Effects on vocal fold collision and phonation threshold pressure of resonance tube phonation with tube end in water

Laura Enflo, Johan Sundberg, Camilla Romedahl and Anita McAllister

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Effects on vocal fold collision and phonation threshold pressure of resonance tube phonation with tube end in water

Enflo, L. [1, 2]

Sundberg, J. [2]

Romedahl, C. [3]

McAllister, A.[1]

[1]Dept. of Clinical and Experimental Medicine, Linköping University, Linköping, Sweden
[2] Dept. of Speech, Music and Hearing, Royal Institute of Technology (KTH), Stockholm, Sweden
[3] Speech-Language Pathologist, Stockholm, Sweden

Corresponding author: lenflo@kth.se

Abstract

Purpose: Resonance tube phonation in water (RTPW) or in air is a voice therapy method successfully used for treatment of several voice pathologies. Its effect on the voice has not been thoroughly studied. This investigation analyzes the effects of RTPW on collision and phonation threshold pressures (CTP and PTP), the lowest subglottal pressure needed for vocal fold collision and phonation, respectively.

Method: Twelve mezzo-sopranos phonated into a glass tube, the end of which was placed under the water surface in a jar. Subglottal pressure, electroglottography and audio signals were recorded before and after exercise. Also, the perceptual effects were assessed in a listening test with an expert panel which also rated the subjects' singing experience.

Results: Resonance tube phonation significantly increased CTP, and also tended to improve perceived voice quality. The latter effect was mostly greater in singers who did not practice singing daily. In addition, a more pronounced perceptual effect was found in singers rated as being less experienced.

Conclusion: Resonance tube phonation significantly raised CTP and tended to improve perceptual ratings of voice quality. The effect on PTP failed to reach significance.

KEY WORDS: collision threshold pressure, phonation threshold pressure, semi-occluded vocal tract, EGG, voice therapy, voice training

Introduction

Resonance tube phonation is a voice therapy method introduced by Antti Sovijärvi (1965; 1969, as cited by Simberg, 2007). It is now commonly used in many countries. The procedure is that the patient phonates into a glass tube, sometimes called 'resonance tube'. The tube is held tightly in the lip opening while the other end is either in free air or a few centimeters below the water surface in a jar. In the latter case phonation produces bubbles in the water. The exercise is mostly performed on a sustained vowel and continued for a shorter or longer period, depending on the patient's needs. It is repeated daily during the therapy period and, if needed, also after treatment (Simberg, 2007).

Sovijärvi gathered a considerable experience of the method and noticed that the length and diameter of the resonance tube, as well as the position of the tube end under the water surface were important to the effect on the voice function. He found that the optimal length varied with age and voice type, around 24 cm for 8-10-year-old children, 26 cm for adult sopranos or tenors, 27 cm for mezzo-sopranos and baritones and 28 cm for altos and basses. He regarded an inner tube diameter of 8 mm and 9 mm optimal for children and adults, respectively (Sovijärvi, 1965 & 1969; Simberg, 2007).

Laukkanen and associates have carried out a series of pre- to post- experiments on the effects of resonance tube phonation (Laukkanen, 1992; Laukkanen et al., 1995; Story et al., 2000; Titze et al., 2002; Laukkanen et al., 2007; Laukkanen et al., 2008; Vampola et al., 2011). In these experiments the tube end was held in air. Apart from lowering the first formant frequency, due to the fact that the resonance tube lengthens the vocal tract resonator, resonance tube phonation was found also to be associated with a decrease of fundamental frequency and with an increase of vocal fold contact area. Further, voice quality improvements have been noted, especially in neutral pitch range. However, also increased phonatory effort was observed in three female subjects (Laukkanen et al., 1995). Gaskill and Erickson (2010) found significant changes, both increases and decreases, of the glottal contact quotient (CQ) in 15 vocally untrained males who had repeatedly phonated into a 50-cm glass tube. However, both inter- and intravariability were great. In a recent study on effects of tube phonation in two groups of male subjects, 10 with no vocal training and 10 with classical vocal training, Gaskill and Quinney (2012) noted an increase of CQ during tube phonation in almost all subjects.

The above investigations concerned resonance tube phonation, where the tube diameter typically is about 8 mm. A related method, commonly used in voice therapy, is phonation with a semi-occluded vocal tract (SOVT). The occlusion is produced by an extreme narrowing of the lip opening, or by phonation through a narrow straw. According to Titze (2006), the straw's lowering of the first formant frequency is beneficial to phonation since it "heightens interactivity between the source and the filter". The situation caused by SOVT differs from that produced by resonance tube phonation in that the constriction generates a high flow resistance which produces a constant reduction of the transglottal pressure drop.

Resonance tube phonation with the tube end in a water jar, henceforth RTPW, was originally intended for the treatment of children with rhinolalia aperta (hypernasality); no bubbles will be produced unless the velum is completely closed. However, Sovijärvi claimed that, due to "efficient lowering of the larynx and the firming of the vibration of the vocal folds" (cited by Simberg, 2007) the method had a positive effect also for a number of other diagnoses, such as professional singers' voice problems (Sovijärvi, 1965, quoted from Simberg, 2007), phonastenia (vocal fatigue) (Sovijärvi, 1969), functional dysphonia (Sovijärvi, 1977) and vocal nodules (Sovijärvi et al., 1989, as cited by Simberg, 2007). RTPW has been found useful also as a training method for patients suffering from neurological disorders such as Parkinson's disease. In such cases soft-walled tubes are used and the result is often a slowing down of the voice deterioration (Simberg, 2007). Further, according to Sovijärvi, RTPW also causes a lowering of the larynx and a "stabilization" of vocal fold vibration. However, as yet the specific physiological effects of RTPW, and the mechanisms producing them, have not been scientifically documented.

