AIR-PRESSURE, VOCAL FOLDS VIBRATION AND ACOUSTIC CHARACTERISTICS OF PHONATION DURING VOCAL EXERCISING. PART 2: MEASUREMENT ON A PHYSICAL MODEL

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The contribution aims to provide material that can be used in development of more realistic physical as well as theoretical models of voice production. The experimental set-up, methodology and the results of measurement of airflow rate, subglottal, oral and generated acoustic air pressures are presented together with the simultaneously measured flow-induced vibrations of a vocal folds replica, made of soft silicon rubber, and recorded by a high speed camera. The data were measured during 'soft' phonation just above the phonation onset, given by the phonation threshold airflow rate, and during 'normal' phonation for the airflow rate of about three times higher. A model of the human vocal tract in the position for production of vowel [u:] was used, and the flow resistance was raised by phonating into a glass resonance tube either in the air or having the other end of the tube submerged under water, and by phonating into a narrow straw. The results for the pressures presented in time and frequency domain are comparable with the physiological ranges and limits measured in humans for ordinary phonation and for production of vocal exercises used in voice therapy.

Keywords: *biomechanics of voice, subglottal, oral and transglottal pressure, flow resistance*

1. Introduction

Phonation under higher than normal supraglottic impedance is used in voice training and therapy (see e.g. [3, 5, 6]). This contribution compares in vitro measurements of phonation on [u:], phonation into a resonance tube and into a narrow straw for a 'normal' phonation and a 'soft' phonation at the phonation onset. The flow resistance of the vocal tract was furthermore increased by phonation through the tube into water making the phonation more difficult due to loading the human phonation system by the hydrodynamic pressure and bubbling. Corresponding in vivo measurements are presented in [4] as Part 1.

2. Measurement set-up and procedure

A schema of the measurement set-up is shown in Fig. 1. The measurements were carried out with silicon vocal folds replicas and with a simplified plexiglass vocal tract model for which the area cross-sections along its length corresponded to a male vocal tract during phonation on vowel [u:] (see [1]). The trachea was modeled by a Plexiglas tube (length

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23 cm and inner diameter 25.5 mm). The vocal tract was prolonged by a glass resonance tube (27 cm in length, inner diameter of 6.8 mm), by this tube having the other end submerged down to 10 cm below the water surface or by a plastic stirring straw (12.7 cm in length, inner diameter 2.5 mm). The first set of measurements was performed for a 'normal' sustained phonation at a fixed airflow rate $Q = 0.45\,\mathrm{l/s}$, and the second set at the phonation threshold defined by the airflow rate measured at a time instant when the flow was slowly gradually decreased until the phonation with measurable acoustic pressure oscillations ended. Then the flow rate was fixed, and the high speed camera, synchronized with the signal of the subglottal pressure was started. The sound pressure level (*SPL*) inside the model of oral cavity was measured using a special microphone probe, and the mean oral pressure (P_{oral}) was measured by a digital manometer connected with the oral cavity by a short compliant tube. Generated acoustic signal outside the vocal tract model was recorded using a microphone installed at a distance of 20 cm from the lips. The recordings were made using 32.8 kHz sampling frequency by the PC controlled measurement system B&K and synchronized with the high speed camera. The mean (P_{sub}) and peak-to-peak subglottal pressures were measured by special dynamic semiconductor pressure transducers. The fundamental vibration frequencies F_0 of the vocal folds and the formant frequencies (acoustic resonances of the vocal tract) were evaluated from the spectra of the pressure signals.

