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EXPERIMENTAL INVESTIGATION OF AIR PRESSURE AND ACOUSTIC CHARACTERISTICS OF HUMAN VOICE. PART 1: MEASUREMENT *IN VIVO*

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Abstract: *This contribution is aimed to provide material that can be used to develop more realistic physical models of voice production. The experimental methodology and the results of measurement of subglottal, oral (substitute for subglottic) and acoustic air pressure (captured at a distance of 20 cm in front of the subject's mouth) are presented. The data were measured during ordinary speech production and when the acoustic impedance and mean supraglottal resistance were raised by phonating into differently sized tubes in the air and having the other end submerged under water. The results presented in time and frequency domain show the physiological ranges and limits of the measured pressures in humans for normal and extreme phonation.*

Keywords: ***Biomechanics of voice, measurement of oral pressure, voice exercises, phonation into tubes.***

1. Introduction

This pilot study is a beginning of the experimental investigation of human voice source substitute by complex physical models of phonation. The modelling follows the previous measurements of vocal folds vibration and acoustic, flow and pressure characteristics of human voice production on simplified models of human voice production carried out on a special test facility in the dynamics laboratory of the Institute of Thermomechanics (see Horáček et al. 2011). The main purpose of the present contribution is to present the methodology tests of experimental techniques and laboratory equipment used for *in vivo* measurement and to obtain real physiological data for normal and some extreme ways of human phonation. A similar study performed afterwards on the test rig will enable a comparison of the results obtained *in vivo* and *in vitro* measurements. This comparison will follow in a later article. For simulation of extreme phonation situations the acoustic impedance of human vocal tract was artificially increased by prolonging of the vocal tract with different tubes or straws and by phonation into water, which makes the phonation more difficult due to loading the human phonatory system by additional hydrodynamic pressure.

Straws and tubes are widely used in vocal exercising and voice therapy (see, e.g. Laukkanen et al. 2012). In Scandinavia a resonance tube method has been used. For a description of the method in more detail, see e.g. Simberg and Laine (2007). Research results have been obtained showing that phonation into a tube may improve laryngeal setting towards a more economic and efficient voice production (Laukkanen et al. 1998, Laukkanen et al. 2008) and that the vocal tract setting may be changed improving sound energy transfer from the vocal tract and thus increasing sound pressure level and loudness. In the studies phonation into air has been used. The present study compares phonation in a resonance tube with the other end in air with that when the outer end is submerged into water and with phonation into a straw. It is of particular interest how much air pressure is needed in phonation and what happens to the voice quality during phonation into a tube or straw.

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2. Material and methods

One female voice trainer, phonated first in a normal way (in speech mode) on [pa:pa], [pi:pi], [pu:pu] at comfortable pitch and loudness, and then into several plastic straws and a resonance tube in the air and with the other end submerged from 2 cm down to 25 cm below water surface into a big aquarium – see the measurement schema in Fig. 1.

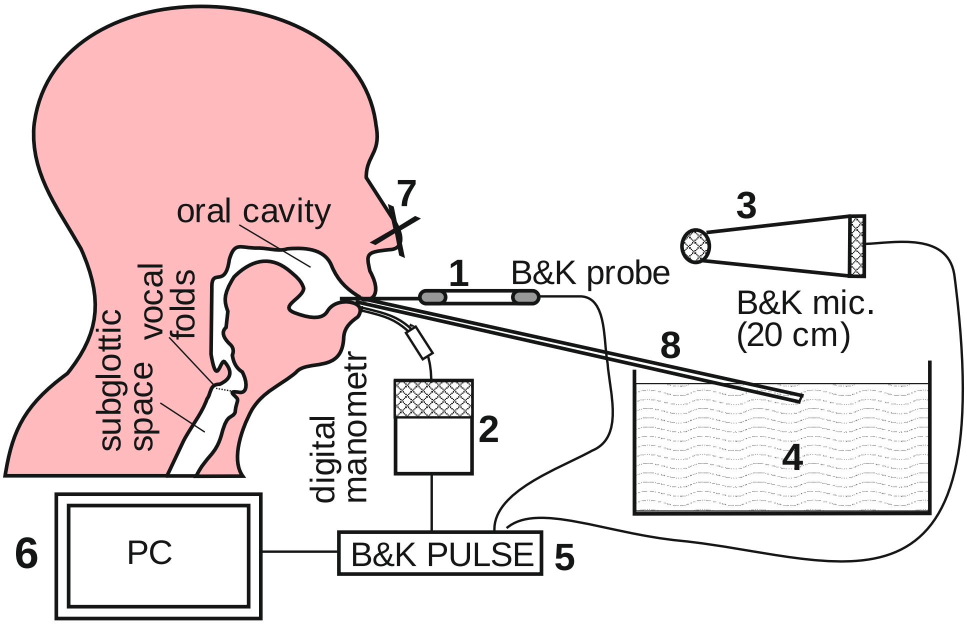

Fig. 1 – Schema of the measurement set up: 1 - B&K microphone probe 4182, 2 – digital manometer Greisinger Electronic GDH07AN, 3 – sound level meter B&K 2239, 4 – aquarium, 5 – B&K measurement system PULSE 10 with Controller Module MPE 7537 A, 6 – personal computer, 7 – clip, 8 – impedance tube.

Tab. 1 – Types of tubes used for increasing of acoustic impedance of the vocal tract.

impedance tube	L – length [mm]	d – inner diameter [mm]
narrow plastic stirring straw	127	2.5
resonance glass tube	264	6.8
drinking straw	150	5.8
long plastic tube	990	4.5

Air pressure was measured intraorally using the B&K special microphone probe type 4182 designed for measurement of acoustic pressure in small cavities in the frequency range between 1 Hz and 20 kHz, and the digital manometer Greisinger Electronic GDH 07AN, the pressure sensor part of which was connected with the oral cavity by a small compliant plastic tube of about 8 cm length and inner diameter of about 1.5 mm. The tubes and straws used are summarized in Table 1. The subject was keeping the lips firmly sealed around the tube or straw and the two probes at the corner of the mouth to measure oral pressure. Pressure during the production of voiceless plosive [p] and manual shuttering of the other end of the tube gave an estimate of subglottic pressure. The nose was closed with a clip to prevent any leakage of air through the nose. A similar approach of measurement technique was used by Titze (2009) for measurement of phonation threshold pressure in occluded vocal tract.

Acoustic signal was recorded using B&K sound level meter type 2239 with the microphone at a distance of 20 cm from the subject’s mouth. The recording was made using 32.8 kHz sampling frequency, and 16-bit amplitude accuracy. The measured signals were joint to the PC controlled B&K

measurement system PULSE 10 with the controller module MPE 7537A. Each phonation trial was recorded for 20 s and afterwards the data were transferred in the WAV and ASCI formats and under sampled to 16 kHz for evaluation of the measured signals in the time and frequency domains by using the Matlab. The subglottal pressure p_{sub}, the mean air pressure p_{av}, the mean root square pressure p_{rms} inside and outside the vocal tract, the pressure spectra, the spectrograms, the fundamental voice frequencies F0 and the formant frequencies F1-F5 were analyzed for each trial from the time records of the pressure signals.

Acoustic analysis was done in Matlab by averaging the frequency spectra calculated by FFT using 1s time windows with 75% overlap (see thin lines in Figures 2-12). Then the resulting spectra were averaged in the frequency bands (windows) equal to the fundamental frequency F0 with overlap of F0-10 Hz. Thus the new curves of "filtered spectra" were obtained (see thick lines in Figures 2-12) and the maxima of these curves were considered as formants.

3. Results

The subglottal pressure was measured using the effect of the vocal tract occlusion by production of the consonant [p] during an ordinary phonation on [pa:pa], [pi:pi], [pu:pu] or by manually repeated shuttering of the outer end of the tube during sustained phonation into it. The subglottal pressure was read from the time signal just when the outer end of the tube was closed and the vocal folds were opened and not vibrating, and consequently when the air pressure in the oral cavity was equal to the pressure in lungs. This occlusion or shuttering was repeated several times during each trial that was 20 s long in total.

