A Pilot Study Assessing the Therapeutic Potential of a Vibratory Positive Expiratory Pressure Device (Acapella® Choice) in the Treatment of Voice Disorders.

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Introduction: Semi-occluded vocal tract exercises (SOVTEs) can involve a single source of vibration (e.g. vocal folds in the straw exercise) or a dual source of vibration (e.g. vocal folds and water bubbling in tube phonation) in the vocal tract. Oftentimes, this secondary source of vibration causes large oscillations in intra-oral pressure and has been likened to a ‘massage effect’. This study assesses the implementation of a positive expiratory pressure (PEP) device (Acapella® Choice) as a possible alternative SOVTE which presents a secondary source of vibration without the need of a water container. **Method**: 22 normophonic participants underwent acoustic, electroglottographic and aerodynamic assessment before, during and after phonation with two different established SOTVEs (Silicone Tube in water and Straw in air) in addition to Acapella® Choice. **Results**: Acapella® Choice produced the largest peak-to-peak amplitudes of intraoral pressure oscillation. Straw in air produced the largest static intraoral pressure. Straw in air and Acapella® Choice presented significantly larger ranges of static pressures than Tube in water phonation. Post-exercise condition showed a statistically larger sound pressure level (SPL) for Acapella® Choice. **Conclusion**: PEP devices, such as Acapella® Choice, may be a promising alternative to established SOVTEs as it promotes large oscillatory pressures in the vocal tract without the need for a water container. This exercise also produces larger SPL with no significant changes in glottic contact quotient, indicating improved vocal economy.

Keywords: Semi-occluded vocal tract exercise, Positive expiratory pressure, Tube phonation, Straw, Acapella, Voice therapy.

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1. Introduction

The therapeutic process often sees clinicians adapting techniques and tools for novel applications. Those engaged in voice rehabilitation are no exception; devices which have been found to have clinical application in dysphonia but which were developed for a different purpose include kazoos[1], 'flow ball' toys[2] and variably occluded face masks[3,4].

These devices serve to partially narrow and/or elongate the vocal tract, and as such, are forms of semi-occluded vocal tract exercise (SOVTE). A common feature of SOVTEs is the increased flow resistance that promotes larger intraoral pressure which, in turn, reduces the transglottal pressure and increases the intraglottal pressure[5–7]. Assuming a constant subglottal pressure, raising the intraglottal pressure causes the vocal folds to separate, reducing adduction. A reduction in the level of vocal fold adduction could be considered advantageous in the treatment of subjects with hyperfunctional voice disorders. In addition, phonation into tubes, causes the first acoustic resonance of the vocal tract to lower towards the fundamental frequency increasing the positive reactance of the vocal tract that aids the mechanical vibration of the vocal folds[8]. This system optimization is further improved by reduced phonation threshold pressure and increased harmonic amplitude caused by faster flow cessation.

SOVTEs using tube phonation can be performed with the distal end of the tube in air or submerged under water. By submerging the distal end of the tube under water, water bubbling is generated adding an oscillatory component to the static intraoral pressure[9–12]. This pressure modulation by the water bubbling is described as producing a 'massage effect' on the laryngeal muscles[6,9,10,13–15] that supposedly counteracts harmful maladaptations such as hyperfunctional phonation. In SOVTEs involving submersion in water, phonation is achieved once the hydrostatic pressure of the depth of the water is overcome. Hence, the depth of water can be manipulated as part of a therapeutic intervention.

Two distinct methods have been suggested for tube phonation with the distal end submerged under water: Resonance Tube Phonation[16] and LaxVox®[17]. Resonance Tube Phonation uses a glass tube submerged under the surface of water in a tank (no volume requirements are prescribed) at about a 45° angle, whilst LaxVox® is implemented via a silicone tube submerged in a water bottle. Due to the flexibility of the silicone tube, no precise angle is prescribed for LaxVox®, however instruction regarding posture and the length and diameter of tube are offered. For more information regarding

Resonance Tube Phonation and LaxVox®, refer to Simberg and Laine[13] and Sihvo and Denizoglu[17] respectively.

Vibratory positive expiratory pressure (PEP) devices are traditionally used to mobilize secretions in the treatment of excessive sputum or secretion retention in conditions such as cystic fibrosis and neurogenic diseases. The PEP devices are variously composed of a mouthpiece attached to a plastic cone containing a metal sphere which is rhythmically displaced by the airflow (such as the FLUTTER®, Aptalis Pharma Inc, Bridgewater, NJ, USA) or to a tube with a distal oscillatory arm that closes and opens with airflow (such as Acapella® Choice, Smiths Medical ASD, Inc., Rockland, MA USA). PEP devices aim to match the frequency of vibration of the ciliary epithelium in the lungs, hence promoting the expectoration of secretions[18] .

A practical limitation for implementing Resonance Tube Phonation in water/LaxVox® is the evident requirement of an accessible water container. PEP, which would seem to offer an alternative source of oscillatory pressure without such requirements, might therefore have potential as a form of SOVTE.

This study sought to evaluate the physiological effects of a vibratory positive expiratory pressure device, Acapella® Choice (Figure 1) on the vocal apparatus with the aim of assessing its implementation as a form of SOVTE. In specific, the oscillatory and static component of the intraoral pressure were assessed and compared to two other well-established SOVTEs, straw phonation in air (henceforth referred to as Straw) and silicone tube in water (henceforth referred to as Tube) on the voices of normal subjects. These exercises were chosen both as useful exemplars of techniques in common clinical use, but also because they represent a variety of degree of resistance and presence/absence of oscillation.

2. Methods

2.1. Participants

Twenty-two participants (mean age 38.2, range 20-58) with no known laryngeal pathology or voice complaint were included in this study: eleven women (mean age 40.1, median 44, range 21-58) and eleven men (mean age 36.5, median 38, range 20-45). There were no professional singers amongst the participants.

2.2. **Phonatory** Tasks

The experimental tasks were: (1) phonation through Acapella® Choice (henceforth referred to simply as Acapella®), (2) phonation through a narrow straw (10cm long/3mm diameter) or (3) phonation through a flexible silicone tube (35cm long/9mm diameter) submerged in 5cm of water. To remove any possible cumulative effect, only one exercise was carried out per study session, and each of three sessions was held on a separate day. Sessions proceeded in the sequence detailed above.

