Vocal Tract and Glottal Function During and After Vocal Exercising With Resonance Tube and Straw

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Summary: Objective. The present study aimed to investigate the vocal tract and glottal function during and after phonation into a tube and a stirring straw.

Methods. A male classically trained singer was assessed. Computerized tomography (CT) was performed when the subject produced [a:] at comfortable speaking pitch, phonated into the resonance tube and when repeating [a:] after the exercise. Similar procedure was performed with a narrow straw after 15 minutes silence. Anatomic distances and area measures were obtained from CT midsagittal and transversal images. Acoustic, perceptual, electroglottographic (EGG), and subglottic pressure measures were also obtained.

Results. During and after phonation into the tube or straw, the velum closed the nasal passage better, the larynx position lowered, and hypopharynx area widened. Moreover, the ratio between the inlet of the lower pharynx and the outlet of the epilaryngeal tube became larger during and after tube/straw phonation. Acoustic results revealed a stronger spectral prominence in the singer/speaker's formant cluster region after exercising. Listening test demonstrated better voice quality after straw/tube than before. Contact quotient derived from EGG decreased during both tube and straw and remained lower after exercising. Subglottic pressure increased during straw and remained somewhat higher after it.

Conclusion. CT and acoustic results indicated that vocal exercises with increased vocal tract impedance lead to increased vocal efficiency and economy. One of the major changes was the more prominent singer's/speaker's formant cluster. Vocal tract and glottal modifications were more prominent during and after straw exercising compared with tube phonation.

Key Words: Vocal exercises–Semi-occlusions–Resonance tube–Vocal tract impedance–Computerized tomography–Electroglottography–Subglottic pressure–Singer's/speaker's formant cluster.

INTRODUCTION

Semi-occluded vocal tract setting has been extensively used by speech pathologists and voice trainers as therapeutic and training exercises, respectively. Various types of tubes have been used to perform these voice exercises. One of them is the traditional Finnish glass tube, "resonance tube," 26–28 cm in length and 8–9 mm in inner diameter.[1,2] A more accessible option is commercial plastic drinking straws. Moreover, Titze[3,4] has proposed the use of stirring straws, shorter and thinner plastic straws, which are commonly used to stir coffee in the United States. Resonance tube phonation into the water (water resistance therapy) also has a long tradition as a therapeutic tool.[1,5]

Several benefits have been attributed to vocal exercises involving tube phonation or other semi-occluded vocal tract postures, such as y-buzz,[6] tongue trill, lip trill, and voiced bilabial fricative [ß:]. Some of these benefits are an increase in vocal tract impedance, specifically resulting in changes in the inertive reactance,[7–11] which may be favorable to voice production by decreasing phonation threshold pressure[10] and by increasing skewing of the glottal flow waveform (faster cessation of the flow).[9,10] The vocal tract impedance can affect the voice source function in two ways (1) through an acoustic-aerodynamic interaction and (2) through a mechano-acoustic interaction.[7,12]

In the former, the shape of the glottal flow pulse is affected by the acoustic pressures in the vocal tract.[7,8] When fundamental frequencies (F_0s) are below the first formant, the skewing of the flow pulse is increased by supraglottic acoustic pressures compared with the glottal area, so that the airflow is suppressed at glottal opening and maintained during the glottal closing phase. This increased skewing of the glottal flow waveform leads to strengthening of the higher harmonics (less spectral tilt), increase in sound pressure level (SPL),[9,13,14] and to a more resonant voice quality, that is, vibratory sensations in the frontal part of face, alveolar ridge, and head area with easy voice production.[15] This is reflected in a brighter and louder sound. Titze and Sundberg[16] pointed out that because the skewing of the glottal airflow signal is one of the determinants of vocal intensity, the source-filter interaction can be used to increase intensity rather than vibrational amplitude, thus avoiding an increase in the vocal fold impact stress.[14]

The second way that glottal source function can be affected by vocal tract impedance is the mechano-acoustic interaction of the vocal tract pressures and the vocal folds.[7,8,17,18] This

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occurs when the increased vocal tract inertance affects the vocal fold vibration itself (through affecting the pressure above and inside the glottis). Specifically, the inertive reactance lowers the phonation threshold pressure (the subglottal pressure required to barely initiate and sustain phonation).[10] A low phonation threshold pressure would produce an ease of phonation (decrease in perceived phonatory effort).

Not only an anterior semi-occlusion or lengthening of the vocal tract can produce this favorable condition but also a narrowing in the lower vocal tract. Titze and Story[10] reported that when the epilaryngeal tube is quite narrow, making the input impedance to the vocal tract comparable to the glottal impedance, there is an important source-filter interaction. The inertance (the positive component of the reactance) of the vocal tract facilitates vocal fold vibration by lowering the oscillation threshold pressure. When the narrowed epilarygeal tube is combined with a wide pharynx, two relevant effects occur: (1) the vocal tract is inertive for a wide range of F_0 values and (2) a formant cluster between F3 and F5 is produced (singer's or speaker's formant), which is desirable to increase the vocal loudness without an increase in vocal effort.

An increased supraglottal pressure and consequently an elevation of the intraglottal pressure have also been reported during semi-occlusions.[3,17,19] When the vocal tract constriction is tight or the tube added to the vocal tract is narrow or long, it increases intraglottal air pressure which tends to separate the vocal folds if not compensated by raising subglottic pressure and adduction. Separation of the vocal folds (decreased adduction), in turn, would explain a decreased contact quotient (CQ).[3,19] Several studies have reported a change in the relative closed time of the glottis on an electroglottographic (EGG) signal (eg, CQ) when semi-occlusion is compared with vowel phonation.[2,3,20–26] Only some of them have shown a decreased CQ.

Different methods have been used to obtain data of the effects of these vocal exercises. Electroglottography,[3,20–26] acoustics,[2,23,25,27–33] modeling, and simulation studies[7,11,19] are the most dominant. In addition, some studies have been carried out using aerodynamic,[3,23,27,34,35] electromyographic,[34,35] endoscopic,[27,32] and radiological[37–39] measurements. Most of them have examined the changes of vocal folds parameters during and/or after semi-occluded exercises. Nevertheless, few researches have reported outcomes related to vocal tract configuration changes (shape modification) as an effect of the semi-occlusion or artificial lengthening of the vocal tract.[37–39]

In this regard, in a recent investigation conducted by Laukkanen et al,[37] one female participant was assessed with magnetic resonance imaging (MRI) and acoustic analysis before and after straw phonation. Midsagittal area of the vocal tract increased and the velar closure improved during and after straw exercising. Furthermore, the ratio of the transversal area of the lower pharynx over that of the epilarynx increased both during and after the straw. Acoustic changes showed a higher total SPL and also more energy in the speaker's formant cluster. The distances between F4 and F3 and F5 and F4 demonstrated a decrease. Authors suggested that the use of straw vocal exercises helps to produce a speaker's formant cluster, which increases loudness and thus improves vocal economy. Similar MRI and acoustic findings were observed in another study designed to observe changes in voice production after warm-up for two professional voice users. One of the participants used semi-occlusions ([ß:], [m:], and closed vowels [y:] and [u:]).[38]

Vampola et al[39] examined the vocal tract shape in a female subject before, during, and after phonation into a tube using computerized tomography (CT) and finite element models (FEMs) to study changes in vocal tract input impedance. Results indicated that the phonation into a tube causes changes in the vocal tract, which remain also when the tube is removed. Authors observed tightened velopharyngeal closure and enlarged cross-sectional areas of the oropharyngeal and oral cavities during and after the tube phonation when phonating on vowel [a:]. FEM calculations revealed an increased input inertance (inertive or positive reactance) of the vocal tract, especially in the frequency range from 2500 to 4000 kHz, and increased acoustic energy radiated out of the vocal tract after the tube phonation.

To date, no studies have been addressed to assess the possible different training effects produced by two different types of artificial lengthening on the vocal tract setting. Few earlier studies have reported differences in glottal source changes when using two or more different semi-occlusions.[2,3,7,19,27,34] The present study therefore aimed at investigating the vocal tract modifications and also the acoustic, aerodynamic, and EGG characteristics of the voice when comparing vocal exercising with two different vocal tract impedances (during phonation into a glass tube and a stirring straw). We hypothesize that the glottis and/or the supraglottic behavior should adapt differently to different load impedances of the vocal tract.

