Measurement of tissue deformation in the tongue during a vowel sequence /ei/ using tagged-cine MRI

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Abstract

The mechanism of producing vowel /i/ was examined to reevaluate the function of the extrinsic and intrinsic muscles of the tongue using tagged-cine MRI with fast sagittal imaging (60 frames / s with 2 slices) and multilayer transverse imaging (12 frames /s with 10 slices). In the results, the anterior half of the tongue was found to elevate with medial compression, and the posterior half of the tongue was found to descend with lateral expansion. The temporal pattern of the tissue deformation revealed a contrast between the two areas in the tongue tissue: the top half of the tongue moves greater, earlier and faster than the bottom half of the tongue. These results indicate that the tongue deformation mechanism for /i/ by the contraction of the anterior and posterior bundles of the genioglossus muscle in the previous studies is insufficient, and the contribution of the intrinsic tongue muscles (such as transverse muscle) is suggested as an additional factor that produces rapid elevation of the anterior part of the tongue for /i/.

1. Introduction

The tongue in a viscoelastic continuum, and its motion essentially results from deformation of the muscle tissue. Therefore, studies of its physiology mechanism require techniques different from those for limb movements. The present study pays attention to the tongue deformation mechanism in production of vowel /i/ that has been discussed regarding tongue deformation mechanism, and analyses three dimension deformation of the internal tongue tissue using a tagged cine-MRI.

The mechanism of tongue deformation in speech has been observed by X-ray cinematography (Perkell, 1969), and its physiological process has been examined with electromyography (Miyawaki et al, 1975; Baer et al, 1988). The results have shown that the activity of the extrinsic tongue muscles is dominant in vowel articulation, and that three major muscles contribute to vowel distinction. That is, the genioglossus works for front vowels, and the styloglossus and hyoglossus together produce back vowels. Among the extrinsic tongue muscles, the contractile effect of the genioglossus is unique:

the posterior bundles drive the tongue surface forward and upward, while the anterior bundles form the midline groove antagonistically. Studies on the function of the tongue have also been conducted by simulation (Kakita et al, 1985; Perkell, 1996; Wilhelms-Tricarico, 1996), and their results were in agreement: the tongue body advances in front vowels by means of the activity of the genioglossus posterior and hydrostat mechanism of the muscle tissue. Articulation of vowel /i/ is raised as an example to show the uniqueness of the tongue deformation mechanism. Fujimura and Kakita (1979) showed that the vowel's formants are stabilized by simultaneous contraction of the whole genioglossus and the inferior longitudinal maintaining the balance of their contractile forces. They propose that the quantal nature found in vowel's acoustic space should be supplemented physiologically by the stabilization mechanism due to co-contraction of the two genioglossus bundles.

In investigating the tongue deformation mechanisms, electromyography on each muscle with certain measurements of tongue deformation may be ideal. However, the simultaneous measurement of multiple muscles or three-dimensional imaging of deformation has been technically difficult. Magnetic resonance imaging (MRI) is capable of visualizing tissue deformation in the tongue during vowel production, and studies using tagged cine-MRI are also reported (Stone, 2001).

In the present study, three-dimensional deformation of the tongue tissue during a vowel sequence /ei/ is measured with tagged cine-MRI to clarify the geometrical and temporal differences in the tongue deformation toward the second vowel. The function of the tongue muscles in producing front vowel /i/ is discussed based on the measurement results.

2. Method

Deformation of the tongue tissue is visualized by using tagged cine-MRI method during articulation of a vowel sequence /ei/. In the sagittal plane, displacement and velocity analyses of the intersection of meshed tag lines were conducted. In the transverse plane, analysis was made on linear tag lines. These results are combined to speculate three-dimensional tongue deformation. MRI motion imaging with a synchronized sampling technique (Masaki, et al 1996) was combined with tagged cine-MRI to record tissue deformation. The tagged-MRI is the technique to control magnetic resonance by special RF pulses that add linear shades to the arbitrary positions on MR images. Thus, the internal deformation of living tissues can be visualized as motions of linear or meshed tag patterns.