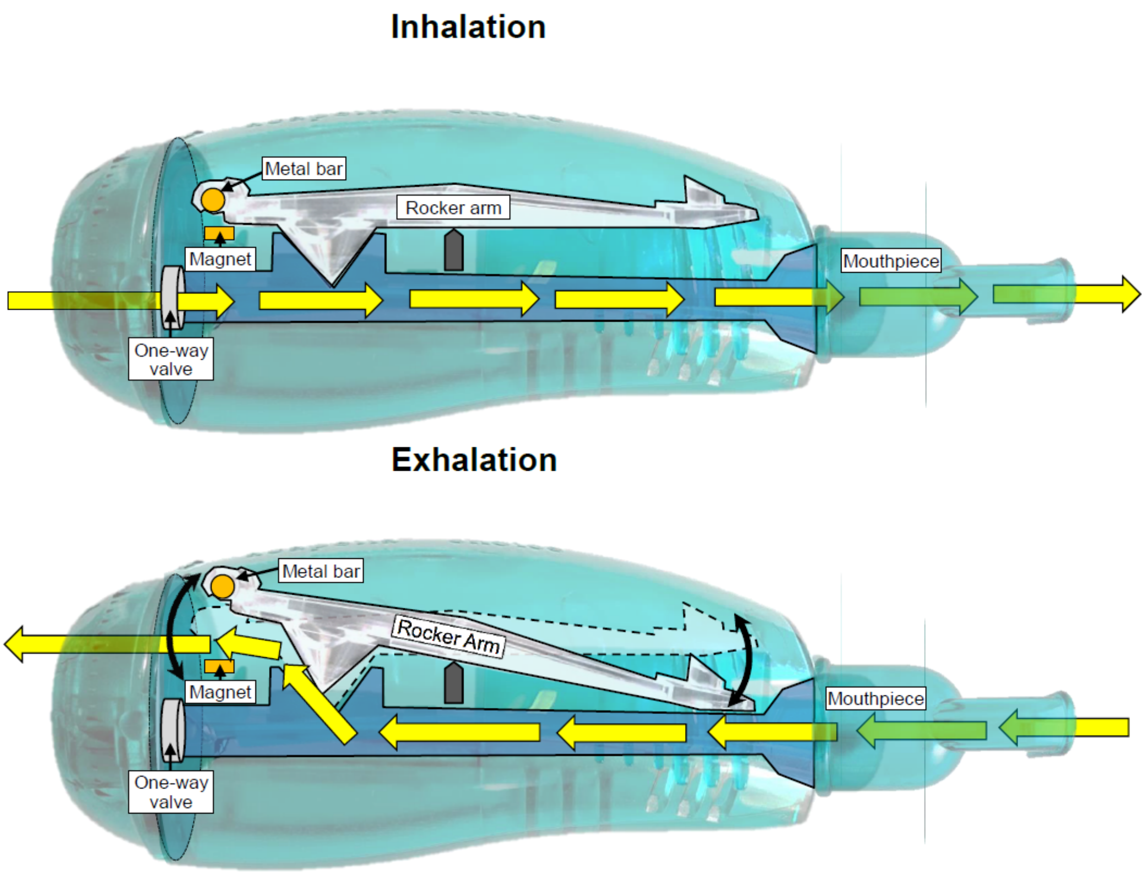

Figure 1: Acapella® Choice

On each visit, participants were required to (1) produce three tokens of sustained /a:/ at a comfortable loudness for acoustic and EGG analysis and (2) produce seven repetitions of the syllable /pa:/ for aerodynamic analysis. Following these baseline measures, the investigator demonstrated the experimental task. Participants were then asked to (3) perform the exercise for three minutes. After one minute of exercise had elapsed, 30 seconds of intraoral pressure measurements and simultaneous EGG signal were recorded. Immediately following three minutes of phonation, the baseline measurements in (1) and (2) were repeated. Baseline recordings were played as a pitch reference and participants were requested to match this as best as possible.

The following variables were considered: for the baseline and outcome conditions - *sound pressure level* (SPL), *singer's/speaker's formant energy*, *cepstral peak prominence* (CPP), *low/high spectral ratio* (LHSR), *mean glottal contact quotient* (mean CQ), *standard deviation of glottal contact quotient* (SDCQ), *mean peak pressure* and *mean flow during voicing*; for the in-exercise condition – mean CQ, SDCQ, *static pressure* and oscillatory pressures (*peak-to-peak amplitude* and *oscillatory frequency*).

2.3. Equipment

Acoustic signals were recorded at 30cm distance with a Shure SM48 microphone (Shure Incorporated, Niles, IL) together with simultaneous electroglottography (dual-channel EGG, KayPENTAX model 6103, Lincoln Park, NJ) through Computerized Speech Lab (CSL 4150, KayPENTAX, Lincoln Park, NJ). The channels were recorded at a sampling rate of 44100 Hz each. Pre (baseline) and post aerodynamic data were collected via the Voicing Efficiency with EGG protocol of the Phonatory Aerodynamic System (PAS 6600, KayPENTAX, Lincoln Park, NJ). During the therapeutic tasks, intraoral pressure modulation was recorded via the PAS 6600's pressure transducer catheter which was inserted into the corner of the mouth of the participant. Owing to its dimensions and configuration, however, it was not possible to insert the PAS 6600's flow head between the participant's mouth and the Acapella® device. As a result, flow data were only collected for pre and post conditions; in-exercise flow data was not obtainable

2.4. Analyses

Using CSL 4150 software, the sustained /a:/ recordings were inspected and one baseline and one outcome token selected on the basis of overall stability and quality of EGG signal. These were then trimmed to the middle 80% of the token. Praat version 6.0.16 (www.praat.org) was used to determine the total SPL (dB) of each token, and a bandpass filter with hanning window was applied to determine the energy (in dB) of the speaker's/singer's formant region (2.5-4kHz). *LHSR* and *CPP* were determined by analysing the tokens with Analysis of Dysphonia in Speech and Voice (ADSV) model 5109 (KayPENTAX, Montvale, NJ). *Mean CQ* and *SDCQ* were extracted from the EGG signal using CSL 4150. Using PAS 6600's Voicing Efficiency with EGG protocol, the middle five tokens of /pa:/ were analysed and *mean peak pressure* during the [p] extracted along with *mean flow during voicing* of the [a:] of the syllables for an estimate of subglottic pressure and transglottic flow, respectively. In-exercise EGG and oral pressures were visually inspected using PAS 6600 software and one token selected for overall signal quality. Once again, CSL 4150 software was used to calculate *mean CQ* and *SDCQ* for the middle 80% of the exercise token.

