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# Water Resistance Therapy as Vocal Warm-Up Method in Contemporary Commercial Music Singers

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**Keywords**
Acoustic and electroglottographic measures · Aerodynamic measure · Singing · Voice training · Warm-up · Semi-occluded vocal tract · Water resistance therapy

**Abstract**

***Background/Aims:*** Although water resistance therapy (WRT) has been widely used in voice training, no data are supporting the effectiveness of WRT as vocal warm-up for singers. The present study aimed to determine the effects of WRT as a vocal warm-up method in contemporary commercial music (CCM) singers. ***Methods:*** Twenty-two CCM singers were randomly assigned to one of two types of 15-min vocal warm-up: open vocal tract (OVT) warm-up and WRT. Self-perceived resonant voice quality and aerodynamic, electroglottographic, and acoustic measures were assessed before, immediately after vocal warm-up, and after 40 min of vocal loading. ***Results:*** Significant results were found immediately after vocal warm-up. Subglottic pressure and inspiratory airflow duration decreased in both groups. SPL decreased for the OVT group. No changes in SPL were found for the WRT group. Significant results were observed after vocal loading. Subglottic pressure and inspiratory airflow duration decreased for both groups after vocal loading. Expiratory airflow duration and electroglottographic contact quotient decreased for the OVT group. ***Conclusion:*** Some objective data suggest that the WRT method is more effective as vocal warm-up than OVT exercises. Since outcomes in self-perceived resonant voice quality for both methods were similar but physiological effects were different, vocal warm-up strategies might produce a placebo effect.

## Introduction

Contemporary commercial music (CCM) has been defined as any nonclassical music [1] where specific sound productions, with its respectively specific and several physiological features, are needed to satisfy the artistic demands of each style [2, 3]. Because of the highly physical and vocal demands required from CCM singers, singing teachers and researchers have been concerned about possible vocal health risks [3, 4]. In this context an effective vocal warm-up [5–7] would be necessary in order to prepare a singer's voice production system to reduce vocal risks and vocal fatigue.

Although several studies have focused on the effects of vocal warm-up and its use is widely accepted by voice

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teachers, singers, and researchers, results and conclusions are not conclusive. There is still no clear scientific evidence supporting or disproving the use of vocal warm-up based on physiological effects [6]. Several authors agree that controversy between studies stems from differences in vocal warm-up methodologies used (e.g., type of vocal exercises, vocal warm-up protocols, vocal task duration), as well as the use of different measures and different research designs [5–8]. Despite this controversy, it seems that the vocal warm-up's main effect would be related to a better self-perceived voice quality, vocal comfort and vocal readiness, regardless of the vocal warm-up protocol applied [9–11]. Thus, although several exercises have been developed to warm up singers, it is possible that not all of them would be adequate to promote significantly physiological changes in voice production [12].

### *Water Resistance Therapy*

Semi-occlusions of the vocal tract have been suggested as a group of vocal exercises that generate a high acoustic impedance (inertance) [13, 14], promoting a high vocal efficiency (the ratio between radiated oral acoustic output power to aerodynamic subglottal input power) [15, 16] and vocal economy (the ratio between voice output and intraglottal impact stress) [16–18]. Vocal economy has been associated with vocal health, involving a maximized voice output at the expense of a minimized impact stress [18], which would also lead to a minimal respiratory and muscular effort applied to the larynx (i.e., effortless voice production) [18, 19]. Hence, semi-occluded vocal tract exercises (SOVTE) could be useful as vocal warm-up if vocal economy is considered one of the main goals in voice training [18, 19].

Several types of SOVTE have been used and described in both voice rehabilitation and voice training. The water resistance therapy (WRT) method (a type of SOVTE) [13, 14, 16] consists of phonating different phonatory tasks into a glass tube, keeping the distal end of the tube submerged in water. Research on WRT has suggested the presence of a massage-like effect on vocal folds and vocal tract tissues, and changes in aerodynamic measures, electroglottographic (EGG) contact quotient (CQ), and vocal tract configuration. These effects are assumed to contribute to vocal economy.

### *Massage Effect of WRT*

A massage-like effect has been attributed to WRT because of bubbling produced during phonation into the water. According to Andrade et al. [20], SOVTE can be classified in two different groups considering the presence of a single or a secondary source of vibration: a "steady" group and a "fluctuating" group of exercises, respectively. The secondary source of vibration exercises (e.g., lip trills, tongue trills, and WRT) produce greater fluctuations on CQ and fundamental frequency (F0) values during phonation, compared to the steady group of exercises (e.g., humming, hand-over-mouth, and straw phonation in the air). Previous studies have found a fluctuating EGG signal and a pulsatile supraglottic pressure during WRT, as a result of a secondary source of vibration in the vocal tract (i.e., bubbling). Authors have advanced that fluctuations of supraglottic pressure related to bubbling might modulate vocal fold oscillation and relax vocal tract walls, which could be interpreted as a massage effect [21–24].

An improvement in vocal fold tissue fluid circulation (which may be associated with a healing effect) has also been suggested as a possible benefit of WRT. Enflo et al. [21] suggested that a change in vocal fold tissue physiology occurs immediately after performing WRT at 1–2 cm of depth, as reflected by the increased collision threshold pressure they reported. The massage effect could cause this increase during WRT performance, which would increase blood flow and thicken vocal folds as tissue viscosity increases. They also reported an improvement in voice quality immediately after WRT.

Bubbling frequency during WRT has also been inspected. Some authors have suggested that bubbling frequency is related to the inner diameter of the tubes and flow rate, but not to water depth [23, 25, 26]. Although the physiological effect of bubbling frequency on voice production is not totally understood, it has been proposed that higher oral pressure oscillation (higher amplitude and lower frequency of vibration of the air into the vocal tract) could be related to larger bubbles, which may intensify the massage effect [22, 26]. This, in turn, could be produced when WRT involves wider diameters of the tube [26].

