

Translation and rotation of the cricothyroid joint revealed by phonation-synchronized high-resolution MRI

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Abstract

The action of the cricothyroid joint for regulating voice fundamental frequency is thought to have two components; rotation and translation. Its empirical verification, however, has faced methodological problems. This study examines the joint action by means of a phonation-synchronized high-resolution Magnetic Resonance Imaging (MRI) technique, which employs two technical improvements; a custom laryngeal coil to enhance image resolution and an external triggering method to synchronize the subject's phonation and MRI scan. The obtained images were clear enough to demonstrate two actions of the joint; the cricoid cartilage rotates 5 degrees and the thyroid cartilage translated 1.25 mm in the range of half an octave.

1. Introduction

Control of voice fundamental frequency (F0) largely relies on the action of the cricothyroid joint for regulating vocal fold tension. This joint connects the thyroid and cricoid cartilages, and allows their mutual geometrical changes. The anatomical literature describes that the joint action has two components, rotation and translation, which are achieved by the contraction of the straight part and oblique part of the cricothyroid muscle, respectively. This mechanism, however, lacks definitive empirical support. In this study, we examine the action of the cricothyroid joint for F0 control by means of magnetic resonance imaging (MRI) with a few technical improvements.

The action of the cricothyroid joint has been discussed in several studies. An earlier anatomical study by Mayet and Mündnich (1958) reported that the action is mainly rotation because the ligaments supporting this joint limit translation [1]. On the other hand, an x-ray study of a singer by Sonninen (1954) demonstrated that translation occurs maximally in 3 mm [2]. A recent study by Vilkmann, et al. (1987) also supported the possibility of translation by histochemical examinations of the ligaments [3]. In order to resolve the question as to whether the joint has rotation and translation components, its action must be measured in vivo, which has yet unexploited due to many technical difficulties. MRI is one possible means to directly observe the joint action by visualizing the configuration of the laryngeal cartilages during phonation. This technique, however, has a few serious problems: the size of the larynx is not large enough to be visualized by the MRI, and the motion of the larynx during respiration causes motion artifacts on the images. In this study, we propose two improvements to obtain high-resolution images of the larynx without motion artifacts. One is a custom laryngeal coil designed for high-resolution

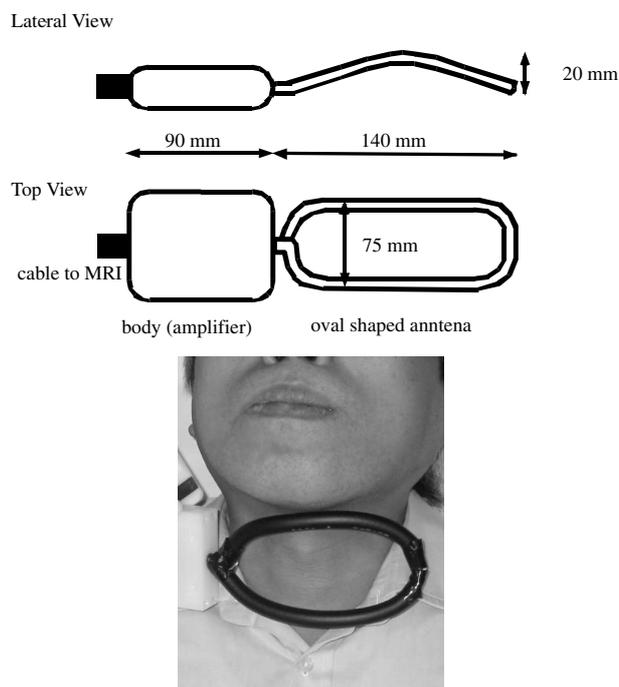


Figure 1: Custom MRI coil for high-resolution imaging of the larynx; the oval antenna of the coil (top) was designed to be placed in front of the neck of the subject (bottom).

imaging, and the other is an externally triggered scan procedure that is synchronized with phonation. Based on these improvements, an experiment was performed on a male subject during vowel production at two different F0 levels. The images were three-dimensionally reconstructed to measure the rotation and translation of the cricothyroid joint.

2. Method

A Japanese male subject (52 y.o.) repeated the vowel /i/ at two F0 levels (low F0 = 120 Hz and high F0 = 180 Hz) in a clinical MRI scanner (Shimadzu-Marconi, Magnex Eclipse 1.5 T). Transverse and coronal images were used for visual examination, three-dimensional (3D) reconstruction of the thyroid and cricoid cartilages, and analysis of the joint action.

