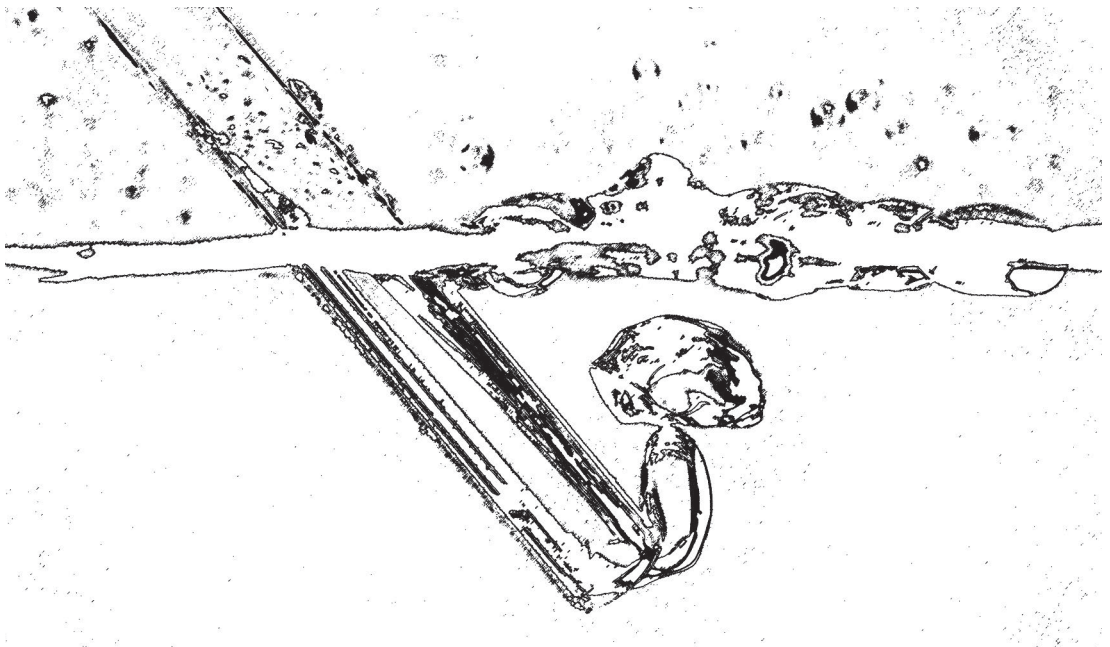


Greta Wistbacka

Oral pressure and flow feedback components in semi-occluded vocal tract exercises





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*Do not tire, never lose interest, never grow indifferent
– lose your invaluable curiosity and you let yourself die.*

It's as simple as that.

Tove Jansson

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Stockholm, June 2017

A handwritten signature in black ink that reads "Greta Wistbacka". The script is cursive and fluid, with the first letter 'G' being particularly large and stylized.

Greta Wistbacka

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REFERENCES

ORIGINAL ARTICLES

LIST OF ORIGINAL PUBLICATIONS

The present thesis is based on the following publications, which will be referred to in the text by their Roman numerals:

I: Amarante Andrade, P., Wistbacka, G., Larsson, H., Södersten, M., Hammarberg, B., Simberg, S., Švec, J.G., & Granqvist, S. (2016). The flow and pressure relationships in different tubes commonly used for semi-occluded vocal tract exercises. *Journal of Voice*, 30, 36–41.

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III: Lã, F., Wistbacka, G., Amarante Andrade, P., & Granqvist, S. (2017). Real-time visual feedback of airflow in voice training: Aerodynamic properties of two flow ball devices. *Journal of Voice*, 31(3), 390.e1–390.e8.

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IV: Wistbacka, G., Amarante Andrade P., Simberg, S., Hammarberg, B., Södersten, M., Švec, J.G. & Granqvist, S. (in press). Resonance tube phonation in water – the effect of tube diameter and water depth on back pressure and bubble characteristics at different airflows. *Journal of Voice*.

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AUTHOR'S CONTRIBUTION

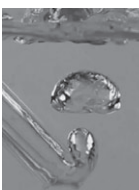
I: The author was responsible for the data collection and analyses as well as writing the manuscript together with the first author of the study.

II: The author did the data collection together with the other authors and was responsible for data analyses and writing the manuscript.

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V: The author was responsible for the data collection and analyses as well as writing the manuscript.



SAMMANFATTNING

Vid röstträning har man under lång tid använt sig av övningar som skapar en förträngning (eng. semi-occluded vocal tract, SOVT) vid munöppningen för att öka flödesmotståndet vid fonation. Ett vanligt sätt att skapa förträngningen på är genom att fonera genom rör som kan variera i längd och diameter. Den fria rörändan hålls i luften eller nedsänkt i vatten.

Syftet med denna avhandling var att undersöka tryck- och luftflödesegenskaper hos tre olika typer av SOVT: fonation genom sugrör/rör med den fria änden i luften, fonation genom rör med den fria änden nedsänkt i vatten samt fonation med två så kallade flödesbollar, som består av ett rör kombinerat med en korg innehållandes en liten boll av cellplast som lyfter när man blåser luft genom röret.

I studierna I, III och IV undersöktes mottryck som funktion av luftflöde. Data samlades in med en flödesdriven ansatsrörssimulator till vilken sugrör/rör/flödesbollar kunde kopplas. I studie II och V undersöktes förändringar i oralt tryck, larynxhöjd och grundtonsmodulation hos röstfriska deltagare som använde den så kallade resonansrörsmetoden, det vill säga fonerade genom glaströr vars fria ände hölls i luften samt nedsänkta i vatten på två djup.

Resultaten av studie I visade att för rör med dimensioner som ofta används i röstträning, påverkar en relativ förändring i diameter tryckeegenskaperna mer än samma relativa förändring i längd för samma luftflöde. När den fria rörändan sänks ner i vatten måste trycket överstiga vattentrycket vid änden av röret innan luftflödet kunde starta. När flödet väl kommit igång följde tryck-flödesprofilen samma mönster som för när röret hölls i luften, med skillnaden att det startade från ett utgångstryck som definierades av vattendjupet. Det resultatet bekräftades även i studie IV. Den oscillerande delen av trycket analyserades i studie IV. Resultaten visade att amplituden av tryckoscillationerna blev större med ökande vattendjup ner till 3 cm djup. Mellan 3 och 7 cm vattendjup hittades inga skillnader i amplituden av tryckoscillationerna.

Resultaten av studie IV visade också att en ökning av luftflödet genom ett rör nedsänkt i vatten påverkade egenskaperna hos bubblorna. Vid låga flöden producerades bubblorna en och en i ett periodiskt mönster. Vid aningen högre flöden producerades bubblorna i par och vid höga flöden var bubbelproduktionen kaotisk och inga tydliga mönster kunde urskiljas. Bubbelegenskaperna påverkades aningen av en förändring i rördiameter från 8 till 9 mm.

Resultaten av studie III visade att tryck-flödes relationen för två varianter av flödesbollar följde samma mönster som motsvarande för sugrör. Tröskelflödet som krävdes för att bollen skulle lyfta var 0.2 L/s. Motsvarande tröskeltryck var 5 cmH₂O för den ena flödesbollen och 20 cmH₂O för den andra.

Resultaten av studierna II och IV visade att fonation genom rör med den fria änden nedsänkt i vatten genererade ett oraltryck som var aningen högre än det hydrostatiska trycket vid röränden. Larynxpositionen sjönk för de flesta deltagare, och grundtonen modulerades vid rörfonation i vatten för deltagarna i studie V.

Resultaten av den här avhandlingen presenterar ny information om de fysikaliska egenskaperna som påverkar fonation genom rör vars fria ände hålls i luften eller nedsänkt i vatten. Resultaten visar också att röstträning med rör nedsänkta i vatten kan påverka röstorganet på olika sätt.

Nyckelord: Röstträning, talterapeutisk röstbehandling, resonansrör, sugrör, luftflöde, tryck, oraltryck, larynxhöjd, vattendjup



ABSTRACT

Vocal training with a semi-occluded vocal tract has been used for a long period of time. One way to obtain a semi-occlusion is by phonating through a straw or tube while keeping the free end of the tube in air or submerged into water.

This thesis aims at investigating pressure and flow characteristics of three types of semi-occluded vocal tract exercises: (i) straw/tube phonation with the free end of the tube in air, (ii) tube phonation with the free end in water and (iii) flow ball devices, which are narrow tubes combined with a basket containing a styrofoam ball that lifts off when air is blown into the tube.

Studies I, III and IV investigated pressure characteristics of these devices as functions of flow. Data were collected with a flow driven vocal tract simulator with an outlet for straw/tube/flow ball connection. Studies II and V investigated changes in oral pressure, vertical laryngeal position and fundamental frequency for vocally healthy volunteers during resonance tube phonation in water at two submersion depths.

The results of study I showed that a change in tube diameter affects the pressure-flow relationship more than a relative change in tube length for tube dimensions commonly used in voice exercises. When the tubes were submerged into water, the flow could not start until the pressure provided by the water depth was overcome, but as flow increased the pressure-flow relationship was similar to that of the tube in air, but with an upward shift in back pressure related to the pressure provided by the water depth. This was also confirmed in study IV. The oscillating part of the back pressure was analysed in study IV, showing that the amplitude of the oscillations increased with increasing water depth up to 3 cm depth. The amplitude of the pressure oscillations were similar at 3-7 cm water depths.

Results from study IV showed that increasing the flow through a tube submerged in water affected the bubble characteristics. At low flows, the bubbles were emitted one-by-one in a periodic manner, at medium flows the bubbles were emitted in pairs of two and at high flows the bubble formation were chaotic and no clear pattern in the bubble characteristics could be identified. Bubble characteristics differed slightly between tubes with 8 and 9 mm diameter.

The results of study III showed that the pressure-flow relationship for two flow ball devices were similar to those of straws. A flow of 0.2 L/s was required for ball lift off for both devices. Back pressure thresholds for ball lift off were 5 cmH₂O for one of the devices, and 20 cmH₂O for the other one.

The results of study II and V showed that resonance tube phonation in water provides an average oral pressure slightly above the equivalent water pressure. The vertical laryngeal position, as measured by dual channel electroglottography,

dropped for most participants during tube phonation in water, and a fundamental frequency modulation appeared during bubbling for the participants in study V.

The results of this thesis presents new information about the physical properties involved in straw phonation with the free end in air and tube phonation with the free end in air and submerged in water. They further suggest that vocal training with phonation through tubes submerged in water can affect the phonatory system in different ways.

Key words: Voice training, voice therapy, resonance tube phonation, straw, flow, pressure, oral pressure, vertical laryngeal position, water depth



ABBREVIATIONS

CIQ	Closed quotient
CT	Computer tomography
CQ	Contact quotient
EGG	Electroglottograph
FB	Flow ball
FBG	Floating ball game (version of flow ball)
HP	High-pass
LP	Low-pass
MRI	Magnetic Resonance Imaging
OQ	Open quotient
p_{back}	Back pressure
p_{sub}	Subglottal pressure
p_{trans}	Transglottal pressure
p_{tube}	Back pressure of tube in air
p_{water}	Water pressure
Re	Reynolds number
RMS	Root of the Mean of the Square
SLP	Speech Language Pathologist
SPL	Sound Pressure Level
SOVT	Semi-occluded Vocal Tract
VFE	Vocal Function Exercises
VLP	Vertical laryngeal position

1. INTRODUCTION

Semi-occluded vocal tract (SOVT) exercises have been used in voice training and therapy for a long period of time. In the exercises, a narrowing is created at the lip area, resulting in a flow resistance. The narrowing can be obtained either by articulatory movements or by adding an artificial constriction such as a tube or a straw. Examples of SOVT exercises are lip trills, tongue trills, raspberries, nasals and phonation through tubes or straws, which free end can be held directly in the air or submerged in water. There are reports of phonation through tubes as a voice training method from as early as a century ago (Spiess, 1904).

Resonance tube phonation is a clinical method that has been used in Finnish voice therapy since the 1960's. It was first described by Antti Sovijärvi, professor of phonetics at Helsinki University, who also taught at the educational programme for speech language pathologists (SLP) at the time. The concept of the method is that the patient phonates through a tube while keeping the free end of it either in free air or submerged in a bowl of water (Sovijärvi, 1964, 1969). Sovijärvi (1964) initially used tube phonation in water when treating children with hypernasality, as no bubbles are produced unless the nasopharyngeal passage is closed. Later, he started to use the method in voice treatment as well as in singing training, and discovered that the exercise seemed to have a lowering effect on the vertical laryngeal position (VLP), as determined by palpation of the larynx. He presented specific instructions regarding tube dimensions based on the patients' voice category and age. He further proposed that the most suitable tube material would be glass and that the water container should be a large open bowl, enabling for bubbling without splashing the water over the sides (Sovijärvi, 1964, 1969). These recommendations are still taken into consideration in clinical practice, and in Finland, it is possible to purchase glass tubes with these specific dimensions in stores providing materials for speech therapy. The tradition of using this method is thus strong in Finland, and positive clinical experiences of using it when treating various voice disorders have been reported (Simberg & Laine, 2007). A similar technique, LaxVox, in which phonation is carried out through a flexible tube submerged in a water bottle, has been presented by Sihvo and Denizoglu (2014). Specific tube dimensions are provided for this technique as well. However, to date there seems to be no clear evidence regarding why and how some specific tube dimensions or type of water container would be more appropriate than others, and to what extent these voice training protocols actually differ with regards to voice training effects.

Despite a growing interest in tube phonation in water within the scientific community, many questions still remain regarding how it affects the phonatory system and how it can be used most effectively in voice therapy. Above all, there seems to be a lack of basic knowledge regarding physical principles of these methods, especially considering the complicated physical system that a tube submerged in water provides. The aim of this doctoral thesis was to investigate physical properties involved in tube phonation in air and in water, with emphasis on back/oral pressure properties as function of flow. Flow feedback components of tube phonation in water and of phonation into flow ball devices were also investigated, as well as changes in oral pressure, VLP and modulation of fundamental frequency (f_0) caused by tube phonation in water.



1.1 An introduction to voice therapy

A voice disorder can be defined as when the voice deviates in pitch, loudness, quality or flexibility from others of similar age, gender and cultural group and/or fails to fulfil environmental vocal demands (Aronson & Bless, 2009; Vilkman, 2004). Voice disorders have traditionally been categorized into organic and non-organic voice disorders (Aronson & Bless, 2009), depending on whether structural or neurological changes can be found at laryngeal level or not. Common diagnoses in treatment-seeking populations are, among others, laryngitis, vocal fold nodules, vocal fold paralysis and functional dysphonia (Coyle, Weinrich & Stemple, 2001; Cohen, Kim, Roy, Asche & Courey, 2012; Herrington-Hall, Lee, Stemple, Niemi & Miller McHone, 1988).

In most cases, the treatment of voice disorders include voice therapy provided by an SLP. The therapy functions either as the primary treatment or in combination with medical and/or surgical treatment (Ramig & Verdolini, 1998). Several treatment protocols for voice therapy have been suggested over the years, such as vocal function exercises (Stemple, Lee, D'Amico & Pickup, 1994), confidential voice therapy (Verdolini-Marston, Burke, Lessac, Glaze & Caldwell, 1995), the accent method (Bassiouny, 1998, Kotby, El-Sady, Bassiouny, Abou-Rass & Hegazi, 1991), resonant voice therapy (Verdolini Abbot, 2008), Lee Silverman Voice Treatment (Fox, Morrison, Ramig & Sapir, 2002; Ramig, Countryman, Thompson & Horii, 1996), laryngeal manual therapy (Mathieson, Hirani, Epstein, Baken, Wood & Rubin, 2009; Roy & Leeper, 1993) and resonance tube phonation in water (Sovijärvi, 1965; Simberg & Laine, 2007).

Overall, review studies on the efficacy of voice therapy have concluded that it provides a rehabilitating effect in the treatment of many voice disorders (see e.g. Desjardins, Halstead, Cooke & Bonilha, 2017; Ramig & Verdolini, 1998; Ruotsalainen, Sellman, Lehto, Jauhiainen & Verbeek, 2007; Speyer, 2008), but results from clinical trials comparing effects of specific therapy approaches have so far not identified many treatment outcome differences between the tested protocols (see e.g. Verdolini-Marston et al, 1995; Pedrosa, Pontes, Pontes, Behlau & Peccin, 2016). This is, however, not surprising, as the therapy protocols overlap each other in content, making the process of identifying the particular parts providing the rehabilitating effect problematic (Van Staan, Roy, Awan, Stemple & Hillman, 2015). Moreover, there seems to be discrepancies in the descriptions and classifications of voice therapy approaches, which complicates generalizations and meta-analyses regarding the specific reasons for vocal improvements even further (Van Staan et al., 2015). This is not an issue exclusive to voice therapy, but a general problem in rehabilitation intervention studies (DeJong, Horn, Gassaway, Slavin & Dijkers, 2004; Dijkers, 2014; Dijkers, Hart, Tsaousides, Whyte & Zanca, 2014; Hart et al., 2014; Whyte et al., 2014). In order to identify the active part in a successful rehabilitation process, detailed descriptions and accurate measures of specific exercise procedures need to be provided (Whyte et al., 2014). This thesis aims at identifying specific physical and some physiological properties related to tube and straw phonation as voice exercises. General outcome effects of a full therapy approach will not be assessed.

1.2 Tube/straw phonation with the free end in air

Vocal effects of tube and straw phonation with the free end in air have been investigated using theoretical and experimental model studies, as well as by measuring physiological effects in humans during and after tube phonation. A wide range of tube/straw dimensions

have been used in these studies. Throughout this thesis, a straw is defined as a soft-walled plastic tube with a narrow diameter. A tube is defined as a hard- or soft-walled plastic or glass tube with a wider diameter. Specific dimensions of investigated straws and tubes in the literature will be presented when considered necessary.

1.2.1. Flow and pressure effects

The flow resistance, hence the relationship between the static back pressure as a function of flow, provided by straws and tubes of different dimensions used in voice training, has been investigated in experimental model studies by Titze, Finnegan, Laukkanen, and Jaiswal (2002) as well as by Smith and Titze (2017). Results from these studies show that the flow resistance is more sensitive to a change in tube/straw diameter than a corresponding relative change in length. Smith and Titze (2017) proposed theoretical models for predicting the back pressure for a set flow for tubes of different dimensions. These models were tested in studies III and IV in this thesis. Effects on the static oral pressure for human participants during straw and tube phonation have also been investigated, showing not surprisingly, a higher oral pressure during phonation through a narrow diameter straw than during phonation through a wider diameter straw/tube (Maxfield, Titze, Hunter, & Kapsner-Smith, 2015; Titze et al., 2002). Laukkanen, Lindholm and Vilkmán (1995a) investigated differences in glottal resistance, hence the ratio of subglottal pressure and glottal flow, before and after tube phonation through an 8 mm diameter tube. The results showed a decrease of glottal resistance due to increased glottal flow, after tube phonation for most participants.

Tube phonation with the tube end in air has been suggested to lower the phonation threshold pressure (PTP), as investigated with excised canine larynges (Conroy et al., 2014). Robieux, Galant, Lagier, Legou, and Giovanni (2015) used tracheal puncture in order to investigate subglottal (p_{sub}) and transglottal (p_{trans}) pressure for two participants during SOVT exercises using e.g. three straws with inner diameters 2, 5 and 8 mm. Their results showed that the p_{sub} increased as the diameter decreased, whereas the p_{trans} increased slightly as the diameter increased for one of the participants, but to a smaller extent than the p_{sub} . For the other participant, the p_{trans} was almost the same using all three diameter straws.

1.2.2 Changes in vocal tract volume and vocal fold adjustments

Changes in the vocal tract volume during tube phonation with the tube end in air have been investigated using electroglottography (EGG), computerized tomography (CT) as well as magnetic resonance imaging (MRI). Laukkanen, Lindholm, and Vilkmán (1995) investigated changes in VLP during tube phonation compared to normal vowel phonation in six vocally healthy participants. They used dual-channel EGG, and found that the VLP tended to rise for most participants during and after tube phonation compared to the baseline. In a study using MRI, Laukkanen, Horáček, Krupa, and Švec (2011) found an increase in the midsagittal area of the vocal tract during straw phonation for a female single subject. After straw phonation, the mouth cavity, pharynx and epilaryngeal region remained larger during vowel phonation as compared to the baseline, but the velar region decreased. The velum was elevated during straw phonation and remained elevated after. Results from studies using CT have suggested that tube phonation increases the volume of the oropharyngeal cavities (Guzman et al., 2017; Vampola, Laukkanen, Horáček, & Švec, 2011a, 2011b), increases vocal tract length due to a decrease of VLP (Guzman, Laukkanen,



et al., 2013; Guzman et al., 2017) and closes the nasopharyngeal passage (Guzman, Laukkanen, et al., 2013; Guzman et al., 2017; Vampola et al., 2011a, 2011b). None of these studies investigated airflow used by the participants during tube phonation and most of them are single-subject studies. However, Guzman et al. (2017) measured vocal tract configuration changes during straw phonation in ten participants with hyperfunctional dysphonia, showing that straw phonation seems to have a direct effect on vocal tract volume. CT has also been used to investigate changes in vocal fold thickness after tube phonation compared to baseline (Hampala, Laukkanen, Guzman, Horáček, & Švec, 2015). However, no prominent changes in vocal fold thickness, glottal width or vocal fold length after tube phonation were found for the two participants.

1.2.3 Acoustic effects

A suggested and investigated acoustic effect of tube phonation is so called impedance matching (Amarante Andrade et al., 2014; Gaskill & Erickson, 2010; Gaskill & Quinney, 2012; Story, Laukkanen, & Titze, 2000; Titze, 2006; Titze & Laukkanen, 2007). The basic concept is that a f_0 lower than the formant F_1 will facilitate vocal fold oscillation, whereas a f_0 above the F_1 makes oscillation more difficult. Impedance matching might occur if f_0 is lower than but close to F_1 , and this will in turn increase the loudness output (Story et al., 2000). The resonance frequencies of a tube depend on tube shape and length (Titze, 2000), and adding an artificial tube to the vocal tract, which acoustically also is a tube, will affect the total vocal tract length thus possibly changing the locations of the resonances (Story et al., 2000). Based on results from experimental model studies it has been hypothesized that impedance matching would have an impact on the vocal fold vibrations (Story et al., 2000; Titze, 2006; Titze & Laukkanen, 2007). However, studies investigating the effect of tube phonation on the ratio between f_0 and F_1 , and possible impact on vocal fold oscillation connected to this change in ratio, have so far presented inconclusive results (Gaskill & Erickson, 2010; Gaskill & Quinney, 2012). In general, the effects on vocal fold oscillations of tube phonation in air, seem to vary both between studies as well as between participants within the same study. When the contact quotient (CQ) has been investigated through EGG measurements, some studies have reported a drop in CQ during and after straw phonation compared to baseline (Guzman, Laukkanen, et al., 2013; Guzman, Rubin, Munoz, & Jackson-Menaldi, 2013) whereas others have reported an increase in CQ or a drop in open quotient (OQ) during and after phonation through a wide diameter tube (Gaskill & Erickson, 2010; Gaskill & Quinney, 2012; Laukkanen et al., 2007). Furthermore, in a study using straw phonation, Guzman et al. (2015) found an increase of CQ on group level. The variability in results can probably at least partly be explained by the differences in tube dimensions used, but it also implies that tube/straw phonation can be carried out in different ways depending at least to some extent on individual factors yet to be identified.

Other reported acoustical effects of tube phonation are an increase of sound pressure level (SPL) by 1-3 dB (Laukkanen, 1992; Vampola et al., 2011a), a decrease in F_1 (Gaskill & Erickson, 2010; Gaskill & Quinney, 2012) as well as a decrease in F_2 and F_4 and an increase of F_3 (Vampola et al., 2011a, 2011b).

1.2.4 Other reported effects

Some treatment effects of straw phonation have been reported. In a randomized controlled trial, Kapsner-Smith, Hunter, Kirkham, Cox, and Titze (2015) compared a treatment

protocol using straw phonation to the vocal function exercises (VFE) therapy described by Stemple (1993). The participants were diagnosed with mild to moderate dysphonia and/or vocal fatigue. The results showed improved quality of life scores based on Voice Handicap Index (Jacobson et al., 1997) for both treatment groups, suggesting that straw phonation and VFE have at least some similar treatment effects. The improvements were significant compared to a control group.

Straw phonation has also been proposed to be used as a tool when measuring vocal characteristics. Titze (2009) suggested that measurements of PTP could be facilitated if doing so during phonation through a narrow straw, as this would limit the risk of articulatory movements affecting the results. Titze and Hunter (2011) also suggested that measurements of voice range profiles could be facilitated using a narrow straw, however some of the participants in this study failed to cover their whole f_0 range during straw phonation.

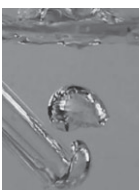
1.3 Tube phonation with tube end in water

1.3.1 The tube recommendations by Sovijärvi

Possibly the first document describing tube phonation with the free end in water is from 1964 (Sovijärvi, 1964). The main purpose of the method was to strengthen the extrinsic muscles of the larynx (Sovijärvi, 1969), enhancing a lowering of the VLP. Sovijärvi (1964) tested different tube dimensions, and came to the conclusion that the tube diameter should be 9 mm for adults and 8 mm for children up to the age of 12 (Sovijärvi, 1969). Further, he recommended specific tube lengths based on the patient's voice category (adults) or age (children). Sovijärvi (1964) claimed that the most appropriate tube length would correspond to the length between the patient's front teeth and the bifurcation of the trachea, hence the tube length should provide a doubling of the vocal tract length. He described how he investigated this with x-ray pictures, but seems to have not provided any systematic report on these findings. Further, he claimed that using the appropriate tube length would lower the larynx at least 3 mm (Sovijärvi, 1978). According to his own reports, he treated hundreds of patients with functional dysphonia using this method from 1953 to 1968, with good results (Sovijärvi, 1969). The specific tube lengths can be found in Table I.

Table I. Recommended tube lengths for resonance tube phonation in water (Sovijärvi, 1964, 1969).

Patient	Tube length [cm]
Children, 8–10 years.	24, 24.5, 25
Children, 11–12 years.	25, 25.5, 26
Sopranos and tenors	26, 26.5
Mezzosopranos and barytones	27, 27.5
Altos and basses	28
Colorature soprano	25.5
Contra bass	28.5



1.3.2 Treatment procedures and reported vocal effects

Simberg and Laine (2007) described how the method has later been used in Finnish clinical practice. They report treating patients with different voice disorders using this method, focusing on phonation, breathing and posture. They presented three versions of the exercise with treatment aims adapted for different voice disorders. The most common procedure was to keep the free end of the tube submerged 1–2 cm into the water during continuous phonation through the tube, using habitual speaking pitch and loudness. This method has been used with patients with e.g. hyper- or hypofunctional voice disorders, vocal nodules or chronic laryngitis. For patients with insufficient vocal fold closure, as during paresis of the recurrent laryngeal nerve, they recommended an exercise in which the tube end is submerged 5–15 cm into the water combined with short phonations. In some cases of breathy phonation, the tube end was recommended to be kept near the water surface or in the air, in order to enhance the auditory feedback for the patient. The authors recommended the exercises to be practiced in the voice clinic until both the SLP and patient are satisfied, followed by a period of home practice for the patient. The suggested exercise protocol consisted of practicing 10 times per day, 1 minute per practice with at least one hour between each practice set (Simberg & Laine, 2007).

Despite positive clinical experiences, there is a lack of evidence and knowledge regarding how these exercises actually affect the vocal apparatus and whether or not they are more effective than other voice exercises. In a randomized clinical trial investigating the effect of voice therapy in groups for students with mild voice disorders, resonance tube phonation was used as the main method for direct voice therapy (Simberg, Sala, Tuomainen, Sellman, & Ronnema, 2006). The results showed less reported vocal symptoms by self-evaluation and an improvement in perceptual vocal quality, as rated by blinded judges, for the treatment group compared to a control group. However, as the resonance tube method was used in combination with other voice exercises, the specific effects of this particular exercise could not be determined. Improvements in voice quality, based on auditory perceptual evaluation, have been reported for female teachers with behavioural dysphonia immediately after resonance tube phonation in water (Paes, Zambon, Yamasaki, Simberg, & Behlau, 2013), as well as for female singers (Enflo, Sundberg, Romedahl, & McAllister, 2013). No control group was used in these two studies.

Detailed analyses of changes in vocal parameters during and after resonance tube phonation in water has been done in a number of studies. The results of these studies have suggested that tube phonation in water increases the collision threshold pressure (Enflo et al., 2013), lowers the VLP and increases the pharyngeal width (Guzman, Castro, Testart, Munoz, & Gerhard, 2013), increases PTP immediately (Radolf, Laukkanen, Horáček, & Liu, 2014), increases the open quotient in the vibratory cycle of the vocal folds (Granqvist et al., 2015) and increases the vibrational amplitude of the vocal folds (Horáček, Radolf, Bula, & Laukkanen, 2014). The tube diameters used in these studies varied between 6 and 9 mm and the water depths between 2 and 10 cm.

In the so-called LaxVox technique the user phonates through a 35 cm long flexible silicone tube, inner diameter 9–12 mm, submerged 2–7 cm into a water bottle (Sihvo & Denizoglu, 2014). Yamasaki et al. (2016) investigated vocal tract adjustments using MRI for ten women with vocal nodules and 10 healthy controls before and after 3 minutes of phonatory training with a LaxVox tube submerged 2 cm in a water bottle. The baseline measurements showed

lower vocal tract volumes for the patients compared to the control group before the exercise. After the exercise, the group differences decreased.

Tyrmi, Radolf, Horáček, and Laukkanen (2017) let people with healthy voices try out both the resonance tube method as well as the LaxVox method at submersion depths 2 and 10 cm in an open bowl. About half of the participants preferred one method to the other, and two participants reported no preference. One difference between the methods reported by the participants was that the resonance tube method generated a sensation of lower airflow during practice than the LaxVox method.

There are also some reports of phonation through narrow straws with the free end submerged in water. Guzman, Jara, et al. (2016) investigated treatment effects of straw phonation in air and in water in a randomized controlled trial. The participants had behavioural dysphonia and were randomly assigned to one out of two treatment groups over an eight-week long therapy period: one using straw phonation in air and one using straw phonation in water at a submersion depth of 5 cm. The straw had an inner diameter of 5 mm and was 25.8 cm long. The results showed vocal improvements in both groups based on self-evaluation and VHI scores. Vocal quality, as rated through auditory-perceptual evaluation, improved only for the group not using water, but no significant differences in treatment outcomes was found between the two groups. Guzman et al. (2015) further found that CQ increased for patients with hyperfunctional dysphonia as well as for a control group during straw phonation with the tube end submerged 3 and 10 cm into water.

Some more extreme tube dimensions as well as water depths have also been investigated. Guzman, Laukkanen, et al. (2016) investigated glottal area parameters based on high-speed digital imaging for eight vocally healthy volunteers during phonation through a flexible tube, 2 cm in diameter and 45 cm in length, submerged 5, 10 and 18 cm into water. The results showed that after phonation through the tube at the 5 cm submersion depth, CQ, closed quotient (CIQ), harmonics-to-noise ratio (HNR) and f_0 increased whereas jitter decreased for most participants. When the tube was submerged deeper into the water, CQ increased more for the participants. The authors concluded that tube phonation at 10 or 18 cm submersion depths might increase respiratory and glottal effort.

1.3.4 Physical properties of tube phonation in water

When the tube end is submerged under the water surface, the pressure behind the tube, hence the oral pressure during tube phonation, needs to overcome the pressure provided by the water depth in order to emit a bubble (Enflo et al., 2013; Granqvist et al., 2015). Furthermore, during tube phonation into water, the oral pressure will oscillate as an effect of the bubbles (Enflo et al., 2013; Granqvist et al., 2015; Radolf et al., 2014). These oral pressure oscillations has been referred to as implementing a kind of massage effect to the larynx (Enflo et al., 2013; Granqvist et al., 2015; Radolf et al., 2014), which probably originates from Simberg and Laine (2007) reporting that their patients often describe the sensation in the larynx during bubbling similar to a massage. However, to date there seems to be no direct measurements of this so-called massage effect reported in the literature.