A Japanese male speaker repeated a vowel sequence /ei/ in an MRI scanner (Magnex Eclipse 1.5 T, Shimadzu Marconi) according to the rhythm of guide tones that are synchronized with the MRI scans. A lattice pattern of an 8 mm interval was tagged onto the sagittal images, and parallel linear tags of a 4 mm interval were applied on the transverse images. In the sagittal sections, MRI data at 60 frames per second were obtained for two slices in the midsagittal and parasagittal planes. In the transverse sections, MRI data at 12 frames per second were recorded for 10 slices from the tongue root to dorsum. An example of the tagged-MRI is shown in Fig. 1. The imaging parameters were TE=3.0 ms, TR=910 ms, NEX=2, 4 mm thickness, 128x128mm of FOV(s), and 256 x 256 pixel.

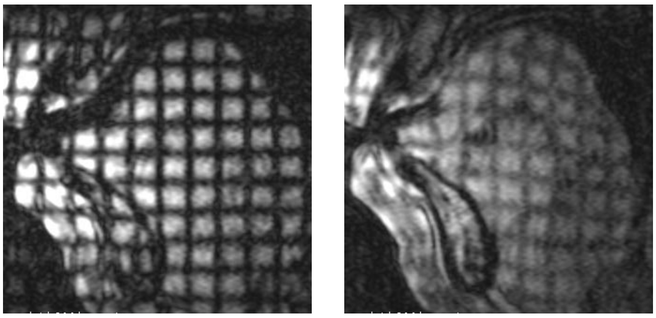


Figure 1. Obtained tagged-MRI during /ei/.
The left is the beginning of /e/, and the right is the end of /i/.

In order to measure vertical displacement of the tongue tissue in /ei/, the time sequence of displacement of the mesh intersections was analyzed on the sagittal data. The vertical and horizontal lines of the tag data were traced on each bitmapped image, and the coordinates of the center of gravity at the region of intersection were measured by AND operation on the traced images. Then, the time series of the intersection points were obtained from the initial frame to the last frame. In order to visualize lateral expansion (widening) and medical compression (narrowing) of the tongue tissue, the tag lines of a 4 mm interval on the transverse section were traced for their temporal changes in the width along the time sequence.

3. Result

3.1. Tracings of sagittal tagged-MRI

Figure 2 depicts the tracings of the tag mesh on the two sagittal planes, the tongue surface, and the mandible during the vowel sequence /ei/. It shows the results at the begining of /e/ (dashed line), the mid-transition (gray solid line), and the end (thick solid line) of /i/. Figure 3 shows displacements of each tag mesh intersections during articulation of /ei/ in the midsagittal and parasagittal planes as a vector diagram. The starting point of each arrow indicates the beginning of /e/, and the orientation of each arrow is the vector toward the end of /i/. The lengths of each arrow were magnified 1.5 times of the actual displacements. The vectors toward downward displacement are shown by dashed lines, and those for upward displacement are shown by solid lines. Among the upward vectors, those with strong forward displacements were indicated by thick lines.

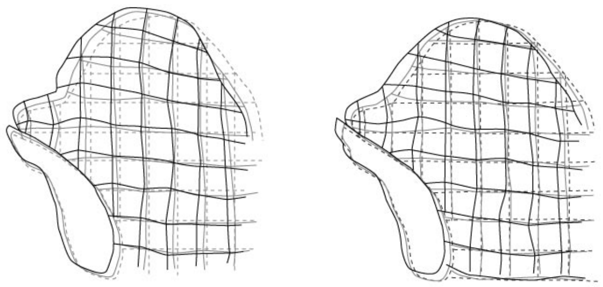


Figure 2. Tracings of the tag mesh, tougne surface and mandible on the sagittal (left) and parasagittal (right) planes. The beginning of /e/ (dashed line), the mid-transition (thin solid line), and the end of /i/ (dark solid line) are superimposed.

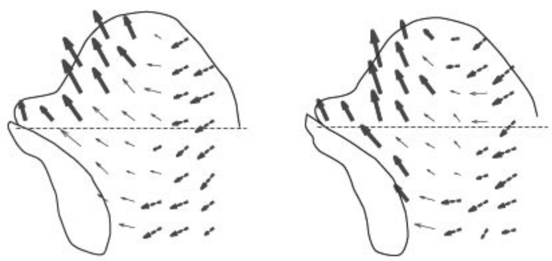
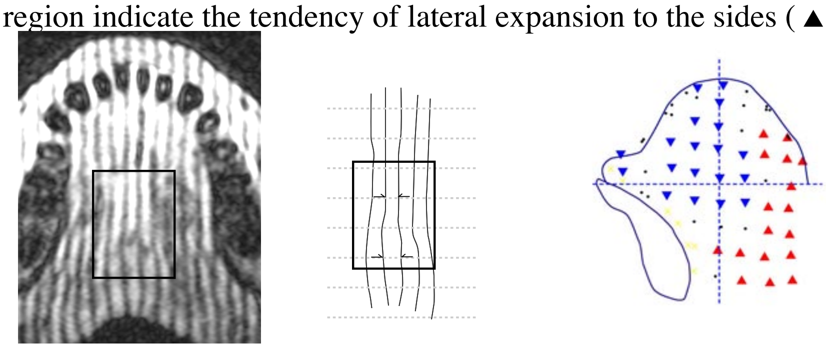


Figure 3. The displacement vectors based on the tag mesh on the sagittal (left) and parasagittal (right) planes.

