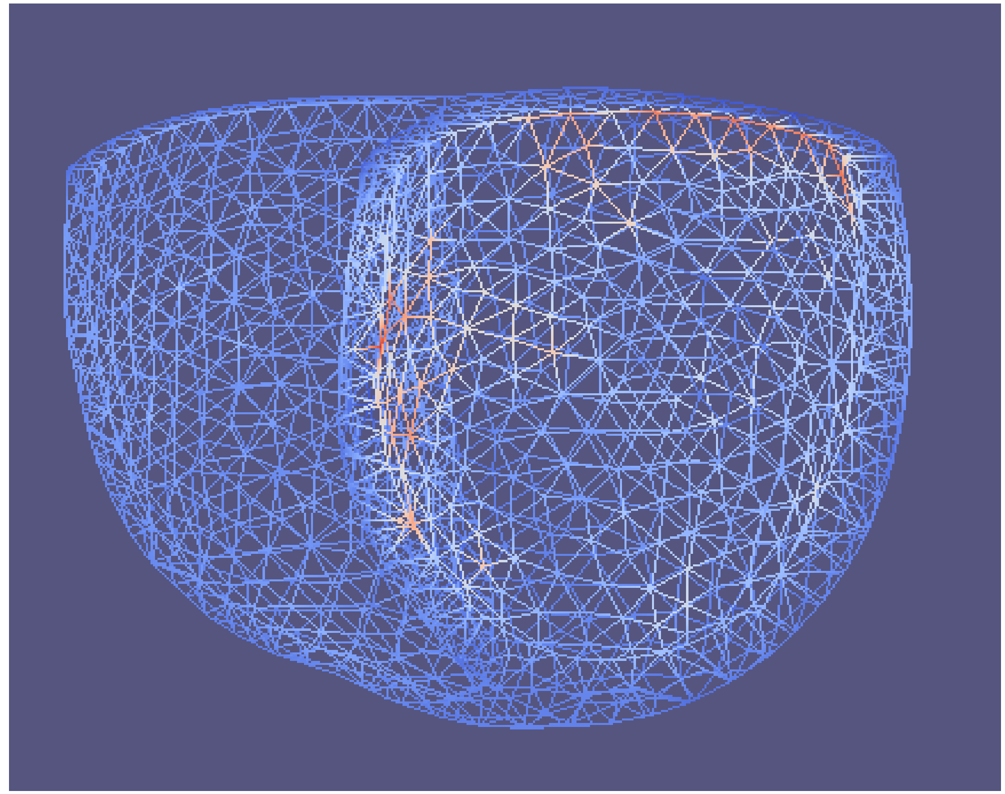
Patient Constrained Ventricular Stress Mapping



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May 1 2015

CENTER FOR CARDIOLOGICAL **INNOVATION**

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Elastic stresses are internal forces that tend to restore the material to its original shape

Stress = Force / Area

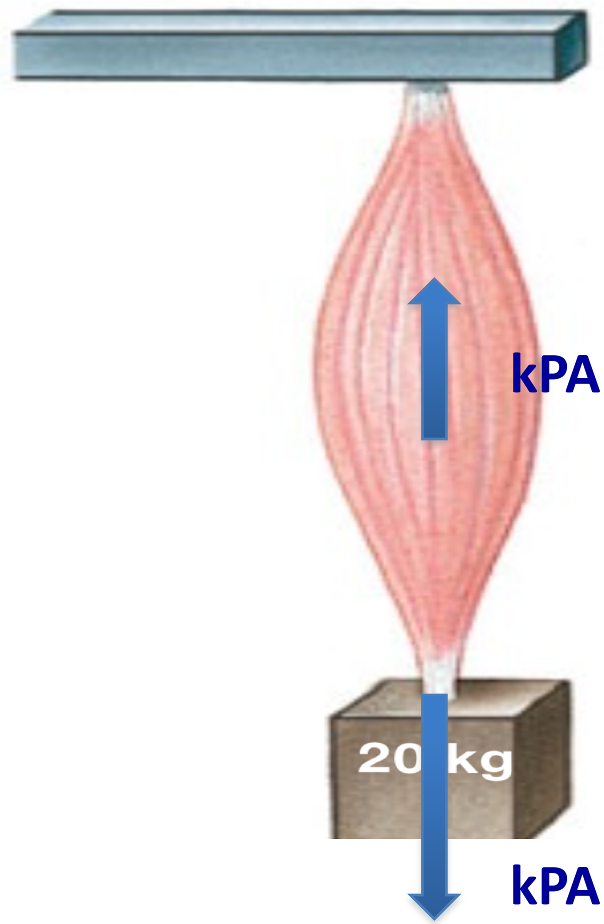
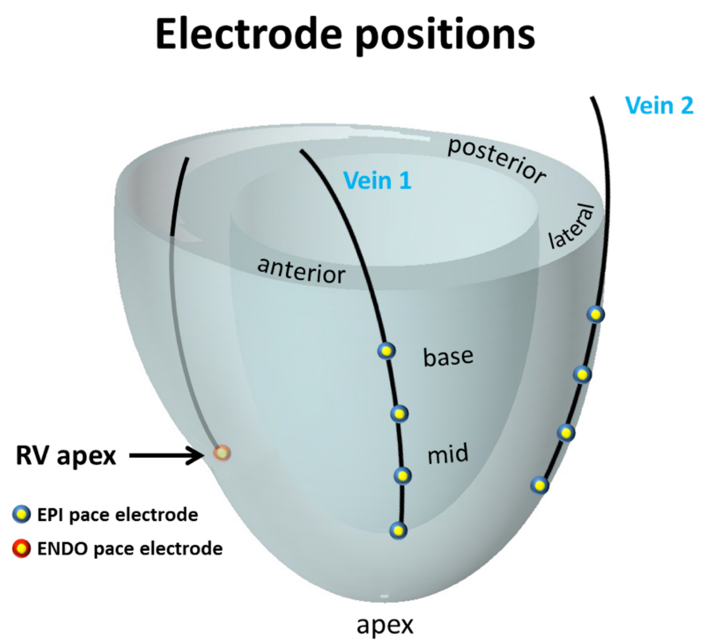


Image source: Human Pysiology 2013

Patient specific stress mapping can give more insight into response rates of cardiac resynchronization therapy (CRT)