The measured results are summarized in Tables 2-6 and in Figures 2-12.

Tab. 2 – Acoustic characteristics for ordinary phonation with occluded vocal tract – pressures and frequencies.

ordinary phonation	**subglot.** p_{sub} [Pa]	**oral** p_{av} [Pa]	**outside** p_{rms} [Pa]	**fund.freq.** F0 [Hz]	**resonances – formants** F1 [Hz]	F2 [Hz]	F3 [Hz]	F4 [Hz]	F5 [Hz]
[pa:pa]	1000	0	0.064	164	<u>780</u>	<u>1210</u>	<u>2840</u>	<u>3630</u>	<u>4250</u>
[pi:pi]	710	0	0.065	172	<u>330</u>	2470	3730	/	/
[pu:pu]	800	15	0.077	170	<u>350</u>	660	<u>2850</u>	<u>3720</u>	<u>4250</u>

The results for phonation on [pa:pa], [pi:pi], [pu:pu] without using any impedance tube are summarized in Table 2 for the measured pressures and frequencies and the results for phonation [pu:pu] are shown in Fig. 2. The estimated subglottal pressure p_{sub} was, in general, considered as the pressure maximum achieved during the whole trial, e.g. $p_{sub} \approx 800$ Pa at the time instant t=2.5 s when the spectrogram of the oral pressure signal clearly shows no vocal folds vibration during production of the voiceless consonant [p] – see Fig. 2. A decrease of the subglottal pressure at the beginning of each occlusion event (e.g. at time t=2 s) was possible to detect in nearly all trials. A reason of it can be a physiological reaction of the subject on a sharp closure of the oral cavity. Mean oral pressure p_{av} during phonation of the vowel [u:] is possible to evaluate from the time signal when the vocal folds are vibrating and the vocal tract is opened at the lips (see e.g. the time interval at about t=6 s where the mean oral pressure was about 15 Pa due to the radiation losses. It is possible to detect the fundamental frequency F0=170 Hz and the higher harmonics (partials) in the spectrogram during phonation on [u:] as well as in the spectrum of the acoustic pressure measured during the whole trial outside the vocal tract. The formant frequencies F1-F5 were evaluated from the spectrum using especially developed program in Matlab. Clearly detectable formant frequencies are underlined in the Tables 2-6. The data for each trial were evaluated from the time records in the same manner. Maximum subglottal pressures measured for ordinary phonation with occluded vocal tract were found between 710 and 1000 Pa. Mean oral pressure was found to be around zero for phonation on [a:] and [i:] because of a larger mouth opening than for the vowel [u:]. The fundamental frequency varied between 164 and 172 Hz. The lowest formant frequencies, in general, correspond to the formants found in humans (Baken & Orlikoff, 2000). It can be noted that according to Hirano (1981) the mean subglottal pressure for normal vowel phonation is in the range of 400-2600 Pa, and up to maximum 5 kPa in extremes.

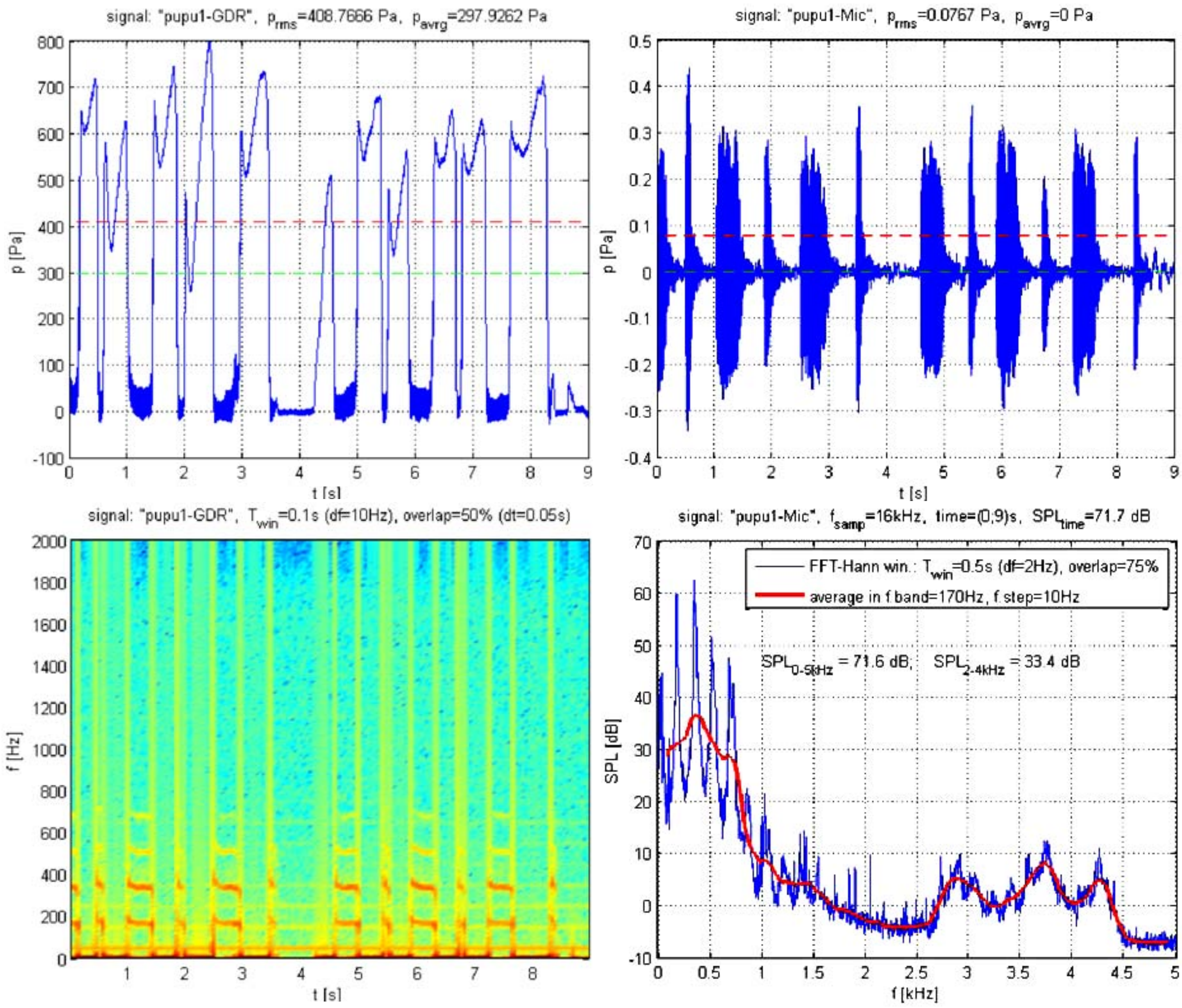

Fig. 2 – Measurement of the phonation [pu:pu]: 1) the oral pressure and its spectrogram (left), 2) the sound signal 20 cm in front of the lips and its spectrum (right).

Tab. 3 – Acoustic characteristics for phonation into the drinking straw – pressures and frequencies.

phonation	**subgl.**	**oral**	**outside**	**fun.fr.**	**resonances – formants**					
drinking straw into	p_{sub} [Pa]	p_{av}/p_{rms} [Pa]	p_{rms} [Pa]	F0 [Hz]	f_b^* [Hz]	F1 [Hz]	F2 [Hz]	F3 [Hz]	F4 [Hz]	F5 [Hz]
air	1200	38/132	0.055	168	/	170	1080	1480	2600	3750
H_2O (2cm)	950	317/-	0.076	150	10-25*	220	360	670	1030	1400
H_2O (5cm)	1250	532/-	0.080	152	15-25*	220	320	600	1040	1440

*frequency interval of bubbling

The results of phonation into a drinking straw for the measured pressures and frequencies are summarized in Table 3 and shown in Figs. 3-5, corresponding to the three ways of phonation: into air and water in the depth of about 2 cm and 5 cm below the water surface. All measured time records and spectrograms for the shuttered phonation are similar like in the previous case for an ordinary phonation, the maximum of the subglottal pressure p_{sub} was achieved at the time instants when no vocal folds oscillation was possible to detect in the spectrograms of the oral pressure, see e.g. a short time interval at about t=9 s in Fig. 3 when a maximum p_{sub}=1200 Pa was achieved, and on the other hand a short time interval just before time t=8 s when the subglottal pressure was much lower ($p_{sub} \approx 650$ Pa) because the vocal folds were vibrating and interrupting the airway that joins the subglottal and supraglottal spaces. Substantial increase in the mean oral pressure p_{av} is related to the hydrodynamic pressure in addition to the pressure looses in the tube itself, see p_{av}=38 Pa in Table 3 for phonation into air. The higher harmonics and formants are clearly visible in Fig. 3 in the spectrum of the oral pressure measured by the B&K microphone probe, and the pressure $p_{rms} \approx 132$ Pa was possible to evaluate in the oral cavity for phonation into air.