### *Aerodynamic Features*

Changes in subglottic ($P_{sub}$) and oral ($P_{oral}$) pressures during WRT have been reported. Maxfield et al. [27] ranked 13 semi-occluded postures according to intraoral pressure levels. Semi-occlusion showing the highest level of $P_{oral}$ was phonation into a tube submerged 7 cm under water (compared to phonation into a tube in the air and other SOVTE).

Radolf et al. [22] measured air pressure variables in real subjects during resonance tube phonation in the air, tube phonation into the water and stirring straw phonation in the air. They found the highest $P_{sub}$ and $P_{oral}$ values during soft phonation into a tube immersed 10 cm under water, suggesting that a high $P_{sub}$ is needed to produce phonation, due to water depth. Recent studies have shown similar findings [28]. However, in a physical modeling study, Horáček et al. [25] found that under artificially controlled conditions, a narrower straw showed the highest values of $P_{sub}$, offering the highest resistance compared to the tube submerged 10 cm under the water. These results suggested that $P_{sub}$ and $P_{oral}$ depend on the degree of airflow resistance.

Amarante et al. [29] found that $P_{oral}$ needs to overcome the hydrostatic pressure when tubes are submerged in water. Hence, $P_{oral}$ would be determined by water depth generating a higher flow resistance compared to tube phonation in the air, which in turn, would increase $P_{sub}$ relatively more than $P_{oral}$ as a compensatory response to sustain phonation and overcome resistance by the water [29]. As for tube phonation pressure-flow relationships, Titze et al. [30] suggested that transglottic pressure ($P_{trans}$) (i.e., the difference between $P_{sub}$ and $P_{oral}$) decreases when airflow resistance increases because of higher supraglottic pressure ($P_{oral}$), but only if $P_{sub}$ is kept constant. However, as both $P_{sub}$ and $P_{oral}$ increase during WRT (being the increment greater in $P_{sub}$), $P_{trans}$ also tends to increase, compared to baseline (e.g., comfortable phonation with an [aː] vowel) [25, 28]. Additionally, Tyrmi and Laukkanen [28] found that $P_{trans}$ was significantly lower during WRT at 10 cm depth, compared to loud and strained [aː] vowel phonation, which suggests that even when $P_{trans}$ increases during WRT, the amplitude of vibration of the vocal folds would be lower than phonotraumatic vocal behaviors.

### *Electroglottographic Contact Quotient*

The EGG CQ is another variable that has been explored during tube phonation into the water. Guzmán et al. [31] studied CQ values in normal-voiced and hyperfunctional dysphonia subjects while phonating with 8 different semi-occluded vocal tract postures. During WRT at 10 cm of water depth, CQ significantly increased compared to 2 cm of water depth and other semi-occluded exercises that did not involve water resistance. This effect was the same in both groups. It seems that WRT produces compensatory glottal adduction in response to higher hydrostatic pressure [31]. Similar findings were reported by Radolf et al. [22].

In a recent high-speed digital imaging study by Guzmán et al. [32], CQ tended to increase during WRT performance compared to comfortable vowel production in normal-voiced subjects. Higher values were found at 10 and 18 cm of immersion compared to 5 cm. WRT phonation at 5 cm depth was softer and more stable, which would suggest a gentler collision of the vocal folds. These findings agree with Tyrmi and Laukkanen [28], who reported higher CQ at deeper immersion, suggesting that WRT increases the vocal effort. Nevertheless, as they found that $P_{oral}$ increased due to water depth, as also did $P_{trans}$ in a controlled way, WRT would not necessarily produce higher impact stress, possibly because of a lower vibratory amplitude of the vocal folds.

### *Vocal Tract Configuration*

Effects of WRT on vocal tract configuration have also been explored. Guzmán et al. [33] studied the effects of different semi-occluded postures on vocal tract configuration in subjects with hyperfunctional dysphonia, through flexible laryngoscopy assessment. Results showed that SOVTE lead to a lower vertical laryngeal position, greater aryepiglottic narrowing, and wider pharynx. WRT produced more prominent changes, compared to the rest of SOVTE, on all laryngoscopic variables. Similar results related to the vertical laryngeal position were found by Wistbacka et al. [24] during WRT at 2 and 6 cm of water depth.

Recently, Yamasaki et al. [34] compared, in a magnetic resonance imaging study, changes on vocal tract configuration between dysphonic and nondysphonic women before and after WRT performed with a silicone tube, submerged 2 cm under water. Immediately after WRT, the experimental group (dysphonic women with vocal nodules) showed an increased distance between the epiglottis and posterior pharyngeal wall, and greater laryngeal vestibule area, while the inclination of the vocal folds decreased due to a decreased elevation of the anterior commissure of the larynx. These findings suggest some positive effects of WRT as a therapeutic tool.

### *Therapeutic Effectiveness of WRT*

Even though several studies have provided information about the underlying physiology and possible effects of WRT, there is still little evidence regarding its therapeutic effectiveness. Research in this field has mainly observed positive outcomes on auditory perceptual and self-assessment measures after WRT in subjects with behavioral dysphonia [35, 36].

Mailänder et al. [37] assessed changes produced after 3 weeks of WRT training in normal-voiced teachers. Improvements on perceived roughness and hoarseness, Acoustic Voice Quality Index, maximum phonation time, upper and lower contour of the voice range profile, and total and physical Voice Handicap Index scores were reported. In a recent randomized controlled trial conducted by Guzmán et al. [38], significant improvements after 8 weeks of WRT in subjects with behavioral dysphonia were found on Voice Handicap Index scores, self-assessment of voice quality, and aerodynamic measures.