For the in-exercise condition, the static and oscillatory pressures were analysed using MATLAB Version R2016b (MathWorks Inc., www.mathworks.com). The *static pressure* was obtained by means of a moving-average filter with a window size of approximately 30 milliseconds. Upon visual inspection, the window size was adjusted as needed to produce optimum results for some signals. Once the static pressure was obtained, the time dependent changes in static pressure (henceforth called *range of static pressure*) was calculated by subtracting the minimum from the maximum pressure value. The *range of static pressure* was obtained in order to quantify any possible changes in static pressure levels during exercise.

For the oscillatory pressure calculation, the signals were first filtered to remove excessive noise. A peak-picking method was then carried out to obtain the *peak-to-peak amplitude* and *oscillatory frequency*. The static and oscillatory pressures were then visually inspected to ascertain accuracy and mean and standard deviation measures for both were taken for each exercise.

As an excessive amount of noise was present in some of the Tube signals, a Long-term average spectrum (LTAS) analysis using Praat was subsequently implemented to confirm the bubbling frequency (i.e. *oscillatory frequency*) obtained through the peak-picking method used with MATLAB. A spectrum analysis for frequency detection was suggested by Horacek et al[19] and, as it does not require filtering, it seems to be a good alternative to the peak-picking method.

A third method was explored for measuring the *oscillatory frequency* for the Acapella® and Tube signals. In this method, a low-pass filter was applied to the electroglottographic signal with a cut-off frequency of 30 Hz. A peak-picking method was then implemented to obtain the oscillatory frequency.

Although less robust, an advantage of this method is that it does not require the acquisition of a pressure signal. However, only 17 out of 22 participants had adequate quality EGG signals to utilise for this method of frequency extraction.

To ascertain the validity of implementing any of the three methods for obtaining the *oscillatory frequency*, an Intraclass Correlation (ICC) analysis was performed. A significant excellent ICC agreement was found for Acapella® among all three techniques (ICC = 0.891; one-way random single measures, confidence interval of 95% from 0.795 to 0.949, $F(21,44) = 25.4$, $P < 0.001$). Pairwise correlation coefficients for Acapella® ranged between 0.93 to 0.99. For Tube, a significant fair ICC agreement was found (ICC = 0.532; one-way random single measures, confidence interval of 95% from 0.283 to 0.746, $F(21,44) = 4.41$, $P < 0.001$). Pairwise correlation coefficients for Tube ranged between 0.42 to 0.67. Therefore it seems that any of the three methods can be used to measure *oscillatory frequency* for Acapella® however care should be taken when selecting the most appropriate method for Tube. Unfortunately, it was beyond the scope of this study to verify which method was the most reliable. Owing to the fact that adequate EGG signals were not available for all subjects, and owing to the filtering and visual inspection needed for the peak-picking method, we decided upon using long-term average spectrum for this study as it was arguably more robust.

2.5. Statistical treatment

Numerical variables were described by mean/median and standard deviation/interquartile ranges. Significant differences in pre-post measures and in-exercise variables between tasks were identified using Repeated Measures ANOVA/paired t-tests or Friedman Repeated Measures ANOVA on Ranks/Wilcoxon Signed Rank Test depending on the distribution of the data. Additionally, relationships among intraoral pressure variables were investigated using Pearson’s product moment correlation. All analyses were performed using SigmaPlot version 13.0 (Systat Software Inc, Chicago, IL, USA).

3. Results

Table 1a: Comparison of static pressure variables by exercise task.

	Exercises			ANOVA	Post-hoc Comparisons		
Static Pressure Variables	**Acapella**	**Tube**	**Straw**	**P-value**	**Acapella /Tube**	**Tube/ Straw**	**Straw/ Acapella**
Mean static pressure (cmH_2O)	6.22 (3.16)	5.09 (1.04)	10.91 (6.69)	<0.001***	0.010*	<0.001***	<0.001***
Range static pressure (cmH_2O)	0.97 (1.15)	0.22 (0.14)	1.66 (1.48)	<0.001*** (R)	0.003**	<0.001***	0.122

NB: Data denote medians and interquartile ranges in brackets.
(R) = Repeated Measures ANOVA on Ranks. **Significance levels**: * = P<0.05, ** = P<0.01, *** = P<0.001

Table 1b: Comparison of oscillatory pressure variables by exercise task.

	Exercises		t-Test
Oscillatory Pressure Variables	**Acapella**	**Tube**	**P-value**
Mean peak-to-peak amplitude (cmH_2O)	4.09 (2.38)	2.20 (1.82)	<0.001*** (W)
SD of peak-to-peak amplitude (cmH_2O)	0.38 (1.17)	0.87 (0.48)	<0.001***
Mean oscillation frequency (Hz)	10.74 (1.56)	10.22 (4.65)	0.948

NB: Data denote medians and interquartile ranges in brackets
(W) = Wilcoxon Signed Rank Test, **Significance levels**: *** = P<0.001

3.1. Static and Oscillatory Pressures

Repeated Measures ANOVAs and post-hoc analyses were used to compare static pressure variables (Table 1a) and indicated three-way significant difference for *mean static pressure*, but no significant difference between Straw and Acapella® for *range of static pressure*. Paired t-tests were used to compare oscillatory pressure values between Acapella® and Tube (Table 1b) and indicated significant differences for *mean peak-to-peak amplitude* and *SD of peak-to-peak amplitude*. There was no significant difference for *mean oscillation frequency*, however the interquartile range for Tube was three times larger than Acapella®. Figure 2 displays a scatterplot for static vs oscillatory pressures with overlaid median and interquartile ranges for the three exercises.

