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Low frequency mechanical resonance of the vocal tract in vocal exercises that apply tubes

J. Horáček[a,*], V. Radolf[a], A.-M. Laukkanen[b]

[a] *Institute of Thermomechanics, The Czech Academy of Sciences, Dolejškova 1402/5, 182 00, Prague, Czech Republic*
[b] *Speech and Voice Research Laboratory, School of Education, Åkerlundink. 5, University of Tampere, 33100 Tampere, Finland*

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ABSTRACT

Phonation into a tube that lowers the acoustic vocal tract resonance frequency and increases vocal tract impedance is used in voice therapy to establish effortless voice production. Additionally, keeping the distal end of the tube in the water results in the water bubbling and a consequent oscillation of oral pressure. This may feel like a massage of the vocal tract and larynx.

A low frequency mechanical resonance of the vocal tract, F_m, could enhance the effect of tube therapy in two ways: 1) by lowering the first acoustic resonance closer to the fundamental frequency of phonation, and 2) by introducing a coalescence of F_m with the water bubbling frequency.

A mathematical model of acoustic-structural interaction is introduced to clarify F_m in the context of phonation into a tube with the distal end in air and in water. The numerical results from the model are compared with the resonance frequencies measured in a male subject phonating on the vowel [uː] into a glass resonance tube with the distal end in air and at 2 cm and 10 cm under water. The effects of phonation through the tube are demonstrated by registering oral air pressure and electroglottography, and by synchronous high-speed filming of the water bubbling.

The first computed acoustic resonance frequency decreased from $F_1 = 200$ Hz for the tube end in air down to about $F_1 = 175$ Hz for the tube end in water, which roughly agrees with the first formant frequency of c. 179 Hz that was experimentally found for the human vocal tract. Considering the mechanical resonance F_m of the vocal tract to be c. 66 Hz, as previously estimated from measurements of a closed vocal tract, then according to the mathematical model for the vocal tract prolonged by a rigid glass tube, this frequency drops to 23 Hz. When the tube is submerged in water, F_m drops further to $F_m = 8$ Hz for the resonance tube and to about $F_m = 10$ Hz for a longer and wider silicon Lax Vox tube. The results thus show that the mechanical resonance can be near the measured water bubbling frequency $F_b = 11$–11.5 Hz.

The results suggest that the mechanical resonance of the vocal tract tissues enhances the effects of the tube during voice therapy.

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1. Introduction

Phonation into tubes of various dimensions is used for voice training and therapy purposes (see e.g. [1–3]). Phonation into a glass resonance tube (24–28 cm in length, 8–9 mm in inner diameter) with the outer end of the tube in air has been used for the voice training of normal voiced subjects to improve loudness and voice quality [1,3]. The beneficial effect of the exercise has been explained by assuming that the prolongation of the vocal tract (VT) lowers the first acoustic resonance of the vocal tract (first formant, F_1) near the fundamental frequency (F_0) in speech. This increases the positive reactance of the vocal tract at the F_0 range, which in turn has been found to assist vocal fold vibration mechanically [4]. Increased reactance decreases the phonation threshold and increases the amplitude of the harmonics without the use of excessive vocal fold collision. Thus, it improves the economy and efficiency of phonation (see e.g. [5,6]). The use of semi-occlusions, e.g. phonation into tubes or the production of voiced fricatives, nasals, and lip and tongue trills, increases the air pressure in the vocal tract. In such conditions, one feels the resonance vibrations in the vocal tract more clearly. It is assumed that during phonation into a tube, one becomes accustomed to how economic and efficient voice production feels and learns to use sensations of resonatory vibrations of the vocal tract tissues in order to monitor voice quality also when the tube is removed from the lips [6,7]. According to mathematical

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[*] Corresponding author.
E-mail addresses: jaromirh@it.cas.cz (J. Horáček), radolf@it.cas.cz (V. Radolf), Anne-Maria.Laukkanen@uta.fi (A.-M. Laukkanen).

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modelling results [8], F_1 is approximately in the range of ordinary speech, i.e. 200–300 Hz, for phonation into hard-walled tubes of 10 cm and 30 cm in length and with an inner diameter of 8 mm. The VT wall was considered to be yielding, having a mechanical resonance frequency (F_m) of its own. The parameters of such a VT model were set to the values suggested in [9], where the lowest acoustic resonance frequency of the closed VT was set to 200 Hz. However, it is plausible to suggest that this value can differ significantly when the VT is prolonged by a hard-walled tube with the distal end immersed in water.

It is known that the low mechanical resonance frequency (F_m) of the vocal tract is caused by the yielding walls of the VT cavities. Sondhi [10] postulated that this mechanical resonance is located below 20 Hz. The effect of the yielding walls is remarkable in speech produced in high ambient pressures, such as by deep-sea divers, and when the vocal tract is occluded or semi-occluded. The mechanical resonance causes shifts in the frequencies of the formants [8,9]. The authors of the papers [9,10] used the value $F_m = 15$ Hz in their computational modelling for the low mechanical resonance frequency of the vocal tract. This was deduced from the experimental data of formant frequencies and bandwidths measured by Fujimura & Lindqvist [11] for a closed vocal tract during plosive consonants. Ishizaka et al. [12] made direct measurements of VT wall impedance. According to their measurements, Liljencrants [13] formulated the dynamic properties of the mechanical resonances for the cheek and neck of a male subject, and estimated that the natural frequencies would range from 32 Hz for a relaxed cheek to 72 Hz for the neck.

