Logopedics Phoniatrics Vocology

ISSN: 1401-5439 (Print) 1651-2022 (Online) Journal homepage: http://www.tandfonline.com/loi/ilog20

The influence of water resistance therapy on vocal fold vibration: a high-speed digital imaging study

Marco Guzman, Anne-Maria Laukkanen, Louisa Traser, Ahmed Geneid, Bernhard Richter, Daniel Muñoz & Matthias Echternach

To cite this article: Marco Guzman, Anne-Maria Laukkanen, Louisa Traser, Ahmed Geneid, Bernhard Richter, Daniel Muñoz & Matthias Echternach (2017) The influence of water resistance therapy on vocal fold vibration: a high-speed digital imaging study, Logopedics Phoniatrics Vocology, 42:3, 99-107, DOI: 10.1080/14015439.2016.1207097

To link to this article: https://doi.org/10.1080/14015439.2016.1207097

LOGOPEDICS PHONIATRICS VOCOLOGY, 2017
VOL. 42, NO. 3, 99–107
http://dx.doi.org/10.1080/14015439.2016.1207097

ORIGINAL ARTICLE

The influence of water resistance therapy on vocal fold vibration: a high-speed digital imaging study

Marco Guzman[a,b], Anne-Maria Laukkanen[c], Louisa Traser[d], Ahmed Geneid[e], Bernhard Richter[d], Daniel Muñoz[f] and Matthias Echternach[d]

[a]Department of Communication Sciences and Disorders, University of Chile, Santiago, Chile; [b]Department of Otolaryngology, Las Condes Clinic, Santiago, Chile; [c]Speech and Voice Research Laboratory, School of Education, University of Tampere, Tampere, Finland; [d]Institute of Musicians' Medicine, Freiburg University Medical Center, Freiburg, Germany; [e]Department of Otorhinolaryngology and Phoniatrics—Head and Neck Surgery, Helsinki University Central Hospital, University of Helsinki, Helsinki, Finland; [f]Department of Otolaryngology, University of Chile, Santiago, Chile

ABSTRACT

Purpose: This study investigated the influence of tube phonation into water on vocal fold vibration.
Method: Eight participants were analyzed via high-speed digital imaging while phonating into a silicon tube with the free end submerged into water. Two test sequences were studied: (1) phonation pre, during, and post tube submerged 5 cm into water; and (2) phonation into tube submerged 5 cm, 10 cm, and 18 cm into water. Several glottal area parameters were calculated using phonovibrograms.
Results: The results showed individual differences. However, certain trends were possible to identify based on similar results found for the majority of participants. Amplitude-to-length ratio, harmonic-to-noise ratio, and spectral flatness (derived from glottal area) decreased for all tube immersion depths, while glottal closing quotient increased for 10 cm immersion and contact quotient for 18 cm immersion. Closed quotient decreased during phonation into the tube at 5 cm depth, and jitter decreased during and after it.
Conclusion: Results suggest that the depth of tube submersion appears to have an effect on phonation. Shallow immersion seems to promote smoother and more stable phonation, while deeper immersion may involve increased respiratory and glottal effort to compensate for the increased supraglottal resistance. This disparity, which is dependent upon the degree of flow resistance, should be considered when choosing treatment exercises for patients with various diagnoses, namely hyperfunctional or hypofunctional dysphonia.

ARTICLE HISTORY
Received 25 May 2015
Revised 6 May 2016
Accepted 23 June 2016

KEYWORDS
High-speed digital imaging; phonovibrograms; semi-occlusion; tube phonation; voice therapy

Introduction

Water resistance therapy includes phonation of a sustained vowel sound into a tube with the distal end submerged in water. The therapeutic process consists of several steps occurring during sessions throughout a period of weeks. At the beginning of water resistance therapy, the patient uses a limited pitch range for the first week(s) of training (1). Gradually, the patient starts to use a more varied intonation such as glides and simple intervals in a glissando mode. The patient is asked to keep the phonation stable and to follow a normal and comfortable breathing pattern in all exercises. Optimal body posture and breath control are also important aspects in water resistance therapy (1).

Two main versions of water resistance therapy have been used: (1) Phonation into a traditional Finnish resonance tube (made of glass, 24–28 cm in length with an 8–9 mm inner diameter) that is submerged in a bowl of water (2); and (2) The Lax Vox technique, which involves phonation into a flexible silicone tube (35 cm in length with an inner diameter of 9–12 mm) that is submerged into a water-filled bottle (3). In both versions of water resistance therapy, the tubes are kept approximately 1 mm between the teeth, with the lips rounded so that no air leaks from the mouth (1). In the glass tube method, tubes are kept 1–2 cm or 5–15 cm below the surface of the water, depending on the patient's needs. With the Lax Vox method, the participant is instructed to keep the tube 1–7 cm in water for voice therapy (3). In both techniques, the patient is asked to feel vibratory sensations in the anterior areas of the facial tissues. According to Titze (4), vibration sensations on these areas are related to the efficiency of the energy conversion process at the glottis.

Although water resistance therapy requires regular practice for at least several weeks, most relevant studies have been performed using tube phonation for a short period of time (seconds or minutes). Some of these studies have been designed to investigate changes in the glottal function or aerodynamic measures of phonation (5,6), while others have looked for changes in the vocal tract configuration (7).

The possible effect of resonance tube phonation in water on phonation threshold pressure and collision threshold pressure (CTP) was studied by Enflo et al. (6). CTP was found to be higher and the voice quality was perceived to be

CONTACT Marco Guzman guzmann.marcoa@gmail.com Avenida Independencia 1027, Santiago 8380000, Chile

better after the exercise. The perceptual changes were more prominent in singers who did not practice singing daily and in singers who had less experience in singing in general (6).

According to the recent *in vivo* measurements by Radolf et al. (8) the mean oral pressure increased about 4 times in habitual comfortable phonation and about 9 times in soft phonation, when the subject was phonating into a resonance tube inserted 10 cm in water. The subglottic pressure doubled in normal phonation and quadrupled in soft phonation, thus the subject compensated for the increase in supralaryngeal resistance. Fundamental frequency (F0) decreased 11–15 Hz. Comparable results were obtained by Horáček et al. (5) using a physical model of voice production. Flow rate was set constant in modeling. Oral pressure increased 10 times with a resonance tube 10 cm in water, and subglottic pressure had to be increased 1.4 times to keep the flow rate constant. Flow resistance increased 1.5 times. F0 remained constant. Larger changes were observed for soft phonation, and F0 decreased 38 Hz (19%).

