Three-dimensional Imaging of High-resolution Computer Tomography of Singers' Larynges—A Pilot Study

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Summary: Objectives/Hypothesis. Biplanar imaging technique is not sufficient for an exact visualization and evaluation of the laryngeal biomechanics during speaking or singing. The aim of this pilot study was to test a 3D-visualization software *MIMICS* (*Materialize Interactive Medical Image Control System*, Materialize, Leuven, Belgium) for visualizing laryngeal cartilages and resonance space of living humans during singing based on high-resolution computed tomography (HRCT) and analyzing the biomechanics thereof.

Study Design. This is a prospective pilot study.

Methods. A total of 10 professional female singers (five sopranos and five altos) was scanned with HRCT in three singing positions fundamental frequency (*ƒ*o), first octave (*ƒ*o+1 8va) and second octave (*ƒ*o+2 8va).

Results. All relevant laryngeal structures and resonance space could be 3D visualized. Superimposing the different HRCT scans showed an inward rotation and rocking of the arytenoid cartilages from *ƒ*o+1 8va to *ƒ*o+2 8va and a backward tilting of the cricoid cartilage from *ƒ*o+1 8va to *ƒ*o+2 8va. Moreover, we could demonstrate a vocal fold elongation of 13% from *ƒ*o to *ƒ*o+1 8va and an additional elongation from *ƒ*o+1 8va to *ƒ*o+2 8va of 10% in type A cricothyroid joints (CTJ) A and 4% in CTJ's type B/C. There were no significant differences between sopranos and altos in all parameters (length of the glottis, subglottic diameter, distance between anterior commissure and cervical spine, and CTJ distribution).

Conclusions. This noninvasive 3D-visualization technique with *MIMICS* allows the anatomical structures and landmarks of the larynx to be analyzed. We believe that this pilot study will serve as a basis for further biomechanical studies on speakers' and singers' larynges.

Key Words: Biomechanics–Larynx–*MIMICS*–Singer–3D.

INTRODUCTION

Throughout the history of mankind, the voice has been one of the primary means of human communication. During the last decades, a number of papers that have improved our understanding of the biomechanics of different laryngeal cartilages have been published.[1–9] Nevertheless, many aspects of voice production while speaking and especially singing are still unclear, eg predicting singers' voice types based on laryngoscopy and laryngeal muscle activities at different frequencies. Some studies examined anatomical differences between sopranos and altos on biplanar images to predict the singer's type.[10–12] Now, high-resolution imaging techniques and sufficient computer software tools, eg *Materialize Interactive Medical Image Control System* (*MIMICS*, Materialize, Leuven, Belgium), are available to analyze and understand voice production mechanisms. As we managed to demonstrate with high-resolution computed tomography (HRCT) scans of cadaver larynges, it is possible to study the biomechanics of the larynx on three-dimensional (3D) reconstructions.[5–8] Therefore, we believe that many unacknowledged questions can be answered by applying these noninvasive high-resolution software tools. The purpose of this pilot study was to answer the following two questions from imaging of professional singers:

(1) Is *MIMICS* suitable for 3D imaging of hard and soft tissues, the air space of the larynx, and resonance space?
(2) Are 3D images obtained by HRCT and *MIMICS* adequate for biomechanical studies of laryngeal function, eg the measurement of different distances in a 3D space and movement and visualization of the trajectory of the laryngeal cartilages during phonation?

This feasibility study should serve as a basis for further biomechanical studies on speakers' and singers' larynges.

MATERIALS AND METHODS

A total of 10 professional female singers (five sopranos [mean age 44 years, range 34–52] and five altos [mean age 43 years, range 33–51]) with at least 5 years of problem-free professional experience was examined. All singers were active as a soloist or in a professional vocal ensemble and were skilled with a singing experience on an average of 15 years (range 5–29 years). We excluded singers older than 60 years (to avoid age-related voice problems), pregnant singers, and singers with a Singing Voice Handicap Index[13,14] of more than 17 points and used only endoscopically normal larynges. The present study was approved by the medical ethics committees of Zurich (Switzerland).

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HRCT imaging

Every singer was scanned three times with HRCT. The first scan was performed during singing the /a/ (as in "C***a***ro mio ben") at middle speaking fundamental frequency (*ƒ*o), and the second and third scans were performed singing the same /a/ one octave (*ƒ*o+1 8va) and two octaves (*ƒ*o+2 8va) higher, respectively. All scans started 2 cm below the glottis and included the upper horn of the thyroid cartilage. All scans were performed on a clinical multislice computed tomography scanner (Siemens Definition AS 64, Siemens Medical Solutions, Erlangen, Germany) with the following parameters: a collimation of 64×0.6 mm, matrix size of 512×512, a slice thickness of 1 mm, pitch of 0.8, an increment of 1 mm, and a rotation time of 1 second. The maximal voltage and tube current were set at 120 kVp and 150 mA, respectively. The scan was performed in a supine position using a high-resolution technique. The maximum effective radiation dosage per singer for all three scans was 2.1 mSv. In comparison with this radiation dose, in Switzerland or USA, the average effective dose of each person amounts to 2.1–3.0 mSv/year from naturally occurring radioactive materials and cosmic radiation. The annual medical effective dose is 1.9 mSv/year.