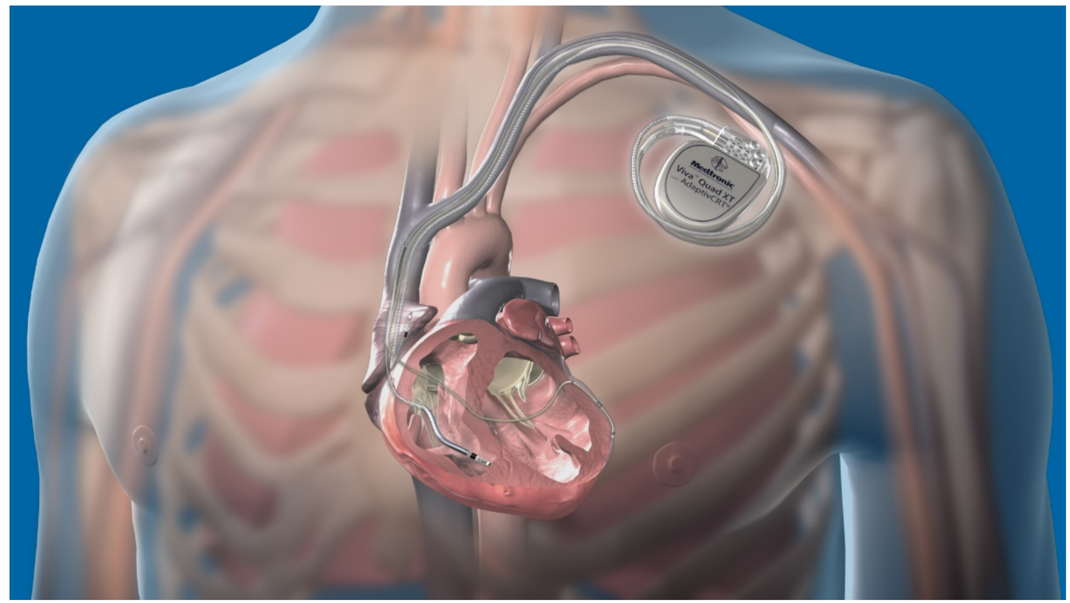
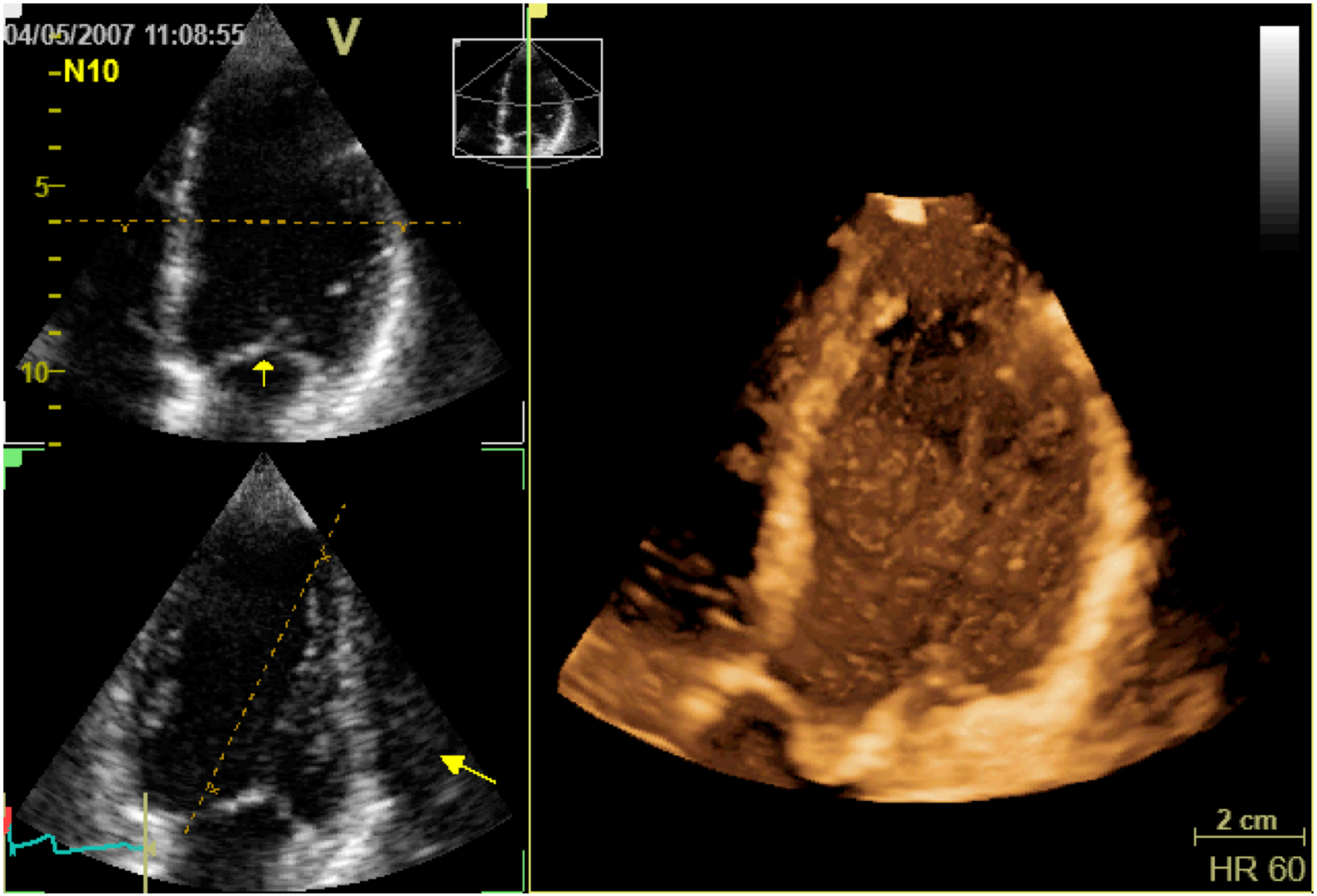


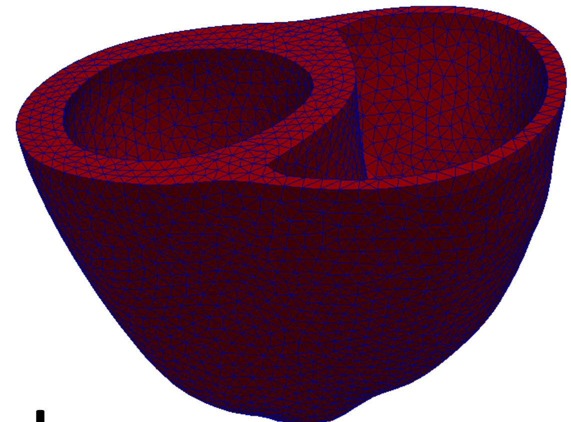
Image source:CCI, Medtronic.com

4D speckle tracking echocardiography provides us with mechanical information about the left ventricle



