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Biomechanical basis for lingual muscular deformation during swallowing

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Napadow, Vitaly J., Qun Chen, Van J. Wedeen, and Richard J. Gilbert. Biomechanical basis for lingual muscular deformation during swallowing. *Am. J. Physiol.* 277 (*Gastrointest. Liver Physiol.* 40): G695–G701, 1999.—Our goal was to quantify intramural mechanics in the tongue through an assessment of local strain during the physiological phases of swallowing. Subjects were imaged with an ultrafast gradient echo magnetic resonance imaging (MRI) pulse sequence after the application of supersaturated magnetized bands in the x and y directions. Local strain was defined through deformation of discrete triangular elements defined by these bands and was depicted graphically either as color-coded two-dimensional strain maps or as three-dimensional octahedra whose axes correspond to the principal strains for each element. During early accommodation, the anterior tongue showed positive strain (expansive) in the anterior-posterior direction (x), whereas the middle tongue showed negative strain (contractile) in the superior-inferior direction (y). During late accommodation, the anterior tongue displayed increased positive x -direction and y -direction strain, whereas the posterior tongue displayed increased negative y -direction strain. These findings were consistent with contraction of the anterior-located intrinsic muscles and the posterior-located genioglossus and hyoglossus muscles. During propulsion, posterior displacement of the tongue was principally associated with positive strain directed in the x and y directions. These findings were consistent with posterior passive stretch in the midline due to contraction of the laterally inserted styloglossus muscle, as well as contraction of the posterior located transversus muscle. We conclude that MRI of lingual deformation during swallowing resolves the synergistic contractions of the intrinsic and extrinsic muscle groups.

tongue physiology; deglutition; muscle mechanics

DURING NORMAL SWALLOWING, the tongue undergoes a stereotypical sequence of muscular deformations. The ingested bolus is initially contained in a groove-like depression in the middle dorsal surface of the tongue (early accommodation). This depression is then translated in a posterior direction until the bolus comes to rest at the posterior edge of the tongue (late accommodation). Finally, the oral stage of the swallow is concluded by the rapid clearance of the bolus retrograde into the oropharynx (propulsion) (5). The extent of muscular tissue deformation during swallowing may

vary under normal conditions as a function of bolus volume (1) or viscosity (9), or it may be modified by pathological effects on muscle contractility and/or neuromuscular regulation (5).

Because of the complexity of lingual anatomy and its material attributes, the relationship between tongue structure and mechanical function is not well understood. The anterior tongue consists of a central region of orthogonally oriented intrinsic fibers (transversus and verticalis) surrounded by a sheath-like tract of longitudinally oriented intrinsic fibers (longitudinalis). The transversus and longitudinalis muscles extend to the posterior tongue (6). The posterior tongue contains a central region of fibers originating at the mental spine of the mandible and projecting in a fan-like manner in the superior, lateral, and posterior directions (corresponding to the genioglossus). There are two major laterally inserted fiber populations, the first directed posterior and inferior (corresponding to the hyoglossus) and the second directed posterior and superior (corresponding to the styloglossus). Furthermore, owing to its highly aqueous content, the tongue tissue is effectively incompressible, and therefore it maintains the ability to deform without altering tissue volume. In view of these factors, the assessment of the intramural mechanics of the tongue during physiological motion on the basis of surface properties alone is problematic (2, 3, 4, 10). We have previously studied the intramural mechanics underlying lingual tissue deformation through the assessment of regional strain by magnetic resonance imaging during relatively simple motions, such as protrusion and bending (10). In the current study, we have extended this magnetic resonance technique to derive three-dimensional maps of intrinsic and extrinsic muscular strain for the more complex deformations associated with swallowing.

MATERIALS AND METHODS

Subjects ($n = 8$) were chosen for study who possessed no history or current abnormalities of speech or swallowing. These studies were approved by the Institutional Review Board for Human Research of Beth Israel Deaconess Medical Center. Dry (saliva only) swallows were elicited from the subjects, and magnetic resonance imaging was performed for each swallow. The timing of image acquisition was determined in such a manner as to visualize the various phases of oral stage deglutition.