In order to eject an air bubble when the end of the tube is immersed into water, the oral pressure needs to exceed a certain value, which is determined by how deeply the end is positioned under the water surface. When a bubble has been ejected, the oral pressure will drop. Hence, RTPW creates a pulsatile oral pressure. If the end of the resonance tube is kept two cm under the water surface, an oral pressure of two cm H_2O is needed for ejecting a bubble. Therefore, the pulsating oral pressure will have a peak-to-peak amplitude of two cm H_2O under these conditions. This pulsating oral pressure seems to imply that RTPW produces massage-like effects on the vocal tract walls. Such an effect may be advantageous in patients with hyperfunctional voices; the massage effect would tend to counteract elevated muscle tonus.

Effects of RTPW are demonstrated in Figure 1. It shows the audio, the derivative of the electroglottograph signal (dEGG) and the oral pressure signal together with the envelopes of the audio and dEGG signals. As can be seen in the bottom panel, the oral pressure was modulated by a peak-to-peak amplitude of almost four cm H_2O, a result of placing the tube end four cm below the water surface. Both the audio and the dEGG signals show a modulation in synchrony with the oral pressure signal. While the dEGG amplitude varies in phase with oral pressure, the audio level lags by about 0.9 ms, which corresponds to the microphone distance (0.3 m). An increase of oral pressure is equivalent to a corresponding decrease of the transglottal pressure driving the vocal fold vibrations. The figure shows that an oral pressure increase reduced the amplitudes of both the audio and the dEGG signals. When the oral pressure is reduced, that is, at the moment of bubble release, these same amplitudes increase. Thus the modulation of oral pressure seems to have expected effects on phonation.

RTPW is somewhat related to a group of voice therapy and warm-up methods using flow driven vibration of the tongue tip or the lips, so-called tongue and lip trill exercises (Roy et al., 2001; Titze, 2006). Apart from producing a low frequency oscillation of oral pressure, these methods provide feedback on airflow. This airflow decreases if phonation is changed towards hyperfunctional. An increase of glottal adduction, i.e. a change towards more hyperfuncional phonation, will decrease transglottal airflow which may stop the flow-driven vibrations. Hence these exercises may provide a sensory feedback on phonatory conditions. In addition, the lip trill exercise has been found to decrease CQ (Gaskill & Erickson, 2008) and the same has been found for the tongue trill exercise (Hamdan et al., 2011), even though the opposite effect has also been observed (Cordeiro et al., 2012).

Based on the findings just described it can be assumed that RTPW affects the characteristics of vocal fold vibration. These properties can be analyzed in terms of the phonation threshold pressure, henceforth PTP, which is the lowest subglottal pressure causing such vibration. Titze (1992) developed an equation describing how PTP varies with F0:

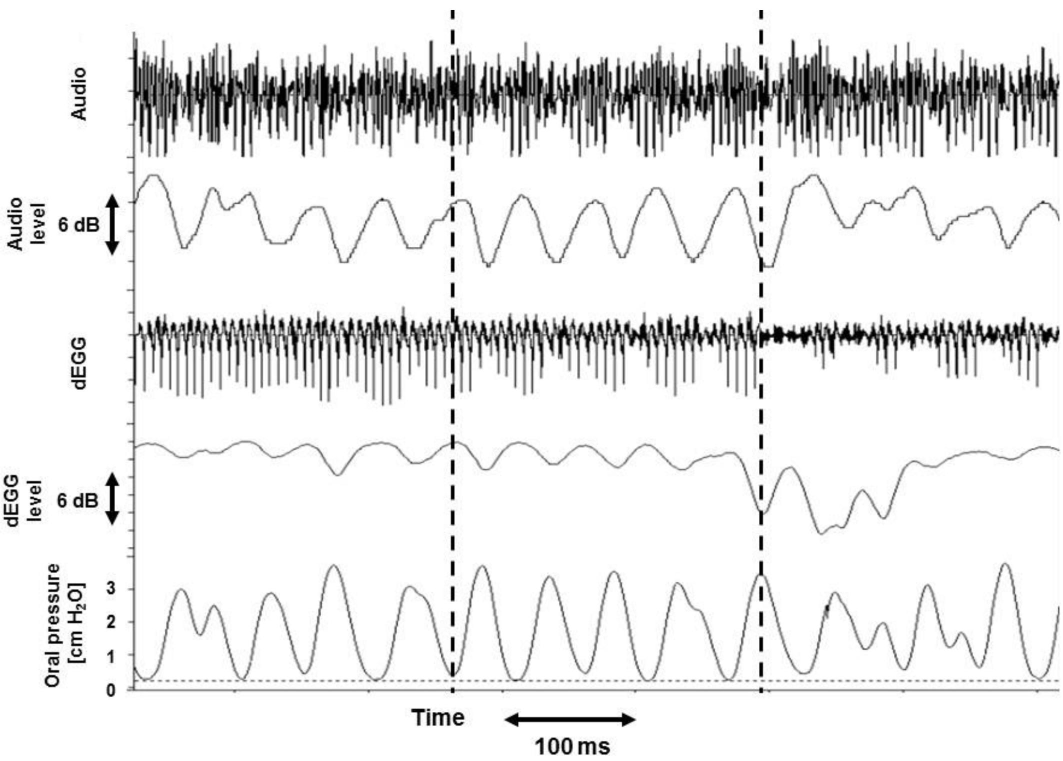
$$PTP = a + b\times(F0 / MF0)^2 \qquad \text{(Equation 1)}$$