In the anterior tongue region, large forward and upward displacements of the tissue points are observed during articulatory movement from /e/ to /i/, while forward and downward displacements of the points are found in the posterior region. In the anterior tongue region, its upper part near the tongue surface showed the largest displacements, while the region near the genial turbercle of the mandible (attachment of the genioglossus) showed smaller displacements.

3.2. Measurement of deformation in horizontal direction

Figure 4 shows an example of the transverse image with tracings. The changes in the tag line width were marked as compression and expansion of the tissue. The regions where the interval of the tag lines is narrower were marked as compression (▼), and the regions showing the opposite changes were marked as expansion (▲). The intermediate cases were indicated by (•). In Fig. 4, the markings on the anterior tongue indicate the tendency of medial compression (▼) toward the midline, while those on the posterior tongue region indicate the tendency of lateral expansion to the sides (▲).

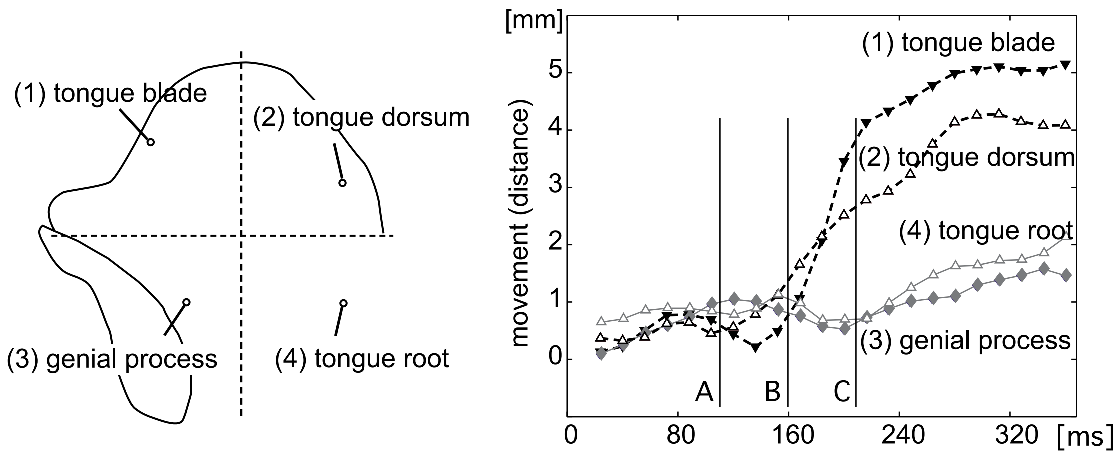


(a) (b) (c)

Figure 4. The tagged-MRI on the transverse plane (a) and its tracings (b) with the indices of deformation on the horizontal direction (c) by expantion (▲) and compression (▼)

3.3. Temporal changes of each region in the tongue

In order to show the regional characteristics of tongue tissue deformation, the tongue is divided into four parts, as shown in Fig. 5 (a). Figure 5 (a) shows the regions of compression and expansion with the markings of (▲) and (▼). Figure 5 (b) shows the temporal changes of distance of the four representative points in the time course of /ei/.



(a) (b)

Figure 5. Displacement of the four internal points in the tongue during /ei/.

The displacement of each point during /ei/ is larger in the tongue blade and dorsum, while it is smaller in the tongue root and the basal region near the genial tubercle. The temporal change of the displacements, as seen in the tilt of the curves in Fig. 5 (b), is greater in the tongue blade, which is followed in the tongue dorsum. In the tongue root and genial tubercle region, the velocity is smaller. The curves also show the peak velocity at 140 -- 200 ms for the tongue blade and dorsum, which is greater than the velocity at about 200 ms for the tongue root and the genial region.