Magnetic resonance imaging. Magnetic resonance imaging was performed with a 1.5 Tesla Siemens Vision MRI system, equipped with an anterior neck coil that used an ultrafast asymmetric gradient echo pulse sequence (TurboFLASH). The imaging parameters were as follows: repetition time/echo

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time, 2.25/0.8 ms; matrix size, 80×128 ; slice thickness, 10 mm; and effective spatial resolution, 1.33×1.33 mm, as previously described (8). The imaging pulse sequence was preceded by saturation radiofrequency tagging pulses (spacing 7 mm) that deform with and track actual tissue deformation. Owing to the fact that image intensity was proportionate to the amount of longitudinal magnetization before the imaging pulse sequence, the tissue affected by the tagging pulses appeared as dark lines in relation to the adjacent tissue. In a two-dimensional (2-D) image of undeformed tissue, magnetic tags appeared as a rectilinear grid (7-mm spacing between taglines), and, as such, deformation of the tagging grid corresponded to local deformation of the actual tissue. For a given subject, the experimental protocol was as follows: 1) application of magnetic tags to the resting undeformed tongue muscle tissue, which, through an audible click, prompted the subject to swallow; 2) variable delay of a set time interval (300–800 ms, in increments of 100 ms); and 3) imaging of the tagged, deformed tissue.

Strain quantification in the deformed tagged image. Deformation was quantified in image postprocessing with measures of nonlinear strain, a unitless measure of localized deformation suited to quantifying large deformations. To resolve the idealized material continuum of the tongue, discrete triangular deforming elements were defined by digitizing nodes at tagline intersections. Thus each triangular element was composed of two independently deforming line elements whose length and angular orientation related the axial and shear strain measured from the actual deforming tongue tissue.

Although this tagging technique is inherently 2-D, the out-of-plane axial strain was calculated by knowing the 2-D strain condition, assuming that tongue muscle is incompressible (hence isochoric) and that out-of-plane shear strains are negligible

$$E_{33} = \frac{1}{2} \left(\frac{1}{(1 + 2E_{11})(1 + 2E_{22})} - 1 \right) \quad (1)$$

where E_{11} , E_{22} , and E_{33} are the principal strains. Because E_{xz} and E_{yz} are assumed nil

$$E_{zz} = E_{33} \quad (2)$$

These assumptions are reasonable because the tongue tissue is highly aqueous (water can be assumed incompressible), the swallow time scale does not allow significant influx and efflux of blood or other fluids into the tissue, and swallow kinematics are generally symmetrical about the midsagittal plane.

Directional axial or shear strains were represented individually as a color-coded “map,” smoothed by bicubic approximating splines, overlaying the original tagged image. The entire strain tensor was alternately represented by a spatial array of octahedra, with each octahedra centered on a tagging element’s centroid. The major and minor axes of these octahedra were oriented according to the directions of the tensorial eigenvectors and scaled to the linear directional axial stretch measured in the given tagging element. In addition, the relative size of an octahedron was based on a scaling factor, f , defined by a function of the strain tensor’s independent eigenvalues (λ_1 and λ_2)

$$f = \sqrt{\lambda_1^2 + \lambda_2^2} \quad (3)$$

Thus the relative size of an octahedron relates an overall measure of strain inherent in the corresponding tongue tissue element.

Data analysis. To obtain mean directional strain data, four regions in the midsagittal slice of the tongue (anterior, midsuperior, posterior, and inferior; Fig. 1) were sampled in the x , y , and z directions. Data were analyzed for each region for three phases of oral-stage deglutition: early accommodation, late accommodation, and propulsion. P values were computed for a one-sided t -test, which tested whether or not a sample mean was significantly greater than or less than zero. The means and standard deviations for the one-sided t -test were computed for each condition.

On the basis of previous determinations of tissue myoarchitecture and function in the midsagittal plane, the anterior tongue region (*region 1*) encompasses the tongue’s intrinsic musculature (transversus, verticalis, and longitudinalis muscles). The middle superior tongue region (*region 2*) encompasses the anterior fibers of the genioglossus muscle and a portion of the intrinsic muscles. The posterior tongue region (*region 3*) encompasses predominantly the posterior fibers of the genioglossus muscle. Although *regions 2* and *3* subdivide the genioglossus muscle, there is precedent for heterogeneous, localized activity in this muscle, as has been previously suggested by electromyography studies (7). The inferior tongue region (*region 4*) encompasses the inferior fibers of the genioglossus muscle, as well as the geniohyoid muscle. These regions were also chosen to help clarify the multidimensional (both time and space) strain data. The coordinate axes x , y , and z correspond to anterior-posterior (x), inferior-superior (y), and medial-lateral (z) directions.

