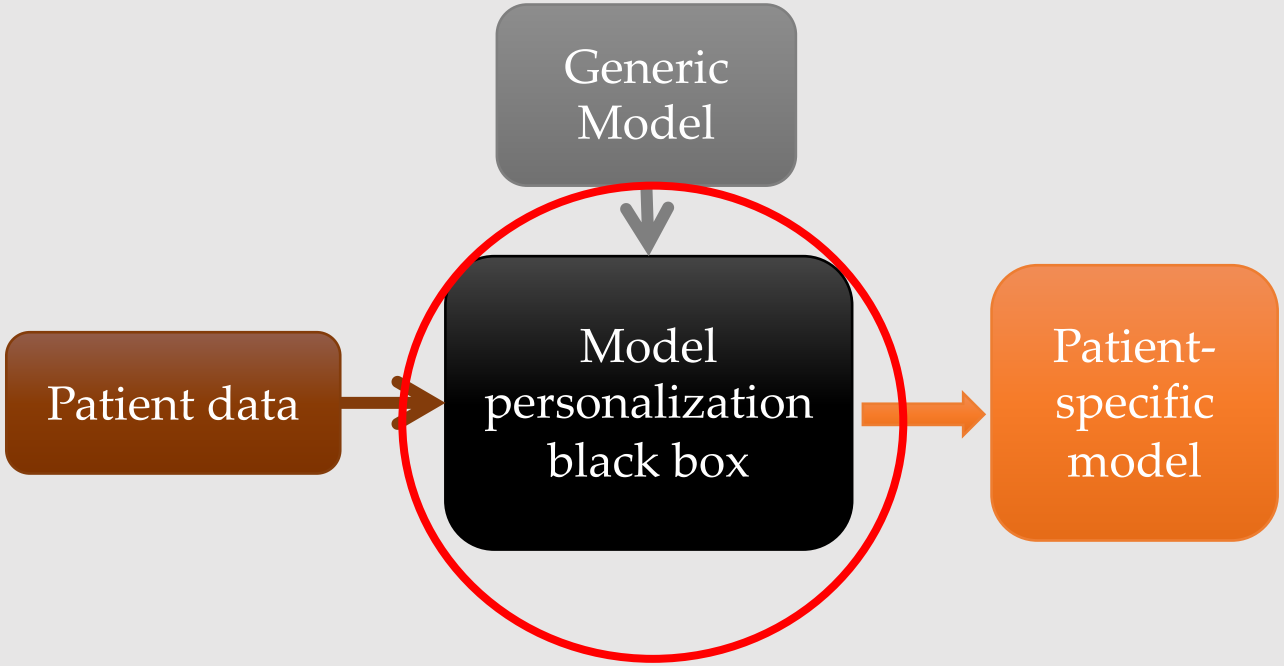
Elasticity maps at different stages during a heart beat

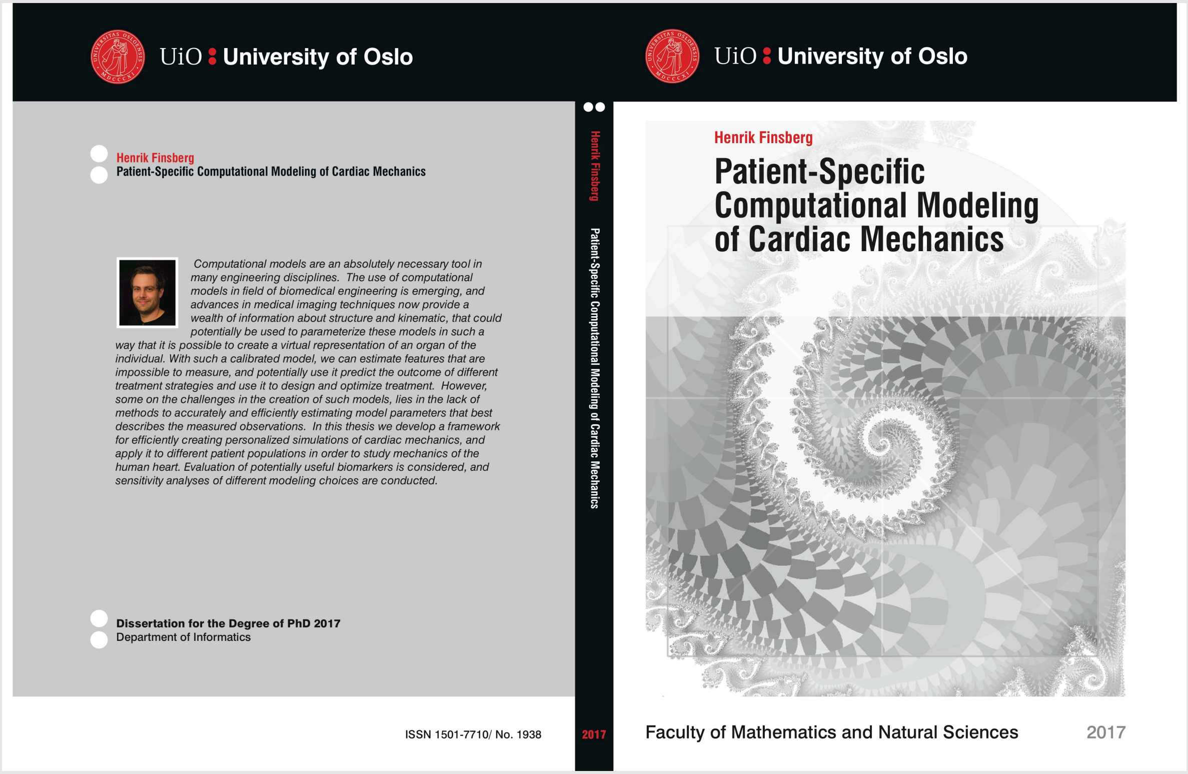


Couade, M. et al, 2011. In vivo quantitative mapping of myocardial stiffening and transmural anisotropy during the cardiac cycle. IEEE transactions on medical imaging, 30(2), pp.295-305.

Patient data can be fused with models using data assimilation

Thank you!

