Journal of Biomechanics 55 (2017) 128–133

Contents lists available at ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech
www.JBiomech.com

Effect of the ventricular folds in a synthetic larynx model

Stefan Kniesburges [a,*], Veronika Birk [a], Alexander Lodermeyer [b,c], Anne Schützenberger [a], Christopher Bohr [a], Stefan Becker [b]

[a] *Department of Otorhinolaryngology, Head and Neck Surgery, Division of Phoniatrics and Pediatric Audiology, University Hospital Erlangen, Medical School at Friedrich-Alexander University Erlangen-Nürnberg, Germany*
[b] *Department of Process Machinery and Systems Engineering, Friedrich-Alexander University Erlangen-Nürnberg, Germany*
[c] *Erlangen Graduate School in Advanced Optical Technologies (SAOT), Friedrich-Alexander Unversity Erlangen-Nürnberg, Germany*

ARTICLE INFO

Article history:
Accepted 16 February 2017

Keywords:
Human phonation
Synthetic larynx model
Ventricular folds
Aerodynamics
Fluid-structure interaction

ABSTRACT

Within the human larynx, the ventricular folds serve primarily as a protecting valve during swallowing. They are located directly above the sound-generating vocal folds. During normal phonation, the ventricular folds are passive structures that are not excited to periodical oscillations. However, the impact of the ventricular folds on the phonation process has not yet been finally clarified.

An experimental synthetic human larynx model was used to investigate the effect of the ventricular folds on the phonation process. The model includes self-oscillating vocal fold models and allows the comparison of the pressure distribution at multiple locations in the larynx for configurations with and without ventricular folds.

The results indicate that the ventricular folds increase the efficiency of the phonation process by reducing the phonation threshold level of the pressure below the vocal folds. Two effects caused by the ventricular folds could be identified as reasons: (1) a decrease in the mean pressure level in the region between vocal and ventricular folds (ventricles) and (2) an increase in the glottal flow resistance.

The reason for the first effect is a reduction of the pressure level in the ventricles due to the jet entrainment and the low static pressure in the glottal jet. The second effect results from an increase in the glottal flow resistance that enhances the aerodynamic energy transfer into the vocal folds. This effect reduces the onset threshold of the pressure difference across the glottis.

1. Introduction

The primary acoustic human voice signal is produced in the larynx by the two elastic vocal folds. For phonation, the vocal folds are excited to periodic oscillations owing to the air flow coming from the lungs. By these oscillations, the gap between the vocal folds, called the glottis, periodically opens and closes, which interrupts the tracheal airflow. The resulting pulsatile jet flow above the vocal folds generates the primary acoustic signal composed of the basic tone and its higher harmonics. This primary sound is further modulated in the vocal tract, forming the voice signal.

Immediately above the vocal folds, the two ventricular folds, also called false vocal folds (FVFs), are located, forming an additional constriction in the larynx. During swallowing, the gap between the FVFs is closed, protecting the lungs from food aspiration. During respiration and normal phonation, the gap between the FVFs is open and they do not move, except for special conditions in professional singing such as Mongolian Kargyraa, Tibetan and Sardinian Bassu singing, yodeling or growls serving as a second sound generator (Bailly et al., 2010).

During normal phonation, an increase in the harmonic components of the produced sound was detected owing to the presence of the FVFs (Finnegan and Alipour, 2009; Birk et al., 2016), possibly generated by an additional acoustic dipole source due to the vortex-FVFs interaction (Zhang et al., 2002).

Furthermore, scientific findings in the literature indicate a strong functional influence of the FVFs on the vocal fold oscillations. Bailly et al. (2008) investigated the impact of the FVFs with varying parameters such as the ventricular gap size and the distance to the vocal folds in a synthetic larynx model, including both static and self-sustained oscillating vocal folds. For parameters being in the physiological range, the presence of the FVFs caused an enhancement of the vocal fold oscillations and a decrease of the onset phonation threshold pressure (onset PTP), i.e. the subglottal pressure required for oscillation onset. Similar observations

---

* Corresponding author at: Waldstrasse 1, 91054 Erlangen, Germany. Fax: +49 (0) 9131 8532687.

E-mail address: stefan.kniesburges@uk-erlangen.de (S. Kniesburges).

http://dx.doi.org/10.1016/j.jbiomech.2017.02.021
0021-9290/© 2017 Elsevier Ltd. All rights reserved.

were made by Zheng et al. (2009) with a computational 2D model that shows larger oscillation amplitudes by including the FVFs. Moreover, Birk et al. (2016) identified a lower onset PTP in the presence of FVFs within excised human larynges.

From an aerodynamic point of view, the presence of the FVFs stabilizes and straightens the glottal jet (Drechsel and Thomson, 2008; de Luzan et al., 2015). As a consequence, during glottis closure, small vortices between the jet and the vocal folds in the divergent glottal duct as found by Oren et al. (2014) in an excised canine larynx have a higher strength resulting in a higher closing force exerted on the vocal folds (de Luzan et al., 2015). Thus, we hypothesize that the presence of FVFs increases the efficiency of the energy exchange between glottal airflow and the vocal fold.

This hypothesis is supported by results provided by Alipour et al. (2007) and Birk et al. (2016), who measured an increase of the glottal flow resistance in excised larynx models by comparing configurations with and without FVFs. In general, the flow resistance is a measure of aerodynamic energy that is withdrawn from the flow and partly converted to dynamical energy of the flow-passed structures being the vocal folds in case of phonation.

