CIBM Center for Biomedical Imaging

CIBM Annual Symposium 2022

Campus Biotech, Geneva | 30th November

Anisotropic stiffness of freshly excised ex vivo swine heart estimated via MR elastography and transversely isotropic nonlinear inversion

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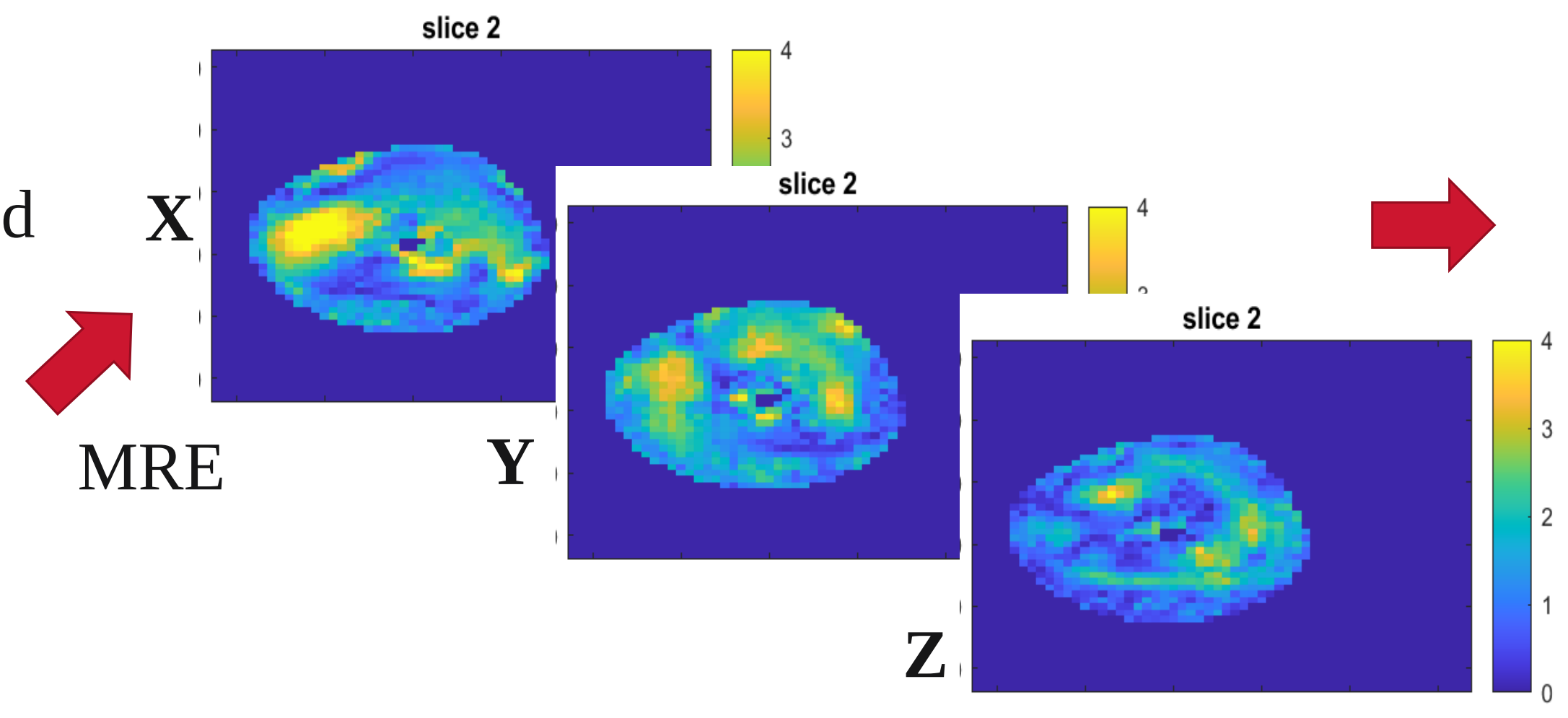
INTRO

To date, cardiac MRE has not considered the anisotropic nature of the myocardial architecture, which is known to introduce variance in MRE results up to 30% (1). Myocytes are stacked together to form sheetlets. Their angulations define the different biomechanical roles or functions of the different myocardial segments (2). Better differentiation of the segmental variation of anisotropic stiffness could help to improve the characterization of this complex structure and understand the biomechanics of various myocardial pathologies.