METHOD

CT scanning

CT was carried out in Surgical Clinic, Department of Imaging and Radiology in Brno, Czech Republic. The CT images were acquired using a Toshiba-Aquilion CT machine. The CT imaging parameters used to provide images of the vocal tract were voltage 120 kV, scan option: helical CT, time of the rotation 0.5 seconds, slice thickness 0.5 mm, and total number of slices: 510. The examination was performed for one male classically trained singer (34 years) who has 7 years of experience using tube phonation and other semi-occlusions as vocal training and warm-up exercises. The subject did not report any known voice or hearing pathology at the time of the experiment. In supine position inside the CT machine, the subject was asked to produce the following phonatory tasks: (1) to sustain vowel [a:], (2) to phonate a sustained vowel-like sound into a glass tube (27 cm in length and 9 mm inner diameter) for 15 minutes, and, immediately after that, (3) to produce another sustained vowel [a:]. All phonations were carried out at habitual loudness level and speaking pitch. The participant was required to produce a stable sound with a good closure at the lips and to feel as strong as possible vibratory sensations on the alveolar ridge, face, and head areas during tube phonation. After 15 minutes of complete silence (vocal rest), phonation into a plastic coffee straw (2.5 mm inner diameter and 13.7 cm in length) was performed for 15 minutes. Immediately after that, the participant was asked to produce another sustained vowel [a:]. This straw was chosen because it was used in a previous study.[1] The subject was scanned two times while producing each phonatory task. He was asked to adopt a relaxed posture in the CT scanner and exactly the same body and head position was kept during the entire CT procedure. The head position was mechanically fixed in a frame during all experiments. The participant was a volunteer and he was informed about the potential health hazards of the CT examination.

CT image analysis

Ten CT midsagittal images (five phonatory tasks × two repetitions) were chosen to perform a series of distance measurements (mm). Anatomic distances (Figure 1) of interest included (1) vertical length of the vocal tract (which is indicative of the vertical laryngeal position [VLP]) measured as the distance between the lowest point of the odontoid process of the Atlas and the vocal folds following a vertical line, (2) horizontal length of the vocal tract measured as the distance between the lowest point of Atlas and the narrowest point between the lips, (3) lip opening measured as the distance between the lower edge of the upper lip and the upper edge of the lower lip, (4) jaw opening measured as the distance between the lowermost edge of the jawbone contour and the anterior end of the hard palate, (5) tongue dorsum height measured as the distance between the lowermost edge of the jawbone and the uppermost point of the tongue dorsum, (6) oropharynx width measured as the distance between the lowest point of the second vertebra and the most posterior part of the tongue contour (for ensuring the same angle, we used straight line from the anterior uppermost edge of the jawbone contour to the anterior lowest point of the second vertebra), (7) velum elevation measured as the distance from the posterior upper edge of the hard palate and the anterior lowest point of the uvula, and (8) hypopharynx width measured as the distance between the lowest point of the pharynx and the internal edge of the epiglottis following a line from the anterior uppermost edge of the jawbone contour to the lower point of the pharynx. All CT measurements were performed using the software *vPACS view*, Version 6.9.5 (Audioscan, Prague, Czech Republic).

Moreover, three cross-sectional areas (mm^2) were measured from the same 10 midsagittal CT images (Figure 2). The areas were (1) oral cavity (A1) measured from the lips to the velum (up to the line connecting the lowermost edge of the jawbone contour and a break of declivity on the velum surface), (2) the pharyngeal region (A2) measured from the line ending A1 down to the horizontal line connecting the lower edge of the third vertebra and the lowermost edge of the jawbone contour, and (3) the epilaryngeal region (A3) measured from the line ending A2 down to the vocal folds.

Additionally, from the transversal CT images, two areas (mm^2) were measured[37,38] (Figure 3): (1) the inlet to the lower pharynx (Ap) just above the collar of the epiglottis and (2) the outlet of the epilaryngeal tube (Ae) just below the collar of the epiglottis where the epilarynx and sinus piriformis form three separate tubes. The ratio between these two areas was also calculated (Ap/Ae). Areas from transversal CT images were chosen taken into account the bending of the vocal tract. A line from backbone to jawbone through the tip of arytenoids in a parallel way to the bottom line of the CT image was use to obtain Ae. A line just above the tip of arytenoids, which was also parallel to the bottom line, was used to obtain Ap.

Recordings

The recordings were performed separately from the CT measurements in a sound-treated room. Three signals were

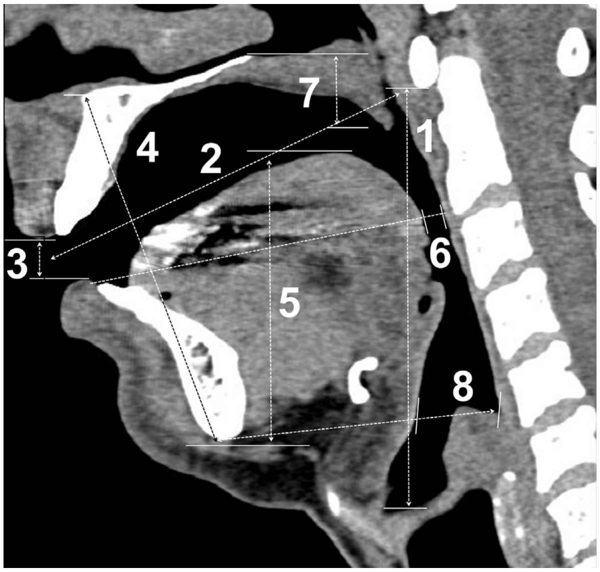

FIGURE 1. Distances (mm) measured in CT midsagittal images: (1) vertical length of the vocal tract, (2) horizontal length of the vocal tract, (3) lip opening, (4) jaw opening, (5) tongue dorsum height, (6) oropharynx width, (7) velum elevation, and (8) hypopharynx width.

FIGURE 2. Areas (mm^2) measured in CT midsagittal images: oral cavity (A1), pharyngeal region (A2), and epilaryngeal region (A3).

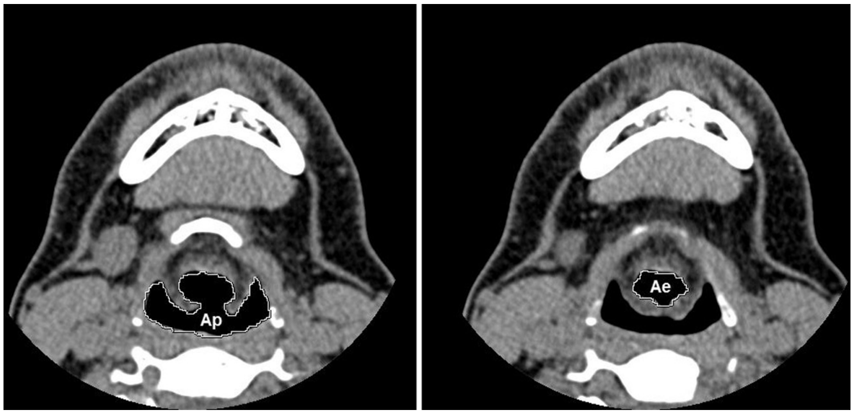

FIGURE 3. Areas (mm^2) measured in CT transversal images: the inlet to the lower pharynx (Ap) and the outlet of the epilaryngeal tube (Ae).

digitized: audio, subglottic (oral) pressure, and EGG signal. The audio signal was recorded by a condenser microphone (Behringer ECM 8000; Behringer, Behringer City, China) at a distance of 40 cm from the mouth. An estimate of the subglottic pressure was recorded from the oral pressure during the occlusion of the consonant [p:] in the syllable [pa:] and by shuttering the outer end of the tube. This pressure was captured with a pressure transducer connected to a thin plastic and flexible tube. The tube was inserted into the corner of the mouth, extending a few millimeters behind the lips, without touching the tongue or any other oral structure. The manometer MSIF2 (Glottal Enterprises, Syracuse, NY) was used.