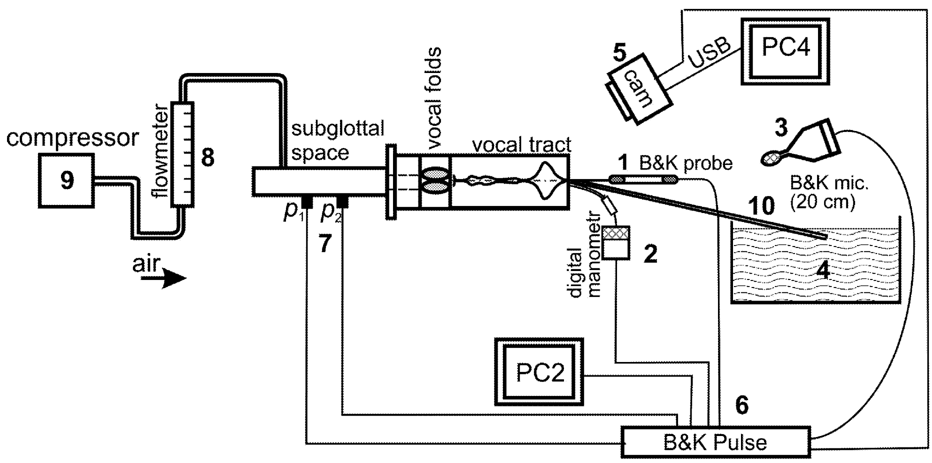


Fig.1: Schema of the in vitro measurement set-up: 1 – B&K microphone probe 4182, 2 – digital manometer Gresinger Electronic GDH07AN, 3 – sound level meter B&K 2239, 4 – aquarium, 5 – high speed camera, 6 – B&K measurement system PULSE 10 with Controller Module MPE 7537 A, 7 – semiconductor pressure transducers, 8 – float flow meter, 9 – air compressor, 10 – resonance tube

3. Results

Figure 2 shows the spectra of the oral pressure for all studied cases of the 'soft' phonation. Only the first resonance frequencies changed substantially: from 16 Hz for bubbling in case of the tube in water (see the detailed spectrum in Fig. 2c) to about 80 Hz for straw (see Fig. 2d) and up to about 100 Hz for phonation into the tube in air (see Fig. 2b). The first resonance frequency at about 260 Hz can be identified in the spectrum in Fig. 2a for phonation on [u:]. The higher resonances at about 650 Hz, 1400–1450 Hz, 2300 Hz, 3950–4050 Hz and 4800–4850 Hz are nearly identical for all cases studied. Thus these higher resonances are probably associated with resonances of all the joint acoustic cavities beginning from the model of the subglottal spaces to the open space at the end. It is caused by the fact that for all of the phonations there was no complete closure between the vocal folds and, consequently, the subglottal and supraglottal acoustic spaces were joined during phonation.

Figure 3 shows the synchronously measured subglottal pressure, glottal gap-width (glottis opening), transglottal pressure ($P_{\rm trans} = P_{\rm sub} - P_{\rm oral}$) and oral pressure for a 'soft' phonation into the resonance tube in air, into the tube submerged 10 cm into water and into the narrow straw. The oral pressure has a large phase shift compared to the subglottal pressure while the transglottal pressure has only some small phase shift. The maximum of the glottis opening is delayed after the maximum of the transglottal pressure. A substantial difference between phonation into the tube in air and into the straw was that the mean value of the transglottal pressure was much lower for the straw. However, the peak-to-peak variation of the transglottal pressure of about 300 Pa as well as the peak-to-peak values for the glottis opening were practically the same in both cases. As mentioned above, there was