RESULTS

Direction-dependent strain fields were acquired for the midsagittal slice of the tongue with the use of a tissue-tagging nuclear magnetic resonance technique. Normal subjects were studied during three phases of dry swallows: early accommodation, late accommodation, and propulsion. Strain data were visualized either as 2-D strain maps (axial strain in the x , y , and z directions) for representative subjects, or as octahedra representing the complete strain tensor (directional strain in principal directions) for each deforming element (Figs. 2–4). In addition, intersubject axial strain means for each of four functional regions of the tongue were also displayed (Table 1).

In early accommodation, the subject contained the bolus in the middle portion of the tongue’s dorsal

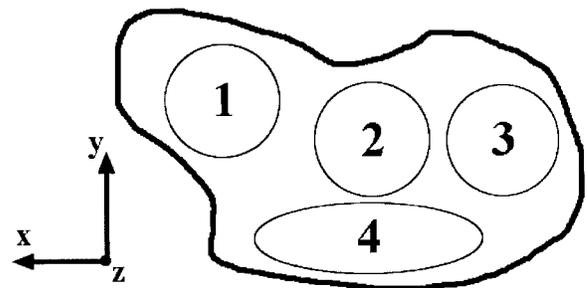


Fig. 1. Regional analysis of tongue mechanics. Segmentation of midsagittal imaging slice was into 4 functional regions. *Region 1*: intrinsic musculature, including transversus, verticalis, and longitudinalis. *Region 2*: anterior genioglossus and posterior intrinsic fibers. *Region 3*: posterior fibers of genioglossus muscle. *Region 4*: inferior genioglossus and geniohyoid fibers. Coordinate axes x , y , and z correspond to anterior-posterior (x), inferior-superior (y), and medial-lateral (z) directions.

Table 1. Axial strain in the tongue during the early accommodative phase of swallowing

	Region 1	P	Region 2	P	Region 3	P	Region 4	P
x	0.135 ± 0.121*	0.0081	0.188 ± 0.071*	0.0001	0.083 ± 0.057*	0.0023	0.093 ± 0.046*	0.0004
y	-0.006 ± 0.105	0.4345	-0.165 ± 0.054*	0.00003	-0.034 ± 0.035	0.0140	-0.050 ± 0.063	0.0312
z	0.034 ± 0.114	0.2140	0.179 ± 0.114*	0.0015	0.021 ± 0.054	0.1526	0.032 ± 0.072	0.1272

Values are means ± SD of axial strain in association with early accommodation ($n=8$) for each region of the tongue (see Fig. 1). The data are represented as axial strain along each spatial direction (x , y , and z). P values were computed for a one-sided t -test, which tested whether or not a sample mean strain was significantly greater than or less than zero. * $P < 0.01$.

surface (Fig. 2). The anterior tongue showed a characteristic pattern of positive (expansive) x -direction strain (peak strain 0.521), whereas the middle tongue showed negative (contractile) y -direction strain (peak strain

-0.319), along with positive x - and z -direction strain (peak strains 0.477 and 0.803, respectively). The posterior and inferior regions of the tongue demonstrated x -direction expansion (peaking at 0.208 and 0.477,