The EGG signal was recorded with a two-channel electroglottograph (EG2; Glottal Enterprises) using a 20 Hz high-pass filtering (to exclude slow variations in the signal amplitude, which could be due to articulatory movements). The electrodes were cleaned with a slightly wet tissue, and a thin layer of conductive gel was applied (Mingograph electrode cream; Siemens-Elema AB, Munich, Germany). They were positioned near the laminae of the thyroid cartilage and secured with a velcro strip, which was wrapped around the participant's neck as tightly as possible to prevent any movement of electrodes throughout the data collection. The quality of the EGG signal was monitored throughout the recordings with an oscilloscope.

Audio signal was calibrated for further SPL measurements in dB (Z) using a 440 Hz tone. Air pressure signal was calibrated using a Glottal Enterprises calibrator, model MCU-4. Pressure and EGG signals were digitized and recorded simultaneously into different channels at a sampling rate of 16 kHz using the Soundswell Signal Workstation (Hitech Development AB, Stockholm, Sweden). Audio signal was recorded at a sampling rate of 48 kHz with 16 bits quantization using a DAT recorder (Marantz PMD 671; Marantz, Mahwah, NJ).

Phonatory tasks

EGG and subglottic pressure signals were recorded during the repetition of the syllable [pa:] at habitual loudness and comfortable pitch before performing the vocal exercises. After this sequence, the subject phonated a sustained vowel-like sound into the glass tube (27 cm in length and 9 mm in inner diameter) as a vocal exercise for 5 minutes using his habitual pitch and loudness. He was asked to produce a stable sound with a good closure at the lips and to feel perceptible vibratory sensations on the alveolar ridge, face, and head areas during phonation. Immediately after tube phonation exercises, the participant produced again the same series of consecutive syllable [pa:] and sustained vowel [a] following the last [pa:], using the same pitch and loudness level to assess the eventual effect of tube phonation after the tube exercising. Because subglottic pressure is one of the important factors that affect SPL, one of the experimenters monitored the SPL during the series of consecutive [pa:] syllable with a sound level meter (American recorder technologies SPL-8810) (American Recorder Technologies, Inc., Simi Valley, CA) positioned at a distance of 40 cm from the mouth. Z frequency weighting and slow time response were used for monitoring SPL. The SPL choice was made by the subject in pre-exercising recording (at comfortable loudness). Then, these pre-exercising made free choices became the targets for postexercising samples. An electronic keyboard was used to give and control the pitch, which was monitored auditorily by the participant and one of the experimenters. The recording captured during this consecutive syllable [pa:] was saved as the sample after tube phonation. After 15 minutes of complete silence (vocal rest), exactly the same entire procedure was performed with a plastic stirring straw of 2.5 mm inner diameter and 13.7 cm in length.

Acoustic, air pressure, and EGG data analyses

To compare the samples recorded before and after tube and straw phonations, acoustic measures were made using *Praat* software (Version 5.2; Boersma and Weenink, 2008, University of Amsterdam, Amsterdam, The Netherlands). Long-term average spectrum (LTAS) and Fast Fourier Transformation (FFT) spectrum (spectral slice and spectrogram) were used. From LTAS analysis, the following variables were assessed: total SPL (energy between 50 and 6000 Hz), F1 energy (spectral energy between 500 and 800 Hz), singer/speaker's formant energy (energy between 2500 and 4000 Hz), and singing power ratio (SPR) (the difference of energy between the highest peak around 0–2 kHz and the highest peak around 2–4 kHz). A frequency bandwidth of 25 Hz and Hanning window was used for LTAS analysis. FFT spectrum was performed to obtain an approximation of the formant frequencies from F1 to F5. The formant frequencies were measured from the strongest peaks or in the middle of the two adjacent equally strong peaks in spectral slices (average from each sample). Wide band spectrograms (bandwidth 260 Hz) were used for a comparison. There the formant frequencies were located in the middle of the bands with the strongest intensity. Frequency distances between formants F2-F1, F3-F2, F4-F3, and F5-F4 were then calculated.

Every sample captured before, during, and after exercising into both tube and straw were analyzed to obtain the average subglottic pressure (estimated from the maximum peak of the oral pressure during the occlusion of the consonant [p:] in the syllable [pa:] and during manual shuttering the outer end of the tube), oral pressure (obtained during nonshuttered phase), and the glottal CQ. Transglottal pressure was also calculated from the difference between subglottic and oral pressures. A Soundswell Signal Workstation (Hitech Development AB) was used to calculate the oral pressure values. EGG CQ (the ratio of the duration of the "contact phase" to the entire glottal period) was obtained with the software *EFxHist*, Version 1.5 (Mark Huckvale, University College of London, UK) from the middle section of the each EGG sample. *EFxHist* software defines the contact phase using a criterion level of 50% from the peak-to-peak amplitude of the EGG signal.

Auditory-perceptual assessment

To evaluate the voice quality of the samples, a perceptual analysis was conducted with four listeners (one man and three women). This group of blinded judges consisted of speech-language pathologists with more than 8 years of experience in voice training and rehabilitation. Samples recorded before and after tube/straw phonation were played in randomized pairs. Raters were required to judge which sample in each pair was produced with a better voice quality or if there was no difference between them. Listeners could replay each sample as many times as they wanted before making their decision and moving on to the next sample. The evaluation was performed in a sound-treated room using a laptop computer and a high-quality Audioengine loudspeaker (Audioengine, Kowloon, Hong Kong). The listeners were located at approximately 2 m from the loudspeaker. All the listeners reported normal hearing.

RESULTS

CT distance measurements

Mean of the two repeated scans for the anatomic distances (mm) calculated from the midsagittal images of the vocal tract obtained from the CT measurements performed before, during, and after tube/straw phonations are presented in Figure 4. Changes were observed in the vertical length (which is indicative of the VLP). It increased during tube phonation (8%) and even more during straw phonation (21%) (Figures 5 and 6). This lowered laryngeal position remained after tube and straw phonations. The most evident change in laryngeal height occurred when comparing phonations before and during straw phonation (19 mm of difference, 21%). Because during the tube and straw phonations the horizontal length is determined by the length of the tube and straw, respectively, this distance was only measured before and after. Small changes were observed in the horizontal length (less than 2% in all samples). An important modification was observed in the velum position, which rose to seal the nasopharyngeal port during the tube and straw phonations (Figures 5 and 6). In both the tube and straw phonations, the uvula rose 7 mm (35%). Although after tube and straw phonations, the velum was not as high as during them, the higher uvula position remained as compared with the position before tube and straw phonations. When comparing oropharynx width before and after straw phonations, there was about 37% of decrease from 8.7 to 5.65 mm, respectively. This difference was also present after the tube phonation (25%), but it was not as clear as compared with

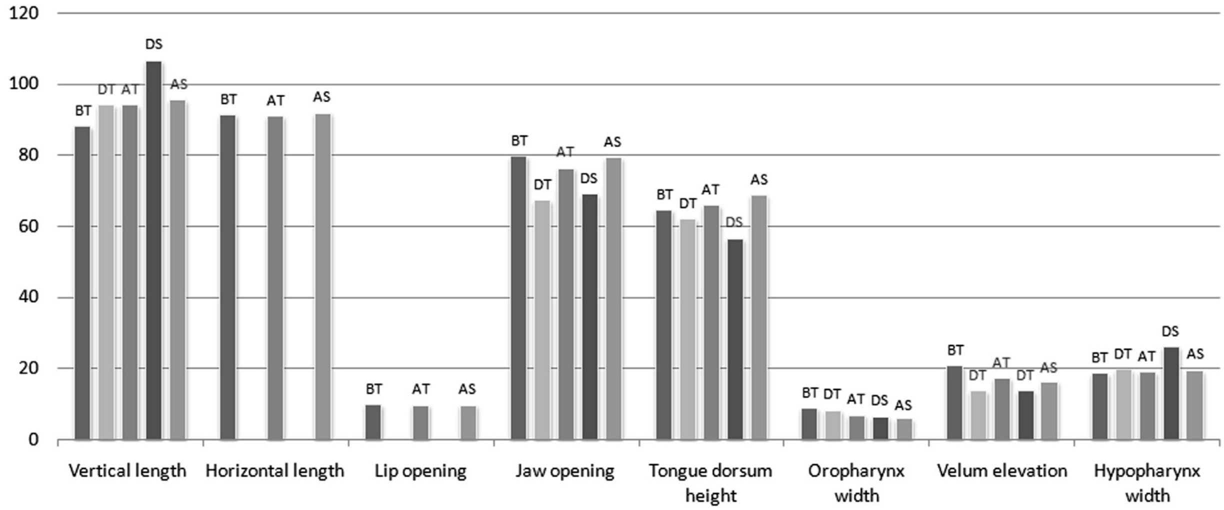

FIGURE 4. Mean of the two repeated scans for anatomic distances (mm) calculated from the midsagittal images of the vocal tract obtained from the CT measurements performed before, during, and after tube and straw phonations. BT, before tube; DT, during tube; AT, after tube; DS, during straw; AS, after straw.

