FEM analysis of aspirated air flow in three-dimensional vocal tract during fricative consonant phonation.

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ABSTRACT

This paper deals with estimations of aspirated air flow in a three-dimensional vocal tract during fricative consonant phonation using the Finite Element Method (FEM). The shape of the 3-D vocal tract during phonation of fricative consonant /s/ is reconstructed from 32 coronal Magnetic Resonance (MR) images. MR images of the dental crown that contains a small amount of water were obtained using a dental crown plate. A 3-D FEM vocal tract model is formed so that the number of elements is 28686, the number of nodes is 7010, and a rigid wall constitutes the vocal tract wall. Results showed that the flow rate was high at the narrow space made between the upper central incisors and the tongue surface. An electric equivalent circuit for fricative consonant phonation was designed in consideration of the location of the noise source.

1. INTRODUCTION

Three-dimensional (3-D) data on vocal tract shapes are essential to the construction of an articulatory model. Several techniques for investigating human speech production have been reported in speech science literature focusing on the vocal tract as a fundamental articulatory organ. In addition, attempts have been made to model the vocal tract and estimate its characteristics.

Magnetic Resonance Imaging (MRI) is a powerful tool for investigating the geometry of the 3-D vocal tract shape and does not involve any known radiation risks.[1][2] However, most previous MRI studies have been limited to investigation of vowels. The reason for this is that, it is difficult to obtain profiles of dental crown shapes that contain a small amount of water using conventional MRI techniques. Thus there is insufficient data on the 3-D shapes of the vocal tract during the phonation of consonants that are produced using the teeth in a steady state.

In response to this problem, we have developed a method that uses a dental crown plate to enable simultaneous MR imaging of the dental crown and the vocal tract .[3]

The purpose of the present study is to apply this method, the Finite Element Method (FEM), to estimation of aspirated air flow in the 3-D vocal tract during fricative consonant /s/ phonation. We describe a method of reconstructing 3-D vocal tract shapes from 3-D MR images, and demonstrate an FEM analysis of the 3-D vocal tract model. Aspirated air flows in the 3-D vocal tract models are also illustrated. In the final section, the transfer characteristics are computed from an electric equivalent circuit based on an fricative consonant phonation model.

2. METHODS

2.1. Measurement of 3-D MR images.

All of the MR images in this study were collected using a 1.0 Tesla superconductive MR system (MAGNEX100HP, Shimadzu Corp., Japan).[3]

The mid-sagittal MR images were measured by the single-slice flip-back spin-echo imaging method at high speed. Each image was acquired with the repetition time TR=200 ms and the echo time TE=15 ms using an image matrix of 256×256 over a field of view of 25 cm. The section thickness of the excited plane was 5 mm. The measurement time was 25 s. The coronal MR images were measured by a multi-slice T1-weighted spin-echo imaging method and were acquired with TR=200 ms and TE=15 ms using an image matrix of 256×256 over a field of view of 25 cm.

3-D MR images consisting of MR images of 32 coronal sections, at intervals of 4 mm, from the tip of the nose to the atlas were obtained. The measurement time was 142 s. The section thickness of the excited plane was 3.5 mm.

Data on dental crown shapes are required in order to analyze the speech production and precisely estimate the acoustical characteristics of the vocal tract. In this study, these data are obtained by means of a dental crown plate, 0.6 mm thick, that is tightly attached to the subject's dental crown by thermoforming and that contains a contrast medium for MR imaging. By attaching the dental crown plate to the subject's upper and lower teeth, profiles of the vocal tract and dental crown can be obtained simultaneously using MRI.

The experiments were performed on a Japanese adult male subject. MR images and the sound uttered by a supine subject in the MR chamber were obtained. The subject's voice was recorded using a high sensitivity condenser microphone.

Figure 1 shows a sample MR image. As can be seen, the dental crown plate allows a clear profile of the dental crown.
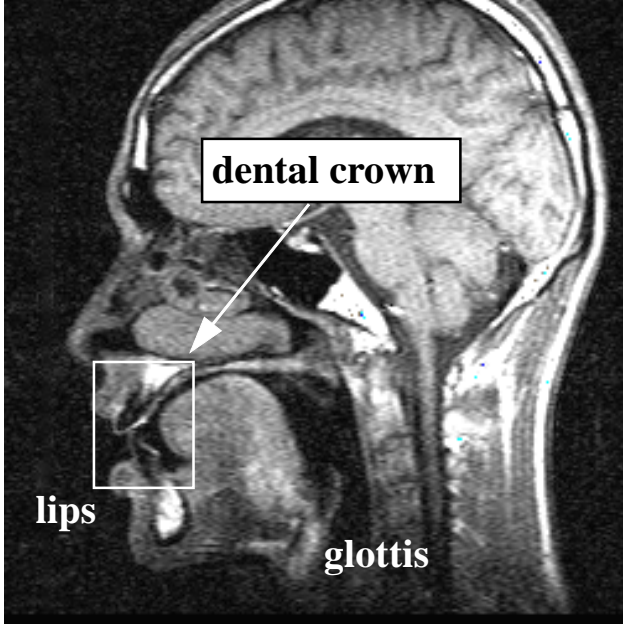
Figure 1: Example of a mid-sagittal MR image.