*The Open Vocal Tract*

The physiological effects of a nonoccluded vocal tract setting have not been studied as much as that of a semi-occluded vocal tract. This vocal tract configuration involves a completely open vocal tract (OVT) shape as in the production of the vowel [aː] and has been associated with a low acoustic impedance condition [16], as well as with a reduced source-filter interaction compared to a semi-occluded vocal tract. It has been established that in order to obtain a maximum acoustic power transfer, a low glottal impedance would be necessary to match the lower vocal tract impedance [16, 17]. These findings suggest that an OVT shape could also be economic [16]. However, this configuration of the vocal tract has been associated with a higher glottal flow and a lower intraglottal pressure, which, in turn, could be related to a higher amplitude of vocal fold vibration, possibly increasing the risk of producing a higher impact stress [16, 17, 28]. Therefore, voice exercises using an OVT configuration could be capable of promoting an efficient voice production, but not necessarily a high vocal economy. Vocal exercises with an OVT are commonly used by CCM singing teachers and singers in Latin-American countries. Supporting the assumption that an OVT would not contribute to an appropriate vocal economy, in a recent study, Portillo et al. [39] suggested that OVT warm-up exercises may not be as economic as SOVTE warm-up exercises in CCM singers. The authors concluded that some changes found immediately after OVT exercises (decreased sound pressure level, SPL, increased glottal airflow, and decreased aerodynamic efficiency) could imply an early stage of vocal fatigue.

According to Titze and Verdolini [40], the goal for professional singers is to obtain an efficient and economic vocal system. In other words, the expected goal is to achieve the best acoustic output in the context of a balanced $P_{sub}$ and airflow in order to generate a controlled contact and amplitude of vibration of the vocal folds. Based on the facts that (1) findings suggest that WRT produces positive effects in voice quality and function, and (2) other SOVTE have been demonstrated to be useful as a voice training and vocal warm-up method [30, 39], the research question of the present study is: can WRT be used as an effective vocal warm-up method? To the best of our knowledge, the effectiveness of WRT as a vocal warm-up exercise for singers has not yet been explored. Therefore, the present study aimed to determine the effects of WRT as a vocal warm-up method in CCM singers. Based on previous data, we hypothesized that WRT would cause a positive warm-up effect, preparing the voice production system to face a demanding vocal performance. Specifically, WRT is expected to promote a more economic voice production, which should be reflected in objective measures, as an increased acoustic output (dB) in the context of an aerodynamic balance and controlled vocal fold adduction (i.e., no changes or a slight increase in both $P_{sub}$ and CQ, not necessarily proportional to the SPL increase). Also, an increased self-perceived resonant voice quality immediately after exercises is expected. Furthermore, the warm-up effect of WRT should be maintained after prolonged vocal loading.

## Methods

*Participants*

The present study was conducted with approval by the Institutional Review Board at SEK University, Chile. Informed consent was obtained from 26 volunteer musical theater singers (11 male, 15 female). The average age was 30 years, with a range of 20–45 years. Inclusion criteria for the present study were: (1) perceptually normal voice (GRBAS scale = 00000), (2) no history of vocal fold pathology during the previous year, (3) no history of voice therapy, (4) absence of self-reported voice problems at the moment of assessment, (5) at least 1 year of singing vocal training, and (6) at least 1 year of experience as musical theater singer. Out of 26 participants initially recruited, 4 subjects were subsequently excluded: two of them presented an upper respiratory tract infection at the moment of assessment, and the other two showed poor quality of the EGG signal. Thus, this study is based on data from the 22 remaining participants (10 male, 12 female).

Participants were randomly assigned to two groups: an experimental group ($n$ = 11) and a control group ($n$ = 11). All subjects were asked to attend to a single assessment and training session lasting about 1.5 h. Both the experimental group and the control group were assessed 3 times: (1) before vocal warm-up exercises (baseline), (2) immediately after vocal warm-up exercises (Post1) and (3) after 40 min of singing vocal loading (Post2). For the experimental group, the vocal warm-up was performed with WRT exercises. For the control group, the vocal warm-up included OVT shape exercises.

*Voice Assessment and Equipment*

Voice assessment was performed in the Voice Research Laboratory at the University of Chile. All participants comfortably sat on a chair during measurements. Aerodynamic, EGG, acoustic, and self-assessment measures were used to determine possible effects of WRT and OVT warm-up. Aerodynamic, EGG, and acoustic signals were captured simultaneously using a phonatory aerodynamic system (model 4500, KayPENTAX, Lincoln Park, NJ, USA) and an electroglottograph (EGG system; model 6103, KayPENTAX). An
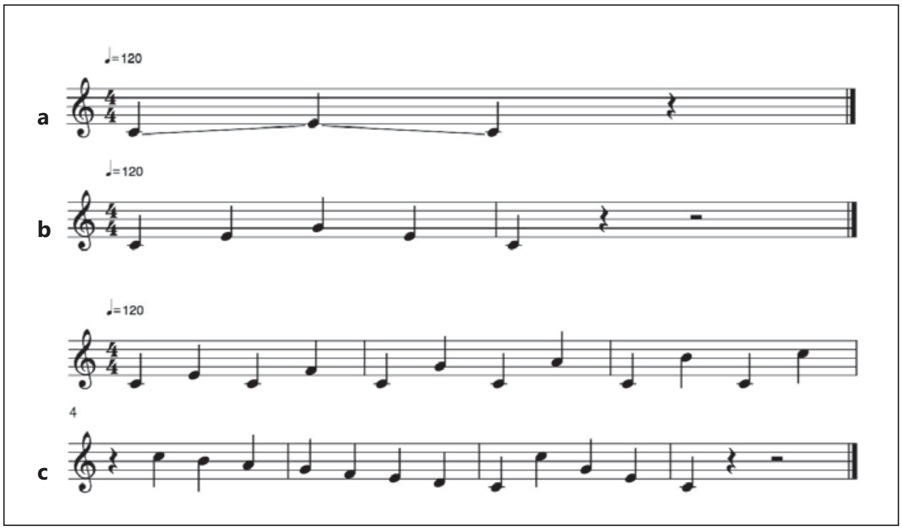
**Fig. 1.** Melodies used for OVT vocal warm-up. **a** Major third-interval slides. **b** Major fifth arpeggio. **c** Major scale agility.

incorporated condenser microphone (AKG CK 77; AKG Acoustics, Vienna, Austria) in the phonatory aerodynamic system was used to record the acoustic signals, at a constant distance of 20 cm from the mouth. A real-time aerodynamic and EGG analysis software (model 6600, version 3.4, KayPENTAX) was used. All samples were digitally recorded at a sampling rate of 22.1 kHz with 16 bits/sample quantization. Airflow and pressure were calibrated for every recording session following the manufacturer's instructions.