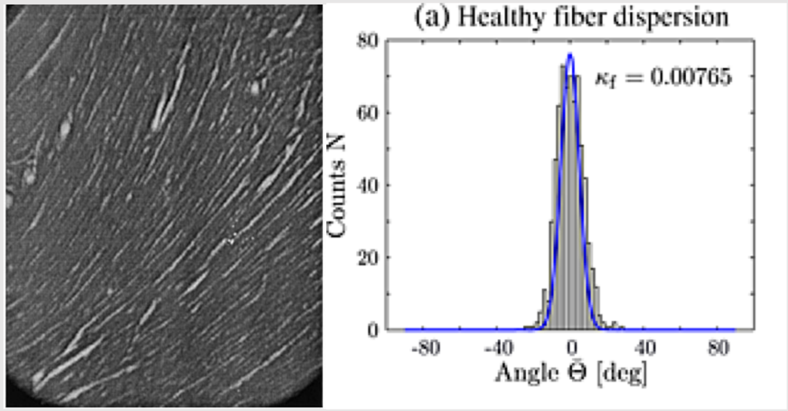




Extra slides

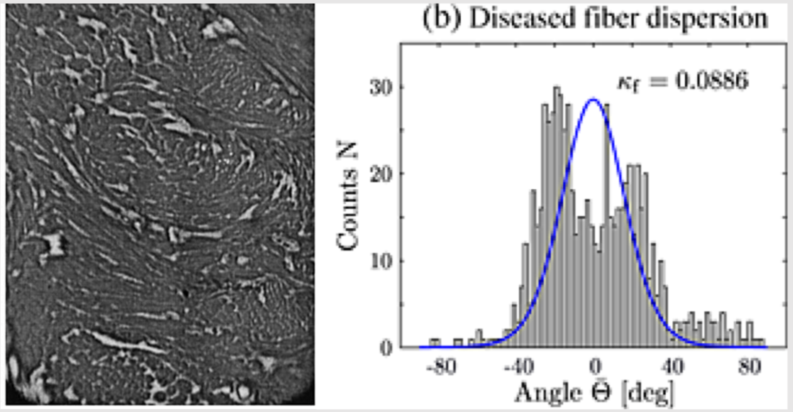
Heart diseases can change the arrangement of muscle fibers

Normal



Eriksson et. al, 2013. Modeling the dispersion in electromechanically coupled myocardium. International journal for numerical methods in biomedical engineering, 29(11), pp.1267-1284.

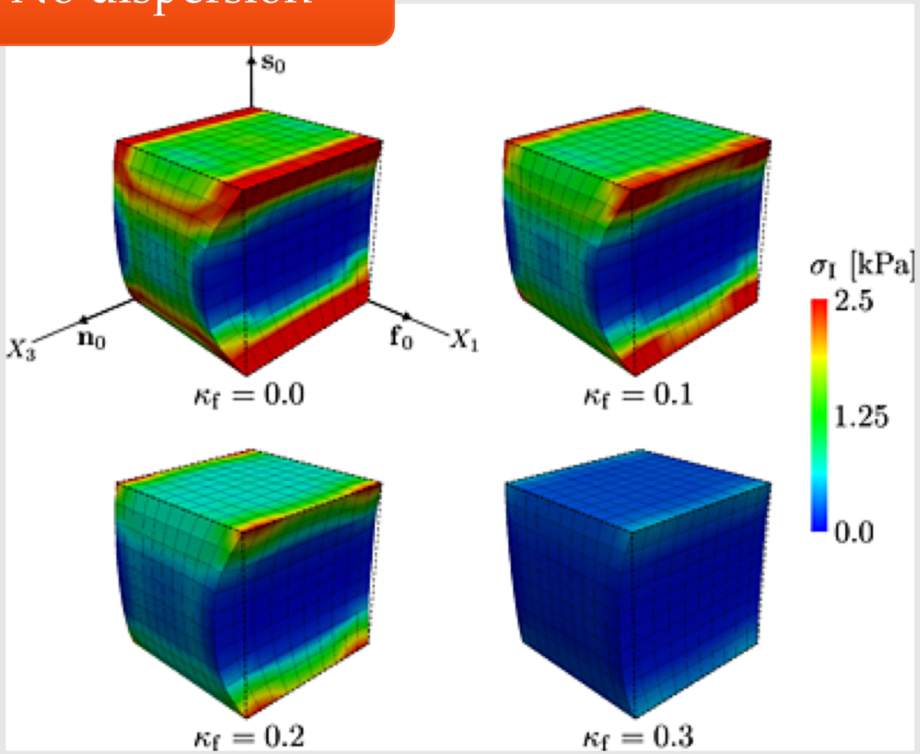
Hypertrophic cardiomyopathy



Karlon et. al, , 2000. Regional dysfunction correlates with myofiber disarray in transgenic mice with ventricular expression of ras. American Journal of Physiology-Heart and Circulatory Physiology, 278(3), pp.H898-H906.

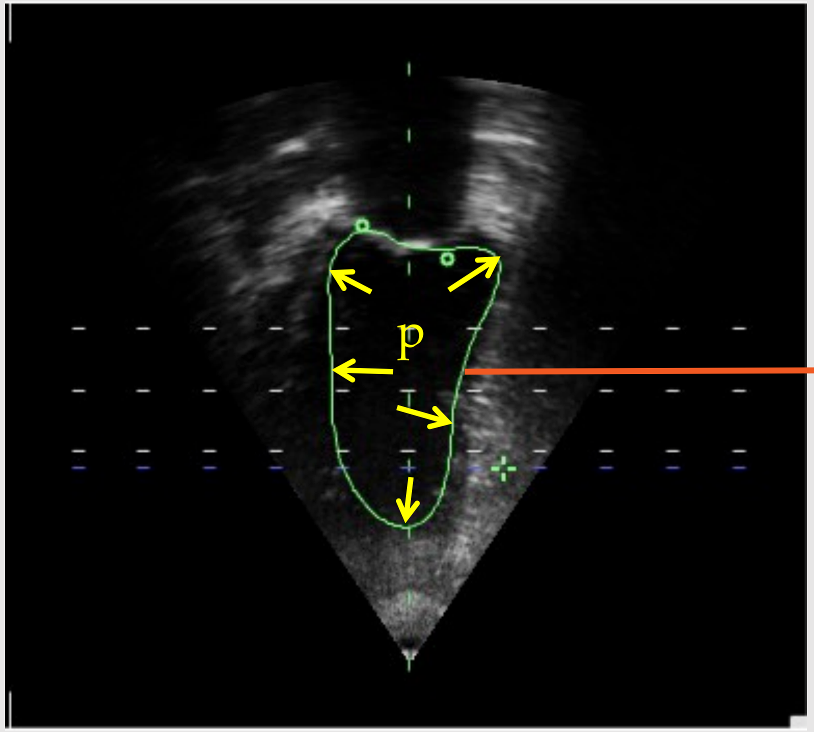
No dispersion

Active cube (+30 mV)