Figure 2: 3-D vocal tract shape during fricative consonant /s/ phonation.

2.2. 3-D vocal tract shape.

The 3-D vocal tract shapes were obtained from profiles of their sagittal sections.

First, sagittal MR images (4 mm interval) were estimated from coronal MR images using grey level interpolation. Second, air-tissue boundaries of the sagittal sections were obtained from each MR image by means of a threshold operation in which the threshold value was taken as the average of the grey level at the air-tissue border points. Adjacent air-tissue boundaries were connected by spline interpolation, since the 3-D vocal tract shapes are constructed by a cascade connection of the air-tissue boundaries.

Figure 2 shows the shape of a 3-D vocal tract during fricative consonant /s/ phonation. The shape shows a narrow oral cavity formed by the upper and lower teeth and the frontal tongue body for fricative consonant phonation.

2.3. FEM analysis of the vocal tract.

When FEM is used for the fluid analysis, the analytic space is approximated as the aggregate of several elements, and the differential equation corresponding to the fluid equation is solved. From the law of conservation of mass comes the continuity equation:

$$\frac{\partial \rho}{\partial t} + \frac{\partial (\rho V_x)}{\partial x} + \frac{\partial (\rho V_y)}{\partial y} + \frac{\partial (\rho V_z)}{\partial z} = 0 \quad \text{——(1)}$$
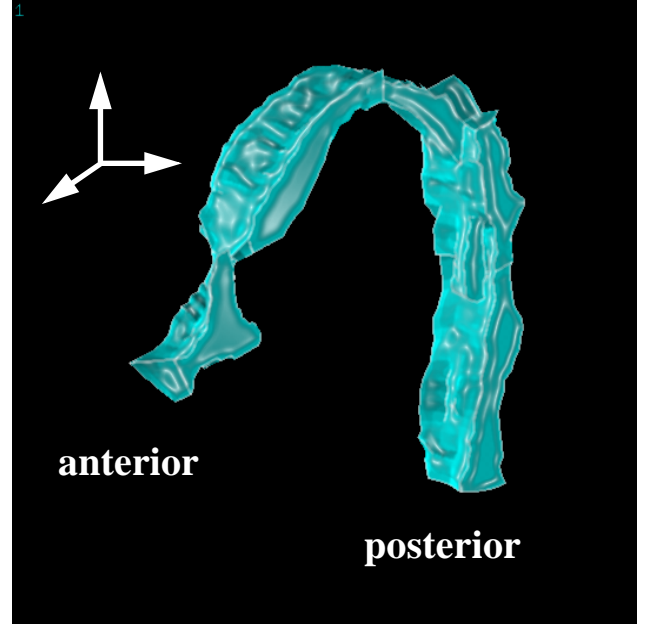
where ρ : density

t : time

$\{V\} = \{V_x, V_x, V_x\}$: velocity

Generally, Navier-Stokes' equation in consideration of external force, pressure and friction is given in the fluid equation. In this study, the internal of the vocal tract is supposed to be ideal fluid:

$$\frac{\partial V_x}{\partial t} + V_x\frac{\partial V_x}{\partial x} + V_y\frac{\partial V_x}{\partial y} + V_z\frac{\partial V_x}{\partial z} = F_x \quad \frac{1}{\rho}\frac{\partial P}{\partial x}$$

$$\frac{\partial V_y}{\partial t} + V_x\frac{\partial V_y}{\partial x} + V_y\frac{\partial V_y}{\partial y} + V_z\frac{\partial V_y}{\partial z} = F_y \quad \frac{1}{\rho}\frac{\partial P}{\partial y}$$

$$\frac{\partial V_z}{\partial t} + V_x\frac{\partial V_z}{\partial x} + V_y\frac{\partial V_z}{\partial y} + V_z\frac{\partial V_z}{\partial z} = F_z \quad \frac{1}{\rho}\frac{\partial P}{\partial z}$$

$$\text{——(2)}$$

where F is external force and P is internal stress. Our FEM formulation is based on the above equations.