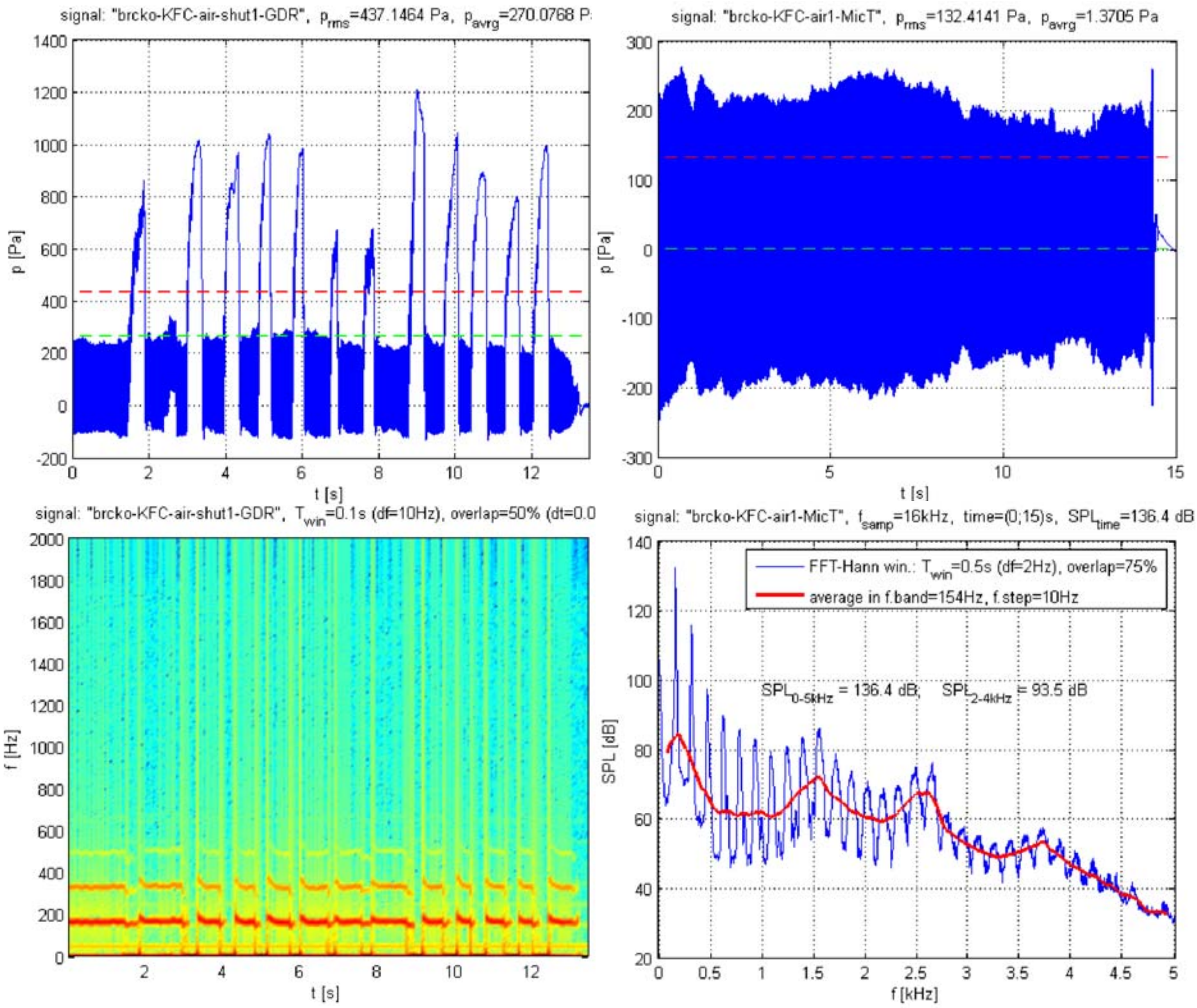

Fig. 3 Measurement of the phonation into drinking straw: 1) oral pressure and its spectrogram (left), 2) sound signal in the mouth and its spectrum (right).

For phonation into water, the frequencies corresponding to water bubbling were detected in the spectra in the lowest frequency region between about 10 Hz and 25 Hz, see Fig. 4 where these frequencies can be identified clearly in the oral pressure signal. It is interesting to note that the subglottal pressure did practically not increased for phonation into water and only slightly compared to the value for normal phonation in Table 2. It might be caused by an air leakage between the straw or two pressure probes and the lips. The fundamental frequency for phonation into water decreased while the mean oral pressure substantially increased and the pressure p_{rms} outside the vocal tract was comparable in all cases to the ordinary phonation with the occluded vocal tract. We can note that the effects of phonation into this type of a drinking straw on the vocal tract setting were studied by Laukkanen et al. (2012) using magnetic resonance imaging technique.

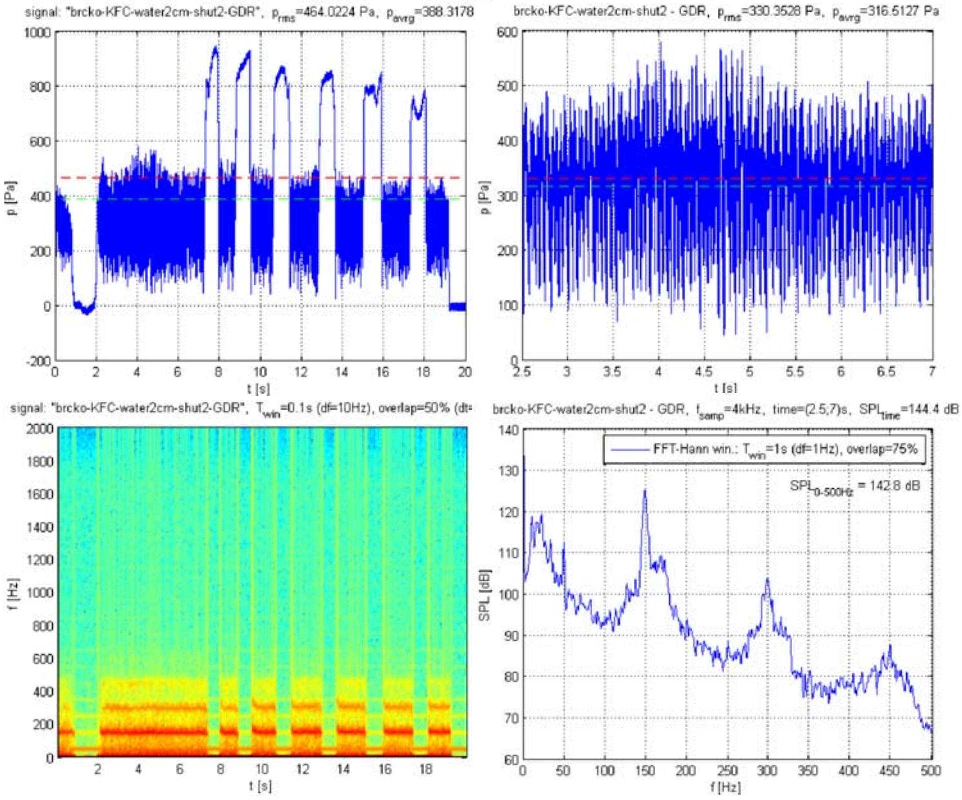

Fig. 4 Measurement of the phonation into a drinking straw submerged 2 cm under water: 1) oral pressure and its spectrogram (left), 2) sound signal in the mouth and its detailed spectrum showing effect of water bubbling in the low frequency range (right).

