Characterization of Soft Tissue Transmural Microstructure

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Statement of Purpose: Understanding the microstructure of tissue components is essential in determining structure-function relationships and in guiding the construction of biomaterials for use in conjunction with other living tissues. Small angle light scattering (SALS) is a proven means of quickly acquiring sample-wide collagenous soft tissue structural information. However, traditional SALS techniques are limited: collection of depth-specific structural information is not possible due to the transmission-based nature of the technique so that location-specific microstructure data is inherently depth averaged. Thus, in order to better study the depth-specific microstructure of native and engineered soft tissues, we have developed a new experimental and analytical method for acquiring *transmural* structural information via SALS, dubbed Transmural SALS (TSALS).

Methods: The SALS technique for collecting structural properties works by raster scanning specimens through the path of a low power laser beam and collecting the location-specific angular distributions of local microstructural fiber from the spatial distribution of scattered light. This process yields large field-of-view microstructure maps that are limited in resolution by only the raster step size and the diameter of the incident beam. Data obtained using SALS techniques takes the form of a two-dimensional set of equally spaced nodes, with each node representing the location-specific orientation distribution function (ODF) $\Gamma[(\theta)]$ obtained from the angular distribution of local microstructural fibers. The ODF is the basis for all further analysis of microstructure properties. Experimentally, TSALS data collection techniques closely match traditional SALS procedures. Yet, rather than scanning intact tissues, samples are histologically sectioned at the desired axial resolution through the depth of the tissue and each individual slice is scanned. These serial scans are registered computationally to match the original configuration of the tissue sample.

To provide a compact method for both data storage and manipulation in modeling, we utilized a 4th rank structure tensor, $\tilde{\mathbf{H}}$, to represent the ODF at each point in the tissue. This is defined as:

$$\tilde{\mathbf{H}} = \mathrm{H}_{ijkl} = \int_{-\pi/2}^{\pi/2} \Gamma[\hat{\mathbf{N}}]\mathrm{N}_i\mathrm{N}_j\mathrm{N}_k\mathrm{N}_l d\hat{\mathbf{N}} = \int_{-\pi/2}^{\pi/2} \Gamma[\hat{\mathbf{N}}(\theta)]\mathrm{N}_i(\theta)\mathrm{N}_j(\theta)\mathrm{N}_k(\theta)\mathrm{N}_l(\theta)\hat{\mathbf{N}}(\theta)d\theta$$

These orientation tensors act as a concise description of the fiber orientation properties, and allow for the close-fit reconstruction of the original ODF using well-defined operations. From $\tilde{\mathbf{H}}$ we can compute all fiber orientation-related parameters such as preferred direction (PD) and orientation index (OI), skew and kurtosis.

To date, this method has been used to characterize the soft tissue microstructure of the following fibrous tissues: bovine tendon, porcine aortic valve leaflets, infarcted porcine myocardium, and porcine sclera. The method can be applied to any fibrous biomaterial of non-trivial thickness.

Results: TSALS yields a spatially accurate, three-dimensional, nodal data set from which we can glean valuable sample-specific information on spatial variation in microstructure property via gradients of scalar, vector, and tensor values throughout the transmural thickness of the tissue. Additionally, 3D reconstructed data can then be visualized using isosurfaces, vector fields, and tensor glyphs in ParaView (Kitware, Clifton Park, NY).

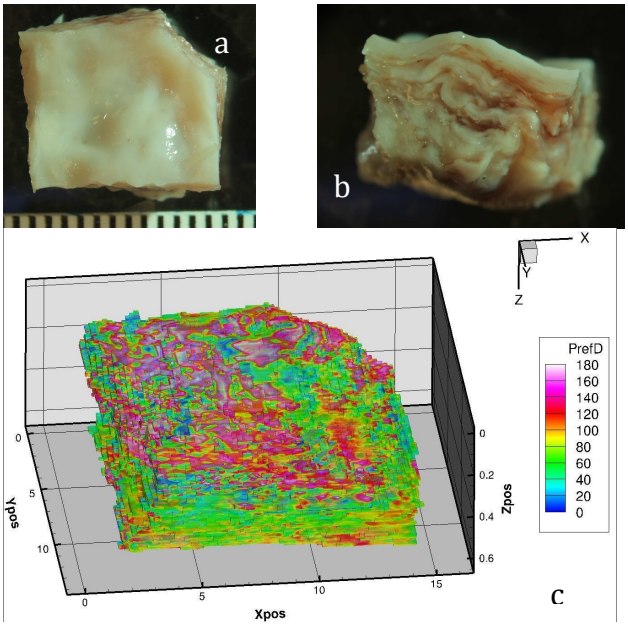

Figure 1a. Apex view of the endocardial surface of intact infarcted ovine myocardium, **b.** Transmural cross-section of tissue with endocardium at the top, **c**. Three-dimensional visualization of transmural microstructure map: shown here is preferred fiber direction.

Conclusions: In conclusion, we present a new technique for succinctly characterizing the microstructure of three-dimensional fibrous soft tissues or tissue-like materials using experimentally proven data acquisition methods, yet utilizing novel and concise structural orientation tensor analysis methods. The technique is mathematically elegant and computationally efficient.

References:

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