We use three ingredients to make a computational mechanics model

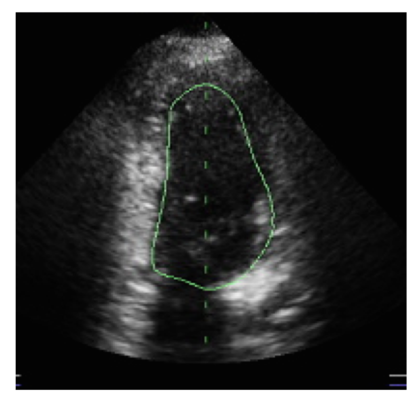
1. Ventricular reference geometry



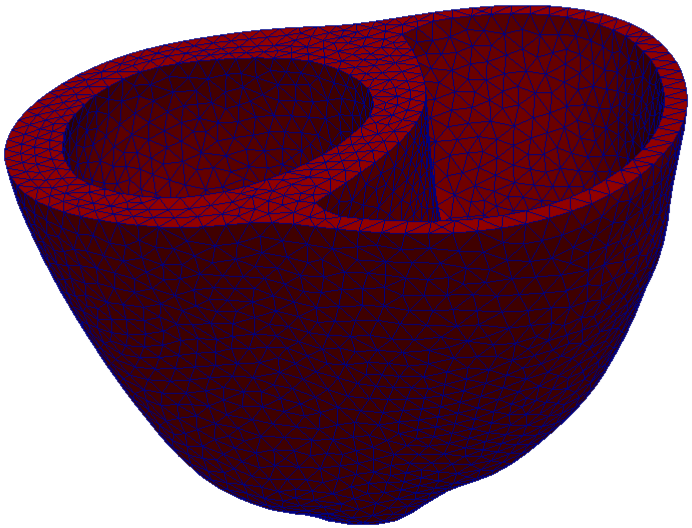
2. Mathematical mechanics model

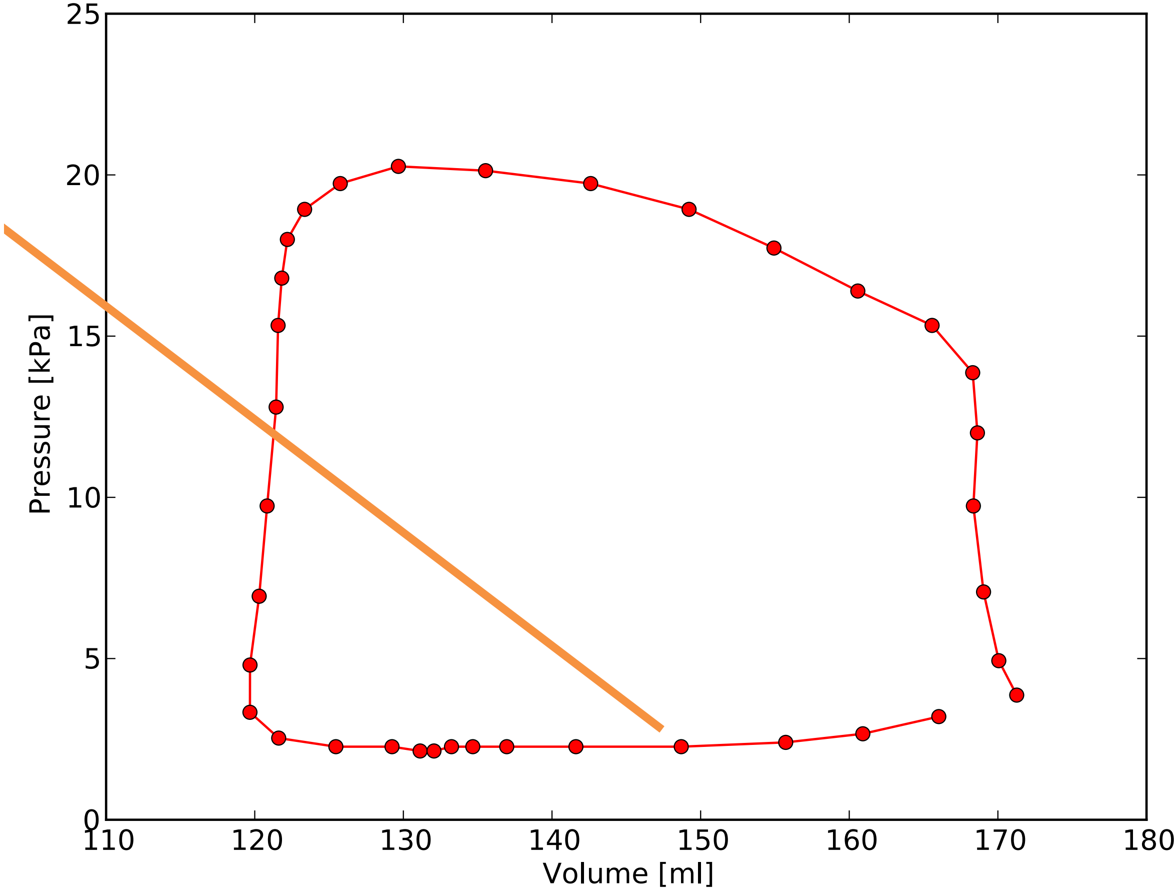
$$\min \Pi(a, b, a_f, b_f, \gamma)$$

3. Ventricular motion data

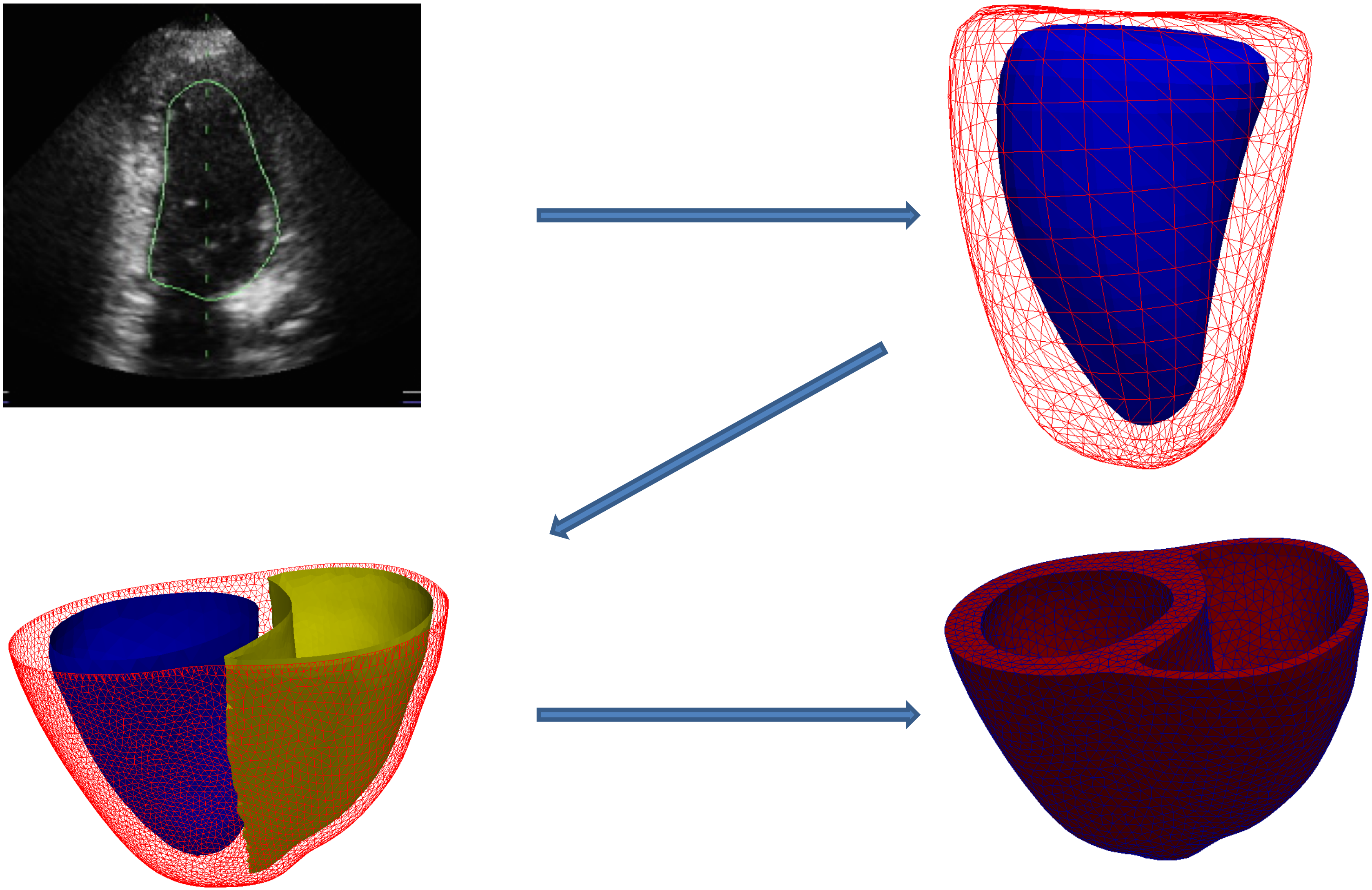


The reference geometry is taken from the assumed minimal stress state