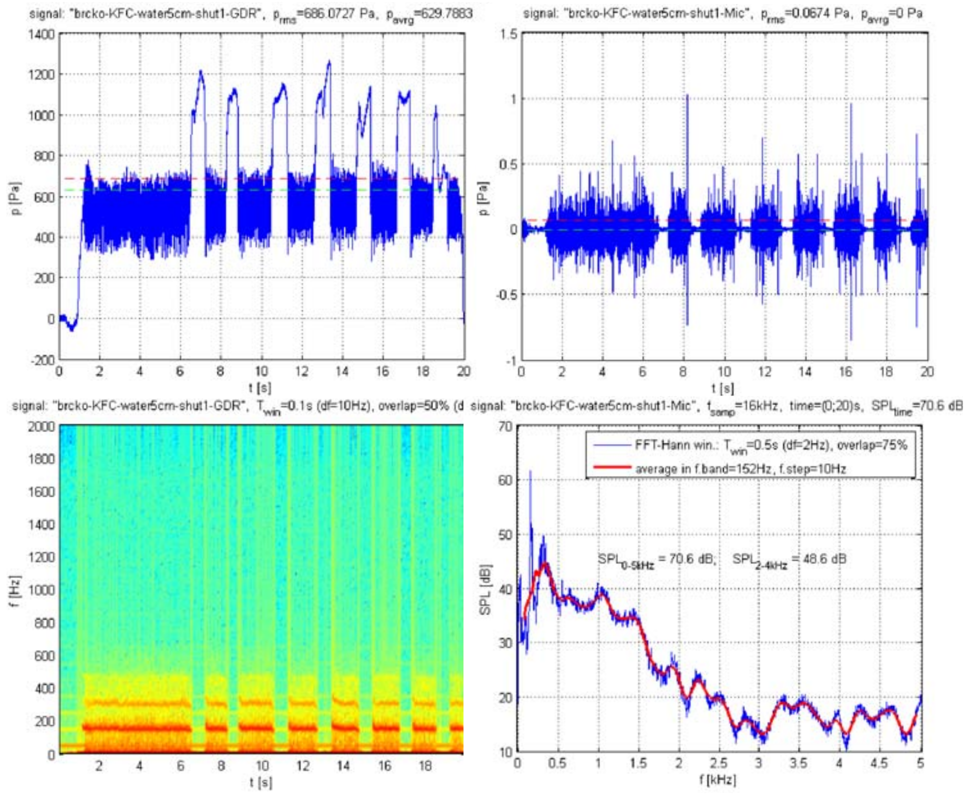

Fig. 5 Measurement of the phonation into a drinking straw submerged 5 cm under water: 1) oral pressure and its spectrogram (left), 2) sound signal 20 cm in front of the lips and its spectrum (right).

The results measured for phonation into the narrow plastic stirring straw are summarized in Table 4 and presented in Figs. 6 and 7 for phonation into air and into water. The subglottal pressure was substantially higher than for both the ordinary phonation and the drinking straw phonation and similarly, the mean oral pressure was higher. The fundamental phonation frequency decreased by phonation into water in a similar way like for the drinking straw. For phonation into air the lowest resonances F2=1700 Hz and F3=2700 Hz are clearly detected in the oral pressure signal measured by the B&K probe. We can note that the effects of phonation into similar stirring straws on the vocal tract setting were studied by Titze et al (2002), Laukkanen et al. (2008) and Titze (2009).

Tab. 4 – Acoustic characteristics for phonation into the narrow plastic stirring straw – pressures and frequencies.

phonation	**subgl.**	**oral**	**outside**	**fun.fr.**	**resonances – formants**					
stirring straw into	p_{sub} [Pa]	p_{av} [Pa]	p_{rms} [Pa]	F0 [Hz]	f_b* [Hz]	F1 [Hz]	F2 [Hz]	F3 [Hz]	F4 [Hz]	F5 [Hz]
air	1430	571	0.020	166	/	115	1730	2640	3830	4140
H_2O (2cm)	1400-1650	700-850	0.036	150	5-30*	440	850	1070	1450	1900

*frequency interval of bubbling

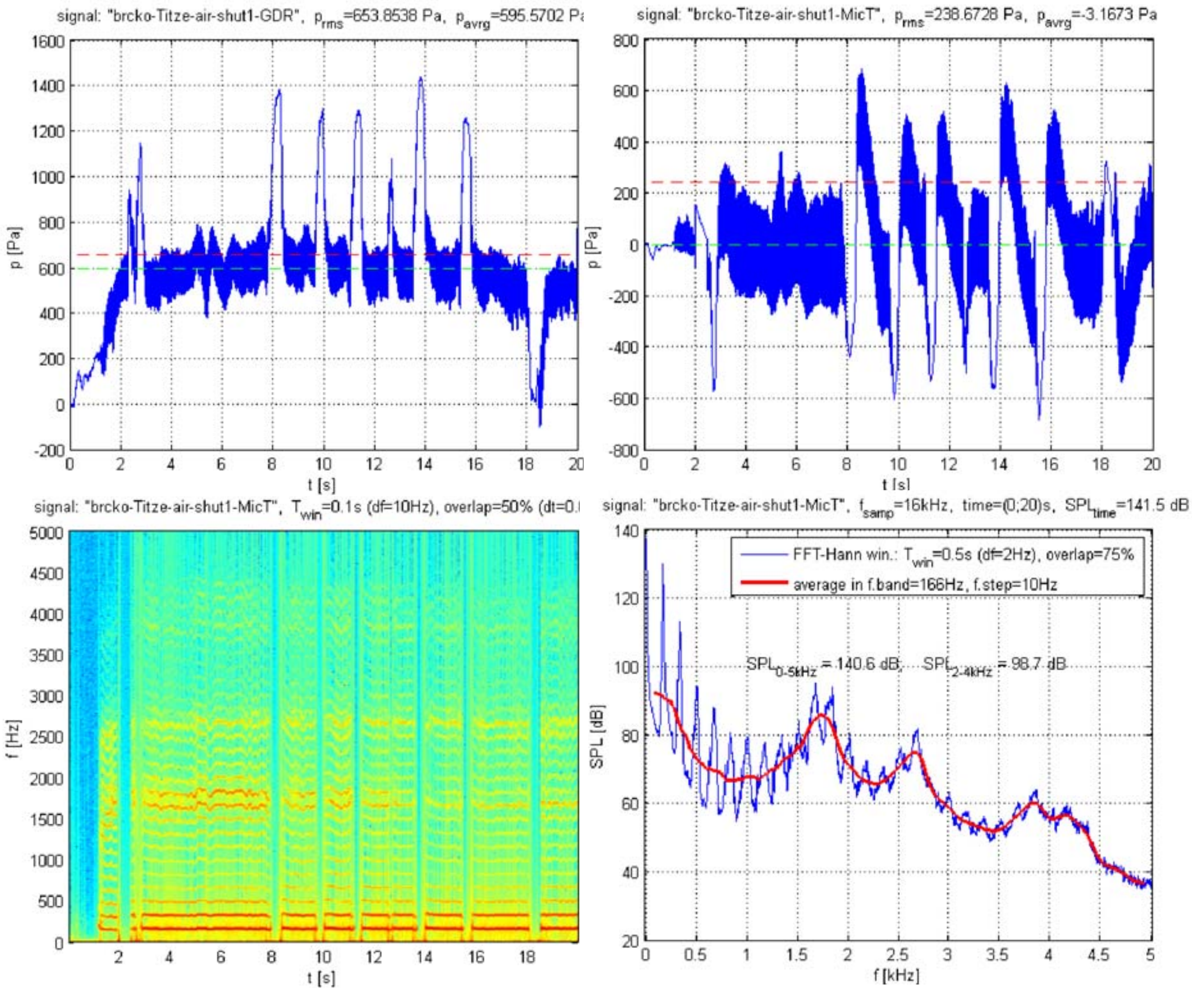

Fig. 6 Measurement of the phonation into the narrow plastic stirring straw: 1) oral pressure and its spectrogram (left), 2) sound signal in the mouth and its spectrum (right).