Bubbles produced during phonation through a tube in water generate a pulsating oral pressure at a frequency of 15–40 Hz (5,8). Therefore, phonation into water may cause a sensation of massage on the laryngeal and pharyngeal tissues. A massage-like effect with reduction of muscle hypertension could be desirable in patients with voice disorders, especially in subjects diagnosed with laryngeal and pharyngeal hyperfunctionality. It has been hypothesized that a massage-like effect during phonation into water could also increase blood flow in the vocal folds. This assumption is supported by evidence from the field of sports medicine indicating that massage increases blood flow in muscles and skin (9–11). Other semi-occluded exercises such as tongue and lip trills may have a comparable effect due to the oscillation of oral pressure produced by tongue and lip vibration (12,13). Even though the massage-like sensation of bubbling via tube phonation into water has been clinically reported, to date there are no data supporting the hypothesis of a massage-like effect on the vocal folds or vocal tract.

Enflo et al. (6) stated that during phonation in the resonance tube in water the water bubbles generate oscillations of oral pressure, EGG, and audio signals. Specifically, oscillation of values of oral pressure modifies the transglottal pressure (which drives the vocal folds) and this, in turn, produces changes in the EGG signal amplitude. The results of the *in vivo* study by Radolf et al. (8) showed about 2–4 times higher peak-to-peak variation in oral pressure with the tube immersed 10 cm in water, compared to phonation on [u:] (larger increase for soft phonation). Contact quotient, measured from the EGG signal, increased 11% in habitual phonation. According to the modeling experiments by Horáček et al. (5) phonation at conversational loudness resulted in 2.2 times larger peak-to-peak pressure variation and 1.6 times larger glottal amplitude variation with the tube submerged 10 cm in water, compared to phonation on [u:]. Thus, the modulation of oral pressure during bubbling (tube phonation into water) seems to have an effect on vocal fold oscillation and possibly on vocal fold tissues. A recent high-speed imaging study, designed to investigate tube phonation, reported modulations of vocal fold vibration and EGG signal due to back pressure when the tube was held in water. Increased mean value of open quotient with increasing water depth was also reported (14).

Earlier investigations support the association between EGG contact quotient and the degree of vocal fold impact stress. When impact stress increases (stronger collision between the vocal folds during vibration), the vocal folds also tend to stay together for longer intervals, thus increasing the value of contact quotient or decreasing the value of open quotient (15).

Guzman et al. (7) evaluated via flexible laryngoscopy the effect of eight different semi-occluded vocal tract postures on vertical laryngeal position (VLP), pharyngeal constriction, and laryngeal compression in subjects diagnosed with hyperfunctional dysphonia. All semi-occluded techniques produced a lower VLP, narrower aryepiglottic opening, and a wider pharynx than in a resting position. More prominent changes were obtained with tube phonation into water 3 cm and 10 cm deep compared to the other semi-occluded exercises that did not involve water. Sovijärvi et al. (16) assumed that the positive outcomes of phonation into a resonance tube in water are due to the efficient lowering of the larynx and an improved vocal fold closure. Sovijärvi stated that the length of the tube and depth into the water should be chosen so that a clear lowering of the larynx would occur during the exercise. The goal after the exercise, however, is normal voicing with a neutral (not lowered) larynx (17–19).

Water resistance exercising precipitates changes in self-assessment of voice. Paes et al. (20) studied the immediate effects of it on teachers with behavioral dysphonia. The Finnish resonance tube immersed 2 cm into water was used. Significantly greater phonatory comfort and improved perceptual voice quality after the exercises were reported by the subjects. Less spectral noise in the acoustic signal and lower fundamental frequency were also observed (20).

Only two longitudinal studies have been conducted using the water resistance therapy. Positive results have been obtained in the treatment of behavioral dysphonia (21,22). Perceptual assessment and results from a questionnaire on the occurrence of vocal symptoms revealed significant changes in the treatment group compared with the control group (21).

Several visualization techniques of vocal fold vibration have been used in the diagnosis of laryngeal disorders and in the investigation of normal voice production. High-speed imaging (HSI) has emerged as an effective method of visualization during the last decades (22). Commercial HSI systems record images of sustained vocal fold vibration at the rate of 2,000 to 10,000 frames per second, which is fast enough to capture the actual phonatory vibrations of the vocal folds (23,24). For research, however, it was shown that using flexible endoscopy high-speed recordings are possible with a frame rate up to 20,000 frames per second, which allows more detailed analysis (24). To obtain precise and objective information from HSI videos, several methods have been developed. Phonovibrography is a fast, robust, and precise image-processing strategy to extract information of the vocal fold movements during phonation (25). The method detects the vocal fold edges and transfers their movement into a static geometric presentation (phonovibrograms). Several glottal variables can be calculated from phonovibrograms (26).

The present study aimed to observe the influence of tube phonation into water on vocal fold vibration by using high-speed digital imaging and phonovibrography. Specifically, we attempted to answer two questions: (1) Is there any influence of tube phonation into water on vocal fold vibration; and (2) Does immersion depth affect vocal fold vibration? We hypothesize that: (1) phonation into water causes modulation in glottal variables; (2) the modulations imply a decrease in the average values of closed quotient, amplitude-to-length ratio, perturbation, noise-to-harmonic ratio, and spectral flatness; (3) the average parameter change observed during water resistance exercising remains in vowel phonation afterwards; (4) the effect is stronger when the immersion is deeper than 5 cm; and (5) deeper than 10 cm immersion in water would promote more glottal compensation for increased airflow resistance (more adducted focal folds and increase of closed quotient), and therefore higher impact stress than shallower immersion.

Methods

Participants and phonatory tasks

Eight volunteer participants (five male and three female) were analyzed using high-speed digital imaging. All participants reported normal voice and hearing at the time of the experiment. The health of the larynx was ascertained through laryngoscopy. Four participants were trained singers; one participant reported experience in speech training, and three had no voice training. The age range of the participants was 23–45 years.