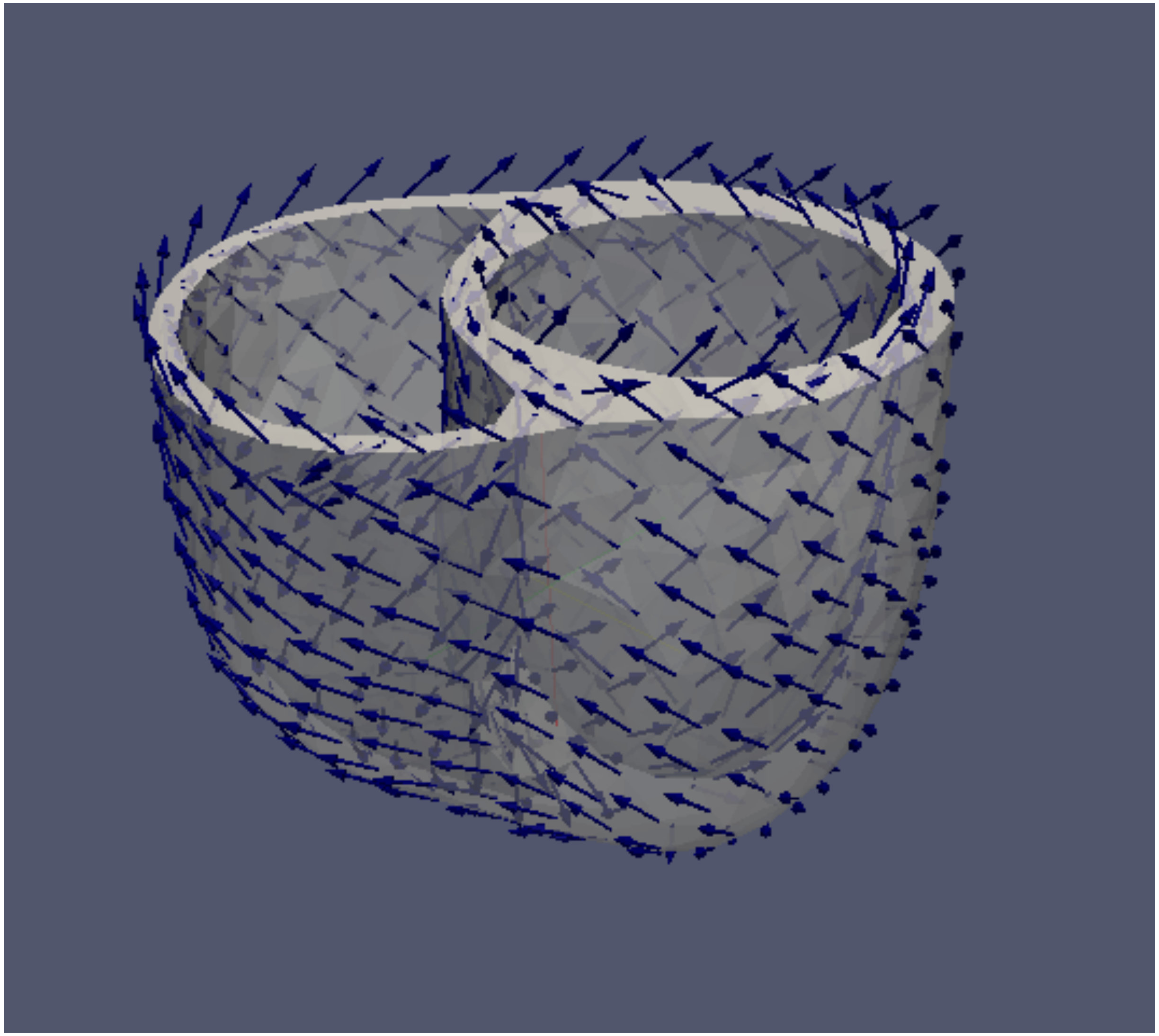




Our reference geometry is made from an echo based LV and a synthetic RV

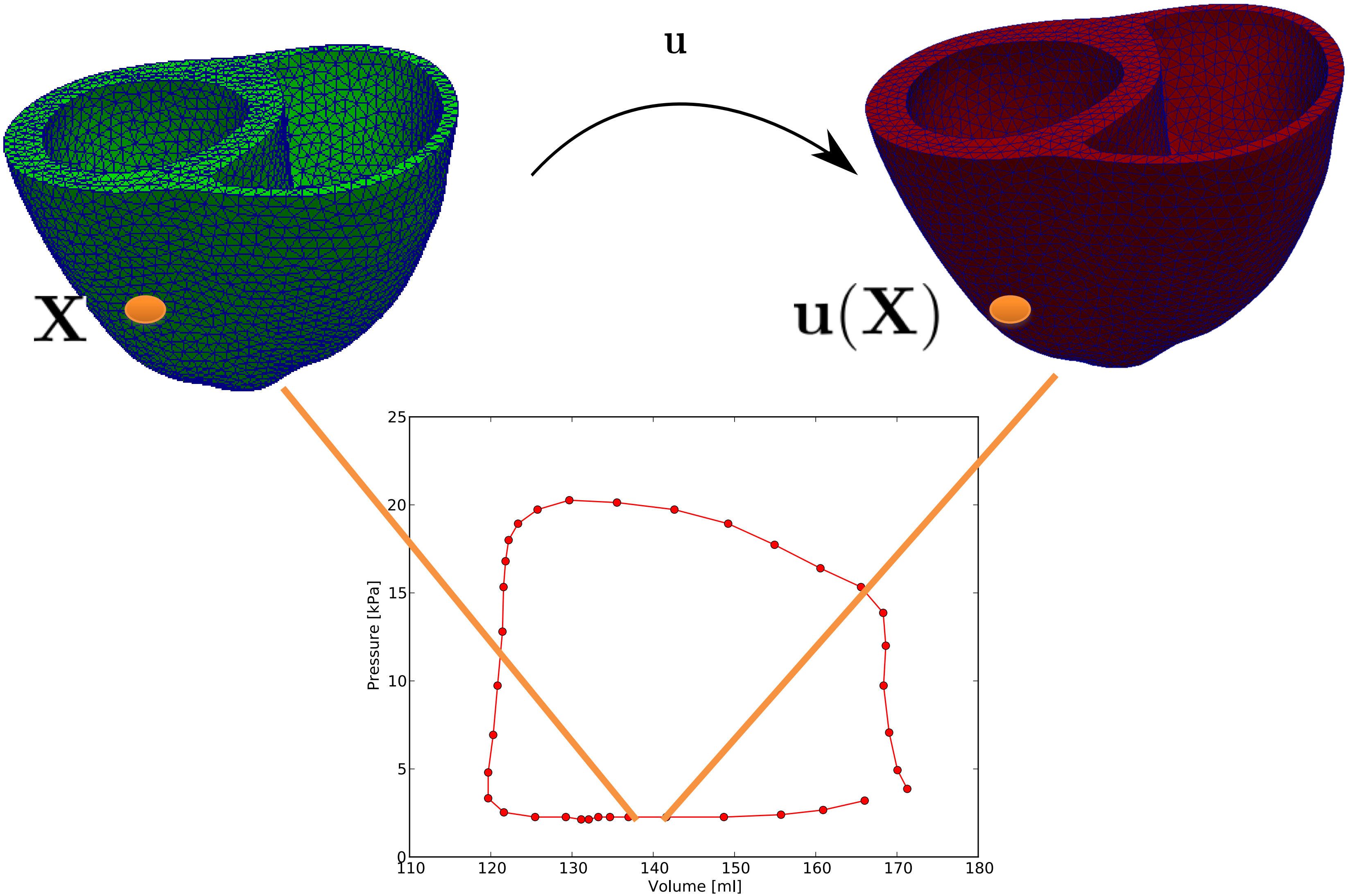


Muscle fiber directions are generated by a rule-based algorithm



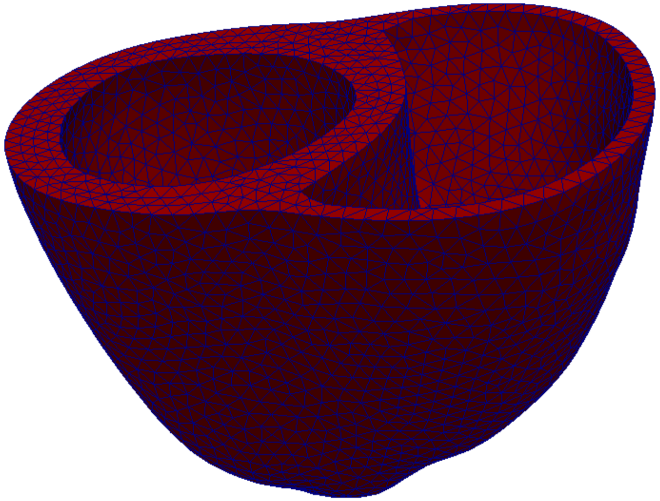
Bayer et al 2012

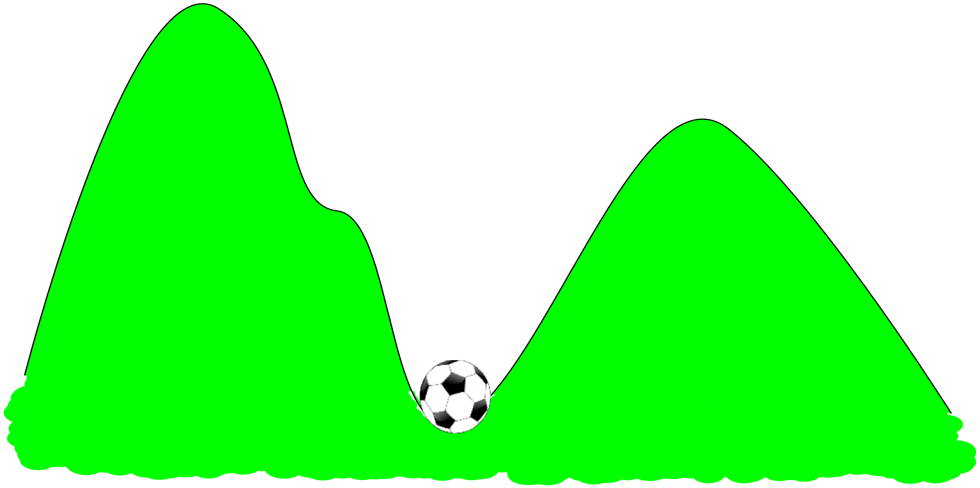
The transformation from one geometry to another can be viewed as a mapping



