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Computer simulation of mucosal waves on vibrating human vocal folds

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ABSTRACT

A three-dimensional (3D) finite element (FE) fully parametric model of the human larynx based on computer tomografy measurements was developed and specially adapted for numerical simulation of vocal folds vibrations with collisions.

The complex model consists of the vocal folds, arytenoids, thyroid and cricoid cartilages. The vocal fold tissue is modeled as a three layered transversal isotropic material composed of the cover, ligament and muscle and compared with a four layered material where part of the cover was substituted by a liquid layer modelling the superficial layer of lamina propria.

First, the basic frequency-modal properties of the model are presented for a given pretension of the vocal folds. The results of numerical simulation of the vocal folds oscillations excited by a prescribed intraglottal aerodynamic pressure are then presented. The results computed in time domain show the 3D motion of the vocal folds in all three directions (horizontal, vertical and anterior-posterior) and the mucosal waves are clearly modeled in the medial cross-section of the vocal folds. The proper orthogonal decomposition (POD) analysis of the excited modes of vibration shows that when taking account of the superficial sub-layer inside the lamina propria with liquid like properties the POD modes are in better agreement with the empirical eigenfunctions (EEF) obtained from measurements performed on excised human larynges.

Finally, the usability of the POD analysis for simulation of pathological situations is demonstrated considering a vocal fold nodule located on the upper cranial margin of the right vocal fold.

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1. Introduction

Understanding the basic principles of voice production is important for better interpretation of clinical findings, detection of laryngeal cancers or other pathologies and for treatment of voice disorders.

Voice production is a complex physiological process, which involves several basic factors like airflow coming from the lungs, vocal folds vibration and acoustic resonances of the cavities of the vocal tract, see Fig. 1. Primary pressure fluctuations arise in the human larynx as a result of the airflow interaction with the vibrating vocal folds. The vocal folds (VF), excited by the airflow, generate a primary laryngeal tone whose fundamental frequency corresponds to the vibrational frequency of the vocal folds. In the airways above the vocal folds, i.e. in the vocal tract, the acoustic resonant phenomena modify the spectrum of the primary laryngeal tone, especially the higher harmonics, see e.g. [1,2].

Design of more exact 3D computer models of the human VF enables to simulate some pathological situations. Such computer models that take into consideration the complicated structure and material properties of the living tissue, and the aerodynamic, inertial and impact forces during VF self-oscillations with collisions, are becoming applicable in phonosurgery (see e.g. [3,4]). The complex 3D approach to the phonatory modeling was published e.g. by Zheng et al. [5]. Such sophisticated 3D models based on FE modeling of flow coupled with the vibrating complicated structure of the VF tissue enable estimation of all normal and shear stresses in the different vocal fold tissue layers in all three directions, however, the computational demands on computers and computer time needed are high and remain limited.

Changes in the structural properties are related to the changes of the vibratory properties of the vocal folds observed in kymograms like for example mucosal waves appearance which is one of the characteristic properties of a healthy VF tissue, see e.g. [6]. Consequences of the mucosal waves traveling on the vibrating vocal folds surface were discussed from the point of view of mechanical stress in phonation and the formation of VF traumas by Sonninen and Laukkanen [7].

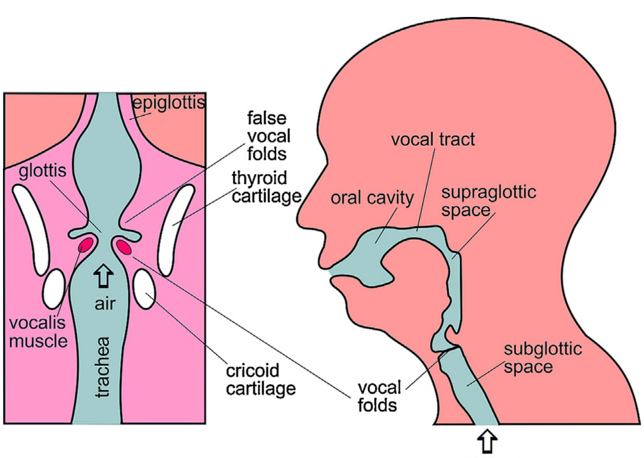

Fig. 1 – Schema of the human vocal tract with a detail of the laryngeal part.

Alipour et al. [8] were probably first, who revealed in a 3D FE vocal fold model the mucosal waves. The model was designed for inhomogeneous, anisotropic materials respecting the cover, ligament, and body of the VF. The authors showed an elliptical motion of the points on the vocal fold surface in a coronal cross section plane.

The similar results were obtained by Berry et al. [9] from measurements on an excised canine larynx. The results revealed that the size of elliptical trajectories increased from inferior to superior edge of the VF. Döllinger et al. [10], in the study of medial surface dynamics of an in vivo canine vocal fold, concluded that during normal phonation the mucosal wave propagates primarily from inferior to superior. Later, Döllinger and Berry [11] and Boessenecker et al. [12] confirmed the elliptical shape of the VF tissue movement by the experiments on excised human larynges. Recent measurements by Bakhshaee et al. [13] on excised porcine larynges showed also that the motion of the VF surface during self-oscillations can be described by elliptical trajectories.

Similarly, such phenomenon was reported by Zhang et al. [14] in a study on aerodynamically driven vocal fold vibrations by using a physical laboratory model. The flow-induced response of self-oscillating synthetic VF models was studied by Murray and Thomson [15]. The models featured mucosal wave-like motion, characteristic which is an important marker of human VF vibration.

Our study intends to present a fundamental principal and the method how the computer simulation of the mucosal waves can be improved by implementing a liquid layer into the VF tissue. First, the morphology of this VF tissue structure is described in detail and then the developed 3D FE fully parametric model of the larynx is presented. This complex model enables variation of the pre-phonatory position of the vocal folds by an independent motion of the cricoid, thyroid and arytenoid cartilages. The 3D FE model also enables easy changes of the shape and the material properties of individual VF tissue layers. This is, why the FE model is utilized here for comparison of the three layered VF model, considering epithelium, vocal ligament and muscle, with the VF model, where part of the ligament is substituted by a liquid layer modeling the superficial layer of the lamina propria. The frequency-modal properties of the VF and the results of the numerical simulation of the VF oscillations with collisions, excited by a prescribed periodic intraglottal aerodynamic pressure, are then presented for both VF models. For simplicity, no fluid structure interaction is considered here, and the primary focus is concentrated on the proper orthogonal decomposition (POD) analysis of the excited modes of vibration and on comparison of the simulated vibration patterns in the VF models with the empirical eigenfunctions (EEF) measured on the excised human larynges during phonation. The magnitudes of the VF displacements in the longitudinal and lateral directions and the stresses computed in the VF tissue without and with the liquid layer are also compared. Then the POD analysis of the excited modes of vibrations is demonstrated by predicting the effect of a vocal fold nodule on the vibration pattern of the vocal folds.