Two test conditions were studied:

1. The sequence for the first condition was: phonation pre, during, and post tube submerged 5 cm into water. In this sequence, subjects were asked to produce a sustained and stable vowel [i:] before and after phonation into the tube. Each individual phonation sample was produced for approximately 5 seconds. Successive sequences of tube phonation were produced for 5 minutes to gain a possible training effect. A flexible silicone (Lax Vox-like) tube (45 cm in length, 2 cm in inner diameter) was used. Participants were asked to phonate at a comfortable pitch and vocal loudness in all three tasks.
2. The sequence for the second condition consisted of three 5-second tube phonation samples with the tube submerged 5 cm (taken from the previous sequence), 10 cm, and 18 cm into water. Participants were asked to use the same comfortable pitch produced in the first sequence for these trials.

Samples of the vocal fold vibration were obtained pre, during, and post tube phonation via a rigid endoscope attached to a plastic mouth piece. The flexible tube was also attached to the same mouth piece (Figure 1). The mouth piece was maintained between the rounded lips, so that no air would leak from the mouth; the free end of the tube was kept submerged in the water as an extension of the vocal tract. Three marks were made on the water container at 5 cm, 10 cm, and 18 cm, to help in maintaining the appropriate depth of immersion. A grand piano was used to give the pitch, which was auditorily monitored by one of the authors (M.G.). Only one recording per phonatory task was performed for each participant. A total of five samples were obtained from each participant (pre tube, phonation during tube submerged 5 cm, post tube, phonation during tube submerged 10 cm, and phonation during tube submerged 18 cm). In each sample, participants phonated for approximately 5 seconds. However, only 1 second of phonation was captured by the high-speed camera. The captured samples were obtained from the mid-portion of each phonatory task.

Figure 1. General view of the experiment setting during high-speed registration.

Instrumentation

Data collection was performed in a room typically used for clinical laryngoscopic assessment of voice. Laryngeal endoscopic procedure was performed using a HRES-Endocam 5562 system (Fa. Wolf, Knittlingen, Germany) coupled with a 90° rigid endoscope (Fa. Wolf, Knittlingen, Germany). This system also includes software for digital storing of the recordings. The high-speed camera allows recording of 4,000 frames per second with a pixel resolution of 256 × 256. For illumination, a 300-W xenon light source (Auto-LP 5131, Richard Wolf, Knittlingen, Germany) was used. To prevent tissue overheating during the recordings, the duration of light exposure was kept at a minimum. No calibration of the images could be performed. Laryngoscopic procedures were performed by a laryngologist and a phoniatrician, both co-authors of this study (M.E. and A.G.). Participants were required to stay in standing position during examinations, and no topical anesthesia was used.

Image processing

Phonovibrography was used to extract information of the vocal fold movements during phonation. For each sample, 1,000 frames (250 ms) of the high speed material were analyzed using the custom-made Phonovibrogram Software Tool (Glottal Analysis Tools v5, Michael Döllinger and Denis

Dubrovsky, Department of Phoniatrics and Pedaudiology, Medical School Erlangen, Germany). The excerpts for the analyses were chosen from the part of the samples where phonation was stable, excluding the onset and offset of voice. There was no randomization in the analyses. The glottis area was first segmented in a single frame and semi-automatically transferred to the other frames. In the next step the glottal length axis was constructed, and a phonovibrogram was established as described before (27).

Glottal area variables

The following glottal variables were derived from all high-speed registrations as described in the literature (28). These parameters were chosen due to the fact that most of them have been used in earlier studies. Moreover, these parameters do not require calibration of the images from pixels into area.

- Amplitude-to-length ratio (A-LR): ratio between vibrational amplitude at the center of the vocal folds and the length of the vocal folds.
- Closed quotient (CQ): ratio between closed phase and the entire glottal period.
- Closing quotient (ClQ): ratio between closing phase and entire glottal period.
- Fundamental frequency (F0): number of cycles of vocal fold vibration per second.
- Harmonic-to-noise ratio (HNR): relation between harmonic energy and noise energy.
- Spectral flatness (SF): spectral declination or spectral tilt (frequency range from 0 to 2,000 Hz). Flatness is maximal for white noise.
- Jitter%: frequency perturbation in percentage.
- Shimmer%: amplitude perturbation in percentage.

It is worth noting that, even though HNR, SF, jitter, and shimmer are often calculated from acoustic signals, in the present study these parameters were calculated from glottal area variation.

Only descriptive statistics were calculated for the variables, including median and interquartile range. We analyzed the trend of values for all parameters and phonatory tasks without using hypothesis testing to avoid lack of statistical power due to small sample size. All analyses and graphics were performed using Stata 13.1 (StataCorp, College Station, TX, USA).

Results

Tables 1 and 2 show median and interquartile ranges for sequence 1 and 2, respectively. Moreover, results are presented below in terms of the observed trends among participants, i.e. when similar changes (compared to vowel phonation) were observed for the majority (five or more) of the participants. Figures 2 and 3 summarize the trends for sequence 1 and 2, respectively.

Table 1. Medians and interquartile ranges for glottal area parameters pre, during, and after tube phonation submerged 5 cm in water (sequence 1).

Parameter	Pre 5 cm	During 5 cm	Post 5 cm
F0	198 ± 89	222 ± 60	216 ± 110
HNR	15 ± 3	14 ± 3	16 ± 8
Jitter	4 ± 4	3 ± 2	2 ± 2
Shimmer	0.3 ± 0.2	0.4 ± 0.5	0.4 ± 0.5
SF	−20 ± 4	−17 ± 3	−20 ± 2
CQ	0.2 ± 0.05	0.3 ± 0.15	0.2 ± 0.13
AL-R (right)	0.08 ± 0.04	0.07 ± 0.05	0.07 ± 0.03
AL-R (left)	0.1 ± 0.05	0.09 ± 0.05	0.09 ± 0.04

Table 2. Medians and interquartile ranges for glottal area parameters during tube submerged 5 cm, tube submerged 10 cm, and tube submerged 18 cm (sequence 2).