Different oral pressure oscillation amplitudes have been reported, from about 1.20 cmH₂O at 15 cm submersion depth (Horáček, Radolf, Bula, Vesely, & Laukkanen, 2012) to 5.51 cmH₂O at 10 cm submersion depth (Radolf et al., 2014). Results from a couple of studies



suggest that the amplitude of these pressure oscillations seems not to be much affected by water depth (Guzman, Castro, et al., 2016; Radolf et al., 2014; Tyrmi et al., 2017). Tube phonation in water have also been reported to affect the p_{trans} (Horáček et al., 2014; Tyrmi & Laukkanen, 2017; Tyrmi et al., 2017).

Some measurements of bubble frequencies during tube phonation in water at different water depths have been reported, ranging from 10 Hz (Granqvist et al., 2015) up to 32 Hz (Guzman, Castro, et al., 2016). The bubble pattern and frequencies are likely to directly affect the oral pressure oscillations. Little examination on bubble characteristics during tube phonation in water has been done, although bubbles in water have been studied thoroughly within other scientific fields. However, some initial reports on bubble characteristics and their importance in tube phonation in water have been presented (Ramlakhan, Oosterbaan-Beks, Goes-de Graaff, Arendse, & Mudde, 2014).

1.4 Vocal training with flow ball devices

The flow ball is a device found mainly in musical stores as a respiratory exercise tool for brass wind instrumentalists. It consists of a tube connected to a basket containing a small styrofoam ball, see Figure 1. When blowing air into the tube, the ball lifts off into the air, providing a visual feedback for airflow. There seems to be no scientific reports regarding effects from training with a flow ball, neither for respiratory nor phonatory training. However, the devices seem to provide a back pressure similar to those provided by straws, although different models of the flow ball might provide different back pressures similar to straws of different dimensions. The first author of study III has used the flow ball in singing lessons, and has positive experiences of the device as a pedagogical tool for visualising airflow during singing exercises (F. Lã, personal communication, June 13, 2016). Real-time feedback has been reported to provide positive learning outcomes in singing lessons (Welch, Howard, Himonides, & Brereton, 2005). There seems to be no previous scientific investigations regarding the physical properties of flow ball devices, which was the reason for investigating this in study III.

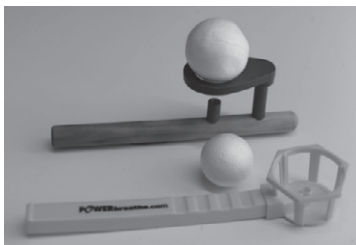


Figure 1. Two flow ball devices from different manufacturers

1.5 Theoretical background

This thesis aims at describing oral pressure variations and flow feedback possibilities which can be expected during tube phonation with the free end in air or in water. The general goal

is to provide a theoretical baseline for SLPs intending to use these methods with patients in the voice clinic. In order to facilitate the understanding of the effects on the vocal apparatus of tube phonation in air and in water, as well as how this can be investigated, a basic overview on flow theory, signal components as well as hydrostatic (water) pressures and air bubbles in water is provided.

1.5.1. Static and oscillatory components of signals

The original data used in the studies in this thesis consist of signals representing changes over time. Most of these signals consist of a static and an oscillatory component. In electronics, the terms direct current DC, and alternating current AC, are used for distinguishing between these components. This terminology is common also in voice literature, however, for pedagogical purposes the terms static and oscillatory will be used throughout this thesis. As will become evident later in this thesis, a pressure signal obtained from tube phonation in water has a static part corresponding to the mean pressure provided by the tube resistance and water depth, and an oscillating part consisting of the pressure fluctuations provided by the bubbles. See Figure 2 for a description.

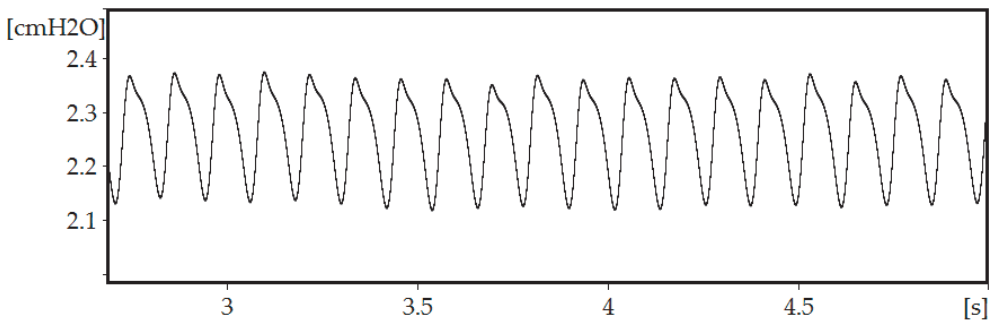


Figure 2. Schematic description of a pressure-time signal consisting of a static and an oscillatory part. The static part is represented by the mean pressure of the signal, which in this case is approximately 2.25 cmH₂O. The oscillatory part corresponds to the variation between approximately 2.15 and 2.37 cmH₂O.

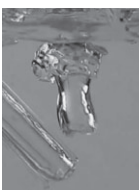
1.5.2 Flow, pressure and resistance in tubes

The term flow, in this thesis equivalent to airflow, describes the movement of gas molecules from a high pressure space to a low pressure space over time. The driving pressure is the pressure difference between the two spaces, and is related to the flow. A tube (or equivalent) through which the flow is moving, provides a resistance to the static part of the flow. The relationship between the three quantities static flow, U , driving pressure, P , and resistance of the pathway, R , is equivalent to Ohms law for electric circuits, hence:

$$P = R \cdot U$$

The unit for flow is expressed by a volume unit over a time unit. Common ways to express flow are millilitres per second (mL/s) or litres per second (L/s).

An air stream in a specific case travels in a specific direction. In flow theory, the terms *downstream* and *upstream* are common, indicating relation between positions in the air



stream. If the downstream system changes, it can affect the behaviour of the air source. If the source maintains a certain pressure regardless of a change in the resistance downstream from the source, it is a constant pressure source. If the source on the other hand maintains a constant flow despite a change in the downstream resistance, it is a constant flow source. A system driven by a constant flow source can be seen as a flow driven system. The data collection in three of the studies in this thesis was done using a *flow driven* vocal tract simulator.

Depending on properties of the gas, amount of flow and tube geometry, flow in tubes occurs in different regimes. These regimes can be divided into laminar and turbulent flow regimes. For a constant flow in the laminar regime, the flow particles move evenly in a predictable way. At any fixed position in the pipe, the speed of the flow will be the same over time. Turbulent flow, on the other hand, is less predictable with irregular velocity fluctuations (Nakayama & Boucher, 2000; Tritton, 1988), even if the average flow is constant. The flow regime in a long tube depends in general on four variables: the diameter of the tube, d , the average speed of flow, u , the density of air, ρ , and the viscosity of air, μ . Based on these four variables, the dimensionless parameter Reynolds number (Re) can be calculated:

$$Re = \frac{\rho u d}{\mu}$$

If Re is less than 30, the flow will always be laminar. If Re is above 30, the flow will find its expected laminar regime after it has passed the inlet region of the tube. If the Re is between 2000 and 10000, transition to turbulent flow will occur at some point (Tritton, 1988). Hence, the flow regime is also affected by other variables than the ones in the equation for Re, so there are no strict critical values of Re for transitions between laminar and turbulent flow. In the inlet region of the tube the flow regime is affected by even more variables than those determining Re. The length of this inlet region varies depending on the flow velocity and the geometry of the volume behind the tube as well as the tube connection to this volume. At low values of Re, the inlet region is short and can mostly be ignored, but as the Re increases the flow in the inlet region will become longer and increasingly difficult to predict (Nakayama & Boucher, 2000; Tritton, 1988). The flow finds its expected regime after it has passed this inlet region. The inlet region possibly complicates the process of building theoretical models of flow during tube phonation in air and in water, because the tubes used in vocal training are sometimes so short that the inlet region might cover the whole tube length.

1.5.3 Hydrostatic pressure and air bubbles in water

Pressure, P , is defined as a force, F , over an area, A :

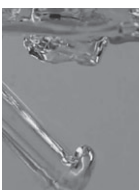
$$P = \frac{F}{A}$$

The unit for pressure is N/m², or pascal (Pa). The atmospheric pressure, hence the normal average air pressure, is $p_0 = 101.3$ kPa.

Hydrostatic pressure, or water pressure, is the pressure created by water at a given depth. The pressure increases with increasing depth. Another common way of expressing pressure

is in centimetres of water column (cmH₂O), which is directly translated as the pressure equivalent to the vertical distance (in cm) to the surface. At a water depth of 2 cm, the hydrostatic pressure will be 2 cmH₂O, or about 0.20 kPa.

When air is blown into water, as during tube phonation in water, bubbles will be emitted at the tube end. The formation of bubbles have been studied for example within the field of chemical engineering (Davidson & Amick, 1956). Bubble formation changes with flow, similarly to the different flow regimes mentioned above. Bubble formation at an orifice is a complicated process affected by a number of variables. These variables are, among others, the size of the orifice, flow rate, depth of submergence, back cavity volume upstream from the orifice and the properties of air and water (Clift, Grace, & Weber, 1978). When flow is increased, the bubble characteristics change. At low flows, bubbles are emitted one by one separated from each other. When flow is increased, the bubbles will start pairing up (Clift et al., 1978; Tufaile & Sartorelli, 2000) to a mushroom-like shape (Nedeltchev, Shaikh, & Al-Dahhan, 2011). When flow is increased even more, the bubble formation will turn chaotic (Nedeltchev et al., 2011; Tufaile & Sartorelli, 2000). Furthermore, changes in bubble frequencies and volumes seems to be nonlinear with respect to flow (Davidson & Amick, 1956).



2. AIMS

The aim of this doctoral thesis was to investigate physical and some physiological properties during tube phonation in air and in water, particularly back/oral pressure properties as functions of flow. Besides the properties of tubes and straws commonly used in voice therapy and training, the pressure-flow properties two flow ball devices were assessed. Immediate physiological effects of tube phonation with the free end in air and in water were investigated.

Study I

The aim of the first study was to investigate the pressure-flow relationship for straws and tubes used in voice training, and how this relationship is affected when the tubes are submerged into water.

Study II

The aim of the second study was to investigate changes in the vertical laryngeal position and oral pressure during resonance tube phonation in water and in air.

Study III

The aim of the third study was to investigate aerodynamic properties of two flow ball devices that can be used in vocal training. Pressure and ball height as functions of flow were investigated.

Study IV

The aim of the fourth study was to investigate pressure variations and bubble formations at different flows, diameters, depths and back volumes for resonance tubes submerged in water.

Study V

The aim of the fifth study was to investigate variations in oral pressure, fundamental frequency and vertical laryngeal position for vocally healthy volunteers during resonance tube phonation in water.

3. METHODS

3.1 Data collection

As the data collection procedures in studies I, III and IV as well as in studies II and V were similar, they will be presented together.

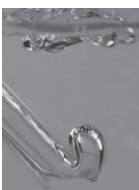
3.1.1. Studies I, III and IV – flow driven vocal tract simulator

In studies I, III and IV, data were recorded using a flow-driven vocal tract simulator. The original simulator was built for study I and some improvements were made for studies III and IV.

The first version of the simulator can be seen in Figure 3. It consisted of a pressurized air cylinder, connected via a flow meter to a large syringe with an outlet for tube connection. The back cavity volume of the syringe was adjustable. A pressure transducer was connected to the syringe to measure the pressure variations inside the cavity. To ensure that the system stayed flow-driven, a piece of fabric was attached downstream to the flow meter, creating a pressure drop across the fabric. This pressure drop determined the flow and was considerably greater than the pressure variations caused by the tubes and tubes in water, thus keeping the flow approximately constant.

The flow meter used in study I enabled for flow measurements, however not for detailed control of the flow. In study I, the amount of flow going into the system was controlled manually from the pressurized air cylinder, which made small adjustments in the flow challenging. For studies III and IV the flow meter was replaced with a flow controller, enabling for digital adjustments of the flow down to 0.001 L/s accuracy. A supplementary custom-made software was used to adjust flow over time. The syringe used in study I was replaced in studies III and IV to increase the measurement accuracy of the cavity volume.

Calibration of the pressure transducer was done using a U-tube manometer. In study I, calibration of flow was conducted using a pneumotach calibration unit without the flow resistance attached, and verified with a rotameter. In study III and IV flow calibration was conducted with the flow controller, calibrated by the manufacturer.



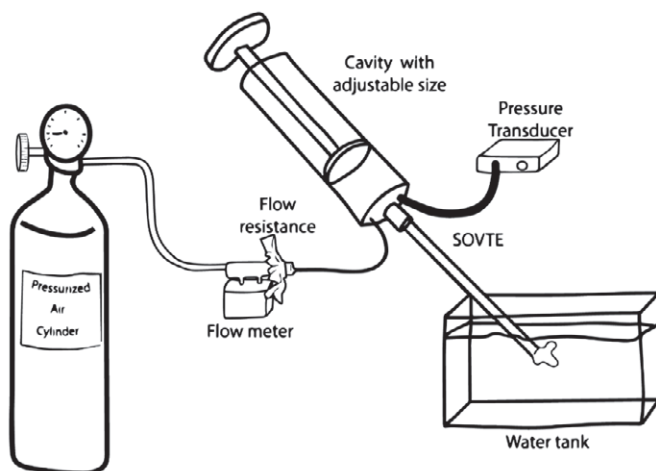


Figure 3. The vocal tract simulator used in study I. The flow meter and flow resistance was replaced with a digital flow controller for studies III and IV. The back cavity volume syringe was also replaced after study I.

Picture design by Pedro Amarante Andrade

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3.1.2. Studies II and V – Human participants

The data collection methods were similar in studies II and V, using dual channel EGG and oral pressure measurements. Audio was recorded for documentation purposes only.

3.1.2.1 Participants

The purpose of studies II and V was to investigate changes induced by tube phonation in water for vocally healthy participants, as well as to investigate the consistency in results between methods for data extraction and analyses. Participants were recruited personally by the thesis author. The two participants in study II were familiar with tube phonation in water, as one of them was a trained speech language pathologist and the other a speech language pathology student. The participants in study V were novel to tube phonation in water. All were vocally healthy as reported by themselves. No standardized screening procedure for vocal pathologies was used. The participants in study V were instructed to the procedure immediately prior to the data collection. After initial analysis, data from two participants were excluded from further analysis due to continuously low values in the static oral pressure, indicating that the intended water depths were not met for these participants.

3.1.2.2 Dual channel electroglottograph and oral pressure measurements

The dual-channel EGG is a device to visualise vocal fold contact in the vibratory cycle. The device consists of two electrode pairs that are placed on the participant's neck, at the height of the glottis. When the vocal folds are in contact, the signal travels easier between the electrodes leading to a higher voltage output. This is due to the fact that human tissue conducts electricity better than air. Hence, the EGG measures relative changes of vocal fold contact area (Rothenberg, 1992).

Besides vocal fold contact, the dual-channel EGG has also been used to analyse changes in the VLP. Changes in the signal strength between the upper and lower electrode pairs are indicative of changes in laryngeal height, which can be estimated by adding a manual calibration procedure of laryngeal height (Rothenberg, 1992). This technique has been used to measure VLP in a series of studies (Iwarsson, 2001; Iwarsson & Sundberg, 1998; Laukkanen, Lindholm, Vilkmán, Haataja, & Alku, 1996; Pabst & Sundberg, 1993). Laukkanen, Takalo, Vilkmán, Nummenranta, and Lipponen (1999) compared the measurement of VLP by dual-channel EGG to simultaneous videofluorographic registration of VLP, finding that the two methods generated more or less similar results in most cases. In studies II and V, the dual-channel EGG was used to obtain information on VLP (II and V) and f_0 modulations (study V). The oral pressure was measured by a pressure transducer connected to a thin plastic tube that the participants held in the corner of the mouth. Pressure was calibrated with a U-tube manometer. The experimental set-up can be seen in Figure 4.

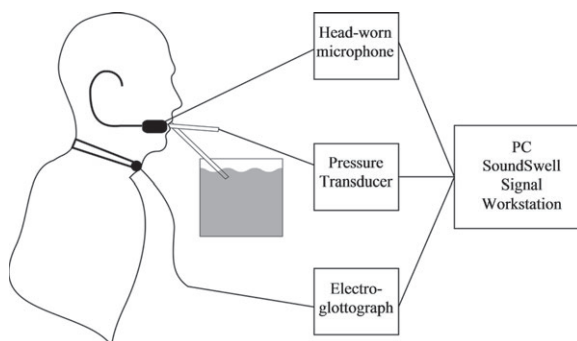


Figure 4. The experimental set-up for studies II and V.

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3.2 Experiments

Study I

The physical properties of eight straws with diameters 3.3–7.5 mm and lengths 1–15 cm were examined, as well as one resonance tube, 26 cm length, 9 mm diameter, glass and a plastic tube similar to a LaxVox tube, 35 cm length, 10 mm diameter. The resonance and LaxVox tubes were further assessed with the free end submerged in water at 1–7 cm, in steps of 1 cm. The angle of submersion was 45° for the resonance tube and 90° for the LaxVox tube, see Figure 5. The flow was controlled by varying the pressure upstream to the flow resistance (fabric). The maximum pressure of 2000 cmH₂O generated a maximum flow of approximately 0.5 L/s. The static back pressure was investigated as a function of flow.





Figure 5. The submersion angles and water depth definitions used in study I. Resonance tube at a 45° angle to the left (same angle and water depth definition was used in study IV), silicone tube resembling a LaxVox tube at a 90° angle to the right.

Picture by Svante Granqvist.

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Study II

The participants phonated through 26 and 28 cm long, 9 mm in diameter resonance tubes, keeping the free end of the tube in air and submerged 2 and 6 cm in water as well as varying the water depth in a linear manner between air and 10 cm submersion depth. The participants used submersion angles of their own choice, resulting in slightly shallower water depths than intended. The VLP signal from the EGG and oral pressure were examined.

Study III

The physical properties of two flow ball devices were examined, henceforth FB and FBG device. Please recall Figure 1 in section 1.4. Four ball sizes were used, diameters 29.0–48.1 mm and weight 0.304–1.595 g. The maximum flow examined was 0.5 L/s.

The ball height was investigated as a function of flow by analysis of a video recording. The static back pressure was investigated as a function of flow. As the pressure-flow profiles resembled those of straws, adaptations to theoretical flow models by Smith and Titze (2017) were made in order to determine equivalent straw dimensions corresponding to the pressure-flow profiles of the two devices.

Study IV

The physical properties of two resonance tubes, diameters 8 and 9 mm, lengths 26 cm, were investigated through five experiments. To ensure that the water depth would be accurate for the whole recording, the bowl was partially covered with plastic. The definition of water depth was the same as in study I, recall Figure 4.

Experiment 1: The static and oscillating back pressure were investigated separately as functions of flow up to 0.38 L/s with the tubes in free air and with the free end of the tubes submerged in water at depths 1–7 cm. The static pressure-flow profile was compared with the theoretical flow models by Smith and Titze (2017), and the model was extended for tubes in water.

Experiment 2: The 9 mm diameter tube was submerged in water depths 2, 4 and 6 cm and the flow was increased slowly up to 0.05 L/s. The bubble modes at three flows were visually inspected from a video recording. Periodicity was further illustrated by means of correlograms of the back pressure oscillations.

Experiment 3: The tubes were submerged at water depths 2, 4 and 6 cm, and flow was slowly increased up to 0.08 L/s. The flow required for shifts between bubble modes was determined by visual inspection of correlograms.

Experiment 4: The tubes were submerged at water depths 2, 4 and 6 cm and flow was set to eleven steps up to 0.04 L/s. The bubble frequency as a function of flow was determined through spectral analysis of the back pressure. The bubble volume as a function of flow was calculated based on bubble frequency and flow values.

Experiment 5: The tubes were submerged at water depth 2 cm at two set flows. The back cavity volume was altered in steps of 6 ml between 6 and 60 ml. The bubble frequency as a function of back volume was determined through spectral analysis of the back pressure. The bubble volume as a function of back volume was calculated based on bubble frequency and flow values.

Study V

The participants phonated through a 28 cm long, 9 mm in diameter resonance tube, keeping the free end of the tube in air and submerged 2 and 6 cm in water in a 45° angle. Eight takes were recorded for each task. For participant 1, only 4 takes per task were recorded. Static and oscillating oral pressure as well as bubble frequency were examined from the oral pressure signal. The analyses were conducted by using spectral methods, correlograms, peak-to-peak measurements and peak counting of the low-pass (LP) filtered oral pressure signal. Different cut-off frequencies were applied to the LP to investigate possible differences in results caused by filtering characteristics. Modulation of f_0 , obtained from the EGG-signal, was analysed by means of a correlogram combined with RMS analysis. Changes in VLP obtained from the EGG were examined by comparing the signal output for the different conditions.

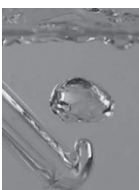
3.3 Analyses

Study I

Flow and pressure data were LP filtered and downsampled in order to remove all oscillating parts of the signals. Pressure-flow profiles were obtained for all investigated tubes in air and in water.

Study II

Oral pressure data were LP filtered at cut-off frequencies 30 Hz for the male participant and 50 Hz for the female participant, in order to filter out the oscillations from the voice but keep the oscillations from the bubbles. Means, peaks and standard deviations of oral pressure and bubble frequency were obtained for the filtered pressure data. The voltage output for the VLP signal was used in order to analyse means and standard deviations of



VLP during bubbling at the two submersion depths and tube in air, compared to baseline. In order to investigate changes in VLP and oral pressure during a varying water depth, both original signals were LP filtered at 5 Hz. The relationship between VLP and oral pressure was then investigated using Spearman's non-parametric correlation test.

Study III

Ball height was digitally measured by analysing changes in pixel brightness in a video recording, resulting in 25 measurements per second. Pressure and flow signals were downsampled to 25 Hz and synchronized with the ball height measurements. Pressure-flow, ball height-flow and ball height-pressure relationships were obtained. The equivalent straw dimensions were found by adaptations of the flow models presented by Smith and Titze (2017) and were made by a solver add-in in *Microsoft Excel* as well as a brute force method implemented in *Matlab*.

Study IV

Experiment 1: The static part of the back pressure as a function of flow was analysed as in study I and compared with a modified flow model (Smith & Titze, 2017). The oscillating part was analysed by high-pass (HP) filtering the pressure signal at cut-off frequency 1 Hz to remove the static component. The Root Mean Square (RMS) was extracted from the filtered signal using a smoothing filter cut-off at 0.3 Hz. The RMS-pressure and flow signals were further downsampled and RMS-pressure-flow profiles were obtained.

Experiment 2: Bubbles were video recorded using a framerate of 50 frames per second with an exposure time of 1/1000 s. Three bubble modes were identified and consecutive images were extracted from the video recording for bubble type illustration. The periodicity of the back pressure for the corresponding times was analysed by means of a correlogram (Granqvist & Hammarberg, 2003) with a window length of 50 ms.

Experiment 3: Correlograms of the back pressure signals were used to visually detect the shifts in bubble types. See Figure 6. The visual inspections were made by two raters. Intra- and interrater reliabilities were analysed using intra class correlation (ICC). Medians and inter quartile ranges were calculated for the flows at the bubble type shifts and nonparametric statistical tests were used in order to compare results for the flow thresholds with regards to tube diameter and water depth.

Experiment 4: Bubble frequency was analysed using a spectrum of the back pressure signal. This method enabled for detecting bubble frequencies in the regular and bimodal bubble modes. In the chaotic bubble mode, no clear peaks could be identified in the spectrum. See Figure 7. Bubble volume was calculated based on bubble frequency values.

Experiment 5: Bubble frequency and volume were analysed as in experiment 4. Statistical analyses were performed as in experiment 3.

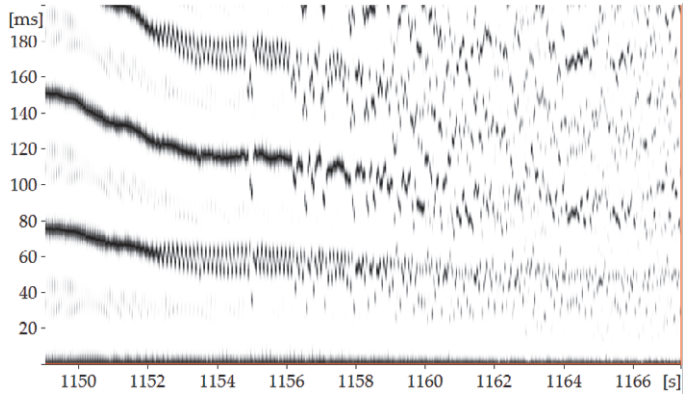


Figure 6. A correlogram of the back pressure signal from an 8 mm diameter resonance tube submerged 4 cm in water during a slowly increasing flow. To the left, during regular bubble formation, the first (lowest) and second candidates are clear and similar. When the bubble formation shifts to bimodal patterns, at 1152 s, the first candidate is separated in two, showing an alternating period time. When flow is increased further, the candidates start to scatter and no clear period times can be seen, at 1158 s, hence the bubble formation has turned chaotic.

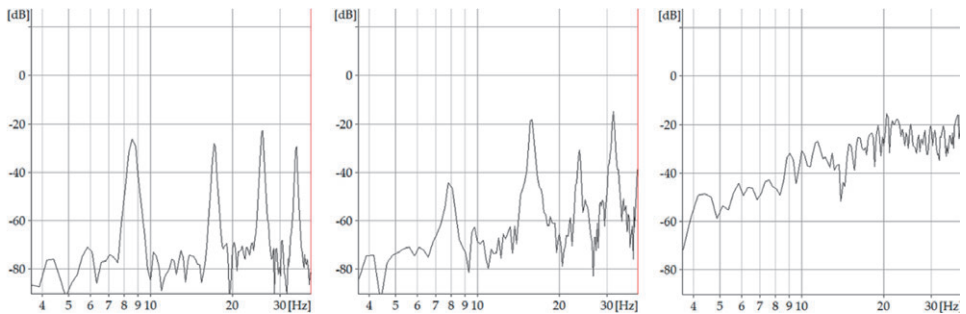
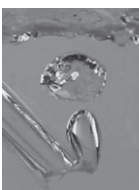


Figure 7. Spectrum of the back pressure signal at three flows, left 0.004 L/s, middle 0.01 L/s, right 0.036 L/s. Note the clear peaks in the left picture (bubble frequency = 8.6 Hz), the bimodal peaks in the middle picture (bubble frequency = 16 Hz), and the lack of peaks in the right picture. This method for bubble frequency extraction was used in experiments 4 and 5 in study IV and in study V.

Study V

The static oral pressure was analysed by calculation of average and standard deviation of the oral pressure signal. The oral pressure oscillation amplitudes were analysed by peak-to-peak measurements after LP filtering the oral pressure signal, using four separate cut-off frequencies, enabling for comparison of results with different filters. The amplitude of the oral pressure oscillations was also investigated by calculation of the RMS by further applying a HP filter with cut-off frequency 1 Hz to the already LP filtered oral pressure signals. The HP filter removed the static part of the oral pressure. An RMS smoothing filter cut-off at 3 Hz was used. Bubble frequency was investigated by (i) means of a correlogram



applied to the LP filtered signals, (ii) by counting the pressure peaks from the LP filtered oral pressure signals, and (iii) by spectral analysis of the unfiltered oral pressure signal. VLP was analysed by comparing averages of the VLP signal from the EGG device.

Modulation of f_0 was analysed by extracting the f_0 from the EGG signal by means of a correlogram using a time window of 5 ms. This generated a signal where the static part showed the f_0 at each time point, and the oscillating part showed possible modulations in the f_0 over time. To remove the average, hence static part of f_0 , the extracted signal was further HP filtered at a cut-off frequency of 3 Hz. RMS of the oscillating part of the f_0 was calculated from the HP filtered signal. This method has earlier been used in a study investigating vibrato in a violin performance (Gleiser, Friberg, & Granqvist, 1998).

4. RESULTS

Study I

The results showed that differences in pressure-flow relationship for tubes in air is predominately determined by the tube diameter, where a narrower diameter provides a larger back pressure for a given flow than a wider diameter. A corresponding relative change in tube length also affects the pressure-flow relationship, but to a smaller extent. The wider tubes with diameters of 9 (resonance tube) and 10 mm (LaxVox tube) produced relatively low back pressures for a given flow. When submerged into water, the back pressure had to overcome the pressure given by the water depth before flow could start. After this constant pressure was overcome, the pressure-flow profile was similar to the one with the tube end kept in air, but shifted upwards approximately corresponding to the water depth. See Figure 8 for a selection of the pressure-flow profiles. The back pressure required for flow to start was slightly less for the 9 mm diameter tube than the 10 mm diameter tube, which mainly was due to the difference in the angle of submersion. The 9 mm diameter tube was submerged at a 45° angle and the 10 mm diameter tube was submerged at a 90° angle, according to different therapy protocols for resonance tubes and LaxVox tubes. With the tube end facing downwards (90° angle) the bubble is pushed deeper than the tube end; this is not the case when the tube end is submerged at a 45° angle.

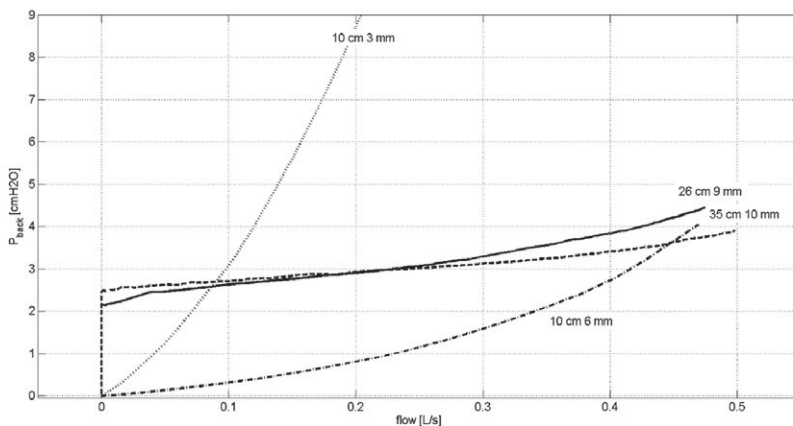


Figure 8. Pressure-flow profiles for two straws with the free end in air as well as a resonance tube and LaxVox tube with the free end submerged 2 cm into water.

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Study II

Oral pressure and VLP were measured from two participants phonating through resonance tubes of two lengths at submersion depths 2, 6 and varying depths between 0 (air) and 10 cm. The mean oral pressure varied between 2.00 and 2.50 cmH₂O at the shallower submersion depth and between 4.47 and 5.42 cmH₂O at the lower submersion depth. Bubble frequencies varied between 14 and 22 Hz, with slightly lower bubble frequencies at the



lower submersion depth compared to the shallower submersion condition. The VLP increased for both participants during tube phonation in air, and decreased during tube phonation with the tube end in water. When increasing the water depth between 0 and 10 cm, the VLP dropped during all takes for the female participant. For the male participant, the corresponding results were more inconclusive with a great variability between takes.

Study III

The two flow ball devices, FB and FBG, were investigated with four different sized balls. Pressure-flow profiles were made on the devices without balls, showing that the FB model generated a considerably lower back pressure for a given flow than the FBG model. For the FB model, the flow and pressure thresholds for the balls to lift off were 0.2–0.5 L/s and 5–25 cmH₂O, respectively. For the FBG model, the flow and pressure thresholds for balls 1–3 to lift off were 0.27–0.4 L/s and 20–50 cmH₂O, respectively. Ball nr 4 failed to lift off for the FBG model for the flows used.

The straw dimension adaptations based on the basic flow model by Smith and Titze (2017) showed that the pressure-flow profile of the FB model was similar to that of a straw with a diameter of 3.7 mm and a length of 31 mm. The profile for the FBG model was similar to that of a straw with a diameter of 3.0 mm and a length of 33 mm. The predictions for back pressure matched the measured data for the FB and FBG model with an average error of 0.14 and 0.17 cmH₂O, respectively.

Study IV

In study IV, pressure components were investigated for two tubes with diameters 8 and 9 mm when submerged in water at different water depths. The back pressure component was divided into the static part and the oscillating part. The static part of the back pressure generated similar pressure-flow profiles as the ones in study I and study III. The results from the analyses of the oscillating part showed that the amplitude of the oscillations increased with water depth for depths of 1–3 cm, but at depths 3–7 cm the amplitude of the oscillations were approximately constant. With increasing flow, the bubbles were emitted from the tube end in three modes: regular, bimodal and chaotic. These bubble modes were inspected visually from a video recording, and the shifts between them were determined by visual inspections of correlograms of the back pressure signal, see Figure 9. Using the narrower tube the shifts in bubble modes appeared at lower flows than with the wider tube. The bubble frequency increased with increasing flow in a nonlinear manner. An increase of back cavity volume led to a decrease in bubble frequency.