where MF0 is the mean F0 for conversational speech. If PTP is measured in cm H_2O the intercept a = 1.40 and the factor b = 0.06. PTP is assumed to reflect the motility of the vocal folds; the higher the motility, the lower the PTP.

However, accurate measurement of PTP is often difficult to obtain due to the very low values. Many subjects, and/or patients, have problems producing extremely soft sounds. As a consequence, PTP analysis is often time-consuming and the data are typically quite scattered (Verdolini-Marston et al., 1990).

Titze (2009) proposed that more reliable PTP data can be obtained by having the subject phonate into a narrow straw, like in the SOVT application mentioned above. He argued that under these conditions, PTP could be measured as the oral pressure during straw phonation and tested the method on ten subjects. Although considerable inter-subject variability was noted, a reasonable degree of agreement with data predicted by

Figure 1: *Audio signal, audio level, dEGG, dEGG level and orally estimated subglottal pressure during the RTPW exercise, observed when the end of the resonance tube was about four centimeters below the water surface.*



Equation 1 was observed. The straw lengthens the vocal tract resonator and affects the glottal input impedance, which alters the vocal fold vibration conditions (Titze, 2006).

Subglottal pressure, (Psub), can be approximated as the oral pressure during /p/ occlusion (see e.g. Löfqvist et al., 1982). This pressure is typically measured with a pressure transducer attached to a plastic tube, which the subject holds in the corner of the mouth. At PTP the vocal folds vibrate with such a small amplitude that they fail to collide, while at slightly higher Psub vocal fold collision normally occurs. Like PTP, the minimal pressure required to initiate and sustain vocal fold collision can be assumed to reflect vocal fold motility. This collision threshold pressure, henceforth CTP, has been measured before and after vocal warm-up and before and after vocal loading (Enflo & Sundberg, 2009; Enflo et al., 2009). The results showed that both PTP and CTP were affected, tending to drop after warm-up, and to rise after vocal loading. The effect of loading tended to be greater in untrained voices than in singers. Moreover, CTP showed a lower inter- and intrasubject variability than PTP, thus suggesting that CTP data are more reliable than PTP data. As vocal fold contact causes a knee in the EGG waveform, such a contact can be easily detected from the dEGG amplitude (Henrich et al., 2004).

Summarizing, the RTPW method has been used for a long time, and reportedly with good results in clinical conditions. This supports the hypothesis that (i) RTPW produces audible effects. Further, RTPW seems comparable to tongue and lip trill exercises, which have been reported to be associated with warm-up effects. According to our previous study, warm-up effects are associated with changes of both CTP and PTP. This supports the hypothesis that (ii) RTPW affects CTP and PTP. Untrained voices tended to show greater effects of vocal loading than singers (Enflo et al., 2009). Hence, it seems reasonable to hypothesize that (iii) the audible effect of RTPW is smaller for subjects who have longer singing training and/or who practice singing daily, and (iv) that the effect of RTPW on CTP and PTP are smaller for these same subjects. The aim of the present exploratory study was to test these four hypotheses.

Method

Twelve female singers volunteered as subjects (average age 31.75 years, standard deviation 5.7 years), see Table 1. They all reported that they were mezzo-sopranos; subjects 1-6 had conservatory education in classical solo singing, subject 7 and 8 studied solo singing privately, while the choral subjects lacked formal training but had extensive experience of high level choral singing. At the time of the recordings none of the participants had any known voice problems or disorders.

Recordings were made before and after RTPW. The subjects repeated the syllable [pa:] in a diminuendo starting at medium loudness and continuing until voicing ceased with an approximate syllable rate of two per second. The exercise was repeated at F0 values separated by three semitones, starting from E3 (164.8 Hz) or G3 (196.0 Hz) and ending with G4 (392.0 Hz) or B4 (493.9 Hz), depending on the subject’s comfortable pitch range. These pitches were presented to the subjects, one by one, on a custom-made singing synthesizer software (“MADDE”, Svante Granqvist, KTH). The subjects were instructed to sing the syllable sequence *legato* since this typically promotes flat oral

Table1: *Subjects' age, extent of singing experience and daily practice of singing; more than three years of singing education and amateur or choral experience without formal training. Subjects 1-7 were classically trained soloists. Subject 8 was trained in non-classical styles.*

Subject number	Age [years]	Singing Experience	Daily Practice
1	26	≥3 years education	yes
2	34	≥3 years education	yes
3	29	≥3 years education	yes
4	26	≥3 years education	yes
5	27	≥3 years education	yes
6	32	≥3 years education	yes
7	30	≥3 years education	no
8	29	≥3 years education	no
9	30	choral	no
10	45	choral	no
11	33	choral	no
12	40	choral	no
	Median age: 30		

pressure peaks; a non-constant pressure peak would reflect a non-constant Psub. At least three takes of [pa:]-sequences were recorded for each F0.