2.1. MRI coil

A clinical MRI scanner is excellent at imaging large organs, but imaging of small organs such as the larynx is often poor in quality. A general way to obtain high-quality images by MRI is to increase the signal-to-noise ratio by approximating the object and the receiver coil. While the standard clinical neck coil was adequate to observe the head and neck region, the coil was tuned for cervical spine imaging and resulted in a low signal-to-noise ratio in the region of the larynx. A test was made with a small surface coil with a flat, circular antenna with a 15-cm outer diameter. When it was placed in front of the neck, the images obtained were of sufficient quality. However, the subject for this test had to bend his head back to allow space for the large antenna. Therefore, we designed a custom coil by replacing the circular antenna with an oval one (the long and short axes = 140 mm and 75 mm, respectively) with a slightly bent form, as shown in Fig. 1. This “laryngeal coil” can be placed close to the larynx without interfering with comfortable positioning of the head and neck. A preliminary experiment revealed that the coil is capable of capturing typical anatomical images with a pixel resolution of 0.25 mm × 0.25 mm under a slice thickness of 1.0 mm to 2.0 mm.

2.2. MRI sequence

Static laryngeal MRI suffers from motion artifacts caused by respiratory and swallowing movements during a long scanning period. To avoid this problem, we developed a phonation-synchronized procedure to allow a scan burst during the subject’s phonation. This is modified from a motion imaging technique using an external trigger device [4] applied to static imaging. This technique uses a program on a personal computer to generate trigger pulse trains to initiate a scan burst and tone burst trains to a subject via a headset. The subject listens to the tone burst as a guide to pace the rhythm of phonation and respiration, while scans are performed during the subject’s phonation.

In this study, a two-tone burst (100 ms tone, 650 ms silence, 2150 ms tone, and 100 ms silence) of a 480-Hz pure tone was presented every three seconds, and repeated ten times in a session followed by an interval of three seconds. Scan pulse trains were fed to the MRI controller every three seconds so that each scan burst was synchronized with the longer tone period (2150 ms), as shown in Fig. 2. The subject listened to the tones and produce a sustained production of /i/ for about two seconds at a time, which was repeated 65 times in total until the scan was completed. In two experimental sessions, the subject produced vowel with fundamental frequencies of 120 Hz and 180 Hz.

The MRI sequence was RF-FAST (TR=390 ms, TE=3.36 ms, and NEX=2) with FOV = 128 × 128 mm, resolution = 256 × 256 pixels, slice thickness = 2.0 mm, and number of slices = 21. The images were resampled to 512 × 512 pixels for the tracings. This sequence was found to be good at visualizing the surface of ossified cartilages as a dark boundary, while it was not always successful for female and young subjects, whose cartilages were not ossified.

2.3. 3D reconstruction

All the tracings of the laryngeal cartilages from the coronal and transverse slices were used to construct their 3D images. Figure 3 shows two transverse slices with cross-sections of the thyroid and cricoid cartilages (top), and an oblique view of the 3D image of the larynx (bottom). The thyroid and cricoid cartilages

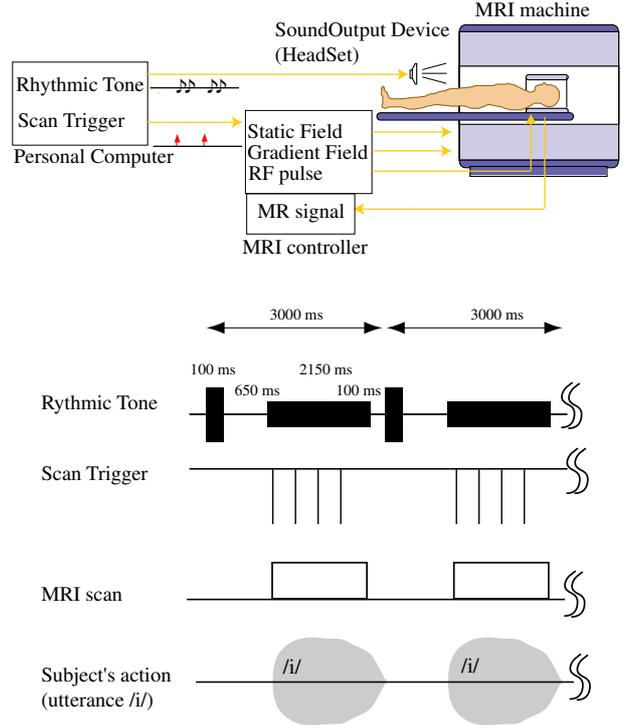


Figure 2: Diagram of phonation-synchronized MRI scan (top), and a time chart of the tone burst train, trigger pulse train, MRI scan burst, and phonation (bottom).

are connected at the cricothyroid joint at the inferior horn of the thyroid cartilage. The border between the thyroid or cricoid cartilage and other tissues was clear on the transverse images. However, the borders of the thyroid and cricoid cartilages were not always clear: tracings were difficult for the bottom of the cartilages except for the mid-sagittal regions.