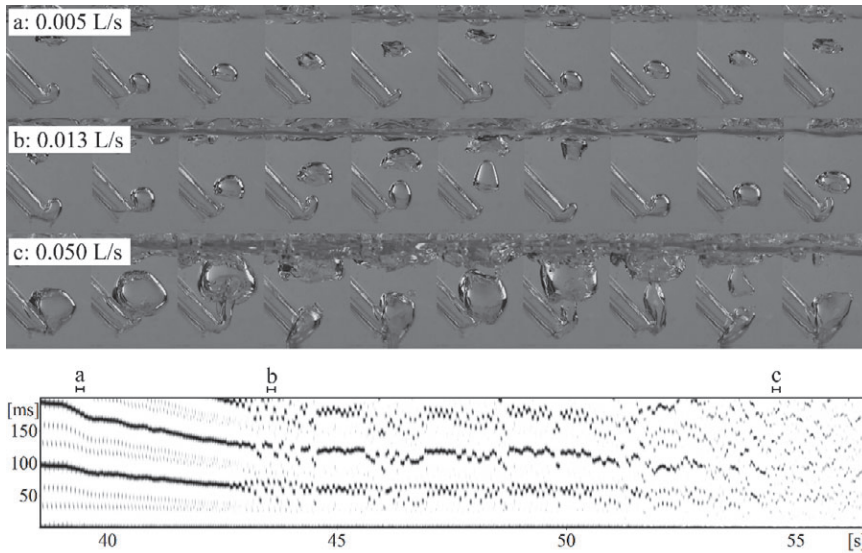


Figure 9. Bubble characteristics at three set flows for a resonance tube, 9 mm diameter, 26 cm long at 4 cm submersion depth, study IV.
 Picture by Svante Granqvist
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Study V

Static and oscillating oral pressure, bubble frequency, f_0 modulations and VLP were measured from four participants phonating through a resonance tube at submersion depths 2 and 6 cm as well as with the tube end kept in air. The mean static oral pressure varied between 2.25 and 3.25 cmH₂O at 2 cm submersion depth and between 6.87 and 7.42 cmH₂O at 6 cm submersion depth. Both the RMS oscillation amplitudes and the peak-to-peak amplitudes were significantly higher at 2 cm than at 6 cm submersion depths, see table II.

The differences in bubble frequencies between the submersion depths were statistically significant for all three methods, showing that the bubble frequencies were higher at 2 cm than at 6 cm submersion depth, see table II and III. The manual counting of peaks generated significantly higher bubble frequency values than the other two methods, according to a one-way ANOVA combined with a post hoc Bonferroni (peak counting – correlogram: $p < .001$; peak count – spectral analysis: $p = .002$).

The modulation of f_0 , as measured by means of a correlogram combined with RMS analyses, showed a modulation of f_0 during bubbling that was not present in tube phonation in air or during normal phonation on a vowel. The f_0 modulation was not affected by water depth, see table III. The VLP dropped for three participants during bubbling and increased for one participant.

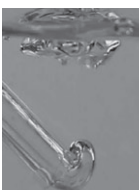


Table II. Group results of differences in oral pressure oscillation amplitudes and bubble frequencies (2 methods) between the two water depths.

Submersion depth	Means and standard deviations on group* level								<i>t</i>	<i>df</i>	<i>p</i>
	2 cm				6 cm						
<i>LP filter cut-off frequency [Hz]</i>	50	40	30	20	50	40	30	20			
<u>Oral pressure oscillation amplitudes</u>											
RMS [cmH ₂ O]	0.91 (0.26)	0.90 (0.26)	0.89 (0.26)	0.82 (0.24)	0.79 (0.24)	0.78 (0.24)	0.77 (0.24)	0.73 (0.21)	3.463	222	.001
Peak-to-peak [cmH ₂ O]	1.32 (0.48)	1.26 (0.48)	1.18 (0.47)	0.97 (0.42)	1.01 (0.52)	0.97 (0.50)	0.91 (0.47)	0.77 (0.38)	4.241	222	<.001
<u>Bubble frequency</u>											
Correlogram [Hz]	15.98 (1.93)	15.98 (1.94)	15.91 (1.89)	15.66 (1.78)	13.34 (2.10)	13.35 (2.04)	13.33 (1.98)	13.10 (1.93)	10.072	222	<.001
Peak count [Hz]	17.71 (3.01)	16.99 (2.33)	16.58 (1.96)	16.24 (1.83)	15.63 (2.77)	15.05 (2.22)	14.71 (2.05)	14.04 (2.04)	10.072	222	<.001

* Participants *n* = 4

RMS: Root Mean Square

Table III. Group results of differences in fundamental frequency modulation and bubble frequencies (1 method) between the two water depths

Submersion depth	Mean and standard deviations on group level*		<i>t</i>	<i>df</i>	<i>p</i>
	2 cm	6 cm			
<u>Fundamental frequency oscillations, RMS [Hz]</u>	8.98 (6.62)	8.69 (5.73)	.174	54	.862
Bubble frequency, spectral analysis	14.98 (2.06)	13.36 (2.77)	2.077	37	.045

* Participant *n* = 4

RMS: Root Mean Square

5. DISCUSSION

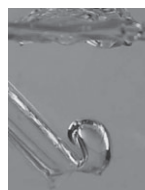
The aim of this dissertation was to investigate back pressure and flow feedback aspects of three types of tube phonation: tube or straw phonation with the tube end in air, tube phonation with the free end in water and phonation with flow ball devices. This dissertation presents physical data regarding how the back/oral pressure is affected during tube phonation with the tube end in free air and in water, as well as physical data regarding back pressure and flow feedback for two flow ball devices. Physiological data as oral pressure, vertical laryngeal position (VLP) and fundamental frequency (f_0) modulations were recorded from in total eight vocally healthy volunteers during tube phonation with the tube end in air and in water.

5.1 Pressure-flow relationship – static pressure

The static part of the pressure-flow relationship of tubes, straws and flow ball devices were investigated in studies I, III and IV. In studies III and IV, the results were compared to a theoretical flow model presented by Smith and Titze (2017). In studies I and IV the free end of the tubes were submerged at 1-7 cm water depths in steps of 1 cm. In studies II and V the average oral pressure, corresponding to the static back pressure, was investigated for tube phonation with the free end kept in air and in water at 2 and 6 cm submersion depths.

With regards to the literature as well as the results from the present studies, it seems rather robust to state that for typical tube dimensions used in voice training, a change in tube diameter affects the static back pressure to a larger extent than a corresponding relative change in tube length. A tube diameter of 8-10 mm (studies I and IV) generates a rather low back pressure for airflows within human ranges. When the tube end is submerged into water, the flow will not start until the pressure provided by the water depth at the tube end is overcome. Once the hydrostatic pressure has been overcome, the pressure-flow profile is similar to that of the tube with the free end in air, but shifted upwards as the pressure baseline starts from the hydrostatic pressure threshold and not from 0. This has earlier been stated by for example Enflo et al. (2013) and Granqvist et al. (2015).

In study III, the flow models presented by Smith and Titze (2017) were used to estimate straw lengths and diameters generating corresponding pressure-flow profiles as the tested flow ball devices. The flow ball devices generated similar pressure-flow profiles as straws, but the two devices differed with regards to back pressure. The estimated difference in the diameters of the flow ball devices was only 0.7 mm, but the narrower device, FBG, generated an almost 2.6 times higher back pressure for a given flow than the FB device. Given that the flow needs to be at least 0.2 L/s for the balls to lift off, and about 0.4 L/s to keep the ball 10 cm in the air, the FBG device requires remarkably higher back pressures than the FB device. The threshold flow of 0.2 L/s can be compared to the flow threshold to chaotic bubble patterns which in study IV appeared before 0.03 L/s. In study V, regular and bimodal patterns could be identified in the spectrum of the oral pressure signal for most participants, indicating that the airflows used were lower than 0.03 L/s. This would point to a possibly important difference between tube phonation in water and phonation with a flow ball device.



In study IV, a combined model for the back pressure for tubes in water was presented, as

$$p_{back} = p_{tube} + p_{water}$$

in which p_{tube} is the back pressure with the tube end in air based on the modified flow model (Smith & Titze, 2017) and p_{water} is the hydrostatic pressure at the tip of the tube end submerged in water. The modified flow model (Smith & Titze, 2017) fitted the results for the experimental data for tubes with the free end in air well. The combined model showed less accuracy with the experimental data, which might be at least partly explained by the models sensitivity to a representative measurement of water depth. Depending on the angle of the tube submersion as well as the details regarding measurement of water depth, the results will slightly differ. The submersion angle used with the simulator in studies I and IV was 45° for the resonance tubes. This angle was considered to be an accurate estimate for how the tubes are submerged into water in the clinic. The LaxVox tube in study I was submerged at a 90° angle, as it would be used in the clinical setting when keeping the tube end in a water bottle.

The tube angle affects how the bubbles are emitted from the tube end. With a 90° angle, the bubble needs to go deeper than the tip of the tube end in order to pass the tube on the side. This would generate a slightly higher pressure before flow can start compared to a tube submerged at a 45° angle. Furthermore, this would result in an underestimation of the actual back pressure for a given flow at a given water depth for the 90° angle with regards to the combined model. For the 45° angle on the other hand, the bubble can leave the tube end without touching the lowest part of the tube end. Based on visual inspection of the video recordings used in study IV, this seems to be the case especially for low flows. This would result in an overestimation of the back pressure for a given flow based on the flow model, which also is seen in some of the results of experiment 1a in study IV. However, the starting pressures in experiment 1 corresponds in most cases to the intended water depth, especially for the 8 mm tube. When flow was increased, the model fitted better at the lower water depths, 6-7 cm, than at shallower depths at 1-5 cm. As in study I, Tyrmi et al. (2017) also investigated the flow resistance for a resonance tube (9 mm diameter, 27 cm length) and a LaxVox tube (10 mm diameter, 35 cm length), using a flow-driven equipment resembling the one used in studies I, III and IV. They measured airflows from 0.06 to 0.6 L/s using submersion angles of 30°, 45° and 90° for both tubes, finding negligible differences in back pressure at a given flow for the different angles.

In measurements on human participants, the average oral pressure needs to be at least corresponding to the hydrostatic pressure, otherwise the actual water depth has been shallower than intended. In study II, the tubes were marked horizontally to help the participants to submerge the tubes to the correct water depths. These markings were however difficult to follow for the participants due to the diagonal submersion of the tube into the water. The submersion angle was chosen spontaneously by the participants and controlled afterwards based on photographs. The actual water depths were estimated based on the submersion angles, and were slightly lower than the intended 2 and 6 cm. The average oral pressure was at least 2 cmH₂O at the shallower depth, and up to 5.4 cmH₂O at the lower submersion depth. In study V, the tube markings indicating the correct

submersion depths were diagonal, and if the markings were kept parallel to the water surface the submersion angle of the tube should be 45°. Also, the water depths and submersion angle was controlled for by the thesis author and not by the participants themselves, which facilitated the procedure in most cases. However, the water depths turned out to have been faulty for two of the participants, and the data obtained from these two were excluded from further analyses. Overall, the tube angle seems most important when defining the water depth if aiming for a high accuracy measurement. However, when a patient is holding the tube by themselves, the precision in water depth will probably be slightly less, making the angle negligible with regards to pressure parameters. Rather, the angle should be adjusted so that the patient can perform the exercise in an adequate posture.

The difficulties concerning the water depth measurements during tube phonation in water makes it difficult to estimate airflows used by the human participants based on the pressure-flow profiles. When flow is increased, the bubbles probably also will be pushed further down into the water, leading to an increase in pressure due to both an increase of flow as well as a slightly lower water depth. Measurement of airflow during tube phonation in water with human participants is not without its methodological challenges, however, it would be important to obtain normative values for this in the future.

In study I, pressure data were difficult to obtain for the lowest flows (< 0.03 L/s) at most water depths. The dashed lines in Figure 5, study I, represent a theoretical estimate for the pressure profile at these flows. In the similar experiment in study IV, data could be obtained also for the lowest flows, as seen in Figure 4, study IV. The reason for the lack of data in study I was probably due to a small air leakage that was discovered in the preparation of the vocal tract simulator for data collection of studies III and IV. The air leakage was so small that it did not affect pressures considerably at higher flows, but at the lowest flows the leakage prevented the pressure to build up adequately. After replacing the syringe used in study I to a smaller one in study III and IV, no leaks were longer observed and data could be obtained for flows between 0.001 to 0.03 L/s, which was crucial for the bubble investigations in study IV to succeed.

5.2 Pressure-flow relationship – oscillating pressure

The oscillating part of the pressure-flow relationship was investigated in study IV, as well as from the oral pressure signals in study II and V. In study II the amplitude of the oscillating part was calculated from the difference between the maximum and minimum pressure peaks of a LP filtered oral pressure signal. In study IV the amplitude of the oscillations was calculated from an RMS analyses. In study V both these methods were used and compared. The results from study IV suggested that the amplitude of the pressure oscillations increases with water depth down to 3 cm submersion depth. After 3 cm, the oscillation amplitude stabilizes and does not change with increasing water depth. A similar result has also been noticed by Guzman, Castro, et al. (2016), when investigating the oscillation amplitudes during tube phonation at 3 and 10 cm water depth for 45 participants and in a single-subject study by Radolf et al. (2014) investigating the pressure oscillations for a female phonating through a tube submerged in water. However, Tyrmi et al. (2017)



reported similar oral pressure oscillation amplitudes for 14 participants phonating through tubes submerged at water depths 2 and 10 cm. The results from study V points in the other direction, as the oscillation amplitudes were significantly higher at 2 cm submersion depth than at 6 cm submersion depth. The reason for this is probably due to lower airflows at the lower water depth.

Using peak-to-peak measurements on LP filtered oral pressure signals in order to obtain the oscillation amplitude might be slightly problematic, as demonstrated in study V. The results of the peak-to-peak measurement seem to be affected by the cut-off frequency of the LP filter to a slightly larger extent than the RMS measure. Overall, it would be appropriate to use a cut-off frequency that enables for as many partials as possible to pass, at the same time as the voice needs to be filtered out. A cut-off frequency of 20–30 Hz would only leave the fundamental frequency of a bubble frequency of about 20 Hz. Cut-off frequencies of 30 Hz have been used in the literature, by for example Tyrmi et al. (2017) as well as in study II in this thesis. Once the LP filter has been applied to the signal, the amplitude of the pressure oscillations can be determined by investigating the peak values, or the RMS value. The risk involved when using the peak value is that the filtering might also affect the phase of the partials, which in turn will affect the peak value. An RMS analysis is insensitive to phase shifts, making it more robust as a measurement of the oscillation amplitudes. However, the results of study V did not imply any large differences between the methods, but on the other hand the amount of data was small. A larger sample would increase the statistical power, hence bring more certain results.

If the amplitude of the pressure oscillations is more or less unaffected by a change in water depth, the question is raised whether the water depth is crucial for the training, or if any water depth might provide the possible effects. However, due to the static part of the pressure, it could be speculated that the possibility of movement in the tissues decreases with increasing water depth. In other words, if the static oral pressure is high due to a low water depth, the tissues might be stretched and less free to move as a result of the pressure oscillations. On the other hand, if the static pressure is low due to a shallow water depth, the tissues might be able to move more by the pressure oscillations. The ability for the vocal tract tissues to oscillate with the oral pressure oscillations during tube phonation in water has to date not been investigated. Since the oral pressure components are the probably most crucial parts separating tube phonation in water from tube phonation in air, investigating tissue movement at different water depths could play a key part in understanding how this exercise could be used most effectively in the treatment of various voice disorders.

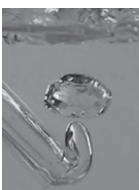
5.3 Bubble characteristics

Study IV investigated bubble properties at different water depths, flows and back volumes for two resonance tubes with different inner diameters. Bubble types at different flows, bubble type transitions, bubble frequencies and bubble volumes were investigated by means of correlograms and spectra of the back pressure signal. In study II and V, bubble frequencies from oral pressure data were analysed by manual calculation of pressure peaks (II & V), spectral method and correlograms (V).

The results from study IV are in many ways similar to results from previous studies regarding air bubbles in water. The research area of air bubbles in water and other liquids has so far not been taken into much consideration in research regarding tube phonation in water. At low flows, the bubbles are emitted from the tube end one by one in a periodic manner. At medium flows, the bubbles are emitted in pairs of two in a bimodal but still periodic manner. At high flows, the bubbles are emitted in a chaotic, less predictable manner. Using the back pressure signal, correlograms and spectral methods, the frequency of the bubbles can only be obtained when the bubbles are emitted one by one or in the bimodal regime. When the bubble pattern turned chaotic, no clear candidates could be identified in the correlogram and no clear peaks were visible in the spectrum. Also, inspection of the videos in study IV reveals that the bubbles merge, which means that the concept of separate bubbles and a well-defined bubble frequency is not valid. The shift to chaotic bubble patterns occurred at a relatively low flow with regards to human air flow during phonation. To date there seems to be no data on human air flow usage during tube phonation in water. In the study by Granqvist et al. (2015), a clearly separated bubble, probably regular or close to bimodal, is visible in their Figure 2, indicating that the participant in this case phonated with a flow that would result in a regular/bimodal bubble pattern. The bubble types were not directly investigated in study II and V with human participants, although the spectral analyses of the oral pressure signals indicated that both regular and bimodal bubble patterns were used by the participants.

The results of study IV implied that the bubble frequency should not be much affected by water depth, yet results from study II and V as well as earlier studies investigating bubble frequencies with human participants (Granqvist et al., 2015; Radolf et al., 2014) imply that the bubble frequency tend to be lower at deeper submersion depths. As the most important factor affecting the bubble frequency is airflow, the results indicate that people spontaneously decrease the airflow when the static oral pressure is increased due to a lower water depth. However, there are other minor effects that might affect bubble frequency. As shown in study IV, the bubble frequency can also be affected by the back volume behind the tube, hence the volume of the vocal tract, indicating that a smaller back volume is related to a higher bubble frequency compared to a larger back volume. Thus, a decrease in bubble frequency could, based on these results, also be related to an enlargement of the vocal tract volume. The vocal tract volume has been shown to be affected by tube phonation with the free end in air (Guzman, Laukkanen, et al., 2013; Vampola et al., 2011a, 2011b). A decrease of adduction could also make the back volume larger by a more prominent connection to the respiratory system. A larger open quotient during tube phonation in water at 6 cm submersion depth compared to 2 cm submersion depth has been presented by Granqvist et al. (2015). However, the dominant factor is probably the airflow, even though the lower bubble frequency at lower submersion depths can also be slightly dependent on these other factors.

Bubble frequencies during tube phonation in water have been investigated by counting period times in a LP filtered pressure signal (Guzman, Castro, et al., 2016; Tyrmi et al., 2017) or by spectral methods (Horáček et al., 2014; Horáček et al., 2012; Radolf et al., 2014). Period time measurements were used in study II, and a spectral method was used in study IV. In



study V, both methods were used as well as means of a correlogram. Based on the results from study IV and V it can be concluded that using LP filters when investigating bubble frequencies, especially at higher flows generating chaotic bubble patterns, might generate questionable period times. Although it might be possible to detect time between peaks, these times are not necessarily representative of separated bubbles. This means, that almost any LP filter might remove fast oscillations, leaving slow oscillations and provide a false representative for the bubble frequencies. This would imply that period time measurements should be avoided at flows generating chaotic bubble formations. The results of study V also showed that values obtained from the spectral method and the correlogram did not differ significantly, however, the manual counting of peaks generated significantly higher bubble frequencies than both other methods.

5.4 Estimations of airflow during tube phonation in water

During typical phonation at habitual loudness, a human uses an average airflow of approximately 0.1–0.2 L/s (Sundberg, 2001). During phonation through tubes and straws with varying dimensions, Titze et al. (2002) approximated that the two singers involved in the study used airflows of 0.07–0.25 L/s. The largest tube tested had an inner diameter of 7.5 mm and was 30 cm long, hence it was slightly narrower than the tube dimensions used in study IV. The airflow range with this tube covered the full range of airflows used overall (Titze et al., 2002). However, the results of study IV imply that airflows are remarkably low during tube phonation in water. When the bubble types were regular, bimodal or in the starting range to chaos, the water foremost stayed in the bowl without much splashing outside it. However, when the flow was increased beyond the threshold for chaotic bubble types, approximately beyond 0.04 L/s, the water behaviour became more aggressive and when increasing the flow even more the water splashed all over the floor. To date, there is no reported data on airflow during tube phonation in water for human participants, but this observation suggest that the flow seldom is higher than approximately 0.04–0.05 L/s, which in turn would indicate that tube phonation in water possibly induces a use of low flow.

5.5 Effects of tube phonation in water on the vertical laryngeal position

Resonance tube phonation in water was originally presented as a method for lowering the VLP (Sovijärvi, 1964, 1969, 1978). According to Sovijärvi, the lowering of the VLP would be most prominent if using the correct tube length, depending on the patient's voice category and age (Sovijärvi, 1964, 1969, 1978).

The VLP is controlled by the extrinsic muscles in the larynx, and moves during normal phonation (Thibeault, 2009). Factors associated with VLP during normal phonation are for example f_0 (Pabst & Sundberg, 1993; Shipp, 1975), vocal timbre (Sundberg & Nordström, 1976), lung volume (Iwarsson & Sundberg, 1998) and posture (Iwarsson, 2001). An elevated VLP is associated with hyperfunctional voice disorders and muscle tension dysphonia (Lowell, Kelley, Colton, Smith, & Portnoy, 2012; Van Houtte, Van Lierde, & Claeys, 2011) and a goal with the therapy for these kind of voice disorders are generally to relax the extrinsic laryngeal muscles using different techniques (Van Houtte et al., 2011). Tube phonation in water has been used as a therapy method with patients with hyperfunctional

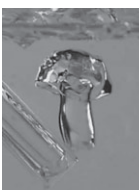
voice disorders (Simberg & Laine, 2007) but little measurements have been done on the possible changes in VLP.

Changes in VLP during tube phonation in water was investigated using dual-channel EGG in studies II and V. In study II, the participants used two tube lengths and in study V the participants used one tube length. The results from study II indicated that the VLP was lowered for both participants for all bubbling conditions, and that the lowering effect was more prominent when the tube end was submerged deeper into the water. In study V, the VLP lowered during the bubbling tasks for three of the four participants. One possible explanation for the lowering is that the bubbling exercises made the participant's breathing deeper, which could have a lowering effect on the VLP due to the tracheal pull (Iwarsson & Sundberg, 1998). Because of the calibration process, it was impossible to blind the participants from the measured variable, and it is possible that knowing the aim made them intentionally or unintentionally affect their larynx position. The participants in study II further had so much experience of tube phonation in water that they were aware of the expected lowering, whereas the participants in study V did not know in which direction the larynx was hypothesized to move. However, all participants were vocally healthy, which would suggest that all of them had normal muscle movement in the laryngeal area, without any extra tension.

The method of investigating VLP by dual-channel EGG is not without challenges. The calibration process increases the validity of the measure, but despite repeated measures it turned out to be difficult to obtain a signal that enabled for a linear calibration that would enable for translating the voltage output to, for example, millimetres. It can also not be ruled out that changes in original voltage output from the EGG can be due to horizontal movement of the larynx, which has been shown by Laukkanen et al. (1999) who compared the VLP-measure from a dual-channel EGG to videofluoroscopy. The results from this study indicated that the measure of VLP using the dual-channel EGG is most reliable for prolonged vowels (Laukkanen et al., 1999), when one can assume that the larynx remains reasonably steady throughout the phonation. The agreement between the dual-channel EGG and the videofluoroscopic filming decreased during phonation on a voiced bilabial fricative (Laukkanen et al., 1999), which was the examined exercise which would resemble closest to tube phonation in water. The device have not been tested for reliability during tube phonation in water. Due to these technical challenges, the results regarding VLP from study II and V should be seen as suggestive and not definite. However, as tube phonation in water requires an upright position, the options for investigating changes in VLP are somewhat limited.

5.6 Modulation of fundamental frequency during tube phonation in water

In study V, the modulation of f_0 during tube phonation in water was analysed via means of correlograms combined with RMS-analyses. The results showed that tube phonation in water induces a modulation in f_0 , suggesting that the pressure oscillations generated by the bubbles also affect the voice source. An oscillating oral pressure most likely leads to a modulating p_{trans} as well, which might explain the f_0 modulation. The f_0 modulation was similar for the two submersion depths investigated.



The mean p_{trans} has been investigated in some studies of tube phonation in water, by calculating the difference between oral pressure and an estimate of p_{sub} based on oral pressure measurements during manual shuttering of the tube end (Radolf et al., 2014; Tyrmi et al., 2017). Results have suggested both increases of p_{trans} during tube phonation in water at 10 cm submersion depth compared to baseline phonation (Radolf et al., 2014), and a decrease of p_{trans} during similar circumstances (Tyrmi & Laukkanen, 2017). Horáček et al. (2014) investigated pressure characteristics during bubbling at 10 cm using a physical model. Interestingly, the pressure oscillations caused by the bubbles seemed to propagate down to the subglottal cavity, affecting the p_{sub} . The extent of the p_{sub} oscillations is likely affected by the glottal resistance, which in turn would suggest that the amount of p_{trans} modulation would depend on the degree of adduction. Thus, it would be important to look into the impact of tube phonation in water on both the static as well as the oscillating part of the p_{trans} and p_{sub} more closely, as these effects are unclear at the moment.

5.7 Clinical implications

This thesis provides a handful of results that can be implemented to the voice clinic. The results of studies investigating changes in the pressure-flow relationship for tubes of different dimensions (Smith & Titze, 2017; Titze et al., 2002) together with the results from studies I, III and IV, have shown that a change in relative tube diameter changes the pressure-flow relationship to a larger extent than a relative change in length. If the tube dimensions are known it is possible to estimate the pressure-flow relationship for tubes in air using the modified flow model equation presented by Smith and Titze (2017). This model matched well with the experimental data in study IV.

Tube phonation with the free end in air provides auditory feedback to the clinician, as well as tactile feedback to the user. The flow ball devices investigated in study III further provides a visual feedback of flow. The back pressure as well as the airflow needs to overcome threshold values in order for the ball to lift off. The device referred to as FB required an airflow of 0.2 L/s and a pressure of approximately 5 cmH₂O to lift off its supplied ball, and an airflow of about 0.4 L/s to keep the ball height at 10 cm. Using this device and striving to keep the ball in the airstream, could encourage the user to learn how to separate the flow and p_{sub} dimensions in his or her own phonation, thus aiming towards a maximum airflow combined with a complete glottal closure without extensive adduction, so called flow phonation (Sundberg, 2001). The other device tested, referred to as FBG, required extensively higher back pressures for the equivalent airflow and ball height compared to the FB model. Keeping the ball 5 cm in the air would require a back pressure of almost 40 cmH₂O, which probably makes it less suitable for vocal training than the FB device.

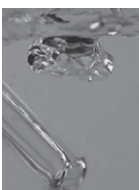
As mentioned earlier, it is likely that the airflow used during tube phonation in water with an open container would be surprisingly low, possibly not more than 0.04–0.05 L/s. In the LaxVox technique (Sihvo & Denizoglu, 2014) the bowl is replaced with a water bottle. This type of closed container could allow for higher flows during training, when the risk of splashing is eliminated. However, this is not necessarily a benefit, since the spontaneous controlled limitation of airflow that presumably happens when using an open container, might be less. This result rather shows that there will be differences in the airflow if using

an open contra a closed container, which should be important knowledge to clinicians. One could also speculate that the more important parameter is not the airflow, but the glottal adduction. As demonstrated by Horáček et al. (2014), the pressure oscillations generated by the bubbles are reflected down to the subglottal cavities. This would impact the p_{trans} , hence the degree of adduction. A low airflow is usually related to a high degree of adduction, which could be harmful to the vocal folds. However, tube phonation in water might provide the possibility to use a low airflow combined with a high p_{sub} but still a low p_{trans} , which would eliminate the risk of too much adduction. This needs to be explored further.

The tube dimensions suggested by Sovijärvi (1964; 1969; 1978) are still taken into consideration in clinical practice (Simberg & Laine, 2007). In Finland, it is possible to purchase “tubes for adults” and “tubes for children” in stores providing materials for SLPs (ELLI Early Learning, 2017). The tubes follow the dimension recommendations presented in table I in this thesis. In study IV, the two inner diameters 8 and 9 mm were compared. The results showed that these two diameters provide different results with regards to back pressure, bubble mode shifts and bubble frequencies. However, when looking closer at the actual pressure, airflow and bubble frequency values, the differences were small. Despite that a diameter change of 1 mm changes the outcome of several physical variables, it is still unclear whether these differences would be crucial in the voice clinic or not. The clinician should however keep in mind that for every millimetre the diameter is decreased, the static back pressure, hence the flow resistance, increases.

The tube lengths recommended by Sovijärvi (1964, 1969, 1978) have not been investigated further in this thesis. During the data collection for study I, pressure-flow profiles were obtained for 27 and 28 cm resonance tubes as well. The profiles were similar to the one obtained from the 26 cm long tube, hence a decision was made not to report them separately in the study. With regards to the results of study I and others (Smith & Titze, 2017; Titze et al., 2002), it can be proposed that a change in tube length of 1–2 cm will have a slight effect on the back pressure, but perhaps not enough to make a clinical difference. Overall, the pressure components investigated in this thesis should not be much affected by an increase of tube length of 1–2 cm. However, Sovijärvi (1964, 1969, 1978) proposed that the tube length should correspond to the voice category of the patient/user, and that the tube length should provide a doubling of the vocal tract length. When considering the acoustic properties of a tube, the length of the tube is more crucial than the diameter (for an overview, see for example Titze, 2000). It is possible that a small change in tube length can facilitate for impedance matching differently depending on the users habitual f_0 . However, these are questions that needs to be addressed in future studies.

Results from study II and V suggested that tube phonation in water might have a lowering effect of the VLP and thus could be used as an exercise for VLP lowering in the voice clinic. However, the lowering was not achieved spontaneously for all participants, suggesting that some training and supervision is needed before the user learn how to perform the exercise. Simberg and Laine (2007) suggest that the patient should not be allowed to perform the exercise unsupervised before the SLP as well as the patient feel comfortable with the patient’s performance. No particular risks connected to performing the exercise “wrong”



have been reported in the scientific literature, but this does of course not mean that there are no risks involved. By performing tube phonation in water, a complicated physical system (tube + water) is connected to another complicated physical/physiological/anatomical system (the phonatory). Many questions still remain regarding possible benefits and potential risks involved with performing the training in different ways, and different risks might be more or less prominent depending on the vocal health of the user.

5.8 Limitations of the studies and suggestions for further research

The driving flow in the vocal tract simulator was a static flow, lacking the oscillating part corresponding to phonation. This raises the question regarding whether the results in the bubble frequencies would have been different if the driving flow had included an oscillatory part. Tufaile and Sartorelli (2000) investigated bubble formations with air pressure and a sound wave amplitude as control parameters. The air pressure (static part) was fixed whereas the sound wave amplitude was changed. The frequency of the sound wave was equivalent to the tube's first resonance frequency. At certain circumstances, the bubble frequency synchronized with the sound frequency at about 140 Hz. This would imply that the oscillating part of the signal can have an effect on the bubble frequencies. However, there seems to be no reports on bubble frequencies this high during tube phonation in water with human participants, so this phenomenon seems unlikely to occur during tube phonation in water.

The actual amount of airflow used during typical tube phonation remains unclear. Results from studies investigating bubble frequencies during bubbling with human participants indicate that a spontaneous decrease in airflow is present when the tube is submerged deeper into the water, but this has so far not been measured. The results from study IV also indicate that the airflows used during tube phonation in water are noticeably lower than during normal unoccluded phonation. It would be important to investigate how much airflow that is used during tube phonation in water, and how much airflow that patients are instructed to use by SLPs. If the airflow during tube phonation in water is much lower than during normal phonation, this training could possibly also impact the breathing muscles and their control. Airflow should also be investigated during tube phonation in water in an open contra a closed container, as it seems reasonable to assume that the airflow might be less using an open container.