During the RTPW exercise, the end of the resonance tube was kept 1-2 centimeters under the water surface in a jar, see left photo in Figure 2. Following Sovijärvi's recommendation for mezzo-sopranos, we chose a 27 centimeters long resonance tube (Sovijärvi, 1969). Likewise, following common tube phonation practice, each subject phonated for a total of two minutes on the vowel [u:] at comfortable pitches of their own choice. Immediately after, and without any intermediate phonation, the

Figure 2: Left: Subject performing the RTPW exercise. Right: Experimental setup for recording of audio, EGG and Psub, the latter captured as oral pressure during /p/ occlusion.

subject produced a new set of [pa:]-sequences using the same procedure and F0 values as before the RTPW exercise. According to co-author CR's clinical experience, audible effects of RTPW often disappear after a few minutes. Therefore, the subjects performed 15 seconds of RTPW before recording each F0. All subjects reported that they felt an improvement of voice function after the RTPW exercise.

The recordings were made in a sound treated booth with the subject in a seated position. Three signals were recorded: audio, oral pressure and EGG (right photo of Figure 2). Audio was picked up by a condenser microphone (B&K 4003, power supply B&K 2812), with amplification set to 0 dB. Oral pressure was recorded by means of a pressure transducer connected to a plastic tube, inner diameter 4 mm, which the subject held in the corner of her mouth (Glottal Enterprises, model MSIF-2). This signal was monitored on an oscilloscope, so that the subject could be notified whenever the pressure peaks were non-flat or tended to be voiced. EGG, collected from the vocal fold contact area output of a Glottal Enterprises EG 2 unit, was recorded using a low frequency limit of 40 Hz. Also this signal was monitored on the oscilloscope. Contact gel was applied to improve signal quality. Each of these three signals was digitized at 48 kHz sampling frequency and recorded on separate tracks by means of the Soundswell Signal Workstation™ software (Core 4.0, Hitech Development AB, Sweden).

The pressure signal was calibrated by recording a few pressure values, all measured by means of a manometer. These values were announced in the recording.

Analysis

Listening test

The effect of the RTPW on voice quality was assessed by means of a listening test performed by a panel of eight voice experts. A PowerPoint test file was prepared with one slide per singer. Each slide contained a set of loudspeaker symbols, one for each F0. Each symbol was connected to a pair of [pa:]-sequences, one recorded before and the other after RTPW; the order within the pair was random. The total number of pairs was 64. In addition, five pairs, randomly selected from each of the F0 values, reappeared in the final slide. By clicking the loudspeaker symbols on the slide the corresponding pair was played over headphones (Sennheiser HD 433, Sennheiser PX 200, Sony MDR-CD480 or Logitech H800). The listeners' task was to mark along visual analogue scales (VAS) if they thought that voice function sounded better or worse in the second [pa:]-sequence. The extremes of the VAS were marked *Much worse* and *Much better,* and the midpoint *No difference*.

After assessing all pairs sung by one subject, the voice experts were asked also to rate the subject's level of singing training by markings on a separate VAS, the extremes of which were marked *Very low* and *Very high,* respectively.

CTP and PTP measurements

Analysis of CTP and PTP was performed using the Soundswell Signal Workstation. The oral pressure during the occlusion for the /p/ consonant was taken as an approximation of the Psub, as described in the Introduction section. Since the oral pressure transducer also picked up some oral sound, it was low pass-filtered at 50 Hz. PTP and CTP measurements were performed on the first three sequences at each F0, unless one or more of them were clearly erratic. In such cases subsequent sequence(s) were measured. In a few high F0 cases, only one or two PTP values could be obtained.

The dEGG amplitude was used as criterion for vocal fold contact, a sudden decrease being interpreted as evidence of disappearing contact. Figure 3 shows a typical example of the signals obtained. CTP was determined as the average of the lowest pressure that generated dEGG spikes (see close-up in Figure 3) and the highest pressure that failed to produce dEGG spikes. The decrease of dEGG amplitude was not always abrupt. This mostly occurred in highly trained voices. In such cases the lowest pressure peak followed by dEGG spikes that continued throughout the tone was considered as lying just above the collision threshold (peak number 8 in Figure 3).

Results

Listening test

Rater consistency was checked in terms of regression analysis of the five paired samples which appeared twice in the listening test. As seen in Table 2, R^2 varied greatly between listeners, from 0.091 to 0.952. For listeners 1 and 6 the very low R^2 values were caused by one single sample pair. In the table, the R^2 values obtained after elimination of these outliers are written within parentheses. The ratings of listener 8 were discarded as the R^2 value remained quite low also after this operation. The portion of the VAS that was actually used by the remaining seven listeners varied greatly, between 41 % and 97 % of the VAS. Therefore, the ratings were normalized with respect to the individual listener's rating range.

Inter-rater agreement was determined by means of Krippendorff's alpha, yielding a concordance of $\alpha = 0.393$ (Hayes & Krippendorff, 2007). The ratings of singing training, on the other hand, generated a higher value ($\alpha = 0.617$).

The listeners heard voice quality differences within the sample pairs, but found it difficult to determine which quality was better. Only in 2.4 % of the pairs the listeners marked no difference and in 57.4 % they rated the sample recorded after RTPW as sounding better. The effect of RTPW was mostly perceived to be stronger for the singers who did not practice daily and for singers without formal singing education, as can be seen in Figure 4a.