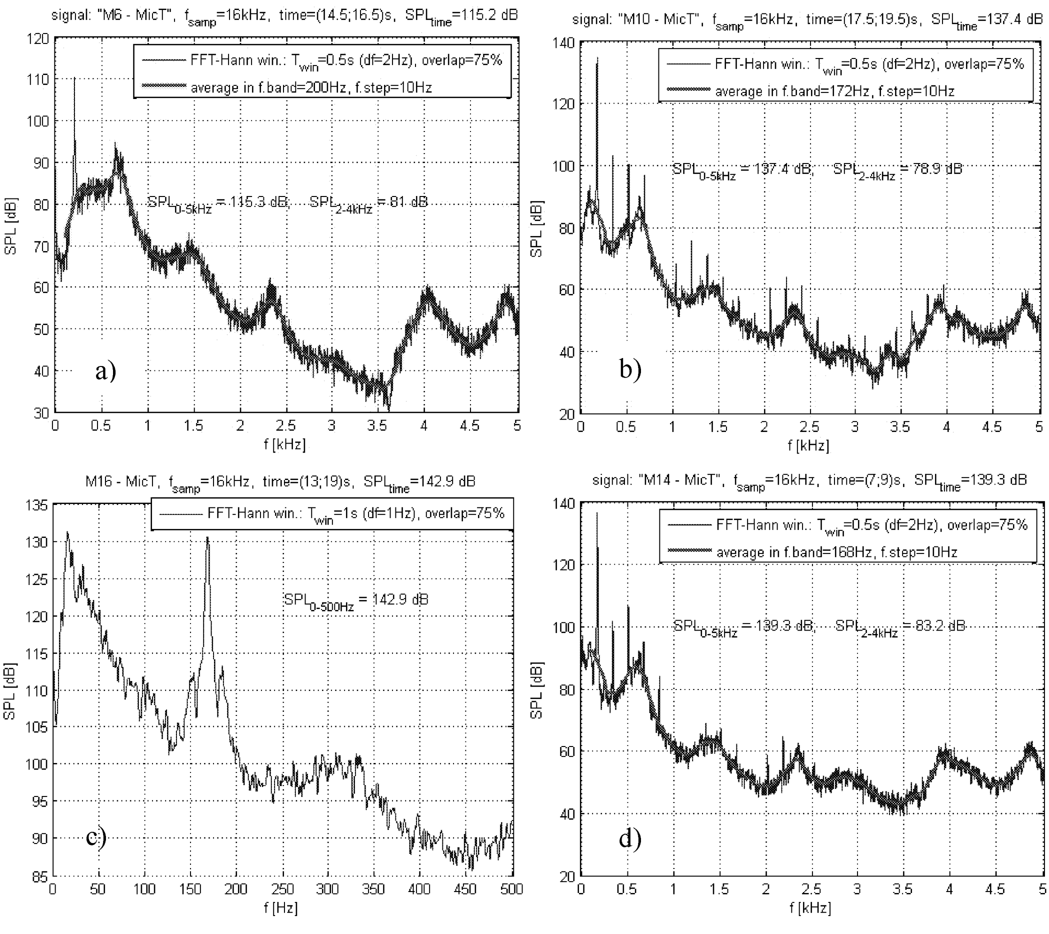


Fig.2: Measured spectra and SPL values of the oral pressure for 'soft' phonation: a) on [u:], b) in tube in air, c) in tube with other end submerged 10 cm deep in water and d) in the straw

