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The flow and pressure relationships in different tubes commonly used for semi-occluded vocal tract exercises

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Abstract

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 (SOVTE), i.e., 8 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 to 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, while 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.

Keywords: 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 lip[2] and tongue trills[3], or the so called hand-over-mouth technique[4,5]. Semi-occluded vocal tract exercises (SOVTE) 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 in water. The method of phonating into tubes submerged into water was first described by Sovijärvi in the 1960's. He developed the so called resonance tube method[6] 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 1990's and in which phonation is performed into a silicone tube in a water bottle[8]. Recent research show that a major feature provided by these exercises consists of the fact that submerging the tube end into water causes an intra-oral pressure modulation produced by the bubbling of the water[9,10].

Due to 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 tract[13] and vocal tract configuration[14-17] i.e. 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. Based on this idea, SOVTE were classified into two groups according to the number of vibratory sources in the vocal tract: single source (e.g. straw phonation) and dual source (e.g. 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 intra-oral pressure levels produced by each SOVTE[20].

Even though great progress has been made towards better describing the differences among SOVTE, little is known about the influences of ~~flow~~ 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. 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.

Method

Setup

A flow-driven vocal tract simulator was used to collect data on back pressure (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, i.e. p_{back}, was measured using a differential pressure transducer 8-SOP MPXV7007DP-ND, Malaysia. A second identical pressure transducer was connected to a Fleisch pneumotachograph in order 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, i.e. the set up generated a flow that was largely independent of the tube resistance. A flow free from oscillation 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 based on published data for the volume of the vocal tract using computer tomography images[14]. In order 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 due to the fact that the air expands after the flow resistance giving a slightly higher flow than 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 prior to data collection using a Pneumotach Calibration Unit MCU-4, Glottal Enterprise.

Recordings and analyses

The data was recorded using the Soundswell Signal Workstation ver 4.00 build 4003 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 analysed. 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, Sweden), and were further analysed using MATLAB. 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 diameter (table 1); a 26 cm long resonance tube (glass) with a 9 mm inner diameter and a 35 cm long silicone (to resemble the Lax Vox technique) tube with a 10 mm inner diameter (i.e. 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 x 15 x 15 cm 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 in order 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 cmH_2O) 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].

Table 1. Dimensions of the tubes used in the experiments

Theory

The back pressure from tubes has been studied in fluid dynamics. This back pressure 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, 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 Reynold's number (Re). The Reynolds Number for cylindrical tubes can be calculated using the formula[22]:

$$\mathrm{Re} = \frac{2U}{\upsilon \pi r}$$

Where U is the flow; υ is the kinematic viscosity of air ($15.68 \cdot 10^{-6}$ m^2/s at 25^oC) and r is the radius of the tube. If Re is below 2300, laminar flow occurs. For 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 paper, 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 paper to completely model the back pressure from the tubes used in SOVTE, for a more elaborate description see textbooks on fluid dynamics (e.g., Nakayama and Boucher, 1998)[22].

For tubes in water a second effect contributes to the back pressure. In order 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. Based on this, a theoretical model can 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 back pressure 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 analysed from three different aspects: pressure-flow relationship for straws of different lengths and diameter, 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 in length) 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 in diameter). The p_{back} produced is larger for thinner straws at a given U. This result is in agreement with investigations by Titze of flow resistance for different semi-occlusions[23].

Figure 5 shows the pressure-flow relationship for a) a 26 cm resonance tube with 9 mm diameter and b) 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 (a) and (b) 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 greater than zero, 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 ~~changes~~shifts upwards; 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 depth ~~was~~ is overcome the flow start~~ed~~s 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 have approximately the same shape as the tubes in free air (0 cm), but are shifted upwards according to the water depth. Furthermore, a small difference in p_{back} can be observed between the resonance tube and 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 higher prior to 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 to 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 c. 1 cm H_2O to c. 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 (e.g., 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 whilst 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, while 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 larger than the p_{back} used during resonance tube phonation.

Therefore, it is possible that the current recommendations for these exercises results 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 etc. 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 (i.e. in air versus 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 back pressure 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.

Conclusion

The changes in tube diameter affect back pressure p_{back} considerably more than 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 while 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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Declaration of interest:

No conflicts of interest were reported by any of the authors in this paper.

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