The 3D reconstructions of the tracings were performed using commercial tools. The tracings were compiled as clusters of small polygons with the Mimics (Materialise), and these polygons were visualized using the LightWave (NewTek/Dstorm) by converting the data with the PolyTrans (OkinoCG).

The measurements of the relative rotation of the cricoid cartilage were taken at the mid-sagittal inferior border of the thyroid cartilage, cricothyroid joint, and anterior superior border of the cricoid cartilage. The translation of the cricothyroid joint was measured on a transverse slice that shows the lowest part of the cricothyroid joint. The length of the glottis was measured as the linear distance between the anterior commissure of the vocal fold to the posterior end of the glottis.

3. Results

Figure 4 shows the 3D reconstructions of the thyroid and cricoid cartilages from the tracings on the MRI data obtained during phonation at a low F0 (120Hz) and a high F0 (180Hz). In the figure, the right half of the thyroid and the cricoid cartilages are shown for the two datasets as semi-transparent pictures. It is obvious that the position of the thyroid cartilage is higher at a high F0 and lower at a low F0. The thyroid cartilage is relatively stable in angle, while the cricoid cartilage shows an obvious angular change. Consequently, the cricothyroid space is narrower

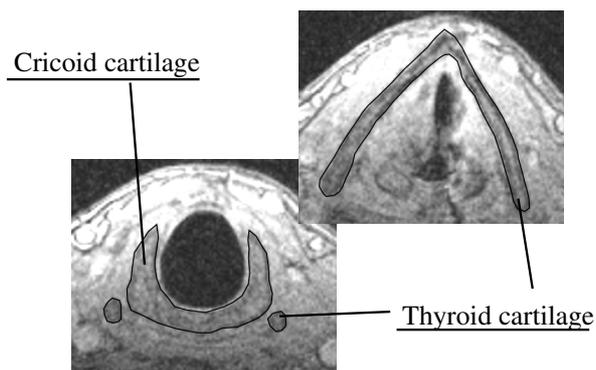


Figure 3: MRI tracings on transverse images (top) and the 3D reconstruction of the thyroid cartilage and the cricoid cartilage (bottom).

at a high F0 than at a low F0, suggesting that joint rotation takes place. At a high F0, the posterior plate of the cricoid cartilage is seen beyond the posterior border of the thyroid lamina, which indicates that the cricoid cartilage translates backward at a high F0.

3.1. Rotation of the cricothyroid joint

The cricothyroid angle was measured graphically on each of the lateral views of the reconstructed images, as shown in Fig. 4. Three landmark points were used for the measurement: the mid-sagittal inferior edge of the thyroid cartilage, bottom of the inferior horn of the thyroid cartilage, and mid-sagittal superior edge of the cricoid cartilage. Then, the angle was measured between the line segments from the point on the inferior horn to the other two landmark points. The angle thus measured was 14.3 degrees at a high F0 and 19.6 degrees at a low F0. The change in the cricothyroid angle between 120 and 180 Hz is approximately 5 degrees. Note that this angular measurement needs a small correction when the translation occurs at the cricothyroid joint simultaneously with the rotation.

3.2. Translation of the cricothyroid joint

Figure 5 shows two transverse slices at the level of the cricothyroid joint at a high and a low F0s. In the figure, cross sections of the inferior horn of the thyroid cartilage and the outline of the cricoid ring are clearly identifiable. Translation of the cricothy-

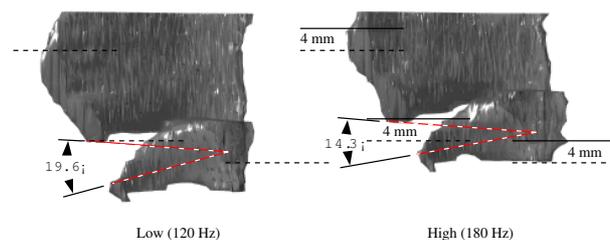


Figure 4: Lateral views of 3D reconstructed images of the thyroid and cricoid cartilages, showing the height and the larynx and the angle of the cricothyroid joint at a low F0 (left) and a high F0 (right).