3.4. Velocity vector of mesh intersections in the tongue tissue

Figure 6 depicts the velocity vector patterns of the intersection points at time of A, B, and C that were indicated in Fig. 5 (b). Figure 6 (a) corresponds to the timing of /e/, which shows backward and downward movements of the tongue blade, genial region, and tongue root. Figure 6 (b) indicates the intermediate state during /ei/ showing upward movements of the tongue blade and downward movement of the tongue dorsum and root, with smaller movement in the genial region. Figure 6 (c) shows the velocity patterns from /e/ to /i/ in the four regions.

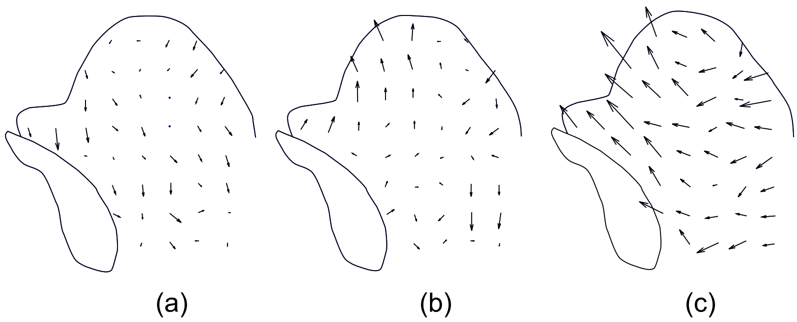


Figure 6. The velocity vector of mesh intersection in tongue tissue. The figures (a)-(c) correspond to the timing A-C in the Figure 6 (b).

4. Discussion

The above result is summarized to below. The changes in the anterior tongue are characterized by forward and upward displacement and medial compression of the tongue tissue, and those in the posterior tongue are marked by forward and downward movement and lateral expansion. These changes are greater and begin earlier in the upper half (blade and dorsum) than in the lower half (root and genial region). Thus, tongue tissue deformation can be described by lateral expansion of the posterior tissue along with advancement and medial compression of the anterior tissue with its forward and upward displacement. The former (deformation of the posterior tissue) can be explained by the mechanism reported previously, while the latter (deformation of the blade) needs a new account. In this section, basing on the above results, the relation between tongue muscles function and tongue deformation is discussed.

There are two possibilities to account for the deformation mechanism of the tongue blade: passive mechanism for the tongue blade to conform to the shape of the palate, and active mechanism to deform the tissue for articulation of /i/. The analysis of the temporal pattern of tissue deformation in this study revealed that deformation of the tongue blade precedes deformation of the tongue root, which strongly suggests a local active mechanism. The tongue blade deforms not only by the hydrostatic pressure effect of genioglossus contraction but also by contraction of regional muscles within the tongue blade. The transverse muscle is the possible muscle that causes the narrowing of the tongue blade. Therefore, the cocontraction of the transverse with the genioglossus can reasonably explain the movement of the anterior tongue preceding that of the posterior tongue.

To summarize, the production mechanism of /i/ can be explained as follows. The posterior tongue advances due to the contraction of the genioglossus posterior and middle bundles, which results in lateral expansion of the posterior tissue. The anterior tongue rises due to the hydrostatic effect of the genioglossus posterior and middle bundles, maintaining the narrow space of the vocal tract in the oral cavity due to the contraction of the genioglossus anterior bundle. The upper tongue advances and rises rapidly, being accompanied by narrowing of the lateral (left-to-right) dimension due to a local contraction of the transverse muscle.

5. Conclusion

The tagged cine-MRI was used to investigate the time course of deformation of the tongue tissue deformation during articulation of a vowel sequence /ei/ to examine three-dimensional deformation mechanism of the tongue. The results indicate a characteristic pattern for /i/: upward movement of the tongue blade begins in advance of forward movement of the tongue root where the genioglossus posterior is located, and it is faster than that of the tongue root. The tongue tissue exhibits medial compression in the anterior part and lateral compression in the posterior part. These findings suggest a new mechanism for articulation of vowel /i/: the rise of the tongue blade in the high-front vowel /i/ results from combined actions of the genioglossus posterior bundle for forward and upward deformation and of the transverse muscle to elevate the anterior tongue by medial compression of muscle tissue.

Acknowledgement

We would like to give special thanks to the members of the ATR Brain Activity Imaging Center. This research was supported in part by the National Institute of Information and Communications Technology. This work was also supported in part by a Grant-in-Aid for Scientific Research No. 18300069, Japan

Society for the Promotion of Science.

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