The mean ratings of level of singing training are shown in Figure 4b, where the singers are rank ordered according to this mean. The singer's level of training and daily practice is symbolized in terms of colors and patterns. As can be seen, the six singers who received the highest mean ratings all had long experience and practiced daily. Moreover, the five lowest ranked all lacked daily practice and only one of them had long experience. Thus, by and large, there was a reasonably good agreement between rated and actual level of singing training/singing experience.

Figure 3: *Recording of audio, dEGG and Psub for a [pa:]-sequence performed on pitch E3 (165 Hz) and illustrating the method for detecting loss of vocal fold contact, CTP and PTP. In this case CTP was calculated as the average of peaks 8 and 10, since the dEGG signal indicated loss of vocal fold contact between these pressure peaks. Similarly, PTP was calculated as the average between peaks 10 and 11, since the flow signal showed cease of vocal fold vibration between these peaks. The lower panel shows a close-up of the dEGG signal following pressure peak 8 illustrating loss of vocal fold contact in terms of disappearing dEGG spikes (striped arrow).*

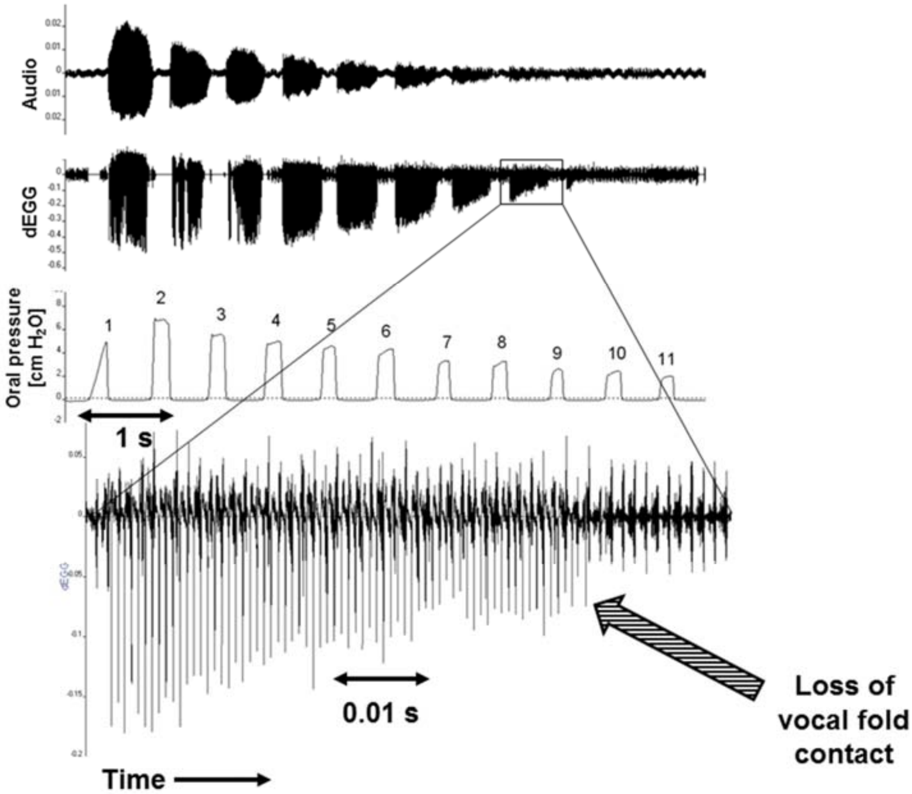
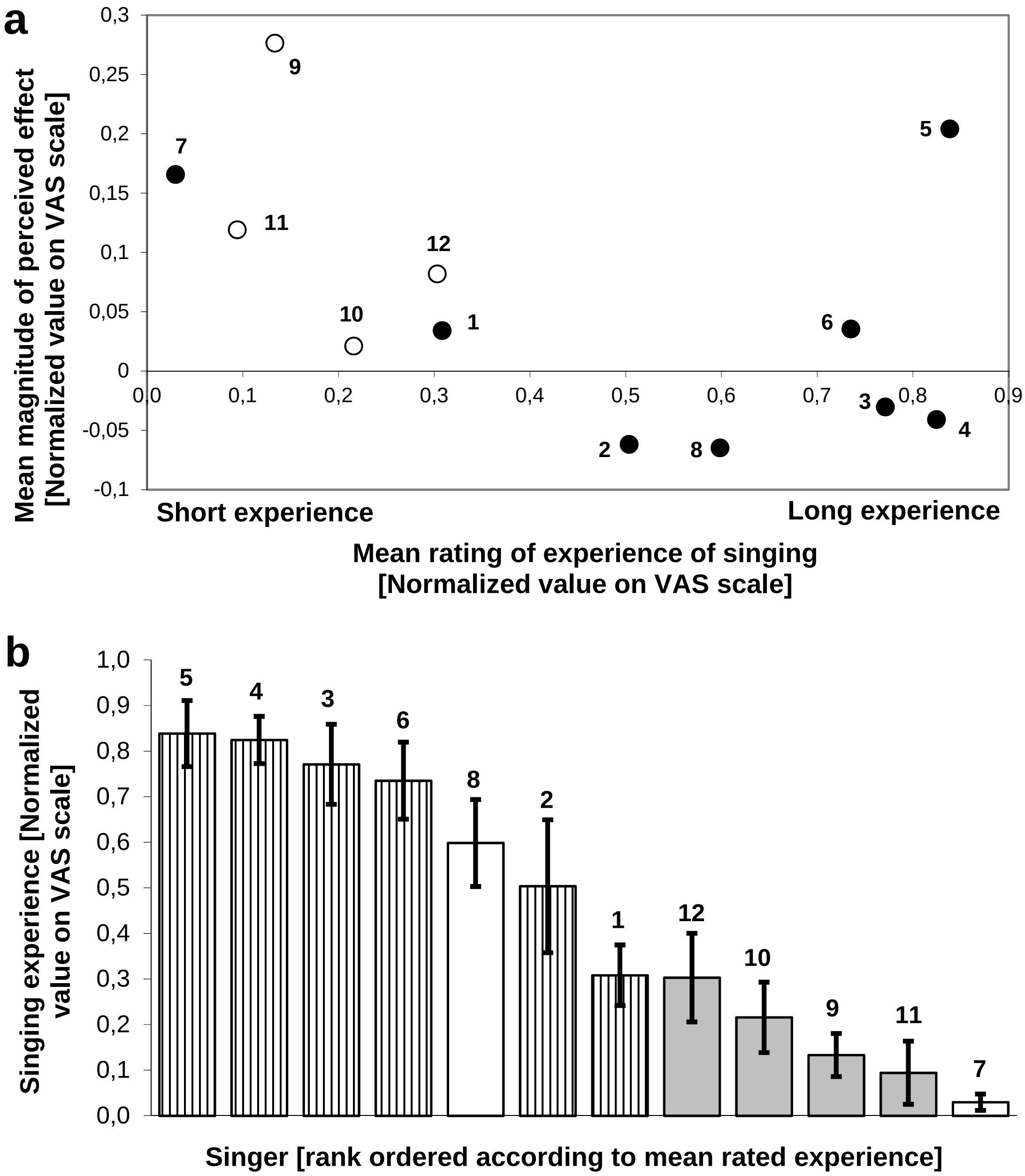