All participants were asked to engage in 3 different phonatory tasks during instrumental voice assessment:

1. To produce a sustained vowel [a:] for 5 s into a sealed mask, in habitual and comfortable speaking pitch and loudness. Three repetitions of the sustained vowel were asked from participants. Variables obtained from this phonatory task were: F0 (Hz), SPL (dB), glottal airflow (L/s), and EGG CQ (%)
2. To repeat the syllable [pa:] several times into a thin and flexible plastic tube inserted into the mouth, at a rate from 2.5 to 4 syllables per second, in habitual and comfortable speaking pitch and loudness. Three sequences of the syllable [pa:] repetition were asked. Variables obtained from this phonatory task were: F0 (Hz), SPL (dB), EGG CQ (%), glottal airflow (L/s), $P_{sub}$ (cm $H_2O$), glottal resistance (cm $H_2O/(L/s)$), glottal efficiency (ppm), and aerodynamic power (W). $P_{sub}$ was estimated from the maximum peak of the $P_{oral}$, which was obtained during the occlusion produced by the voiceless consonant [p:]. Phonation threshold pressure was also obtained by asking the singers to produce a repetition of the same syllable ([pa:]), but as softly as possible without whispering
3. To sing a song into a sealed mask, using a comfortable vocal range for 60 s, breathing inside the mask without removing it. All subjects were asked to sing "Aquarius" from the Broadway musical "Hair." Variables obtained from this phonatory task were: expiratory airflow duration (EAD) (s), inspiratory airflow duration (IAD) (s), expiratory volume (L), and inspiratory volume (L).

Singers were asked to maintain the same pitch (controlled using an electronic keyboard) during the three voice assessment time points (baseline, Post1, and Post2). One of the experimenters perceptually controlled loudness level. Only the most stable sections from the middle part of the aerodynamic, EGG, and acoustic samples were analyzed. A criterion level of 25% from the peak-to-peak amplitude of the EGG signal was used for CQ analysis.

### *Self-Assessment of Voice*

Participants self-assessed their resonant voice quality (i.e., vibratory sensations in the front part of the mouth and head, and easy phonation sensation) before each objective measurement, using a 100-mm visual analog scale, where 0 (zero) represents "no resonant voice at all" and 100 represents "very resonant voice." Singers were asked to sing a small piece of the song mentioned above to be able to self-assess voice quality.

### *Vocal Warm-Up Exercises*

OVT warm-up consisted of vocal exercise sequences performed with the vowel [a:]. Participants were asked to sing three different simple melodies (Fig. 1) played on a keyboard in an ascending and descending musical tonality by half steps. No specific minimum or maximum F0 was asked (vocal warm-up was performed throughout a comfortable vocal range). Habitual speaking loudness level was asked during vocal warm-up. Each melody lasted 5 min, completing 15 min of total warm-up.

WRT warm-up consisted of three phonatory tasks performed with a vowel-like sound into a plastic commercial drinking straw (6 mm inner diameter and 20 cm in length) with the free end submerged 5 cm into the water. Participants were asked to perform exercises with habitual speaking loudness level and were encouraged to feel vibratory sensations in the front part of the face. Each exercise lasted 5 min, completing 15 min of warm-up in total. The following phonatory tasks were included, based on Dr. Guzmán's vocal warm-up protocol [39]:

(a) comfortable, sustained pitch (habitual speaking pitch);
(b) comfortable glides up and down (*glissandos*);
(c) comfortable loudness and pitch accents (habitual speaking pitch).

Singers from both groups were required to use registers freely as they needed in order to prevent vocal effort during both vocal warm-up methods. To avoid confusions about the register concept and, hence, inter- and intrasubject variability, one of the experimenters (voice pathologist and musical theater singer) gave practical demonstrations about different registers that could be used, before vocal warm-up exercises. The same experimenter perceptually supervised the degree of vocal effort during vocal warm-up. Easy phonation (i.e., the effortless voice production possible, considering the interaction of the three main subsystems of the voice: breathing, phonation, and resonance) was required from subjects of both groups.

### *Vocal Loading Task*

After vocal warm-up, all participants were asked to sing a single musical theater song as many times as required to complete 40 min of singing, with a brief pause (80 s) between each repetition. This pause corresponds to the musical introduction of the song before singing. All participants were required to perform comfortable physical movements (e.g., walking, dancing) while singing. These physical movements were the same for all singers and were predetermined before the experiment. One of the experimenters controlled movement performance to be the same across singers, avoiding extra physical effort. The combination of singing and body movements resembles what musical theater singers do when they perform on stage. The song chosen was "Aquarius" from the Broadway musical "Hair." This song was adapted in tonality (pitch range) for each singer, according to his or her voice classification, by one of the experimenters, who assessed and confirmed the key of the song. Also, nonspecific vocal mechanism or vocal quality (e.g., mixed voice, belt, falsetto) was asked during this task. Singers were required to perform using their most daily and comfortable voice, avoiding extra effort. One of the experimenters also controlled this condition.

### *Statistical Analysis*

Data were analyzed and plotted with R. Mixed-effect models were fitted for each dependent variable of interest considering *subjects* as a random variable, *vocal warm-up* as a fixed factor, and *measure* as a repeated measure nested within *subjects*. Models fitted for each variable consisted of *vocal warm-up*, *measure*, and the interaction term (*vocal warm-up*/*measure*). Analyzes including *measure* always consider baseline measures as the reference category. Therefore, reported interactions are 2 × 2 interactions testing group differences between baseline measures and either Post1 or Post2. No main effects are reported whenever the interaction term in a given fitted model was observed to be significant. Since between-group baseline levels are sometimes significantly different, post hoc Tukey pairwise contrasts were also conducted separately for each group on repeated measures. These contrasts are intended to gauge how each vocal warm-up impacts on variables in time. All reported $p$ values are two-sided. Spearman pair-wise correlation tests were also conducted for all variables on each task. Only significant correlations were reported.