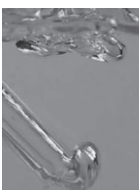
Studies II and V both have a small number of participants, which makes it impossible to draw any general conclusions based on these data. All data from each participant were collected during the same session. It would have been interesting to follow up the data collection with a second, similar, data collection to investigate if the trends were similar for the participants over time.

It has been reported that the pressure oscillations during tube phonation in water provides a sensation of massage in the vocal tract (Simberg & Laine, 2007) and the method has been suggested to induce a kind of *massage effect* on the vocal tract tissues (Enflo et al., 2013; Radolf et al., 2014). It is not farfetched to hypothesize that the pressure oscillations in the oral cavity induce some kind of manipulation in the larynx that could give the tactile experience of a massage. This raises the question what actually constitutes a massage effect. Direct effects of massage therapy such as increase of blood flow in the palpated tissues and

reduced stress have been suggested in literature (Field, 2014, 2016; Sefton, Yarar, Berry, & Pascoe, 2010), but to date these kind of effects have not been investigated for tube phonation in water. It would be important to investigate for example tissue movement, muscle activity in the laryngeal muscles and possibly perceived stress during tube phonation in water at different water depths.

In the long run it would be important to carry out larger clinical trials, where acoustic, physiological, perceptual and quality of life effects from tube phonation in water is investigated. However, based on the results of this thesis it seems evident that types of SOVT and protocols used for tube phonation in water result in different direct effects and feedback. Aspects regarding human airflow during exercising as well as direct effects to the laryngeal tissues are still not known. If wanting to investigate treatment outcomes of particular methods, it is important to be able to control the parameters used in the treatment. So far this is not the case especially for the different protocols involving tube phonation in water. As shown in this thesis, the airflow used by patients and recommended by clinicians during tube phonation in water is unknown and probably largely affected by the water container as well as instructions.

As speech language pathologists, as for any other group of health care professionals, it is important that our treatment methods are evidence based. Future studies of treatment outcomes for tube phonation in water need to be done, however to date some more groundwork regarding physical properties and immediate effects might be beneficial in order to be able to design reliable trial protocols.

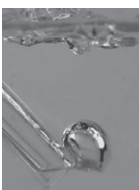


6. CONCLUSIONS

- A change in tube diameter will affect the pressure-flow relationship of the tube more than a relative change in tube length
- To emit a bubble from the tube orifice, the oral pressure needs to overcome the hydrostatic pressure.
- Bubble characteristics can provide details regarding airflow during tube phonation in water due to visual feedback.
- The amplitude of the pressure oscillations are unaffected by water depth at flows below 0.02 L/s. At higher flows, the pressure oscillation amplitude is unaffected by water depths below 3 cm.
- Tube phonation in water with an open water container might encourage to lower airflows than those used during tube phonation in air and during normal phonation without tubes.
- Tube phonation in water provides modulation of the fundamental frequency, suggesting that tube phonation in water modulates the transglottal pressure.
- Tube phonation in water possibly has lowering effect on the vertical laryngeal position.
- The back cavity volume, hence the volume of the vocal tract behind the tube, can affect the bubble frequency at especially medium flows.
- Flow balls can be used as a visual feedback of airflow. Different flow ball devices requires different back pressures for ball lift off.

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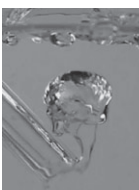
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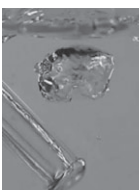
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ORIGINAL PUBLICATIONS

The Flow and Pressure Relationships in Different Tubes Commonly Used for Semi-occluded Vocal Tract Exercises

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Summary: This experimental study investigated the back pressure (P_{back}) versus flow (U) relationship for 10 different tubes commonly used for semi-occluded vocal tract exercises, that is, eight straws of different lengths and diameters, a resonance tube, and a silicone tube similar to a Lax Vox tube. All tubes were assessed with the free end in air. The resonance tube and silicone tube were further assessed with the free end under water at the depths from 1 to 7 cm in steps of 1 cm. The results showed that relative changes in the diameter of straws affect P_{back} considerably more compared with the same amount of relative change in length. Additionally, once tubes are submerged into water, P_{back} needs to overcome the pressure generated by the water depth before flow can start. Under this condition, only a small increase in P_{back} was observed as the flow was increased. Therefore, the wider tubes submerged into water produced an almost constant P_{back} determined by the water depth, whereas the thinner straws in air produced relatively large changes to P_{back} as flow was changed. These differences may be taken advantage of when customizing exercises for different users and diagnoses and optimizing the therapy outcome.

Key Words: Semi-occluded vocal tract exercises–Straw–Resonance tube–Lax Vox tube–Voice therapy–Flow–Pressure–Back pressure.

INTRODUCTION

Voice exercises with a semi-occluded vocal tract are widely used in voice therapy and training. The semi-occlusions can be achieved by constricting the vocal tract, for example, when phonating into different types of tubes or straws,¹ using lip² and tongue trills,³ or the so-called hand-over-mouth technique.^{4,5} Semi-occluded vocal tract exercises (SOVTEs) differ by the type and level of occlusion applied to the vocal tract. Trills presenting an oscillatory semi-occlusion have been used in voice therapy for centuries to improve voice quality.² The hand-over-mouth technique adds a large resistance caused by the constriction of the hand, only allowing a small passage for the air between the fingers.⁴ Tubes and straws varying in length, diameter, and material elongate the vocal tract, thus changing its acoustics and resistance.¹

Phonation into tubes can be carried out keeping the free end of the tube in air or water. The method of phonating into tubes submerged into water was first described by Sovijärvi in the 1960s. He developed the so-called resonance tube method⁶ using glass tubes submerged into a bowl of water. The method has been further developed by voice clinicians, and the most common exercise is to phonate through the tube while keeping

the free end submerged 1–2 cm below the water surface.⁷ An alternative technique is the Lax Vox technique, which has been used since the 1990s and in which phonation is performed into a silicone tube in a water bottle.⁸ Recent research shows that a major feature provided by these exercises consists of the fact that submerging the tube end into water causes an intraoral pressure modulation produced by the bubbling of the water.^{9,10}

Because of the positive clinical experiences with SOVTE, an interest for scientific explanations on the mechanics and acoustics of the methods has emerged. Theoretical studies using computer models have shown effects of different types of semi-occlusions on the impedance and reactance of the vocal tract.^{1,11–14} In addition, studies with human subjects have found effects of SOVTE on muscle contraction in the vocal tract¹³ and vocal tract configuration,^{14–17} that is, lowering of the vertical larynx position, widening of the pharynx, and narrowing of the aryepiglottic opening.

A common characteristic of SOVTE is the static component of the intraoral pressure produced by the vocal tract semi-occlusion. In some cases, an oscillatory component is introduced by a secondary source. On the basis of this idea, SOVTEs were classified into two groups according to the number of vibratory sources in the vocal tract: single source (eg, straw phonation) and dual source (eg, tubes in water or lip trills).¹⁸ Exercises with a dual source of vibration showed modulation of the vocal fold vibrations and were associated with the massage effect.^{18,19} Another SOVTE classification was further suggested in which a series of SOVTE was rank ordered based on the intraoral pressure levels produced by each SOVTE.²⁰

Although great progress has been made toward better describing the differences among SOVTE, little is known about the influences of volume flow (U) on the oral pressure produced by SOVTE that make use of phonation into tubes. Nevertheless, both static and oscillatory components are dependent on flow.

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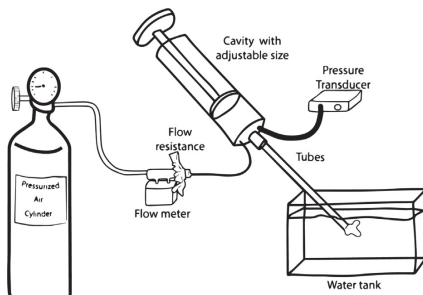


FIGURE 1. Flow-driven vocal tract simulator.

The purpose of this study was to investigate the static back pressure (P_{back}); analogous to the intraoral pressure; and the U relationship for different tubes commonly used for voice therapy and training with SOVTE.

METHODS

Setup

A flow-driven vocal tract simulator was used to collect data on P_{back} and U for different tubes (Figure 1). The vocal tract simulator setup consisted of a pressurized air cylinder, connected via a flow resistance to a cavity with an adjustable size (large syringe) with an outlet for tube connection (Figure 2).

The pressure difference between the cavity and the surrounding air, that is, P_{back} , was measured using a differential pressure transducer 8-SOP MPXV7007DP-ND, Freescale Semiconductor, Petaling Jaya Malaysia. A second identical pressure transducer was connected to a Fleisch pneumotachograph to measure the flow through the system. After the flow meter, an additional flow resistance was added which consisted of a piece of fabric. The pressure upstream from the pneumotachograph was manually controlled by a pressure regulator.

In most cases, as the resistance of the fabric was much larger than the resistance of any of the tested tubes, the flow was largely determined by the upstream pressure and the resistance of the fabric, that is, the setup generated a flow that was largely independent of the tube resistance. This setup, produced a flow free from oscillation which is advantageous as it allows for a reliable detection of the

flow-pressure profile for each of the tubes used in the study. Also, the large resistance and the constant-flow property effectively created a well-defined system isolating the tube and back cavity from the upstream part of the setup. The syringe's piston was set to 1 cm away from the outlet creating a cavity of approximately 36 cm^3 in volume. This volume was selected on the basis of published data for the volume of the vocal tract using computer tomography images.¹⁴ To make the back volume well defined, the additional flow resistance was connected after the flow meter; otherwise, the dead volume of the flow meter might have influenced the effective volume of the back cavity. However, this arrangement introduced a systematic error because of the fact that the air expands after the flow resistance giving a slightly higher flow than that was registered in the flow meter. A calibration procedure was therefore applied, during which the actual flow was measured with a rotameter connected to the outlet of the simulator and related to the flow that was registered by the flow meter. All measurements were compensated for the deviations that were found.

Pressure calibration was performed before measurements using a syringe and a U-tube manometer. The flow meter was calibrated without the flow resistance before data collection using a pneumotach calibration unit MCU-4 (Glottal Enterprise Syracuse, NY, USA).

Recordings and analyses

The data were recorded using the Soundswell Signal Workstation Version 4.00 Build 4003 (Core 4.0, Hitech Development AB, Sweden) with an analog library SwellDSP 4.00 and DSP card LSI PC/C32. Three channels, audio, P_{back} , and U , were recorded at a sampling rate of 16 kHz per channel. The audio signal was recorded for documentation purposes only and was not further analyzed. The P_{back} and U signals were later downsampled to 5 Hz using the *Sopran* software program (Tolvan Data 2009-2014 Version 1.0.5; Tyresö, Sweden) and were further analyzed using *MATLAB* (Mathworks version 7.10.0.499 [R2010a]). The downsampling procedure reduced the amount of data and also effectively removed any frequencies above 2.5 Hz, thus reducing the pressure oscillations induced by water bubbles.

Experiment

Altogether, 10 tubes were used in this study to represent the SOVTE. Seven straws commonly used in therapy with different lengths and diameters (Table 1); a 26-cm-long resonance tube (glass) with a 9-mm inner diameter and a 35-cm-long silicone

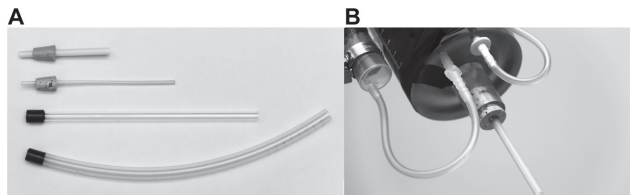


FIGURE 2. Flow-driven vocal tract simulator attachments. (A) Examples of straws and tubes used in the experiments, from top to bottom: a 10 cm $\varnothing 7$ mm straw, a 15 cm $\varnothing 3$ mm straw, a 26 cm $\varnothing 9$ mm resonance tube, and a 35 cm $\varnothing 10$ mm silicone tube. (B) A 10 cm $\varnothing 5$ mm straw in air connected to the flow-driven vocal tract simulator.

TABLE 1.
Dimensions of the Tubes Used in the Experiments

Tube	Length (cm)	Diameter (mm)	Flow Value of Reynolds Threshold Number for Nonlinear Flow (Re = 2300 L/s)
Straw/"Hand Over Mouth"	1	5	0.14
Straw 1	5	5	0.14
Straw 2	10	5	0.14
Straw 3	12.5	5	0.14
Straw 4	15	5	0.14
Straw 5	10	3.3	0.08
Straw 6	10	6	0.17
Straw 7	10	7.5	0.20
Resonance tube	26	9	0.25
Silicone tube	35	10	0.28

(to resemble the Lax Vox technique) tube with a 10-mm inner diameter (Figure 2A) were used. Additionally, to facilitate the comparison among exercises, a 1-cm-long tube with a 5-mm inner diameter inserted into a cork was used to mimic the hand-over-mouth exercise. The hand-over-mouth exercise is not easily quantifiable as it depends on the adjustments of the hand against the mouth and level of finger constriction; hence, it will be considered an approximation of the hand-over-mouth exercise. All straws were connected to the flow-driven vocal tract simulator using a 2-cm-long cork with a 13–17 mm diameter (Figure 2B). The chosen lengths and diameters for each straw were based on current availability of drinking and cocktail straws. Some straws were shortened for comparing different straw lengths. Each tube and straw was connected to the setup outlet and assessed with the open end in air (Figure 2B). The resonance tube and silicone tube were further assessed submerged in water at the depth from 1 to 7 cm, in 1-cm steps, into a $21 \times 15 \times 15 \text{ cm}^3$ water tank. The water depth was measured from the water surface to the lowest point of the submerged tube (Figure 3). This method for measuring the depth of water in which the tube is submerged was based on a similar study by Granqvist et al.¹⁰ To approximate typical angles used in clinical practice, a 45° angle was maintained for the resonance tube and a 90° angle was maintained for the silicone tube. For each recording in water, a photo of the setup was taken to document the water depth.

For the purpose of recording the U and P_{back} values, the pressure produced by the pressurized air cylinder was increased slowly and continuously until a sufficient pressure was reached. Pressures up to approximately 200 kPa (2000 cm H₂O) before the flow resistance were used to generate flows up to 0.5 L/s. This covers the flow range expected to be produced by humans.²¹

Theory

The P_{back} from tubes has been studied in fluid dynamics. This P_{back} originates mainly in two effects: the kinetic entry pressure loss and the viscous pressure loss. The first is associated with the energy required to accelerate the air inside the tube and the second is associated with viscous friction in the air.

Depending on the flow and the dimensions of the tube, flow can be either laminar or turbulent, and the threshold between

these is determined by the Reynolds number (Re). The Re for cylindrical tubes can be calculated using the formula²²:

$$\text{Re} = \frac{2U}{\nu\pi r}$$

where U is the flow; ν is the kinematic viscosity of air ($15.68 \times 10^{-6} \text{ m}^2/\text{s}$ at 25°C); and r is the radius of the tube. If $\text{Re} < 2300$, laminar flow occurs. For $\text{Re} > 4000$, flow is turbulent presenting unstable and chaotic characteristics. Between these values, flow can be either laminar or turbulent.

However, the theory for turbulent flow describes the flow at a distance from the inlet of the tube; the flow has to propagate some distance inside the tube before the turbulent flow is fully developed. At the entry of the tube, there is an inlet region in which flow is more or less laminar even if the flow becomes turbulent further downstream. For the flows and dimensions of tubes studied in this article, the length of the inlet region mostly exceeds the tube length, and this affects both the kinetic entry pressure loss and the viscous pressure loss. It is however beyond the scope of this article to completely model the P_{back} from the tubes used in SOVTE; for a more elaborate description, see textbooks on fluid dynamics (eg, Nakayama and Boucher²³).

For tubes in water, a second effect contributes to the P_{back} . For any static flow to occur, the water surface inside the tube must reach the depth of the tip so that bubbles can be ejected. Thus, the air pressure inside the tube must overcome the water pressure at the tip. On the basis of this, a theoretical model can



FIGURE 3. Definition of water depth. The resonance tube was used at an angle of 45° (left) and the silicone tube at 90° (right) with respect to the horizontal plane.

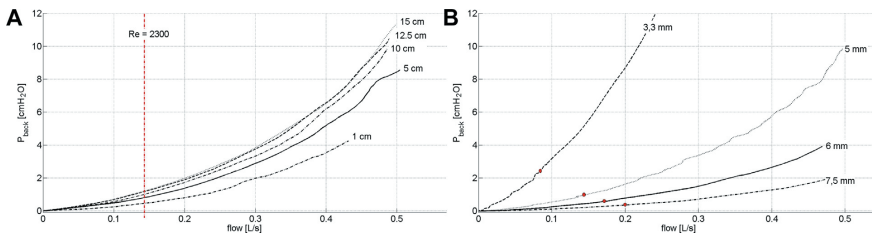


FIGURE 4. P_{back}/U relationship for different straws. (A) 5-mm diameter straws with 1, 5, 10, 12.5, and 15 cm in length. (B) 10-cm long straws with 3.3, 5, 6, and 7.5 mm in diameter. Vertical dash-dot line (A) and dots (B) represent the Reynolds number ($Re = 2300$) for each straw.

be formulated for the pressure-flow relationship, where the static flow is zero until the air pressure corresponds to the water depth. Once that pressure is reached, the flow starts, resulting in an added P_{back} from the flow resistance in the tube. Thus, the pressure profile can be seen as a sum of the constant pressure provided by the water pressure at the tip and the pressure generated by the flow resistance.

RESULTS

The results for pressure-flow relationships were analyzed from three different aspects: pressure-flow relationship for straws of different lengths and diameters, pressure-flow relationship for different water depths for resonance and silicone tubes, and a comparison of the pressure-flow relationships for the two first groups.

Figure 4 shows pressure-flow relationship for straws of different lengths and diameters. In Figure 4A, 5-mm-diameter straws with different lengths (1, 5, 10, 12.5, and 15 cm) are analyzed. The P_{back} produced is larger for longer straws at a given U . Figure 4B shows 10-cm-long straws with different diameters (3.3, 5, 6, and 7.5 mm). The P_{back} produced is larger for thinner straws at a given U . This result is in agreement with investigations by Titze *et al*²³ of flow resistance for different semi-occlusions.

Figure 5 shows the pressure-flow relationship for a 26-cm resonance tube with 9-mm diameter and a 35-cm silicone tube with 10-mm diameter, respectively. The dashed lines at

very low flows represent a theoretical model for pressures not sufficient to eject air from the tube (bubbles). The lowest curve in parts A and B of Figure 5, respectively, shows the P_{back} response for the tubes in air. Consecutively, in an ascending order, the pressure values increase proportionally as the tube ends are submerged deeper into the water. This is in agreement with Granqvist *et al*.¹⁰

Figure 6 shows the pressure-flow relationship for selected tubes measured in this study. For any given straw, the P_{back} increases as a function of flow. However, for the tubes submerged into water, the P_{back} starts at the pressure determined by the water depth, which is needed to be overcome for the flow to start. For flows >0 , the P_{back} increases only slightly as the flow increases.

DISCUSSION

Vocal exercises with a semi-occluded vocal tract can be carried out using many different kinds of semi-occlusions. The purpose of this study was to investigate the relationship between flows and generated back pressures among different tubes that are commonly used for voice therapy with SOVTE.

The result of this study shows that different sizes of tubes provide different pressure-flow relationships. In addition, once a tube is submerged into water, its pressure-flow relationship profile shifts upward; the minimum P_{back} for resonance and silicone tubes in water is determined by the corresponding water depth. Once the pressure corresponding to the water

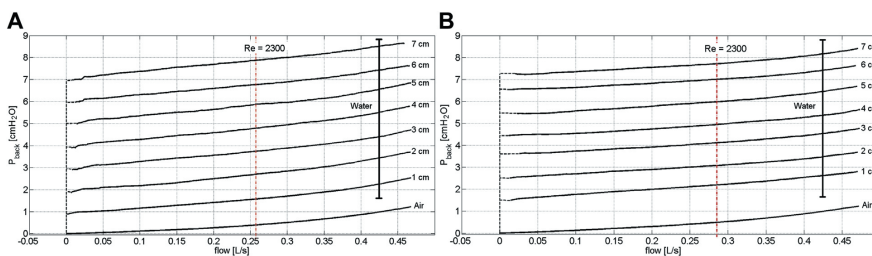


FIGURE 5. (A) Pressure-flow relationship for a resonance tube 26 cm \varnothing 9 mm. (B) Pressure-flow relationship for a silicone tube 35 cm \varnothing 10 mm. The curves represent P_{back} at 0- to 7-cm water depth. The dashed lines represent a theoretical pressure-flow relationship for very low flows. The dash-dotted lines represent the Reynolds number ($Re = 2300$) for each specific tube.

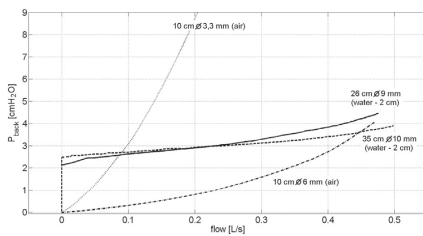


FIGURE 6. Pressure-flow relationships for semi-occlusions: resonance tube 26 cm \varnothing 9 mm and silicone tube 35 cm \varnothing 10 mm submerged 2 cm into water compared to two straws 10 cm \varnothing 3.3 mm and 10 cm \varnothing 6 mm, respectively.

depth is overcome, the flow starts to increase, which leads to a slight additional increase in P_{back} . This small change in P_{back} as a function of flow is probably explained by the flow resistance of the relatively wide tube itself. Figure 5 illustrates this relationship where each of the curves for the resonance and silicone tubes has approximately the same shape as the tubes in free air (0 cm) but is shifted upward according to the water depth. Furthermore, a small difference in P_{back} can be observed between the resonance tube and the silicone tube. This difference can be attributed to the different angles in relation to horizontal plane in the experiment (Figure 3). Therefore, P_{back} was slightly greater before flow onset for the silicone tube as the bubbles produced were released at a slightly greater depth.

The analysis of tubes in air showed that the P_{back} increased more rapidly for higher flows. Straws with smaller diameters produced a larger increase in P_{back} when compared with straws with a larger diameter. A dramatic effect on the P_{back} could be seen when comparing straw diameters; for example, changing from 6 to 3.3 mm diameter increases the P_{back} from approximately 1 cm H_2O to approximately 10 cm H_2O at around 0.22 L/s (Figure 4B). Changes in the length of the straw also affected the P_{back} , but doubling the length of the tube from 5 to 10 cm only had a marginal effect on the P_{back} (Figure 4A). These findings corroborate previous straw resistance measurements.^{13,23} Hence, altering the straw diameter is more effective to achieve changes in P_{back} . On the other hand, if a small change in P_{back} is required, lengthening or shortening straws can also be practical.

The comparison among our subset of tubes showed that at specific points (Figure 6 [approx. 0.1 L/s]), the straws in air produce the same P_{back} as the resonance and silicone tubes in water. However, any changes in flow will produce a strong effect in P_{back} for thin tubes although remaining almost constant for the wider tubes. Thus, for the wider tubes in water, the main decisive factor for the P_{back} is the water depth, whereas for the thin tubes in air, the decisive factor for the P_{back} is the flow. This shows that the exercises with and without water result in quite different feedback to the user, not completely comparable and possibly beneficial for different purposes.

When comparing the resonance tube and Lax Vox exercises, it can be noted that the recommendations for the techniques

differ in terms of water depth and hence the amount of back pressure. During resonance tube phonation in water, the tube is usually submerged 1–2 cm below the water surface.⁷ During Lax Vox, the recommended water depth is 4–7 cm.⁸ This means that the P_{back} used during Lax Vox is typically greater than the P_{back} used during resonance tube phonation. Therefore, it is possible that the current recommendations for these exercises result in different effects on the vocal apparatus for the user, although the basic physical principles are similar.

Apart from the static pressure-flow relationship, there are also other effects of the SOVTE. These include a modulation of the P_{back} by water bubbles or lip trills, acoustic/resonant effects, and so forth. For simplicity, these more complex effects have been left out of the scope of this study and will be addressed in future research.

The differences among the tubes and how they are implemented (ie, in air vs in water) should be considered when designing the most suitable exercise method for clients in clinical practice. As wider tubes in water produce a constant pressure defined by the water depth, patients with voice problems can exercise consistently in a way agreed by the clinician which may be desirable according to the motor learning theory.²⁴ Conversely, the relative large changes in P_{back} produced by thinner tubes in air may be better suited for voice users who need more awareness of their voice functioning such as professional singers. Certainly, the optimal use of the different tubes in air and water deserves much more attention in future studies.

CONCLUSIONS

The changes in tube diameter affect P_{back} considerably more than the changes in length. Additionally, once the resonance and silicone tubes were submerged into water, the P_{back} had to overcome the pressure corresponding to the water depth before flow could occur. Once the flow had started, only small changes in P_{back} were observed. Therefore, the resonance and silicone tubes submerged into water produced an almost constant P_{back} determined by the water depth, whereas the thinner straws in air produced relatively large changes to P_{back} as flow was changed. These differences may be taken advantage of when customizing exercises for different users and diagnoses and optimizing the therapy outcome.

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ORIGINAL ARTICLE

Vertical laryngeal position and oral pressure variations during resonance tube phonation in water and in air. A pilot study

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Abstract

Resonance tube phonation in water (RTPW) is commonly used in voice therapy, particularly in Finland and Sweden. The method is believed to induce a lowering of the vertical laryngeal position (VLP) in phonation as well as variations of the oral pressure, possibly inducing a massage effect. This pilot study presents an attempt to measure VLP and oral pressure in two subjects during RTPW and during phonation with the free tube end in air. VLP is recorded by means of a dual-channel electroglottograph. RTPW was found to lower VLP in the subjects, while it increased during phonation with the tube end in air. RTPW caused an oral pressure modulation with a bubble frequency of 14–22 Hz, depending mainly on the depth of the tube end under the water surface. The results indicate that RTPW lowers the VLP instantly and creates oral pressure variations.

Key words: Dual-channel electroglottograph, oral pressure, resonance tube phonation in water, vertical laryngeal position, voice therapy

Introduction

Vocal exercises with a semi-occluded vocal tract (SOVTE) are common practice in voice therapy. Such occlusions can be accomplished with, for example, lip trills (1), tongue trills, bilabial fricatives (2), or different kinds of artificial extensions such as tubes or straws (3–17).

The so-called resonance tube phonation with the tube end submerged in water, henceforth RTPW, is a method that was originally launched in Finland by Sovijärvi in the 1960s. It has since then been used both in voice therapy and voice training (4–6,17). The most common exercise is to keep the free end 1–2 cm below the water surface, henceforth immersion depth, while phonating into the tube keeping a steady pitch and loudness, creating bubbles (4–6). The exercise is carried out several times a day during the therapy period. The method and its variations, which have been used with patients with different kinds of voice disorders (4–6), have been described in detail by Sovijärvi (4,5). It has later been slightly modified by Simberg and Laine

(6). According to Sovijärvi, the amount of exercise, the tube length, and the immersion depth should be chosen for each patient individually, depending on diagnosis and therapy goal (6). The method is presently in frequent use in Finnish clinical practice (6). Since 2006, it has been presented and demonstrated at workshops and international conferences and rapidly spread also outside Finland (Susanna Simberg, personal communication).

Lately, the therapeutic effects of RTPW have been analysed scientifically (18–20). In a clinical study of overall effects of voice therapy given to groups of patients with mild voice disorders, RTPW was used as the main method (20). The results showed significant voice improvement in the treatment group as compared to a control group; however, because RTPW was used in combination with other voice exercises, the effect of RTPW could not be determined. RTPW has also been found to affect the voice quality (18,19), vocal fold collision threshold pressure (19), and the open quotient in the vocal fold vibration cycle (21).

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According to Sovijärvi (4,5) one of the main effects of RTPW is that it lowers the vertical laryngeal position (VLP), a common therapeutical goal in cases of muscle tension dysphonia (22,23). A VLP change may affect the tension or angle between the laryngeal cartilages, which in turn affects the resting lengths of the intrinsic muscles (24). Therefore, an adequate VLP is believed to facilitate the fine motor adjustments of the intrinsic laryngeal muscles in phonation (25), keeping the laryngeal skeleton stable (24). A lowering of the VLP is a therapeutical goal also in other exercises, e.g. prolonged /b/ (26) or, more traditionally, yawning and sighing (27). Effects on VLP have been observed in phonation into resonance tubes with the free end in air (14,15).

Sovijärvi used different tube dimensions in order to find the tube size that produced a lowering of the VLP most effectively (4,5). He recommended tube lengths between 26 and 28 cm depending on the patient's voice type, with an inner diameter of 9 mm, glass as material, and a water bowl large enough to avoid splashing (4,5). These recommendations are still followed in clinical practice (6). On the other hand, there seems to be no scientific understanding why these specific dimensions should be critical and optimal.

Patients using RTPW have described the effect as a sensation of 'relaxing, like a massage' (6). The reason has been assumed to be the induced pulsations of the oral pressure, which would exert a time-varying force on the vocal tract walls and vocal folds (18). The background is that, for expelling an air bubble into the water, the oral pressure needs to be raised to a value corresponding at least to the immersion depth. In other words, for an immersion depth of 2 cm, the oral pressure needs to be raised to at least 2 cmH₂O in order for a bubble to be ejected. After the bubble has been ejected, the oral pressure will drop rapidly and then start to build up again, preparing for ejection of the next bubble (18,21).

Bubble dynamics has been studied for a long time in the field of chemical engineering, e.g. by Davidson and Amick (28). In a series of experiments on bubble frequencies in water, they found that the pattern and frequency of the bubbling depends on several factors, such as air flow, back volume, immersion depth, and the diameter of the orifice. Also, the characteristics of bubbling in RTPW have recently been analysed (21,29,30).

Summarizing, for many decades RTPW has been commonly used in voice therapy, and the results have reportedly been good. The effects have been assumed to involve also a lowering of VLP, an aspect that as yet has been documented only by means of palpation (4,5). VLP can be measured non-invasively by means of the dual-channel

electroglottograph (31). The aim of the present study was to test if effects of RTPW on VLP can be documented by this technique and to analyse the relationship between this effect and oral pressure. Ethical consent was obtained from the ethical committee at the Department of Psychology and Logopedics, Åbo Akademi University, Finland.

Materials and method

Subjects and equipment

A male (25 years old) and a female (27 years old), vocally healthy, volunteered as subjects. Both had previous experience of both teaching and clinically using RTPW. Both subjects had had some previous vocal training and were members of high-standard university choirs and were thus able to keep a steady pitch and loudness also during RTPW exercises.

The experiment was designed in close agreement with Sovijärvi's recommendations. Two resonance tubes of the recommended extreme lengths, 26 cm and 28 cm, were used, both made of 1 mm thick glass, and with an inner diameter of 9 mm (4,5). The water bowls were approximately 13 cm × 13 cm × 9.5 cm (4–6). To control immersion depth, markings were made 2 cm, 6 cm, and 10 cm from the free end of the tube. The subjects performed all tasks in sitting position, with straight back and relaxed shoulders. The subjects held the tubes in a comfortable angle of their own choice.

Posture was photographed for documentation purposes, and for estimating the tube angle and immersion depth (Figure 1, Table I). The male subject kept the tubes in an angle of approximately 60° under the water surface, and the female kept the tubes in an angle of approximately 50°. Due to the differences in immersion depths for the two subjects, the depths will be referred to in terms of the tube markings.

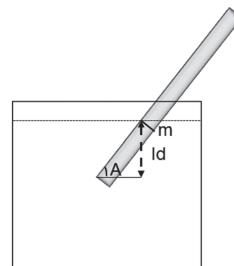


Figure 1. Calculation used for estimating the immersion depth I_d , given the immersion angle A and the marker position m on the tube: $\sin A = m / I_d$; hence: $I_d = m / \sin A$.

Table I. Estimated immersion depths derived from the tube markings and the immersion angles.

Tube marking (cm)	Depth of water (cm)	
	Male subject, 60° angle	Female subject, 50° angle
2	1.73	1.53
6	5.20	4.60
10	8.66	7.66

Audio, VLP, and oral pressure were recorded in a sound-treated studio at the KTH (Royal Institute of Technology), Stockholm, Sweden. Figure 2 shows the experimental set-up. The VLP signal was recorded using a dual-channel electroglottograph (Glottal Enterprises MC2-1, Syracuse, NY, USA). The electrodes were placed on both sides of the subjects' thyroid cartilage and held in place with an elastic cardboard ribbon. Contact paste was used to improve contact. The VLP signal was calibrated by sliding the electrodes up and down on the throat while the subject sustained an /a/ vowel. The oral pressure was recorded with a pressure transducer (Glottal Enterprises MSIF-2) attached to a thin plastic tube (inner diameter 4 mm) which the subject held in the corner of the mouth. For documentation purposes the audio signal was recorded by a head-worn microphone, placed 5 cm from the subjects' mouths. Data were collected using the SoundSwell Signal Workstation for Windows.