Table2: *Constant of determination R2 for the indicated listeners' first and second ratings of replicated stimuli. Values within parentheses were obtained after one outlier value was removed.*

Listener	R^2 for related stimuli
1	0.092 (0.691)
2	0.506
3	0.930
4	0.689
5	0.838
6	0.269 (0.783)
7	0.952
8	0.091 (0.173)

Figure 4: *a) After-to-before change of the listeners' mean ratings of voice quality plotted as a function of mean rated experience of singing. Both types of ratings were normalized with respect to the individual listener's rating range. Positive values refer to perceived improvement after RTPW. Numbers refer to individual singers (see Table 1). Filled circles refer to singers with more than three years of singing education, and open circles to choir singers without formal singing training. b) Means of voice experts' rankings of the singers' level of singing training. Bars show ± one standard error. The ratings were normalized with respect to the individual listener's rating range. Striped columns refer to singers who were practicing daily and had at least three years of singing training. White and grey columns refer to singers with long and short singing experience, respectively, who did not practice daily. Numbers refer to individual singers (see Table 1)*



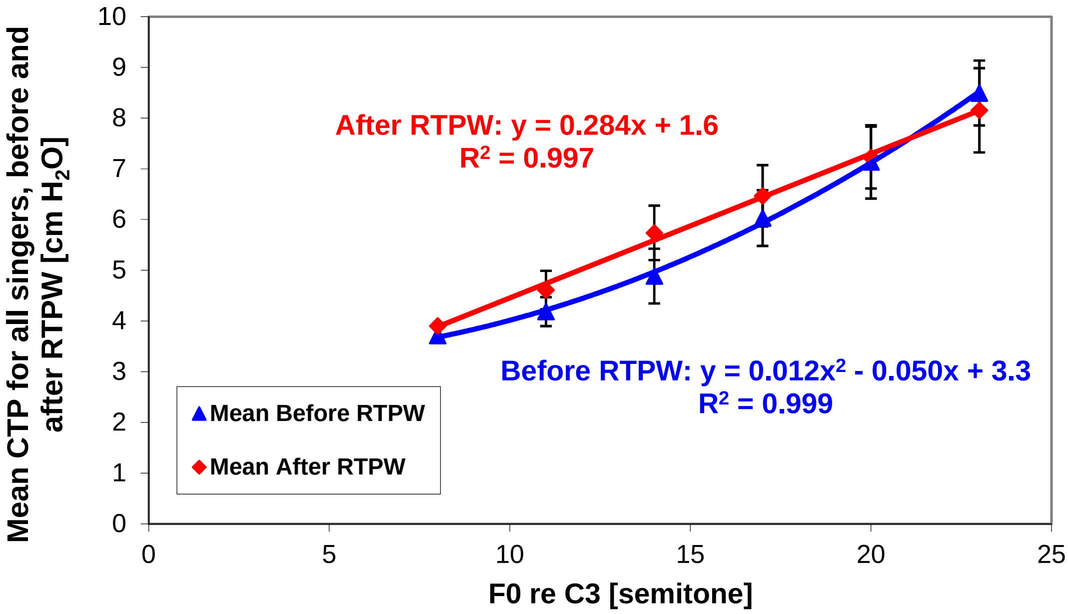
Threshold measurements

CTP before and after RTPW, averaged across all singers, is shown with trendlines in Figure 5. The values are plotted as a function of F0, expressed in the logarithmic semitone unit relative to C3 (130.8 Hz). The CTP before RTPW could be approximated by a nonlinear trendline, but after RTPW more accurately with a linear trendline.