FIGURE 5. Midsagittal images of the vocal tract. Before tube (left), during tube (middle), and after tube phonation (right). The two most dominant changes are the higher velum and the lower laryngeal position in both during and after tube phonations.

the sample after the straw phonation. Hypopharynx became wider during straw phonation (38%). During and after tube phonation, negligible changes were found in the hypopharynx width. Jaw opening also showed a decrease during both tube and straw phonations (15% and 13%, respectively). However, this change was probably a direct consequence of the straw and tube presence between lips. Jaw opening did not change substantially after tube/straw phonation. Small changes were revealed in tongue dorsum height for all sample types (less than 7%), except for the sample during straw (13%). No clear differences were demonstrated in lip opening throughout the sequence. Because during tube and straw phonations the lip opening is determined by the diameter of the tube and straw, respectively, this distance was only measured before and after. Additionally, midsagittal images also show a more frontal tongue position in both during and after tube/straw phonation. This change was more evident during that after exercising (Figures 5 and 6).

The mean differences between phonation before compared with phonation during and/or after tube/straw were greater than the differences between repetitions for vertical length of vocal tract, velum elevation, pharyngeal width, jaw opening, and tongue dorsum height (Table 1). Therefore, one may suggest that the reported variations between before, during, and after tube/straw phonations are true differences.

CT area measurements

Mean of the two repeated scans for the cross-sectional areas (mm^2) measured from the midsagittal and transversal images of the vocal tract obtained from the CT scannings before, during, and after tube/straw phonations are presented in Figure 7. Ap area increased both during tube and straw phonations compared with vowel phonation before them. This increment was clearly much larger during straw (91%) than glass tube (9%) phonation (Figure 8). Negligible changes were observed when comparing Ap between vowel phonations before and after tube and straw phonations (0.2% and 3.5%, respectively). The Ae area became larger during straw phonation (65%) (Figure 9), but no clear changes were observed comparing the phonations before and during tube phonation (2%). The same area showed a decrease after tube (16%) and even more after straw phonation (23%) (Figure 10). The ratio of areas Ap/Ae measured from the transversal CT images showed a clear tendency: during tube, the ratio increased by 7.9%; after tube, by 19.4%; during straw, by 16%; and after straw, by 35%. A change was observed in oral cavity area (A1), which decreased during both tube and straw phonations (37% and 29%, respectively) Figures 5 and 6). Although the oral cavity remained smaller after tube and straw phonations compared with the vowel production before them, this change (1% and 9% for tube and straw, respectively) was not as substantial as the modification during them. Because the presence of tube and straw phonations might affect the oral cavity area, the changes during exercising should be taken with caution. The pharyngeal region (A2) showed the same increase (15%) during tube and straw phonations as compared with vowel production before exercising, but it decreased after tube and straw phonations compared with phonation before them (20% and 27%, respectively). The epilaryngeal region (A3) became larger during both glass tube (13%) and straw (73%) phonations, the change being clearly much larger during

FIGURE 6. Midsagittal images of the vocal tract. Before straw (left), during straw (middle), and after straw (right). Likewise as in Figure 2, the two most evident changes are the higher velum and the lower laryngeal position in both during and after straw phonations. Additionally, the hypopharynx is much wider during straw phonation. The straw is not visible due to the fact that it is made of a very thin walled and a very soft material, which is out of the CT scan possibilities.

TABLE 1.
Results of Acoustic Analysis of Vowel [a:] Pre- and Posttraining With Tube and Straw for LTAS and FFT

Acoustic Parameters	Before Tube and Straw 1 (dB)	Before Tube and Straw 2 (dB)	Difference Before 1 and 2	After Tube 1 (dB)	After Tube 2 (dB)	Difference After Tubes 1 and 2	After Straw 1 (dB)	After Straw 2 (dB)	Difference After Straws 1 and 2	Mean Before (dB)	Mean After Tube (dB)	Mean After Straw (dB)	Difference Mean Before/ After Tube	Difference Mean Before/ After Straw
SPL at 40 cm	75.8	75.9	0.1	76.1	75.9	0.2	76.9	75.3	1.6	75.9	76.0	76.1	0.1	0.2
Energy SF cluster	27.5	27.1	0.4	27.6	26.6	1.0	30.3	29.4	0.9	27.9	27.1	29.8	0.8	1.9
SPR	19.6	19.7	0.1	17.7	16.7	1.0	14.4	16.0	1.6	19.6	17.2	15.2	2.4	4.4
F1 energy	49.8	50.0	0.2	48.4	47.3	1.1	49.1	48.9	0.2	49.9	47.9	49.0	2.0	0.9

Formant Frequencies	Before Tube and Straw 1 (Hz)	Before Tube and Straw 2 (Hz)	Difference Before 1 and 2	After Tube 1 (Hz)	After Tube 2 (Hz)	Difference After Tubes 1 and2	After Straw 1 (Hz)	After Straw 2 (Hz)	Difference After Straws 1 and 2	Mean Before (Hz)	Mean After Tube (Hz)	Mean After Straw (Hz)	Difference Before/ After Tube	Difference Before/ After Straw
F1	707	697	10	624	614	10	588	624	36	702	619	606	83.0	96.0
F2	1143	1060	83	1008	1007	1	1010	1008	2	1102	1008	1009	94.0	93.0
F3	2691	2681	10	2587	2589	2	2608	2598	10	2686	2588	2603	98.0	83.0
F4	3200	3197	3	2940	2920	20	2962	2961	1	3199	2930	2966	269.0	233.0
F5	3761	3636	125	3361	3346	15	3332	3355	23	3699	3354	3344		

Formant Distances	Before Tube and Straw 1 (Hz)	Before Tube and Straw 2 (Hz)	Difference Before 1 and 2	After Tube 1 (Hz)	After Tube 2 (Hz)	Difference After Tubes 1 and 2	After Straw 1 (Hz)	After Straw 2 (Hz)	Difference Straws 1 and 2	Mean Before (Hz)	Mean After Tube (Hz)	Mean After Straw (Hz)	Difference Before/ After Tube	Difference Before/ After Straw
F2-F1	436	363	73	384	393	9	422	384	38	399.5	388.5	403	11	4
F3-F2	1548	1621	73	1579	1582	3	1598	1590	8	1584.5	1580.5	1594	4	10.5
F4-F3	509	516	7	353	331	22	354	363	9	512.5	342	358.5	170	154
F5-F4	561	439	22	421	426	5	370	394	33	500	423.5	382	77	118
F5-F3	1070	955	115	774	757	17	724	757	33	1012.5	765.5	740.5	247	272

Differences Between Formant Distances	Before/After Tube 1 (Hz and %)	Before/After Tube 2 (Hz and %)	Difference Before/After Tubes 1 and 2	Before/After Straw 1 (Hz and %)	Before/After Straw 2 (Hz and %)	Difference Before/After Straws 1 and 2	Mean Before/After Tube (Hz and %)	Mean Before/After Straw (Hz and %)
F2-F1	52 (11.9)	−30 (8.3)	22	14 (3.2)	−21 (5.8)	7	11 (11.9)	−3.5 (4.5)
F3-F2	−31 (2.0)	39 (2.4)	8	−50 (3.2)	31 (1.9)	19	4 (2.2)	−9.5 (2.6)
F4-F3	156 (36.6)	185 (35.9)	29	155 (30.5)	153 (29.7)	2	170.5 (36.25)	154 (30.1)
F5-F4	140 (24.9)	13 (2.9)	127	140 (24.9)	13 (2.9)	127	76.5 (13.9)	76.5 (13.9)
F5-F3	296 (27.7)	198 (20.7)	128	346 (32.3)	198 (20.7)	148	247 (24.2)	272 (26.5)