Parameter	During 5 cm	During 10 cm	During 18 cm
F0	222 ± 60	235 ± 81	216 ± 72.4
HNR	14 ± 3	14 ± 3	13 ± 1.9
Jitter	3 ± 2	4 ± 0.9	4 ± 4.2
Shimmer	0.4 ± 0.5	0.4 ± 0.2	0.5 ± 0.3
SF	−17 ± 3	−19 ± 3.7	−18 ± 5.08
CQ	0.3 ± 0.2	0.3 ± 0.11	0.2 ± 0.13
A-LR (right)	0.07 ± 0.05	0.07 ± 0.02	0.08 ± 0.05
A-LR (left)	0.09 ± 0.05	0.1 ± 0.05	0.1 ± 0.03

First sequence: phonation pre, during, and post tube submerged 5 cm into water

During phonation into a tube submerged in water to a depth of 5 cm, CQ decreased (5 of 8 participants) compared to baseline condition, HNR decreased (6 participants), spectral flatness decreased (5 participants), A-LR (right and left vocal folds) decreased (5 and 6 participants, respectively), F0 increased (6 participants), and jitter decreased (5 participants). Thus phonation seemed to be less tight, softer, a bit more noisy, and yet more stable. After phonation into tube 5 cm in water there was an increase in CQ (6 participants), ClQ (5 participants), HNR (5 participants), and F0 (5 participants) and a decrease in jitter (5 participants). Thus, it seems that phonation was tighter, and the voice was less noisy and more stable.

Second sequence: tube submerged 5 cm, 10 cm, and 18 cm into water

CQ decreased with the tube 5 cm in water (5 participants), increased during phonation into a tube submerged in water to a depth of 18 cm (6 participants), ClQ increased during phonation into a tube submerged in water to a depth of 10 cm (6 participants), HNR and A-LR decreased for all tube depths (6 and 5 participants, respectively), jitter decreased for the tube 5 cm in water (5 participants) and increased for the tube 10 cm in water (5 participants), and F0 increased for the tube 5 cm and 10 cm in water. SF decreased during tube submerged 5 cm, 10 cm, and 18 cm below the water surface (5 participants for each condition). These findings seem to imply less tight phonation for the tube 5 cm in water, while the results for deeper immersion are more difficult to interpret. Decreased A-LR, HNR, and SF seem to imply softer phonation (less collision between the vocal folds), while increased ClQ and CQ suggest the opposite.

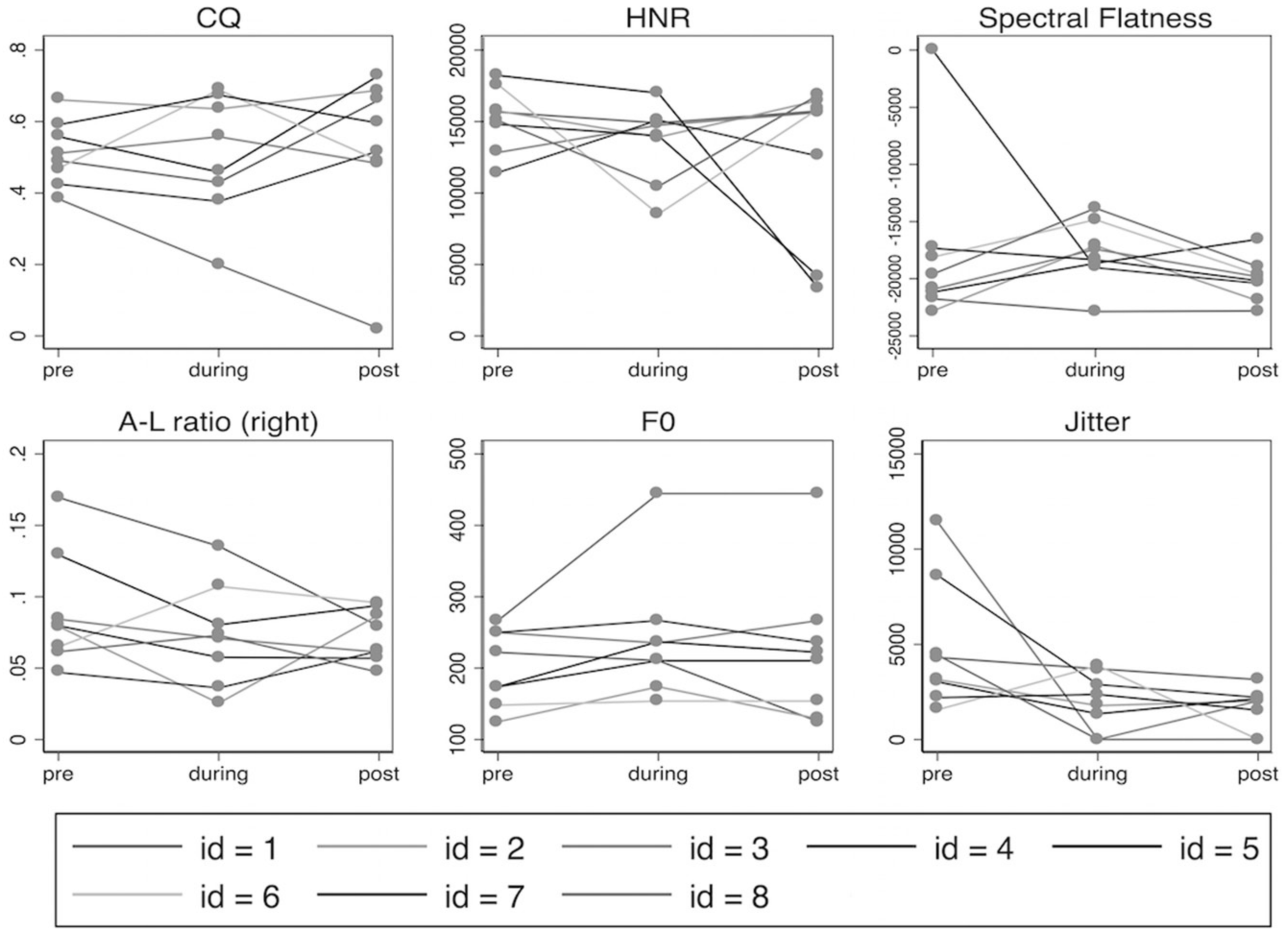

Figure 2. Trends for sequence 1 (phonation pre, during, and post tube submerged 5 cm into water).

