Experimental study on level difference between left and right vocal folds

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1. Introduction

It has been known that asymmetry between left and right vocal folds, induced, e.g., by vocal cord nodules, polyps, and vocal cord atrophy, is one of the leading causes of voice disorders. The asymmetric configuration may lead to incomplete glottal closure and results in a variety of voice instabilities such as subharmonics, biphonation, and chaos. Careful examinations are needed to investigate the effect of asymmetry on the voice production. Ishizaka and Isshiki [1] introduced left-right asymmetry to the two-mass model of the vocal folds to simulate pathological voices. Steinecke and Herzel [2] simplified the asymmetric two-mass model to study bifurcations underlying the voice instability. Lucero *et al.* [3] derived analytical formula for the phonation onset of the asymmetric vocal fold model. Phase difference between the left and right vocal folds [4,5], subharmonics [6], biphonations [7], and irregular chaotic oscillations [8] have been reported.

The preceding studies mainly focused on asymmetry with respect to tension imbalance and geometrical difference between the left and right vocal folds. It has been known, however, that the level difference, that is defined as the distance between the upper surfaces of the bilateral vocal folds in the inferior-superior direction, is also a typical result of atrophy of the paralyzed vocal fold. Kadota and Yumoto [9] measured the level difference of patients with unilateral recurrent laryngeal nerve paralysis using a computed radiography system and reported that the level difference provides a good index for the quantitative assessment of the effectiveness of phonosurgical treatment. Hong and Jung [10] also reported a variety of level differences between paralyzed and normal vocal folds for patients with unilateral vocal fold paralysis.

Although the level difference between the left and right vocal folds may have an influence on laryngeal functions, its effect on voice production has not yet been thoroughly investigated. The aim of the present letter is to utilize three types of physical models of the vocal folds to study the effect of the level difference on the vocal folds vibration. We measure the phonation threshold pressure as a primary index for quantifying the difficulty in phonation. Our experiments reveal that the phonation threshold pressure increases signifi-

cantly as the level difference is extended. Our preliminary study suggests that the level difference may have a potential effect on voice production, which should be taken into account for the diagnosis and treatment of voice disorders.

2. Physical experiment

2.1. Method

As a physical model of the vocal folds, three types of models, referred to as “M5,” “MRI,” and “EPI,” were constructed following the methods of Murray and Thomson [11]. Figure 1 shows schematic illustrations of the three models. The M5 model had a two-layer body-cover structure, created based on the geometry of Drechsel and Thomson [12]. Due to its simplified geometry, the oscillating cycles are known to exhibit only a minor mucosal wave-like motion. The MRI model was based on a geometry from magnetic resonance imaging (MRI) data of a human larynx [13]. The model was fabricated in the same manner as the M5 model except that the cover layer is created with a softer material. The EPI model had a multi-layer structure. Instead of a single cover layer, an extremely flexible superficial layer of the lamina propria (SLLP) layer, covered by a thin epithelium layer, was created. The SLLP layer was attached to the body layer with a support of ligament layer. It has been reported that both MRI and EPI models oscillate with a pronounced convergent-divergent motion, showing a clear evidence of vertically traveling mucosal waves.

The three models were created using liquid two-part silicone (EcoFlex® 00-30, Smooth-On, Inc.), stiffer two-part silicone mixture (Dragon Skin® 10 Fast, Smooth-On, Inc.), and silicone thinner compounds (Silicone Thinner®, Smooth-On, Inc.), where mixture of these materials with desired ratio produced different stiffness and strength of the individual layers. No tension was applied to the ligament layer of the EPI model.

2.2. Experiment

As shown in Fig. 1, the vocal fold model was attached to a 1.2 cm thick rigid acrylic orifice plate using a high vacuum sealing compound (HIVAC-G, Shin-Etsu Chemical Co., Ltd.) so that no air was leaked. Thin plates of 0.3 mm thickness were assembled to create a level difference in the inferior-superior direction. For each model, the level difference was increased from 0 mm at increments of 0.3 mm. For each level difference, the medial-lateral distance between the left and right vocal folds was set to be the same.