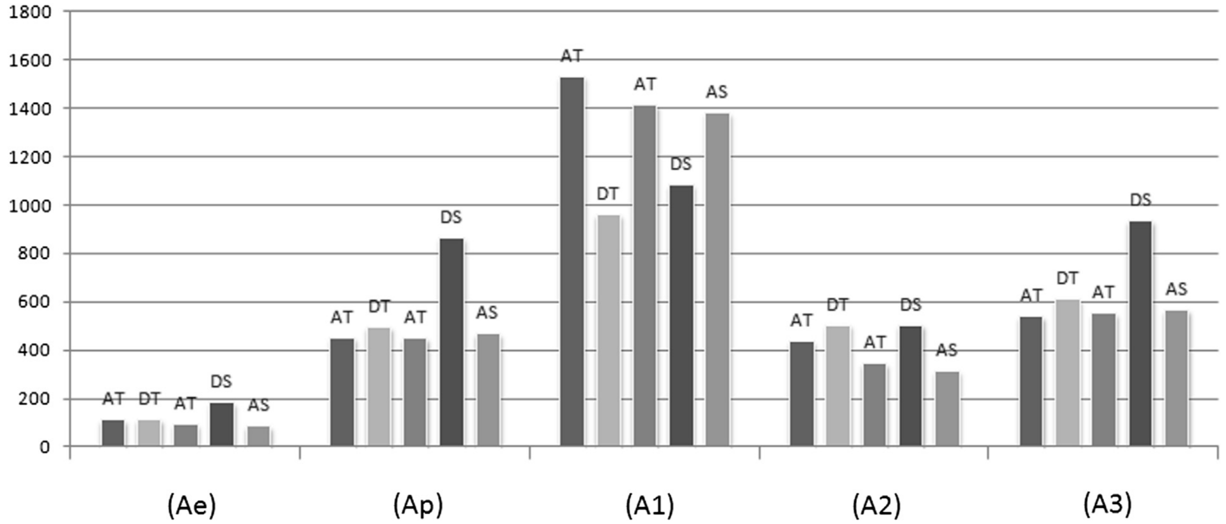

FIGURE 7. Mean of the two repeated scans for the cross-sectional areas (mm^2) calculated from the midsagittal and transversal images of the vocal tract obtained from the CT measurements performed before, during, and after tube and straw phonations. For definitions of the areas, Ae, Ap, A1, A2, and A3, recall Figures 2 and 3. BT, before tube; DT, during tube; AT, after tube; DS, during straw; AS, after straw.

straw. Epilaryngeal region demonstrated small changes after tube (2.4%) and after straw (5%) (Figures 5 and 6). The mean differences between phonation before compared with phonation during and after tube/straw were greater than the differences between repetitions for most of the area measurements. More detailed numerical information about CT distances and area measurements are presented in the Appendix.

Acoustic analysis results

Table 1 shows the results of acoustic analysis of vowel [a:] pre- and posttraining with tube and straw for LTAS and FFT. Some of the LTAS measures (SPL and F1 energy) did not change substantially after tube and straw phonations as compared with phonation before training (less than 1.6 dB; 4%). The major change was observed in SPR, which decreased after both tube (2.5 dB; 12%) and straw (4.4 dB; 22%) phonations, the difference being larger after straw. The energy in the speaker/singer's formant cluster region increased in average 2.5 dB after straw (Figure 11). The mean differences between phonation before compared with phonation after tube/straw phonation were greater than the differences between repetitions for SPR and the energy in the speaker/singer's formant cluster region (Table 1). Therefore, one may suggest that the reported variations between before and after tube/straw phonations are true differences.

Formant frequencies values from F1 to F5, distances between F2-F1, F3-F2, F4-F3, F5-F4, and F5-F3 before and after training with tube and straw, and the differences in hertz and percentage of the formant frequency distances are also showed in Table 1. The most evident change related to formant frequencies in the different phonations is found in F1 values. It decreased after both tube and straw by 12% and 14%, respectively. Changes in the rest of the other formant frequencies measured were smaller than the change found in F1 (8% for F2, 4% for F3, 8% for F4, and 9% for F5). It is interesting to note that all formant frequencies of vowel [a:] became lower after both tube and straw training. From Table 1, it is possible to point out that the clearest change was found in F4-F3 distance difference. F3 and F4 were closer to each other after exercising with both tube and straw. The difference was in average 170 Hz (36.2%) and 154 Hz (30.1%) after tube and straw, respectively. This formant cluster between F3 and F4 was located in 2588–2930 Hz and 2603–2966 Hz after tube and straw, respectively.

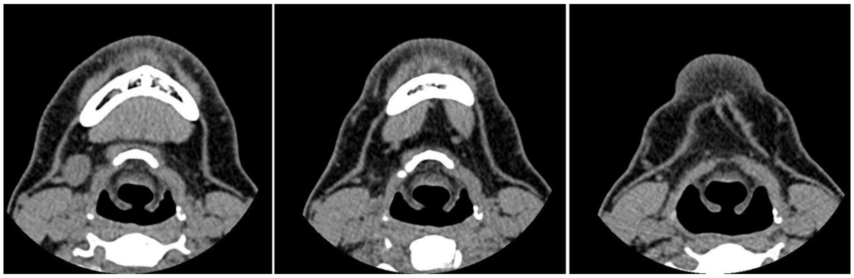

FIGURE 8. Transversal images of the vocal tract. Before tube/straw (left), during tube (middle), and during straw (right). Ap increased during both tube and straw phonations compared with vowel phonation. This increment was clearly larger during straw phonation than during glass tube phonation.

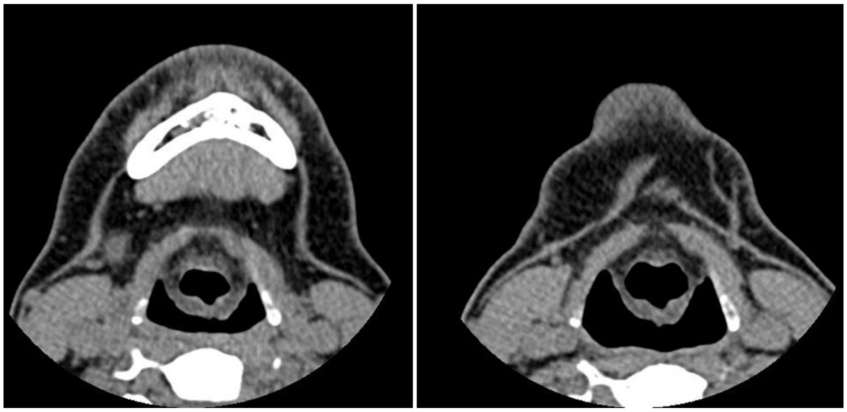

FIGURE 9. Transversal images of the vocal tract. Before straw (left) and during straw (right). The Ae area became larger during straw phonation.

The average F_0 measured throughout the sequence was 113 Hz with a range of 111–115 Hz.

Auditory-perceptual analysis

Table 2 displays the results of the listening test. Data show that there is a high degree of agreement among listeners for straw phonation samples. All the samples produced after straw exercises were evaluated by the four judges as better in voice quality than the samples before. Assessment for tube phonation did not show the same degree of agreement found in straw phonation recordings.

Air pressures and CQ

Subglottic pressure, oral pressure, transglottal pressure, and CQ values before, during, and after tube and straw phonations are presented in Table 3. There was an increase of subglottic pressure during straw phonation (18%), and this increment remained after removing the straw (7%). Subglottic pressure value did not demonstrate a significant change during tube phonation and became higher after tube phonation (6%). There was also an increase of oral pressure during both tube and straw phonations. Transglottal pressure decreased during both tube and straw phonations. Oral pressure increased 17 times more during a straw than a tube phonation, and transglottal pressure decreased about two times more during a straw phonation.

Glottal CQ decreased during both tube and straw phonations 4.5% and 20%, respectively. This change remained both after tube (8.3%) and after straw phonations (9.2%). Figure 12 shows representative EGG waveforms from the samples before, during, and after straw phonation.