However, there are some discrepancies reported in the literature. In contrast to Birk et al. (2016), Alipour and Finnegan (2013) reported an increase of the onset PTP in the presence of FVFs. Furthermore, contrary to results by Alipour et al. (2007) and Birk et al. (2016), Zhang et al. (2002) and Zheng et al. (2009) found a decrease of the glottal flow resistance for cases with FVFs. The reason for these discrepancies is mainly owing to the large variety of larynx models. Alipour and Finnegan (2013) used excised canine larynges with and without supraglottal structures also including the epiglottis. Zheng et al. (2009) applied a 2D computational model of the larynx neglecting three-dimensional effects, whereas Zhang et al. (2002) further simplified their model by only simulating one vocal fold. However, by only considering one vocal fold, key features as the glottal jet deflection cannot be reproduced.

Although there is a large variety of larynx models and scientific procedures, the reported scientific findings support the hypothesis mentioned above that the presence of the FVFs increase the efficiency of normal phonation. Hence, the aim of this work is to analyze the basic aerodynamic effects that cause this efficiency increase. Owing to the better reproducibility and highly controlled conditions compared to excised larynges, an experimental synthetic larynx model was used that has been previously introduced elsewhere (Kniesburges et al., 2013; Lodermeyer et al., 2015).

2. Experimental setup and data analysis

2.1. Flow channel and synthetic larynx model

The experimental setup is displayed in Fig. 1 and includes a mass flow generator, an acoustic silencer and the main synthetic larynx model. The whole flow region of the synthetic larynx has a rectangular cross-section with $\Delta y \times \Delta z = 18 \times 15\ \text{mm}^2$, corresponding anatomically to the lateral–longitudinal orientation of the vocal folds.

The mounting device for the synthetic vocal folds divides the synthetic larynx into a subglottal region (below) and a supraglottal region (above the vocal folds). The shape of the vocal folds is based on the M5 model (Scherer et al., 2001; Thomson et al., 2005; Pickup and Thomson, 2009) and they consist of `ECOFLEX 30` (Smooth-On) silicone rubber, the stiffness of which can be varied by adjusting the mixing ratio of the precursors. Two types of homogeneous vocal fold models with a different stiffness were used: type 114 with a Young's modulus $E = 2.5$ kPa and type 113 with $E = 4.4$ kPa, both characteristic of human vocal fold tissue (Tran et al., 1993; Min et al., 1995; Titze and Alipour, 2006; Chan and Rodriguez, 2008). For both model types, the glottis was initially closed before the flow is switched on. The vocal fold models showed self-sustained periodical oscillations after exceeding the onset PTP. The vocal folds exhibit two oscillation modes depending on the applied mean subglottal pressure. Immediately above the onset PTP, the vocal folds oscillated in the first mode M1, characterized by small-amplitude oscillations without contact between the two vocal folds typically observed during phonation onset.

When further increasing the subglottal pressure, a transition to the second oscillation mode M2 occurred showing the periodical glottis closure during normal human phonation. In both oscillations modes, the vocal fold models formed a convergent shape of the glottal duct during glottis opening and a divergent shape during glottis closing phase. This is known as mucosal wave-like motion (Hirano, 1981; Titze, 1988; Döllinger and Berry, 2006; Mittal et al., 2013). The oscillation frequency for the model 113 was between 131 and 150 Hz, for the model 114 between 93 and 110 Hz, depending on the oscillation mode and the applied subglottal pressure being in the physiological frequency range of human phonation (Kniesburges et al., 2011). A detailed description of the oscillation pattern of these vocal fold models is given by Lodermeyer et al. (2015). Therein, the comparison of further characteristic parameters with physiological values shows the good validity of this model for representing the human phonation.

Three channel configurations in the supraglottal region were selected: without supraglottal channel (noSC), with channel (SC)

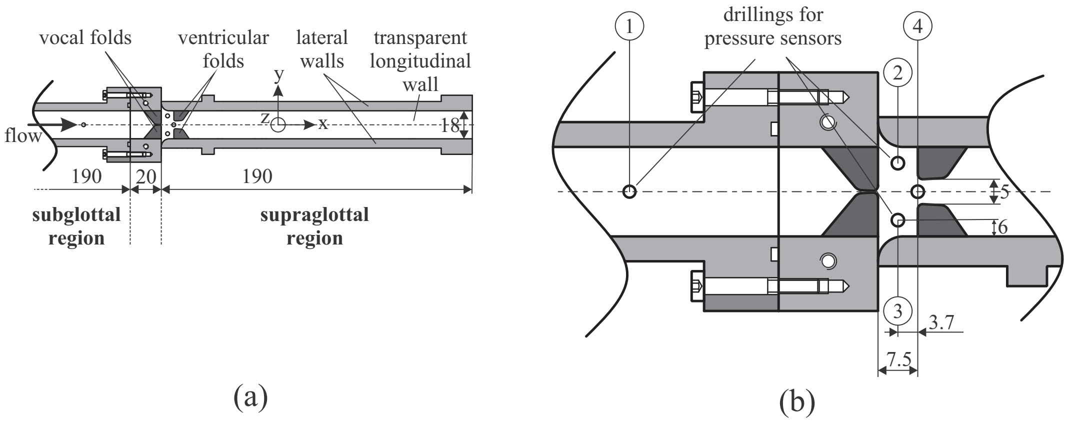

Fig. 1. Schematic of the synthetic larynx setup in (a) a total and (b) a close-up representation of the glottal area. The four positions of the pressure sensors are indicated by numbers in (b). All dimensions in mm.