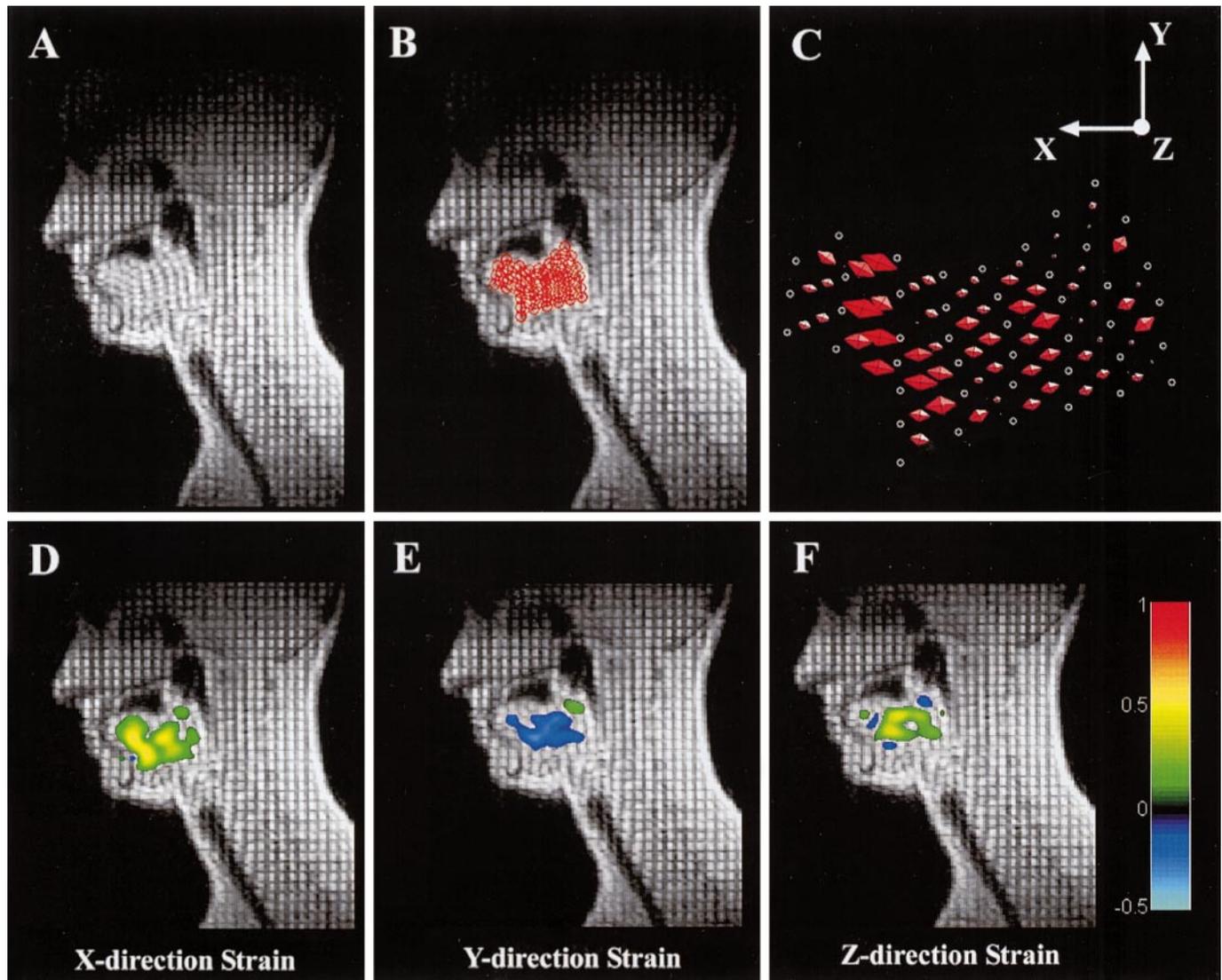


Fig. 2. Lingual strain during early accommodation. Direction-dependent strain fields were acquired for midsagittal slice of tongue with use of tissue-tagging nuclear magnetic resonance imaging and discrete element analysis. A grid of saturation magnetic resonance imaging tags was applied to resting tissue to create a set of deforming elements. Strain data were visualized either as two-dimensional (2-D) strain maps (axial strain in x , y , and z directions) or as octahedra representing complete strain tensor (directional strain in principal directions) for each deforming element. *A*: deformed grid associated with tongue movement. *B*: triangular finite element mesh associated with tongue movement. *C*: three-dimensional strain tensor depicted as octahedra corresponding to each element. *D–F*: 2-D strain maps depicting axial strain in x (*D*), y (*E*), and z (*F*) directions. Bolus containment is associated with negative y -direction strain consistent with a synergistic contraction of anterior genioglossus and hyoglossus, with concomitant x - and z -direction expansion.