DISCUSSION

One of the major differences observed between samples before and both during tube and during straw phonations is the increase in the vertical length of the vocal tract, which reflects a lower VLP and also a larger overall vocal tract length. This change remained during vowel production after tube and straw phonations. Findings from the acoustic analysis are concordant with the CT results. FFT showed a decrease in the frequency of the first five formants. According to the acoustic theory of speech, the formant frequencies depend on the length of the vocal tract and the cross-sectional shape of the vocal tract as a function of its length.[40,41] Vocal tract length determines the average location of formant frequencies. In this regard, as length increases, the value of the formant frequency will decrease. In a previous study performed with MRI, similar results were observed in a male subject who lowered the larynx after vocal warm-up with spoken exercises.[38] On the other hand, in two MRI studies performed with a female participant,[37,38] no changes were reported in the VLP neither after straw phonation nor after other semi-occluded vocal tract exercises ([ß:], [m:], [y:], and [u:]). It is important to point out that both the male subject from the present study and the male subject from the earlier MRI investigation[38] have classical singing voice technique, whereas the female participant has a long experience in speaking voice training. Because the classical singing is produced with a “covered” sound which implies a longer vocal tract due to a lower VLP and lip protrusion,[42,43] it is possible to question whether the lowered VLP demonstrated by our subject is due to the effect of tube phonation or not.

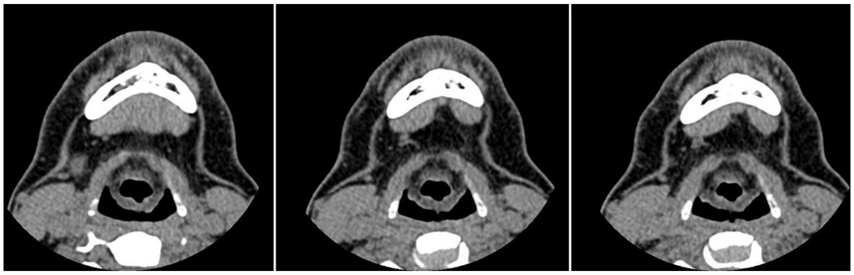

FIGURE 10. Transversal images of the vocal tract. Before tube/straw (left), after tube (middle), and after straw (right). Ae area became smaller after tube phonation and even more after straw phonation.

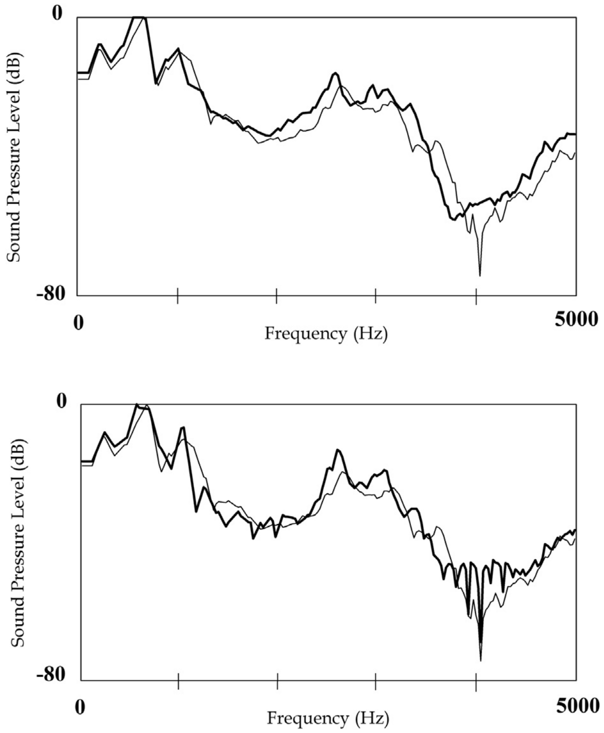

FIGURE 11. Top: comparison between LTAS of vowel [a:] before (thin line) and after (thick line) tube phonation. Bottom: comparison between LTAS of vowel [a:] before (thin line) and after (thick line) straw phonation. The energy of the singer/speaker's formant region increased after exercising, especially after straw phonation.

An important aspect that may be regarded is that the tube or straw may make the perception of vibratory sensations stronger and incite the subjects to change the vocal tract and glottal setting in such a way that it is prone to intensify and pertain these sensations. Therefore, the adjustments could be modified according to the previously learned voice patterns, which are regulated by the voice use type (speech or singing or different styles of singing). According to Titze, the origin of vibratory sensations in resonant voice could be due to the efficiency on the energy conversion process at the glottis (from aerodynamic to acoustic energy). When this process is efficient, the vibrations are distributed all over the face and head areas. On the other hand, when the energy conversion process is poor, the vibrations will remain mostly in the laryngeal area.[15]

In earlier investigations performed with other assessment methods, there is evidence for both the effects, laryngeal lowering and laryngeal raising compared with the resting laryngeal position. Some studies have evidenced a lower VLP during semi-occluded tasks,[40,44] whereas others have reported the opposite.[23,34] Because people diagnosed with hyperfunctional dysphonia commonly present a high VLP due to the abnormal contraction of suprahyoid muscles,[46] semi-occlusions and lengthening of the vocal tract might have an important therapeutic effect if they really produce a laryngeal lowering. In this regard, according to Sovijärvi et al,[47] the positive outcomes of the resonance tube method are due to the efficient lowering of the larynx and the firming of the vibration of the vocal folds. The author pointed out that the length of the tube should be chosen according to the lowering of the larynx during the tube phonation.[1–48]

Later also Simberg and Laine[5] stated that to choose the tube that best enhances the lowering of the larynx during the phonation is an important factor. Both Sovijärvi and Simberg and Laine used tubes submerged into the water (water resistance therapy). It is important to mention that tube phonation has not only been used in cases of hyperfunction as mentioned but also in patients with hypofunctional dysphonia.[5,47] As it comes to the amount of laryngeal lowering, Sovijärvi[49] remarked that it may just be some millimeters or rather avoidance of raising the larynx, so the aim of the method was not to cause a similar laryngeal lowering as in classical singing.

The velum position was another important vocal tract modification in the present study. It rose to seal the nasopharyngeal port during and after the tube and straw phonations. Our results are concordant with previous investigations carried out with MRI and CT.[37–39] A suitable explanation for this change could be the increased oral pressure produced during semi-occluded vocal tract postures.[3,19] The oral pressure measured in the present study during both tube and straw phonations was higher than during vowel production.

An improved energy transfer by decreasing the damping caused by the nasal tract and hence an increase in the total SPL may be expected with a proper velar closure.[37] Nevertheless, our findings did not show an SPL increment after tube/straw phonation. This lack of change is probably because the participant was required to produce the same loudness level during vowel production before and after exercising to avoid spectral changes merely caused by intensity increments. Related to this, the energy of F1 did not show important changes

TABLE 2.
Auditory-Perceptual Assessment of Voice Quality in Vowel Production Before and After Tube and Straw Phonations

Sample	Before Tube	After Tube	No Difference	Before Straw	After Straw	No Difference
Sample 1	1	2	1	0	4	0
Sample 2	2	2	0	0	4	0
Total	3	4	1	0	8	0

The numbers indicate the amount of listeners regarding which sample in each pair was produced with a better voice quality or if there was no difference between them. Listeners n = 3 in total.

TABLE 3.
Subglottic Pressure, Oral Pressure, Transglottal Pressure, and CQ Before, During, and After Tube and Straw Phonations

	CQ (%)	Psub (cm Water)	Poral (cm Water)	Ptrans (cm Water)
Before tube and straw 1	58.5	9.6	0.2	9.4
Before tube and straw 2	56.2	10.1	0.2	9.9
During tube 1	52.6	6.1	0.6	5.5
During tube 2	57.4	7.8	0.7	7.1
After tube 1	53.3	9.4	0.2	9.2
After tube 2	52.2	11.2	0.2	11.0
During straw 1	42.2	10.9	5.6	5.3
During straw 2	49.9	12.2	8.5	3.7
After straw 1	51.8	10.0	0.2	9.8
After straw 2	52.8	10.9	0.2	10.7
Mean before tube and straw	57.6	9.8	0.2	9.6
Mean during tube	55,0	6.9	0.6	6.3
Mean after tube	52.8	10.3	0.2	10.1
Mean during straw	46.1	11.6	7.0	4.6
Mean after straw	52.3	10.5	0.2	10.3

during the sequence either. This is not surprising because the spectral energy of F1 region supports most of the overall SPL.