Close to isotropic

Image-based geometries are not stress-free



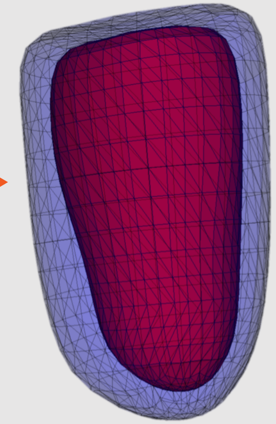
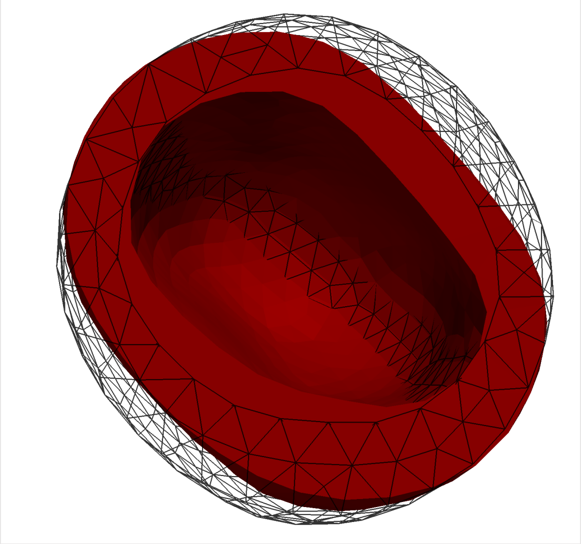


Image-based geometry

Stress-free geometry



Myocardial anisotropy can be modeled using strain energy density functions

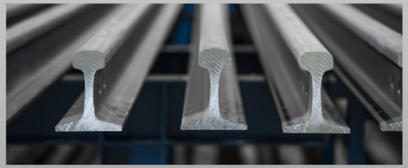
Stress is related to strain via a strain-energy density function

$$\boldsymbol{\sigma} = \frac{1}{\det \mathbf{F}} \frac{\partial \Psi(\mathbf{F})}{\partial \mathbf{F}} \mathbf{F}^T$$

Linear isotropic

$$\Psi(\mathbf{F}) = \frac{\mu}{2}(I_1 - 3)$$

Example: Steel



$$I_1 = \mathrm{tr}(\mathbf{F}^T \mathbf{F})$$

Nonlinear isotropic

$$\Psi(\mathbf{F}) = a(e^{b(I_1 - 3)} - 1)$$

Example: Rubber

Nonlinear transversally isotropic (anisotropic)

$$\Psi(\mathbf{F}) = a(e^{b(I_1 - 3)} - 1) + a_{\mathrm{f}}(e^{b_{\mathrm{f}}(I_{4\mathrm{f}} - 1)^2} - 1)$$

$$I_{4\mathrm{f}} = (\mathbf{F}\mathbf{f}_0)^T \mathbf{F}\mathbf{f}_0$$

$\mathbf{f}_0$: Vectors pointing along the fibers

Example of an orthotropic structural model for the passive myocardoum

$$\Psi(\mathbf{F}) = \frac{a}{2b}\left(e^{b(I_1-3)} - 1\right) + \sum_{i=\mathrm{f,s}} \frac{a_i}{2b_i}\left(e^{b_i(I_{4i}-1)_+^2} - 1\right) + \frac{a_{\mathrm{fs}}}{2b_{\mathrm{fs}}}\left(e^{b_{\mathrm{fs}} I_{8\mathrm{fs}}^2} - 1\right)$$

$$I_{4\mathrm{s}} = (\mathbf{F}\mathbf{s}_0)^T \mathbf{F}\mathbf{s}_0$$

$$I_{8\mathrm{fs}} = (\mathbf{F}\mathbf{f}_0)^T \mathbf{F}\mathbf{s}_0$$

Holzapfel and Ogden (2009)

The myocardium is nearly incompressible

Compressible model – Penalty method (PEN)

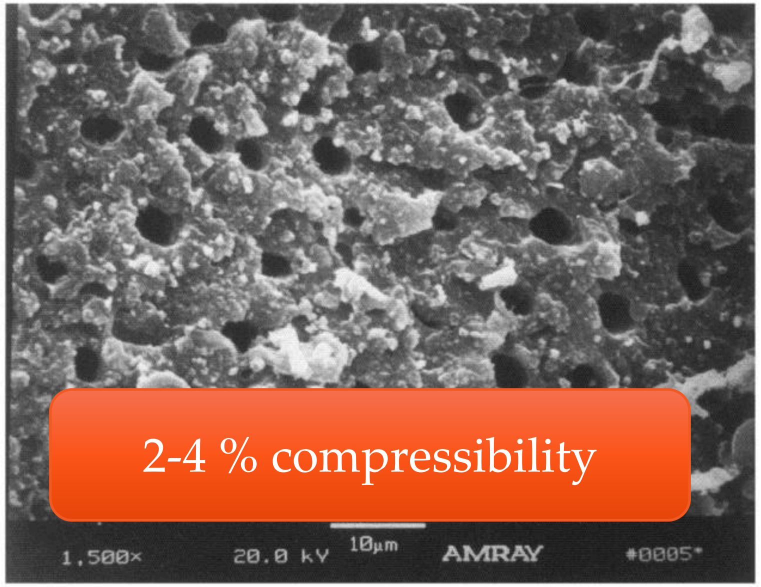
$$\tilde{\Psi}(\mathbf{F}) = \Psi(\mathbf{F}_{\text{iso}}) + \kappa\Psi_{\text{compressibility}}(\mathbf{F}_{\text{vol}})$$

$$0 \leq \kappa < \infty \implies \text{compressible}$$

$$\kappa \to \infty \implies \text{incompressible}$$

Incompressible model – Lagrange multiplier method (LM)