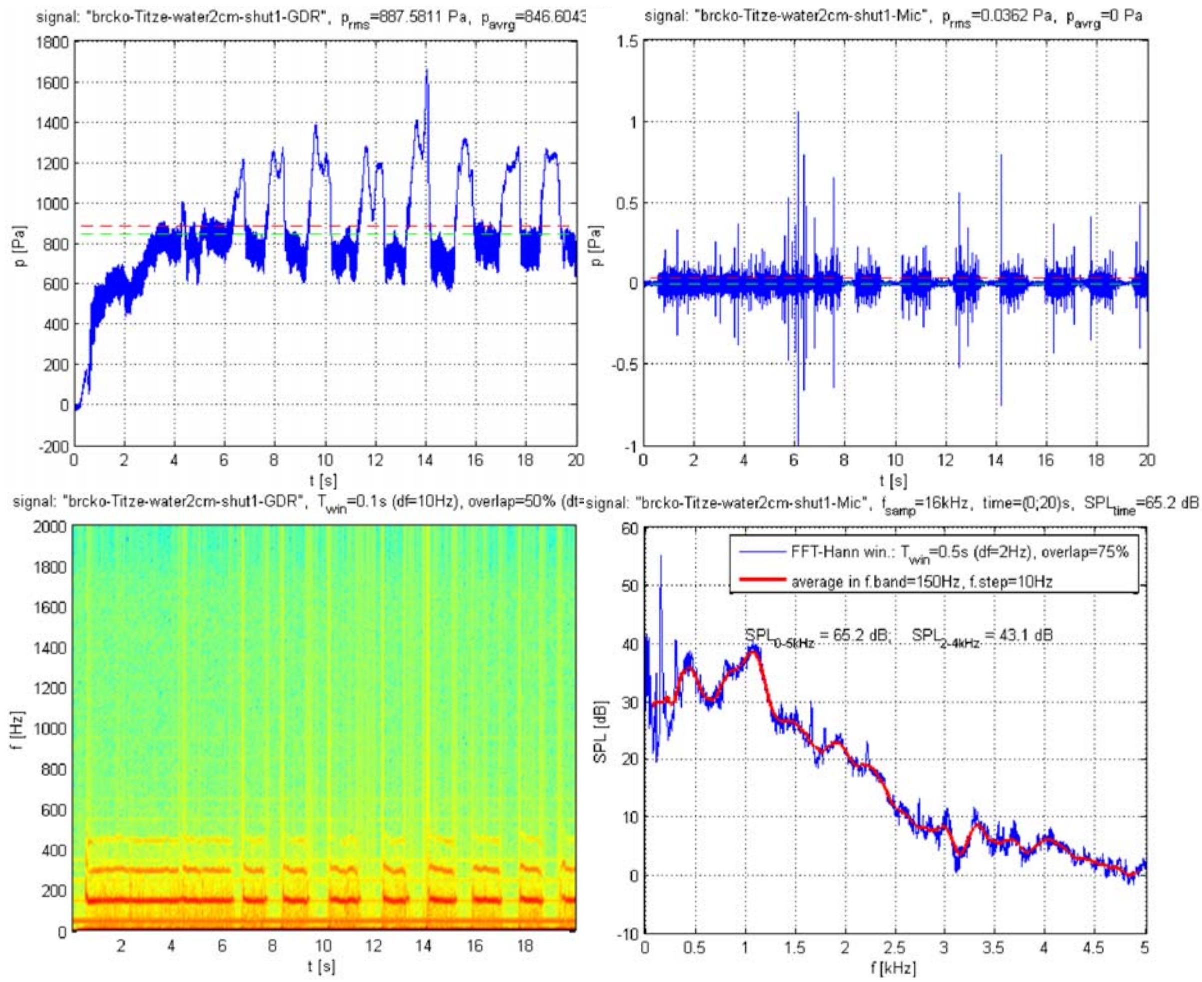

Fig. 7 Measurement of the phonation into the narrow plastic stirring straw submerged 2 cm under water: 1) oral pressure and its spectrogram (left), 2) sound signal 20 cm in front of the lips and its spectrum (right).

Tab. 5 – Acoustic characteristics for phonation into the glass tube (so called resonance tube) – pressures and frequencies.

phonation	**subgl.**	**oral**	**outside**	**fun.fr.**		**resonances – formants**				
glass tube	p_{sub}	p_{av}/p_{rms}	p_{rms}	F0	f_b^*	F1	F2	F3	F4	F5
into	[Pa]	[Pa]	[Pa]	[Hz]	[Hz]	[Hz]	[Hz]	[Hz]	[Hz]	[Hz]
air	900	52/34	0.077	146	/	620	1300	1910	2520	3180
H_2O (2cm)	1150	251/107	0.115	156	18*	680	1100	1450	2540	
H_2O (10cm)	1700	1068/-	0.092	152	15*	430	600	1100	1500	
H_2O (15cm)	2450	1605/117	0.074	158	15*	450	1000	1500	1900	2200

*frequency of bubbling

The measurements for phonation into the resonance glass tube are presented in Table 5 and in Figs. 8-11. The subglottal pressure for phonation into air was comparable with the phonation [pu:pu] and lower than for phonation into the drinking straw as well as for the stirring straw. The mean oral pressure given by the tube impedance was comparable with phonation [pu:pu] and into the drinking tube, and substantially lower than for the stirring straw. The fundamental frequency was considerably lower than for the ordinary phonation with the occluded vocal tract and increased for phonation into water. The subglottal pressure as well as the mean oral pressure p_{av} increased with the water depth due to the hydrodynamic pressure. The root mean square oral pressure p_{rms} also increased considerably by phonation into the water, nearly four times compared to phonation into air, i.e. from about 123.8 dB in air up to 135.3 dB for the water depth 15 cm. We should note that the maximum oral pressure p_{rms}=132 Pa i.e. 136.4 dB, was obtained for phonation into the drinking straw. In general, the SPL measured outside the vocal tract was between 60 dB and 75 dB in all cases.

Substantial differences were found in the spectra of the pressure signals measured inside the oral cavity by the B&K microphone probe and outside measured by the B&K sound level meter (see Figs. 9 and 11). Especially, some low frequency and dominant formants at about 600 Hz in Fig. 9 and at about 300 Hz in Fig. 11 measured outside the vocal tract are not detected in the spectra of the oral pressure. The dominant frequency of the water bubbling was at about 18 Hz for phonation into the water depth 2 cm and 15 Hz for the higher water levels. The difference found in the spectra inside and outside the vocal tract can be attributed to a high intensity of bubbling; moreover it may be also influenced by a plastic foil by which it was necessary to cover the aquarium especially for the higher water levels.