The 3-D vocal tract shape with a radiational space is divided with a tetrahedral element (28,686 elements, 7,010 nodes). Figure 3 shows a 3-D FEM vocal tract model during fricative consonant /s/ phonation. The aspirated air is supposed to flow into the vocal tract vertically to glottis surface.
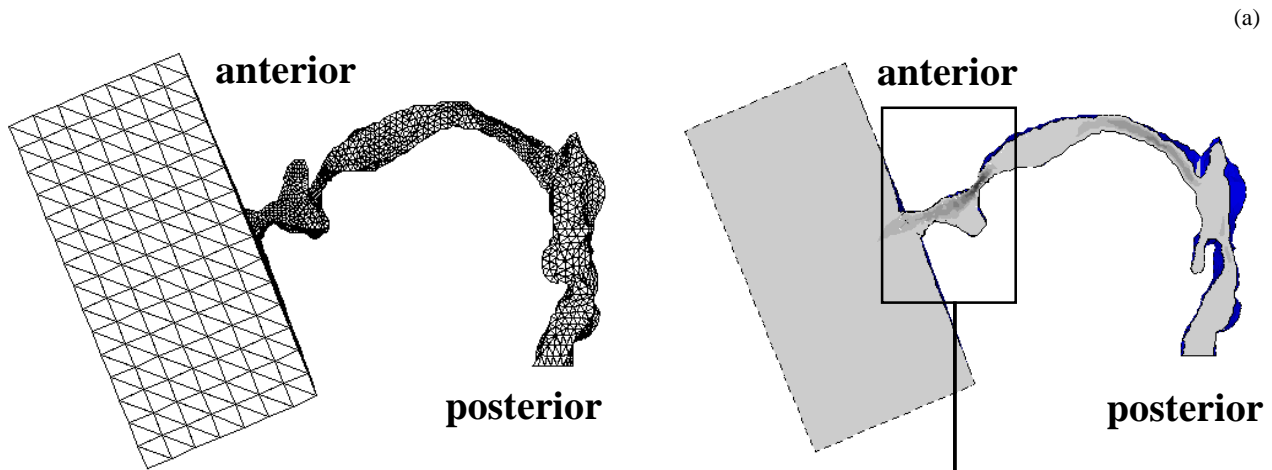
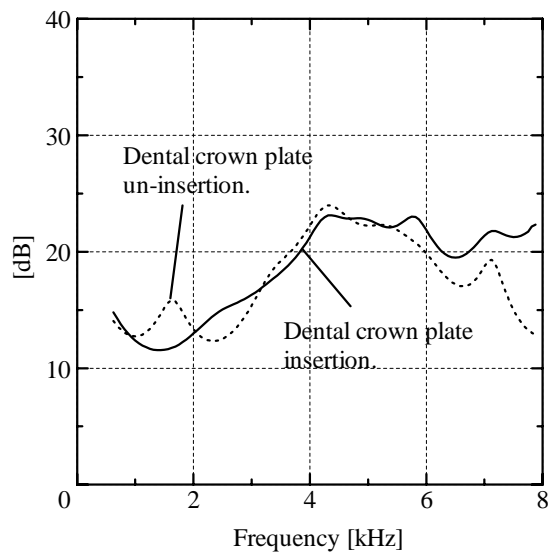**Figure.3:** 3-D FEM vocal tract model with radiational space.

Figure 4: Spectrum of fricative consonants /s/.

Figure 5: (a) Aspirated air flow in the vocal tract during fricative consonant /s/ phonation (mid-sagittal section) and (b) specially magnified detail drawing detailing the necessary section (vector diagram of flow rate).

3. RESULTS

3.1. Acoustic analysis and influence of the dental crown plate.

We next investigated the influence of the dental crown plate on the phonation of the fricative consonant /s/. For this acoustic analysis, a spectrum was computed for the fricative consonant /s/ by means of a 16th order LPC analysis of successive 32 ms long frames with a sampling rate of 16 kHz.

Figure 4 shows the spectrum of the fricative consonant /s/. The solid line indicates the spectral pattern of the insertion of the dental crown plate, and the dotted line indicates the spectral pattern of the removal of t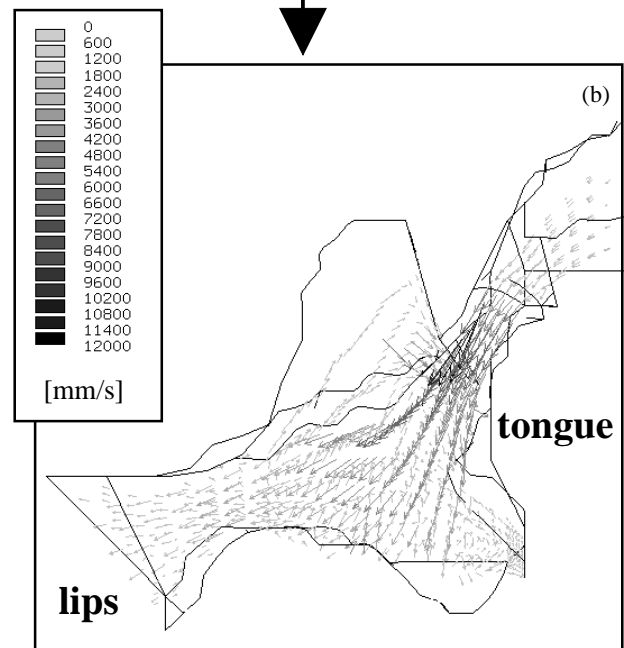he dental crown plate. As can be seen, the two spectra are almost identical. These results indicate that there were negligible influences on the fricative consonant phonation.