$$\tilde{\Psi}(\mathbf{F}, p) = \Psi(\mathbf{F}) + p(\det(\mathbf{F}) - 1)$$

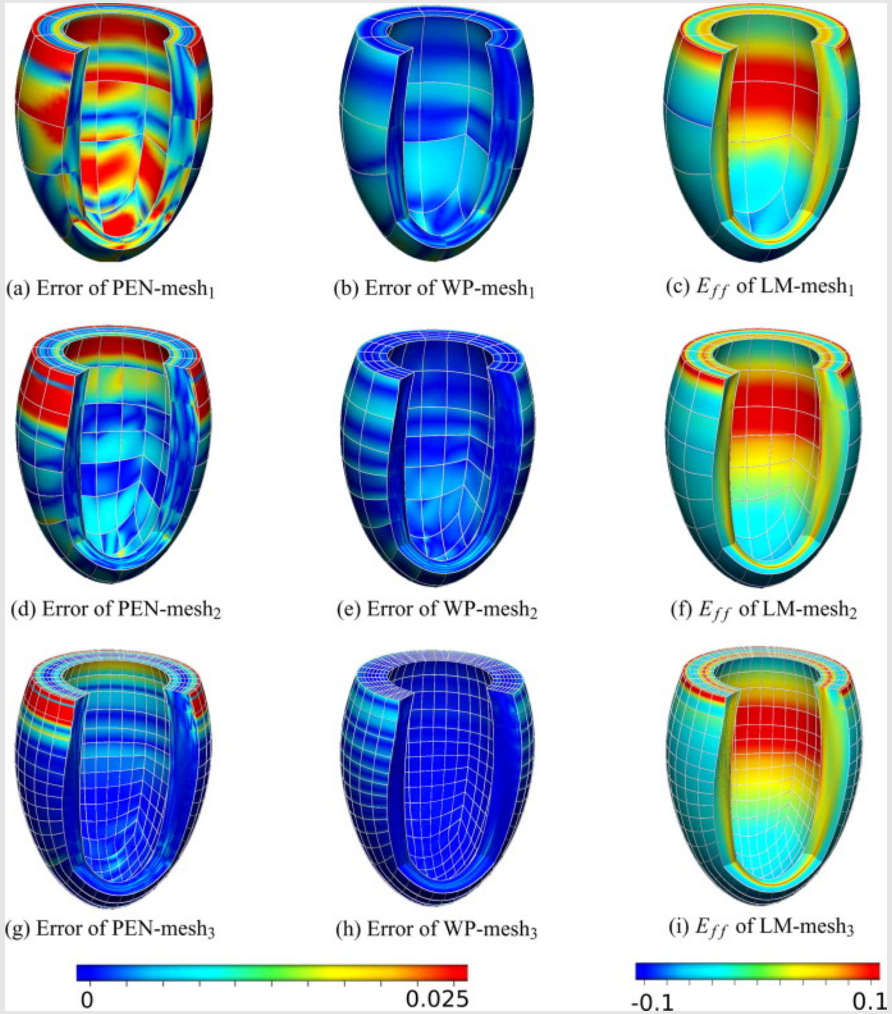


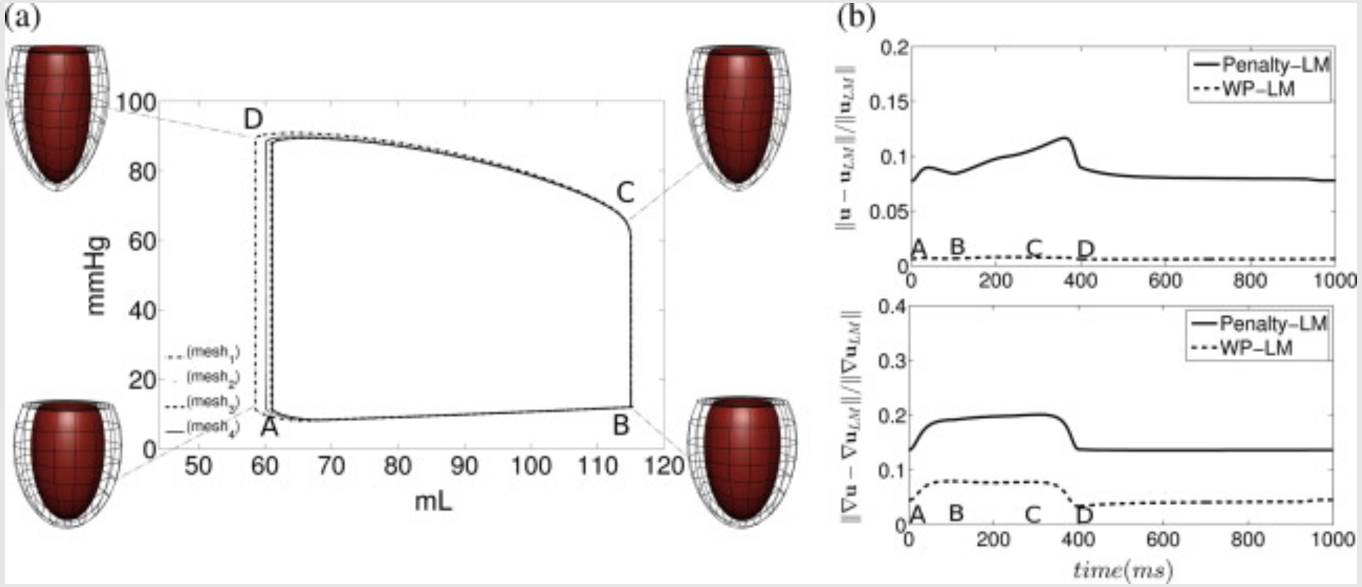
2-4 % compressibility

Fig. 4. Scanning electron micrograph of a transverse section of a canine interventricular septum showing the large number of capillaries interspersed among and surrounded by solid myocardial tissue. Specimen was fixed at a perfusion pressure of 50 mmHg.