Postprocess imaging

MIMICS is a segmentation software. The computed tomography scans were first segmented into cartilage, soft tissue, and air column and later transformed into a 3D model.[6] To ensure that all of the relevant anatomical structures and landmarks were visible on the 3D images, we identified the superior and the inferior horns of the thyroid cartilage, the thyroid notch and the laminae, both vocal and muscular processes of the arytenoid cartilages, the cricoid cartilage, both the cricoarytenoid joint and the cricothyroid joint (CTJ), the cervical spine, the subglottic space, and the resonance space of the vocal tract. The distance of the vocal fold from the anterior commissure to the vocal process was measured on all three voice pitches (*ƒ*o, *ƒ*o+1 8va, and *ƒ*o+2 8va).

The air column of the larynx and of the subglottic space was visualized by *MIMICS*. In a sagittal plane, we measured the anteroposterior diameter of the trachea 1 cm below the glottal plane and the distance of the anterior commissure to the cervical spine (according to Roers et al.[10]). To measure the length of the glottis (distance from the anterior commissure to the posterior glottis), a horizontal plane was defined by both vocal processes and the anterior commissure. To depict the movement of the cricoid cartilage during phonation over the octaves (*ƒ*o, *ƒ*o+1 8va, and *ƒ*o+2 8va), we superimposed the 3D images of all three acquisitions. Then, the real rotation axis could be calculated as described by Storck et al.[8]

RESULTS

Visualization of the laryngeal cartilages and resonance space

First, all laryngeal cartilages were segmented and visualized in 3D. All relevant structures were identified in 3D images by *MIMICS*. Ossified parts of the cartilages were adequately segmented (and hence visualized in 3D) using the automatic detection threshold of *MIMICS*. Nonossified parts of the cartilages, especially in younger singers, could be adequately segmented by setting the threshold manually. Additionally, the cricoarytenoid joint and the CTJ could be visualized in all larynges (Figure 1). We were able to recognize the type A CTJ on 3D images (Figure 1); although, it was not possible to distinguish between type B and type C CTJs on 3D images because the cricoid surface was flat in both types. Therefore, we only distinguished between type A and type B/C CTJs. We referred to the articles from Storck et al. and Tschan et al., which show the different 3D images of the CTJs.[8,16] The soprano and alto groups each had three type A and two type B/C CTJs. In all singers, the subglottic space and the resonance space were visible and measurable (Table 2). In the laryngeal part, the Morgagni sinus and also the subglottic dome in the posterior glottis could be well visualized in 3D. In the pharyngeal part, the piriform sinus and the vallecular space were also well recognizable.

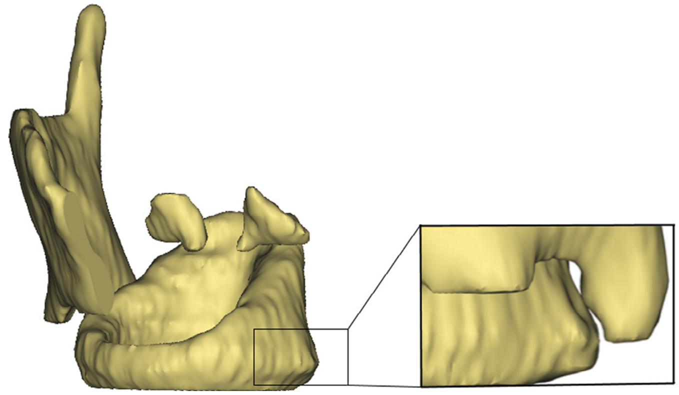

FIGURE 1. *Left*: Oblique frontal view on the 3D-rendered HRCT scan of the larynx showing the right half of the thyroid cartilage. All relevant anatomical structures can be visualized (thyroid, cricoid, arytenoid, cricoarytenoid joint, and cricothyroid joint). *Right*: An enlarged cricothyroid joint is visible and can be categorized (here is a Type A joint according to Maue and Dickson[15]).

Movement of the arytenoid cartilage during singing

The movement of the arytenoid cartilage during singing from *ƒ*o to *ƒ*o+2 8va could be visualized by superimposing the three different cricoid cartilages. The backward movement of the arytenoid from *ƒ*o to *ƒ*o+1 8va is shown in Figure 1. As shown in Figure 2, the arytenoid rocks inward (from *ƒ*o+1 8va to *ƒ*o+2 8va) on the shoulder of the cricoid joint and rotates medially around a virtual vertical axis, and the vocal process moves posteriorly and inferiorly.

Movement of the cricoid during singing

The movement of the cricoid cartilage could be visualized by superimposing the thyroid cartilages of the different 3D images of *ƒ*o, *ƒ*o+1 8va, and *ƒ*o+2 8va. In Figure 3, the right half of the larynx is shown in the position of the cricoid during singing *ƒ*o and *ƒ*o+1 8va. The cricoid plate tilts backward and thereby elongates the vocal folds. We could observe that 6 of 10 subjects had a type A CTJ with a rotation axis running near or through both CTJs, whereas 4 of 10 subjects had a type B/C CTJ with