The effect of RTPW on CTP, quantified in terms of the CTP after-to-before difference, was significant (paired sample t-test, *p*=0.011). A repeated measures ANCOVA was carried out to analyze in more detail this result [between-subject factors: singing training (long, short) and daily practice (yes, no); covariate: F0]. The main effect of F0 was significant, $F(1, 732) = 57.75$, $p=.000$, $\eta_p^2 = .295$. However, there were no significant effects of singing training, $F(1, 138) = .496$, $p=.483$, $\eta_p^2 = .004$, nor of daily practice, $F(1,138) = 2.62$, $p=.108$, $\eta_p^2 = .019$. The within-subjects factor (repeated measures) showed a significant effect of RTPW on CTP, $F(1, 138) = 9.677$, $p=.002$, $\eta_p^2 = .066$. Thus, not surprisingly, there was a significant interaction between RTPW effect and F0, $F(1,138) = 7.469$, $p=.007$, $\eta_p^2 = .051$.

The CTP after-to-before difference varied substantially with F0, as expected (Enflo & Sundberg, 2009; Enflo et al., 2009). Therefore, for each singer, the after-to-before CTP ratio was computed and averaged across all F0 values. The results are shown in Figure 6a. On average, this CTP ratio exceeded 1.0 after RTPW, indicating that RTPW increased CTP.

Figure 5: *Mean CTP values, averaged across all singers, before and after RTPW (triangles and diamonds, respectively). The bars represent ± one standard error (no SD is shown for the points at F0=8 semitones, because those values originated from one single subject). Also shown are the trendlines for before RTPW and after RTPW, and their equations.*



As mentioned previously, the relationship between PTP and F0 can be approximated by Equation 1, according to Titze (1992). An attempt was made to approximate the observed PTP and CTP values by modifying the intercept *a* and the factor *b*, which describe the frequency variation, in Equation 1. Minimizing the value of the squared differences

Figure 6a and b: *After-to-before ratio for CTP and PTP, averaged across F0 for each of the singers (panels a and b, respectively). White and striped columns refer to subjects with and without daily practice. The black filled columns show the average for the two groups.*

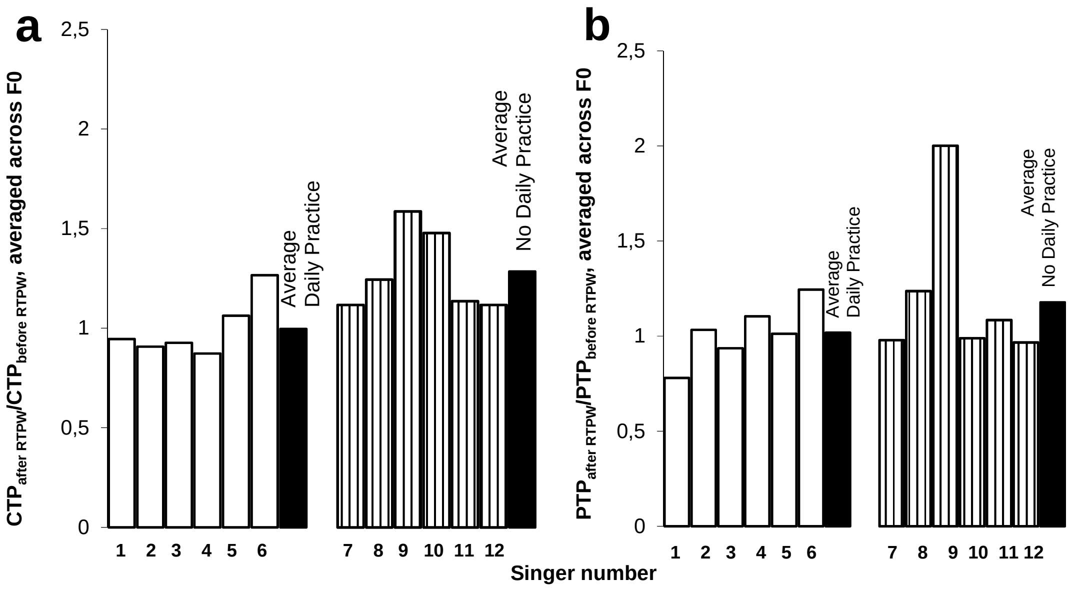


Table 3: *Values of constant a and factor b in Titze's equation (Equation 1), when modified for optimal fit of the data observed before and after RTPW (Bef and Aft). The value used as MF0 for conversational speech in the equation was 190 Hz. For comparison, the corresponding values obtained before and after vocal warm-up for the pitch range F3 to A4 are also listed (Enflo & Sundberg, 2009). The summed squared differences between observed values and the values obtained with the equation are given in the rightmost column.*

	a	b	Sum of squared differences
Titze PTP	1.40*	0.60	
RTPW			
PTP Before	1.70	0.50	0.05
PTP After	1.76	0.50	0.34
CTP Before	2.70	1.00	0.19
CTP After	4.20	0.70	1.60
Vocal warm-up			
PTP Before	0.18	0.60	0.19
PTP After	0.42	0.40	0.05
CTP Before	5.00	0.70	0.36
CTP After	4.50	0.90	0.67