Yin et. al (1996)

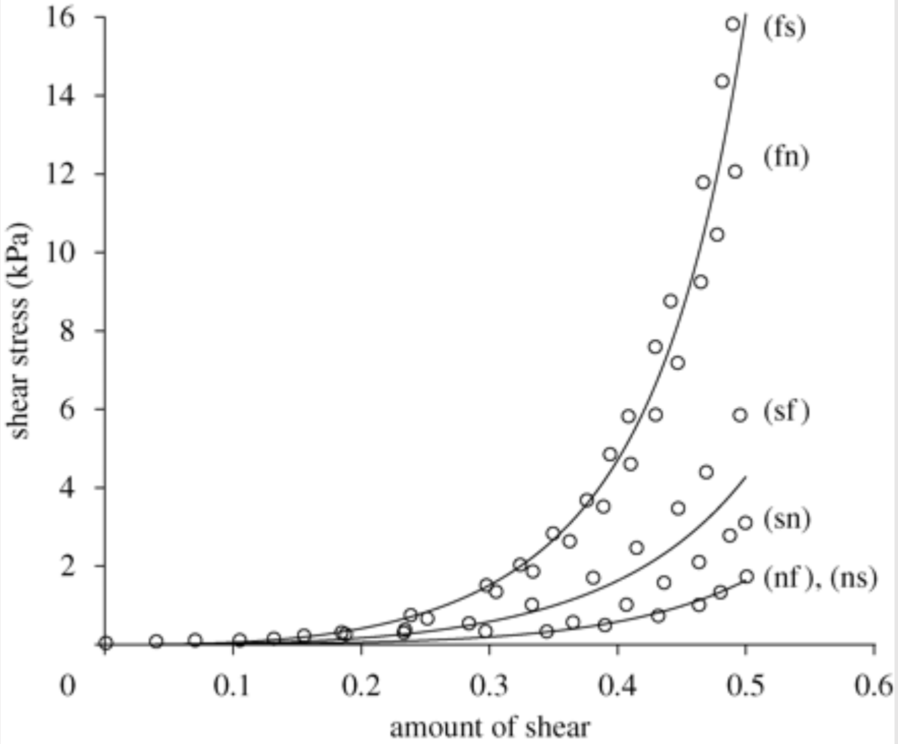
Comparing incompressible and compressible models



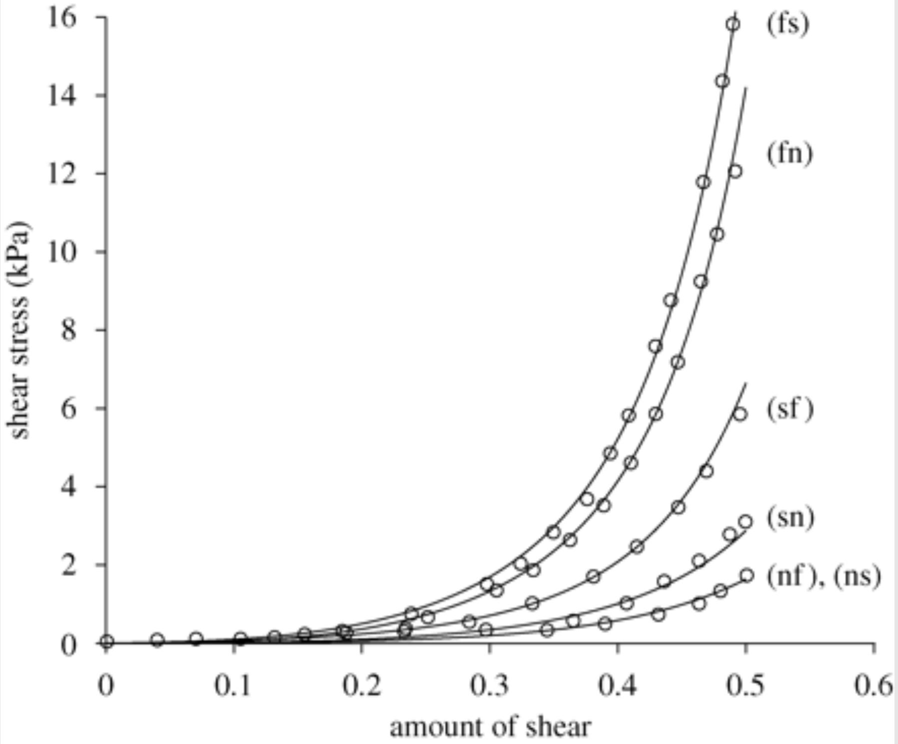


Hadjicharalambous et. al (2014)

We lose information about the shear properties when not including orthotropicity



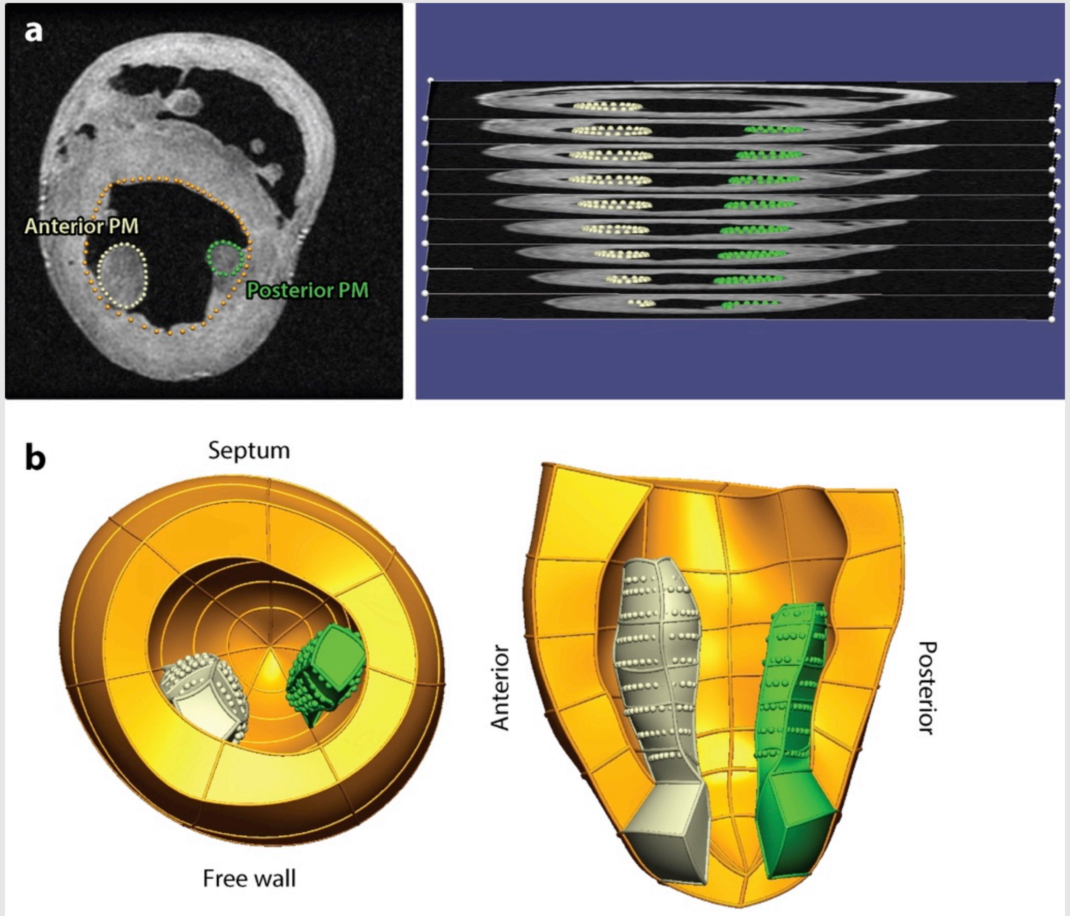
Model without the final term –
Can not distinguish shear properties



