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Associating the mesoscale fiber organization of the tongue with local strain rate during swallowing

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Abstract

The tongue is an intricately configured muscular organ that undergoes a stereotypical set of deformations during the course of normal human swallowing. In order to demonstrate quantitatively the relationship between 3D aligned lingual fiber organization and mechanics during swallowing, the tissue's myoarchitecture and strain rate were imaged before and during the propulsive phase of a 3.0 ml water bolus swallow. Mesoscale fiber organization was imaged with high-resolution diffusion tensor imaging (DTI) and multi-voxel myofiber tracts generated along maximum diffusion vectors. Tissue compression/expansion was obtained via lingual pressure-gated phase-contrast (PC) MRI, a method which determines local strain rate as a function of the phase shift occurring along an applied gradient vector. The co-alignment of myofiber tract direction and the localized principal strain rate vectors was obtained by translating the strain rate tensor into the reference frame with the primary axis parallel to the maximum diffusion vector using Mohr's circle, resulting in the generation of fiber-aligned strain rate (FASR). DTI tractography displayed the complete fiber anatomy of the tongue, consisting of a core region of orthogonally aligned fibers encased within a longitudinal sheath, which merge with the externally connected styloglossus, hyoglossus, and genioglossus fibers. FASR images obtained in the mid-sagittal plane demonstrated that bolus propulsion was associated with prominent compressive strain aligned with the genioglossus muscle combined with expansive strain aligned with the verticalis and geniohyoid muscles. These data demonstrate that lingual deformation during swallowing involves complex interactions involving intrinsic and extrinsic muscles, whose contractility is directed by the alignment of mesoscale fiber tracts.

Keywords: MRI; Phase contrast; DTI; Tractography; Muscle imaging; Strain

1. Introduction

Associating microscopic fiber organization with tissue deformation is a challenging task in tissues where the constituting myofibers express complex geometries. The mammalian tongue is an apt model for such studies since its myoarchitecture is comprised by an intricate 3D network of intrinsic and extrinsic muscles (Sonntag, 1925; Wedeen et al., 2001; Napadow et al., 2001) (Fig. 1). Lingual intrinsic musculature consists of a core region of orthogonally aligned fibers, contained within a sheath-like tract of longitudinally oriented fibers. These intrinsic fibers merge with extrinsic muscles that modify shape and position from a superior (palatoglossus), posterior (styloglossus), and inferior direction (genioglossus and hyoglossus). During swallowing, the tongue undergoes a characteristic set of deformations, dictated largely by its hydrostatic properties (Smith, 1986; Smith and Kier, 1989; Napadow et al., 1999a, 2002; Gilbert et al., 2007), which serve to shape the ingested bolus (early accommodation), transfer the bolus from the anterior to the posterior oral cavity (late accommodation), and then transfer the configured bolus into the pharynx (propulsion) (Napadow et al., 1999b).

NMR methods have been developed depicting mesoscale representations of 3D fiber organization and mechanics.

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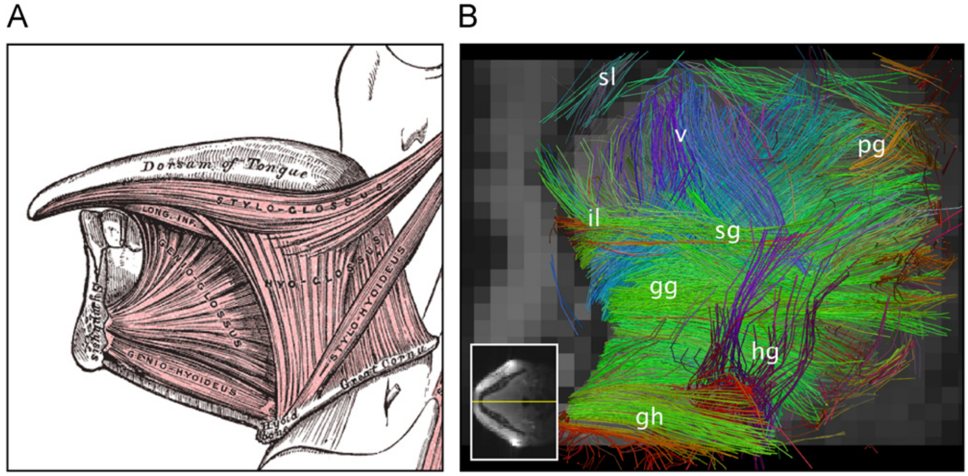