Discussion

This study analyzed vocal fold oscillatory patterns during phonation into a tube submerged at different depths into water. In general, it was demonstrated that vocal fold oscillation is affected by tube phonation. This has been noted before when phonation through a tube in the air has been studied, e.g. using air pressure and electroglottographic registration (29), by calculating the electroglottographic contact quotient (30,31), and by applying high-speed filming (32).

In line with earlier results (31,32), our results showed that participants behaved differently and thus no statistically significant differences were observed in any parameters studied. This suggests that water resistance exercises do not give automatically certain results but the effect depends on how a person reacts to the increased airflow resistance. Certain trends were observed, though.

A-LR was in most cases lower during phonation into water, for all immersion depths. A decrease in A-LR could be expected during semi-occlusions because of the decrease in transglottal pressure (the driving force for phonation). A low A-LR is expected to imply a low impact stress on vocal folds. Therefore, a phonotraumatic reaction would be unlikely. To the best of our knowledge, only one earlier study used a similar measure, the amplitude-to-dynamic length (A-DL) ratio, in investigating the effects of tube phonation. An increased A-DL ratio was found for the longest tube, which, according to the authors, may suggest a raised vocal effort (increased subglottic pressure) (32). In the present study, a relatively high A-LR was found for some subjects with the tube 18 cm in water.

To date, no clear patterns have been evidenced regarding contact quotient from electroglottography (CQ_{EGG}) signal during and after semi-occlusions (30,31,33–39). Some studies have found a decrease in CQ_{EGG} during and after semi-occluded exercises, while others have reported an increase. An interesting trend was detected for CQ (closed quotient obtained from high-speed samples) in the present study. Tube phonation into 18 cm of water showed higher values of CQ than the other conditions and baseline. Phonation into 5 cm of water in turn demonstrated a decrease in CQ compared to baseline condition. It is possible to speculate that the effect of vocal exercises on CQ depends on the degree of flow resistance (e.g. depth of immersion) and on the subjects' reactions to it (38). From our findings, it seems that a shallower depth tends to lead to a decrease in CQ, while a deeper submersion tends to increase the glottal CQ. Similarly, Laukkanen et al. (32) in a high-speed imaging study found higher CQ for longer tubes compared with shorter ones. Results from the study by Horáček et al. (5) showed how tube diameter also affects glottal function. Since depth of immersion, and tube length and inner diameter all affect the amount of flow resistance, it seems plausible to expect that they also affect CQ. An increase of CQ could

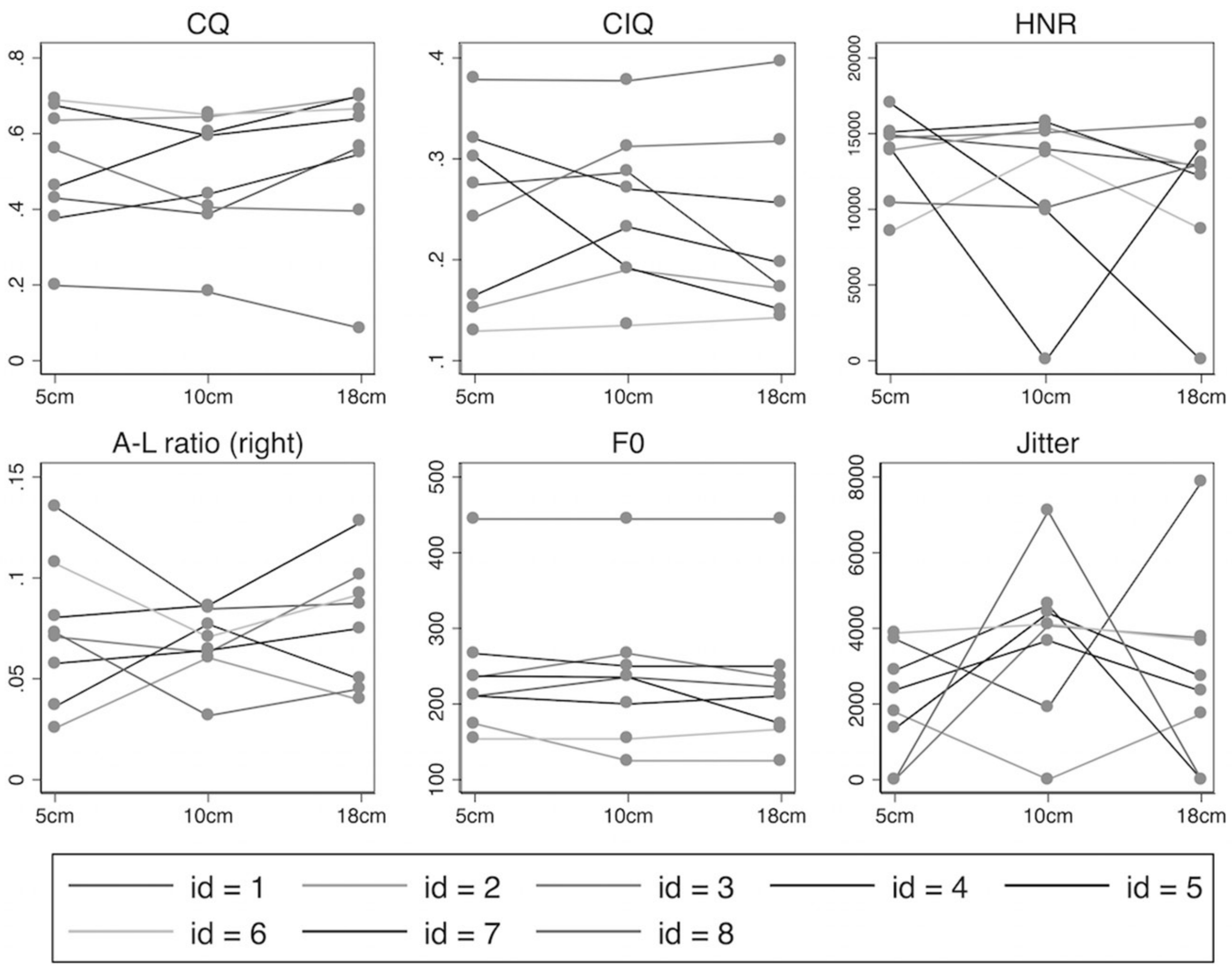

Figure 3. Trends for sequence 2 (phonation during 5 cm, 10 cm, and 18 cm into water).

result from increased adduction, or it could be a passive consequence of increased subglottic pressure (5). It is most likely that in speech production these variables co-vary and the glottis reacts reflexively to the information from various sensory receptors. As mentioned before, the importance of CQ during tube phonation is due to the fact that there is a relationship between CQ and vocal fold impact stress (15).