## **Results**

### *Mixed Effects*

Figure 2 shows mean plots for all variables in Task 1. Significant results were observed for the variables EGG CQ (an interaction effect when comparing baseline/Post2, $p = 0.02$). This interaction effect is supported by significant Tukey post hoc contrasts for the OVT group (baseline/Post1, $p = 0.049$; baseline/Post2, $p < 0.001$) which showed an incremental CQ decrease over time. WRT group values appear to be more stable, with no significant differences between measures. Significant results were also observed for self-perceived resonant voice quality (main effect for contrast baseline/Post1, $p < 0.001$, and contrast baseline/Post2, $p < 0.001$), which significantly increase after vocal warm-up and after vocal loading for both groups. Tukey post hoc analyses were highly significant ($p < 0.001$) for contrasts baseline/Post1 and baseline/Post2 in both groups.

Figure 3 shows mean plots for all variables in Task 2. Significant results were observed for SPL. An interaction effect was observed when comparing baseline/Post1 ($p = 0.046$), with significant post hoc contrasts for baseline/Post1 ($p < 0.001$) and Post1/Post2 ($p = 0.001$) in the OVT group, showing a decreased SPL after vocal warm-up, and an increased SPL after the vocal loading task. Furthermore, significant post hoc contrasts for baseline/Post2 ($p = 0.002$) were found for the WRT group, showing a decreased SPL only after vocal loading. $P_{sub}$ also displayed significant results. A main effect for the contrasts baseline/Post1 ($p < 0.001$) and baseline/Post2 ($p < 0.001$) was observed. Post hoc contrasts were significant for baseline/Post1 ($p = 0.006$ for the OVT group, and $p = 0.002$ for the WRT group) and baseline/Post2 ($p = 0.002$ for the OVT group, and $p < 0.001$ for the WRT group). Results showed a significant $P_{sub}$ decrease, both after vocal warm-up and vocal loading in both groups.

Figure 4 shows an interaction plot for all variables in Task 3. Significant results were observed for EAD. An interaction effect was observed when comparing baseline/Post2 ($p = 0.001$), showing a decreased EAD for the OVT group after vocal loading, whereas it increased for the WRT group. No significant post hoc contrasts were observed for this measure. Also significant was the main effect for IAD (baseline/Post1, $p = 0.01$, and baseline/Post2, $p < 0.03$), showing a decrease in both groups. The post hoc contrast was significant only for baseline/Post 2 ($p = 0.041$).

### *Spearman Correlation*

Pair-wise correlation tests were conducted for all variables in each task, collapsing measures and groups. Therefore, each correlation test was conducted over 66 observations. Given this sample size, coefficients within the range ±0.5 are not reported. For Task 1, none of the observed

