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Dental imaging using a magnetic resonance visible mouthpiece for measurement of vocal tract shape and dimensions

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1. Introduction

Magnetic resonance imaging (MRI) plays an important role not only in medicine but also in speech science. Speech scientists have measured the shape, dimensions, and motion of the speech organs during speech production by MRI. On the basis of MRI measurements, for example, vocal tract acoustics have been analyzed and physiological articulatory speech synthesizers have been developed. In the past decades, MRI has contributed to the exploration of the mechanisms and acoustics of speech production [1,2].

The teeth are one of the important speech organs, particularly for fricative consonants; however, they are imaged with a signal intensity as low as that for air by MRI. It is thus difficult to identify the boundary of the vocal tract around the teeth and impossible to measure the vocal tract shape and dimensions accurately from MR images. It is generally known that X-ray CT scanners can be used to measure tooth shape accurately, but their use is prohibited in scientific research.

Several methods have been proposed to solve the problem of the lack of dental images. Yang and Kasuya [3] and Takemoto *et al.* [4] proposed methods for measuring the three-dimensional shape of the teeth and superimposing it onto MR images acquired during speech production. In the former study, the three-dimensional tooth shape was measured by MRI scanning of the participant's upper and lower plaster dental casts soaked in water. However, it takes time to make plaster dental casts. In the latter study, participants held blueberry jelly juice inside their mouth as an oral contrast medium while lying in a prone position during the scanning of their teeth. Since blueberry juice is rich in manganese and gives a high MR signal [5], the boundary of the teeth can thus be exactly identified on the MR images. The participants, however, must endure holding the blueberry jelly juice inside their mouth for around 10 minutes for scanner calibration and volumetric data scanning.

Around the same time as Takemoto *et al.* [4], Olt and Jakob [6] also tried to visualize the teeth using contrast media. They instructed participants to fill their mouth with water or MR contrast media and obtained three-dimensional MR data. Most recently, Tymofiyeva *et al.* [7] measured the teeth without using a contrast agent and evaluated the results from the viewpoint of dentistry and orthodontics.

Wakumoto *et al.* [8] developed a "dental crown imaging plate" comprising a dental crown plate enclosing a contrast medium. With this plate, the dental crown shape can be visualized in MR images. This method therefore has the advantage that there is no need to superimpose volume data of the teeth onto MR images. However, because the resinous layers of the dental crown imaging plate are a few millimeters thick, the dental crown shape cannot be exactly identified. Moreover, the plate can affect the participant's articulation.

In the present study, measurement of the tooth shape is conducted separately from MRI data acquisition during speech production, similar to in the studies conducted by Yang and Kasuya [3] and Takemoto *et al.* [4]. The head region of a participant with a thermoplastic elastomer dental mouthpiece in her mouth was scanned by MRI. The tooth image could be extracted from the MR images because the dental mouthpiece gives a high MR signal, whereas the teeth are MR-invisible.

2. Materials and methods

2.1. Dental mouthpiece

A dental mouthpiece was formed with a thermoplastic elastomer (Septon(R) compound JN-10N, Kuraray Plastics, Co., Ltd.). An elastomer is a high-molecular-weight compound with high elasticity. Septon is easily molded and has high rubber elasticity, and it has been used for many products such as teething rings and screwdriver handles. Furthermore, this thermoplastic elastomer gives a high MR signal in adequate scanning parameters.

We designed the shape of the dental mouthpiece to be as tight as possible on the participant's teeth and not to have any air gaps. The cross-sectional shape of the dental mouthpiece is a wedge for the front teeth and a rectangle for the back teeth. The depth of the grooves of the dental mouthpiece is set to be longer for the front teeth than that for the back teeth. The groove for the upper teeth is a few millimeters anterior to that for the lower teeth to accommodate natural dental occlusion.