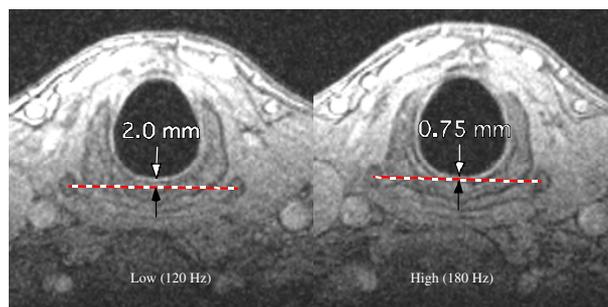


Figure 5: Transverse images of the cricoid ring at the level of the inferior horn of the thyroid cartilage at a low F0 and a high F0. The dashed lines connect the right and left inferior horns.

roid joint was measured by drawing a line segment between the right and left points of the inferior horn and then counting the pixels between the line to the posterior surface of the trachea. The numbers of the pixels measured were eight pixels at a high F0 and three pixels at a low F0, which corresponded to 2.0 mm and 0.75 mm, respectively. Therefore, in this measurement, the inferior horn translates forward 1.25 mm between 120 Hz and 180 Hz. Again, this value needs a small correction when the joint rotation occurs with translation

3.3. Other measurements

The height of the larynx was measured for the two data sets using the landmarks of the thyroid notch, mid-sagittal inferior border of the thyroid cartilage, and cricothyroid joint. The range of the vertical movement of the larynx was 4 mm, as shown in Fig. 4. Figure 6 shows the images of the whole glottis (the membranous and cartilaginous parts). The length of the glottis is 23 mm at a low F0 and 26 mm at a high F0. The glottis is about 3mm longer in 180 Hz than in 120 Hz.

4. Discussion

We developed a combined MRI method using a custom laryngeal coil and a phonation-synchronized scan technique for high-resolution imaging of the larynx. The data obtained demonstrated clear images of the laryngeal cartilages and confirmed that the method was very effective for visualizing the larynx.

From the reconstructed images of the thyroid and cricoid cartilages obtained during phonation at a low F0 (120 Hz) and high F0 (180 Hz), we measured geometrical changes of the

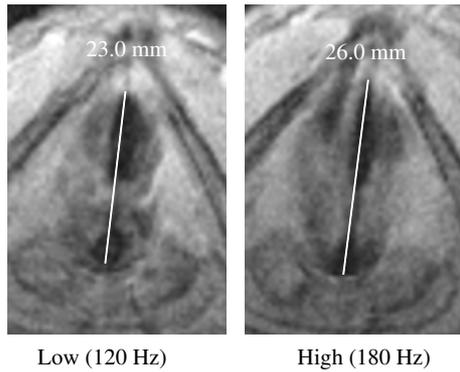


Figure 6: *Transverse images of the glottis at a low F_0 and a high F_0 , with a straight line indicating the length of the glottis.*

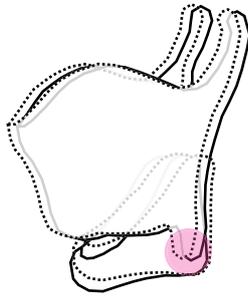


Figure 7: *A schematic figure of the displacement of the larynx; The rotation and the sliding of the cricothyroid joint are illustrated.*

cricothyroid joint. The results indicated that rotation of the joint was about 5 degrees, and that translation was about 1.25 mm. Figure 7 shows a schematic figure of the larynx, indicating that the thyroid cartilage translates forward as the cricoid cartilage rotates backward at a high F_0 .

The above results indicate that the cricothyroid joint rotates and translates at F_0 changes in the mid-range of the vocal pitch, which supports Sonninen (1956) and Vilkmán et al., (1987) [2, 3]. The joint translation (1.25 mm) significantly contribute to stretching the glottis (3 mm). This result further implies that the oblique part of the cricothyroid muscle plays a role in translation of the joint. If the oblique part contracts and the translation occurs, the vocal folds are directly stretched to increase their tension (Arnold, 1961) [5]. Since this action is more effective in F_0 change than rotation, the oblique part of the cricothyroid muscle may be considered as the major muscle for regulating F_0 . In further studies, we will separate the joint actions into rotation and translation components and examine individual variation of the actions of the cricothyroid joint.

5. References

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