METHODS

FOV = 340 mm^2;
TR/TE =540/109 ms;
BW=1730 Hz, 3 slices and 2x2x2 mm^3
Vibrations @ 100Hz



u: displacement field

$$\nabla\cdot\left(\mu(\nabla \boldsymbol{u}+\nabla \boldsymbol{u}^T)\right)+\nabla(E\nabla\cdot\boldsymbol{u})=-\rho\omega^2\boldsymbol{u}$$

Shear modulus $=\mu_R + i\,\mu_I$
= storage modulus + i*loss modulus

Young's modulus

Density of tissue

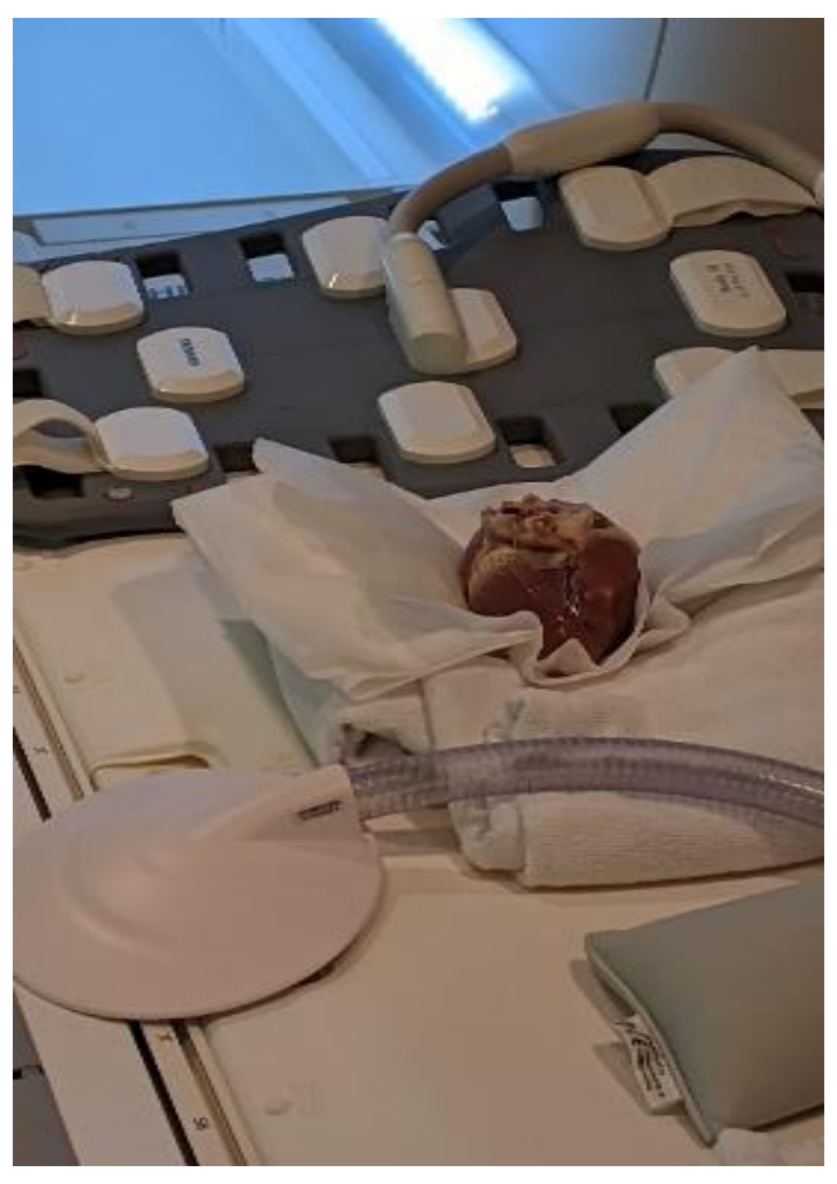
$2\,\pi\,Freq.$

Goal: Estimate the material properties $(\boldsymbol{\mu}, \boldsymbol{E})$:

$$\Phi=\sum_{\Omega}\|\mathbf{u}_c(\theta)-\mathbf{u}_m\|^2$$

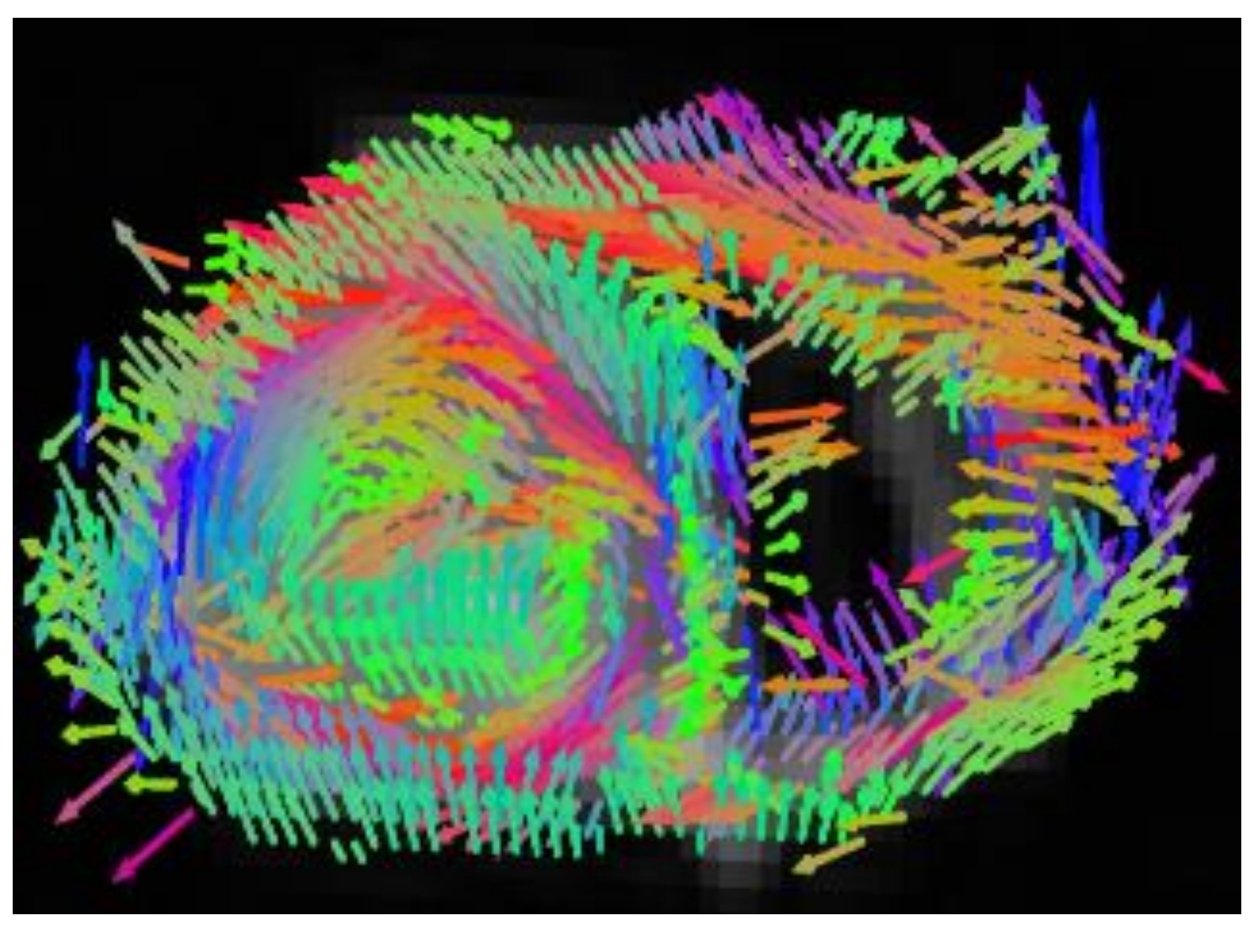
$\boldsymbol{u_c}$: expected
$\boldsymbol{u_m}$: measured