Because velum elevation has been found, through MRI examination, to be a common modification in classical singers during singing,[50–53] it could be argued that the higher velum position in the present study may be due to the classical vocal background of our participant. Nevertheless, previous radiological studies have demonstrated the same modification when using artificial vocal tract lengthening with a tube in subjects who have an extensive experience teaching speaking voice technique.[37,38] Therefore, phonation into a narrow tube may be a useful tool for the treatment of hypernasality as previously reported for using a narrow tube in air or a resonance tube in water.[4,54]

CT transversal images demonstrated a clear tendency that the ratio Ap/Ae increases during and after both the tube and straw phonations. Ap/Ae has been suggested to be an important factor for the singer's formant cluster production (a prominent spectrum envelope peak near 3 kHz associated with the "ringing" voice quality). Sundberg[55] suggested that when the cross-sectional area in the pharynx is at least six times wider than that of the laryngeal tube opening, the epilaryngeal tube is acoustically unlinked from the rest of the vocal tract acting as a separate resonator. Therefore, an extra formant would be added to the vocal tract transfer function. If additionally the sinus of Morgagni is wide, this extra formant would be tuned between the third and fourth formants. Furthermore, if the sinus piriformis are wide, the fifth formant would lower down to about 3 kHz.[55] These three things can be reached by lowering of the larynx.

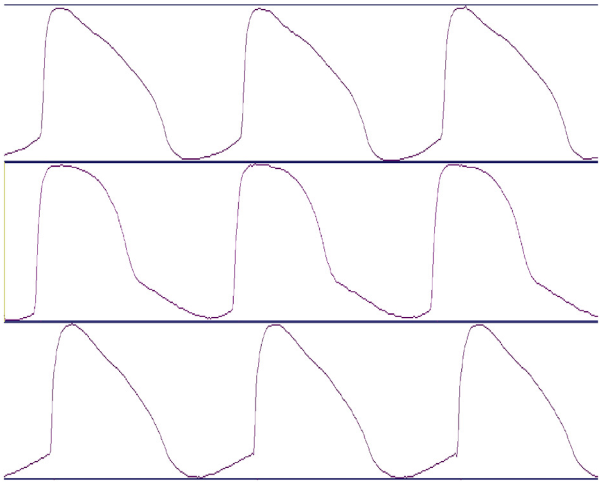

FIGURE 12. Representative EGG waveforms from the samples before (top), during (middle), and after (bottom) straw phonation. Horizontal axis is time and vertical is impedance (increasing downward).

In the present study, the greatest Ap/Ae ratio was observed after straw phonation (5.5), which is close to the value suggested by Sundberg (6).[55] Interestingly, acoustic results of the present study showed the largest increase in the energy of the speaker/singer's formant cluster region after straw. Additionally, the SPR showed the largest decrease after straw phonation as well. Recall that SPR is a spectral measurement created originally for quantifying the singer's formant.[56] Therefore, if the singer/speaker's formant region demonstrates more energy after exercising, it is expected that SPR value will be lower. Thus, it is possible to state that the outcomes obtained from CT are in line with acoustic analysis results. These data suggest a clear immediate effect on spectral characteristics after straw phonation, specifically an increased spectral prominence in the singer's/speaker's formant region and also a change in the spectral slope declination (ie, less steep slope). Values of SPR after straw represent an increased energy in the higher harmonics of the spectrum compared with the lower ones. The increase of SPL in the singer/speaker's formant region has also been reported after tube phonation in earlier works.[37–39] Furthermore, two studies[30,31] whose aim was to compare the effect on spectral energy distribution of semi-occluded vocal exercises and open vowel exercising demonstrated that sustained vowel production after phonation into stirring straws and vocal function exercises (voice program which involves semi-occlusions)[57] produced more spectral energy increase in the higher part of the spectrum (2000–5000 Hz) than vocalizations with open vocal tract setting. The acoustic differences between tube and straw phonations found in the present study (more increase of SPL in the singer/speaker's formant after straw than tube) seem to be in line with the results of the listening test. All samples after straw phonation were rated as representing a better voice quality by all the listeners. Assessment for tube phonation did not show the same degree of agreement as found in straw phonation recordings.

As mentioned above, the singer/speaker's formant, in general terms, can mainly be explained as a resonatory phenomenon arising from a clustering of third, fourth, and fifth formants. According to our findings, there was a clear cluster of F3 and F4 after exercising with both a glass tube and a straw. This formant cluster of F3 and F4 was located in 2500–3000 Hz for vowel [a:] after exercising. F5 also showed a decrease, and the frequency difference between F5 and F4 was smaller after tube/straw phonation as compared with vowel production before them. However, this change was not as clear as the change in F4-F3. A significant decrease in the formant frequency distance after straw phonation was also found by Laukkanen et al.[37] This formant cluster may have contributed to the changes mentioned above (lower SPR and higher SPL between 2500 and 4000 Hz).

According to Sundberg,[55] the larynx lowering, typical of male classical singing, seems to be a way to obtain a high ratio between the cross-sectional area of the low pharynx and the epilaryngeal tube opening and drawing the higher formants F3-F5 closer to each other. Therefore, the lowered VLP observed during and after both tube and straw phonations in the present study might be the physiological cause of the strengthening of the singer's formant cluster range showed by our participant. However, if a low VLT is desirable to produce a singer's formant, how can it be explained that without a laryngeal lowering it is also possible to observe a formant cluster in vocally trained speakers[37,38] There are some differences between the singer's and speaker's formant cluster. The former is usually located between 2 and 3 kHz, whereas the later is produced between 3 and 4 kHz.[55,58] The lower frequency of this peak in singers may be related to lowering of the larynx.[55] On the other hand, the VLP change does not seem to be the main cause of the speaker's formant. Previous studies suggested that a speaker's formant could be obtained through a slight narrowing of the epilaryngeal region, widening of the back of the mouth cavity, and narrowing of the front part of it.[58,59] The modeling results by Leino et al[58] suggest that these two modifications may be responsible for the peak at 3.5 kHz showed in male actors. In addition, there is empirical evidence that vocal tract changes other than laryngeal lowering are able to produce a spectral prominence and a brilliant singing voice quality.[60,61]

Regarding the increase of SPL in the singer/speaker formant region, it is important to point out that not only a formant clustering could be the explanation for this change but it could also be explained by increased input impedance of the vocal tract, for example, due to the higher Ap/Ae ratio. Higher input impedance produces a faster cessation of the glottal flow and consequently a less tilting spectrum and a more resonant voice quality[9] (as found in the present study after straw) and easy voice production.[34] Therefore, both a resonance strategy (formant cluster, possibly only due to changes in the vocal tract length and thus formant frequencies) and increased aerodynamic-acoustic interaction of the vocal tract might contribute to a louder voice without increasing the vocal effort. These resonance and acoustic-aerodynamic changes are desirable effects for both vocal warm-up and voice training. A change in the lower vocal tract may simultaneously cause these both.[10] In addition, an increase of subglottic pressure after straw phonation (as found in the present study) would also be a possible explanation for somewhat higher SPL in the singer/speaker's formant region. An SPL rise of 1 dB is typically associated with a 1.5 dB difference near 3000 Hz in the LTAS.[62] However, in the present study, SPL was controlled to be the same before and after exercising, and there was an increase of just 0–1.1 dB between the samples before and after exercising, whereas the energy of the singer's formant cluster increased up to 2.8 dB after the straw.

The CQ values decreased during both tube and straw phonations and remained lower after them as compared with vowel phonation before them. This change was larger for straw than tube phonation. Several studies have reported a change in CQ when semi-occlusion is compared with vowel phonation.[2,3,20–26] However, only some of them have demonstrated a decrease. There is no clear pattern regarding the effect of semi-occlusion or lengthening of the vocal tract on CQ_{EGG}. From the theoretical point of view, an important effect of straw phonation, voiced bilabial fricative and also tube phonation when the tube is submerged into water is the resistance against airflow. This will produce an increased supraglottal pressure, which consequently will cause a decrease of the transglottal air pressure (the force driving vocal fold vibration) as found in our data during both tube and straw and an elevation of the intraglottal pressure if not compensated by increasing subglottic pressure and adduction. Increased intraglottal air pressure, in turn, would produce a lower CQ.[3,17,19] Titze[19] stated that a semi-occluded setting (especially during phonation into a thin straw) may produce a slight separation of the vocal folds and hence a smaller CQ. If this really occurs, it is possible to assume that occlusions of the vocal tract might be beneficial to decrease the vocal fold impact stress. When the vocal folds impact stress increases (due to more intense vocal folds collision), the CQ tends to rise and *vice versa*.[63] However, it is not a strictly linear phenomenon.