Full Model –
Can distinguish shear properties

Holzapfel and Ogden (2009)

Role of papillary muscles

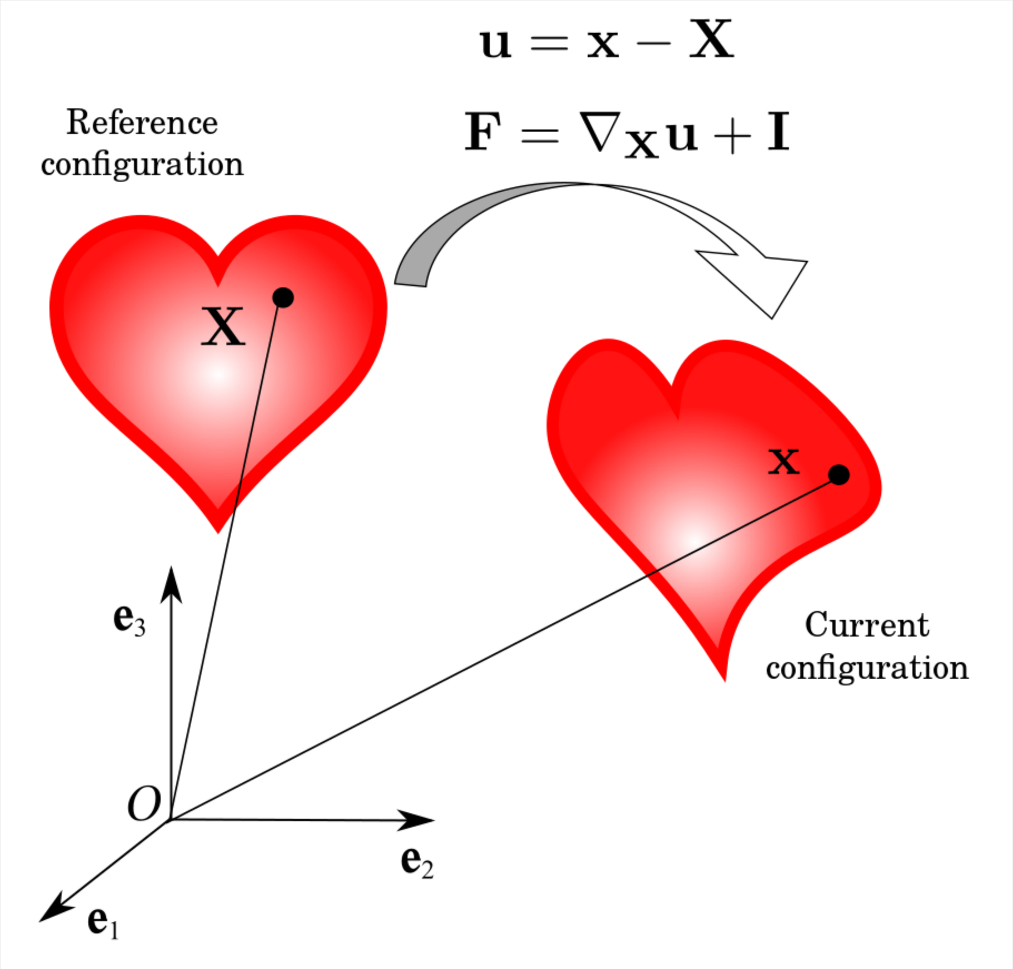


Wang VY, et al. 2015.
Annu. Rev. Biomed. Eng. 17:351–83

Limitations

- Compressibilty versus incompressibiliy
- Models for active contraction and multi-scale models
- Role of including more geometry
  - Papillary muscle
  - Single ventricle / Bi ventricle / Whole heart / Heart in torso

Deformation of a body is computed relative to a reference configuration

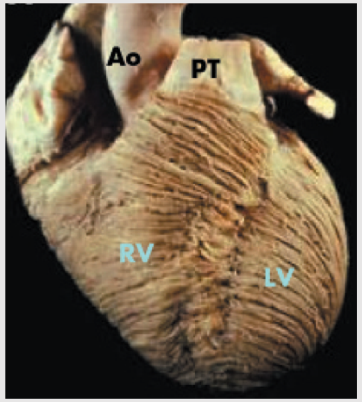


Mapping of coordinates: $\mathbf{x} = \mathbf{X} + \mathbf{u}$

Mapping of vectors: $\mathrm{d}\mathbf{x} = \mathbf{F}\mathrm{d}\mathbf{X}$

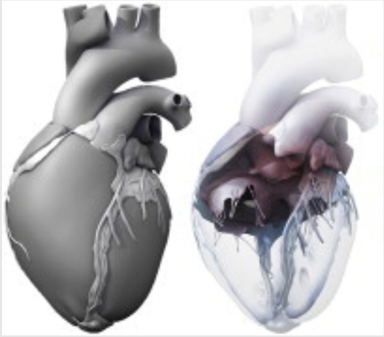
Structure represents geometrical properties at different scales