Pig heart scanned at 3T



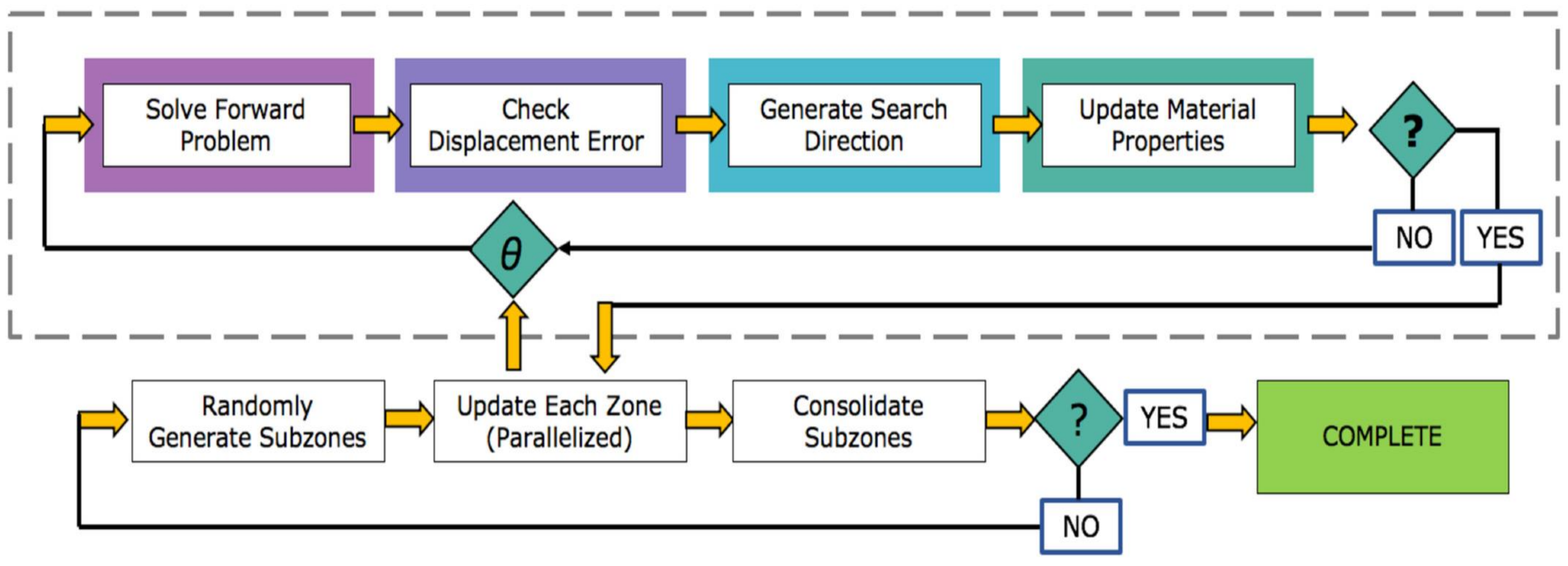
Match MRE resolution
32 diffusion-encoding gradients
b=557 s/mm² (3 averages);
TR/TE = 1500/70ms.

DTI



Main fiber direction

Nonlinear inversion - subzone optimization



Anisotropic material:
Use rotation matrix between
The strain tensor (ε) and the diffusion tensor

Correlation verified with:

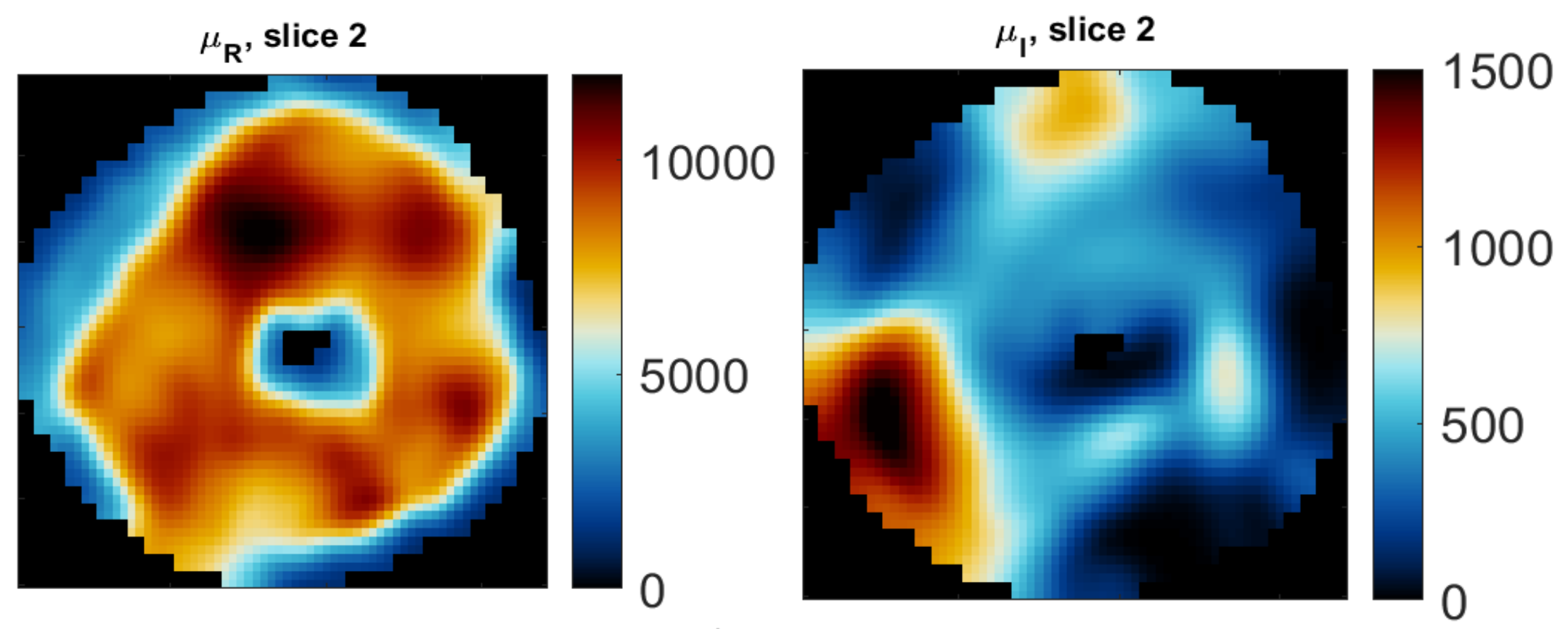
$$\varepsilon_{\parallel/\perp}=\frac{\frac{1}{2}\left(\varepsilon^f_{12}+\varepsilon^f_{13}\right)}{\varepsilon^f_{23}}$$