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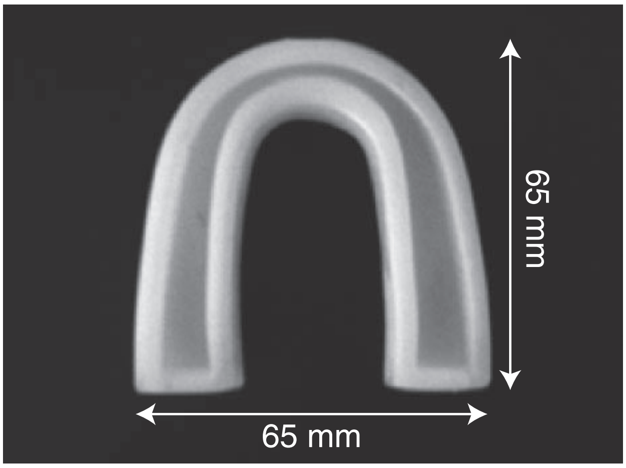

Fig. 1 Thermoplastic elastomer dental mouthpiece.

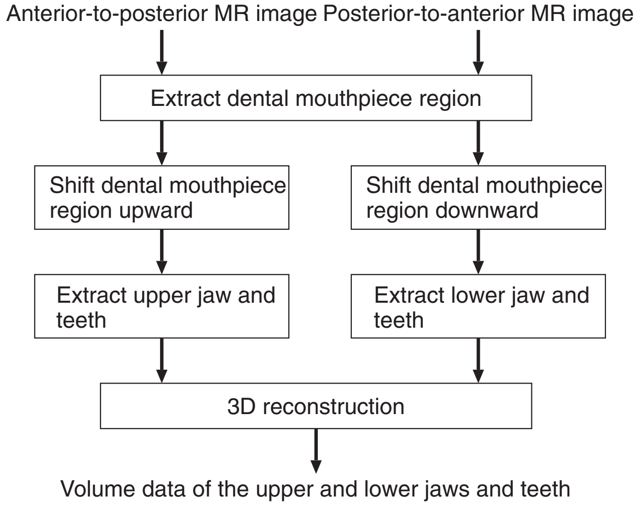

Fig. 2 Procedure for obtaining volume data of the upper and lower jaws and teeth from anterior-to-posterior and posterior-to-anterior MR images.

Figure 1 is a top view of the dental mouthpiece. Its length, width, and height are approximately 65 mm, 65 mm, and 20 mm, respectively. The thickness of the occlusal clearance between the upper and lower teeth is approximately 4 mm, which is designed to be sufficiently thicker than the resolution of MR images even when participants bite the mouthpiece. Either end of the dental mouthpiece can be cut to fit the mouths of participants with smaller jaws.

2.2. MR image acquisition

A female participant with no history of previous or current jaw disease was studied. The experimental protocol was approved by our institutional ethical and safety committees. Written informed consent was obtained after a full explanation of the procedure. The participant was positioned to lie supine on the platform of a 3T MRI scanner (MAGNETOM Verio 3T, Siemens AG), holding the dental mouthpiece in her mouth. A flexible coil was then positioned over the subject's head region, and MR images of the upper and lower jaws were acquired. The imaging sequence was a sagittal volume interpolated gradient breath hold examination (VIBE) series with 1 mm slice thickness, no slice gap, no averaging, a 192×192 mm field of view, a 384×384 pixel image size, 80 slices, 10° flip angle, 2.06 ms echo time, and 10.0 ms repetition time.

The thermoplastic elastomer causes a chemical shift artifact, i.e., the dental mouthpiece is shifted from its actual position in MR images, and the artifact affects the tooth image. For example, when a downward chemical shift artifact occurs (the direction of the chemical shift artifact depends on the phase encoding direction), the upper teeth appear longer and the lower teeth appear shorter.

By shifting the image of the dental mouthpiece in the inverse direction to that of the chemical shift artifact, the accurate shape and length of the teeth can be obtained. In the above example, the shape and length of the upper teeth can be corrected; those of the lower teeth, however, cannot be corrected because it is impossible to restore the shape of teeth hidden by the chemical shift artifact. We therefore measured two MR images with the anterior-to-posterior and posterior-to-anterior phase encoding directions. Hereafter, the former and latter MR images are referred to as anterior-to-posterior and posterior-to-anterior MR images, respectively. The dental mouthpiece is shifted downward in an anterior-to-posterior MR image and the opposite effect occurs in a posterior-to-anterior MR image.

To prevent air gaps between the dental mouthpiece and teeth, we filled the grooves of the mouthpiece with a contrast-medium paste made of an iron-containing beverage (Alfe neo, Taisho Pharmaceutical Co., Ltd.) and an instant liquid thickener (Toromi-Up V, The Nisshin Oillio Group, Ltd.) before the participant bit the mouthpiece.