Two trends were observed for ClQ. It increased after 5 cm phonation compared to baseline condition and during phonation in the tube 10 cm in the water. In other words, the closing phase seemed to be relatively longer compared to baseline condition. Different changes were observed by Laukkanen et al. (32). ClQ values were smaller for longer tubes. As mentioned before, a long and/or narrow tube could be equivalent to a tube submerged deep under the water surface because of the high flow resistance. Since a low ClQ is related to the abruptness of vocal fold closure, one may expect that high flow resistance exercises (i.e. long and/or narrow tubes or deep immersion) cause a higher vocal fold impact stress compared to shallower depth of immersion. However, this was not observed in our data.

Harmonic-to-noise ratio was also examined in the present study, based on image analysis. This parameter demonstrated an increase after tube phonation submerged into 5 cm of water compared to pre tube samples. Thus, more harmonic energy compared to noise was observed. Decreased noise after semi-occlusion exercises has been reported in previous works, based on acoustic signal analysis (20,42,43). This change has been observed after a few minutes of exercises (20), and after several weeks of treatment (43). However, the subjects of these studies were patients with hyperfunctional dysphonia.

Related to harmonic energy, spectral flatness decreased in tube phonation for all immersion depths compared to baseline. Therefore, it is possible to state that our data show a steeper spectral slope for all conditions compared to baseline. Recall that SF in the present study was derived from glottal area variation. No trend was observed in the present study in samples obtained after tube phonation. Earlier studies on acoustic spectra have shown a less steep spectral slope after phonation with different semi-occluded vocal tract exercises (2,39,44,45), suggesting that semi-occlusions produce an increased spectral energy in the higher part of the spectrum. The amplitude of higher harmonics is particularly sensitive to the speed at which the glottal airflow decreases at the end of the closing phase (46). A lower SF during phonation through a tube in water seems to imply a smoother collision between the vocal folds (47).

The effect of the depth of immersion on perturbation measures was also analyzed. There was an interesting trend that jitter decreased during and after phonation into a tube submerged 5 cm in water for most participants. A number of investigations have used acoustic measures to observe the effect of semi-occluded exercises. However, only few of them have utilized perturbation measures. Jitter and shimmer were recently assessed before and after stirring straw phonation in a group of school teachers with slight dysphonia (42). Both parameters were found to be significantly lower after performing vocal exercises. Furthermore, Barrichelo-Lindström et al. (48) reported a decrease of jitter and shimmer in normal-voiced participants after vocal warm-up using Y-buzz, another semi-occluded exercise. It is possible to speculate that lower perturbation values may reflect better sensory-motor control (49) or greater activity in laryngeal muscles if one increases subglottic pressure and adduction during and after tube phonation (50–53). A negative correlation has been found between perturbation measures and F0 and SPL. Earlier studies have suggested that a higher F0 and SPL would imply higher muscle activity, and this, in turn, would reduce perturbation of F0 and amplitude (49–52).

Earlier investigations have reported that tube phonation and other semi-occluded exercises may also modify F0. Our data showed higher values for most conditions compared to baseline. Most previous studies regarding semi-occluded vocal tract exercises have reported a decrease in F0 during exercising (2,20,29,40–43). Others have indicated an increase (13), no change (5), or no clear trend. According to two previous studies, F0 shifts depended on the length of the tube and depth of immersion. Laukkanen et al. (32) found lower F0 values for longer tubes compared to shorter ones. Furthermore, Horáček et al. (5) observed (for soft phonation) that F0 was lower with a resonance tube in water and with a thin straw. Therefore, it seems that F0 is related to the degree of airflow resistance.

It is important to mention that F0 results could depend on the instructions given in the recording process. In several studies, participants have been instructed to keep the same pitch before and after exercising in order to make the results comparable (as it was required in the present study). Moreover, considering that all earlier studies have demonstrated changes of only a few Hz, these data should be taken with caution because it likely has no clinical impact and it can be only a physical modification. Additionally, no F0 changes have clearly remained after exercising.

It seems that choosing the most appropriate semi-occlusion (e.g. length/diameter of the tube and depth of immersion) for each subject would promote the best vocal function. The results suggest that there is a tendency for smoother collision between the vocal folds and increased stability in phonation through a tube in water with a smaller immersion depth. A decrease in SF, HNR, and A-LR observed in most cases in tube phonation for all immersion depths suggests a smoother collision between the vocal folds. The increase in CQ for deep immersion depth, however, suggests that the possibility for increased vocal loading cannot be excluded when deep immersion depth is used. The desired vocal goal always depends on what the starting-point is. Our results suggest that a shallow immersion may be suited for patients with hyperfunctional voice disorders, while deep immersion may be a good option for patients with hypofunctional voice disorder. Thus, our results are in line with the common clinical tradition (see e.g. Simberg and Laine) (1). Even though technical characteristics of semi-occlusions (e.g. length or inner diameter of tube) are important, instructions and guidance on how to perform the exercise are also crucial when these exercises are used in voice rehabilitation and training.

As mentioned above, it has been found that CQ correlates with impact stress. However, during phonation into a tube in water the bubbling of water affects the vocal fold vibration. Therefore, variation in CQ values can be also present. Further studies are needed to know how well a mean CQ and other mean values of glottal area variables characterize vocal fold vibration and impact stress during water resistance therapy.