Because only within-subject analyses were made, VLP data were collected only in terms of output voltage. Polarity was made such that a positive change corresponded to a VLP rise. Pressure was calibrated by recording pressures measured by means of a manometer.

Tasks

The subjects performed three groups of tasks, in the following order:

1. Phonation into a 26 cm long tube with the free end: (a) in air; (b) kept with the 2 cm marking by the water surface; (c) kept with the 6 cm marking by the water surface
2. Phonation into a 28 cm long tube with the free end: (a) in air; (b) kept with the 2 cm marking by the water surface; (c) kept with the 6 cm marking by the water surface
3. Phonation while an assistant lifted the water bowl up and down, thus continuously varying the immersion depth between 0 cm (air) and the 10 cm marking. In this way, the subject could keep body posture constant. The assistant lifted the bowl up and down twice, giving a variation in immersion depth from air to maximum twice during each take, and finally ending with the tube end in air. The mean duration of each take was $M = 9.12$ s ($SD = 1.07$). Both subjects performed this task first with the 26 cm long tube, and then with the 28 cm long tube.

The subjects performed each part of tasks 1 and 2 three times in succession, but repeated task 3 as many times as they felt comfortable, between 6 and 11 takes. The subjects were asked to keep a steady loudness and a comfortable pitch of their own choice. The mean F0 was 153 Hz (SD 6) for the male subject and 214 Hz (SD 10) for the female subject.

Before all three tasks, the subjects were asked to pronounce the syllable /pa/ three times, so as to provide reference values for VLP.

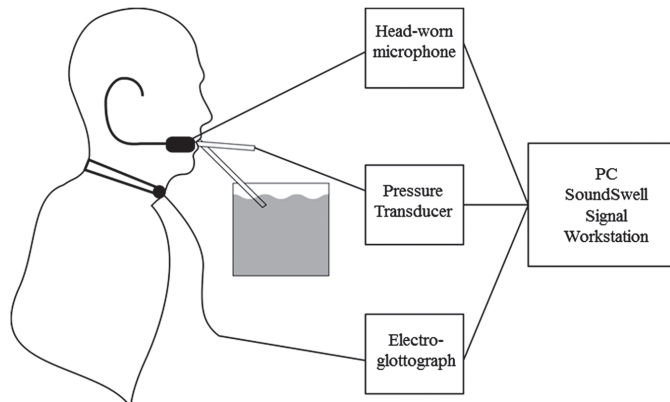


Figure 2. Experimental set-up. The bowl with water was raised or lowered as needed.

Analyses

The oral pressure for normal phonation was measured during the occlusion of the plosive /p/ during the repetitions of the syllable /pa/. During normal phonation it amounted to 6 cmH₂O, approximately. During RTPW it was low-pass filtered at 30 Hz and 50 Hz for the male and the female subject, respectively, thus eliminating the audio component. The filtering was done by means of the Sopran software program (Tolvan Data 2009–2014, Version 1.0.5, Tyresö, Sweden). From tasks 1 and 2, 0.5 s segments of VLP and oral pressure were analysed for normal phonation and phonation with the tube end in air, and 1 s segments for phonation with the tube end immersed in water, RTPW. Some of the segments for normal phonation and phonation with the tube end in air were shorter than 1.5 s ($M=1.88$, SD 0.31 for normal phonation and $M=2.08$, SD 0.41 for tube phonation in air), while the segments of RTPW were between 1.86 and 4.87 s long ($M=3.05$, SD 0.82). All segments were started 0.5 s after the audio signal onset and consisted of 2,000 data points/s. As all conditions were produced three times, three segments were obtained, one from each token, giving a total of $3 \times 0.5 \times 2000 = 3000$ data points for normal phonation and phonation with the tube end in air, and $3 \times 1.0 \times 2000 = 6000$ data points for the different RTPW segments. The mean value of these segments was used in the analyses. For

measuring the mean frequency of the bubble pattern, the time separation between each peak in the oral pressure was determined. Because the immersion depth was continuously varied in the third task, the whole phonation was analysed for this condition. The VLP and oral pressure signals were low-pass filtered at 5 Hz, by means of the Sopran software program, so as to eliminate ripple due to the bubbles. The filtered signal was sampled at 160 Hz. The segments were between 7.63 and 10.68 s long for the female subject ($M=8.80$, SD 1.07) and between 7.96 and 11.21 s long for the male subject ($M=9.37$, SD 1.03). For each segment Spearman’s non-parametric correlation test was used to analyse the correlation between the VLP and oral pressure output signals. The statistical analyses were made using IBM SPSS Statistics 21 for Windows.

Results

The means and standard deviations of the VLP output voltage can be seen in Figure 3. For both subjects it rose when they phonated with the tube ends in air, and dropped during RTPW. The corresponding values for oral pressure during RTPW can be seen in Table II.

The mean time intervals between the peaks in the pressure signals, corresponding to the mean bubble frequency, varied between 46 and 70 ms,

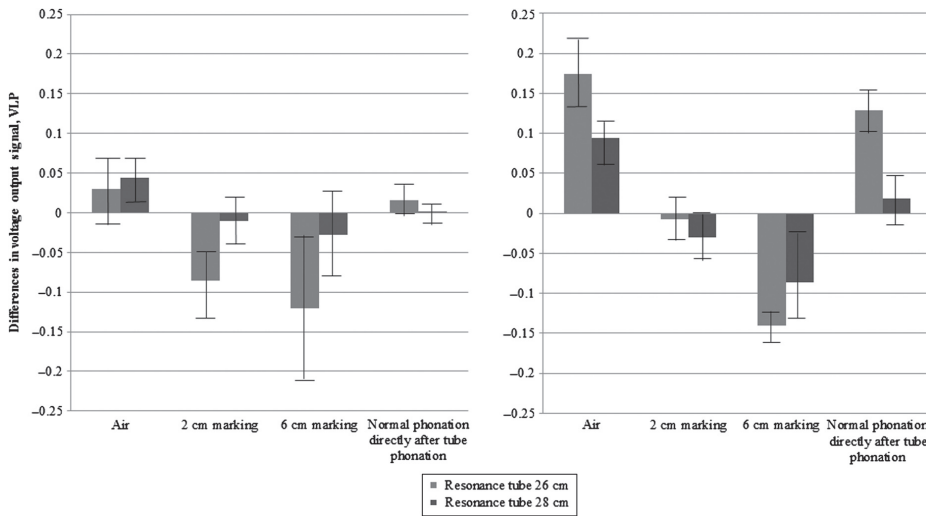


Figure 3. Mean vertical laryngeal position (VLP) voltage deviations from values observed for normal phonation observed during phonation with the tube end in air, and with indicated immersion depth markings. The left and right panels show values for the male and female subject, respectively. The two rightmost columns refer to normal phonation measured directly after RTPW with the 6 cm marker. Positive and negative values represent raised and lowered larynx, respectively. The bars represent one standard deviation.

Table II. Mean (M), minimum (Min), and maximum (Max) of oral pressure during RTPW (cmH₂O).

Tube marking (cm)	Male								Female							
	Tube 26 cm				Tube 28 cm				Tube 26 cm				Tube 28 cm			
	M	Min	Max	SD	M	Min	Max	SD	M	Min	Max	SD	M	Min	Max	SD
2	2.18	1.13	2.99	0.58	2.23	0.22	4.32	1.03	2.00	0.00	3.74	0.91	2.50	0.65	4.37	0.80
6	5.42	3.96	7.05	0.53	4.74	3.35	5.99	0.57	5.13	3.41	7.13	0.63	4.47	2.72	6.10	0.70

corresponding to a bubble frequency between 14 Hz and 22 Hz (Table III).

The results of task 3 with the continuously varying immersion depth can be seen in Table IV and Figure 4. For the male subject, the results varied between the repetitions, some repetitions showing a positive correlation, and others a negative correlation. For the female subject the correlation was negative between oral pressure and VLP voltage during RTPW. In other words, high pressures were associated with a low VLP.

Discussion

This pilot study was aimed at testing methods for gaining objective information on the effects of RTPWs on VLP and oral pressure. VLP data were collected using dual-channel electroglottography. Such data can be efficiently measured also by CT and MRI, which in addition provide possibly relevant information about the shape and volume of the oral cavity (32,33). However, as RTPW requires that the subject is either sitting or standing, these methods were inappropriate for the present study.

The dual-channel electroglottography method has been used in several studies (15,33), and the results have been compared to data obtained by videofluorographic filming (34). Even though small changes in the electroglottographic (EGG) voltage signal could be caused also by sagittal movements of the larynx, the findings generally corroborated the electroglottographic measurements (34). Unlike Laukkanen et al. (34) we experienced problems in attempts to calibrate the VLP voltage by sliding the electrodes on the neck while the subject was sustaining

a vowel. For this reason VLP effects induced by RTPW could not be determined in quantitative terms.

As compared with normal phonation, the VLP voltage dropped for both subjects during RTPW. On the other hand, it rose during tube phonation with the tube end in air. For the latter condition, Laukkanen et al. (15) found a rise of VLP for some subjects, but a drop for others, and Guzman et al. (14) observed a VLP drop during and after resonance tube phonation in a male classically trained singer. It is possible that phonatory habits play an important role as regards effects of tube phonation when the tube end is in free air.

The experiment with continuously varied immersion depth showed varied results for the subjects. For the male subject, the correlations were weak and of varied signs between takes, while the female subject showed high and consistently negative correlations. Thus, just as during RTPW with constant immersion depths, her larynx dropped when oral pressure was increased by a greater immersion depth. The absence of a similar effect in the male subject may be caused by several factors. For example, VLP is controlled by muscles which can be influenced by fatigue or reaction to unfamiliar phonatory conditions.

As pointed out by Enflo et al. (18) and by Granqvist et al. (21), the oral pressure needed to eject a bubble must be at least as high as the immersion depth; with an immersion depth of 4 cm, the pressure needed to eject a bubble is 4 cmH₂O or more (18,21). Our results are in good agreement with this; for both subjects the mean oral pressure during RTPW was around 2 cmH₂O for the immersion depth obtained with the 2 cm marking, and around 5 cmH₂O for the 6 cm marking.

Table III. Mean, standard deviation, and bubble frequency values for the bubble period time (ms), extracted from peak-to-peak values from the pressure signal.

Tube marking (cm)	Male						Female					
	Tube 26 cm			Tube 28 cm			Tube 26 cm			Tube 28 cm		
	M	SD	Hz	M	SD	Hz	M	SD	Hz	M	SD	Hz
2	59	12	17	59	14	17	46	18	22	55	17	18
6	70	21	14	65	21	15	57	22	18	64	22	15

Table IV. Bivariate correlation between the vertical laryngeal positions (VLP) and oral pressure for both subjects when phonating into two different tube lengths with varied water depth. Negative values refer to the case that an increase of oral pressure was associated with a drop of VLP.

Take number	Male		Female	
	26 cm tube	28 cm tube	26 cm tube	28 cm tube
	r_s	r_s	r_s	r_s
1	-0.060	-0.388	-0.840	-0.872
2	0.294	-0.512	-0.869	-0.719
3	0.714	-0.435	-0.797	-0.723
4	0.364	0.100	-0.764	-0.772
5	-0.404	0.013	-0.865	-0.786
6	-0.552	0.222	-0.787	-0.808
7	-0.008	-0.331	-	-0.852
8	-0.238	0.108	-	-0.738
9	-0.167	-0.333	-	-0.839
10	0.395	-	-	-0.413
11	-0.015	-	-	-

The oral pressure signal provided information also on the bubble frequency. It tended to decrease with increasing immersion depth. This is not surprising. Assuming a constant air flow, it will take longer time to build up a high pressure than a low pressure in the tube. Likewise, for a given airflow it must take longer time to build up a given overpressure in a longer tube than in a shorter tube. Hence, the bubble frequency should be lower in a longer than in a shorter tube, which was also observed for the female subject (Table III).

Overall, the bubble frequencies observed in this study are higher than those presented by Granqvist et al. (21). However, the bubble frequency is

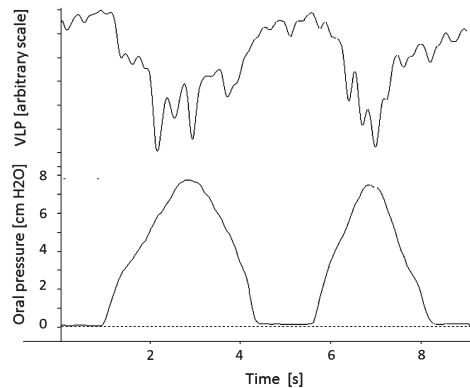


Figure 4. Vertical laryngeal position (VLP) and oral pressure signal for the female subject recorded during RTPW into a 28 cm long tube while the immersion depth was continuously varied between 0 cm and 7.7 cm. The data refer to take 1, with a correlation of -0.872 between VLP and oral pressure.

dependent on many factors, such as airflow, subglottal pressure, vocal tract volume, and dimensions of the tube (28). Nevertheless, the bubble frequency may be a valuable auditory control parameter for clinicians, since it reflects the combination of parameters that are highly relevant to phonation.

In the studies just mentioned, bubble-synchronized oscillations of the oral pressure were observed during RTPW (18,21). Our recordings corroborated these observations. The amplitude of these oscillations seems a relevant parameter. At the approximately 2-cm immersion depth we observed an amplitude of the bubble-synchronized oral pressure variations ranging between 2 and 4 cmH₂O. A pressure variation of this magnitude will exert an undulating pressure on the vocal tract walls, which may be quite important, since it would produce a massage-like effect. Such effects are known to be associated with relaxation of muscle tension (35) as well as with increase of blood flow and blood volume (36). In any event, this effect of RTPW seems worthwhile to examine more extensively in the future.

Conclusions

Combining dual-channel electroglottography and simultaneous recordings of oral pressure seems to be a useful method for analysing how RTPW affects VLP and phonation. Under identical experimental conditions the method yielded systematic and reasonably similar results for the two subjects studied. Lowering of VLP and bubble-synchronous pulsations of the oral pressure were observed for an immersion depth of 2 cm and also for an exaggerated depth of 6 cm RTPW.

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Real-Time Visual Feedback of Airflow in Voice Training: Aerodynamic Properties of Two Flow Ball Devices

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Summary: Objectives. Flow ball devices have been used as teaching tools to provide visual real-time feedback of airflow during singing. This study aims at exploring static back pressure and ball height as function of flow for two devices, marketed as flow ball and floating ball game.

Study Design. This is a comparative descriptive study.

Methods. A flow-driven vocal tract simulator was used to investigate the aerodynamic properties of these two devices, testing them for four different ball sizes. The flow range investigated was between 0 and 0.5 L/s. Audio, flow, pressure, and ball height were recorded.

Results. The flow pressure profiles for both tested devices were similar to those observed in previous studies on narrow tubes. For lifting the ball, both devices had a flow and a pressure threshold. The tested floating ball game required considerably higher back pressure for a given flow as compared with the flow ball.

Conclusions. Both tested devices have similar effects on back pressure as straws of 3.7 and 3.0 mm in diameter for the flow ball and the floating ball game, respectively. One might argue that both devices could be used as tools for practicing semi-occluded vocal tract exercises, with the additional benefit of providing real-time visual feedback of airflow during phonation. The flow threshold, combined with the flow feedback, would increase awareness of flow, rather than of pressure, during exercises using a flow ball device.

Key Words: Flow ball–Floating ball game–Real-time visual feedback of airflow–Semi-occluded vocal tract–Voice training.

INTRODUCTION

Phonation into narrow tubes has been substantially used in voice training. For example, resistant straws have been used to promote vocal economy, ie, the production of normal vocal intensity with less mechanical trauma to the vocal folds' tissues. Previous investigations have suggested that such effect is achieved by engaging the vocal tract to transforming aerodynamic energy into acoustic energy by means of a back pressure created when phonating into a narrow tube.¹ Glass tubes submerged in water have also been applied in clinics to treat, for example, hypernasality, hypo- and hyper-phonation, and vocal nodules.² Although not yet described in the literature, there are other types of devices that can be explored as tools to train efficient voice use. For example, the flow ball (FB) is a device available for respiratory training. This type of device is claimed to be beneficial for respiratory training, especially for wind instrumentalists and singers.^{3,4} Different devices can be found in the market. They contain a squared plastic tube that connects to a plastic basket

with a narrow passage. The latter has a hole in the middle through which air passes when exhaling through the device, lifting a small polystyrene ball that comes with it. Other devices can be found in early learning centers, referred to as floating ball games (FBG) (Figure 1).

The use of the FB as a voice training device was implemented for the first time in singing lessons by author FL several years ago. This idea emerged from the fact that this device could facilitate the visualization of flow via inspecting the ball height when phonating. Simultaneously, it also provides the potential effect of a semi-occlusion of the vocal tract. Students practicing with it realize the easiness of phonation when changing airflow according to the frequency and the intensity of each note in an exercise or when singing a musical phrase. This visualization of breath management (ie, *appoggio*)³ is of paramount importance for a classical trained singing to avoid timbre changes associated with pressed phonation, especially when singing fortissimo. Classically trained singers are expected to be able to change frequency and intensity of tones keeping the same phonation mode. Pressed phonation involves a high adduction force, and consequently low flow amplitudes, ending in greater vocal effort when compared with flow phonation.⁴ The latter promotes vocal economy as an increased acoustic output is achieved with lower subglottal pressure (P_{sub}) and a more moderate adduction.⁴ Adding to FL's anecdotal experience results of a preliminary investigation on the effects of FB use on voice revealed a decrease in contact quotient immediately after its use for professional singers performing a *mesa di voce* at different pitches.⁵ Positive experiences have also been reported by singing students using the FB as a respiratory exercising tool and as a phonatory training device.³ Instructions on its use include the following: (1) holding the proximal end firmly between the lips while phonating into the tube; and (2) maintaining control of

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¹http://www.thomann.de/intl/thomann_flowball.htm?sid=2df448726396b313dfcd22787ec1f2d4 (accessed July 12, 2016, 16:51).

²<http://www.powerbreathe.com/flowball-blue> (accessed July 12, 2016, 16:51).
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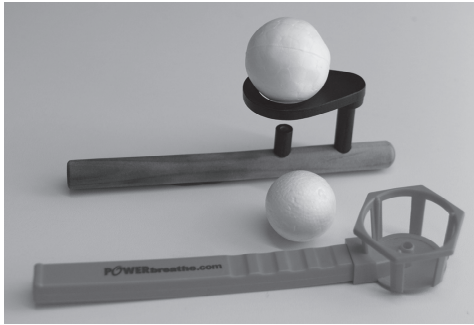


FIGURE 1. The two flow ball devices tested in this study: the floating ball game model (top) and the flow ball model (bottom).

breath and phonation so that the ball is kept in the airstream while phonating. This is possible as the ball stays near the center of the airstream due to the pressure being the lowest where the air speed is the highest (ie, Bernoulli effect).

The results of previous studies suggest that the provision of meaningful and quantitative feedback in a singing lesson encourages the development of consistent subsequent repetitions of the same neuromotor behavior, ie, “Knowledge of Results.”⁶ Misunderstanding of the information prior to and after providing feedback might be avoided if the feedback is immediate.⁶ Moreover, phonation habits seem to change quicker in a singing lesson when using visual feedback (eg, electrolaryngographic displays) together with verbal instructions.^{7,8} Visual feedback also assists in the development of student’s independence, self-correction, self-evaluation, and appraisal skills, promoting cognitive and associative stages of learning.⁹

Finally, the FB might also add the benefits of a semi-occluded vocal tract, as phonation into a narrow tube is required. As suggested earlier, phonation into narrow tubes increases the static back pressure (P_{back}) (ie, analogous to intraoral pressure) in the vocal tract for a given flow.¹⁰ These authors measured the back pressure–flow (P_{back} – U) relationship for different tube lengths and diameters commonly used in voice training, concluding that a change in tube diameter would affect the flow resistance more than a corresponding relative change in tube length. This has later been confirmed by Smith and Titze, who based on flow theory and empirical data suggested two models for the pressure–flow relationship.¹¹

This paper aims at exploring the physical properties of two different flow ball devices, the FB and the FBG, in terms of relationships among P_{back} , air flow (U), and ball height (h_b).

METHODS

The flow ball (FB)

For the purposes of this experiment, two flow ball devices were investigated. The first device, FB, consisted of a 140-mm long tube with a rectangular cross section of 7×10 mm. A basket with a narrow, upward facing opening of 3.9 mm in diameter¹² was



FIGURE 2. The flow ball device and its constituting parts (by POWERBreathe©).

attached to the tube. The device was supplied with a polystyrene ball of $\text{Ø} 29$ mm (Figure 2).

The floating ball game (FBG)

Another device was tested, the FBG made of wood. With a total length of 147 mm, this device had an inner longitudinal tube with $\text{Ø} 7$ mm. At a distance of 95 mm along the length of this tube, a smaller tube with 20 mm length and 3.5 mm inner Ø was inserted perpendicularly. In this particular tested specimen, the smaller tube was inserted deep into the tunnel so that it created a narrow passage between the two attached tubes. On the wood shaft, there was a ring also made of wood where the ball was placed. The FBG was provided by a polystyrene ball of $\text{Ø} 34.5$ mm (Figure 3).

Experimental setting

The P_{back} – U characteristics of these flow ball devices were measured with a flow-driven vocal tract simulator similar to the one used in a previous study.⁶ A ruler was kept next to the devices during video recordings in order to calibrate h_b . An air pressure of approximately 100 kPa was supplied from a pressurized air cylinder to a mass flow controller (Alicat Scientific Model MCR-50SLPM-TFT), connected to a 60-mL size syringe set with an inner cavity volume of 36 mL.⁶ A pressure transducer (8-SOP MPXV7007DP-ND NXP Freescale Semiconductor, Petaling by Digi-Key Electronics, UK)⁶ was attached to the syringe and FB and FBG were placed at the end, sealed with plasticine. A representation of this experimental setting is shown in Figure 4.

⁶<http://www.digikey.co.uk/en/supplier-centers/nxp-semiconductors>.

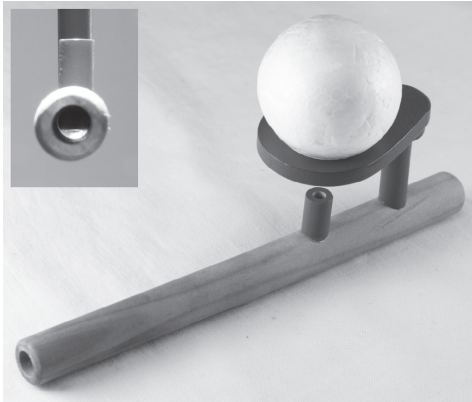


FIGURE 3. The floating ball game device and its constituting parts. The narrow constriction at the connection between the two tubes can be visualized by a strong light from above (*upper left image*).

Recordings and analysis

The experiments were recorded using a Canon (Canon, Tokyo, Japan) 700D digital camcorder with a Canon EF-S 18–200 mm lens. Video recordings of h_b were carried out at a rate of 25 frames per second, at a resolution of 1920×1088 pixels. In order to determine the range for h_b to be recorded, typical singing exercises with the FB device were performed by author FL prior to the experiments. A range of h_b of 2–7 cm was used to determine the range of U needed.

Audio, U , and P_{back} signals were recorded at a sampling rate of 16 kHz using the Soundswell signal workstation (Version 4.00 Build 4003, Core 4.0, Hitech Development AB, Stockholm, Sweden) and a DSP board (Loughborough Sound Images plc, Loughborough, UK) allowing DC input. The transducer for P_{back} was calibrated using a U-tube manometer. A visible clap of the

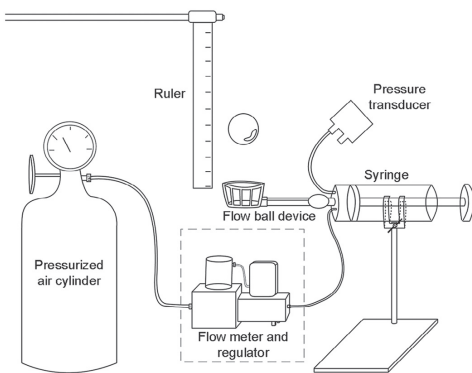


FIGURE 4. Schematic representation of the experimental setup.

TABLE 1.
Sizes and Weights of the Balls Tested in This Study

Ball Number	Diameter (mm)	Weight (g)	Density (g/cm ³)
1	29.0	0.304	0.0461
2	34.5	0.347	0.0371
3	37.2	0.652	0.0600
4	48.1	1.595	0.0878

Balls # 1 and #2 were supplied with the flow ball and the floating ball game, respectively.

hands was used to synchronize audio, U , and P_{back} with the video. The audio was also recorded for documentation purposes. Based on the h_b observed in the singing exercises, a U range of 0–0.5 L/s was used. This was supplied over 90 seconds by the custom-made software *Mjau* (by author SG).

The h_b was measured from the digital video recording using a *Matlab* (Mathworks, Natick, Massachusetts, USA) script. An area of the video containing only the ball and the neutral background was selected. The top edge of the ball was detected by looking for the increased pixel brightness caused by the white ball. Also, two positions on the ruler were associated with pixels in the video, enabling absolute calibration of h_b . This procedure resulted in 25 measurements per second of h_b .

The P_{back} and U signals were calibrated and down-sampled to 25 Hz using the custom-made *Sopran* software (by author SG) and synchronized with the h_b measurement. Thus, the experiment resulted in a data file at 25 Hz sampling rate, with channels containing U , P_{back} , and h_b . The signals were low-pass filtered to smooth the graphs plotted using *Matlab*.

This procedure was performed for the recordings of the two devices tested with four balls of different sizes (Table 1), as well as for recordings made without the balls. When recording the P_{back} – U characteristics without the ball, the experiments were not video-recorded. Although the balls that originally come with the devices are similar in shape and size, four different ball sizes were tested as they might be replaced by other sizes when the original ones are damaged or lost. In addition, singing teachers might want to change P_{back} and U relationships using the same device, thus using different ball sizes to achieve such combinations.

Straw dimension adaptations

The P_{back} – U relationship appeared to be similar to that of a straw; thus, adaptations to the Smith and Titze’s basic flow model (Equation 1) and modified flow model (Equation 2) were attempted to compute equivalent straw diameters and lengths. For these adaptations, both the solver add-in in *Microsoft Excel* (2010, Albuquerque, New Mexico, USA) and a brute force method implemented in *Matlab* were tested.

$$P_{back} = \left(1.446 \cdot 10^{-6} \cdot \frac{\rho}{D^4} \right) U^2 + \left(0.1752 \cdot \frac{\mu L}{D^4} \right) U \quad (1)$$

$$P_{back} = \left(3.7631 \cdot 10^{-7} \cdot \frac{L}{D^{4.4997}} + 1.0268 \cdot 10^{-6} \cdot \frac{1}{D^{4.0416}} \right) U^2 + \left(3.9913 \cdot 10^{-9} \cdot \frac{L}{D^{5.0089}} + 8.0169 \cdot 10^{-7} \cdot \frac{1}{D^{3.7696}} \right) U \tag{2}$$

where P_{back} is the flow-dependent back pressure from the tube in Pa, ρ is the density of air (1.225 kg/m^3), D is the tube diameter in m, U is the flow in L/s, μ is the dynamic viscosity of air ($1.983 \cdot 10^{-5} \text{ Pa}\cdot\text{s}$), and L is the length of the tube in m.

RESULTS

The FB

Figure 5 shows the results for the FB with all balls tested. A P_{back} - U relationship similar to that of the FB without the ball was found when adding all balls, except for the range between 0 and 0.1 L/s for the smallest ball. With respect to this ball, it stayed in the basket covering the hole until 0.1 L/s where it started to bounce. At 0.2 L/s, it started to lift off. For higher flows, the h_B seemed to increase linearly with U , reaching 10 cm at 0.4 L/s. Another way of looking at the results is considering how the h_B depends on the P_{back} ; about 5 cmH₂O was required for the ball to lift off. However, the relationship between h_B and P_{back} did not appear to be linear.

For ball #2, the results were almost identical, the main difference being the absence of the hump in the P_{back} - U profile. For the considerably larger ball, ball #3, the threshold for lift off was increased to about 0.3 L/s and 10 cmH₂O. For ball #4, lift off occurred beyond 0.5 L/s and a P_{back} of about 25 cmH₂O.

The FBG

Figure 6 shows the results for all balls tested using the FBG. No humps were found in the P_{back} - U profile for this device; the balls never covered the hole.

Considering ball #1, the h_B revealed a similar behavior as to the FB, but a slightly higher U was required for lift off: about 0.25 L/s. For higher U , the h_B appeared to relate linearly with increasing U . However, the P_{back} required for lift off was about 20 cmH₂O, hence four times higher than for the FB.

Ball #2 required a slightly higher U for lift off as compared with ball #1: about 0.27 L/s. A linear relationship between U and h_B was still observed. The P_{back} - h_B relationship for this ball revealed a threshold P_{back} of about 20 cmH₂O for lift off.

Ball #3 required high U and P_{back} for lift off: >0.4 L/s and 50 cmH₂O.

Ball #4 did not lift off for the flows used in this study.

While carrying out the recordings, a bouncing of the ball in the airstream was observed. When inspecting these oscillations closely, it was found that they occurred at a frequency of 1.5–2 Hz, as exemplified in Figure 7.

Straw dimension adaptations

When adapting the recorded data to the modified flow model provided by Smith and Titze, the *Excel* solver method did not converge to an optimum. The brute force method implemented in *Matlab* found an optimum match for a straw with a negative length, which is of course unrealistic. Using the basic flow model, *Excel* and *Matlab* provided nearly identical optima and resulted in a positive straw length. The predictions of P_{back} by the basic model matched measured data with an average error of 0.14 and of 0.17 cmH₂O for the FB and FBG, respectively (Table 2).

Figure 8 compares the measured results for P_{back} - U relationships for both FB and FBG with no balls; the predictions were made applying the basic flow model.

DISCUSSION

The present investigation aimed at describing the physical properties of a device recently implemented in singing lessons. The

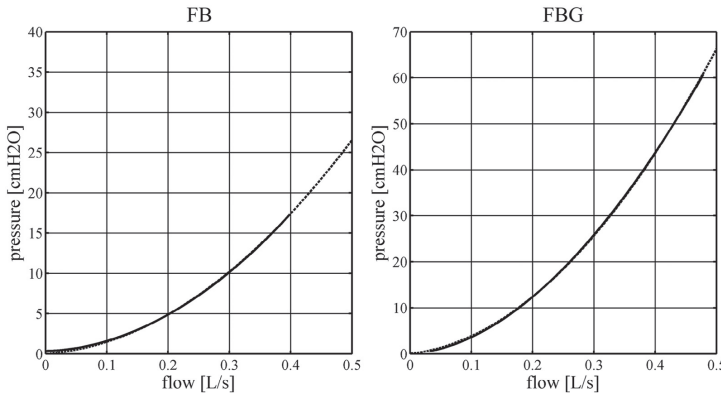


FIGURE 5. Back pressure and flow relationship for the flow ball (FB) and floating ball game (FBG) devices (solid lines) and for the adaptation of the basic flow model to the data represented in Table 2 (dashed lines).