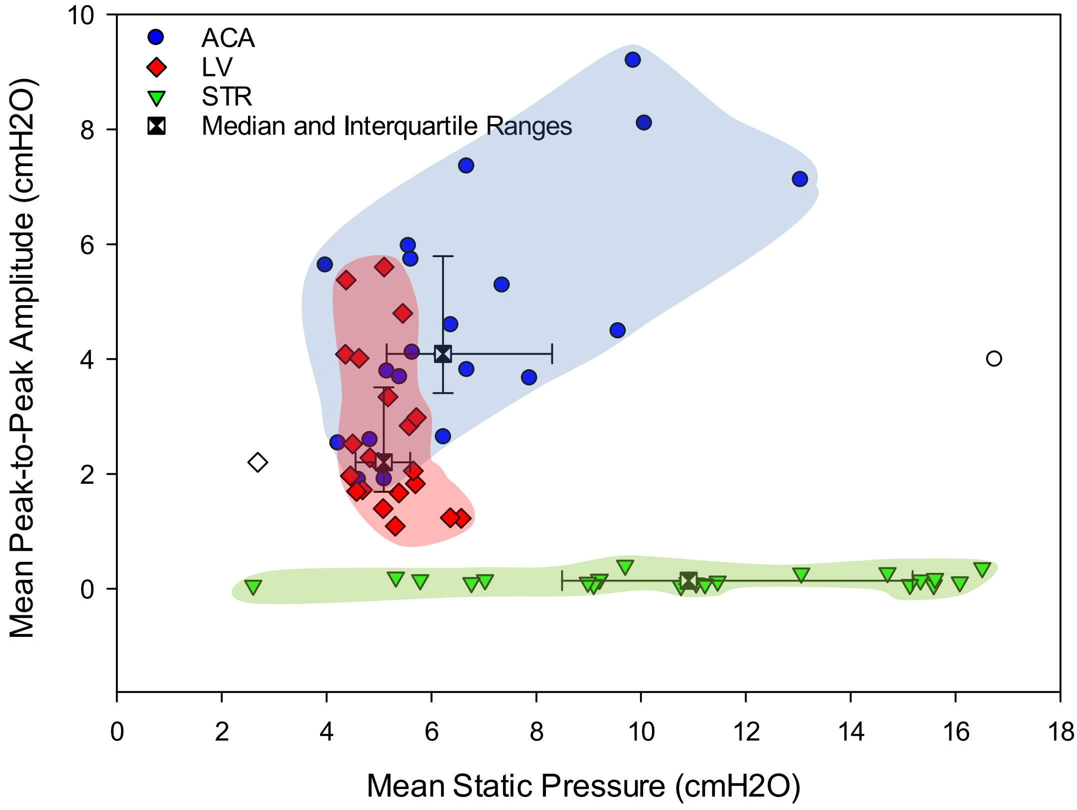

Figure 2: Static pressure vs peak-to-peak amplitudes for all participants overlaid with median and interquartile ranges.

We then considered the relationships between *static pressure, peak-to-peak amplitude* and *oscillation frequency* for Acapella® and Tube. Beginning with Acapella®, a correlation analysis demonstrated a moderate to strong positive linear relationship between *static pressure* and *peak-to-peak amplitude* ($r_s = .59$, $p = 0.005$). A multiple regression analysis was then used to investigate if *static pressure* and *peak-to-peak amplitudes* were likely predictors of *oscillatory frequency*. The results of the regression indicated that both predictors explain 79.6% of the variance ($r^2 = .77$, $F(2,18)=35.31$, $p<0.001$). It was found that the *static pressure* significantly predicted *oscillatory frequency* ($\beta = .75$, $p<0.001$) however, *peak-to-peak amplitude* alone showed no statistical significance as a predictor ($\beta = .19$, $p = 0.17$). For Tube, correlation analysis demonstrated no significant relationship between *static pressure* and *peak-to-peak amplitudes* ($r_s = -.32$, $P = 0.15$). Further, a multiple regression on these variables and oscillatory frequency was not significant ($r^2 = .09$, $F(2,19)=2.05$, $p = 0.15$).

3.2. Electroglottographic Variables

Two-Way Repeated Measures ANOVAs were conducted on the influence of exercise and condition (pre, in-exercise and post) on the EGG variables *mean CQ* and *SDCQ*. The results are shown in Table 2. Only 17 subjects had EGG signals of sufficient quality across all conditions and analysis was confined to these. For *mean CQ*, main effects of exercise (F(2,64)=0.18, p=0.83) and condition (F(2,64)=0.61, p=0.61) separately were not significant, however the interaction of exercise x condition was significant (F(4,64)=3.24, p=0.018). Post-hoc analysis identified a borderline significant difference (difference of means: 2.60, p=0.053) between Acapella® and Tube, such that in-exercise *mean CQ* increased for Acapella® and decreased for Tube. There were no significant changes pre to post.

For *SDCQ*, the main effect of exercise was significant (F(2,64)=5.19, p=0.01), the main effect of condition was borderline significant (F(2,64)=3.28, p=0.051), and the interaction of exercise x condition was significant (F(4,64)=4.295, p<0.01). Post-hoc analyses indicated that for the in-exercise condition, *SDCQ* significantly increased over baseline (pre) levels for Acapella® (t=3.00, p=0.01) and Tube (t=2.93, p=0.01), and both were significantly greater than *SDCQ* for Straw (Acapella® vs Straw: t=3.92, p<0.001; Tube vs Straw: t=4.68, p<0.001). Post exercise, *SDCQ* dropped significantly for Tube when compared to the in-exercise condition (t=2.91, p=0.01). There were no significant changes pre to post.

Table 2: Means and Standard Deviations of Mean CQ (%) and SD CQ (%)

	Mean CQ			**SDCQ**		
Condition	**Acapella**	**Tube**	**Straw**	**Acapella**	**Tube**	**Straw**
Pre	44.4 (4.5)	44.9 (3.7)	44.3 (4.5)	1.21 (0.44)	1.35 (0.54)	1.32 (0.59)
In-Exercise	45.8 (5.6)^{T}	43.2 (4.6)^{A}	44.2 (4.4)	1.80 (0.80)^{Pre*}	1.92 (0.90)$^{Pre*, Post**}$	1.15 (0.53)$^{A***, T***}$
Post	43.1 (4.6)	44.3 (4.0)	43.3 (3.5)	1.50 (0.63)	1.36 (0.59)	1.47 (0.62)

Figures in brackets represent standard deviation. Superscripts show significant post-hoc tests.
Key: (A)capella, (T)ube, Pre, Post. **Significance levels**: * = P<0.05, ** = P<0.01, *** = P<0.001

3.3. Acoustic and aerodynamic

Tables 3a and 3b display pre and post data for acoustic and aerodynamic variables. Data were analysed by Two-Way Repeated Measures ANOVAs.