Conclusion

Even though subjects showed individual variation for most glottal area parameters, data from the present study suggest that tube phonation into water causes changes in glottal variables. In most cases the amplitude-to-length ratio, harmonic-to-noise ratio, and spectral flatness (derived from glottal area) decreased, which seems to imply a smoother collision between the vocal folds. However, the effect does not necessarily remain in vowel phonation after tube phonation. Findings obtained from shallow immersion suggest a favorable mechanical and physiological interaction in terms of decreased closed quotient and reduced jitter. Deeper immersion, instead, showed higher closed quotient. This may imply an increased respiratory and glottal effort (higher subglottic pressure and more adducted vocal folds) to compensate for the strongly increased supraglottal resistance. Thus, the impact stress during phonation through a tube into water may increase during deep immersion. The results suggest that this disparity of the effects, which is dependent upon the degree of flow resistance, should be considered when choosing treatment exercises for patients with different types of diagnoses, namely hyperfunctional or hypofunctional dysphonia. Deeper immersion could be more beneficial for patients with vocal fold paralysis or presbyphonia. On the other hand, glottal function of patients with hyperadduction or vocal fatigue could be improved using shallower depths.

Acknowledgements

Special thanks to Denis Dubrovsky and Michael Döllinger for providing the phonovibrogram software.

Disclosure statement

The authors report no conflicts of interest. The authors alone are responsible for the content and writing of the paper.

Funding

In Germany, this study was supported by the Deutsche Forschungsgemeinschaft [grant Ec 409/1-1 and Ri 1050/4-1]. In Finland, it was supported by the Finnish Academy of Sciences [grant number 1128095].

References

1. Simberg S, Laine A. The resonance tube method in voice therapy: description and practical Implementations. Logoped Phoniatr Vocol 2007; 32: 165–70.
2. Laukkanen A-M. About the so called ‘resonance tubes’ used in Finnish voice training practice. Scandinavian Journal of Logopedics & Phoniatrics 1992; 17: 151–61.
3. Sihvo M. Terve ääni, äänen hoidon A B C [Healthy voice. The A B C for voice care]. Helsinki: Kirjapaja; 2006. [In Finnish]
4. Titze IR. Acoustic interpretation of resonant voice. J Voice 2001; 15: 519–28.
5. Horáček J, Radolf V, Bula V, Laukkanen A-M. Air-pressure, vocal folds vibration and acoustic characteristics of phonation during vocal exercising. Part 2: measurement on a physical model. Engineering Mechanics 2014; 21: 193–200.
6. Enflo L, Sundberg J, Romedahl C, McAllister A. Effects on vocal fold collision and phonation threshold pressure of resonance tube phonation with tube end in water. J Speech Lang Hear Res 2013; 56: 1530–8.
7. Guzman M, Castro C, Testart A, Muñoz D, Gerhard J. Laryngeal and pharyngeal activity during semioccluded vocal tract postures in subjects diagnosed with hyperfunctional dysphonia. J Voice 2013; 27: 709–16.
8. Radolf V, Laukkanen A-M, Horáček J, Liu D. Air-pressure, vocal fold vibration and acoustic characteristics of phonation during vocal exercising. Part 1: measurement in vivo. Engineering Mechanics 2014; 21: 53–9.
9. Mori H, Ohsawa H, Tanaka TH, Taniwaki E, Leisman G, Nishijo K. Effect of massage on blood flow and muscle fatigue following isometric lumbar exercise. Med Sci Monit 2004; 10: CR173–8.
10. Hinds T, McEwan I, Perkes J, Dawson E, Ball D, George K. Effects of massage on limb and skin blood flow after quadriceps exercise. Med Sci Sports Exerc 2014; 36: 1308–13.
11. Weerapong P, Hume PA, Kolt GS. The mechanisms of massage and effects on performance, muscle recovery and injury prevention. Sports Med 2005; 35: 235–56.
12. Miller DG, Schutte HK. Effects of downstream occlusions on pressures near the glottis in singing. In: Gauffin J, Hammarberg B, editors. Vocal fold physiology. Acoustic, perceptual and physiological aspects of voice mechanisms. San Diego (CA): Singular Publishing; 1991. p. 91–8.
13. Schwarz K, Cielo CA. Modificações laríngeas e vocais produzidas pela técnica de vibração sonorizada de língua. Pró-Fono 2009; 21: 161–6.
14. Granqvist S, Simberg S, Hertegård S, Holmqvist S, Larsson H, Lindestad PA, et al. Resonance tube phonation in water: high-speed imaging, electroglottographic and oral pressure observations of vocal fold vibrations—a pilot study. Logoped Phoniatr Vocol 2014; 28: 1–9.
15. Verdolini K, Chan R, Titze I, Hess I, Bierhals W. Correspondence of electroglottographic closed quotient to vocal fold impact stress in excised canine larynges. J Voice 1998; 12: 415–23.
16. Sovijärvi A, Häyrinen R, Orden-Pannila M, Syvänen M. Äänifysiologisten kuntoutusharjoitusten ohjeita [Instructions for voice exercises]. Helsinki: Publications of Suomen Puheopisto; 1989.
17. Sovijärvi A. Die Bestimmung der Stimmkategorien mittels Resonanzröhren. In: Int Kongr Phon Wiss 1965. p. 532–5.
18. Sovijärvi A. Äänifysiologiasta ja artikulaatiotekniikasta [On voice physiology and articulatory technique]. Helsinki, Finland: Department of Phonetics, University of Helsinki press; 1966. [in Finnish]
19. Sovijärvi A. Nya metoder vid behandlingen av röstrubbningar. Nordisk Tidskrift for Tale og Stemme 1969; 3: 121–31.
20. Paes SM, Zambon F, Yamasaki R, Simberg S, Behlau M. Immediate effects of the finnish resonance tube method on behavioral dysphonia. J Voice 2013; 27: 717–22.
21. Simberg S, Sala E, Tuomainen J, Sellman J. The effectiveness of group therapy for students with mild voice disorders: a controlled clinical trial. J Voice 2006; 20: 97–109.
22. Tapani M. Resonaattoriputki toiminnallisen ääihäirion hoitmenetelmänä. Seitsemän naispotilaan Seurantatutkimus [Resonance tube as a therapy method for a functional voice disorder. A follow-up study of seven female patients]. Helsinki, Finland: University of Helsinki; 1992. [in Finnish]
23. Patel R, Dailey S, Bless D. Comparison of high-speed digital imaging with stroboscopy for laryngeal imaging of glottal disorders. Ann Otol Rhinol Laryngol 2008; 7: 413–24.
24. Krausert CR, Olszewski AE, Taylor LN, McMurray JS, Dailey SH, Jiang JJ. Mucosal wave measurement and visualization techniques. J Voice 2001; 25: 395–405.
25. Wittenberg T, Tigges M, Mergell P, Eysholdt U. Functional imaging of vocal fold vibration: digital multislice high-speed kymography. J Voice 2000; 14: 422–42.
26. Echternach M, Döllinger M, Sundberg J, Traser L, Richter B. Vocal fold vibrations at high soprano fundamental frequencies. J Acoust Soc Am 2013; 133: 82–7.
27. Lohscheller J, Toy H, Rosanowski F, Eysholdt U, Dollinger M. Clinically evaluated procedure for the reconstruction of vocal fold vibrations from endoscopic digital high-speed videos. Med Image Anal 2007; 11: 400–13.
28. Inwald EC, Döllinger M, Schuster M, Eysholdt U, Bohr C. Multiparametric analysis of vocal fold vibrations in healthy and disordered voices in high-speed imaging. J Voice 2011; 25: 576–90.
29. Titze IR, Finnegan EM, Laukkanen A-M, Jaiswal S. Raising lung pressure and pitch in vocal warm-ups: the use of flow-resistant straws. Journal of Singing 2002; 58: 329–38.
30. Gaskill CS, Erickson ML. The effect of an artificially lengthened vocal tract on estimated glottal contact quotient in untrained male voices. J Voice 2010; 24: 57–71.
31. Gaskill C, Quinney D. The effect of resonance tubes on glottal contact quotient with and without task instruction: a comparison of trained and untrained voices. J Voice 2012; 26e: 79–93.
32. Laukkanen A-M, Pulakka H, Alku P, Vilkman E, Hertegård S, Lindestad PA, et al. High-speed registration of phonation-related glottal area variation during artificial lengthening of the vocal tract. Logoped Phoniatr Vocol 2007; 32: 157–64.
33. Laukkanen A-M, Lindholm P, Vilkman E, Haataja K, Alk P. A physiological and acoustic study on voiced bilabial fricative/β:/ as a vocal exercise. J Voice 1996; 10: 67–77.
34. Gaskill C, Erickson M. The effect of a voiced lip trill on estimated glottal closed quotient. J Voice 2008; 22: 634–43.
35. Cordeiro GF, Montagnoli AN, Nemr NK, Menezes MH, Tsuji DH. Comparative analysis of the closed quotient for lip and tongue trills in relation to the sustained vowel/ε/. J Voice 2012; 26: e17–22.
36. Hamdan AL, Nassar J, Al Zaghal Z, El-Khoury E, Bsat M, Tabri D. Glottal contact quotient in mediterranean tongue trill. J Voice 2012; 26: 669.e11–15.
37. Guzman M, Rubin A, Muñoz D, Jackson-Menaldi C. Changes in glottal contact quotient during resonance tube phonation and phonation with vibrato. J Voice 2013; 27: 305–11.
38. Guzman M, Laukkanen A-M, Krupa P, Horáček J, Švec J, Geneid A. Vocal tract and glottal function during and after vocal exercising with resonance tube and straw. J Voice 2013; 27: 523.e19–34.
39. Guzman M, Calvache C, Romero L, Muñoz D, Olavarria C, Madrid S, et al. Do different semi-occluded voice exercises affect vocal fold adduction differently in subjects diagnosed with hyperfunctional dysphonia? Folia Phoniatr Logop 2015; 67: 68–75.
40. Titze I. Theoretical analysis of maximum flow declination rate versus maximum area declination rate in phonation. J Speech Lang Hear Res 2006; 49: 439–47.
41. Laukkanen A, Titze I, Hoffman H, Finnegan E. Effects of a semi-occluded vocal tract on laryngeal muscle activity and glottal adduction in a single female subject. Folia Phoniatr Logop 2008; 60: 298–311.
42. Guzmán M, Higueras D, Fincheira C, Muñoz D, Guajardo C. Immediate effect of a vocal exercises sequence with resonant tubes. Revista CEFAC 2011; 14: 471–80.