Another possible explanation for the decreased CQ during and after tube/straw phonation could be the low VLP. Earlier studies have shown that a low VLP has also been correlated to low glottal CQ.[64,65] Therefore, it seems to be that lower VLP is associated with less glottal adduction. This phonatory effect might be due to an abductive component of tracheal pull when the larynx is low.

During straw phonation, not only the lowest CQ but also the highest subglottic pressure across the three stages of the sequence (before, during, and after) was found. Increased subglottic pressure has also been reported in a previous study carried out with stirring straw phonation.[3] Earlier research has shown that impact stress increases with lung pressure, that is, the impact stress is higher at higher lung pressure values.[66,67] However, in the present study, a high subglottic pressure was observed seemingly without increment of impact stress. This assumption is based on the fact that low CQ was obtained during straw. What drives the vocal folds is the transglottal pressure, that is, the difference between the subglottal and the supraglottal pressure. As mentioned above, a downstream occlusion increases the supraglottal air pressure and reduces the transglottal air pressure, which in turn reduces the adductive force. Occlusion of the vocal tract makes it possible to lower the transglottal pressure (which is desirable) even if the subglottal pressure is high. In this regard, Titze et al[3] mentioned that with narrow straws, high subglottal pressure can be reached without a high risk of vocal fold impact stress.

Interesting modifications were also observed in the pharyngeal region. First, the Ap area increased during both straw and tube phonations compared with vowel phonation before them (Figure 8). Second, and related to the first one, anterior-posterior width of the hypopharynx became wider during straw phonation (Figure 6). Moreover, the pharyngeal region area (A2) showed an increase during both tube and straw phonations as compared with vowel production before exercising (Figures 5 and 6), and finally, the epilaryngeal region area (A3) became larger during both glass tube and straw phonations (Figures 5 and 6). All these modifications were larger during straw than tube phonation. An important therapeutic application could arise from these observations: the widening of the pharyngeal area in people with vocal hyperfunction. Vocal hyperfunction is considered as excessive and/or imbalanced use of muscular forces, which is characterized by excessive laryngeal and extralaryngeal tension.[68–70] One of the common features treated by voice therapists in patients diagnosed with excessive muscle tension is the relaxation of the laryngo-pharyngeal muscles and widening of the vocal tract, especially in the pharyngeal area. The relaxation of this area is also an important goal of classical singing and speaking voice pedagogy. Different exercises to promote an open throat sensation have been one of the most used tools to produce freedom or lack of excessive tension in the area of the throat and a better tone quality in both normal and pathologic voices.[71–73] From our finding, it is possible to state that straw phonation might be an option to produce the same effect. Results from other CT and MRI studies support our findings related to the modification of the pharyngeal area with tube or straw exercises[37–39] The increased oral pressure during straw may push the pharyngeal tissues and maybe it also then has the possibility to aid muscle relaxation in the pharyngeal area.

Different from earlier studies,[37–39] the present investigation did not show neither an increase in jaw opening nor an increase in the lip opening after tube/straw phonation. The previously cited reports[37–39] were obtained from a female subject who has mainly speech training experience, whereas our participant owns a classical singing voice background. This fact could be a suitable explanation for the discrepancy in the results. Because jaw opening and lip opening seem to be directly related in classical singing technique,[50,52,53,74] the lack of changes in both together (jaw and lip opening) in the present study appears reasonable. Nevertheless, this relation (the fact that lip and jaw may go together) should not be taken as a rule for all cases. In earlier studies using tube phonation, it was possible to see lowering of the jaw, which was not directly related to lip opening.[37] A similar movement relationship has been also observed between jaw opening and tongue dorsum height. They vary independently.[52,74] Likewise, our outcomes showed negligible changes for tongue dorsum height after both tube and straw phonations. Moreover, no important changes were observed after tube and straw phonations in A1 area (oral cavity). These results differ from previous MRI and CT studies where oral cavity was found larger after exercises with straw and tube, respectively.[37,38] Last, but not least, midsagittal images also showed a more frontal tongue position during and after tube/straw phonations, which is in line with earlier studies.[37,39] This would imply that the pharyngeal constriction was reduced; however, this implication did not occur in all CT samples in the present study. The change in the tongue configuration could also have affected some vowel formants, especially F2.[75] A more frontal tongue position is supposed to raise F2; however, this acoustic change was not observed in our data.

CONCLUSION

Our results suggest that both straw and tube phonations may have vocal training and vocal warm-up effects, one of the major being an increased spectral prominence in the singer/speaker's formant cluster region. This may be explained by an increase of the ratio between the cross-sectional area of the low pharynx and the area of the epilaryngeal tube opening. The lower laryngeal position observed in the CT images could be a reasonable explanation for this finding. Moreover, listening test demonstrated a better voice quality after straw/tube than before exercising, hence, this finding seem to be in line with the acoustic and anatomic results. Therapeutic effects could also arise from our data such as a better velar closure (as treatment for hypernasality), a widening of the pharyngeal region (as treatment for patients with laryngeal and extralaryngeal muscle hypertension), and possibly a laryngeal lowering (as an exercise for subjects with high larynx position due to vocal hyperfunction). Some of these therapeutic effects have been described earlier.[47,48,54,76–78] Because the changes in the vocal tract, CQ_{EGG}, subglottic pressure, acoustic parameters, and auditory-perceptual findings were greater during and after exercising with the straw than with the tube, it is reasonable to state that more prominent changes are obtained when the vocal tract input impedance during exercises is higher. Considering all the observed effects in the present study, it would be possible to state that vocal exercises with increased vocal tract impedance assist in increasing vocal efficiency and economy (more loudness without an increase of vocal loading due to increased vocal fold collision). In the present study, only immediate results after exercising were obtained, long-term effects still remain to be studied.

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APPENDIX

CT Distances (mm) and Cross-Sectional Areas (mm^2)

Measurements	Before Tube 1	Before Tube 2	During Tube 1	During Tube 2	After Tube 1	After Tube 2	During Straw 1	During Straw 2	After Straw 1	After Straw 2	Mean Before	Mean During Tube	Mean After Tube	Mean During Straw	Mean After Straw
Distance (mm)															
Vertical length	88	87.9	93	95	95	93	106	107	95	96	87.95	94	94	106.5	95.5
Horizontal length	91.9	90.6			90.9	90.8			91.9	91.6	91.25		90.85		91.75
Lip opening	9.7	9.5			9.5	9.5			9.5	9.5	9.6		9.5		9.5
Jaw opening	76.1	83.1	65.9	68.5	75.8	76.6	68.7	69	78.7	79.5	79.6	67.2	76.2	68.85	79.1
Tongue dorsum height	64.7	64.2	61.8	62.1	65.5	66	57.3	55.5	68.4	68.9	64.45	61.95	65.75	56.4	68.65
Oropharynx width	8.8	8.6	8	8.1	7	6.3	6	6.5	5.2	6.1	8.7	8.05	6.65	6.25	5.65
Velum elevation	21.6	19.5	13.9	13.4	16.8	17.4	13.7	13.4	15.8	16.6	20.55	13.55	17.1	13.55	16.2
Hypopharynx width	18.7	18.2	19.5	19.5	19	18.7	26.1	25.8	19.5	18.7	18.5	19.5	18.9	26	19.1
Area (mm^2)															
Outlet of the epilaryngeal tube (Ae)	114	109	110	117	95	91	187	181	84	87	111.5	113.5	93	184	85.5
Inlet to the lower pharynx (Ap)	460	444	495	497	498	404	881	849	471	465	452	496	451	865	468
Oral cavity (A1)	1577	1489	958	964	1478	1353	1083	1087	1367	1393	1533	961	1415.5	1085	1380
Pharyngeal region (A2)	429	444	522	489	377	313	416	594	312	317	436.5	505.5	345	505	314.5
Epilaryngeal region (A3)	547	533	608	616	551	555	933	938	547	587	540	612	553	935.5	567