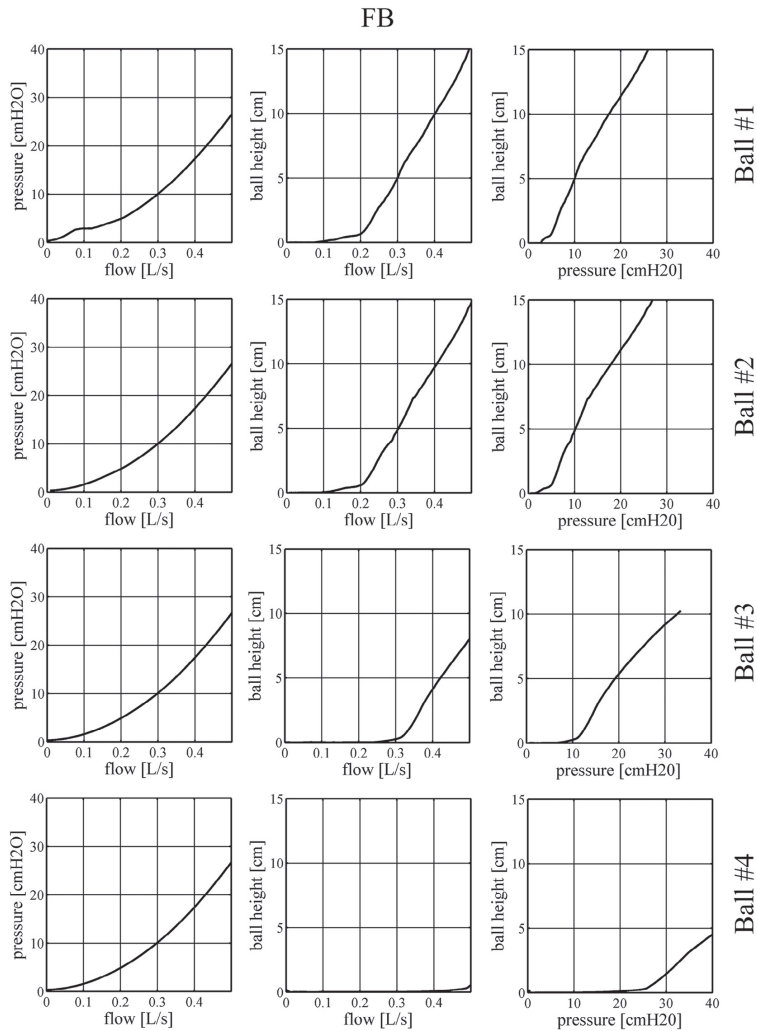


FIGURE 6. Results for the flow ball device (FB). The following relationships are represented for the four tested ball sizes: back pressure and flow (*left panel*), ball height and flow (*middle panel*), and back pressure and ball height (*right panel*).

FB and an FBG with four ball sizes were compared. Relationships among P_{back} , U , and h_B were investigated.

Both devices showed similar $P_{back}-U$ profiles to that of a straw, although with different dimensions. Both FB and FBG had thresholds for the ball to lift off regarding U and P_{back} . The U thresholds were similar, but the P_{back} threshold for the FBG was considerably higher than for the FB. The FBG had a narrower opening, hence a $P_{back}-U$ profile that resembles a considerably thinner straw.

The FBG device provides an almost 2.6 times higher P_{back} as compared with the FB for the same U .

Previous studies on the effects of phonating into a glass tube and a stirring straw have found a decreased glottal adduction, presumably as a direct physiological result of the increased pressure in the vocal tract.¹³ Increasing the oral pressure, maintaining P_{sub} and glottal resistance, would reduce the transglottal pressure and U . This would be true both for straws and for both FB

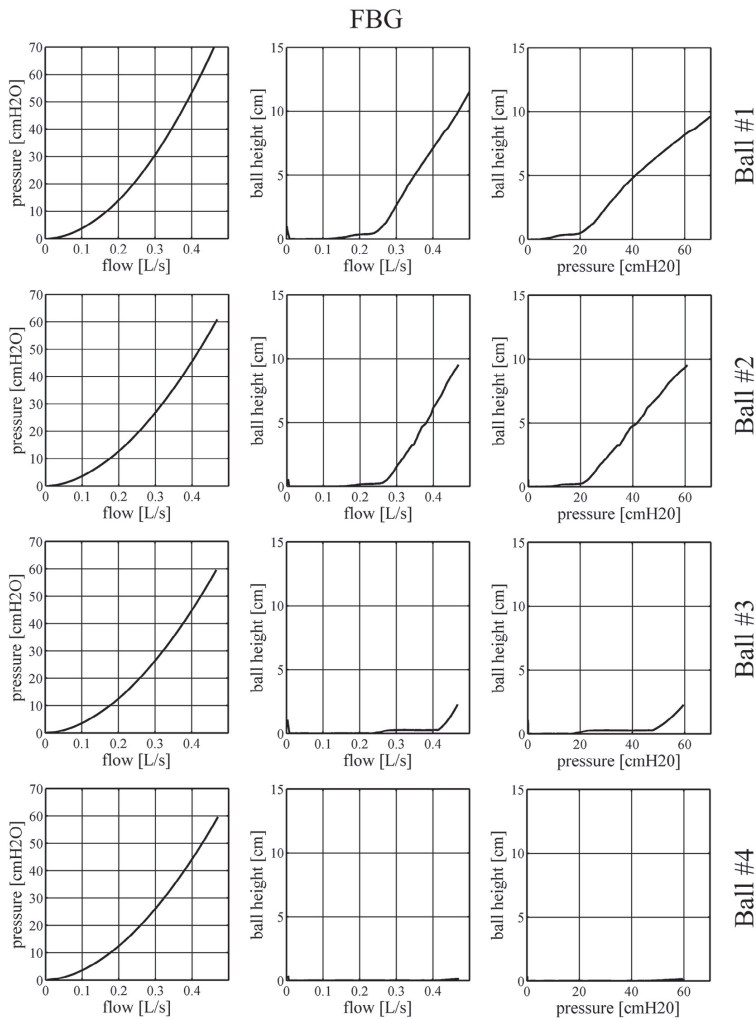


FIGURE 7. Results for the floating ball game device (FBG). The following relationships are represented for the four tested ball sizes: back pressure and flow (left panel), ball height and flow (middle panel), and back pressure and ball height (right panel).

and FBG due to their similar $P_{back}-U$ profiles. However, the results of this and previous investigations¹⁰ suggest that even small changes in tube diameter might have a considerable effect on P_{back} , emphasizing the need for awareness of the physiological effects of P_{back} during voice training.

The predictions of tube lengths based on the two flow models by Smith and Titze varied considerably.¹¹ It appears that although the models work well for predicting a P_{back} from tube

dimensions, they are numerically ill-conditioned when applied backwards, ie, when trying to predict tube length from P_{back} data. It has been shown that a change in relative tube length affects the P_{back} to a much lesser degree than the corresponding relative change in tube diameter¹⁰; a relatively large change in tube length only affects the P_{back} slightly. When the $P_{back}-U$ relationship is applied backwards, this results in a slight change in P_{back} data that may lead to a large change in the estimation of the tube

TABLE 2.
Estimated Diameters and Lengths for Straws With Equivalent Back Pressure and Flow Profiles to the Ones Found for the Flow Ball (FB) and the Floating Ball Game (FBG) Devices, Applying the Basic and the Modified Flow Models by Smith and Titze

Device	Basic Flow Model		Modified Flow Model	
	Diameter (mm)	Length (mm)	Diameter (mm)	Length (mm)
FB	3.7	31	2.7	-112
FBG	3.0	33	2.3	-85

Note the unrealistic negative lengths that resulted from applying the modified flow model.

length. With that in mind, the equivalent tube lengths found in this paper should be considered as rough estimations. It is true that a straw with the suggested dimensions will have a similar P_{back} - U profile as the flow ball devices, but other tube dimensions may also have similar profiles.

A finding from the video recordings was that the ball occasionally started to oscillate, sometimes at an amplitude so high that it fell out of the airstream. Looking closer at these oscillations, they occurred in the frequency range between 1 and 2 Hz. Thus, it appears as if the device with the ball in the air has similarities with a resonant system, with a resonant frequency near 1–2 Hz. If the singer would provide a flow with oscillations in this frequency range, corresponding to 60–120 BPM, these oscillations would be amplified and the ball could fall out of the airstream. One could argue that this property of the device would promote the use of a steady flow with a more legato-like phonation, eg, during *messa di voce* or arpeggio exercises.

The h_B provides visual feedback of the amount of airflow used. Thus, a flow ball device could be used as a U meter. Different

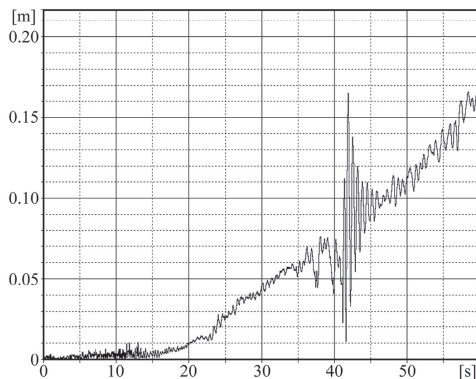


FIGURE 8. Graphic representation of the ball height as a function of time during one recording of the flow ball device with its supplied ball (ie, ball #1). At approximately 42 seconds, the ball height oscillates at a frequency of 1.6 Hz.

phonation types could be visualized through the amount of U the singer would apply. The h_B range of 0–10 cm for the FB would correspond to U of 0.2–0.4 L/s. It could be speculated what behavioral changes this might lead to. At a glottal level, high flow and low transglottal pressure correspond to a low flow resistance, ie, a small amount of adduction. Using the FB, the singer could choose between applying a high P_{sub} and using less adduction to achieve a sufficiently high U . The lift of the ball and its maintenance in the airstream could therefore encourage use of less adduction, promoting the awareness that pressure and flow are different dimensions that can be changed separately. From a pedagogical point of view, this seems also worthwhile because the student could be encouraged to explore the sensation of achieving maximum flow with a complete glottal closure. This type of phonation, ie, flow phonation, has been associated with an improved vocal function, as it requires lower P_{sub} and moderate degree of adduction force.^{4,14}

Moreover, the combination of visual feedback with verbal instructions can assist both teacher and student in achieving a common vocabulary voided of multiple translations of sound quality into words.^{15,16} Additionally, the different types of learners in a singing lesson (ie, intellectual, aural, kinesthetic, and visual) call for the need for applying different types of feedback and a teaching model distant from the “one model fits all.”¹⁷

In summary, the results here discussed confirm that flow ball devices have a similar P_{back} - U profile as narrow tubes. However, when applied to singing lessons, the flow ball device provides visual real-time feedback of airflow during phonation.

CONCLUSIONS

The results of this study suggest that flow ball devices seem to be useful pedagogical tools for singing practice. On the one hand, they provide real-time visual feedback of airflow. The ball height can be used as an indication of the amount of airflow that is being used, an essential element in singing training. Flow phonation is the most advantageous phonation type in terms of ease of phonation, thus being emphasized when training voices.¹⁸ In addition, as previous results have suggested, visual feedback (when combined with verbal feedback) might have a significant positive effect on student’s development. It is, however, important to emphasize that different flow ball devices might have different lift off, flow/pressures, and aerodynamic properties. Therefore, it seems worthwhile to assess these characteristics before using them and to make sure that they correspond to the needs of the intended exercises.

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Resonance Tube Phonation in Water—the Effect of Tube Diameter and Water Depth on Back Pressure and Bubble Characteristics at Different Airflows

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Summary: Objectives. Resonance tube phonation with tube end in water is a voice therapy method in which the patient phonates through a glass tube, keeping the free end of the tube submerged in water, creating bubbles. The purpose of this experimental study was to determine flow–pressure relationship, flow thresholds between bubble types, and bubble frequency as a function of flow and back volume.

Methods. A flow-driven vocal tract simulator was used for recording the back pressure produced by resonance tubes with inner diameters of 8 and 9 mm submerged at water depths of 0–7 cm. Visual inspection of bubble types through video recording was also performed.

Results. The static back pressure was largely determined by the water depth. The narrower tube provided a slightly higher back pressure for a given flow and depth. The amplitude of the pressure oscillations increased with flow and depth. Depending on flow, the bubbles were emitted from the tube in three distinct types with increasing flow: one by one, pairwise, and in a chaotic manner. The bubble frequency was slightly higher for the narrower tube. An increase in back volume led to a decrease in bubble frequency.

Conclusions. This study provides data on the physical properties of resonance tube phonation with the tube end in water. This information will be useful in future research when looking into the possible effects of this type of voice training.

Key Words: Resonance tube phonation in water–Back pressure–Tube diameter–Water depth–Voice therapy.

INTRODUCTION

Semiocluded vocal tract (SOVT) exercises have a long history in voice training. Semioclusions can be accomplished via lip trills, tongue trills, raspberries, the hand-over-mouth technique, or phonation into differently sized tubes with the free end kept in air or in water. Common for all these exercises is that they provide a flow resistance, leading to an increase in oral pressure and a decrease in transglottal pressure.^{1–3}

Resonance tube phonation in water is an exercise in which the user phonates into a glass tube, keeping the free end of the tube submerged a few centimeters into a bowl of water.⁴ This method provides an increase in oral pressure that fluctuates as a result of the water bubbles.^{5–7} Clinicians have reported good clinical results using this method when treating patients with

different kinds of voice disorders, such as vocal nodules, hyper- and hypofunctions, and vocal fold paresis,^{4,8} and positive immediate effects have been reported in dysphonic patients⁹ and healthy singers.⁵

The developer of the method, Antti Sovijärvi,⁴ claimed that the tubes should have specific dimensions depending on the patient's voice category and age. Sovijärvi recommended tubes between 26 and 28 cm in length with a diameter of 9 mm for adults. Tubes for children should be between 24 and 26 cm in length with a diameter of 8 mm.⁴ These recommendations are still taken into consideration in clinical practice,⁸ although there is, to our knowledge, no scientific evidence for why these specific tube dimensions would be more appropriate than others.

Amarante Andrade et al¹⁰ investigated the pressure–flow relationship for different tube dimensions used in voice exercises. The results showed that a change in diameter affects the flow resistance to a greater extent than a corresponding relative change in length. The typical resonance tube diameter of 9 mm⁴ generated a relatively low flow resistance for a given flow, compared to narrower diameters of, for example, 3.3 or 6 mm.¹⁰ Later, Smith and Titze¹¹ conducted a similar study with the end of the tubes in free air, resulting in a model for the pressure–flow relationship, based on flow theory and empirical data. Submerging the tube into water adds another pressure component affecting the back pressure (p_{back}). When in water, the flow will not start until the pressure given by the water depth has been overcome.¹⁰

In the clinical setting, Simberg and Laine⁸ suggest three different versions of the resonance tube in water exercise depending on the aim of the training. For treating for example hyperfunction or vocal nodules, Simberg and Laine recommend continuous phonation while keeping the tube end submerged 1–2 cm into

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the water. For treating patients with insufficient vocal fold closure, they recommend short phonations while keeping the tube end submerged as deep as 15 cm into the water, resembling pushing exercises. For treating hypofunction, for example, they recommend continuous phonation while keeping the tube end close to the water surface, with the end of the tube partially open. A similar voice training method is the LaxVox technique, in which continuous phonation through a silicone tube submerged into a water bottle is used.¹² The water depth recommended in this technique is 1–7 cm, hence deeper than that in the resonance tube method.

When the tube end is submerged into water during continuous phonation, the bubbles cause oscillation in the oral pressure.^{5–7,10} Patients using this version of the method have referred to the sensation in the throat as ‘relaxing, like a ‘massage’,¹⁸ and the oscillations in the oral pressure have later been referred to as implementing a “massage effect” in the larynx.^{2,5,7,13,14} However, it remains unclear exactly what constitutes this presumed effect.

Little systematic examination of bubble formation and frequency for resonance tube phonation in water has been performed. Ramlakhan et al¹⁵ used high-speed imaging to visually observe bubble formations during resonance tube phonation in water, suggesting that bubbles exit the tube in a steady but alternating pattern followed by a backflow of water into the tube. Further, there are some reports on bubble frequencies with human participants without measurement of flow.^{6,7,13,16} However, the effects of flow on the formation of bubbles in water and other fluids with upward-facing orifices were examined already in the 1950s by Davidson and Amick,¹⁷ among others. Davidson and Amick found that for low flows, the bubble size was almost independent of flow, and thus the bubble frequency was proportional to the flow. For higher flows, the bubble size increased with flow, and the bubble frequency plateaued at a maximum rate. Also, Davidson and Amick found that the volume of the cavity behind the tube inlet affected the bubble size and frequency. For certain flows, Davidson and Amick also observed bimodally (pairwise) emitted bubbles, forming the shape of a mushroom. Tufaile and Sartorelli¹⁸ also observed doublets of bubbles being formed from upward-facing orifices, but in a mixture of water and glycerin. For higher

flows, Tufaile and Sartorelli observed quadruplets and chaotic behavior in the formation of bubbles.

During resonance tube phonation in water, the static and oscillating parts of p_{back} directly affect the vocal apparatus.^{5–7,16} Apart from this, the bubbles may play an important role, providing visual, auditory, and tactile feedback for the clinician and patient during the exercise. The purpose of the present study was to investigate characteristics of p_{back} and bubbles generated by glass tubes submerged in water. The tubes were connected to a flow-driven vocal tract simulator with a variable back cavity volume. The simulator provided a continuous airflow to resemble the exercises with continuous phonation described by Simberg and Laine.⁸

METHODS

Setup

A flow-driven vocal tract simulator was used, consisting of a pressurized air cylinder, connected via a mass flow controller (Alicat Scientific model MCR-50SLPM-TFT, Alicat Scientific, Tucson, Arizona, United States) to a 60-mL syringe, providing a cavity with an adjustable size and an outlet for tube connection. A differential pressure transducer (8-SOP MPXV7007DP-ND; Freescale Semiconductor, Petaling Jaya, Malaysia) was attached to the syringe (see Figure 1). Calibration of pressure was performed by means of a U-tube manometer.

The pressure in the back cavity, the flow signal from the flow controller, and the audio were recorded using the *Soundswell Signal Workstation for Windows* Version 4.00 Build 4003 with an analog library *SwelDSP 4.00* and DSP card LSI PC/C32 (Neovius Data och Signalsystem AB, www.neovius.se). The channels were recorded at a sampling rate of 16 kHz each. The audio signal was used for logging purposes only. For measurements requiring a varying flow, the custom written software *Mjau* (by author SG), was used to control the flow controller. Some recordings were supplemented with video filming using a Canon 700D model (Canon Inc., www.canon.com) at a rate of 50 frames per second and an exposure time of 1/1000 second. The data analyses were made using *Sopran* software Version 1.0.12 (Tolvan Data, www.tolvan.com) and *MATLAB* Version R2015b (MathWorks Inc., www.mathworks.com). Statistical analyses were

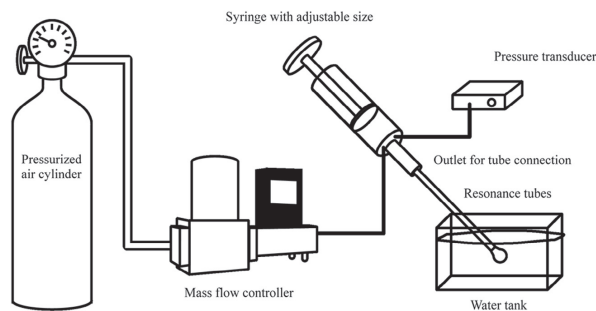


FIGURE 1. The airflow-driven vocal tract simulator.

made using *IBM SPSS Statistics 24 for Windows* (IBM, Armonk, New York, United States).

Materials

Two glass tubes with inner diameters of $\varnothing 8$ and $\varnothing 9$ mm, a glass thickness of 1.0 mm, and a length 26 cm were used.⁴ In the clinical setting, patients were instructed to keep a good, relaxed posture, avoiding bending the neck or lowering the chin.⁸ Based on these posture recommendations, the tubes in the present study were submerged in water at a 45° angle, which should be an accurate estimate of the angle that patients use in the clinical setting. All water depths were measured from the surface to the lowest part of the tube end (see [Figure 2](#)). The size of the bowl used in the experiments was 165 × 105 × 95 mm. In experiments 1–4, the back volume of the syringe was set to 36 cm³ to approximate the volume of the vocal tract.¹⁹ The same angle of tube submersion as well as back volume were used in a previous study investigating p_{back} for differently sized tubes with the free end in air and in water.¹⁰

Experiments

Experiment 1: pressure as a function of flow

The two tubes were assessed in air and at seven different water depths (1–7 cm) to measure p_{back} as a function of flow. The flow was increased from 0 up to 0.38 L/s by the control software for 65 seconds. The static and oscillating components were analyzed separately.

Static component. The flow and pressure signals were resampled to 5 Hz in *Sopran* (this procedure automatically included low-pass filtering at 2.5 Hz to avoid aliasing effects) and exported to *MATLAB*. To prepare the graphs, flow and pressure were further smoothed in *MATLAB* using a 4-second moving average window.

For comparison, curves describing theoretical estimations were added. Based on the findings by Amarante Andrade et al,¹⁰ a combined model for p_{back} was formulated:

$$p_{\text{back}} = p_{\text{water}} + p_{\text{tube}} \quad (1)$$

where p_{water} is the water pressure at the tube end and p_{tube} is the pressure determined by the flow through the tube and the tube resistance. p_{tube} was modeled by the modified flow model presented by Smith and Titz¹¹:

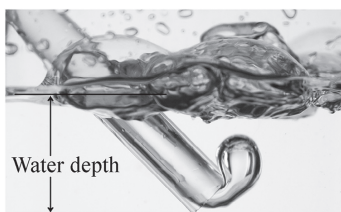


FIGURE 2. The definition of water depth used in this study.

$$p_{\text{tube}} = \left(3.7631 \cdot 10^{-7} \cdot \frac{L}{D^{4.4997}} + 1.0268 \cdot 10^{-6} \cdot \frac{1}{D^{3.0416}} \right) U^2 + \left(3.9913 \cdot 10^{-9} \cdot \frac{L}{D^{5.0089}} + 8.0169 \cdot 10^{-7} \cdot \frac{1}{D^{3.7696}} \right) U \quad (2)$$

where p_{tube} is the flow-dependent back pressure from the tube in free air in pascal, D is the tube diameter in meter, U is the flow in liter per second, and L is the length of the tube in meter.

Oscillating component. The pressure signal was processed in *Sopran* by high-pass filtering at 1 Hz to remove the static component, extracting the root of the mean of the squares (RMS) from the filtered pressure signal using a smoothing filter cutoff at 0.3 Hz. The flow and RMS-pressure signals were resampled to 5 Hz and exported to *MATLAB*.

To prepare the graphs, the flow, pressure, and RMS-pressure were further smoothed in *MATLAB* using a 4-second moving average window.

Experiment 2: bubble types and video recording

The $\varnothing 9$ mm tube was submerged at depths of 2, 4, and 6 cm. Initial tests were conducted to visually identify different bubble patterns—regular, bimodal, and chaotic. Based on these findings, video recordings were made during a slowly increasing flow. From these recordings, three flows (0.005, 0.013, and 0.050 L/s) were selected and consecutive images were extracted from the video recordings to illustrate the bubble types. The periodicity of p_{back} was analyzed by means of a correlogram using a window length of 50 ms. The correlogram is a method originally developed for analysis of voices with a high amount of perturbation in the fundamental frequency, using the correlation between two time windows of the signal. A correlogram shows the time on the x -axis, the time between windows on the y -axis, and the correlation coefficient on the z -axis displayed as a gray scale in a similar manner as in a spectrogram. Different candidates for time periods appear as horizontal dark stripes. For a detailed description of correlograms, see Granqvist and Hammarberg.²⁰

Experiment 3: bubble types as a function of flow

To identify the flow thresholds between the different bubble patterns, the two tubes were submerged in water at depths of 2, 4, and 6 cm. For each depth, 10 recordings were made while the flow increased from 0 to 0.08 L/s during 70 seconds. This range of flow was determined by the initial tests to be sufficient for covering the thresholds between the investigated bubble types. The shifts between bubble formation modes were determined by visual inspection of correlograms by authors GW and SG. All conditions were rated twice by both raters to obtain intrarater reliability. Four shifts were determined (see [Figure 3](#)). The first shift appeared when the first candidate started to deviate, whereas the second candidate remained stable. The second shift appeared when the first candidate was clearly divided in two. The third shift appeared when the separation in the first candidate became less clear and the second candidate started to become less stable, and the fourth shift appeared when no stable first and

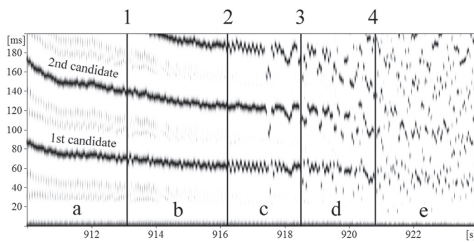


FIGURE 3. Correlogram analysis of the back pressure signal from a tube \varnothing 9 mm, with a length of 26 cm, submerged 2 cm in water. The airflow is increasing from 0.001 to 0.07 L/s, left to right. The letters represent the different bubble modes: a, regular; b, regular with bimodal components; c, bimodal; d, bimodal with chaotic components; and e, chaotic. The lines show the visual detection of shifts from (1) regular to regular with bimodal components, (2) regular with bimodal components to bimodal, (3) bimodal to bimodal with chaotic components, and (4) chaotic. The back cavity volume is 36 cm³ and the angle of tube submersion is 45°.

second candidates were visible. Flows at the shifts were noted for analyses, giving four flow threshold values for all takes: regular-regular with bimodal components-bimodal-bimodal with chaotic components-chaotic. Medians and interquartile ranges were determined. Inter- and intrarater reliabilities were calculated using intraclass correlation (ICC) on the entire data sets. Differences in flow values at different shifts were analyzed using nonparametric statistics with regard to diameters and water depths.

Experiment 4: bubble frequency and volume as functions of flow

The two tubes were submerged at water depths of 2, 4, and 6 cm. The flow was set to 11 different values between 0 and 0.04 L/s and kept steady at intervals of about 10 seconds. This reduced flow range was determined based on the results of experiment 3. All conditions were recorded 12 times. The bubble frequency was measured for each steady interval using a spectrum of the p_{back} signal over 4 seconds. The bubble frequencies were extracted for the cases when

the bubbles were emitted regularly or bimodally. In the bimodal region, the second spectral peak was extracted for analysis; that is, the frequency reflects the actual number of bubbles per second, not the number of bubble pairs per second. Flows generating chaotic bubble patterns did not result in clear peaks in the spectra; therefore, no measurements of bubble frequency were made for these flows.

The bubble volume was calculated by dividing the flow by the bubble frequency:

$$V = \frac{U}{f} \quad (3)$$

where V is the volume of a bubble in liter, U is the flow in liter per second, and f is the bubble frequency in hertz. Empirical mathematical models to describe the relation between flow and bubble frequency-volume were determined using the trendline function of *Microsoft Office Excel 2013* (Microsoft, Redmond, Washington, United States). The power function resulted in the highest correlation coefficient.

Experiment 5: bubble frequency and volume as functions of back cavity volume

The two tubes were submerged in 2-cm water depth. Each tube was recorded using two fixed flows of 0.005 and 0.02 L/s, whereas the volume of the back cavity was changed in intervals of about 10 seconds. Ten different volumes were set, ranging from 6 to 60 mL in steps of 6 mL. All conditions were recorded 10 times. Bubble frequency and volume were measured as in experiment 4. Differences in bubble frequencies and volumes between back volumes and tube diameters were analyzed using nonparametric statistics.

RESULTS

Experiment 1: pressure-flow relationship

The static component of the pressure-flow relationship can be seen in Figure 4. When the tube ends were kept in air, p_{back} increased slightly with increasing flow. When the tube ends were kept in water, p_{back} needed to reach a pressure near the

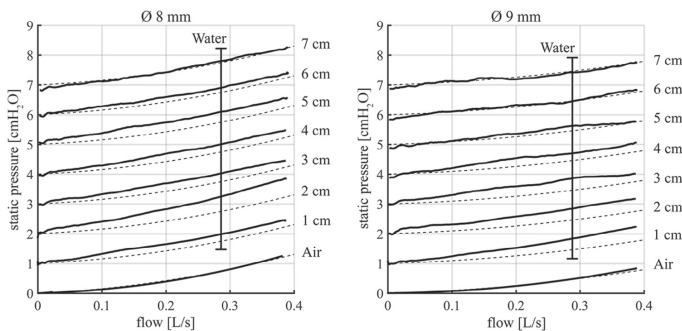


FIGURE 4. The flow-pressure relationship for resonance tubes, \varnothing 8 mm (left) and \varnothing 9 mm (right), 26-cm length in air, and at 1–7 cm of water depth. The back cavity volume is 36 cm³ and the angle of tube submersion is 45°. The dashed lines represent our combined model for p_{back} .

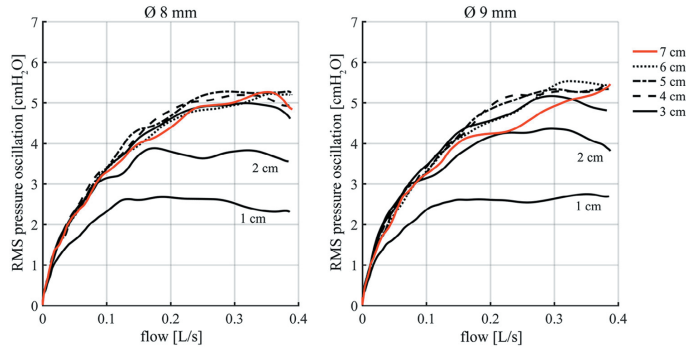


FIGURE 5. The oscillating component of the pressure as a function of flow for resonance tubes, \varnothing 8 mm (left) and \varnothing 9 mm (right), with 26-cm length, at 1–7 cm of water depth. The back cavity volume is 36 cm³ and the angle of tube submersion is 45°. RMS, root of the mean of the squares.

corresponding water depth (as defined in this paper) before the flow could start. A further increase in the flow resulted in a slightly increased p_{back} . The shapes of the curves for different depths were similar but shifted upward by an amount approximately corresponding to the water depth. For very low flows, the required pressure occasionally was slightly lower than the corresponding water depth. The p_{back} from the \varnothing 8 mm tube increased slightly more with flow than from the \varnothing 9-mm tube.

The predictions for the pressure-flow theory for tubes in air by Smith and Titze¹¹ provided a good match to the pressures for the tubes in free air. Our combined model predicts the p_{back} of the tube in water with a slight underestimation.

The RMS of the oscillating pressure component (p_{rms}) as a function of flow can be seen in Figure 5. The p_{rms} values at 1- and 2-cm water depths were lower than those at the other water depths.

Experiment 2: bubble types and video recording

The different bubble types are presented in Figures 6–8. At 0.005 L/s, the bubbles were produced one by one in a regular pattern; see upper sequence “a” in Figures 6–8. When increasing the flow to 0.013 L/s, the bubble pattern changed to a bimodal version where the bubbles were produced in periodic pairs of two bubbles that merged into a mushroom-like shape; see middle sequence “b” in Figures 6–8. When flow was increased to 0.05 L/s, the bubble pattern

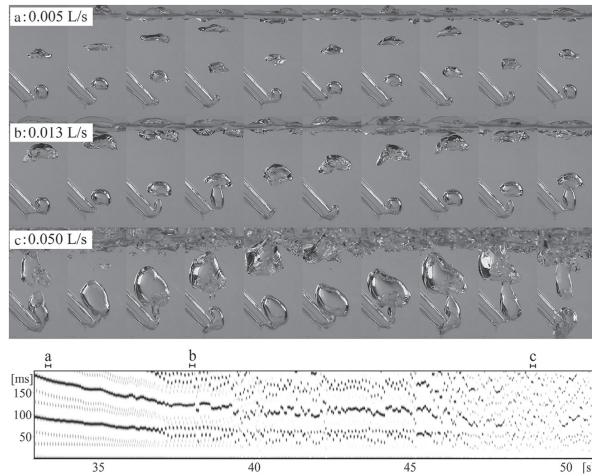


FIGURE 6. Regular (a), bimodal (b), and chaotic (c) bubble modes at different flows using a \varnothing 9-mm, 26-cm resonance tube submerged 6 cm in water, presented as picture extractions from the video recording and the corresponding time points in a correlogram of the pressure signal.

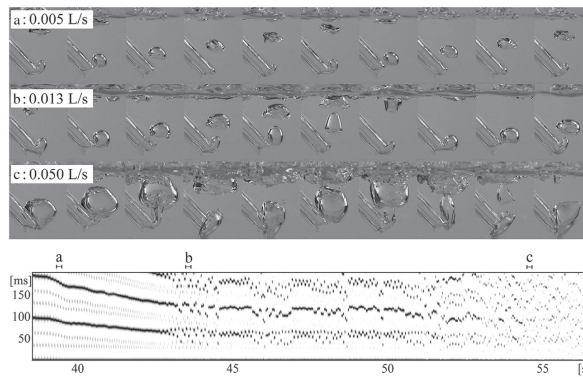


FIGURE 7. Regular (a), bimodal (b), and chaotic (c) bubble modes at different flows using a Ø 9-mm, 26-cm resonance tube submerged 4 cm in water, presented as picture extractions from the video recording and the corresponding time points in a correlogram of the pressure signal.

turned chaotic and no regularities were visible; see lower sequence “c” in Figures 6–8. Locations corresponding to sequences a–c are also indicated above the correlograms.