Shear strain in planes //

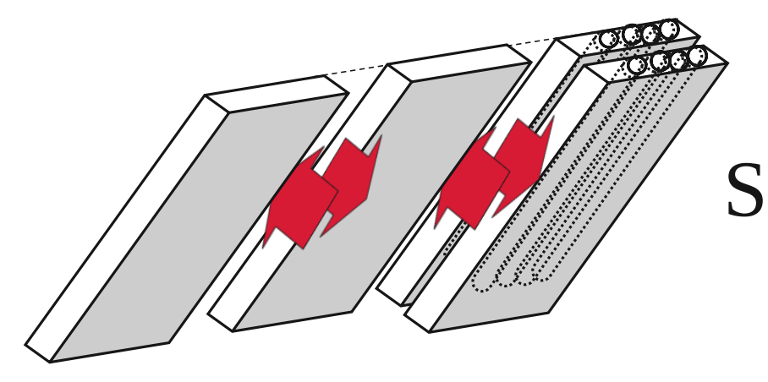
in planes ⊥

aligned with E_{11}

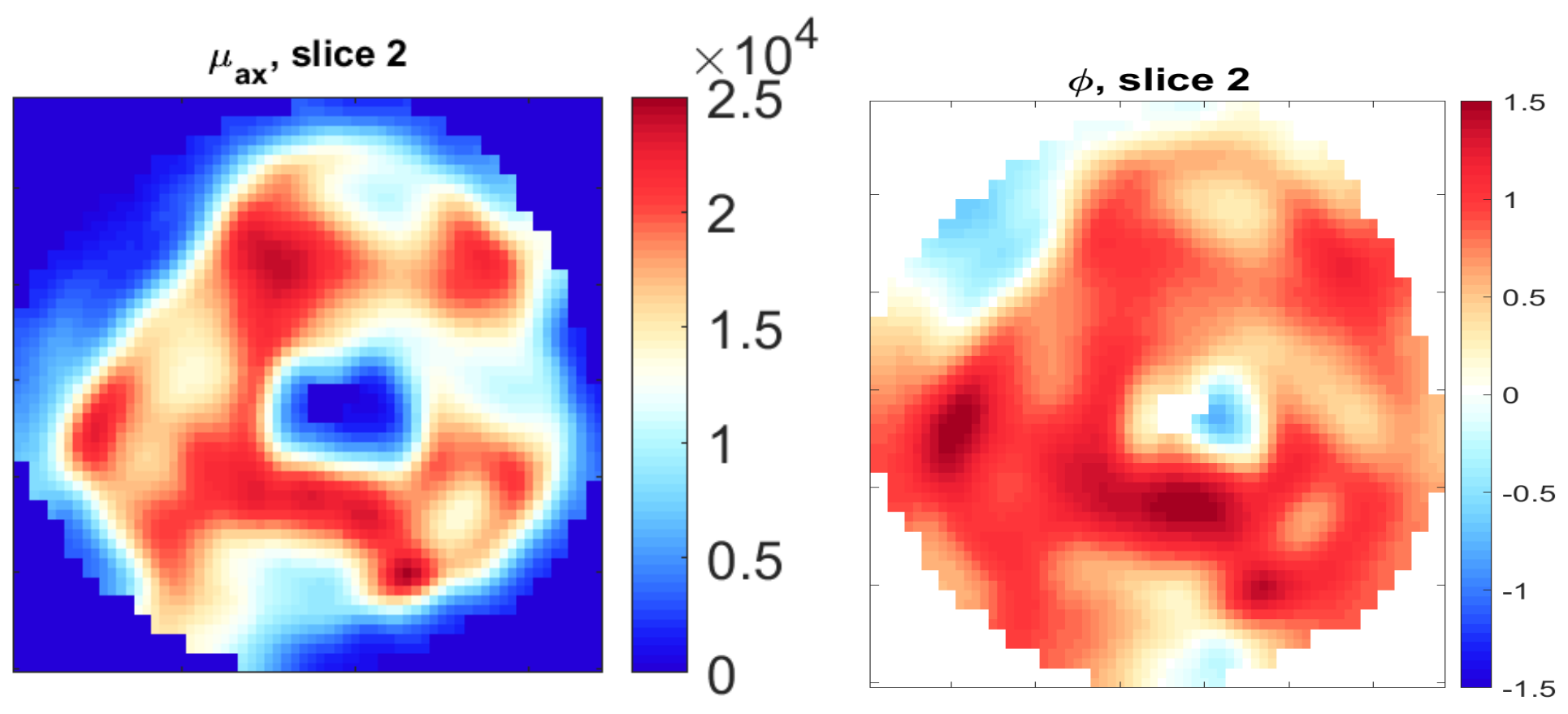
RESULTS

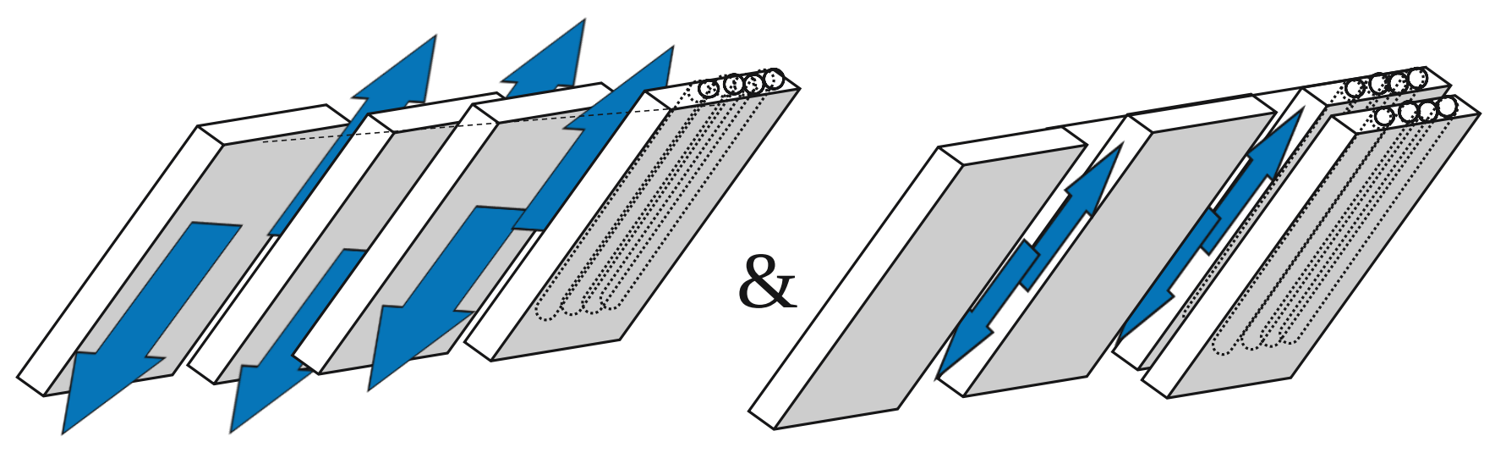


$\mu=\mu_R+i\mu_I$

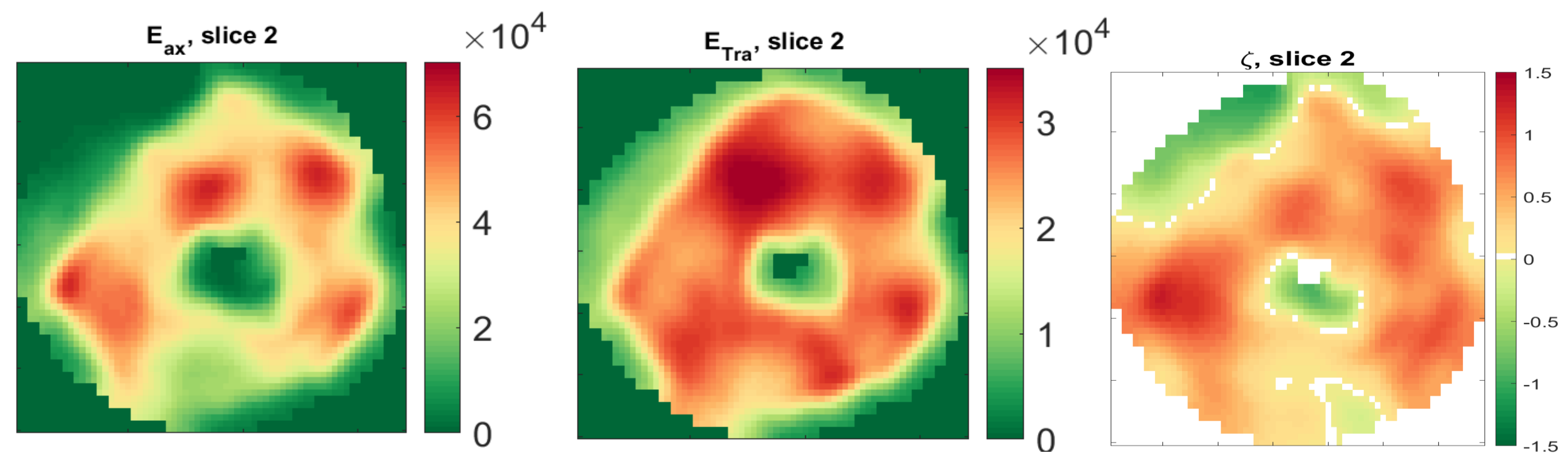


Shearing in the plane normal to the fiber axis: μ_R



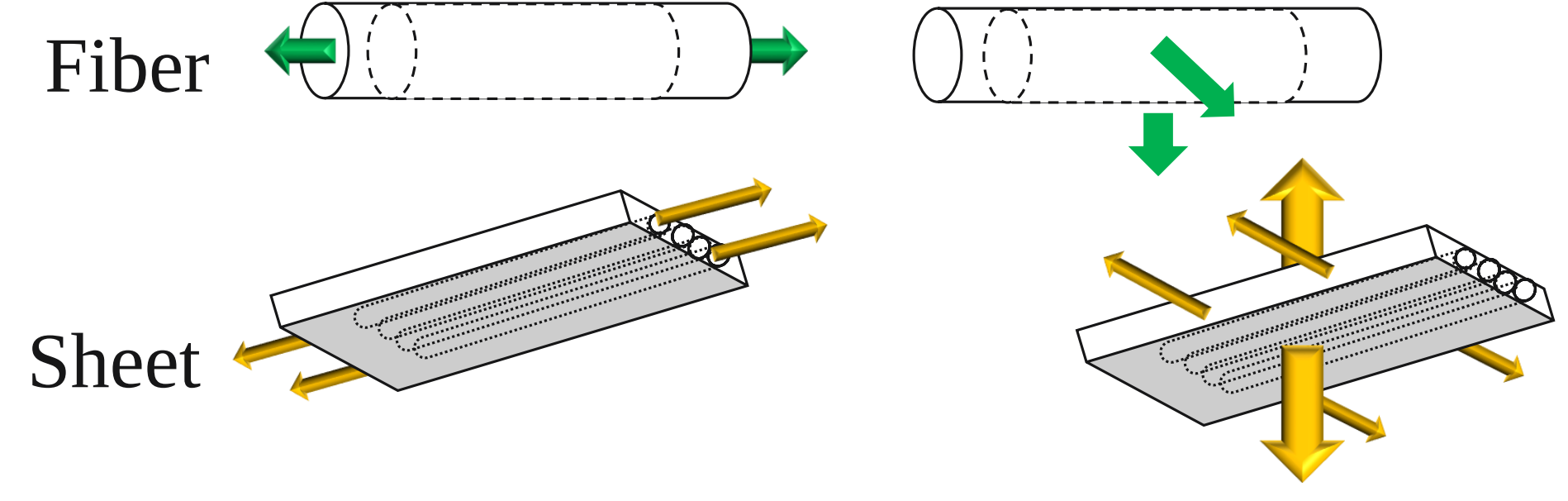


Shearing along the fiber axis
$\mu_{ax}=\mu_{Tra}(1+\phi)=\mu_R\,(1+\phi)$



$E_{ax}=E_{Tra}(1+\zeta)$=$E_{RealYoung}(1+\zeta)$=$3\mu_R(1+\zeta)$

Axial Young modulus (E_{ax}) Real Young modulus $(E_{RealYoung}=E_{Tra})$



DISCUSSION & CONCLUSION