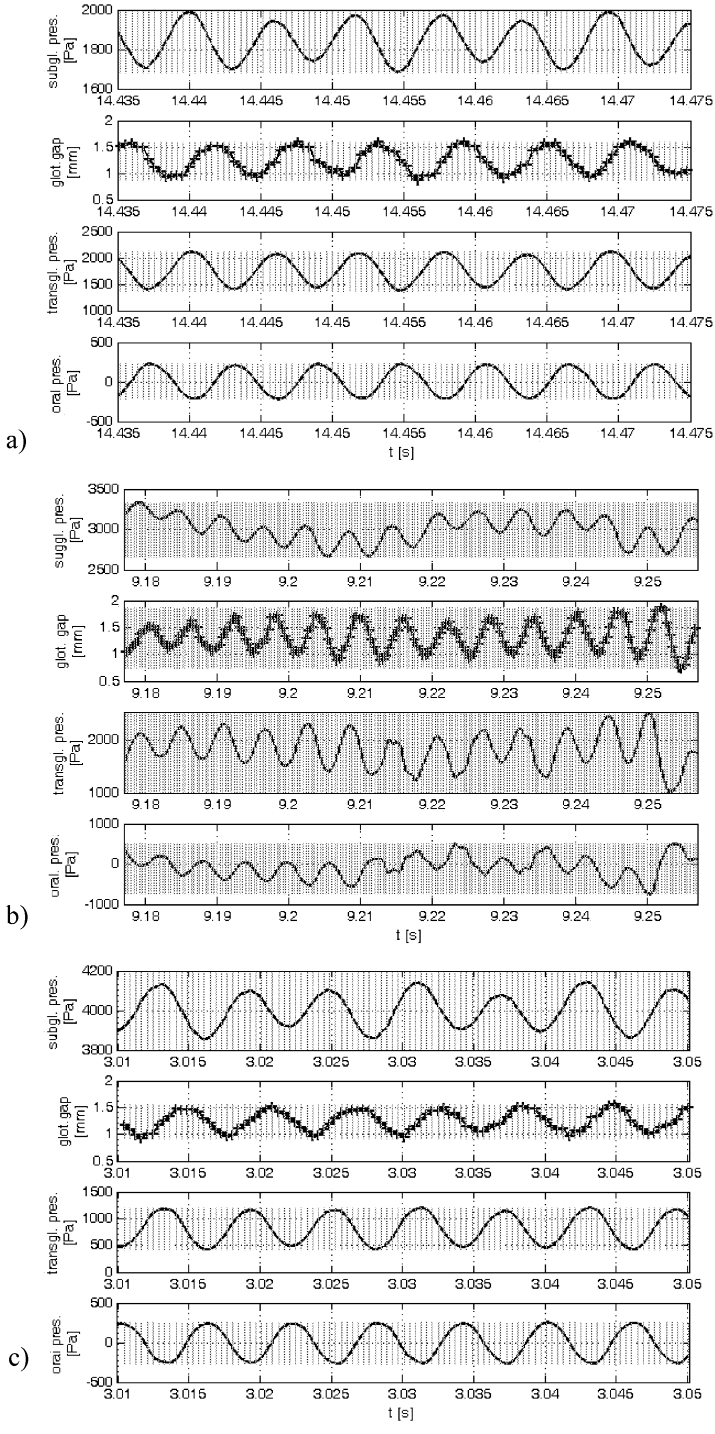


Fig.3: Measured signals for subglottal pressure (first panels), glottis opening measured at the midpoint of the glottis (second panels), transglottal (third panels) and oral pressures (lower panels) for a 'soft' phonation into: a) the tube, b) the tube 10 cm in water and c) the straw ($F_0 = 168{-}172$ Hz, $Q = 0.12$ l/s)

no complete glottis closure and therefore the vocal folds vibrations were in all studied cases without collisions.

The transglottal pressure for the tube phonation into water is considerably influenced by bubbling. The most important part of the acoustic energy inside the oral cavity is associated with a bubbling effect at about the frequency $F_\mathrm{b} = 16\,\mathrm{Hz}$, where the resonance peak in amplitude is even higher than for the fundamental frequency $F_0 = 168\,\mathrm{Hz}$ (recall Fig. 2c). The effect of bubbling on all signals in time domain can clearly be seen in Fig. 3b, where the higher fundamental frequency is superimposed on the low frequency oscillations caused by bubbling. Consequently the bubbling has an important influence on the vocal fold tissue if this technique is used in the voice therapy.

Figures 4–6 summarize the main results. The column graphs for the 'soft' and 'normal' phonations are ordered according to the increasing values of the measured flow resistance, i.e. for phonations on: vowel [u:], tube in air, tube in water and straw.

Figure 4a shows the flow rates obtained as results for a 'soft' phonation at the phonation onset, given by the so-called phonation threshold flow rate (Q_PT), and for the prescribed

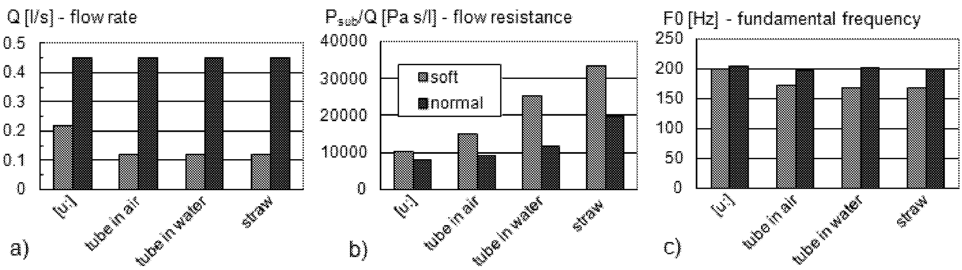


Fig.4: Flow rate, flow resistance and fundamental frequency for 'soft' and 'normal' phonation on vowel [u:], into the tube in air, into the tube 10 cm in water and into the straw