Experiment 3: bubble types as a function of flow

The shifts between regular, regular with bimodal components, bimodal, bimodal with chaotic components, and chaotic bubble types were identified in the correlogram of the p_{back} signal (recall Figure 3).

The median flow values for the shifts in bubble mode were determined by a visual inspection of correlograms by two raters (Table 1). Inter- and intrarater agreements were calculated using ICC. The ICC between the raters was ICC = 0.859 (single measures, confidence interval of 95% from 0.834 to 0.881, $F(479) = 13.175$, $P < 0.001$). The intrarater agreement for rater 1 was ICC = 0.959 (single measures, confidence interval of 95% from 0.948 to 0.968, $F(239) = 47.873$, $P < 0.001$) and that for rater 2 was ICC = 0.932 (single measures, confidence interval of 95% from 0.913 to 0.947, $F(239) = 28.445$, $P < 0.001$). Thus,

the ICC analyses indicated good to excellent intra- and inter-rater agreements in all cases.²¹

Kruskal-Wallis tests showed that there was a statistically significant difference in airflow at the different shifts in bubble modes ($\chi^2(3) = 799.334$, $P < 0.001$). The mean rank scores for the different shifts were 169.42 for shift 1, 328.62 for shift 2, 591.47 for shift 3, and 832.49 for shift 4. A statistically significant difference between water depths was also found ($\chi^2(2) = 12.362$, $P = 0.002$), with mean rank scores of 490.19 for 2 cm of water depth, 513.27 for 4 cm of water depth, and 438.05 for 6 cm of water depth. This showed that the shifts in bubble modes occurred at lower flows at 6 cm of water depth than at 2 cm of water depth. The highest flows required for shifts in bubble modes were detected at 4 cm of water depth. A Mann-Whitney U test showed a statistically significant difference between tube diameters ($U = 99,152.5$, $P < 0.001$). The mean rank scores were 447.07 for the Ø 8-mm tube and 513.93 for the Ø 9-mm tube, showing that the shifts in bubble modes occurred at lower airflows for the narrower tube.

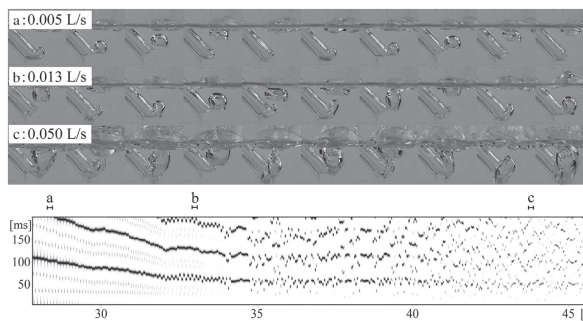


FIGURE 8. Regular (a), bimodal (b), and chaotic (c) bubble modes at different flows using a Ø 9-mm, 26-cm resonance tube submerged 2 cm in water, presented as picture extractions from the video recording and the corresponding time points in a correlogram of the pressure signal.

TABLE 1.
Median and Interquartile Range of the Airflow at Points of Shift in Bubble Modes From Experiment 3, Determined Visually by Two Raters Using Correlograms

Diameter (mm)	Water Depth (cm)	Flow at Bubble Mode Shifts (L/s)			
		Shift 1	Shift 2	Shift 3	Shift 4
		Regular-Regular With Bimodal Components	Regular With Bimodal Components-Bimodal	Bimodal-Bimodal with Chaotic Components	Bimodal With Chaotic Components-Chaos
8	2	0.0082 (0.0076–0.0084)	0.0119 (0.0105–0.0131)	0.0180 (0.0169–0.0194)	0.0297 (0.0280–0.0369)
	4	0.0097 (0.0089–0.0100)	0.0100 (0.0098–0.0102)	0.0193 (0.0180–0.0197)	0.0274 (0.0250–0.0325)
	6	0.0089 (0.0087–0.0092)	0.0094 (0.0091–0.0096)	0.0117 (0.0111–0.0130)	0.0247 (0.0220–0.0299)
9	2	0.0081 (0.0076–0.0089)	0.0127 (0.0118–0.0145)	0.0180 (0.0170–0.0196)	0.0253 (0.0233–0.0290)
	4	0.0110 (0.0105–0.0116)	0.0114 (0.0110–0.0122)	0.0186 (0.0179–0.0206)	0.0259 (0.0235–0.0297)
	6	0.0099 (0.0096–0.0105)	0.0110 (0.0106–0.0117)	0.0160 (0.0153–0.0184)	0.0269 (0.0236–0.0321)

The ratings were performed twice by both raters on 10 takes per task. Hence, all values are based on 4×10 flow values. The numbering of the shifts corresponds to those in Figure 3.

Experiment 4: bubble frequency and volume as a function of flow

The bubble frequency and volume as functions of flow are shown in Figures 9 and 10, respectively. The bubble frequency was extracted by identifying peaks in the spectra of p_{back} . The bubble frequency was only possible to register reliably up to the shifts to chaotic bubble patterns. The shifts varied between takes; thus, the bubble frequency was sometimes detectable for the higher flows and sometimes was not detectable. The highest flows enabling measurement of the bubble frequencies differed between the diameters and water depths, as seen in Figures 9 and 10.

Experiment 5: bubble frequency and volume as a function of back volume

The bubble frequency and volume as functions of the back volume can be seen in Figures 11 and 12, respectively. Ten different back volumes were set, ranging from 6 to 60 mL in steps of 6 mL. For the higher flow (0.02 L/s) and small back volumes, the bubble patterns varied between bimodal and chaotic, sometimes making detection of bubble frequency impossible. The numbers of detectable bubble frequencies at different back volumes during 0.02 L/s flow are shown in Table 2.

A Kruskal-Wallis test showed that changing the back volume had a statistically significant effect on the bubble frequency for the higher flow ($\chi^2(8) = 48.868$, $P < 0.001$; mean rank scores for the different back volumes: 12 mL = 124.67, 18 mL = 115.86, 24 mL = 104.25, 30 mL = 93.79, 36 mL = 83.88, 42 mL = 67.18, 48 mL = 59.20, 54 mL = 45.50, and 60 mL = 41.75), resulting in lower bubble frequencies at larger back volumes. A similar change in back volume for the lower flow did also result in statistically significant changes in the bubble frequencies, although on a lower significance level ($\chi^2(9) = 17.749$, $P = 0.038$; mean rank scores for the different back volumes: 6 mL = 120.95,

TABLE 2.
The Total Number of Detectable Bubble Frequency Values at Different Back Volumes at a Set Flow of 0.02 L/s

Back Volume (mL)	Tube Diameter (mm)	
	8	9
6	0	0
12	2	1
18	2	5
24	6	10
30	9	10
36	10	10
42	10	10
48	10	10
54	10	10
60	10	10

12 mL = 129.30, 18 mL = 120.60, 24 mL = 105.75, 30 mL = 3.00, 36 mL = 100.15, 42 mL = 91.63, 48 mL = 84.42, 54 mL = 75.95, and 60 mL = 83.25).

Correspondingly, the bubble volumes increased significantly with increasing back volume for both flows ($\chi^2(8) = 48.868$, $P < 0.001$, for the higher flow (0.02 L/s), mean rank scores for the different back volumes: 12 mL = 21.33, 18 mL = 30.14, 24 mL = 41.75, 30 mL = 52.21, 36 mL = 62.13, 42 mL = 78.83, 48 mL = 86.80, 54 mL = 100.50, and 60 mL = 104.25; and $\chi^2(9) = 17.749$, $P = 0.08$, for the lower flow (0.005 L/s), mean rank scores for the different back volumes: 6 mL = 80.05, 12 mL = 71.70, 18 mL = 80.40, 24 mL = 95.25, 30 mL = 108.00, 36 mL = 100.85, 42 mL = 109.38, 48 mL = 116.57, 54 mL = 125.05, and 60 mL = 117.75).

The Mann-Whitney U tests showed that the bubble frequencies were significantly higher for the \emptyset 8-mm tube than for the \emptyset 9-mm tube ($U = 8663.0$, $P < 0.001$, mean rank scores: 209.74

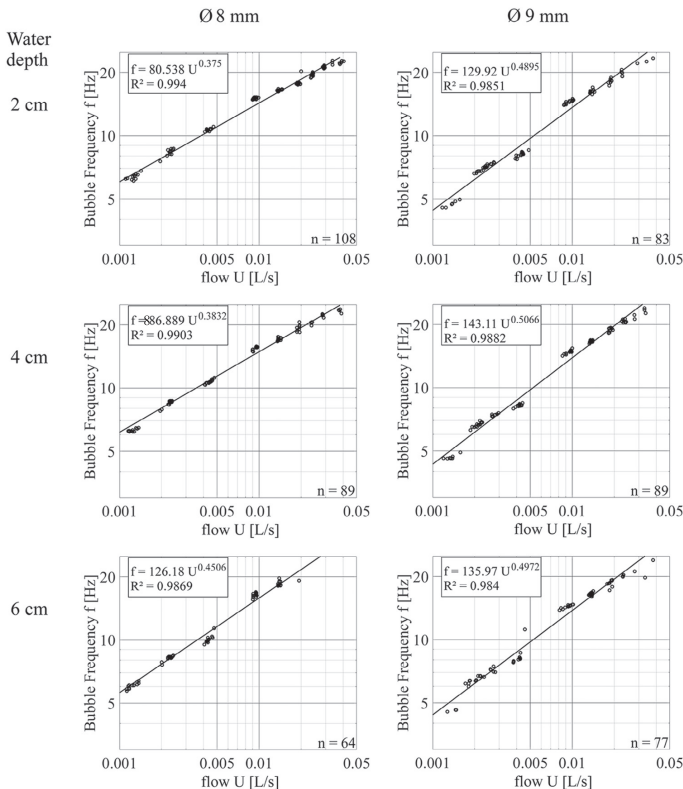


FIGURE 9. Bubble frequency as a function of flow at three different water depths with Ø 8-mm (left) and Ø 9-mm (right), 26-cm-long resonance tubes. The back cavity volume is 36 cm³ and the tube angle is 45°. Each point represents one measurement. The total amount of points is noted in the lower right corner of the graphs.

for the Ø 8-mm tube and 137.72 for the Ø 9-mm tube), and the bubble volumes were correspondingly smaller for the Ø 8-mm tube than for the Ø 9-mm tube ($U = 7963.0$, $P < 0.001$, mean rank scores: 132.12 for the Ø 8-mm tube and 212.26 for the Ø 9-mm tube). The bubble frequencies and volumes were significantly lower for the lower flow than for the higher flow ($U = 0$, $P < 0.001$, mean rank scores: 100.5 for the 0.005 L/s flow and 273.0 for the 0.02 L/s flow, for both bubble frequencies and volumes).

DISCUSSION

The purpose of the present study was to examine the back pressure and bubble formations provided by resonance tubes with the tube end in water. In vocal exercises, the back pressure corresponds to the oral pressure. Five experiments were performed using a flow-driven vocal tract simulator with a back cavity volume resembling the vocal tract.

The first experiment investigated the flow-pressure relationship for the two diameter tubes, in air and at seven different water depths. The static and oscillating parts of the p_{back} were analyzed separately. The static part of p_{back} was strongly dependent on the water depth and slightly dependent on flow. In practice, this means that the static component of the oral pressure is largely determined by the water depth and that the subglottal pressure has to overcome that for bubbles to appear. At closer observation, the flow sometimes started slightly below the pressure that the corresponding water depth would induce. This finding is probably due to how the water depth was measured. Because of the angle of 45°, the air column did not reach all the way down to the tube end between bubbles for the lowest flows, which resulted in a lower average pressure during the bubble cycle than the pressure at the lower end of the tube would provide. However, for higher flows the air column did reach the lower end of the tube for most of the time, resulting in a higher average pressure

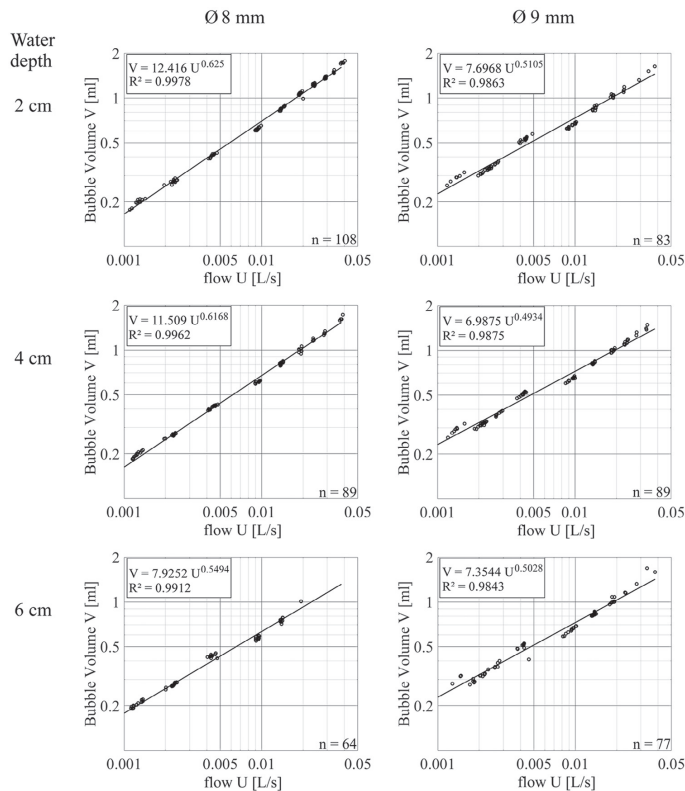


FIGURE 10. Bubble volume as a function of flow at three different water depths with $\varnothing 8$ -mm (left) and $\varnothing 9$ -mm (right), 26-cm-long resonance tubes. The data points were calculated directly from the bubble frequency data in Figure 9. Each point represents one measurement. The total amount of points is noted in the lower right corner of the graphs.

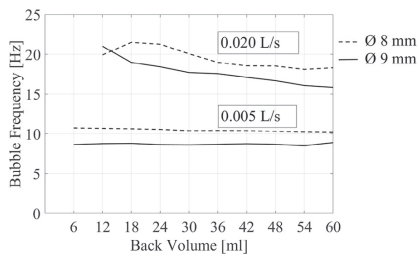


FIGURE 11. Bubble frequency as a function of back volume at two set flows for two diameter tubes at 2 cm of water depth.

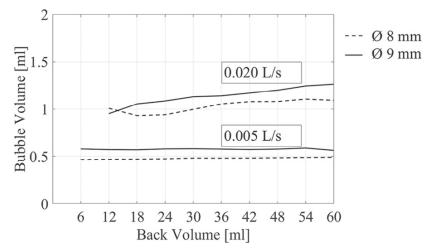


FIGURE 12. Bubble volume as a function of back cavity volume at two set flows for two diameter tubes at 2 cm of water depth.

approximately corresponding to the pressure at the lower end of the tube. This result could also be seen in the video recordings in experiment 2 (see top sequences a–c in Figure 6). The agreement between back pressure and the pressure at the lower end of the tube is coincidental and relies on the angle of approximately 45°. If using a downward (90°) angle of submersion, the model would have to be modified accordingly, because the actual depth for an emitted bubble would be greater than the depth at the tube end, as shown in figure 3 of Amarante Andrade et al.¹⁰

In addition to the pressure given by the water depths, there was also a small flow resistance in the tubes. The Ø 8-mm tube showed a slightly steeper increase of p_{back} during increasing flow than the Ø 9-mm tube, which would be expected because of the higher flow resistance of the narrower tube. A comparison of our experimental data to the model of pressure-flow relationships for tubes in free air¹¹ showed that our data generated a similar p_{back} as the model. The measured data show a small but systematic underestimation of the back pressure in our combined model for the tube in water. This underestimation may be explained by the resistance of the extra constriction that appears when there is water in and near the tube end. The difference in resistance between tube diameters of 8 and 9 mm seems to be so small (resulting in a pressure difference of less than 1 cmH₂O), so it might not be of any clinical importance.

In addition to the static component, p_{rms} was quantified using the RMS amplitude of the oscillating component of p_{back} . The oscillating component has earlier been referred to as providing a so-called massage effect.^{2,6,14} The largest values of p_{rms} were found to plateau around 5–6 cmH₂O at high flows, and occurred for water depths of 3–7 cm. For 2 cm of water depth, p_{rms} plateaued near 4 cmH₂O, and at 1 cm of water depth, p_{rms} plateaued at around 2.5 cmH₂O (recall Figure 5). For all water depths, the p_{rms} decreased toward zero flow. The p_{rms} values were slightly larger for the Ø 9-mm tube than for the Ø 8-mm tube.

The plateauing of p_{rms} is interesting, especially as Simberg and Laine⁸ recommend not submerging the tube end deeper than 2 cm while keeping a steady phonation. This water depth will provide medium p_{rms} , without a large static p_{back} , as the oscillating part will not change with greater depths than 3 cm. Submerging the tube end beyond 3 cm will not increase p_{rms} considerably; however, the static part of the p_{back} will increase with increasing water depth. However, the oscillating component causes the peak vocal tract pressures to be considerably higher than the static pressures. The constant p_{rms} for depths over 3 cm is in line with the findings of Guzman et al.,¹³ who found no significant differences in the peak-to-peak amplitudes of the oral pressure modulations for 45 subjects during bubbling at 3- and 10-cm water depth using a 55-cm-long silicone tube. This knowledge might be important to consider in the clinical setting.

The second and third experiments focused on bubble formation modes. The formation of bubbles when air is blown into water was studied already in the 1960s and earlier, but to our knowledge, this research has not been put in the context of voice training with resonance tube phonation in water. Most of the earlier research was carried out with a vertical, upward-facing tube end, in contrast to the tube phonation where the tube has a downward angle of about 45°. Our research shows, however,

that the formation of bubbles is similar to that of the vertical end, where the bubbles at low flows are emitted one by one in a periodic manner; at medium flows, the bubbles are emitted in pairs, resulting in a mushroom-like shape, and at high flows, the bubbles are emitted in a chaotic manner.¹⁷ No data on human airflow usage during resonance tube phonation in water seem to be available, so to date it is unclear which bubble mode actually is the most commonly used with patients and whether the patients could use the bubble mode as a feedback. Figure 2 of Granqvist et al.⁶ shows a picture of a possible regular-to-bimodal bubble pattern produced by a participant instructed to perform the exercise in a normal way. This finding indicates that the participant used a flow resulting in the bimodal region. However, typical airflow usage during resonance tube phonation in water needs to be investigated in future studies.

In experiments 2 and 3, the time between bubbles was studied by means of a correlogram. Extracting the time between bubbles is nonproblematic at low flows providing regular bubble formations. Methods used for extracting fundamental frequency can be applied. However, for the bimodal and chaotic regions, the same problem occurs as with voices with a high degree of perturbation in the fundamental frequency. The correlogram presents several candidates for a time period and has a better time resolution than spectral methods. Thus, a correlogram serves the purpose well of illustrating the periodicity of signals with both regular and irregular time periods, such as p_{back} .

In experiment 3, the determination of where the shifts occurred was slightly problematic, as there was a randomness in the appearance of the bimodal and chaotic occurrences (recall Figure 3). For example, in the region marked as bimodal, the second candidate would have been expected to be completely smooth if the signal had been perfectly bimodal. However, this is not the case and this type of irregularity is typical for the present data. Nevertheless, we find it worthwhile to attempt to categorize the shifts between bubble modes as presented because the modes seem to appear in all takes although with a random component in how they occur.

Despite the inconsistencies of the system, the reliability between the raters was good.²¹ The transitions between bubble modes occurred at slightly lower flows for the narrower tube, although exceptions could be noted in some of the takes. The transitions occurred at the lowest flows at the 6-cm water depth, and at the highest flows at the 4-cm water depth. This finding indicates that bubble emissions are affected differently at different water depths. In the present study, the transitions were only rated at an increasing flow. The shifts may have occurred at slightly different flows if using decreasing flow, because of the chaotic nature of the system. However, this phenomenon was not investigated in this paper. The fourth experiment investigated the bubble frequencies and volumes at different airflows. Not surprisingly, the bubble frequency increased with increasing flow, but at a lower rate for high flows. Hence, the volume of the bubbles also increased with increased flow. Only small differences in bubble frequencies could be seen between the different tube diameters and water depths. The bubble frequencies reached 22–23 Hz and 20–22 Hz, with the Ø 8- and Ø 9-mm tubes, respectively, for the highest possible flows before entering the chaotic oscillatory

modes. The graphs (Figures 9 and 10) extend to higher flows than the average points of shift to chaos in experiment 3, which is possible because of the fact that the last points represent the few takes where the shift to chaos had not yet appeared.

The fifth experiment investigated bubble frequencies and volumes at two fixed flows with a varying back volume at a 2-cm submersion depth. The results showed that the bubble frequencies decreased with an increasing back volume, especially for the higher flow (Figure 11). This finding could also be relevant in voice therapy, as changes in vocal tract volume have been observed during and after SOVT exercises.¹⁹ It could also be speculated that the degree of glottal adduction may be reflected in the bubble frequency and bubble volume. Less adduction opens the passage to the subglottal tract, and thus the back cavity appears larger.

If the subglottal pressure is kept constant, an increased oral pressure leads to a decreased transglottal pressure. Results from earlier studies suggest that a narrow straw providing a high flow resistance might be useful, for example, during warm-up for singing or other vocally demanding tasks,¹ because it enables the singer to keep a high subglottal pressure combined with a low transglottal pressure. This effect should also be present in tube phonation in water.

The modulation of the oral pressure modulates the vocal fold oscillation.^{6,22} If the subglottal pressure is constant, the transglottal pressure oscillation has the same amplitude as the oral pressure variations. If, on the other hand, the subglottal pressure also becomes modulated by the p_{back} of the tube, the transglottal pressure oscillation would be smaller. Horáček et al²³ provide some data from a physical model of the vocal folds and vocal tract during resonance tube phonation in water at a 10-cm water depth. In Horáček et al's figure 3b,²³ a low-frequency pressure oscillation of about 60 ms, presumably related to the reported bubble frequency of 16 Hz, modulates subglottal, transglottal, and oral pressures. Thus, the p_{back} oscillations do propagate to the subglottal cavity, and it would be reasonable to assume that glottal resistance would affect the extent of subglottal pressure oscillation. It could be speculated that a larger transglottal modulation would be present for pressed voice than for flow phonation. This finding implies that the resonance tube could potentially be used as a feedback device for adduction. This needs to be investigated further.

The static oral pressure can be controlled for via the water depth. The recommendation of a water depth of 1–2 cm⁸ during continuous phonation will provide a relatively low static oral pressure. However, for patients with vocal fold paresis and incomplete closure of the glottis, the same authors recommend short phonations at a greater water depth to resemble pushing exercises.⁸ The static part of the p_{back} enables the therapist to have some control over the subglottal pressure that the patient produces.

Some studies have looked at bubble frequencies during resonance tube phonation in water with human subjects. Granqvist et al⁶ reported bubble frequencies between 10 and 13 Hz. Wistbacka et al⁷ reported bubble frequencies between 14 and 22 Hz. Both studies investigated bubble frequencies at two different submersion depths with two participants, using Ø 9-mm glass tubes of lengths between 26 and 28 cm. Guzman et al¹³

reported bubble frequencies between 12 and 32 Hz, with an average of 22 Hz for 45 participants using a Ø 10-mm, 55-cm-long silicone tube at immersion depths of 3 and 10 cm. Horáček et al²⁴ used a Ø 6.8-mm, 26.4-cm-long glass tube at three different water depths to measure bubble frequencies from spectra of the oral pressure signal. The frequencies reported varied between 15 and 18 Hz. Interestingly, from the pressure spectrum shown in the study²⁴ for phonating through the tube at a 2-cm water depth, the dominant spectral peak of 18 Hz appears to be the second partial of a bimodal spectrum, where the first partial appears near 9 Hz. There might be an inconsistency between different studies whether the terminology “bubble frequency” refers to the actual number of bubbles per second or the number of bubble pairs per second. In all these studies except for Guzman et al,¹³ a lower bubble frequency was associated with larger water depths. None of these four studies measured flow, and according to the present study, differences in flow as well as tube diameter can explain the different bubble frequencies. The results from the present study provide the possibility to estimate flow based on bubble frequency and tube diameter. Transitions to chaotic bubble formation occur at surprisingly low flows. Therefore, in regular and bimodal bubble regimes, the flows during resonance tube phonation in water can be expected to be lower than during normal phonation as well as during tube phonation with the free end in air, as estimated by Titze et al.¹ Previous studies on humans have mainly focused on immediate and short-term physiological, perceptual, and acoustical effects of tube phonation.^{1,5–7,13,22,25,26} However, the resonance tube can also be seen as a feedback and control device in voice therapy. The three modes of bubble formation and bubble frequencies can serve as flow feedback. In particular, if the therapeutic goal is to lower the airflow, the patient could be instructed to produce “calm” bubbles, associated with regular or bimodal bubble formations. Using an open bowl encourages the use of a low flow to avoid splashing. This highlights a difference between resonance tube phonation in water and the LaxVox technique, in which the bowl is replaced by a water bottle. A closed container allows for the use of a higher flow without splashing. This indicates that the two methods might be differently suited for different therapy goals.

The tube dimensions recommended by Sovijärvi⁴ suggest different tube diameters depending on whether the patient is an adult or a child. Tubes with a diameter of 9 mm are recommended for adults, and tubes with a diameter of 8 mm are recommended for children.⁴ However, the physical differences investigated in this study between the two diameters were small and possibly not clinically important. Sovijärvi further recommends different tube lengths depending on voice category.⁴ Possible effects of tube length were not investigated in the present study.

Although differences found between the Ø 8- and Ø 9-mm tubes were small, there may be important interaction parameters between the system and the patient within the clinical setting that were not investigated in the present study. These parameters could include the acoustic interaction with the vocal fold oscillations, the perception of sound, and the tactile experience by the patients. Thus, several mechanisms have been identified

that the voice therapist can take advantage of, to provide appropriate visual, perceptual, and tactile goals to the patient. These goals may improve the reproducibility of the exercise during home practice.

CONCLUSIONS

A flow-driven vocal tract simulator was used to obtain information on the physical properties of resonance tubes submerged in water. The results from the present study provide information about the static and oscillatory components of back pressure, bubble frequency, volume, and mode, as well as how these variables depend on airflow, water depth, tube diameter, and back cavity volume. The results provide a scientific ground facilitating further systematic development of SOVT exercises as well as understanding of the differences between their different types.

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ORAL PRESSURE, FUNDAMENTAL FREQUENCY MODULATION AND VERTICAL LARYNGEAL POSITION DURING RESONANCE TUBE PHONATION WITH TUBE END IN WATER

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Abstract

Resonance tube phonation with the free end in water is a voice therapy method in which the patient phonates through a glass tube while keeping the free end of the tube submerged into a bowl of water. The method affects the oral pressure, inducing a pressure modulation due to the water bubbles. There are also some suggestions that the method would enhance a lowering of the vertical laryngeal position. The purpose of this study was to measure oral pressure components, fundamental frequency modulations and vertical laryngeal position changes during resonance tube phonation in water performed by vocally healthy volunteers. The results showed that the static oral pressure was higher than the hydrostatic pressure. The pressure oscillation amplitudes and bubble frequencies varied with water depth. Fundamental frequency variations were present during bubbling for all participants, and the vertical laryngeal position lowered for most participants during bubbling. The results suggest that the water depth affects phonation through spontaneous changes in flow. Further, the bubbles affect the vocal fold oscillations.

Introduction

Resonance tube phonation with the free end in water, henceforth RTPW, is a voice exercise in which the patient phonates through a glass tube while keeping the free end of it submerged in water. The method has been used in Finnish clinical practice since the 1960's (Sovijärvi, 1964; Simberg & Laine, 2007) and clinicians have reported positive clinical experiences of it when treating patients with different kinds of voice disorders (Simberg & Laine, 2007). Results from measurements of physical and physiological effects of RTPW have shown that during training, the method (i) generates a pulsating pressure, i.e., a back pressure in the oral cavity (Amarante Andrade et al., 2016; Enflo, Sundberg, Romedahl, & McAllister, 2013; Granqvist et al., 2015; Wistbacka et al., in press), (ii) increases the open quotient of the vocal fold vibratory cycle (Granqvist et al., 2015) and (iii) lowers the vertical laryngeal position (Guzman, Castro, Testart, Munoz, & Gerhard, 2013; Wistbacka, Sundberg, & Simberg, 2016). Immediately after training, a raise in collision threshold pressure (Enflo et al., 2013) as well as an improvement in

perceptual vocal quality have been observed (Enflo et al., 2013; Paes, Zambon, Yamasaki, Simberg, & Behlau, 2013).

RTPW is a rather complex physical system, with several variables possibly affecting the outcome of the exercise. Such variables would be the tube dimensions adding length to the vocal tract and affecting the mouth opening (Titze, 2006; Titze & Laukkanen, 2007). The tube dimensions also affect the flow resistance of the tube (Titze, Finnegan, Laukkanen, & Jaiswal, 2002; Amarante Andrade et al., 2016; Smith & Titze, 2017; Wistbacka et al., in press). Furthermore, the water depth adds a static component to the back/oral pressure (Amarante Andrade et al., 2016; Granqvist et al., 2015; Horáček, Radolf, Bula, Veselý, & Laukkanen, 2012; Wistbacka et al., in press) as well as an oscillating component caused by the bubbles (e.g. Horáček et al., 2012; Wistbacka et al., in press). The characteristics of these oscillations are flow dependent (Wistbacka et al., in press). The tube dimensions recommended by Sovijärvi (1965) are still taken into consideration in clinical practice in Finland (Simberg & Laine, 2007). The tubes, 24–28 cm in length, 8–9 mm in inner diameter and made of 1 mm thick glass, provide an elongation of the vocal tract and a narrowing at the lip area. Water depths of 1–2 cm are typically recommended for patients with vocal nodules, vocal fatigue and hyperfunctional voice disorders, whereas water depths of 5–15 cm have been recommended for treating insufficient vocal fold closure (Simberg & Laine, 2007). To date, there seems to be no explicit recommendations regarding flow during RTPW, although the bubble characteristics and amount of splashing of water could provide a flow feedback component, especially if using an open water container (Wistbacka et al., in press).

For tubes kept in free air and within the dimensions usually used in voice exercises, the back pressure for a given flow is mainly determined by the tube diameter and to a lesser extent by the tube length (Amarante Andrade et al., 2016; Smith & Titze, 2017; Titze et al., 2002; Wistbacka et al., in press). During RTPW, the hydrostatic pressure at the tube end in the water will further affect the oral pressure. The oral pressure needs to overcome this hydrostatic pressure before flow can start (Amarante Andrade et al., 2016; Enflo et al., 2013; Granqvist et al., 2015; Wistbacka et al., in press).

The back pressure during RTPW can be divided into two components, the static component (DC part) and the oscillating component (AC part). The static component is mainly determined by the water depth (Wistbacka et al., in press), whereas the oscillating component is generated by the water bubbles, which thus generates a pressure modulation in the supraglottal vocal tract (Enflo et al., 2013; Granqvist et al., 2015; Guzman et al., 2016; Wistbacka et al., in press) and

possibly also in the subglottal cavity (Horáček, Radolf, Bula & Laukkanen, 2014). These pressure modulations have been hypothesized to induce a “massage” effect in the vocal tract and to the vocal folds (e.g. Enflo et al, 2013; Granqvist et al, 2015).

The pressure oscillation during RTPW has been investigated using different methods, most commonly by peak-to-peak analysis or by RMS measurements of a low pass filtered oral pressure signal (Granqvist et al, 2015; Wistbacka et al, 2016; Guzman et al, 2016; Wistbacka et al, in press). For RTPW with water depths of 2 and 6 cm, Granqvist et al (2015) found an RMS modulation amplitude of about 1.5-2.5 cmH₂O in two participants. Guzman and associates reported a pressure modulation amplitude of 3.6-3.9 cmH₂O peak-to-peak for 45 participants’ during tube phonation in water using a silicone tube submerged at 3 and 10 cm water depths (Guzman et al., 2016). In addition, Wistbacka et al. (in press) used a flow driven vocal tract simulator to investigate pressure characteristics generated by 26 cm long glass tubes, inner diameters of 8 or 9 mm. The results showed an RMS pressure modulation up to 5.5 cmH₂O, which increased with flow and with water depths down to 3 cm. At water depths between 3 and 7 cm, the RMS pressures remained approximately constant.