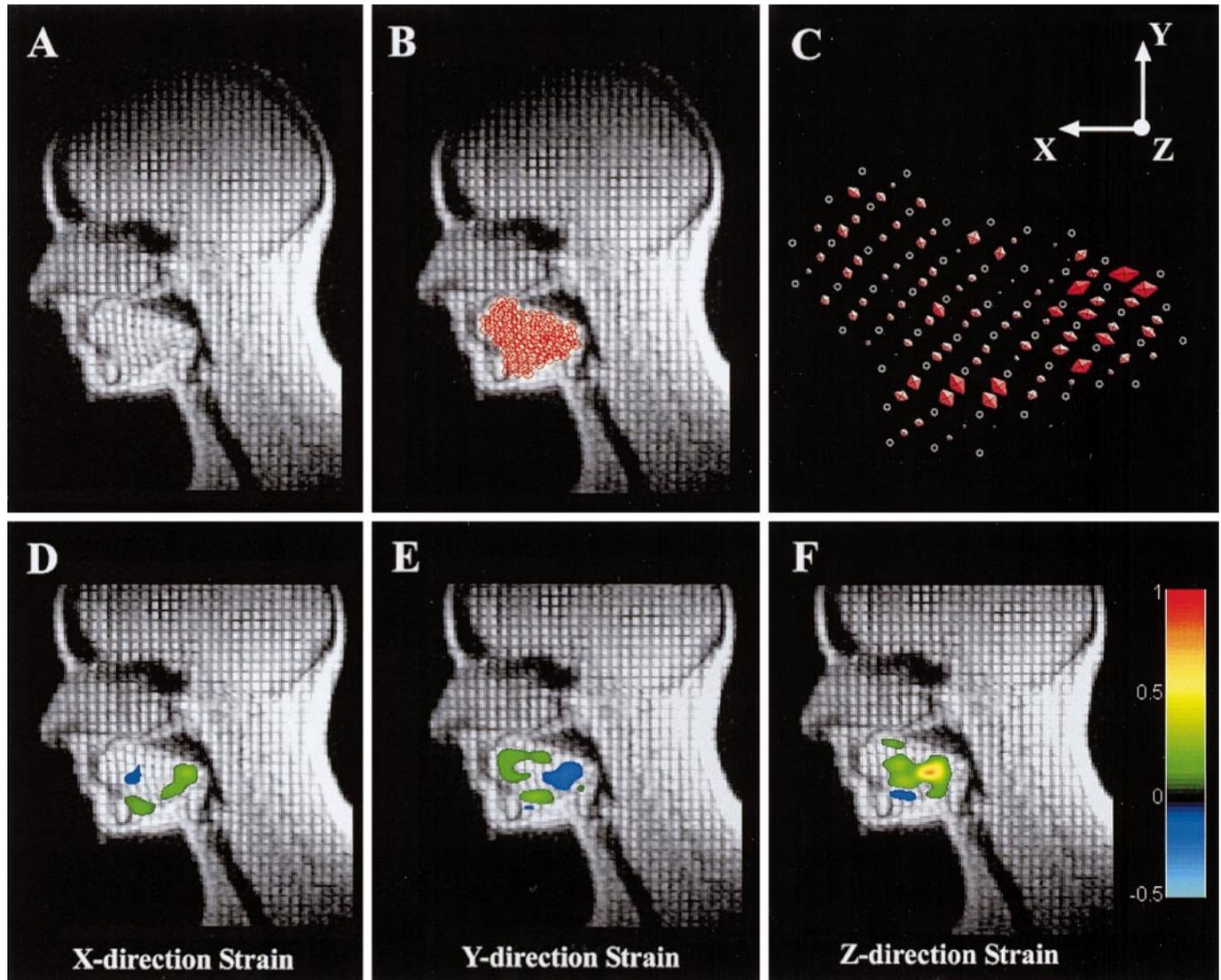


Fig. 3. Lingual strain during late accommodation. Direction-dependent strain fields (A–F) are as described in Fig. 2. Combination of *y*-direction contraction in posterior tongue and expansion in anterior tongue results in shifting of bolus to posterior dorsal surface of tongue, consistent principally with contraction of posterior genioglossus and concomitant *x*- and *z*-direction expansion.

respectively). Intersubject mean data corroborated these deformation patterns ($P < 0.01$; Table 1).

During late accommodation (Fig. 3), with the subject holding the bolus in a posterior depression, the anterior tongue displayed positive *y*-direction strain (peak strain 0.151). The posterior tongue displayed significant negative *y*-direction strain (peak strain -0.302) with commensurate expansion along the *x* and *z* directions (peaking at 0.358 and 1.845, respectively). Intersubject mean data also corroborated these deformation pat-

terns ($P < 0.01$; Table 2). Thus bolus accommodation (early and late) principally represents a combination of contraction of the intrinsic core muscles in the anterior tongue (with commensurate anterior or superior expansion) and inferiorly-directed contraction of the extrinsic muscles (genioglossus and hyoglossus) in the middle and posterior regions of the tongue.