Participants' tokens were significantly louder (i.e. *SPL*) following Acapella® (F(2,42)=4.383, p=0.02); no such change was found following Tube or Straw. A similar result was found when considering specifically the *speaker's/singer's formant energy*, but significance was only borderline (F(2,42)=3.11, p=0.055). For *mean peak pressure*, there were no significant differences pre to post (F(2,42)=2.91, p=0.10), or between exercises (F(2,42) = 0.79, p=0.46).

Baseline data were analysed by gender and significant pre-exercise differences were found between men and women for *CPP* (t=-8.779, P<0.001), *mean flow during voicing* (U=436, P<0.001) and *LHSR* (U=962, P<0.001) such that men had significantly higher values for all three measures (Table 3b). These differences remained after the exercises (i.e. there was a main effect of gender).

In Tube, however, there was also a significant pre-post main effect for *mean flow during voicing* (F(1,20)=6.07, P=0.023) and *LHSR* (F(1,20)=6.21, P=0.022). This was seen more strongly for men in the former case and women in the latter, such that men tended to have significant gains in flow and women tended to have significant reductions in spectral ratio. The interaction of gender and pre-post condition, however, fell short of statistical validity (*mean flow during voicing*: F(1,20)=3.62, p=0.072; *LHSR*: F(1,20)=3.1, p=0.091).

Table 3a: Means and Standard Deviations of Acoustic and Aerodynamic Variables

	Acapella	Tube	Straw
SPL (db)			
Pre	65.20 (4.74)	65.86 (4.98)	65.59 (3.94)
Post	66.73 (4.38) Pre**	65.61 (5.00)	65.37 (4.34)
Singer's/Speaker's (db)			
Pre	45.57 (8.11)	46.11 (8.08)	46.91 (7.46)
Post	48.01 (6.96) Pre	46.93 (8.36)	46.24 (7.70)
Mean Peak Pressure (cmH_2O)			
Pre	10.35 (4.06)	10.63 (3.37)	10.50 (3.23)
Post	10.37 (3.74)	11.14 (3.55)	11.22 (3.85)

Figures in brackets represent standard deviation. Superscripts show significant post-hoc tests.
Key: Pre **Significance levels**: ** = P<0.01

Table 3b: Means and Standard Deviations of Gender-Variant Acoustic and Aerodynamic Variables

	Acapella		**Tube**		**Straw**	
	M	F	M	F	M	F
CPP (db)						
Pre	14.49 (1.15)	12.44 (1.21)^{M***}	14.61 (1.21)	12.22 (1.88)^{M**}	14.23 (0.92)	12.91 (1.43)^{M*}
Post	14.53 (1.29)	12.84 (1.28)^{M**}	14.86 (1.58)	12.39(1.54)^{M**}	14.52 (1.02)	12.48 (1.26)^{M***}
L/H Spectral Ratio (LHSR) (db)						
Pre	31.86 (4.93)	27.53 (4.29)^{M*}	31.99 (4.78)	28.90 (4.96)	31.21 (4.21)	25.89 (3.09)^{M**}
Post	31.99 (4.24)	26.51 (3.00)^{M**}	31.59 (4.81)	26.49 (4.38)$^{M*, Pre**}$	31.52 (5.87)	26.35 (3.74)^{M**}
Mean Flow Voicing (l/s)						
Pre	0.32 (0.18)	0.15 (0.13)^{M**}	0.28 (0.09)	0.13 (0.10)^{M*}	0.33 (0.13)	0.12 (0.08)^{M***}
Post	0.32 (0.12)	0.13 (0.11)^{M**}	0.38 (0.20)^{Pre**}	0.15 (0.10)^{M***}	0.34 (0.13)	0.14 (0.11)^{M***}

Figures in brackets represent standard deviation. Superscripts show significant post-hoc tests.
Key: (M)ale, Pre. **Significance levels**: * = P<0.05, ** = P<0.01, *** = P<0.001

4. Discussion

On the basis of the results, Acapella®, Tube and Straw represent three significantly distinct combinations of static and oscillatory pressures. Straw offered a relatively high static pressure with no oscillation, Tube offered relatively low static pressure with moderate peak-to-peak amplitudes of oscillation and Acapella® offered comparatively moderate static pressure with large peak-to-peak amplitudes. The oscillation frequencies of Acapella® and Tube were not significantly different, although the latter exercise had greater inter-subject variability.

Static pressure together with *peak-to-peak amplitude* were found to be significant predictors for *oscillation frequency* in Acapella®. For Tube, these variables had no clear effect on the bubbling frequency. It is worth noting that our data for bubbling frequency in Tube (mean 10.74Hz) is in the range found by Granqvist et al[10], i.e. 10-12Hz, for a rigid tube with the same internal diameter as the silicone tube used in the present study. Other in-vivo studies have reported frequencies which were somewhat higher, i.e. Wistbacka et al[11] (14-22Hz) and Guzman et al[20] (12-32Hz), but these involved tubes of slightly different diameters and submersion depths. Wistbacka et al[21] further urge caution in determining bubbling frequencies as bubbling progresses from single, to bimodal to chaotic bubble configurations. Finally, these other in-vivo studies, as with the current investigation, did not measure in-exercise flow which Wistbacka et al[21] found to be a determinant of bubbling frequency.