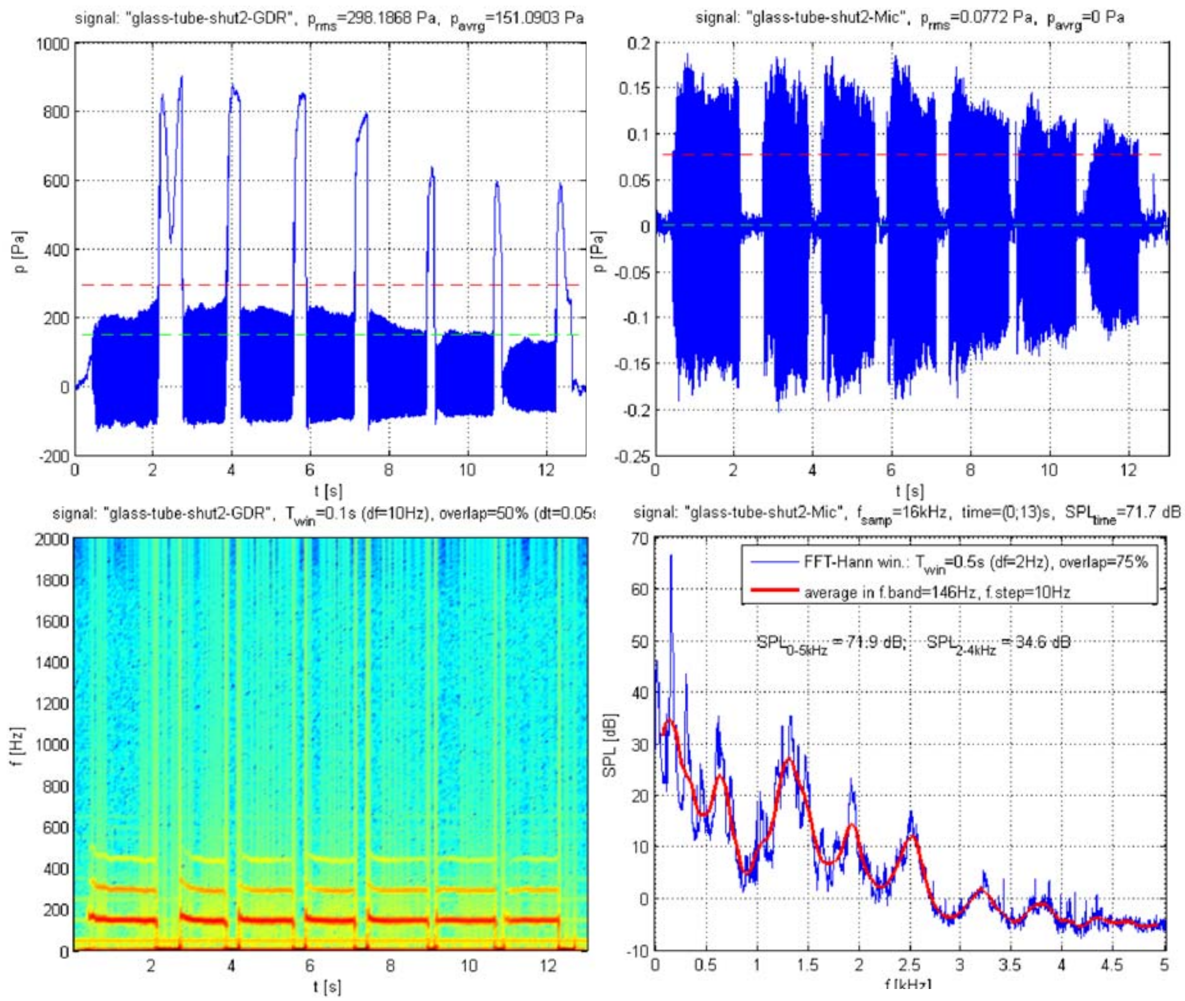

Fig. 8 Measurement of phonation into the glass (resonance) tube: 1) oral pressure and its spectrogram (left), 2) sound signal 20 cm in front of the lips and its spectrum (right).

Extreme phonation was compared between male and female subjects by phonation into the very long plastic tube. Table 4 and Fig. 12 show the differences between female and male phonation when the water depth was continuously changed during the phonation from 0 cm (phonation into air) down to about 25 cm and shuttering the tube end. The measured maximum of the subglottal pressure for the female subject was about p_{sub}=2.55 kPa and for the male subject p_{sub}= 3.25 kPa, and similarly the mean oral pressure p_{av} measured in male was about 460 Pa higher than in female.

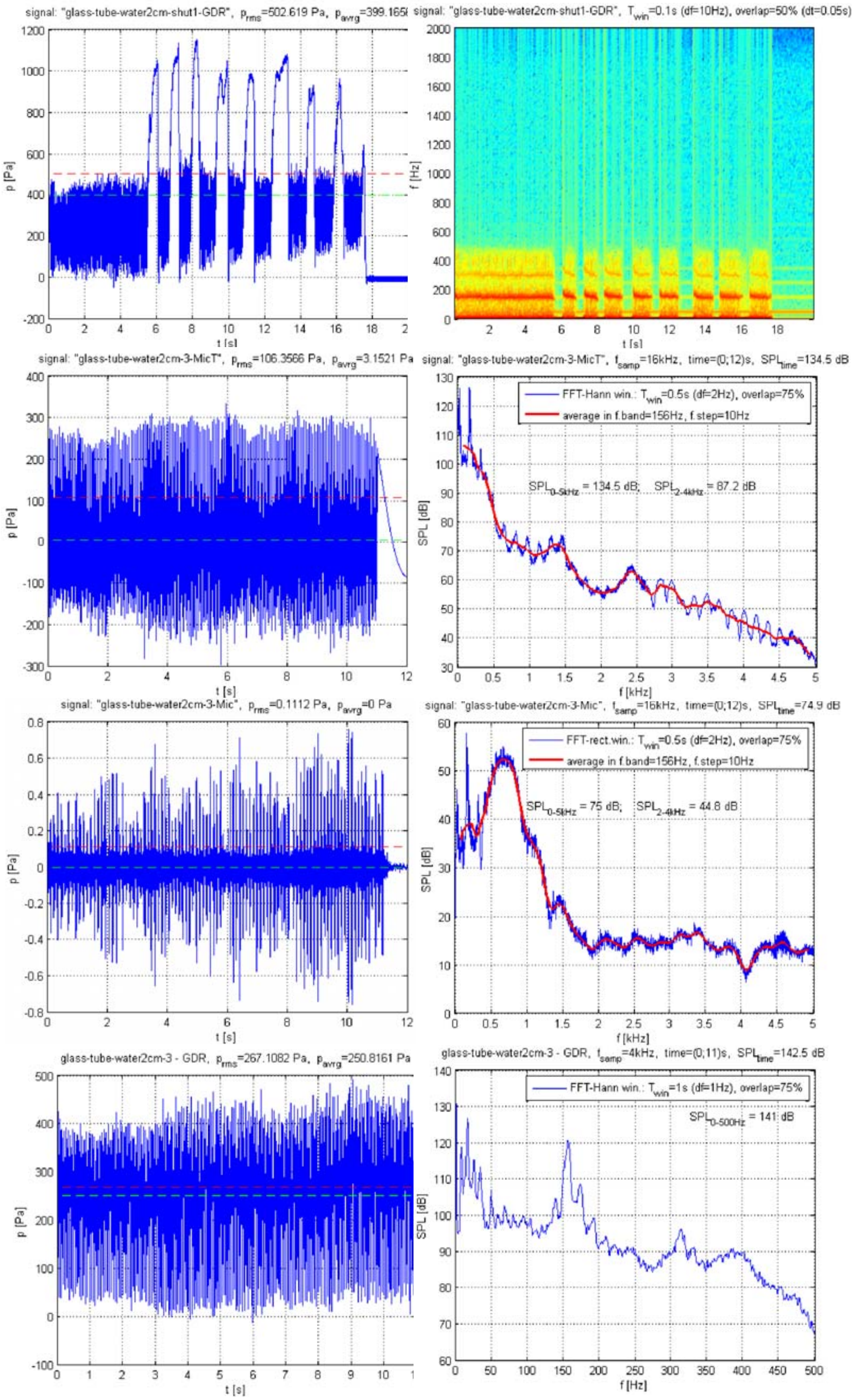

Fig. 9 Measurement of the phonation into a resonance glass tube submerged 2 cm under water: 1) oral pressure and its spectrogram (upper panel), 2) sound signal in the mouth and its spectrum (2nd panel), 3) sound signal 20 cm in front of the lips and its spectrum (3rd panel), 4) oral pressure and detail of its spectrum showing bubbling effect in the lowest frequency range (bottom).