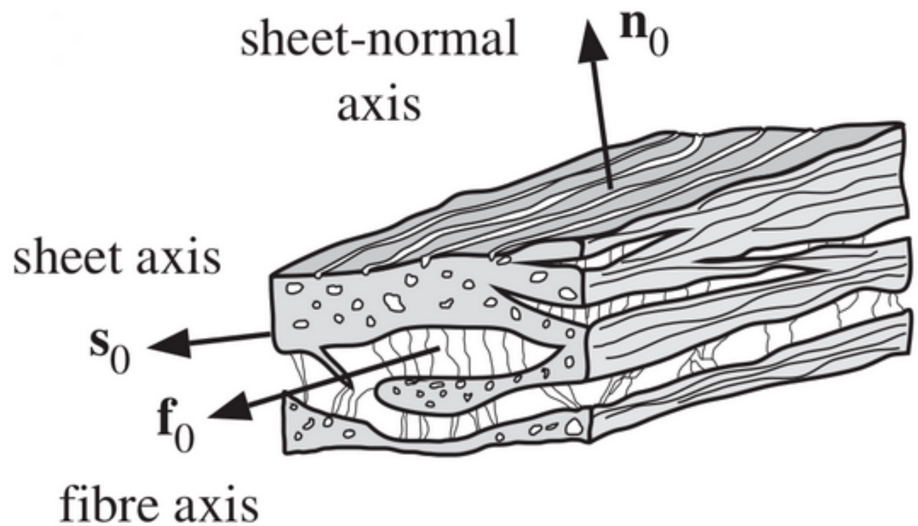
At each point in the cardiac cycle a deformed geometry is calculated by minimizing energy

$$
\begin{aligned}
\Pi = &\int_{\Omega} \psi_{elastic} + p(J-1)\ dx \\
&+ p_{rv} \int_{\partial\Omega_{endorv}} \mathbf{u} \cdot \mathbf{n}\ dS \\
&+ p_{lv} \int_{\partial\Omega_{endolv}} \mathbf{u} \cdot \mathbf{n}\ dS
\end{aligned}
$$