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Fig. 1 Experimental set-up. The air-flow, which comes from a tracheal tube, passes through synthetic vocal folds. Level difference between the left and right vocal folds was created by inserting thin plates to the bottom of the right vocal fold. Acoustical sound and subglottal pressure were measured simultaneously by microphone, and pressure transducer, respectively.

The other experimental setup is briefly summarized as follows [details can be also found in [14]]. The length of the polyvinyl chloride (PVC) tube, which was connected to the vocal fold model, was 70 cm. No supraglottal tube was attached. An expansion chamber (inner cross-sectional diameter: 30 cm, length: 50 cm) was connected to an air pump (SilentAirCompressor Sc820, Hitachi Koki Co., Ltd.) through a 9 m long rubber hose. The volumetric flow rate through the glottis was controlled by a pressure regulator (10202U, Fairchild), which was inserted between the air pump and the rubber hose. The subglottal pressure was monitored using a pressure transducer (Differential pressure transducer, PDS 70GA, Kyowa; Signal conditioner, CDV 700A, Kyowa), which was mounted flush with the inner wall of the tracheal tube, 2 cm upstream of the vocal fold plates. The sound generated from the physical model was recorded by an omnidirectional microphone (Type 4192, Brüel and Kjær; Nexus conditioning amplifier).

To measure the phonation onset pressure, the flow-rate was increased by adjusting the pressure regulator until the vocal folds start to oscillate. The phonation threshold pressure was detected at the point when the oscillation amplitude of the subglottal pressure exceeded 0.07 kPa. If no oscillations were initiated until the flow rate reached to 50 l/min, the pressure was not measured. Next, from the point above the phonation onset, the phonation offset pressure was measured by lowering the flow-rate until the vocal folds oscillations stopped. For each setting of the level difference, this measurement was repeated for three times and the average was computed for the onset and offset pressures.

2.3. Results

Figure 2 shows dependence of the oscillation threshold pressure on the level difference. The phonation onset and offset are drawn by solid and dotted lines, respectively, for the three vocal fold models. The maximum level difference, above which no vibration was observed, was 3.3 mm for the M5 model, 5.7 mm for the MRI model, and 3.9 mm for the EPI model. For both phonation onset and offset, the threshold

Fig. 2 Dependence of the phonation onset (solid line) and offset (dotted line) pressures on the level difference for three models of the vocal folds. (a): M5 model, (b): MRI model, (c): EPI model.

pressure increased as the level difference was increased. For all models, the onset pressure was higher than the offset pressure, indicating the hysteresis phenomena. This implies that two stable states (vocal fold oscillation and stable equilibrium) may coexist between the onset and offset pressures.

As seen in Fig. 2, individual models show different tendencies of the onset pressure. The phonation threshold pressures for the M5 and EPI models were in a similar range up to the level difference of 1.5 mm, above which the pressure increased more rapidly in the M5 model. Since the M5 and EPI models have similar dimensions, this difference might be due to the difference in the stiffness of the cover layer. According to Titze [15], decrease in the mucosal wave that propagates on the surface of the cover layer lowers the threshold pressure. Since the wave velocity is slower for the soft material, the EPI having a softer cover showed a smaller increase in the threshold pressure. The MRI model, on the other hand, showed oscillations in an extended range of the level difference up to 5.7 mm. Since the MRI model has a

Fig. 3 Dependence of the fundamental frequency on the level difference for three models (M5: solid line, MRI: dashed line, EPI: dotted line). The frequency was measured at the phonation onset point.

rounded intraglottal shape, the thickness of the part of the vocal fold, which touches with the other side of the vocal fold, did not change too much as the level difference was increased. Because the thickness of the vocal folds is one of the major determinants of the threshold pressure [15], the MRI model was more tolerant against the level difference. The overall pressure was relatively high in the EPI model, but its increase was not sharp, probably because of the soft cover layer.

Figure 3 shows fundamental frequencies of the three models measured at the phonation onset point. The frequency decreased as the level difference was increased. This can be interpreted as a frequency drop induced by an increased damping in a mass-damper-spring system. Among the three models, the EPI model showed the lowest frequency, because of the extremely soft SLLP layer. This tendency agrees with the preceding study [11].