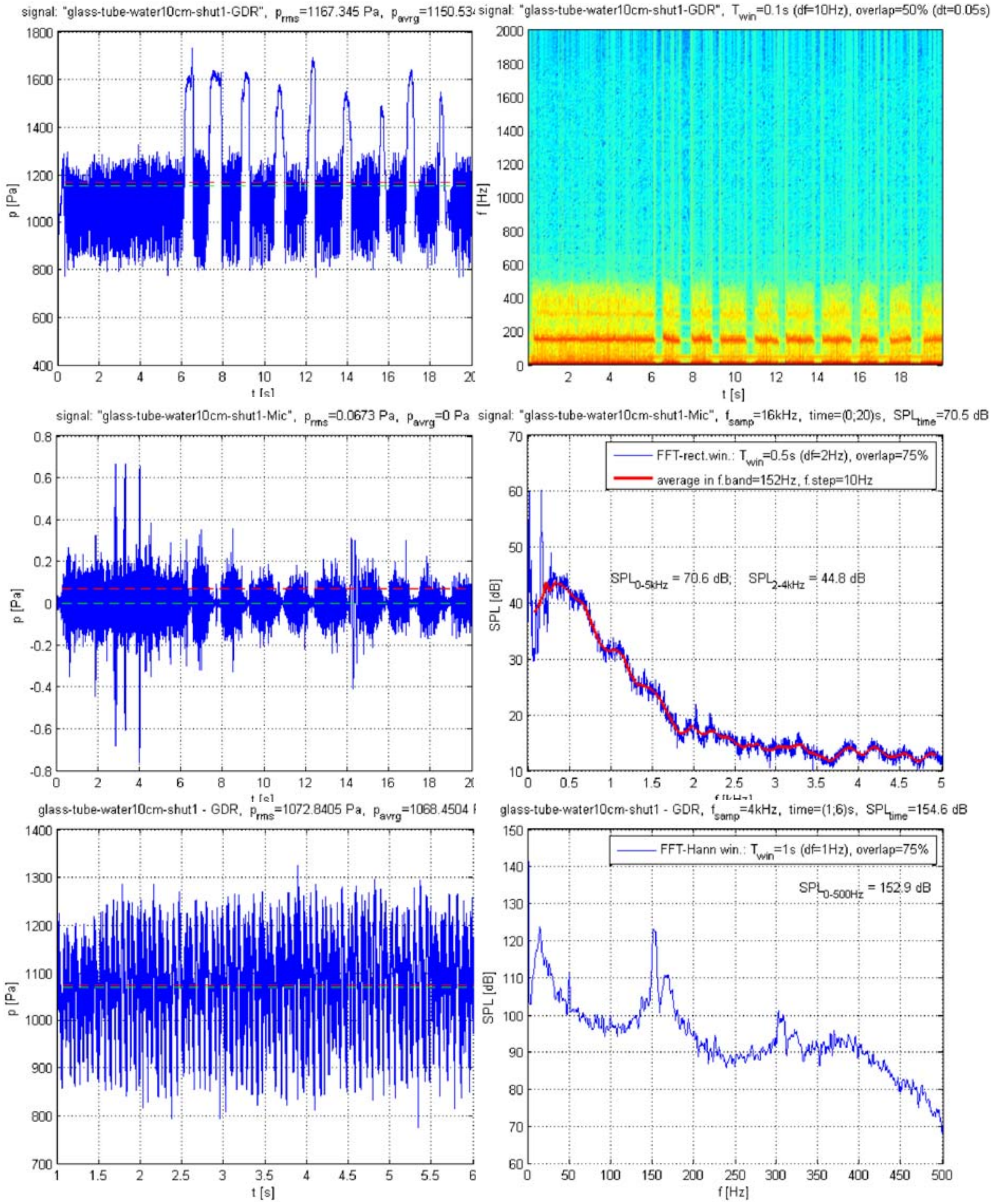

Fig. 10 Measurement of the phonation into a resonance glass tube submerged 10 cm under water: 1) oral pressure and its spectrogram (upper panel), 2) sound signal 20 cm in front of the lips and its spectrum (2nd panel), 3) oral pressure and detail of its spectrum showing bubbling effect in the lowest frequency range (bottom).

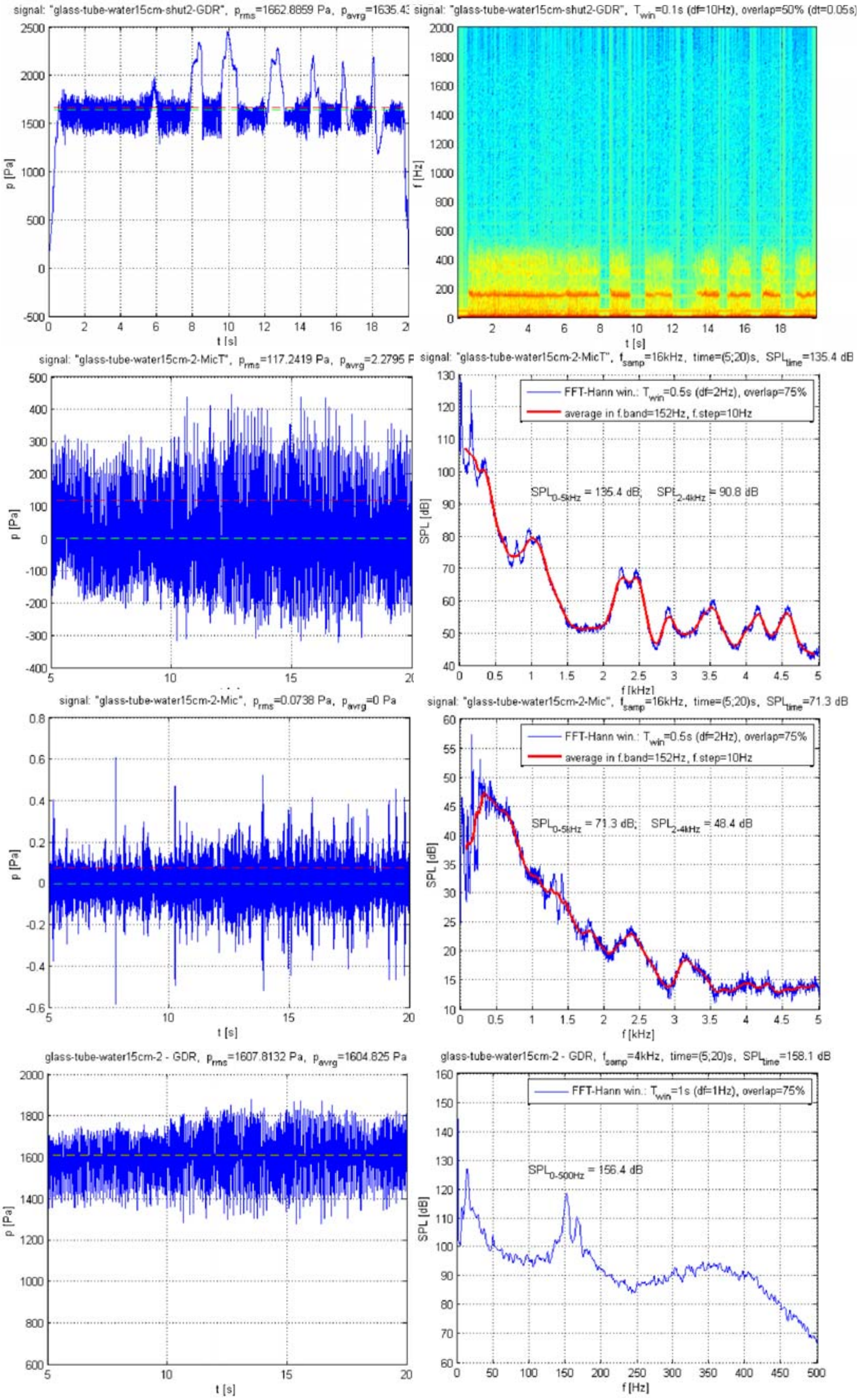

Fig. 11 Measurement of the phonation into a resonance glass tube submerged 15 cm under water: 1) oral pressure and its spectrogram (upper panel), 2) sound signal in the mouth and its spectrum (2nd panel), 3) sound signal 20 cm in front of the lips and its spectrum (3rd panel), 4) oral pressure and detail of its spectrum showing bubbling effect in the lowest frequency region (bottom panel).