* Enflo & Sundberg (2009) erroneously listed this constant as 0.14.

between observed and calculated values was used as the optimization criterion. Table 3 shows the results. Also shown in Table 3 are the corresponding values observed in the previous investigation of the effect of vocal warm-up. Titze's equation approximates our results rather closely in many cases, as shown in the summed squared difference column. For example, for PTP before RTPW both *a* and *b* were similar to those given by Titze. On the other hand, *a* was considerably higher in the present study than in the vocal warm-up investigation. However, the constant *a* is the intercept (in cm H_2O) and PTP values are low and therefore – in reality – the discrepancy is minute.

With respect to PTP, no significant effects of RTPW were found. Thus, the PTP after-to-before difference was non-significant (paired sample t-test, p=0.054). A repeated measures ANCOVA [between-subject factors: singing training (long, short) and daily practice (yes, no); covariate: F0] revealed a significant effect only of F0, $F(1, 732) = 39.59$, $p=.000$, $\eta_p^2 = .223$, but no significant effects of singing training, $F(1, 138) = .111$, $p=.740$, $\eta_p^2 = .001$, nor of daily practice, $F(1,138) = 1.88$, $p=.173$, $\eta_p^2 = .013$. The within-subjects factor (repeated measures) showed non-significant effect of RTPW, $F(1, 138) = 1.236$, $p=.268$, $\eta_p^2 = .009$, and the interaction between RTPW effect and F0 was also non-significant, $F(1,138) = 1.903$, $p=.170$, $\eta_p^2 = .014$.

As with the analysis of CTP, the after-to-before ratio was computed and averaged across F0 also for PTP. The results are shown in Figure 6b. As can be seen in the figure, the effects varied considerably between subjects.

Discussion

Our results confirmed two of the hypotheses mentioned in the introduction. Expert listeners perceived an improvement of voice quality after RTPW and the improvements were particularly marked in singers who were rated as less experienced and who did not practice daily. It seems likely that singers who practice daily reach an improved every-day phonatory condition that is not likely to be further improved with a short and simple exercise.

The two remaining hypotheses concerned effects of RTPW on CTP and PTP. Our main finding was that CTP increased significantly after RTPW. PTP was also found to increase, although the effect failed to reach significance. There was no significant difference in the effects observed in subjects who had and lacked daily singing training and who had and lacked long singing education. The CTP increase after RTPW was unexpected, and needs to be viewed against the background of previous research.

Laukkanen and colleagues (1995) studied the effect of resonance tube phonation in three female and two male non-singer subjects. The tube dimensions were similar to those used in the present study but the tube end was in air. With respect to the female subjects, the amplitude of the EGG signal increased after tube phonation. This suggests a larger vocal fold contact area and thus, presumably thicker folds. Such an effect may be caused by a larger blood flow in the vocal fold tissues. The considerable variation of oral pressure caused by RTPW is likely to impart a massage-like effect on these tissues and massage has been found to increase blood flow (see e.g. Goats, 1994). It seems reasonable to assume that increased blood flow increases the mass of the folds, making them thicker and thus raising CTP which, in turn, changes needed muscle activity.

The duration of RTPW used in the present investigation was two minutes before the first recorded F0 and, after that, 15 seconds before each recording of the remaining F0. The tube end was held at a depth of 1-2 centimeters during the exercise. We chose this depth and duration in accordance with the considerable clinical experience of co-author CR. In previous investigations shorter durations have generally been used. For example, Laukkanen and collaborators (2008) and Gaskill and Quinney (2012) used only about one-minute phonation in their studies which concerned phonation with the tube end in air. As the effects of RTPW have not been experimentally analyzed before, it seemed advisable to follow experience from clinical practice.

An increase of CTP was found also after vocal loading (Enflo et al., 2009). This poses the question whether RTPW sessions may cause vocal fatigue. However, the effects of the vocal loading experiment seem to differ importantly from those gained in the present study. First, fatigue tends to impair voice quality but in the present experiment voice quality improved after RTPW according to the listening test. Second, all non-singer subjects who participated in the vocal loading experiment reported that they perceived vocal fatigue, while in the present study the singers reported that phonation became more comfortable. It should also be mentioned that the CTP increase after vocal loading was much greater than that after RTPW, about 20% as compared to 6% in the present study. These differences support the conclusion that the effect of RTPW was an improvement of phonatory function. It seems plausible that a rise of CTP may result from two effects, (1) a remaining stiffening of vocal fold tissues caused by vocal loading, and (2) from an increase of vocal fold mass caused by an increased blood flow.

Conclusion

The present study has shown that RTPW produces a pulsating oral pressure of a magnitude determined by the position of the tube end under the water surface. According to perceptual ratings by expert listeners, RTPW caused audible improvement of voice quality. The effect was more pronounced in singers rated as being less experienced. RTPW was found to significantly increase CTP. The reason is not clearly understood, but a plausible explanation is that the pulsating oral pressure has a massage-like effect on the vocal tract walls, including the vocal folds, likely to change their bio-mechanical properties. Further experimentation and modeling work is needed to elucidate the effects of RTPW on phonation.

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