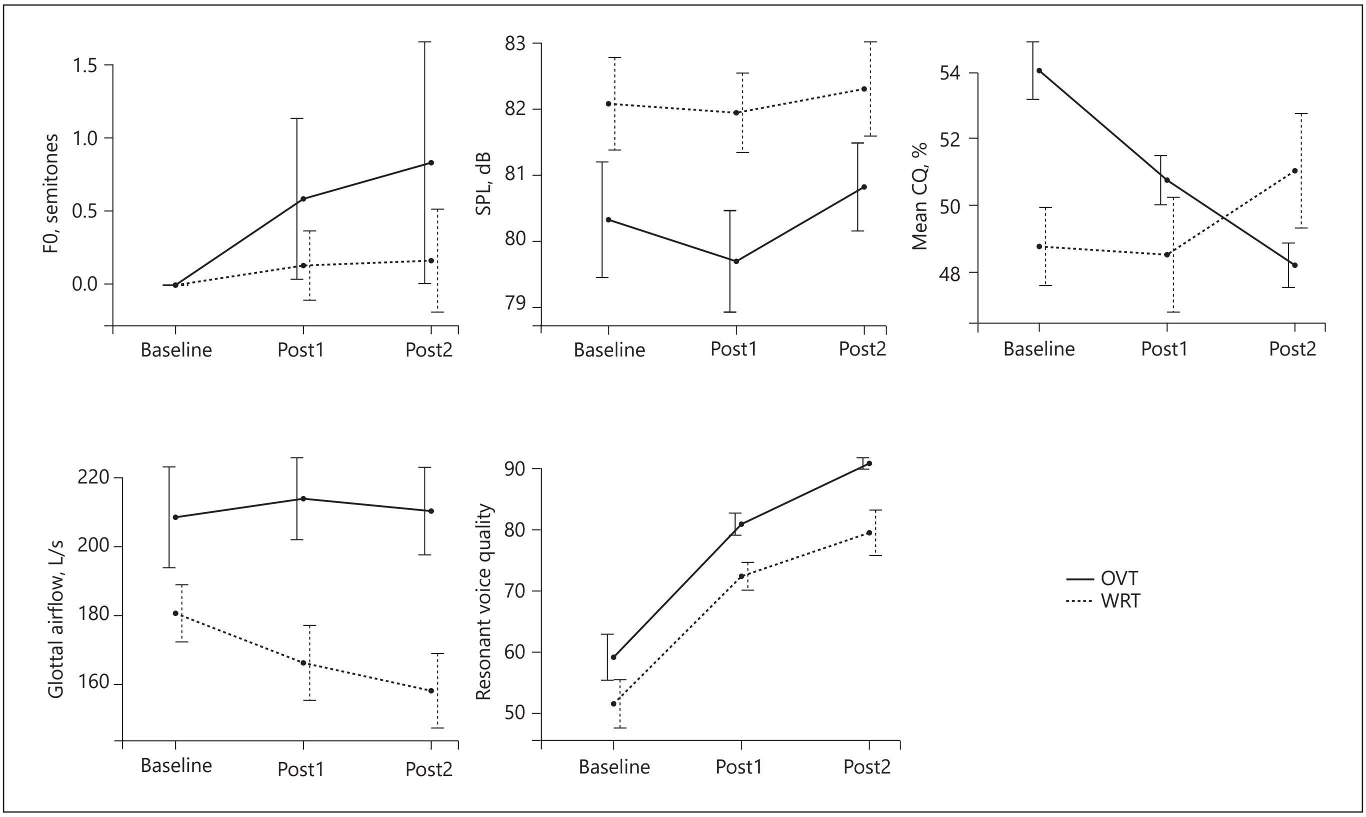

**Fig. 2.** Interaction plots for Task 1. Error bars represent one unit of standard error.

contrasts' coefficients met the adopted criteria to report correlation results. For Task 2, sizable correlation values were observed for pairs mean SPL/$P_{sub}$ ($\rho = 0.66$, $p < 0.001$), mean SPL/aerodynamic efficiency ($\rho = 0.73$, $p < 0.001$), $P_{sub}$/aerodynamic power ($\rho = 0.52$, $p < 0.001$), glottal airflow/aerodynamic resistance ($\rho = -0.82$, $p < 0.001$), and aerodynamic efficiency/aerodynamic resistance ($\rho = 0.54$, $p < 0.001$). For Task 3, sizable correlation values were observed for pairs IAD/inspiratory volume ($\rho = 0.52$, $p < 0.001$), and inspiratory volume/expiratory volume ($\rho = 0.94$, $p < 0.001$).

## Discussion

The present study aimed to determine the effects of an SOVTE (WRT) that has been suggested as useful for voice therapy, although it had not been studied as a vocal warm-up method for CCM singers. We hypothesized that WRT would promote a more economic voice production: increased acoustic output (dB) in the context of an aerodynamic balance and controlled vocal fold adduction. Also, an increased self-perceived resonant voice quality immediately after WRT exercises would be found. Findings showed that WRT warm-up may produce some positive immediate and post-vocal-loading effects, unlike OVT warm-up. Our data suggest that WRT might be of use as a vocal warm-up method for CCM singers.

### *Immediate Effects of WRT and OVT Warm-Up*

Significant differences in some objective measures were found immediately after both vocal warm-up protocols. SPL decreased after OVT warm-up while no significant changes were observed after WRT. Portillo et al. [39] found similar SPL results when OVT warm-up exercises were compared to straw phonation in the air, suggesting that warm-up exercises involving an OVT promote an early stage of vocal fatigue because of a loading effect. Several authors suggested that a common symptom of vocal fatigue is reduced vocal projection and power (i.e., decreased loudness) [41, 42]. McHenry and Evans [43] found a decreased SPL and a lower $P_{sub}$, in bodily fatigued classically trained singers after physical aerobic exercises. Similarly, our results showed a significant decreased $P_{sub}$