Tab. 6 – Acoustic characteristics for phonation into the long plastic tube varying the submerge depth in water from zero to a maximum of about 23 cm under the water for female and up to about 25 cm for male – pressures and frequencies.

phonation into a long tube	**subgl.** p_{sub} [Pa]	**oral** p_{av} [Pa]	**outside** p_{rms} [Pa]	**fun.fr.** F0 [Hz]	**resonances – formants** F1 [Hz]	F2 [Hz]	F3 [Hz]	F4 [Hz]	F5 [Hz]	F6 [Hz]
female	750 - 2550	250 - 2290	0.042	156	360	550	1030	2500	3260	4040
male	2000 - 3250	250 - 2750	0.060	115	280	1140	1640	2250	3560	4120

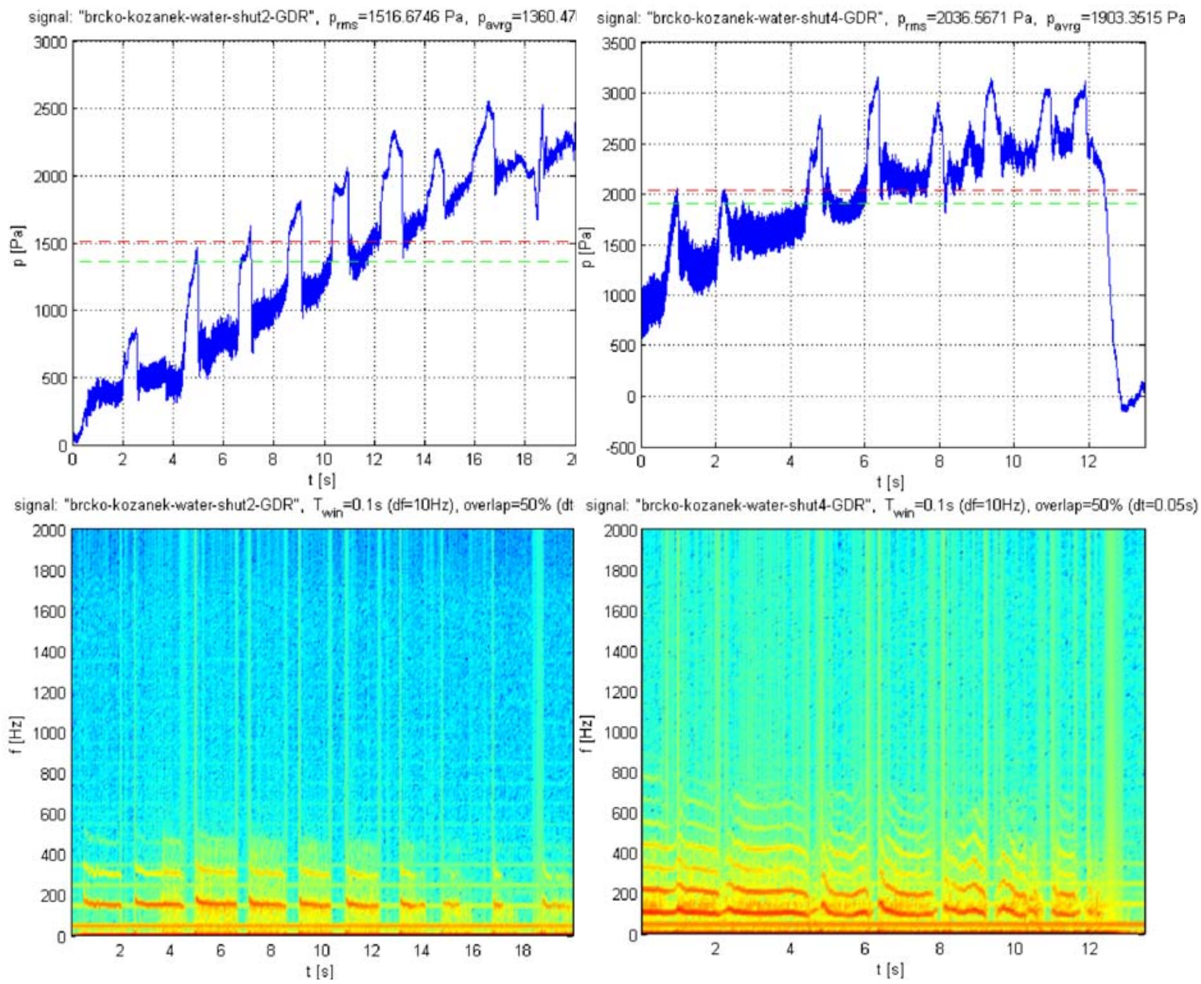

Fig. 12 Measurement of phonation into long plastic tube ("1 m") starting in air and submerging the tube continuously deeper and deeper into water: 1) female phonation (F0=156 Hz) up to about 23 cm H_2O, 2) male phonation (F0=115 Hz) up to about 25 cm H_2O.

4. Discussion and concluding remarks

According to the results in Tables 1-6 for the female phonation the subglottal pressure p_{sub} varied in all cases studied between 710 Pa and 2550 Pa, the mean oral pressure p_{av} varied from 0 Pa for phonation on [a:] and [i:] to the maximum 2290 Pa for phonation into the long plastic tube at about 23 cm under the water. The fundamental frequency F0 varied between 146 and 172 Hz. Water bubbling frequency varied in the interval between 5 Hz and 30 Hz for all cases studied.

The air pressure used for phonation into the resonance tube in the air was approximately the same as in vowel phonation. Phonation into straw offers a higher resistance, as already presented by Titze et al. (2002). The subglottal pressure p_{sub} measured in our case for phonation into the stirring straw was 1430 Pa and the oral pressure p_{av}=571 Pa; for phonation into the resonance tube we measured p_{sub}=900 Pa and p_{av}=52 Pa (see Tabs. 4 and 5) These values corresponds well with the measurements by Titze et al. They measured p_{sub} approximately from 1 to 2.5 kPa for the male and the oral pressure in the range 0-1.5 kPa in the lowest pitch (F0=147 Hz). For the female the lowest pitch was 220 Hz, the subglottal pressure varied between 1.5-2.5 kPa, and the oral pressure approximately between 0.5-1.8 kPa. Titze estimated lung pressure needed for phonation into a resonance tube (30 cm in length, 7.5 mm inner diameter) in air: 0.73 kPa and for the smallest stirring straw (11.5 cm in length, 2 mm inner diameter) 5.13 kPa assuming the air flow rate 0.2 l/s. Similar estimation was done for the oral pressure: 90 Pa for a resonance tube and 4.6 kPa for the stirring straw. Titze et al. (2002) concluded that the male who had considerably more practice with this type of phonation raised lung pressure by ca 100%, while the female raised it by 50%.

The subglottal pressure as well as the oral pressure measured for the resonance tube 2 cm under water was higher than in the air, but lower than needed for the straws. The highest pressures were measured for the resonance tube 15 cm under water.

The maximum root mean square pressure inside the oral cavity 136.4 dB was measured for phonation into the drinking straw, however many p_{rms} values for the signal from the B&K probe were not possible to evaluate due to difficulties with fixing correctly the two probes in addition to a straw or tube between the subject's lips. It is the reason why many p_{rms} values measured inside the oral cavity are missing in the tables.

A higher subglottic pressure is needed with increasing the water depth that also offers a higher pressure oscillation in the vocal tract. Voice therapy tradition pays attention to that tube 10 cm or deeper under water should only be used for a short time and proper guidance of phonation is needed (see Simberg and Laine, 2007). With a higher supraglottic resistance a higher subglottic pressure and tighter adduction of the vocal folds is needed. However, the air pressure inside the glottis also increases, thus reducing collision between the vocal folds.

Acoustic results show that the fundamental frequency F0 lowers with the hydrodynamic pressure for the drinking and stirring straws submerged into water, however an opposite tendency was measured for phonation into the resonance tube where F0 being the lowest for phonation into air.

Similar measurements were performed on a physical model of phonation, and the results of both measurements will be compared in another paper. The results of the present studies will be used for testing the models of the vocal fold prosthesis in the laboratory.

Acknowledgements

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