Microstructural architechture



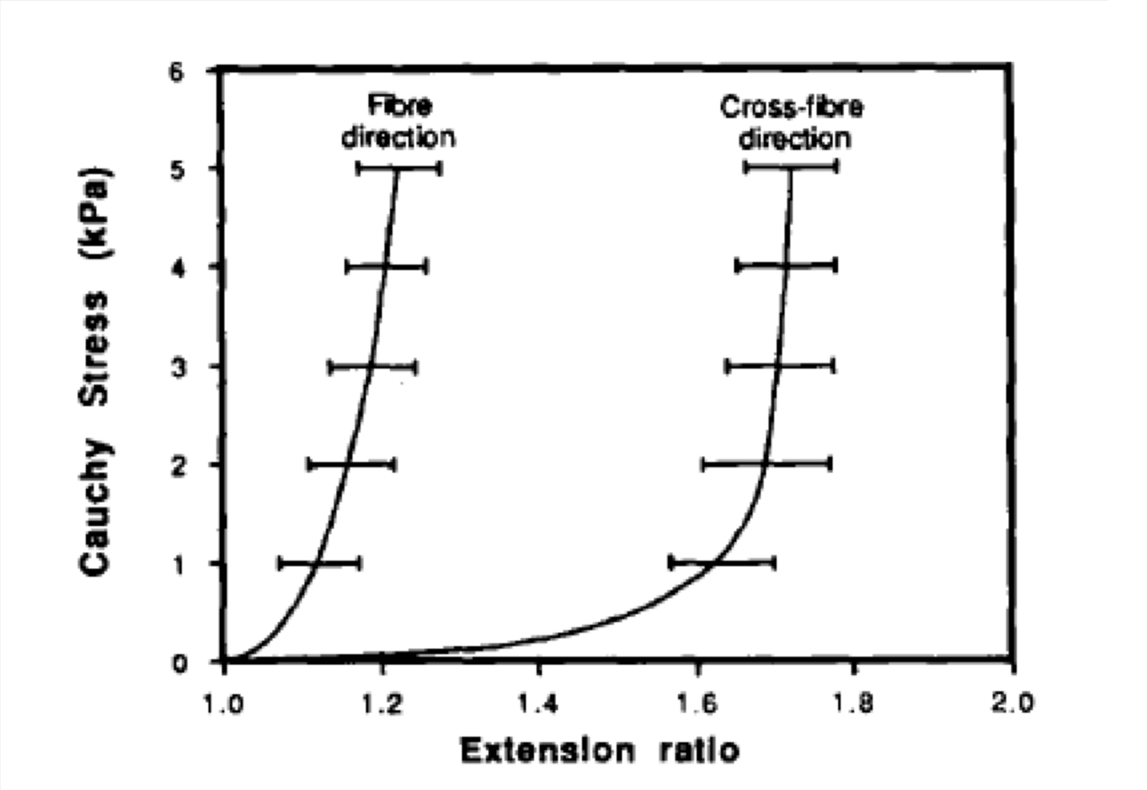
Boundary conditions

Geometry



Pathology

The myocardium is a nonlinear and anisotropic material



Hunter (1988), doi:10.1016/0079-6107(88)90004-1

Fiber Orientation in the Canine Left Ventricle during Diastole and Systole

DANIEL D. STREETER, Jr., HENRY M. SPOTNITZ, DALI P. PATEL, JOHN ROSS, Jr. and EDMUND H. SONNENBLICK

Circ Res. 1969;24:339-347
doi: 10.1161/01.RES.24.3.339

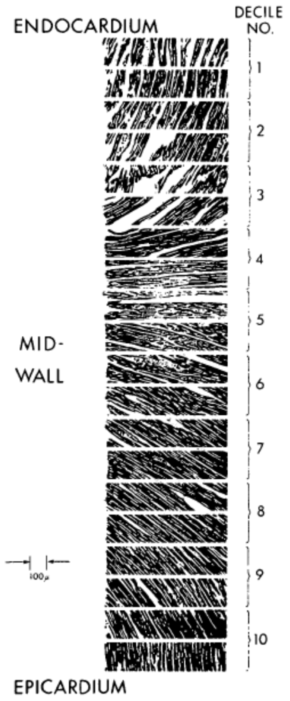


FIGURE 3

Typical sequence of photomicrographs showing fiber angles in successive sections taken from a heart in systole at region Tc. The sections are parallel to the epicardial plane. Fiber angle is +90° at the endocardium, running through 0° at the midwall to −90° at the epicardium. The sequence of numbers refers to deciles of wall thickness.

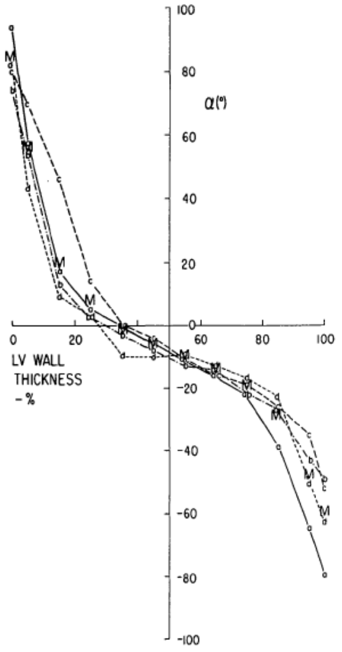


FIGURE 4

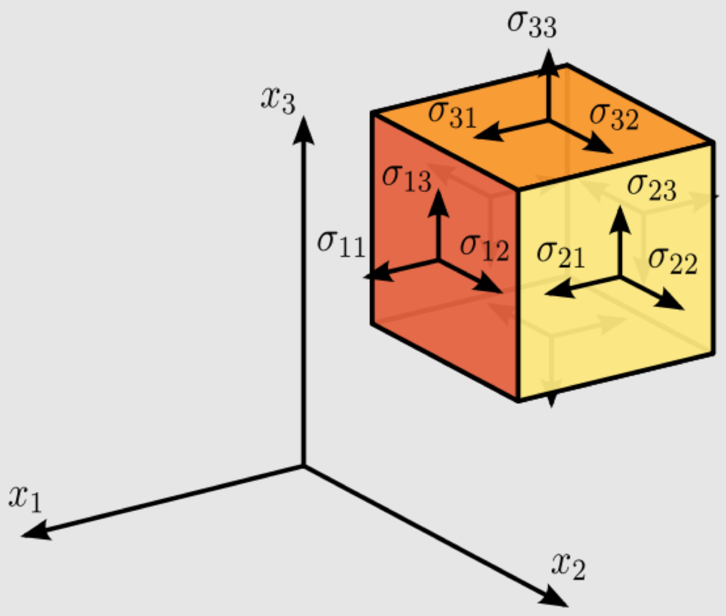
Fiber angles for four sampling sites, a through d, in a T-top section from a heart in diastole are plotted as a function of percent wall thickness. Zero percent of wall thickness implies the endocardial surface. M represents the mean of the data at these four sites.

proximately 18% in the fiber plane parallel to the epicardium.