The internal potential energy in our system is determined by the elastic energy in the tissue



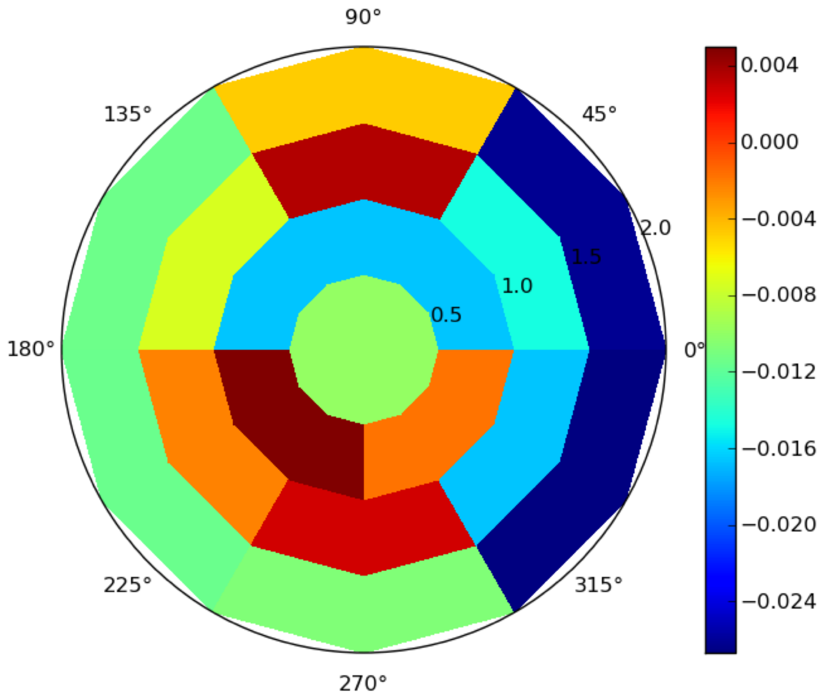
$$\psi_{elastic} = \underbrace{\frac{a}{2b}\left(e^{b(I_1-3)} - 1\right)}_{\textbf{Isotropic term}} + \underbrace{\frac{a_f}{2b_f}\left(e^{b_f(I_{4,f_0}-1)_+^2} - 1\right)}_{\textbf{Transversely isotropic term (fibers)}}$$

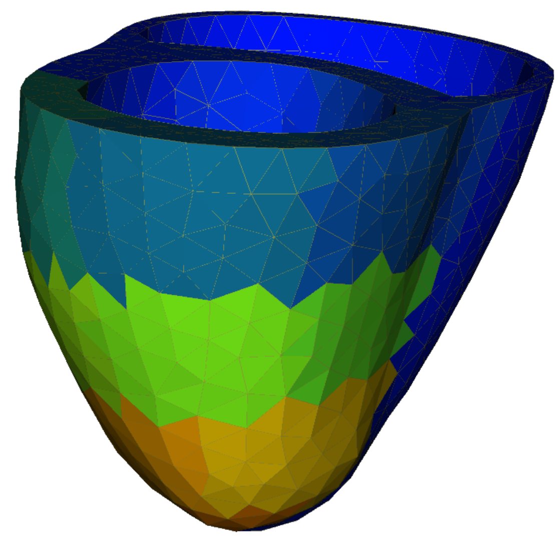
Holzapfel and Ogden 2009

The contraction parameter γ is time dependent and varies across the strain regions (ASE segments)

$$\mathbf{F} = \mathbf{F}_e \mathbf{F}_a$$

$$\mathbf{F}_a = (1-\gamma)\mathbf{f}_\circ \otimes \mathbf{f}_\circ + \frac{1}{\sqrt{1-\gamma}}(\mathbf{I} - \mathbf{f}_\circ \otimes \mathbf{f}_\circ)$$

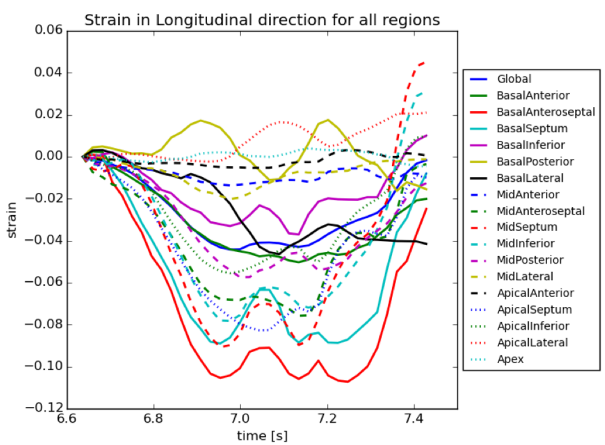




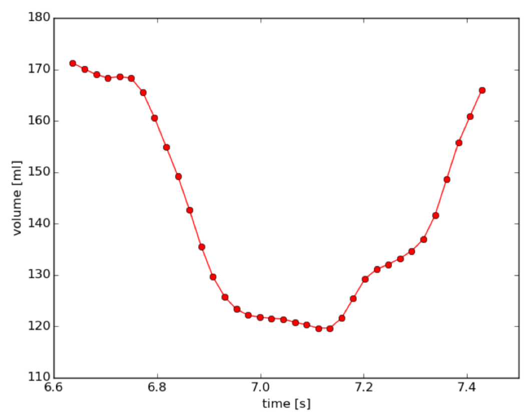
The energy functional is made specific to a patient by calibrating the 5 model parameters to clinical data