Fig. 1. Lingual muscular anatomy. The musculature of the tongue is classically divided into two types of muscle, intrinsic and extrinsic. The intrinsic muscles include the superior and inferior longitudinalis, the transversus, and the verticalis muscles. The transversus, verticalis, and longitudinalis muscles also extend to the posterior tongue, where they are merged with the extrinsic muscles. These muscles enter the tongue proper from a superior direction (palatoglossus), postero-superior direction (styloglossus), postero-inferior direction (hyoglossus) and antero-inferior direction (genioglossus). The genioglossus comprises the bulk of the posterior tongue and enters the tongue in a fan-like projection, originating at the mental spine of the mandible. The tongue rests on a muscular floor composed of the geniohyoid muscle, which runs in the mid-sagittal plane from the mental spine of the mandible to the body of the hyoid bone; and the mylohyoid, which runs from the mylohyoid line of the mandible to the raphe and body of the hyoid bone. Shown in this figure is an anatomical drawing obtained from Gray's anatomy (A) is presented in comparison to a sagittal 3D view of lingual myoarchitecture based on in vivo DTI tractography (B). Note the close structural correlation between genioglossus (gg), geniohyoid (gh), hyoglossus (hg), and styloglossus (sg) merged with the inferior longitudinalis (il). Not shown in the anatomical drawing, but generally visible in tractography images are the superior longitudinalis (sl) and verticalis (v) fibers in the anterior tongue, and the palatoglossus (pg) in the posterior tongue. Inset in left lower corner of (B) demonstrates the reference location of the MRI image.

Diffusion-weighted NMR defines myoanatomy as an array of elements representing directional differences of proton diffusion (Stejskal and Tanner, 1965), and can be used to define 3D fiber alignment in terms of principal fiber direction at the voxel (Basser et al., 1994; Wedeen et al., 2001; Napadow et al., 2001; Gilbert et al., 2006a) or multi-voxel scale in terms of myofiber tracts generated by streamline tractography (Gilbert et al., 2006b; Gaige et al., 2007). Moreover, we have employed gated phase contrast MRI (Felton et al., 2007), a method which derives directional change of compression or expansion based on the difference between adjacent velocity vectors (Dou et al., 2003; Ebbers et al., 2002; Wedeen et al., 1995) to map the distribution of local strain rate during swallowing, The goal of the current study was to merge these measures to define relationships between aligned myofiber populations and local strain rate. This approach associates the orientation of the principal diffusion vectors and the principal strain rate vectors for each voxel resulting in a measure of the deformation of the underlying fiber, termed fiber-aligned strain rate (FASR). thus deriving a mesoscale representation of local mechanical function referenced to its myoarchitecture.

2. Methods

2.1. General methods

Lingual myoarchitecture and strain rate were determined with high-resolution diffusion tensor and phase-contrast MRI in normal volunteers. Subjects ($n = 4$, 3 males, 1 female, ages 21–24) possessed no history or current abnormalities of speech or swallowing. The study was approved by the MIT Committee on the use of humans as experimental subjects.

2.2. Diffusion tensor imaging (DTI) with tractography

DTI tractography derives the orientation of fiber populations by measuring anisotropic proton diffusion at each location in a tissue (Basser et al., 1994; Wedeen et al., 2001). The physical basis by which diffusion-weighted MRI infers fiber direction in muscular tissue has been published (Wedeen et al., 2001; Napadow et al., 2001, Gilbert et al., 2006a, b, Gaige et al., 2007) and validated relative to microscopy (Napadow et al., 2001). In brief, diffusion represents the random translational motion of protons contained in water molecules and is principally modulated by the presence and location of macromolecular barriers to water displacement. The diffusion tensor depicts net proton diffusion in a volume of tissue with a symmetric 2nd rank tensor, and can be interpreted as an ellipsoid whose axes are constructed along its three orthogonal eigenvectors with each axis proportional to its eigenvalues. The application of gradients, configured as evenly spaced directions on the surface of a model sphere, results in a system of linear equations that over-constrains the components of the diffusion tensor and may be solved using multiple linear regression. Diffusion-weighted gradients were applied in 90 unique directions employing single shot echo-planar (EPI) spatial encoding and the following imaging parameters: TR = 3000 ms, TE = 80 ms, field of view 192 mm × 192 mm, 3 mm slice thickness, and a b-value of 500 s/mm^2. These parameters allowed complete acquisitions for the DTI tractography image set to be accomplished in approximately 5 min. Maximum diffusion is a vector defined as the largest eigenvector of the diffusion tensor. Multi-voxel myofiber tracts were generated along the maximum diffusion vector per voxel employing streamline construction, a method for constructing connections along the vector directions in a vector field, as previously described (Gilbert et al., 2006b). The specific method operates by applying the constraint that a certain angular threshold must be met to establish