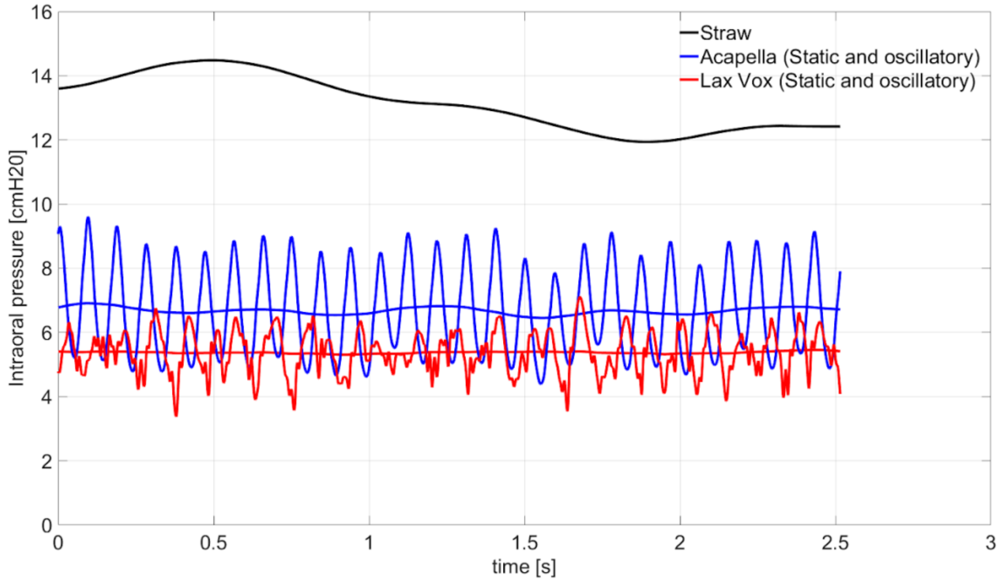

Figure 3: Static and oscillatory pressures for one subject

Despite not being able to collect data for in-exercise flow in our study, it is possible to hypothesise its influence in the spread of *static pressure* values for Acapella® and Straw in Figure 2 (between-participant variation) and the *range of static pressure* data in Table 1a (within-participant variation). Figure 3 graphically represents the longitudinal drift of static pressure traces (most visible for this participant for Straw). For the participants in this study, *static pressure* varied 7.5 times more during Straw and 4.4 times more during Acapella® in comparison to Tube, where it varied very little. In their study using an airflow-driven vocal tract simulator, Andrade et al[12] and Wistbacka et al[21] found that the static component of 'back pressure' generated by 9mm diameter glass tubes in water was strongly dependent on water depth and only slightly dependent on airflow. It could be inferred from this that both Acapella® and Straw offer a proportionally larger flow-dependent component to static pressure than Tube.

If flow is likely to have an impact on static pressure for Acapella®, and we have observed that static pressure is correlated with peak to peak amplitudes for the device, it is expected that flow is also likely to affect oscillatory pressures. Wistbacka et al[21] found that variations in flow positively affected the frequency and peak-to-peak amplitude modulation of bubbling in Tube exercises, and similar findings were also demonstrated by Mueller et al[22] using Acapella®. In the present study, Acapella® offered not only a significantly greater mean peak-to-peak amplitude than Tube, which participants subjectively reported as more ‘intense’, but one which was significantly more regular (i.e. lower SD of *peak-to-peak amplitude*). It could be said that Acapella® offers a more mechanistic modulation of intraoral pressures, which is clear when two sample traces of intraoral pressure for the two exercises are visually inspected (see Figure3).

As with *static pressure*, the range of inter-subject *peak-to-peak amplitudes* for Acapella® in Figure 2 is larger than for Tube. Following Mueller et al[22], this range of amplitudes is likely to do with differences in flow used by different participants when exercising with Acapella®. Wistbacka et al[21] found that the peak-to-peak amplitude in Tube exercises plateaued once submersion depths exceeded 3cm of water and flow exceeded 0.2L/s. Similarly, Guzman et al[20] found no significant difference in peak-to-peak amplitudes for their subjects bubbling at 3cm and 10cm depths. It could be concluded, therefore, that Acapella® offers greater peak-to-peak amplitudes than is practically obtainable in Tube and that this is likely due to the way that the device behaves at different airflows.

Cochrane[23] explains that vibratory load is dependent on four parameters: frequency, amplitude, acceleration and duration. If a proposed ‘massage effect’ of SOVTEs might be considered stronger with a higher vibrational load (transmitted by the oscillating intraoral pressure) then Acapella® should have a greater ‘massage effect’ than Tube owing to its larger amplitudes. It is worth noting from Figure 2, however, that the lower end of Acapella®’s range of intraoral pressure values overlapped with the data for Tube, offering similar static and oscillatory pressures. It can be inferred, therefore, that at low static pressures at least, Acapella® and Tube are not significantly different from one another and therefore any proposed ‘massage effect’ likely to be similar.

EGG data during the oscillatory exercises (Acapella® and Tube) confirm the findings of others[6,10,14] in that oscillation of intraoral pressure modulates vocal fold oscillation. In this study, both oscillating exercises gave rise to significant increases in the variability of closed quotient (*SDCQ*), both over baseline levels and in comparison to Straw. There was no difference in the magnitude of in-exercise change for *SDCQ* when Acapella® and Tube were directly compared to each other, and there were no significant changes to this variable after exercises.

The pattern with *mean CQ* before, during and after exercising is more complicated. As discussed above, there was an observed trend for *mean CQ* to increase during exercise with Acapella®, decrease during Tube and remain roughly the same during Straw. Although the difference in *mean CQ* in the 'in-exercise' condition was significant between Acapella® and Tube, there was still a degree of inter-subject variability. As has been demonstrated in other studies[24–28], subjects seem to have responded differently to the same exercise conditions, with some demonstrating an increase in *mean CQ* and some a decrease.

Following exercising with Acapella®, participants showed a significantly louder output (statistically significant) with a comparatively lower subglottic pressure approximated by the variable *mean peak pressure* (although this was not a significant difference). Additionally, this increase in loudness did not come with a concomitant increase in *mean CQ*. This combination of increase in *SPL* and unchanged/lowered *mean CQ* would denote a lower impact stress and improved vocal economy[29].

There was a significant baseline difference between men and women for *CPP*, *LHSR* and *mean flow during voicing*. Awan et al[30] explains the gender difference for *CPP* and *LHSR* as a likely reflection of men having relatively more spectral energy at the location of the fundamental and lower harmonics and that such a difference would be greater for sustained vowels (as in this study). Chen et al[31] found a similar significant difference in *CPP* amongst the adolescents in their study. As regards *mean flow during voicing*, Zraick et al[32] found a similar significant gender difference for this variable in a normative study for the Kay Pentax PAS 6600.

For these variables, the main finding is that pre-exercise gender differences remained after exercising with no significant post-exercise change. There was one exception, and that was a significant pre-post main effect identified for subjects using Tube. Following the exercise, participants had higher *mean flow during voicing* values and lower *LHSR* (primarily for men in the former case and women in the latter). As *LHSR* (essentially a measure of spectral tilt) is related to perceptual breathiness[33], this result could be understood to represent two sides of the same coin, i.e. a higher post-exercise transglottal flow.