During the propulsive phase of the swallow (Fig. 4), the bolus is propelled retrograde into the oropharynx by posterior displacement and deformation of tongue

Table 2. Axial strain in the tongue during the late accommodative phase of swallowing

	Region 1	<i>P</i>	Region 2	<i>P</i>	Region 3	<i>P</i>	Region 4	<i>P</i>
<i>x</i>	0.027 ± 0.063	0.1726	-0.009 ± 0.040	0.2981	$0.131 \pm 0.043^*$	0.0003	$0.073 \pm 0.047^*$	0.0063
<i>y</i>	$0.136 \pm 0.089^*$	0.0067	-0.074 ± 0.062	0.0163	$-0.125 \pm 0.061^*$	0.0020	-0.010 ± 0.070	0.3688
<i>z</i>	-0.048 ± 0.066	0.0685	$0.192 \pm 0.093^*$	0.0020	$0.202 \pm 0.134^*$	0.0071	0.023 ± 0.101	0.2984

Values are means \pm SD of axial strain in association with early accommodation ($n=6$) for each region of the tongue. The data are represented as axial strain along each spatial direction (*x*, *y*, and *z*). *P* values were computed as for Table 1. * $P < 0.01$.

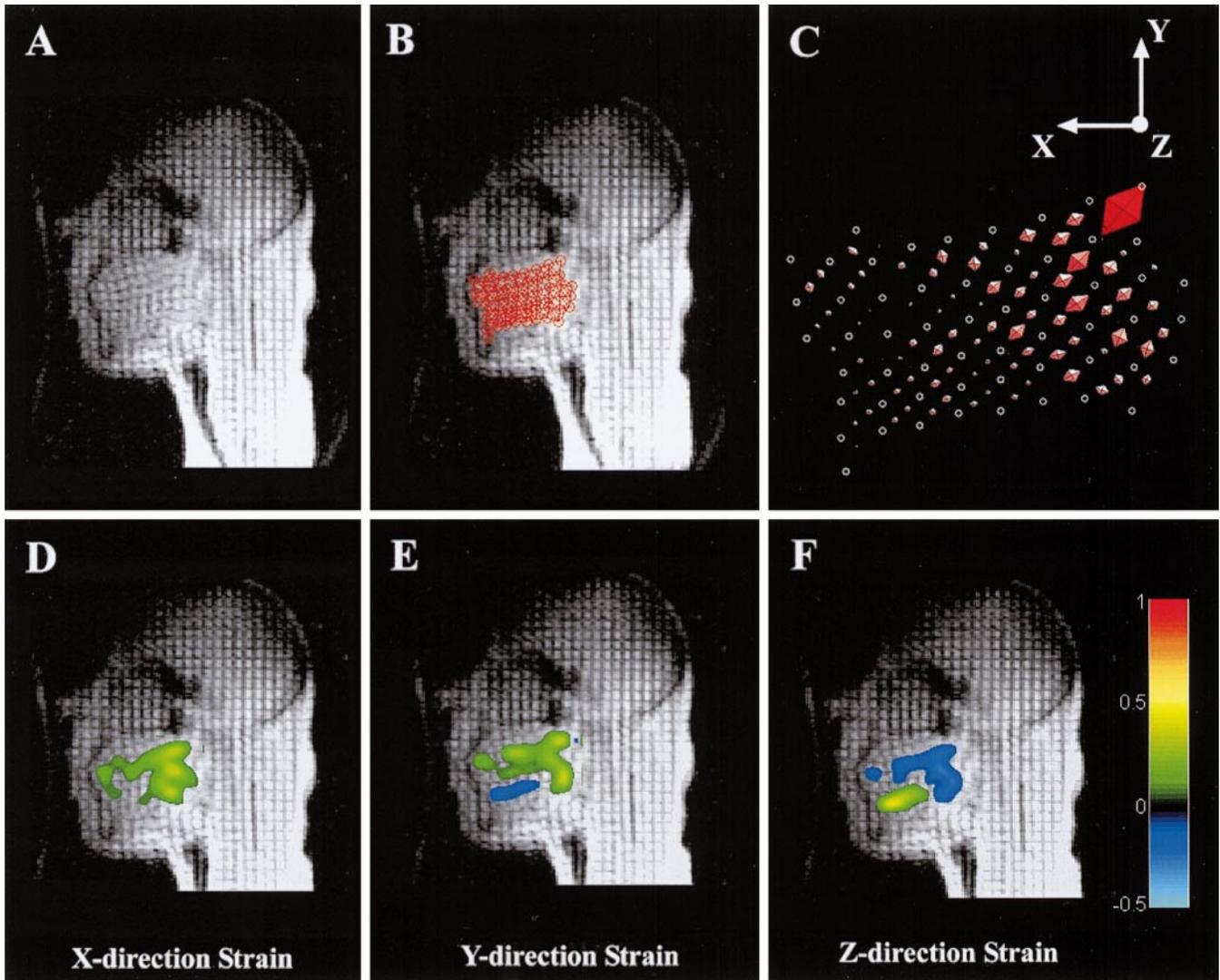


Fig. 4. Lingual strain during propulsion. Direction-dependent strain fields (A–F) are as described in Fig. 2; *x*- and *y*-direction expansion in posterior tongue was consistent with contraction of laterally inserted styloglossus (with associated passive drag) and *z*-direction contraction of posterior located transversus fibers.

tissue. During this phase, the strain results in the posterior genioglossus presented expansive *x*- and *y*-direction strain (peaking at 0.469 and 0.684, respectively) and contractile *z*-direction strain (peaking at -0.374). These results were also seen as statistically significant deformation patterns in intersubject mean strain calculations ($P < 0.001$; Table 3). This result was consistent with the existence of postero-superior-directed passive stretch in the midline, and suggests concurrent contraction of the laterally inserted styloglossus (not visualized in the current study), as well as