When comparing results between studies it is important to acknowledge the difference between RMS and peak-to-peak measurements. In addition, the accuracy of the measures are challenged by the low-pass (LP) filtering required to separate the pressure modulation induced by the bubbles from the pressure modulation induced by the voice. The filter characteristics, particularly the cut off frequency of the LP filter, will affect the remaining signal, and possibly affect the peak-to-peak and RMS values.

The back pressure modulation can also be used for studying the bubble frequency during RTPW. Bubble frequencies have been reported for different tube diameters and water depths (Granqvist et al., 2015; Guzman et al., 2016; Horáček et al., 2012; Wistbacka et al., 2016). It has been measured by detecting peaks or zero crossings in the oral pressure oscillation (Granqvist et al, 2015; Guzman et al., 2016; Wistbacka et al., 2016). These procedures require a preparation of the oral pressure signal in terms of an LP filtering similar to what is needed for investigating pressure modulation amplitudes. Another option is to use spectral analysis, which presents the bubble frequency as a spectrum peak (Horáček et al., 2012; Wistbacka et al., in press). This procedure requires no filtering. Bubble frequency has been shown to be affected most importantly by airflow and tube diameter (Wistbacka et al., in press); factors that can easily be changed in the voice clinic. At constant flow, no noticeable differences in bubble frequency were found between commonly used submersion depths.

Bubble periodicity changes with increasing flow. Over a certain flow, the bubble pattern will lose its regularity, making frequency extraction problematic (Wistbacka et al., in press). To date it is unclear whether the airflows commonly used during RTPW generate periodic bubble patterns or not; to our knowledge no results of measurements of human airflow during RTPW has been published.

The oral pressure oscillations also have a direct effect on the vibratory characteristics of the vocal folds. Granqvist et al. (2015) investigated modulation of voice f_0 and glottal area during RTPW at two water depths and for two participants. The results showed both f_0 and glottal area modulation when the tube end was submerged into water. The glottal area modulation decreased with increasing water depth for both participants, whereas the f_0 modulation decreased with increasing water depth for one participant and increased for the other.

Some studies have been published of vertical laryngeal position during semi-occluded vocal tract exercises, as well as during RTPW. Laukkanen, Lindholm, and Vilkman (1995) investigated the effect on VLP in five participants phonating through a resonance tube with the tube end in air, resulting in both lowered and raised VLPs for the participants. A pilot study with two participants by Wistbacka et al. (2016) suggested that RTPW had a lowering effect on the larynx, with a more prominent effect at lower water depths. However, the participants in that study were familiar with the method and might have been accustomed to letting the exercise affect the VLP. It is also possible that RTPW affects respiration, and that the lowering was due to an increase in lung volume. Lung volume has been found to affect VLP (Iwarsson & Sundberg, 1998).

The purpose of the present study was to measure oral pressure, bubble frequencies, f_0 modulations as well as changes in vertical laryngeal position during RTPW in healthy volunteers. A second purpose was to examine the effect of the cut-off frequency of the LP filter applied to the oral pressure signal.

Method

Ethical approval for this study was granted by the Ethics committee for research in psychology and logopedics at Åbo Akademi University, Finland. Written consent was obtained from all participants.

Participants

A total of six vocally healthy volunteers participated in the study, three males and three females. None of them had previous experience of RTPW. The mean age was 30 years, range 26–36 years. Participant characteristics can be found in table I.

Table I. Participant characteristics.

<u>Participant</u>	<u>Gender</u>	<u>Age</u>
1	Male	31
2	Female	26
3	Female	27
4	Female	36
5	Male	28
6	Male	27

Equipment

Data were collected using a dual-channel electroglottograph (EGG) (Glottal Enterprises MC2-1) and the pressure transducer in the Glottal Enterprises MSIF-2 unit. The EGG electrodes were placed on the participants' neck on the thyroid cartilage, at the level of the vocal folds. Calibration of VLP was obtained by sliding the electrodes up and down on the participants' neck while they phonated on a vowel (Rothenberg, 1992). The oral pressure signal was recorded with a pressure transducer attached to a plastic tube, inner diameter 4 mm, which the participants held in the corner of the mouth. The pressure was calibrated using a U-tube manometer. Audio was recorded for documentation purposes only. All signals were recorded using the Soundswell Signal Workstation for Windows, using a sampling rate of 16 kHz per channel. All subjects used a 28 cm long resonance tube, inner diameter 9 mm, marked at 2 and 6 cm so as to allow control of the submersion depth. The markings were diagonal, to facilitate a 45° submersion angle of the tube into the water. This angle has previously been used in studies investigating tube phonation in water (Amarante Andrade et al., 2016; Tynmi, Radolf, Horáček, & Laukkanen, 2017; Wistbacka et al., in press).

Procedure

The participants were given oral instructions and time to try the method immediately prior to the data collection. They were asked to phonate into the tube under three conditions, with steady pitch and loudness; (i) with the tube end in air, (ii) with the tube end submerged 2 cm in water and (iii) with the tube end submerged 6 cm in water. Before recording each token, the subjects

produced a normal phonation of the vowel /u/ without the tube so as to provide a baseline for VLP and to decrease the impact of the previous tube task on the following one. For each of the three conditions, a total of 8 phonations were recorded in a predetermined order, although for subject 1, the first participant in the experiment, only 4 phonations per condition were recorded. The experimenter orally instructed the participants about the task for the following token. The testing protocol is attached in appendix I.

Analyses

Data were analysed using the Sopran software (www.tolvan.com) and the Soundswell Signal Workstation. Statistical analyses were made using IBM SPSS statistics 24 for Windows.

The static part of the oral pressure

For each token the mean oral pressure was measured during the stable part of the phonation, approximately 2 seconds. These pressure values were further used to obtain averages and standard deviations for each condition.

The oscillating part of the oral pressure

The oral pressure contained phonatory oscillations as well as pressure variations caused by the bubbling. The former oscillations were attenuated by LP filtering at 50, 40, 30 and 20 Hz. The remaining pressure signal contained a static, DC component that varied with the submersion depth, as well as an oscillating, AC component reflecting the bubbling. The amplitude of the oscillating component was measured using two methods. In the first method, the peak-to-peak amplitude, p_{pp} , of each cycle over approximately 2 seconds was manually measured for each token of the bubbling conditions. In the second method, the signal was processed further by eliminating the DC component using a high-pass (HP) filter at 1 Hz. The RMS pressure, p_{rms} , of the resulting signal was analysed using a smoothing filter at 3 Hz. An average RMS over approximately 2 seconds was extracted from all tokens of the bubbling conditions.

Averages and standard deviations were calculated for the peak-to-peak as well as the RMS amplitudes from the averages of the tokens belonging to each condition. The effects of the different LP filters were compared for both methods.

Bubble frequency

Bubble frequency was analysed by three methods. In the first method, spectral analysis of the pressure signal was used, with an analysis bandwidth of 3 Hz. The spectrum was obtained from

the unfiltered oral pressure signal and spectral peaks in the frequency region up to 30 Hz were interpreted as bubble frequency. For some tokens, no clear peaks were found in the spectrum, probably due to high flow resulting in aperiodic bubble formations. In the second method, the LP filtered signals were used and pressure peaks were manually counted over approximately 2 seconds. In the third method, bubble frequency was extracted from the LP filtered signals by means of a correlogram (Granqvist & Hammarberg, 2003).

Fundamental frequency modulation

Fundamental frequency of the voice was extracted from the EGG signal by means of a correlogram (Granqvist & Hammarberg, 2003) with a time window of 5 ms. In some cases, f_o differed slightly between tokens. To remove the effect of this, the extracted f_o signal, which consisted of a DC part representing mean f_o and an AC part representing the f_o modulation, was HP filtered at 3 Hz. The resulting signal thus contained only the f_o modulation. The RMS of this f_o modulation was determined for all tokens and the averages and standard deviations were calculated for all tokens belonging to each condition.

Vertical laryngeal position

Means of the VLP-signal during each token was extracted. Averages and standard deviations were calculated over all tokens belonging to each condition.

Results

Static part of the oral pressure

The averages and standard deviations of the static part of the oral pressure for each condition can be seen in table II. In the bubbling conditions participants 1 and 3–5 had consistently higher static oral pressure values than the minimum expected for the given hydrostatic pressure. This indicates that the submersion depth were as intended or possibly slightly lower. The results for participants 2 and 6 showed static oral pressures lower than expected during RTPW, indicating that the water depths had been shallower than intended. Hence, participants 2 and 6 were excluded from further analyses.

Table II. Mean and standard deviation of the static part of the oral pressure [cmH₂O].

Participant	Baseline	Tube in air	Tube in water	
	(vowel phonation /u/)		2 cm	6 cm
1	0.24 (0.07) ^a	0.15 (0.05) ^b	2.25 (0.25) ^b	6.87 (0.39) ^b
2	1.02 (0.78) ^c	0.44 (0.20) ^d	1.31 (1.00) ^d	1.99 (2.27) ^d
3	0.26 (0.07) ^c	0.20 (0.17) ^d	3.25 (0.30) ^d	7.31 (0.31) ^d
4	0.62 (0.20) ^c	0.24 (0.05) ^d	2.61 (0.28) ^d	7.20 (0.54) ^d
5	0.69 (0.33) ^c	0.51 (0.24) ^d	2.63 (0.35) ^d	7.42 (0.21) ^d
6	0.33 (0.26) ^c	0.26 (0.20) ^d	0.67 (0.18) ^d	2.55 (0.84) ^d

^a*n* = 13; ^b*n* = 4; ^c*n* = 26; ^d*n* = 8

Oscillating part of the oral pressure

The differences in the RMS of the oscillating part of the oral pressure at two depths are presented in table III and the corresponding peak-to-peak amplitudes in table IV. Both methods of analysis showed significantly higher oral pressure oscillation amplitudes during bubbling at 2 cm water depth than at 6 cm according to independent-sample t-tests, see tables III and IV, respectively.

A one-way ANOVA was used to investigate the effect of the different cut-off frequency filters. It showed that the filters had no significant effect on the RMS oscillation amplitudes at either water depths ($p = .535$ and $p = .814$ for water depths 2 and 6 cm, respectively). However, a statistically significant difference between the filters was found for the peak-to-peak amplitudes at 2 cm submersion depth ($F(3, 111) = 3.036, p = .032$). A post hoc Bonferroni test revealed that the only significant difference between the filters was found between the 50 Hz and 20 Hz cut off frequencies ($p = .036$). At 6 cm submersion depth, no differences in the peak-to-peak amplitude were found between filters ($p = .273$).

An independent-samples t-test was conducted to compare the RMS and peak-to-peak amplitudes. As expected, the scores for the former ($M = 0.83, SD = 0.25$) were significantly lower than those of the latter ($M = 1.05, SD = 0.49$), $t(446) = -5.989, p < .001$. However, when analysing the low passed filtered signals and water depths separately, statistically significant differences were found only for the 50Hz, 40Hz and 30Hz filters at 2 cm submersion depth (LP 50 Hz: $t(54) = -3.889, p < .001$, LP 40 Hz: $t(54) = -3.466, p = .001$, LP 30 Hz: $t(54) = -2.842, p = .006$, LP 20 Hz: $t(54) = -1.588, p = .118$). At 6 cm submersion depth, however, statistically significant differences between these filter settings were found only for the 50Jz and 40Hz filters (LP 50 Hz: $t(54) = -1.985, p = .052$, LP 40 Hz: $t(54) = -1.738, p = .088$,

LP 30 Hz: $t(54) = -1.355, p = .181$, LP 20 Hz: $t(54) = -.470, p = .640$). These results indicate that the differences between RMS and peak-to-peak measures slightly decreased when using a filter with a lower cut off frequency.

Table III. Differences in the RMS oscillation amplitude at the two water depths.

Submersion depth	RMS oscillation amplitude, mean and standard deviations [cmH ₂ O]								<i>t</i>	<i>df</i>	<i>p</i>	
	2 cm				6 cm							
	<i>LP filter cut off [Hz]</i>	50	40	30	20	50	40	30				20
Participant												
1	0.79 ^a (0.16)	0.79 ^a (0.16)	0.78 ^a (0.16)	0.77 ^a (0.16)	0.62 ^a (0.11)	0.62 ^a (0.11)	0.62 ^a (0.11)	0.61 ^a (0.11)	3.816	30	.001	
3	1.13 ^b (0.12)	1.12 ^b (0.12)	1.10 ^b (0.12)	1.02 ^b (0.11)	1.07 ^b (0.08)	1.07 ^b (0.08)	1.05 ^b (0.08)	0.97 ^b (0.07)	2.002	62	.05	
4	1.03 ^b (0.23)	1.02 ^b (0.23)	1.01 ^b (0.23)	0.92 ^b (0.23)	0.82 ^b (0.20)	0.81 ^b (0.20)	0.80 ^b (0.20)	0.76 ^b (0.18)	3.888	62	<.001	
5	0.64 ^b (0.14)	0.63 ^b (0.14)	0.61 ^b (0.14)	0.55 ^b (0.13)	0.56 ^b (0.08)	0.55 ^b (0.08)	0.55 ^b (0.08)	0.53 ^b (0.08)	2.202	62	.031	
Group average	0.91 ^c (0.26)	0.90 ^c (0.26)	0.89 ^c (0.26)	0.82 ^c (0.24)	0.79 ^c (0.24)	0.78 ^c (0.24)	0.77 ^c (0.24)	0.73 ^c (0.21)	3.463	222	.001	

^a*n* = 4; ^b*n* = 8; ^c*n* = 28

RMS: Root Mean Square

Table IV. Differences in peak-to-peak amplitude between the two water depths.

Submersion depth	Peak-to-peak amplitude, mean and standard deviations [cmH ₂ O]								<i>t</i>	<i>df</i>	<i>p</i>	
	2 cm				6 cm							
	<i>LP filter cut off [Hz]</i>	50	40	30	20	50	40	30				20
Participant												
1	1.25 ^a (0.28)	1.21 ^a (0.28)	1.13 ^a (0.27)	1.01 ^a (0.26)	0.76 ^a (0.11)	0.74 ^a (0.10)	0.71 ^a (0.10)	0.65 ^a (0.09)	6.300	30	<.001	
3	1.83 ^b (0.26)	1.77 ^b (0.26)	1.69 ^b (0.25)	1.41 ^b (0.21)	1.75 ^b (0.10)	1.69 ^b (0.09)	1.58 ^b (0.09)	1.30 ^b (0.05)	1.569	62	0.122	
4	1.39 ^b (0.33)	1.32 ^b (0.33)	1.24 ^b (0.32)	1.01 ^b (0.29)	0.86 ^b (0.23)	0.82 ^b (0.22)	0.76 ^b (0.19)	0.66 ^b (0.18)	6.680	62	<.001	
5	0.77 ^b (0.17)	0.71 ^b (0.16)	0.64 ^b (0.14)	0.46 ^b (0.10)	0.53 ^b (0.16)	0.51 ^b (0.15)	0.48 ^b (0.15)	0.41 ^b (0.13)	3.915	62	<.001	
Group average	1.32 ^c (0.48)	1.26 ^c (0.48)	1.18 ^c (0.47)	0.97 ^c (0.42)	1.01 ^c (0.52)	0.97 ^c (0.50)	0.91 ^c (0.47)	0.77 ^c (0.38)	4.241	222	<.001	

^a*n* = 4; ^b*n* = 8; ^c*n* = 28

Bubble frequency

The mean and standard deviation of the bubble frequencies extracted by spectral analysis, by correlogram and by peak counting can be seen in table V, VI and VII, respectively. Independent-samples t-tests showed that on group level, the bubble frequencies were significantly higher at 2 cm water depth than at 6 cm water depth for all three methods of data extraction; however, at individual level the differences in bubble frequencies at the two water depths were not always significant.

Table V. Differences in bubble frequencies between the two water depths.
Data extracted from spectral analyses.

Submersion depth	Bubble frequency, means and standard deviation [Hz]		<i>t</i>	<i>df</i>	<i>p</i>
	2 cm	6 cm			
<u>Participant</u>					
1	11.55 (0.13) ^a	10.49 (0.87) ^a	2.411	6	.053
3	15.57 (0.93) ^c	15.60 (0.56) ^c	-.061	12	.952
4	15.49 (0.53) ^c	12.33 (3.04) ^a	1.351	10	.206
5	16.98 (0.37) ^b	-*	-	-	-
Group average	14.98 (2.06) ^c	13.36 (2.77) ^d	2.077	37	.045

a: *n* = 4; b: *n* = 5; c: *n* = 8; d: *n* = 14; e: *n* = 25

* No data available due to no clear peaks in the spectrum

Table VI. Differences bubble frequencies between the two water depths.
Data extracted by means of correlograms.

Submersion depth	Bubble frequency, mean and standard deviations [Hz]								<i>t</i>	<i>df</i>	<i>p</i>
	2 cm				6 cm						
<i>LP filter cut off [Hz]</i>	50	40	30	20	50	40	30	20			
<u>Participant</u>											
1	11.90 ^a (0.86)	11.86 ^a (0.79)	11.87 ^a (0.81)	11.83 ^a (0.73)	11.69 ^a (1.31)	11.46 ^a (1.06)	11.42 ^a (1.01)	11.40 ^a (1.00)	1.218	30	.233
3	16.13 ^b (0.79)	16.15 ^b (0.83)	16.08 ^b (0.81)	15.87 ^b (0.67)	15.79 ^b (1.02)	15.71 ^b (1.01)	15.68 ^b (0.98)	15.42 ^b (0.94)	1.915	62	.060
4	16.39 ^b (0.66)	16.38 ^b (0.69)	16.31 ^b (0.64)	16.08 ^b (0.68)	13.11 ^b (1.65)	13.18 ^b (1.51)	13.09 ^b (1.51)	12.85 ^b (1.51)	11.361	62	<.001
5	17.49 ^b (0.80)	17.48 ^b (0.82)	17.35 ^b (0.72)	16.94 ^b (0.79)	11.98 ^b (1.43)	12.11 ^b (1.43)	12.19 ^b (1.33)	11.88 ^b (1.13)	19.967	62	<.001
Group average	15.98 ^c (1.93)	15.98 ^c (1.94)	15.91 ^c (1.89)	15.66 ^c (1.78)	13.34 ^c (2.10)	13.35 ^c (2.04)	13.33 ^c (1.98)	13.10 ^c (1.93)	10.072	222	<.001

^a*n* = 4; ^b*n* = 8; ^c*n* = 28

Table VII. Differences bubble frequencies between the two water depths.
Data extracted by peak counting.

Submersion depth	Bubble frequency, mean and standard deviations [Hz]								<i>t</i>	<i>df</i>	<i>p</i>
	2 cm				6 cm						
<i>LP filter cut off [Hz]</i>	50	40	30	20	50	40	30	20			
<u>Participant</u>											
1	12.47 ^a (0.45)	12.47 ^a (0.45)	12.47 ^a (0.45)	12.47 ^a (0.45)	12.07 ^a (1.34)	11.87 ^a (1.33)	11.87 ^a (1.33)	11.87 ^a (1.33)	1.737	30	.093
3	18.17 ^b (1.56)	17.53 ^b (1.05)	17.11 ^b (0.74)	16.62 ^b (0.69)	16.78 ^b (1.53)	16.33 ^b (1.08)	16.33 ^b (1.08)	16.33 ^b (1.08)	3.134	62	.003
4	17.27 ^b (1.33)	16.91 ^b (1.03)	16.83 ^b (1.01)	16.44 ^b (0.72)	14.81 ^b (2.11)	14.47 ^b (1.83)	14.15 ^b (1.75)	13.42 ^b (1.63)	7.136	62	<.001
5	20.31 ^b (2.58)	18.78 ^b (1.74)	17.84 ^b (1.15)	17.54 ^b (1.27)	17.11 ^b (3.18)	15.93 ^b (2.20)	15.07 ^b (1.75)	13.47 ^b (1.42)	5.653	62	<.001
Group average	17.71 ^c (3.01)	16.99 ^c (2.33)	16.58 ^c (1.96)	16.24 ^c (1.83)	15.63 ^c (2.77)	15.05 ^c (2.22)	14.71 ^c (2.05)	14.04 ^c (2.04)	10.072	222	<.001

a: $n = 4$; b: $n = 8$; c: $n = 28$

A one-way ANOVA was used to investigate the differences in bubble frequencies between the three methods of data extraction. The result revealed a significant difference between the three methods ($F(2, 486) = 17,602, p < .001$). A post hoc Bonferroni test showed a significant difference between using the correlogram and the peak count ($p < .001$) as well as between the peak count and spectral analysis ($p = .002$). However, no differences were found between the correlogram and spectral method ($p = 1.000$).

In measuring the bubble frequency, four filter settings were used. A one-way ANOVA was applied to investigate the difference obtained with these settings. The results showed a statistically significant difference for peak counting at 6 cm water depth ($F(3, 111) = 2.363, p = .075$). A post hoc Bonferroni test revealed a significant difference only between the 50 Hz and 20 Hz LP filters ($p = .063$). At 2 cm, no significant corresponding effect was found ($p = .108$). The same result was found for the bubble frequency values derived from the correlograms ($p = .905$ and $p = .958$ at 2 and 6 cm water depths, respectively).

Fundamental frequency modulation

The mean and standard deviation of f_o for the different conditions are listed in table VIII. Results from a one-way ANOVA showed no statistically significant f_o differences at group level between conditions ($p = .999$).

The differences in RMS of the f_o modulation for the two water depths can be seen in table IX. A statistically significant difference was found for participant 1 ($t(6) = 3.155, p = .02$), but not for the other participants.

Table VIII. Mean and standard deviation of the fundamental frequency in the separate conditions [Hz]

Participant	Baseline (vowel phonation /u/)	Tube in air	Tube in water	
			2 cm	6 cm
1	162.87 (3.96) ^a	164.60 (5.41) ^b	161.82 (4.37) ^b	164.35 (3.63) ^b
3	233.26 (14.66) ^c	231.92 (16.15) ^d	232.01 (14.68) ^d	232.96 (15.48) ^d
4	206.34 (5.21) ^c	205.54 (5.79) ^d	206.73 (5.64) ^d	205.49 (4.89) ^d
5	124.29 (0.57) ^c	124.51 (0.55) ^d	122.01 (1.01) ^d	123.53 (1.25) ^d

^a $n = 13$; ^b $n = 4$; ^c $n = 26$; ^d $n = 8$

Table IX. Differences in RMS of the f_o modulation at the two water depths.

RMS of the f_o modulation, mean and standard deviations [Hz].							
Participant	Baseline	Tube in air	Tube in water		t	df	p
			2 cm	6 cm			
1	0.24 (0.02) ^a	0.25 (0.05) ^b	2.66 (0.54) ^b	1.77 (0.17) ^b	3.155	6	.02
3	0.73 (0.14) ^c	0.61 (0.10) ^d	7.66 (2.28) ^d	9.23 (4.17) ^d	-.931	14	.368
4	0.71 (0.36) ^c	0.55 (0.13) ^d	16.38 (8.08) ^d	14.46 (5.41) ^d	.559	14	.585
5	0.40 (0.06) ^c	0.42 (0.08) ^d	6.06 (1.04) ^d	5.85 (2.24) ^d	.237	14	.816
Group average	0.56 (0.28) ^c	0.49 (0.15) ^f	8.98 (6.62) ^f	8.69 (5.73) ^f	.174	54	.862

f_o = fundamental frequency,

^a $n = 13$; ^b $n = 4$; ^c $n = 26$; ^d $n = 8$; ^e $n = 91$; ^f $n = 28$

RMS: Root Mean Square

Note: Vowel baseline and tube in air values are provided as references.

Vertical laryngeal position

The changes in vertical laryngeal position for each participant are presented in Figure 1. The results showed that for three participants, the VLP tended to be lower during RTPW than the baseline condition. Two of these participants showed the largest lowering for RTPW at 6 cm. One participants increased their VLP in all tube tasks as compared to baseline.

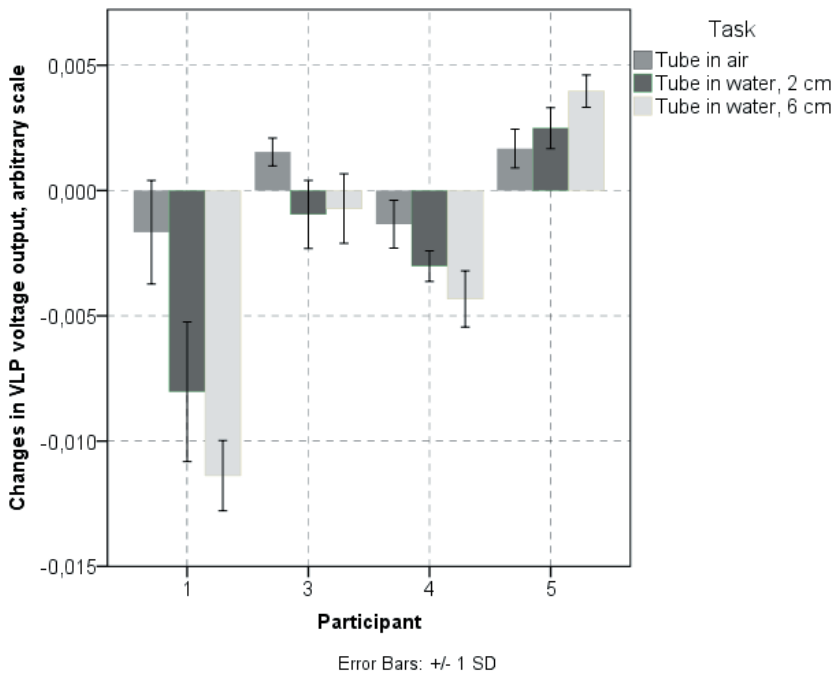


Figure 1. Participants' changes in vertical laryngeal position from baseline vowel.

Discussion

This study aimed at investigating oral pressure, f_o and vertical laryngeal position variations during resonance tube phonation with tube end in water. Different methods for data extraction were used. Data were collected from six vocally healthy volunteers. The participants phonated through a resonance tube that was kept with the tube end in air or submerged 2 and 6 cm under the water surface. Data for the amplitude and frequency of the oral pressure oscillations were analysed using two and three methods, respectively, allowing comparison between extraction methods as well as with results from previous studies.

In studies using a vocal tract simulator, the static part of the back pressure induced by a tube and corresponding to the static part of the oral pressure in humans, has been found to be close to the hydrostatic pressure at the tube end (Amarante Andrade et al., 2016; Wistbacka et al., in press). This means that when the tube end is submerged 2 cm in water, the mean oral pressure needs to be at least 2 cmH₂O in order for airflow to start. In the present study, the first author manually controlled for the water depth by holding the bowl at an appropriate height, fixating

the tube in the water with the help of markings. These markings were diagonal, so as to facilitate a 45° submersion angle. Four of the six participants had means of the static part of the oral pressure between 2.25 and 3.25 cmH₂O when the tube end was submerged at 2 cm, and between 6.87 and 7.42 cmH₂O when the tube end was submerged at 6 cm in the water. Such deviations from hydrostatic pressures were expected, taken into consideration that the tube itself provided a resistance increasing the back pressure for a given flow (Amarante Andrade et al., 2016; Wistbacka et al., in press). However, for two participants, the mean of the static part of the oral pressure indicated that the water depth had been shallower than intended. These participants were excluded from further analyses.

The bubbles in RTPW create oral pressure oscillations. Wistbacka et al. (in press) investigated the amplitude of the oscillating part of the back pressure by RMS analysis. The results showed that the RMS pressure increased with water depth between 1 and 3 cm, but between 3 and 7 cm they remained relatively constant (Wistbacka et al., in press). Based on analysis from 45 participants of oral pressure during RTPW at 3 and 10 cm submersion depth also Guzman et al. found consistency of pressure oscillation amplitudes for different water depths (Guzman et al., 2016). In the present study, the oral pressure oscillation amplitudes were higher at 2 cm submersion depth than at 6 cm submersion depth. This was found both for RMS oscillation amplitudes and peak-to-peak amplitudes. One explanation for this could be that the participants used a lower airflow during RTPW at 6 cm than at 2 cm, as oscillation amplitudes increase with increasing flow (Wistbacka et al, in press).

The results of the bubble frequency analyses also indicated that the participants produced lower airflows at 6 cm water depth than at 2 cm; these water depths have been shown to not affect bubble frequencies, provided constant flow (Wistbacka et al, in press). The bubble frequencies varied between approximately 11 and 17 Hz at the 2 cm submersion depth and between 8 and 16 Hz at the 6 cm submersion depth. All three methods of data extraction resulted in statistically significant differences in bubble frequency between these two depths. Furthermore, no significant difference was found between the spectral analysis and the correlogram, whereas the peak count showed significantly higher bubble frequency values. This suggests that bubble frequency must be measured with caution.

Wistbacka et al. (in press) showed that the bubble periodicity is disturbed already after approximately 0.03 L/s flow. Yet, the bubble frequency could be measured from the spectral analyses in all cases except one. This indicates periodic or nearly periodic bubble patterns. The airflows at 2 cm submersion depth were estimated to be about 0.007–0.02 L/s, and about 0.003–

0.01 L/s at 6 cm submersion depth. This estimate was based on the RMS amplitude and bubble frequency as well as on analyses of flow threshold (Wistbacka et al. (in press). These flow values are considerably lower than in normal phonation (Sundberg, 2001) and what has been estimated for tube phonation with the free end in air (Titze et al., 2002). Thus, RTPW seems to provoke surprisingly low flows.

One of the traditional main purposes with RTPW is to lower the vertical laryngeal position (Sovijärvi, 1964). An inadequate position of the VLP is generally assumed to affect vocal fold vibration and correlates with induced tension in the extrinsic laryngeal muscles (Lowell, Kelley, Colton, Smith, & Portnoy, 2012). In the present study, possible effects on the VLP varied between participants. Qualitative inspection of the VLP signal indicated that the VLP was lower during RTPW than during vowel phonation for three of four participants. However, this result must be interpreted with caution, as CT studies have suggested that tube phonation may increase vocal tract volume not only by lengthening the vocal tract length (Vampola, Laukkanen, Horáček, & Švec, 2011a, 2011b). VLP measurement obtained from dual channel electroglottography has been shown to be sensitive to larynx movement in the horizontal as well as the vertical plane (Laukkanen, Takalo, Vilkmán, Nummenranta, & Lipponen, 1999).

The present study indicated that the oral pressure variation caused by RTPW also affects the voice source and vocal fold vibrations; f_0 modulation increased when the tubes were submerged in water. According to Horáček, Radolf, Bula, and Laukkanen (2014) these pressure modulations propagate also to the subglottal region. It seems worthwhile to analyze in further detail the effects of RTPW on both oral and subglottal pressure, particularly the effects on the phonatory function.

Conclusions

This study investigated effects of resonance tube phonation in water (RTPW) on oral pressure, f_0 modulations and vertical laryngeal position. The results indicate that low flows are used during RTPW, and that the oscillating part of the oral pressure modulates f_0 .

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Appendix I

PROTOCOL FOR DATA COLLECTION

The full protocol was repeated once, resulting in a total of 8 tokens per condition.

Token	Task	Condition
1	Normal vowel phonation /u/	Baseline
2	Tube in air	1
3	Normal vowel phonation /u/	Baseline
4	Tube in water, 2 cm	2
5	Normal vowel phonation /u/	Baseline
6	Tube in water, 6 cm	3
7	Normal vowel phonation /u/	Baseline
8	Tube in water, 2 cm	2
9	Normal vowel phonation /u/	Baseline
10	Tube in air	1
11	Normal vowel phonation /u/	Baseline
12	Tube in water, 6 cm	3
13	Normal vowel phonation /u/	Baseline
14	Tube in water, 6 cm	3
15	Normal vowel phonation /u/	Baseline
16	Tube in air	1
17	Normal vowel phonation /u/	Baseline
18	Tube in water 2 cm	2
19	Normal vowel phonation /u/	Baseline
20	Tube in air	1
21	Normal vowel phonation /u/	Baseline
22	Tube in water 6 cm	3
23	Normal vowel phonation /u/	Baseline
24	Tube in water, 2 cm	2
25	Normal vowel phonation /u/	Baseline



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