$$\psi_{elastic} = \psi_{elastic}(a, b, a_f, b_f, \gamma)$$

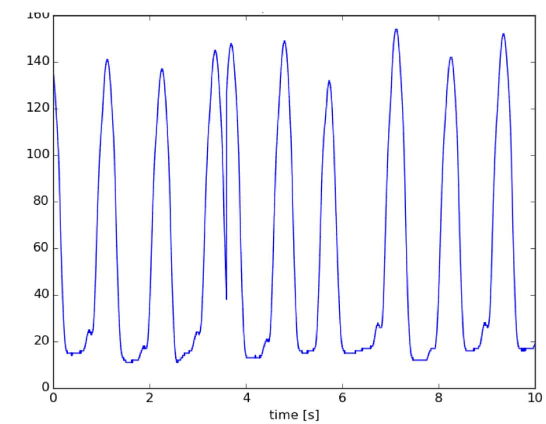
Strain



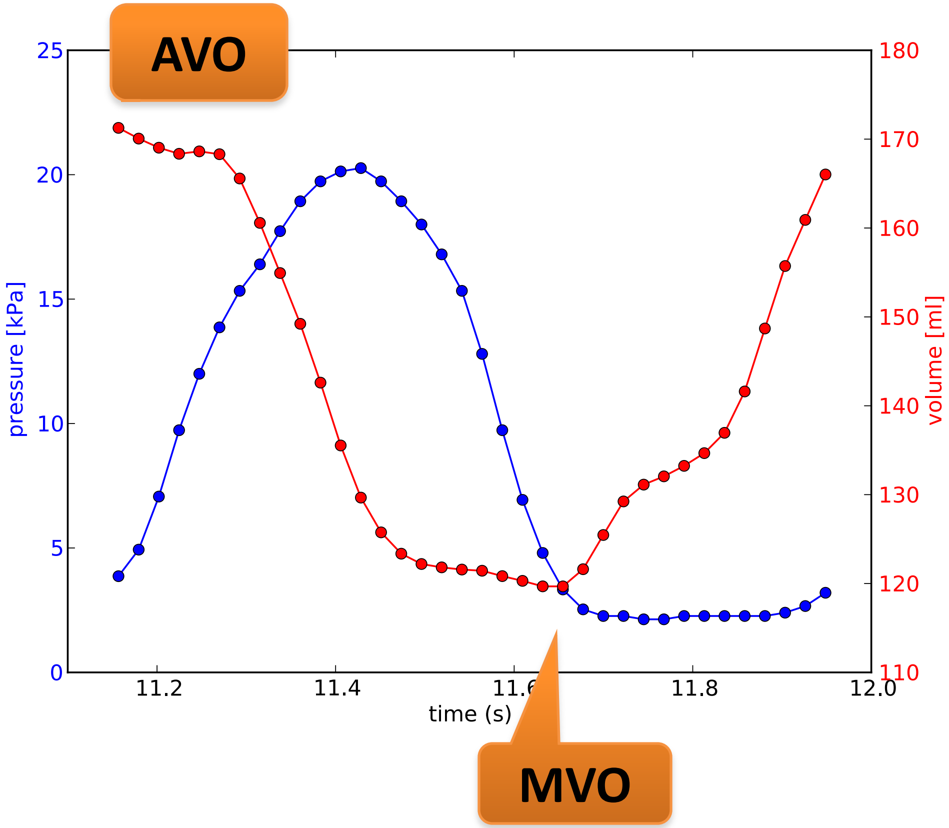
Volume

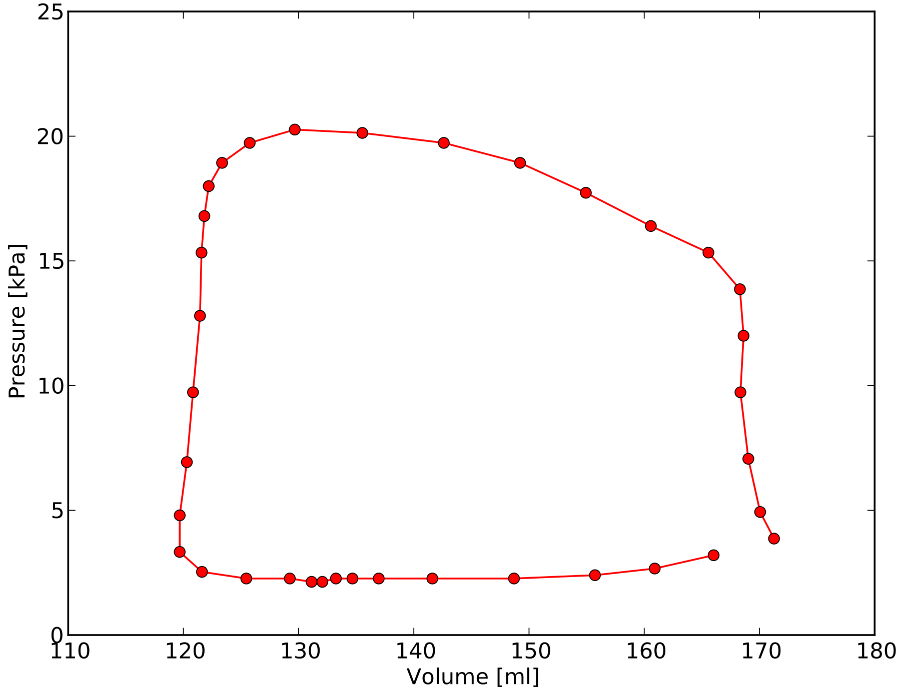


Pressure

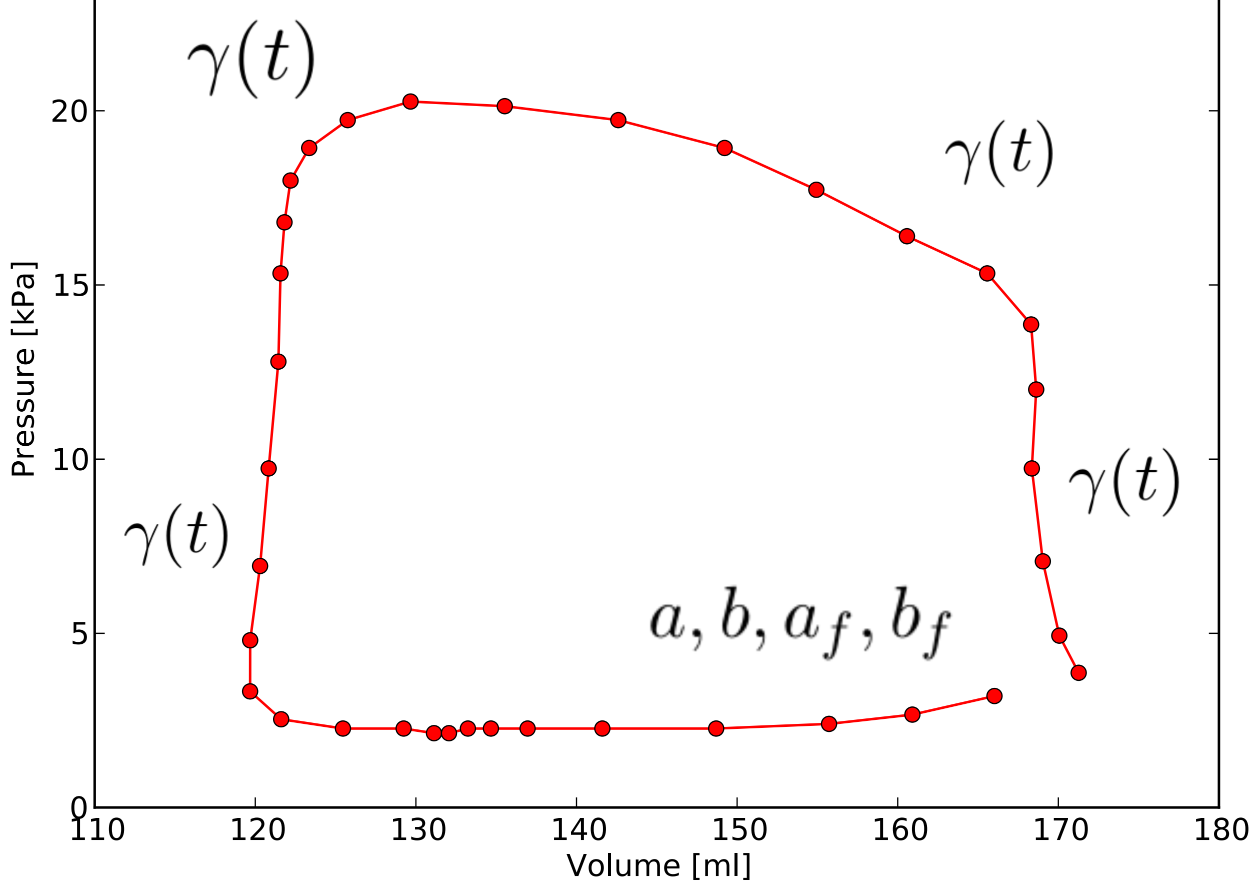


We match pressure and volume in order to generate a patient specific pressure-volume loop





Different parts of the cardiac cycle can be used to calibrate different parameters



We optimize a weighted strain and volume matching in order to estimate the tissue stiffness

$$I = (1-\alpha) I_{strain} + \alpha I_{vol}$$

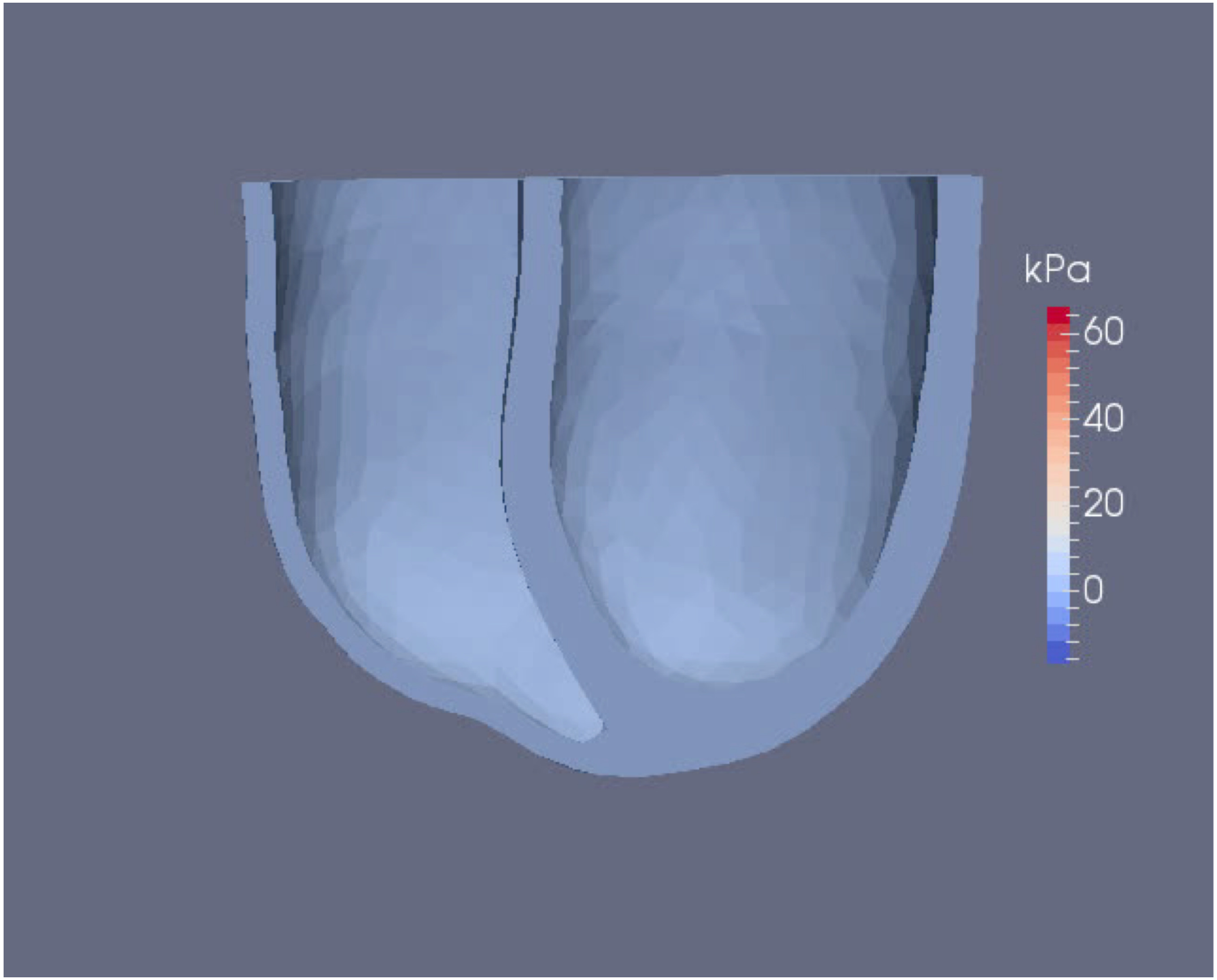
$$I_{strain} = \sum_{i=1}^{\#PV points} \sum_{j=1}^{\#regions} \sum_{d \in \{c,l,r\}} \lambda_{j,d} \left(\epsilon_{measured} - \epsilon_{simulated}\right)^2$$

$$I_{vol} = \sum_{i=1}^{\#PV points} \left(\frac{V_{measured} - V_{simulated}}{V_{measured}} \right)^2$$

Parameter estimations performed with a patient data set show a tradeoff between matching strain and volume

	α	a	b	a_f	b_f	I_{strain}	I_{vol}
Initial		0.73	7.4	21.5	40.02	0.14	0.029
Optimized	0.0	100.0	4.8	21.5	40.02	0.017	0.016
	0.2	56.2	6.1	21.5	40.02	0.017	0.015
	0.4	10.8	7.3	21.5	40.02	0.019	0.01
	0.5	6.9	7.4	21.5	40.02	0.022	0.0075
	0.6	4.9	7.3	21.5	40.02	0.025	0.0052
	0.8	3.1	7.4	21.5	40.02	0.033	0.0016
	1.0	2.1	7.4	21.5	40.02	0.045	0.0003

Putting the model and data together results in stress calculations at various points in the cardiac cycle



In conclusion, personalized mechanics models can be used to calculate patient-specific ventricular stress