2.3. Image processing

Figure 2 is a diagram that indicates the image processing procedure for obtaining volume data of the jaws and teeth from the anterior-to-posterior and posterior-to-anterior MR images. First, regions of the dental mouthpiece were identified by a threshold method. The extracted regions were then shifted in the direction opposite that of the chemical shift artifact; they were shifted upward in the anterior-to-posterior MR images and downward in the posterior-to-anterior MR images. The upward shift of the dental mouthpiece image for the anterior-to-posterior MR image corrected the shape and length of the upper teeth but did not correct those of the lower teeth, as explained above. The opposite is true for the downward shift of the dental mouthpiece image for the posterior-to-anterior MR image. Next, the regions of the upper and lower teeth and the surrounding bone were extracted from the MR images after correcting the chemical shift artifact. We extracted these regions manually in this study. By merging the extracted images, volume data of the upper and lower jaws and the teeth were reconstructed.

The displacement of the dental mouthpiece in the MR images by the chemical shift artifact can be predicted from the imaging frequency and pixel bandwidth of the scanner. The imaging frequency and pixel bandwidth of the scanner are 123.1 MHz and 383 Hz/pixel, respectively. The chemical shift of the thermoplastic elastomer is approximately 3.5 ppm, which was measured using the MRI scanner. The resonance frequency is thus $123.1 \times 3.5 = 430.85$ Hz, and as a result,

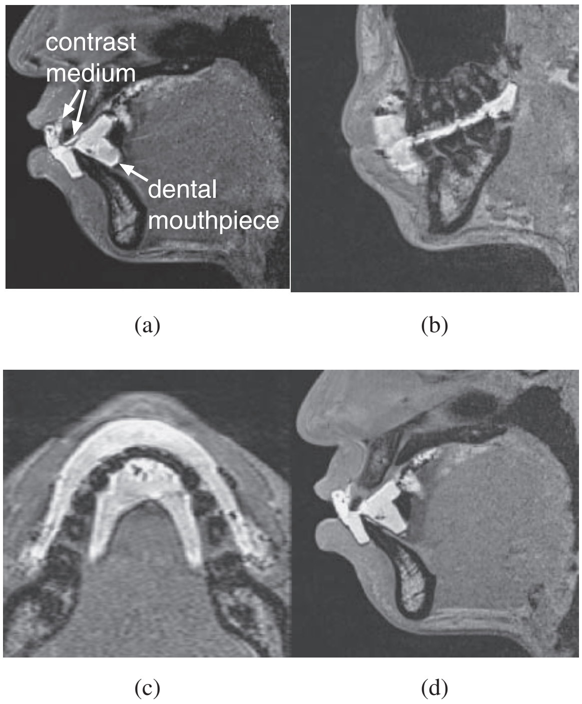

Fig. 3 Anterior-to-posterior MR images on the (a) mid-sagittal plane, (b) sagittal plane passing through the left posterior teeth, and (c) transverse plane passing through the lower teeth, and (d) posterior-to-anterior MR image on the mid-sagittal plane.

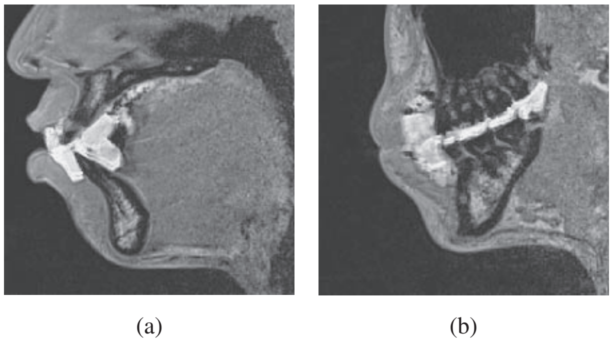

Fig. 4 Anterior-to-posterior MR images after correcting the downward chemical shift artifact by shifting the dental mouthpiece region 1 pixel upward. The shifted images of the dental mouthpiece are overlapped with the original ones. The original images of (a) and (b) are shown in Figs. 3(a) and 3(b), respectively.