contraction of the *z*-directed muscle fibers characteristic of the intrinsic transversus muscle.

DISCUSSION

The tongue is a muscular organ that is instrumental in the manipulation, configuration, and delivery of the ingested bolus from the oral cavity to the pharynx during swallowing. These functions are carried out through a series of characteristic deformations, which are designed to first control (early and late accommoda-

Table 3. Axial strain in the tongue during the propulsive phase of swallowing

	Region 1	P	Region 2	P	Region 3	P	Region 4	P
<i>x</i>	0.034 ± 0.053	0.0680	0.065 ± 0.081	0.0388	$0.173 \pm 0.045^*$	0.00003	$0.064 \pm 0.044^*$	0.0043
<i>y</i>	0.083 ± 0.067	0.0085*	0.050 ± 0.093	0.1045	$0.098 \pm 0.050^*$	0.0010	0.008 ± 0.058	0.3713
<i>z</i>	-0.031 ± 0.064	0.1252	-0.014 ± 0.080	0.3323	$-0.109 \pm 0.040^*$	0.0002	-0.004 ± 0.061	0.4275

Values are means \pm SD of axial strain in association with early accommodation ($n=7$) for each region of the tongue. The data are represented as axial strain along each spatial direction (*x*, *y*, and *z*). *P* values were computed as for Table 1. * $P < 0.01$.

tion) and then rapidly propel the bolus (propulsion). To determine the intramural dynamics of the lingual musculature associated with these deformations, we have used tagging magnetic resonance imaging to quantify local muscle deformation (i.e., strain) in relation to overall tissue shape. Strain, which was the measured result of our analysis, is a unitless measure of normalized deformation. Positive strain signifies expansion, whereas negative strain signifies tissue contraction. Through this analysis, we have elaborated a series of spatially resolved strain maps corresponding to regional muscular activity during the functional phases of swallowing.

