Complex Fiber Architecture of the Tongue and Esophagus Revealed by MRI Diffusion Spectrum Tractography

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Introduction:

The muscular organization of the various sections of the gastrointestinal tract consists of complex arrays of variably aligned fibers, which determine the possible functional deformations attainable by these tissues (1,2). In most instances the precise 3D relationships among the constituting fibers in situ is not well understood. DSI is an MRI technique for interrogating tissue microstructure based on the measurement of average spin displacement function due to proton diffusion, and is particularly well suited for defining complex intravoxel fiber architecture. Tractography formalisms may be employed with DSI to derive intervoxel connectivity, a property which infers mechanical continuity. We present here the application of DSI with tractography for delineating crossing fibers in two organs of the GI tract, the tongue and the esophagus.

Methods:

Diffusion spectrum imaging (DSI) is a method for measuring the behavior of an average diffusion propagator. The average diffusion propagator is the sum of probability density functions for all possible spin initial positions, weighted by the proton density distribution. The advantage of employing the average diffusion propagator is that it is not derived from a particular geometric model, and therefore makes no assumptions about the underlying microstructure or the physical nature of the diffusive process. In comparison, since DTI assumes that diffusion is Gaussian for all starting points, it is less accurate in representing restricted diffusion associated with biological boundaries. DSI yields an ensemble probability density function (PDF) for the set of molecular displacements as a function of molecular motion, and is based on the Fourier relationship between the PDF and the diffusion signal for the spin echo obtained at various gradient strengths. This average spin displacement qualitatively relates to the probability of spin displacement in the voxel. The spin displacement function should possess local maxima corresponding to fiber population directions in the voxel. DSI acquisitions sampled 515 q-values comprising the points of rectangular grid contained within a sphere (3). Fresh cow tongue specimens were imaged in a 3T clinical scanner (Siemens Allegra), using a multislice EPI SE 3000/150 sequence (4) with spatial resolution of 3 or 4 mm isotropic and maximum diffusion sensitivity $b_{max} = 8 \times 10^3$ s/cm^2. Fresh cow esophageal specimens were imaged in a 4.7T Brucker instrument with an SE DSI with 3DFT EPI spatial encoding (2DEPI in {x,y}-plane + 1D Fourier phase encoding in 'z'), with maximum gradient sensitivity $b_{max} = 1.5 \times 10^4$ s/cm^2 DSI data were reconstructed by 3DFT with hanning filter, orientation vectors of maximum diffusion identified at each voxel, and integral curves found among these vector fields integrated to fiber tracts with a simple streamline algorithm.

Results and Discussion:

The tractography images presented in Figures 1 and 2 depict novel information regarding the relative alignment of muscular fibers in these tissues. We demonstrate in the tongue a near seamless relationship between the various intrinsic muscles in the core region (transverses, verticalis, and longitudinalis) and the extrinsic fibers. Comparison between various DSI acquisition parameters revealed that higher b-value scans produced greater delineation of crossing fibers, although there was also greater variation in the angularity. We demonstrate in the esophagus the presence of helically crossing fiber populations located in the circumferential-aligned region of the tissue. Fibers are color-coded according to the helix angle with respect to the central axis. Shown are a set of longitudinal fibers (red) over which are two sets of helical fibers (purple-blue and yellow-green), each comprising a cylinder. Remarkably, these two fiber populations of contrasting helix angles are not concentric, but are displaced with respect to one another and interwoven as fascicles, along two longitudinal zones ("zippers"). These findings show the capacity for DSI with tractography to delineate mechanically relevant fiber populations in tissues of the gastrointestinal tract, typified by complex crossing patterns.

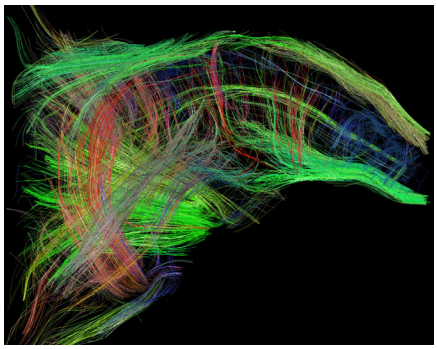

Figure 1: DSI tractography image of bovine tongue (sagittal). Only tracts which pass through the sagittal median plane of the tongue are shown. The intrinsic core of the tongue contains faint red and blue crossing fiber patterns. The imaging resolution is 2.8 mm isotropic, and the maximum b-value is 5.5 x 10^3 s/cm^3.

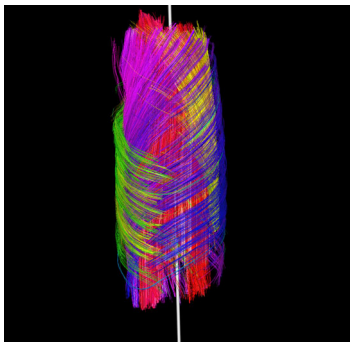

Figure 2: DSI tractography image of bovine esophagus. Imaging resolution is 0.7 mm isotropic, and the maximum b-value is 1.5 x 10^4 s/cm^2. Tract coloring scheme is based on the helical angle about the vertical center axis shown. Green and blue merging fiber populations are prevalent.

Conclusions:

Both the tongue and the esophagus contain intersecting muscle fascicles, whose architecture may be resolved by diffusion spectra, but is otherwise inaccessible to diffusion tensor imaging. The crossing fiber pattern in the core of the tongue is critical to achieve the vast array of physiological shapes needed for normal speech and swallowing. The esophageal fiber architecture of crossed cylinders permits the integration of muscle components of opposite helicity and equal radius. Our study has shown that the characteristic complexity of the gastrointestinal musculature is well demonstrated by high angular resolution diffusion MRI tractography.

References: 1) Napadow, et al. J Biomechanics, 32: 1-12, 1999, 2) Wedeen, et al. Biophys J, 80: 1024-1028, 2001, 3) Wedeen, et al. ISMRM. 2000, 4) Reese, et al. Magn Reson Med, 49(1): 177-82, 2003.