3.2. Aspirated air flow in the vocal tract.

Figure 5 shows aspirated air flow in the vocal tract during fricative consonant /s/ phonation.

As can be seen, the flow rate was high at the narrow space made between the upper central incisors and the tongue surface. The distance from the lips was 18 mm at the point where the velocity was highest.
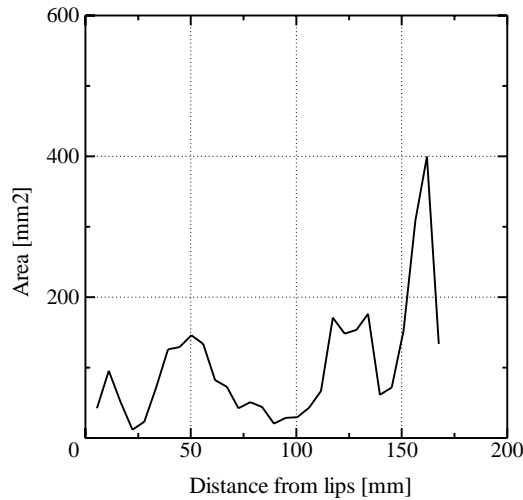
Figure 6: Vocal tract area function /s/.

Figure 7: Spectrum of fricative consonants /s/. Comparison of the the spectrum that the subject uttered with the computed results from the equivqlent circuit.

The behavior of the aspirated air flow was determined from the vector diagram of the flow rate. Generally, a fricative consonant is produced when the vocal tract is constricted somewhere along its length sufficiently to produce a noise when air is forced through the constriction. This result suggests that the noise is generated at the site of an abrupt obstacle to the air flow, such as at the teeth.

3.3. Equivalent circuit model for fricative consonant phonation.

This study suggests that the noise source is generated at the place where the flow rate is the fastest. In this study, an electric equivalent circuit was designed in consideration of the location of the noise source. The transfer characteristics were computed from a circuit based on the fricative consonant phonation proposed by Shirai et al.[4], and were compared with its transfer characteristics and the spectrum of /s/ that the subject uttered. The circuit parameters were calculated from the vocal tract area function (**Figure 6**) estimated from the 3-D vocal tract shape.

Figure 7 shows a comparison between the spectrum of /s/ that the subject uttered and the computed results from equivalent circuit. Both spectra show almost the same characteristics. However, it is necessary to fully consider the characteristics of the noise source in order to construct a precise equivalent circuit model.

4. CONCLUSIONS

This study was performed to estimate aspirated air flow in the 3-D vocal tract during fricative consonant /s/ phonation using FEM. The 3-D FEM vocal tract model was obtained from MR images. A method of obtaining the upper and lower teeth profiles by MRI using the dental crown plate was developed, and the influence of the dental crown plate on the phonation was investigated. The result indicated that the plate had a negligible influence on the fricative consonant phonation.
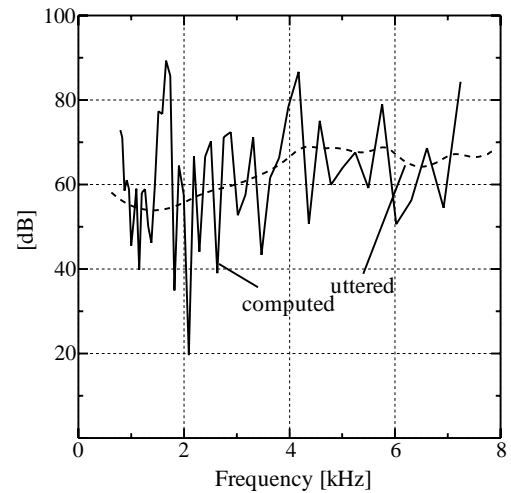
The aspirated air flow in the 3-D vocal tract was estimated and a velocity vector diagram was obtained. In these results, the location of the noise source was estimated, and then the electric equivalent circuit was designed in consideration of the location of the noise source. Finally, we compared the spectrum of /s/ that the subject uttered with the computed results from the equivalent circuit. Both spectra show almost the same characteristics. We conclude that this method should be applicable for other fricative consonants.

5. REFERENCES

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