2.4. Theory of phonation threshold pressure

The experimental results presented in the previous subsection are examined by the theory of phonation threshold pressure. The theory, which will be reported in detail elsewhere [16], is based upon the small amplitude approximation of the vocal fold oscillations [15]. By neglecting the acoustic loads from both sub- and supraglottal systems and assuming symmetric dynamics between the left and right vocal folds, the oscillation threshold pressure is given by

$$P_s \geq \frac{d}{(d - \Delta d)^2} B v_{mw} x_0. \quad (1)$$

Here, d and Δd stand for thickness and level difference of the vocal folds, respectively. x_0 , B , v_{mw} represent prephonatory glottal half-width, damping coefficient per unit area of the vocal fold medial surface, and mucosal surface wave velocity, respectively. In the case that the level difference is zero (i.e., $\Delta d = 0$), the above formula becomes $P_s \geq \frac{Bcx_0}{d}$, which is equivalent to the result of Titze [15]. The effect of the level difference is that it increases the oscillation threshold pressure as $P_s \sim \frac{1}{(d - \Delta d)^2}$.

To examine the experiment, theoretical curves $P_s = \frac{\alpha \tilde{d}}{(d - \Delta d)^2}$ were fitted to the phonation onset pressures measured in Fig. 2. The two parameters $\{\alpha, \tilde{d}\}$ were optimized by using `lsqcurvefit` subroutine of the MATLAB Statistical

Fig. 4 Theoretical curves (solid lines) fitted to experimental data (M5: circles, MRI: squares, EPI: crosses). The red, blue, and black colors indicate M5, MRI, and EPI models, respectively.

Toolbox. Figure 4 shows the results. For the three models, the theoretical curves fit to the experiments reasonably well. For the M5, MRI, and EPI models, the correlation coefficients between the theory and experiment were $r = 0.98$, 0.84 , and 0.87 , respectively, which were all significant ($p < 0.05$). The estimated parameter values for the vocal fold thickness were $\tilde{d} = 10.0$ mm for M5 model, $\tilde{d} = 33.5$ mm for MRI model, and $\tilde{d} = 21.1$ mm for EPI model. The corresponding thicknesses of the vocal folds were approximately $d \approx 10$ mm, 13 mm, and 10 mm, respectively. The M5 model was in a very good agreement with the experimental condition, whereas the vocal fold thickness was overestimated for the MRI and EPI models. This might be due to the asymmetric dynamics (large phase difference), which was not assumed in the theory but present in the MRI and EPI models. The model fitting was worse in the MRI model compared to that in the EPI model, because of its rounded intraglottal shape, which made the MRI model insensitive to the level difference as discussed in Sect. 2.3.

3. Summary

The effect of the level difference on the vocal fold oscillation was studied. Three types of the vocal fold models were utilized to carry out the physical experiment. The main findings are that the phonation threshold pressure was significantly increased as the level difference was increased. The experimental results were in good agreement with the theory of phonation threshold pressure. For the simplified M5 model, the pressure increase was about 0.3 kPa, which may have a strong influence on the phonation. The pressure increase was suppressed to 0.2 kPa for the MRI and EPI models, because of their more detailed structure with softer materials implemented in the cover layer. Up to date, there have not been much physiological reports on the level difference except for few [9,10], because of the difficulty of measuring the absolute depths of the left and right vocal fold surfaces *in vivo*. We nevertheless consider that our setting of the level difference of 3 – 5 mm is plausible for subjects with laryngeal pathology. Our results therefore suggest that the level difference might be one of the possible causes of strained voice, from which patients with voice disorders may suffer.

Of particular interest of the present study is its application to the understanding and diagnosis of voice pathology. As

discussed above, the level difference might be one of the underlying causes of strained voices. There have been however not much reports on the physiological measurement of the level difference, because conventional tools such as stroboscopy and high-speed video endoscopy are limited to providing information regarding glottal movement in the transverse plane [17]. Recently, various attempts have been made to obtain three-dimensional information of the vocal fold dynamics, e.g., laser systems [18], stereo endoscopy [19], and others. Such advanced measurements may provide more precise information about the left-right vertical asymmetry and enable us to study the relation between the level difference and the difficulty of phonation.

Lastly, we note that further investigations [16] are needed to deepen the present study. For instance, the effect of the supraglottal vocal tract, which have not been considered in our experiment, should be carefully examined, since the supraglottal resonance may facilitate the vocal folds vibrations.

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