As discussed previously, Tube also tended to create an in-exercise drop to *mean CQ* which did not continue into the post-exercise condition. Other studies[6,20,26] have found that SOVTEs involving oscillation of the lips or tongue tended to create the lowest in-exercise CQ when compared to other SOVTEs, with the suggestion that this was a result of needing enough transglottal flow to maintain oscillation of the articulators. In this study, Tube offered the lowest flow-resistance and participants performing the exercise were encouraged to produce a steady and lively stream of bubbles. It is possible that this visual feedback and relatively low resistance encouraged a less-adducted glottic configuration and more transglottal flow. And in the case of flow, this was maintained post-exercise.

Acapella®, however, offered a relatively higher flow resistance together with large peak-to-peak amplitude. In this way, it approximates deep submersion Tube in water exercises. Guzman et al[20] found that for Tube in water exercises, as the depth of the water submersion increased, so did the in-exercise CQ. In the present study, both Tube and Acapella® exercises exerted oscillatory pressures on the vocal folds and resulted in higher *SDCQ*. The main difference, however, was that Acapella®'s *peak-to-peak amplitude* was twice that of Tube and significantly more stable (*SD of peak-to-peak amplitude*). We suggest that perhaps this much larger and predictable oscillatory pressure was enough to trigger a compensatory adjustment in adduction in order to minimise the destabilising effect of variations in intraoral pressure. The lack of this destabilising oscillation might explain why fewer participants experienced a similar increase to *mean CQ* during Straw.

If this phenomenon is indeed a form of compensation, it might represent something akin to 'vibration exercise' in sports medicine. Although not fully understood, the strengthening mechanism of acute indirect vibration exercise is thought to represent neural, neuromuscular processes and muscle tuning and is known to increase muscle force and power[23,34]. The human body has been compared to a spring-mass system where muscles act like springs to store and release energy[34] and which can be partly controlled by adjusting position and muscle stiffness[35]. One of the proposed mechanisms of vibration exercise is muscle tuning, whereby muscles are activated to reduce the oscillations which are passing through them[36]. Whether something similar is taking place with high resistance and oscillatory SOVTEs requires further study.

Perhaps the clearest limitation to this study, as already mentioned, was the inability to measure flow during the three exercises investigated. Its influence on the intraoral pressure parameters of the three exercises in this present study requires further investigation. Another obvious limitation of the present study is the inclusion of only phononormal participants, which led us to focus on the objective measures of aerodynamics, acoustics and electroglottography. Future studies should include perceptual-auditory analysis and self-perceived ratings of ease of phonation so that the subjective experience of participants and expert opinion on changes to voice quality are considered. Inclusion of a voice disordered population in further work will allow investigation as to whether Acapella®, with its greater oscillatory pressures, induces a reduction in hyperfunction via a 'massage effect', or whether it improves laryngeal muscle tone in those with hypofunctional voice like a 'vibration exercise'. Despite its unique properties, Acapella® does lack the visual feedback component of Tube-in-water exercises and it may prove more difficult in terms of self-monitoring for voice patients. Owing to the wider range of *static pressure* generated in Acapella®, it is also less easy for a clinician to be sure that the patient is exercising at the prescribed level of resistance than it is for Tube.

5. Conclusions

Acapella®, Tube and Straw offered distinct combinations of static and oscillatory pressure profiles to the vocal tract, suggesting that Acapella® may well represent a valid and promising new addition to other more established SOVTEs. Acapella® stood apart from Tube in this study by offering significantly greater oscillatory pressures and was the only of the three exercises to create a significant change in SPL. Tube appeared to have an effect on measures of flow and spectral measures of breathiness. As this study involved only participants with healthy voice, it remains to be seen how different categories of pathological voice, i.e. hyperfunctional and hypofunctional, respond to the exercising with Acapella®.

6. References

1. Middendorf JH. Phonotrauma in children: Management and treatment. *ASHA Lead*. 2007.

2. Lã FMB, Wistbacka G, Andrade PA, Granqvist S. Real-Time Visual Feedback of Airflow in Voice Training: Aerodynamic Properties of Two Flow Ball Devices. *J Voice*. 2017;31(3):390.e1-390.e8. doi:10.1016/j.jvoice.2016.09.024

3. Mills R, Hays C, Al-Ramahi J, Jiang JJ. Validation and Evaluation of the Effects of Semi-Occluded Face Mask Straw Phonation Therapy Methods on Aerodynamic Parameters in Comparison to Traditional Methods. *J Voice*. 2017;31(3):323-328. doi:10.1016/j.jvoice.2016.04.009

4. Awan SN, Gartner-Schmidt JL, Timmons LK, Gillespie AI. Effects of a Variably Occluded Face Mask on the Aerodynamic and Acoustic Characteristics of Connected Speech in Patients With and Without Voice Disorders. *J Voice*. 2018. doi:10.1016/j.jvoice.2018.03.002

5. Titze IR, Finnegan E, Laukkanen A-M, Jaiswal S. Raising lung pressure and pitch in vocal warm-ups: the use of flow-resistant straws. *J Sing*. 2002.

6. Andrade PA, Wood G, Ratcliffe P, Epstein R, Pijper A, Svec JG. Electroglottographic study of seven semi-occluded exercises: LaxVox, straw, lip-trill, tongue-trill, humming, hand-over-mouth, and tongue-trill combined with hand-over-mouth. *J Voice*. 2014. doi:10.1016/j.jvoice.2013.11.004

7. Story BH, Laukkanen AM, Titze IR. Acoustic impedance of an artificially lengthened and constricted vocal tract. *J Voice*. 2000. doi:10.1016/S0892-1997(00)80003-X

8. Titze IR, Story BH. Acoustic interactions of the voice source with the lower vocal tract. *J Acoust Soc Am*. 1997. doi:10.1121/1.418246

9. Enflo L, Sundberg J, Romedahl C, McAllister A. Effects on vocal fold collision and phonation threshold pressure of resonance tube phonation with tube end in water. *J Speech Lang Hear Res*. 2013. doi:10.1044/1092-4388(2013/12-0040)