In the LV, tensile anisotropy was $\zeta=0.32\pm0.43$, shear anisotropy was $\phi=0.66\pm0.40$, and shear modulus was $\mu_{tr}=6.9\pm2.15$ KPa. Sheetlets are 1.66 times more resistant to shear *in* the fiber planes compared to shearing *through* their plane (μ_{ax} *vs* μ_{tr}). Fibers were ~1.3 times higher in axial tensile stiffness than transverse, which is in line with tensions test (3). Resistance along the fiber (E_{ax}) increases when ||HA|| decreases, means that fibers or sheets have more resistance to stretch when fibers are circumferential (i.e. HA=0, midwall, TA=0). Consequently, endocardial and epicardial fibers ease more to stretch while providing more longitudinal shortening (higher HA). Thanks to their inward angulation (higher TA) and ease to longitudinal stretching, they provide more decoupling between the endo and epicardium. Sheetlets experience more resistance (μ_{ax},μ_{tr}) when they are parallel to the circumferential plane (TA=0) and on the contrary experience less resistance at the endo and epicardium when they are tilted inward (high TA). The structural and MRE characteristics show that when motion is required, fiber lengthening and shortening or sheetlet tilting (endo-epicardium), the resistance is optimized.

(1)Anderson 2016, (2)Colombo 2014, (3)Sommer 2015

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