Early accommodation was characterized by the containment of the bolus in a grooved depression at the middle portion of the tongue's dorsal surface. This grooved depression appeared to have been created by a contraction of the anterior genioglossus in combination with the hyoglossus, verticalis (intrinsic), and transversus (intrinsic) muscles. Verticalis contraction was seen as a region of negative y -direction strain in the anterior tongue (Fig. 2D), resulting in x -direction expansion of the tongue tip toward the incisors. Transversus contraction was suggested on the basis of subtle z -direction negative strain (Fig. 2E). There was, however, strong evidence of negative y -direction strain directly below the bolus, producing a depression of the containing groove. This tissue contraction could be the direct result of genioglossus contraction or could have been caused through passive drag by contraction of the hyoglossus, which inserts into the midportion of the tongue body laterally from below (hence not visualized in the midsagittal slice). Genioglossus contraction in the swallow has been demonstrated by previous EMG studies (7), whereas synergistic involvement of the hyoglossus could be inferred from the strain tensor visualization map (Fig. 2C). This strain map demonstrated that the contractile eigenvectors (visualized as the short axes of octahedra: the direction of greatest contractile strain when z -direction strain is positive) were oriented postero-inferiorly. Because the midsagittal slice is directly medial to the lateral insertions of the hyoglossus, this strain pattern was consistent with either genioglossus or hyoglossus contraction, occurring independently or in concert. These contractions were associated with x - and z -direction expansion in this region, elongating the grooved depression and improving bolus containment. The x -direction expansion in the posterior tongue aided in closing off the pharynx.

Late accommodation was characterized by a shifting of the bolus toward the posterior dorsal surface of the tongue, in effect "priming the lingual pump" before eventual propulsion into the oropharynx. The soft palate was shifted superiorly, thus closing off the nasopharynx. The most prominent finding during this phase was an increase of negative y -direction strain (i.e., inferior-directed contraction) in the posterior region of the tongue, which contained the bolus. This contraction is responsible both for the creation of enhanced posterior depression and for extension of the

bolus depression in the x and z directions (due to tissue incompressibility). As noted above, although strain was directly imaged within the genioglossus, contraction of either the hyoglossus or the genioglossus could also have contributed to this pattern. Conceivably, the degree to which these muscles contribute to the accommodating depression in the posterior tongue may also vary as a function of bolus volume or viscosity or as a function of pathological regulation of tongue contractility. Translation of the contractile region from the anterior to the posterior genioglossus (early to late accommodation) transferred the bolus retrograde via the grooved depression, preparing the bolus for propulsion.

Bolus propulsion was characterized by the retrograde motion of the tongue toward the pharyngeal wall, thus expelling the cradled bolus from the oral cavity. The most prominent effect was on the posterior tongue, with significant expansion of the tissue in the x and y directions and concomitant z -direction contraction. Contraction of intrinsic transversus muscle fibers in the posterior tongue most likely produced this pattern, because tissue expansion in the x and y directions (due to incompressibility of the tongue tissue) was seen. Octahedra in the posterior tongue had their principal eigenvector (octahedral long axis), or the direction of greatest expansion, oriented in a postero-superior direction. This observation suggests that the styloglossus may have also been contracted. Sole contraction of the styloglossus (in a postero-superior direction) could not produce expansive strain above its insertion point, in the midportion of the tongue's lateral surfaces because the tongue is constrained from below. Styloglossus contraction should stretch only the tongue tissue located between its insertion point and the tongue's inferior attachment. Because we observed postero-superior expansion in the posterior tongue all the way to the dorsal surface, a synergistic mechanism involving the posterior transversus and styloglossus may be in effect.

Our data were consistent with a biomechanical model in which the intrinsic and extrinsic fibers function synergistically rather than as independent actuators. In this regard, the unique myoarchitecture of the tongue allows the organ to function efficiently as a muscular hydrostat (8, 11), a term whose properties include tissue incompressibility derived from a highly aqueous composition and the ability to elicit tissue deformation while simultaneously providing skeletal support for that tissue. The former is evidenced by contracting lingual myofibers, which induce tissue compression along fiber directions and tissue expansion along directions orthogonal to the fibers (due to tissue incompressibility). In both accommodation and propulsion, physiological function may have been performed through a synergistic combination of tissue compression and expansion. In fact, tissue incompressibility necessitates the simultaneous existence of both compression and expansion for a given tissue element, whereas the tongue's interdigitating myofibers ensure that compression/expansion coupling synergistically produces the

intended function. Conceivably, deglutitive function in patients with oral phase dysphagia may be impaired through a pathological reorganization of the underlying myoarchitecture and the concomitant alteration of compression/expansion distribution.

In summary, we have used magnetic resonance imaging techniques to study intramural muscle mechanics for the tongue during normal swallowing. Our results provide evidence for a synergistic mechanical model involving the intrinsic and extrinsic muscles during physiological tissue deformation and suggest a basis for examining structure-function relationships in this tissue during normal and pathological conditions.

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