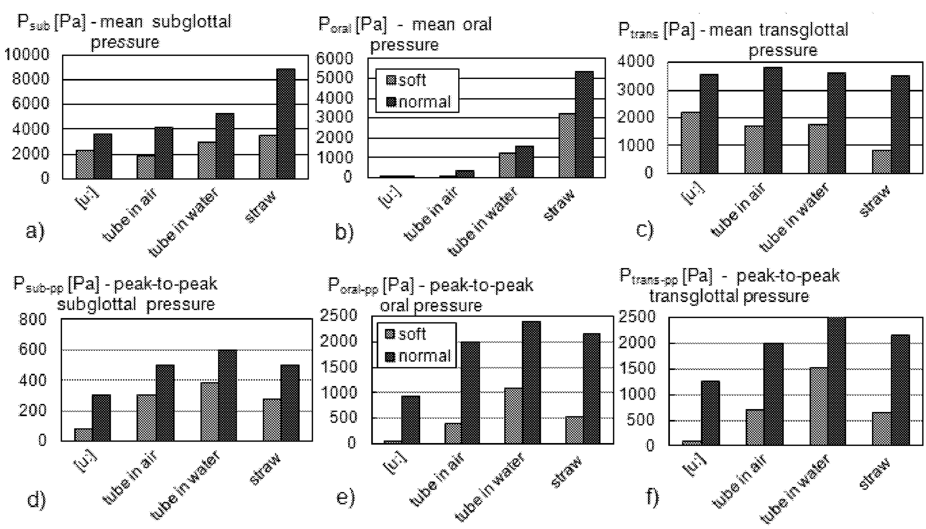
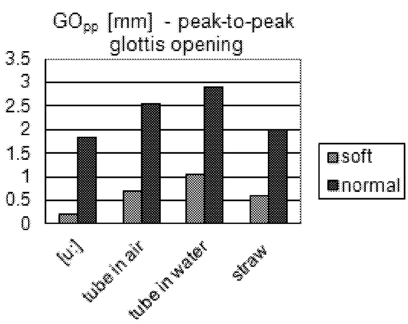


Fig. 5: Mean and peak-to-peak values of the subglottal, oral and transglottal pressures for 'soft' and 'normal' phonation on vowel [u:], into the tube in air, into the tube 10 cm in water and into the straw

constant flow rate $Q = 0.45$ l/s for the 'normal' phonation. The higher $Q_{\mathrm{PT}} = 0.22$ l/s was found only for vowel [u:], and in all other cases measured for 'soft' phonation the phonation threshold flow rate was found to be lower: $Q_{\mathrm{PT}} = 0.12$ l/s. The measured flow resistance defined by the ratio of the mean subglottal pressure and the mean flow rate (P_{sub}/Q) increased from the case of phonation on vowel [u:] up to a maximum for the straw (see Fig. 4b) for both the 'soft' and 'normal' phonation. The fundamental frequency of phonation was nearly constant ($F_0 \approx 200$ Hz) for all 'normal' phonations as well as for the 'soft' phonation on vowel [u:], but less ($F_0 \approx 170$ Hz) for the 'soft' phonations into the tube and straw (see Fig. 4c).

Figure 5 shows the mean and peak-to-peak values of the subglottal, oral and transglottal pressures. Mean values of the subglottal and oral pressures increased approximately in accordance with the measured flow resistance being the lowest for [u:] and the highest for straw. However, the mean transglottal pressure for 'soft' phonation has an opposite tendency and is nearly a constant for 'normal' phonation. Peak-to-peak values of all three pressures (subglottal, oral and transglottal) had very similar trends, being the highest for phonation into tube submerged 10 cm down into water, and having the lowest values for phonation on vowel [u:].