The physical laws in classical mechanics are based principles of conservation

Conservation of mass

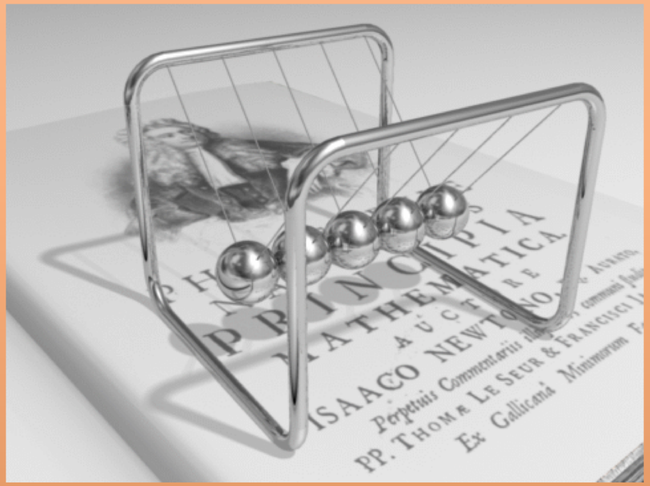
$$\mathrm{mass}(\mathbf{X}) = \mathrm{mass}(\mathbf{X} + \mathbf{u})$$



Cauchy stress tensor: $\boldsymbol{\sigma}$

Conservation of linear momentum

$$\nabla_{\mathbf{x}} \cdot \boldsymbol{\sigma} + \mathbf{b} = \rho \dot{\mathbf{v}}$$

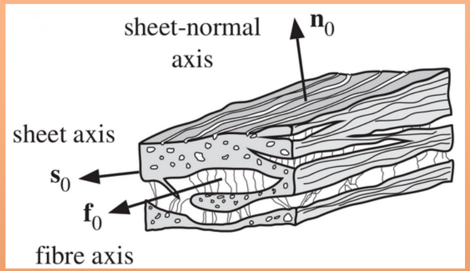


Conservation of angular momentum

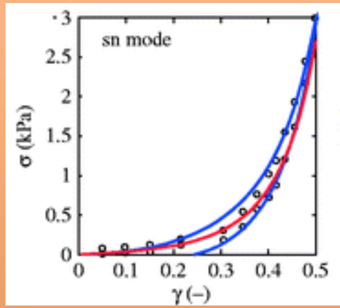
$$\boldsymbol{\sigma} = \boldsymbol{\sigma}^T$$

How the mechanics matter in regard to cardiac modeling depends on the modeling assumptions

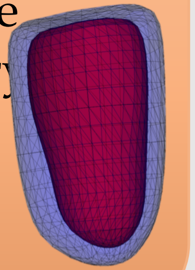
Material anisotropy



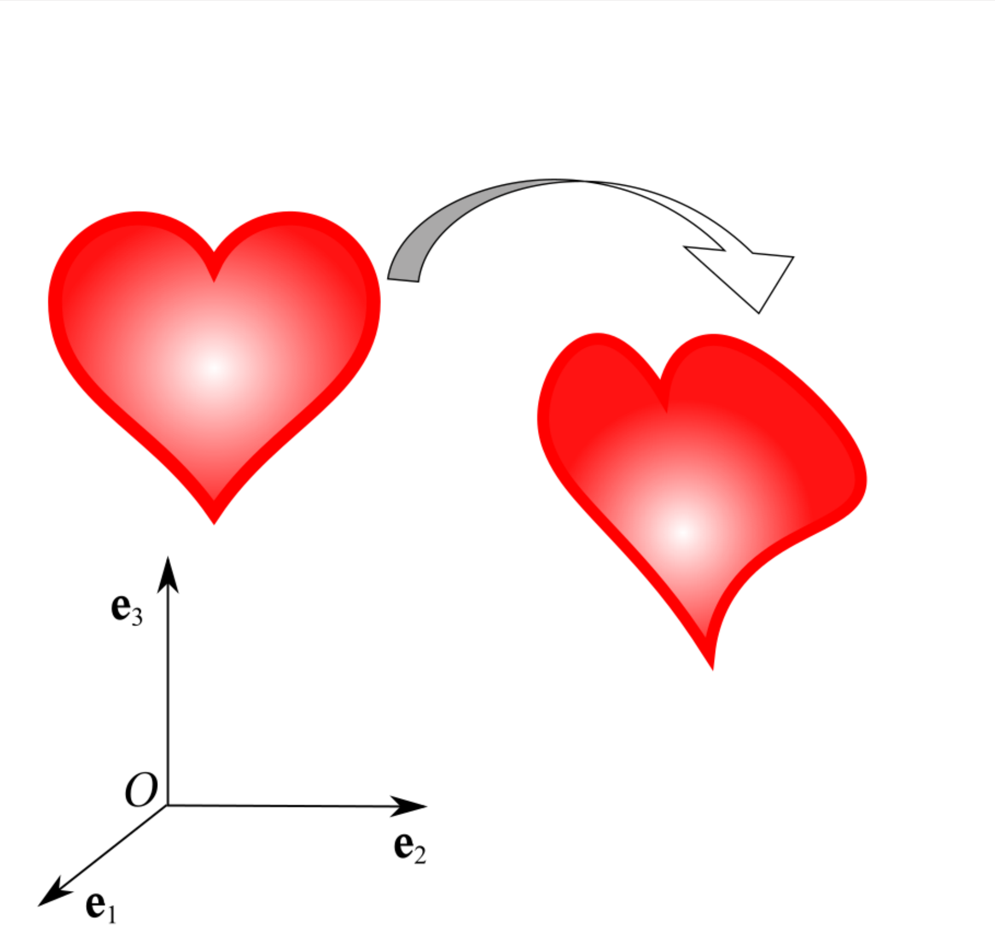
Elastic versus viscoelastic



Choosing the reference geometry



An incompressible material does not change volume during deformation



Volume before deformation = Volume after deformation

$\implies$ incompressible $\implies \det(\mathbf{F}) = 1$

Volume before deformation ≠ Volume after deformation

$\implies$ compressible $\implies \det(\mathbf{F}) \neq 1$