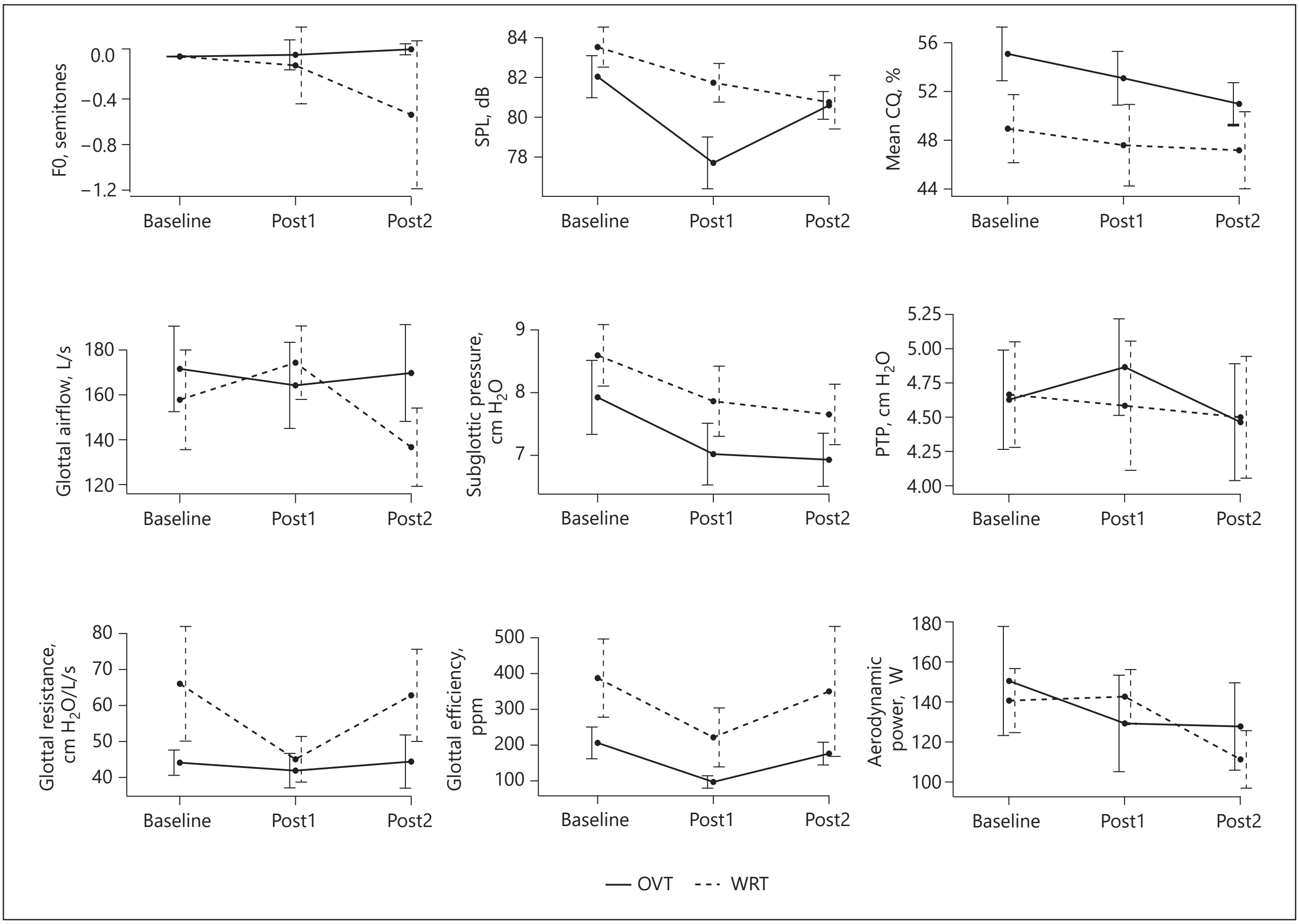

**Fig. 3.** Interaction plots for Task 2. Error bars represent one unit of standard error. PTP, phonation threshold pressure.

for both groups. Since $P_{sub}$ has been defined as the primary variable for vocal intensity control [44], it seems likely that decreased $P_{sub}$ caused decreased SPL in the OVT group. However, for the WRT group, a decreased $P_{sub}$ does not seem to affect SPL, which remained stable after vocal warm-up. In this case, the lower $P_{sub}$ found may be considered as a result of a balanced driving force for phonation to produce less effort, stabilizing SPL.

If the OVT group's lower SPL after warm-up reflects an early stage of vocal fatigue, a decreased $P_{sub}$ might also be related to the vocal loading effect. Titze [45] suggested that respiratory muscle fatigue may result in reduced $P_{sub}$ capacity, contributing to the onset of vocal fatigue. However, there are no conclusive results in the scientific literature supporting the possible relationship between $P_{sub}$ and loading effect [46]. Hence, it is not possible to establish that OVT vocal warm-up generated vocal fatigue based on $P_{sub}$ outcomes only. In this context, it is important to consider that although mean EGG CQ did not change significantly after both vocal warm-up protocols, there was a tendency to decrease for the OVT group and to remain stable for the WRT group. Additionally, mean glottal airflow tended to stay higher for the OVT group and lower for the WRT group. According to Eustace et al. [47], less contact of the vocal folds with higher flow rates may be related to vocal fatigue. Hence, it is suitable to speculate that changes found related to SPL and $P_{sub}$ (including the correlation found in our data between SPL and $P_{sub}$; $\rho = 0.66$, $p < 0.001$) would be in line with Titze's hypothesis. These results may be also related to vocal tract configurations that we used in each vocal warm-up protocol [16].

IAD decreased in both groups, which means that singers invested less time inhaling during singing after vocal

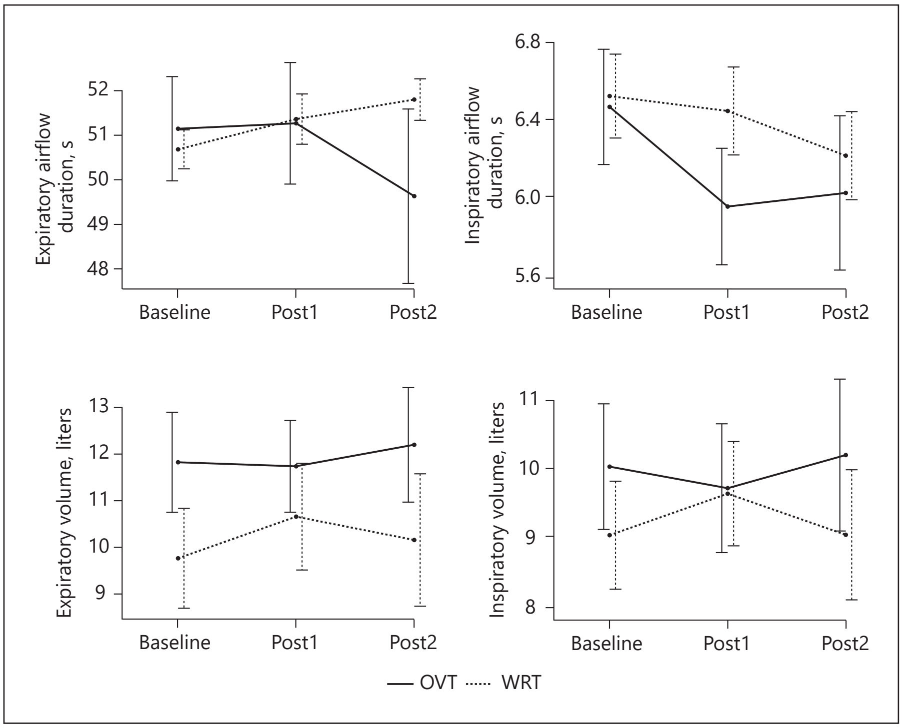

**Fig. 4.** Interaction plots for Task 3. Error bars represent one unit of standard error.

warm-up. It has been suggested that during singing inspirations should be shorter and deep enough [48] to produce an increased thoracic volume and inspiratory airflow, allowing a higher inspiratory drive [49] to build the $P_{sub}$ needed to meet singers' vocal demands [50]. Excessively brief inspirations might not allow for an optimal inspiratory drive, which may prevent adequate breath management. Since after both vocal warm-up methods a decreased IAD was observed, this variable should not be analyzed without taking into account other related measures (e.g., SPL and $P_{sub}$) in order to establish how positive or negative IAD decrease is.

As for self-assessed resonant voice quality, both groups showed a significant increase, suggesting that singers felt a more resonant voice quality (more vibratory sensation in the front part of the face and easier phonation sensation) after vocal warm-up. Results showed no significant differences between groups. Similar results were reported by Portillo et al. [39] when immediate effects of OVT and physiological vocal warm-ups were compared in CCM singers. Duke et al. [11] also found no significant differences in perceived phonatory effort when comparing traditional vocal warm-up and a SOVTE (straw phonation).