43. Guzman M, Callejas C, Castro C, García-Campo P, Lavanderos D, Valladares M, et al. Therapeutic effect of semi-occluded vocal tract exercises in patients with type I muscle tension dysphonia. Revista Logopedia Foniatría y Audiología 2012; 32: 139–46.
44. Guzman M, Angulo M, Muñoz D, Mayerhoff R. Effect on long-term average spectrum of pop singers' vocal warm-up with vocal function exercises. Int J Speech Lang Pathol 2013; 15: 127–35.
45. Guzman M, Higueras D, Finchiera C, Muñoz D, Guajardo C, Dowdall J. Immediate acoustic effect of straw phonation exercises in subjects with dysphonic voices. Logoped Phoniatr Vocol 2013; 38: 35–45.
46. Story B, Laukkanen A-M, Titze I. Acoustic impedance of an artificially lengthened and constricted vocal tract. J Voice 2000; 14: 455–69.
47. Fant G. Acoustic theory of speech production. The Hague: Mouton Press; 1960.
48. Barrichelo-Lindström V, Behlau M. Perceptual identification and acoustic measures of the resonant voice based on "Lessac's Y-Buzz" – a preliminary study with actors. J Voice 2007; 21: 46–53.
49. Titze IR. Principles of voice production. Englewood Cliffs, NJ: Prentice-Hall; 1994.
50. Orlikoff RF, Baken RJ. Consideration of the relationship between the fundamental frequency of phonation and vocal jitter. Folia Phoniatr (Basel) 1990; 42: 31–40.
51. Orlikoff RF, Kahane JC. Influence of mean sound pressure level on jitter and shimmer measures. J Voice 1991; 5: 113–19.
52. Laukkanen A-M, Ilomäki I, Leppänen K, Vilkman E. Acoustic measures and self-reports of vocal fatigue in female teachers. J Voice 2008; 22: 283–9.
53. Leppänen K, Laukkanen A-M, Ilomäki I, Vilkman E. A comparison of the effects of voice massage and voice hygiene lecture on self-reported vocal well-being and acoustic and perceptual speech parameters in female teachers. Folia Phoniatr Logop 2009; 61: 227–38.