10. Granqvist S, Simberg S, Hertegård S, et al. Resonance tube phonation in water: High-speed imaging, electroglottographic and oral pressure observations of vocal fold vibrations - A pilot study. *Logop Phoniatr Vocology*. 2015. doi:10.3109/14015439.2014.913682

11. Wistbacka G, Sundberg J, Simberg S. Vertical laryngeal position and oral pressure variations during resonance tube phonation in water and in air. A pilot study. *Logop Phoniatr Vocology*. 2016. doi:10.3109/14015439.2015.1028101

12. Amarante Andrade P, Wistbacka G, Larsson H, et al. The Flow and Pressure Relationships in Different Tubes Commonly Used for Semi-occluded Vocal Tract Exercises. *J Voice*. 2016. doi:10.1016/j.jvoice.2015.02.004

13. Simberg S, Laine A. The resonance tube method in voice therapy: Description and practical implementations. *Logop Phoniatr Vocology*. 2007. doi:10.1080/14015430701207790

14. Guzmán M, Castro C, Madrid S, et al. Air Pressure and Contact Quotient Measures During Different Semioccluded Postures in Subjects With Different Voice Conditions. *J Voice*. 2016;30(6):759.e1-759.e10. doi:10.1016/j.jvoice.2015.09.010

15. Radolf V, Laukkanen A, Horacek J, Liu D. In vivo measurements of air pressure, vocal folds vibration and acoustic characteristics of phonation into a straw and resonance tube used in vocal exercising. In: *Proceedings of the 19th International Conference Engineering Mechanics, Czech Republic.* ; 2013:478-483.

16. Sovijärvi A. Die Bestimmung der Stimmkategorien mittels Resonanzröhren. [Voice classification according to resonance tubes]. In: *Fifth International Congress of Phonetic Sciences. Basel, NY*. ; 1965.

17. Sihvo M, Denizoglu I. LaxVox voice therapy technique (downloadable handouts). http://laxvox.com/documents/LAXVOX%20handouts.pdf.

18. Patterson JE, Hewitt O, Kent L, Bradbury I, Elborn JS, Bradley JM. Acapella (R) versus `usual airway clearance’ during acute exacerbation in bronchiectasis: a randomized crossover trial. *Chron Respir Dis*. 2007;4(2):67-74. doi:10.1177/1479972306075483

19. Horáček J, Radolf V, Bula V, Veselý J, Laukkanen AM. Experimental investigation of air pressure and acoustic characteristics of human voice. Part 1: measurement in vivo. In: *18th International Conference ENGINEERING MECHANICS, Svratka, Czech Republic*. ; 2012:403-417.

20. Guzman M, Muñoz D. Do Different Semi-Occluded Voice Exercises Affect Vocal Fold Adduction Differently in Subjects Diagnosed with Hyperfunctional Dysphonia ? 2015:68-75. doi:10.1159/000437353

21. Wistbacka G, Andrade PA, Simberg S, Hammarberg B, Sodersten M. Resonance Tube Phonation in Water-the Effect of Tube Diameter and Water Depth on Back Pressure and Bubble Characteristics at Different Airflows. *J Voice*. 2018;32(1):126.e11-126.e22.

22. Mueller G, Bersch-Porada I, Koch-Borner S, et al. Laboratory Evaluation of Four Different Devices for Secretion Mobilization: Acapella Choice, Green and Blue Versus Water Bottle. *Respir Care*. 2014;59(5):673-677. doi:10.4187/respcare.02654

23. Cochrane DJ. Vibration exercise: The potential benefits. *Int J Sports Med*. 2011. doi:10.1055/s-0030-1268010

24. Guzman M, Higueras D, Fincheira C, Muñoz D, Guajardo C, Dowdall J. Immediate acoustic effects of straw phonation exercises in subjects with dysphonic voices. *Logop Phoniatr Vocology*. 2013. doi:10.3109/14015439.2012.731079

25. Guzman M, Laukkanen A-M, Krupa P, Horáček J, Švec JG, Geneid A. Vocal Tract and Glottal Function During and After Vocal Exercising With Resonance Tube and Straw. *J Voice*. 2013;27(4):523.e19-523.e34. doi:10.1016/j.jvoice.2013.02.007

26. Gaskill CS, Erickson ML. The Effect of a Voiced Lip Trill on Estimated Glottal Closed Quotient. *J Voice*. 2008. doi:10.1016/j.jvoice.2007.03.012

27. Gaskill CS, Quinney DM. The effect of resonance tubes on glottal contact quotient with and without task instruction: A comparison of trained and untrained voices. *J Voice*. 2012. doi:10.1016/j.jvoice.2011.03.003

28. Gaskill CS, Erickson ML. The Effect of an Artificially Lengthened Vocal Tract on Estimated Glottal Contact Quotient in Untrained Male Voices. *J Voice*. 2010. doi:10.1016/j.jvoice.2008.05.004

29. Laukkanen AM, Mäki E, Leppänen K. Electroglottogram-based estimation of vocal economy: “Quasi-output-cost ratio.” *Folia Phoniatr Logop*. 2009;61(6):316-322. doi:10.1159/000252847

30. Awan SN, Roy N, Jetté ME, Meltzner GS, Hillman RE. Quantifying dysphonia severity using a spectral/cepstral-based acoustic index: Comparisons with auditory-perceptual judgements from the CAPE-V. *Clin Linguist Phonetics*. 2010;24(9):742-758. doi:10.3109/02699206.2010.492446

31. Chen G, Feng X, Shue Y, Alwan A. On Using Voice Source Measures in Automatic Gender Classification of Children ’ s Speech. *InterSpeech 2010*. 2010;(September):673-676.

32. Zraick R, Smith-Olinde L, Shotts L. Adult Normative Data for the KayPENTAX Phonatory Aerodynamic System Model 6600. *J Voice*. 2012;26(2):164-176.

33. Klich R. Relationships of vowel characteristics to listener ratings of breathiness. *J Speech Hear Res*. 1982.

34. Cochrane DJ. The potential neural mechanisms of acute indirect vibration. *J Sport Sci Med*. 2011. doi:10.1055/s-0030-1268010

35. Mester J, Kleinöder H, Yue Z. Vibration training: Benefits and risks. *J Biomech*. 2006. doi:10.1016/j.jbiomech.2005.02.015

36. Nigg BM. Impact forces in running. *Curr Opin Orthop*. 1997. doi:10.1097/00001433-199712000-00007