There is currently substantial evidence suggesting that vocal warm-up exercises produce positive changes in self-perceived voice quality and effort [9–11] which could be interpreted as singers perceiving better voice quality and less effort regardless of the type of vocal warm-up. According to Barr [12], even if differences might exist among vocal exercises, with some protocols being physiologically more efficient than others, vocal warm-up could produce a placebo effect in singers. Singers might effectively feel good voice results even if inefficient exercises are used. Our findings are consistent with Barr's statement, suggesting that self-assessed voice quality and effort may not be sensitive enough measures to determine the physiological effects of different vocal warm-up protocols.

In summary, even if both WRT warm-up and OVT vocal warm-up produced better self-perceived resonant voice quality, they seem to differ in terms of preparing an efficient and economic voice production system. This conclusion is supported by the fact that OVT vocal warm-up seems to generate an early stage of respiratory and phonatory fatigue, characterized by lower SPL, decreased IAD, reduced capacity to build $P_{sub}$, and a tendency to a decreased CQ and higher glottal airflow, which is consistent with Titze's hypothesis [45].

### *Vocal Loading Effect after WRT and OVT Warm-Up*

Singers from both groups felt a better resonant voice quality after the vocal loading task (no significant differences between groups were found). Nevertheless, both groups showed decreased IAD and $P_{sub}$, compared to baseline. As mentioned before, excessively brief duration of inspiration might lead to suboptimal inspiratory drive, which will probably generate less $P_{sub}$ for singing. Thus, prolonged singing and physical demand may produce respiratory muscle fatigue in CCM singers. However, observed groups seem to respond differently to this fatigue. Significant decreased EAD for the OVT group was found after vocal loading, which means that singers sustained phonation for less time during singing. Eustace et al. [47] found lower-than-normal maximum phonation time in vocally fatigued subjects. On the other hand, our WRT group showed an increase in EAD after vocal loading. Sonninen et al. [51] suggested that optimum breath support for singers should translate into longer maximum phonation time. In this regard, it seems that WRT could promote a better condition of vocal physiology after vocal loading, even when singers seem to show possible respiratory muscle fatigue.

The mean CQ showed significant differences between groups after vocal loading. During comfortable, sustained vowel [a:], a decreased CQ for the OVT group was found, while the WRT group showed no significant changes (similar to Post1, where the OVT group showed a decreased CQ after vocal warm-up; $p = 0.049$ Tukey post hoc baseline/Post1 contrast). Even though no significant differences were found when inspecting glottal airflow values, airflow rate tended to increase for the OVT group over 200 mL/s (and to decrease for WRT, under 170 mL/s), which could be related to a decreased CQ (less contact time of the vocal folds). Since lower CQ values have been linked to a hypofunctional glottal configuration [52], decreased CQ found among singers in the OVT group possibly suggests vocal fatigue after the vocal loading task. Kankare et al. [52] observed that CQ reliably distinguishes phonation types (pressed, normal, and breathy), the lowest CQ values being related with a breathy type of phonation. Also, Eustace et al. [47] suggested that incomplete glottal closure, along with higher flow rates and decreased maximum phonation time, may be related to laryngeal muscle weakness produced by voice abuse, misuse, or overuse. Stemple et al. [53] observed anterior glottal chinks after a prolonged speaking task in healthy subjects. The authors suggested that this may be a consequence of laryngeal muscle fatigue, specifically weakness of the thyroarytenoid muscles. Since the WRT group showed no significant CQ changes after the vocal loading task and CQ values for the OVT group decreased, it might be the case that vocal warm-up with WRT exercises reduces the risk of vocal fatigue after a demanding voice performance.

According to the results described above, the vocal loading task used in the present study (40 min of singing during physical activity) seemed to cause vocal fatigue in both groups affecting more negatively singers who engaged in the OVT warm-up. These changes were reflected mainly in EAD and CQ measures.

In summary, WRT may be useful to prepare the voice production system to face a demanding vocal performance and also to promote an economic voice. Specifically, WRT seemed to produce a positive effect considering the main variables that changed after vocal warm-up in both groups: WRT was found to provide the highest voice output (dB) (in this study SPL remained stable) with a stable CQ, and a slight decrease in both $P_{sub}$ and IAD. A tendency of a lower airflow for WRT compared to OVT was also observed. Moreover, after vocal loading, WRT showed a slight decrease in SPL and $P_{sub}$ (factors related to possible vocal fatigue) with a stable CQ, an increased EAD, and a slight IAD decrease, with a tendency of a lower airflow compared to OVT.

A limitation of this study may lie in the fact that we did not control the vocal mechanism or register (e.g., chest or falsetto) used by singers during Task 3. Also, during this task they were asked to sing during 60 s into a sealed mask. These two conditions may have impacted EAD and IAD measures: (1) it is well known how vocal fold configuration and contact can influence the airflow (lower airflow for chest and higher for falsetto), and (2) phonating into a seal mask may increase acoustic impedance, which could affect vocal fold configuration and aerodynamics. Despite this, the remaining variables showing significant differences during Task 1 and Task 2 should not have been affected by this limitation. Vocal registers and the use of a seal mask during assessment may be taken into account in future studies.

Future research might also compare the effects of a single source of vibration exercises (e.g., straw phonation in the air) and WRT in order to establish whether our results are exclusively related to a secondary source of vibration (water bubbling) or the simple use of semi-occluded postures of the vocal tract.

## Conclusion

Even though subjective outcomes (self-perceived resonant voice quality) might reflect a positive effect of both WRT and OVT vocal warm-up methods in CCM singers, it is also possible that this perception of a better voice may be a placebo effect. This is based on the fact that a variety of vocal warm-up methods produce the same effect on self-perceived voice quality regardless of physiological and objective changes. In the present study, some objective changes may indicate that the WRT method is more effective than OVT exercises to avoid an early stage of vocal fatigue both immediately after vocal warm-up and after a prolonged period of vocal loading. The best vocal warm-up method should be chosen based not only on subjective sensations, but also on potential physiological effects.

## Disclosure Statement

The authors have no conflicts of interest to declare.

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