Figure 6 shows the measured peak-to-peak vibration amplitudes (GO_{pp}) of the vocal folds vibration together with the example of the vibrating vocal folds. The tendencies in changes of GO_{pp} for the 'soft' and 'normal' phonations are similar, and a good correlation between the glottal opening (GO_{pp}) and the transglottal pressure variation (see $P_{\text{trans-pp}}$ in Fig. 5) is evident for the 'normal' and 'soft' phonations, with the values of GO_{pp} and $P_{\text{trans-pp}}$ being the lowest for vowel [u:] and the highest for phonation into the tube submerged in water. Only one exception was found for the 'normal' phonation when GO_{pp} for the tube in air was higher than for the straw, while for the transglottal pressure variation ($P_{\text{trans-pp}}$) it was the opposite.



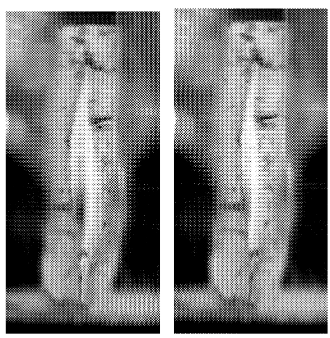


Fig.6: Measured peak to peak glottis opening for 'soft' and 'normal' phonation on vowel [u:], into the tube in air, into the tube 10 cm in water and into the straw (left); the images of vibrating vocal folds at the phases of maximum and minimum glottis opening during phonation into the tube (right)

4. Discussion and conclusions

The flow resistance increases with the tube and straw compared to vowel in 'normal' and 'soft' phonation, as expected, being higher for tube in air and even more for tube in water, and the highest for straw. A similar tendency was found for the pressures P_{oral} and P_{sub}, especially for 'normal' phonation. The opposite results were obtained for the transglottal pressure in 'soft' phonation. In 'normal' phonation it stayed nearly a constant in all cases. The time variation amplitude of the subglottal pressure was comparable in both types of phonation : the smallest for [u:] and the highest for tube phonation into water. The same tendency was found for peak-to-peak variations of the transglottal pressure and of the maximum glottal width. The *SPL* values in the oral cavity were substantially higher in all cases of the prolonged vocal tract compared to vowel [u:]. In phonation into water a considerably high acoustic energy was generated by bubbling, whose dominant frequency varied between 16–19 Hz in 'soft' phonation and increased up to about 40 Hz in 'normal' phonation. The increased oral *SPL* and pressure fluctuations may be important in bringing along a massage effect on the vocal folds in humans during phonating into a tube or a straw, especially when the outer end is in water.

The vibration amplitudes of the vocal folds perfectly correlate with the peak-to-peak transglottal pressure variation. The results for 'soft' phonation show that the phonation onset is given by the airflow rate which was found to be identical for tube, tube in water and straw even if the mean values of the subglottal, oral and transglottal pressures varied considerably. It confirms the theoretical conclusions found in [2] that the primary controlling mechanism for phonation onset is given by a critical mass flow rate when the vocal folds start to vibrate due to the aeroelastic instability of the system by flutter. Only exception was found for vowel [u:] where the flutter frequency (F_0) was higher than for all other cases studied, that according to the theory resulted in a higher airflow rate needed for the loss of the system stability.

The results of the *in vitro* measurements partially confirmed an influence of changing the acoustic impedance of the vocal tract by its prolongation on the phonation threshold pressure (PTP) given by the subglottal pressure as it was observed in humans [3–6]. PTP was found lower for tube in air in soft phonation compared to [u:]. A good correlation between the results of this paper and the parallel *in vivo* measurements [4] was obtained only for changes of the mean subglottal pressure and the peak-to peak values of the oral pressure for normal phonation. The other parameters showed more discrepancies. The reason could be that in contrary to the model, the human phonation system can interactively react to the acoustic impedance changes, for example, by changing the geometry and volume of the supraglottal acoustic spaces and/or the fundamental phonation frequency related to the lowest formant frequency. The results also show that the effect of a considerable increase in the flow resistance can be more dominant than the effect of acoustic impedance, especially in cases of phonation into a very narrow straw or into a tube with the other end submerged in water. This would require either changes in respiratory and/or adductory muscles to maintain phonation.

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