Švec et al. [14] investigated the resonance properties of the laryngeal structures *in vivo*. Laryngeal vibrations were excited via a shaker placed on the neck of a male subject and observed by means of videostroboscopy and videokymography. The resonance frequency of the ventricular folds was found to be close to 70 Hz. The aryepiglottic folds and arytenoid cartilages were suspected to have resonances below 50 Hz, because when a sinusoidal excitation of 50 Hz was applied, large oscillations of the laryngeal collar were seen. The vocal folds oscillated as a unit with other laryngeal structures. Large vibration amplitudes at frequencies of 50 Hz caused uncomfortable sensations in the subject, so measurements for frequencies lower than 50 Hz were not performed.

Therefore, it is known that there is a mechanical resonance (or resonances) below c. 70 Hz in the vocal tract. The role of this resonance becomes more prominent in phonation when the vocal tract is occluded or semi-occluded, as in the production of closed vowels, voiced consonants, or phonation into tubes, especially if the outer end of the tube is inserted into water, as in water resistance therapy [3].

Earlier studies by the authors [15,16] proved that the soft tissues of the human VT cavities had a considerable effect on the first formant frequency F_1 when the VT was prolonged by a tube. The measured F_1 for the VT model with hard walls corresponded to the computed value of 78 Hz. The experiments with a human subject instead resulted in a much higher value of F_1, at about 200 Hz. The results confirm that a VT model with yielding walls must be considered for the mathematical modelling of human voice production.

Recently, many studies have also focused on water resistance voice therapy, where the subject phonates into a tube (either a glass resonance tube or a silicon Lax Vox tube), the outer end of which is submerged in water (see e.g. [17–19]). Such an exercise increases vocal tract impedance, and the impedance can be regulated by changing the depth the tube is immersed in the water. Bubbling frequency can be used to control the steadiness and rate of expiratory airflow. Water bubbling has been reported to feel like a massage, and it has been suggested that it could have the positive effects of massage (see e.g. [20,21]). In water resistance therapy, the mechanical low-frequency resonance of the soft tissue in the larynx could play an even more important role than for phonation on (semi-)occluded speech sounds or through a tube in air.

An experimental study [22] on gas bubble formation in water showed that the bubbling frequency F_b increases with flow rate from $F_b \cong 0$ at a nearly zero flow rate ("static bubble") to a maximum value F_{bmax} depending on the inner diameter d of the tube orifice. For orifices from $d = 0.34$–15.8 mm and flow rates from $Q = 0.01$ ml/s to $Q = 0.25$ l/s, the maximum bubbling frequency was found to range from about $F_{bmax} = 25$ Hz for the largest orifices to about $F_{bmax} = 75$ Hz for the smallest orifices. It was also found that water container widths from 3 to 10 square inches had no effect, and that the orifice submergences from about 2.54 cm to about 25.4 cm had a negligible effect on the bubbling process. The dimensions of the tubes used in water resistance therapy as well as the airflow rates typically used in speech are within the range of the parameters studied in [22].

Based on the above-mentioned earlier findings, we first hypothesize that the lowest mechanical resonance F_m of the vocal tract can raise F_1 during vocal exercising through a tube with its outer end in air. Therefore, F_m may affect the efficacy of the exercise. Second, we hypothesize that F_m may support the effect of water bubbling in water resistance voice therapy. Consequently, either a more efficient massage-like effect or even unpleasant sensations could be perceived on the vocal tract and vocal fold tissues when the bubbling frequency F_b is close to or coincides with the lowest mechanical resonance F_m of the vocal tract.

In order to test the hypotheses, we introduce here an improved mathematical model of the human vocal tract prolonged by a hard-walled tube. In the calculations, we will take into account the acoustic-structural interaction, which can help to clarify the physical background of the influence of the soft tissues of the vocal cavities on the formant frequencies.

2. Methods

2.1. Theoretical and mathematical background of the numerical modelling

Let us consider a coupled mechanical-acoustical system consisting of vocal tract cavity 1 and tube 2 with a cross-sectional area S_2 and a length L_2 (see Fig. 1). The glottis is closed by a yielding wall that has a mass m_w and vibrates with a displacement $w(t)$ on a spring of stiffness k_w and a damper b_w. The yielding wall with a cross-sectional area S_0 may consist of the soft tissue in the larynx, for example, the whole vocal folds body vibrating predominantly in a vertical direction inside the larynx or the larynx itself. Other walls of both the vocal tract and the tube are considered to be hard.

The wave equation for air in the acoustic cavities of the vocal tract can be written as (see e.g. [23])

$$\frac{\partial^2 \varphi}{\partial x^2} + \frac{1}{S} \cdot \frac{\partial S}{\partial x} \cdot \frac{\partial \varphi}{\partial x} - \frac{1}{c_0^2} \cdot \left(\frac{\partial^2 \varphi}{\partial t^2} + c_0 \cdot r_N \cdot \frac{\partial \varphi}{\partial t} \right) = 0, \tag{1}$$

where φ is the flow velocity potential related to the acoustic pressure p and the acoustic volume velocity U as

$$p = -\rho_0 \partial\varphi/\partial t - c_0\, \rho_0\, r_N\, \varphi,\ \mathrm{U} = S\partial\varphi/\partial x, \tag{2}$$

where x is the longitudinal coordinate along the VT, t is time, c_0 is the speed of sound, ρ_0 is the air density inside the VT, and $S(x,t)$ is the cross-sectional area of the acoustic cavity at the distance x from the vocal folds.

Specific acoustic resistance r_N due to fluid dynamic viscosity μ is defined as (see [24])

$$r_N = \frac{1}{c_0\, R(x)} \sqrt{\frac{2\,\omega\,\mu}{\rho_0}}, \tag{3}$$

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