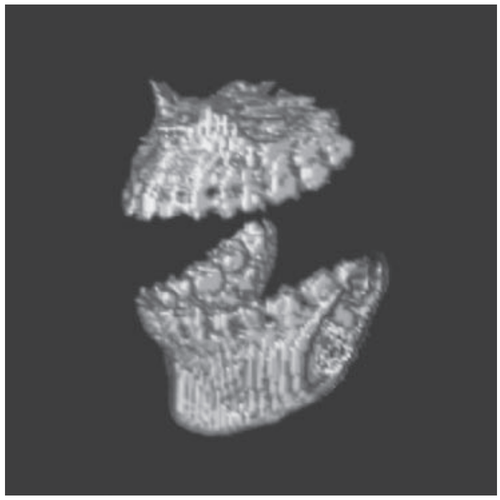

Fig. 5 Isosurface reconstruction of the upper and lower jaws and teeth.

the displacement in the lower frequency direction is $430.85 \div 383 \approx 1.12$ pixel. Consequently, we shifted the dental mouthpiece region 1 pixel, which was rounded down from 1.12, in this study.

3. Results

Figure 3 shows anterior-to-posterior MR images on (a) the mid-sagittal plane, (b) a sagittal plane passing through the left posterior teeth, (c) a transverse plane passing through the lower teeth, and (d) a posterior-to-anterior MR image on the mid-sagittal plane. These images confirm that the dental mouthpiece and the contrast medium give a high MR signal. The image of the dental mouthpiece is shifted downward and upward in the anterior-to-posterior and posterior-to-anterior sagittal MR images because of the chemical shift artifact, respectively.

By shifting the image of the dental mouthpiece in the opposite direction to that of the chemical shift artifact, the position of the dental mouthpiece was corrected. Figure 4 shows the sagittal anterior-to-posterior MR images (Figs. 3(a) and 3(b)) after the 1-pixel upward shift of the dental mouthpiece image to correct the length of the upper teeth. In the figures, the shifted images are overlapped with the original ones.

Figure 5 shows the visualized volume data of the upper and lower jaws and teeth with no smoothing effect on the surface. This figure demonstrates that the proposed method enables us to measure the three-dimensional shape of the jaws and teeth.

4. Discussion

In this study, we proposed a novel method of measuring the three-dimensional tooth shape using a thermoplastic elastomer dental mouthpiece, which gives a high MR signal. The result demonstrates that the three-dimensional tooth shape could be measured after canceling the chemical shift artifact of the dental mouthpiece.

The extracted volume data can be superimposed onto MR images acquired during speech production by various methods. For example, Takemoto *et al.* [4] superimposed tooth data by aligning the position of some anatomical landmarks between the volume data of the jaws and teeth and the MR image acquired during speech production.

The resolution and signal-to-noise ratio of the volume data obtained in this study are lower than those of X-ray CT data, and our method thus is insufficient for use in dental examinations; however, the proposed method has no risk of radiation exposure, and it can thus be applied to healthy participants. Furthermore, the resolution of the volume data ($0.5 \times 0.5 \times 1$ mm/pixel) is sufficiently high for most acoustical analyses of the vocal tract, because differences of around 1 mm in the vocal tract dimensions generally have little impact on the result.

The proposed method requires the acquisition of two MR images, i.e., anterior-to-posterior and posterior-to-anterior MR images, and the correction of the chemical shift artifact to reconstruct the volume data. In contrast, the method of Takemoto *et al.* [4] does not require such a process because the blueberry jelly juice does not cause any chemical shift artifact. However, the participant need only lie supine while biting the dental mouthpiece during scanning in the proposed method, whereas participants had to lie prone holding blueberry jelly juice inside their mouth in the latter method. Our method thus imposes less physical strain on participants.

As is well known, some types of dental prosthesis cause halation in MR images. For participants who have such a dental prosthesis, the proposed method cannot be used to measure the shape of the teeth around the prosthesis accurately, whereas the method of Yang and Kasuya [3], in which the three-dimensional tooth shape is obtained by scanning the participant's plaster dental casts, is not affected.

In conclusion, the proposed method enables us to measure the three-dimensional tooth shape by a method less demanding on participants. The method solves the MRI-specific problem of the lack of dental images and is expected to contribute to accurate measurements of the vocal tract shape and dimensions. Our future works are to evaluate the accuracy of the proposed method.

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