Effects of a Variably Occluded Face Mask on the Aerodynamic and Acoustic Characteristics of Connected Speech in Patients With and Without Voice Disorders

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Summary: Objective. This study reports on experiments designed to examine the effects of a variably occluded face mask (VOFM) on (a) estimated subglottal pressure (P_{sub}) in normophonic participants and (b) aerodynamic and acoustic characteristics of voice in dysphonic participants.

Design. A prospective design was used for experiment 1, and a prospective, randomized cohort design was used for experiment 2.

Methods. The outlet ports of disposable anesthesia face masks were fitted with plastic caps with variable diameter drilled openings (9.6, 6.4, 3.2, and 1.6 mm) to create a series of mask openings. In experiment 1, P_{sub} was measured in normophonic participants using the face mask during syllable repetitions in unoccluded and variable diameter opening conditions. In experiment 2, aerodynamic and acoustic measures were obtained in a group of dysphonic speakers before and after syllable and speech repetition tasks using the VOFM.

Results. In experiment 1, mean P_{Sub} was observed to decrease while using the VOFM in all occlusion conditions versus nonocclusion, with a significant reduction in P_{sub} observed between the baseline and the 6.4 mm condition. In experiment 2, standardized mean differences showed that many dysphonic participants produced reduced P_{sub}, increased airflow, and improved acoustic measures after the use of the VOFM in at least one occlusion condition.

Conclusions. Beneficial changes in both aerodynamic and acoustic characteristics of voice may be obtained in dysphonic speakers using a VOFM. By moving the place of occlusion outside of the oral cavity, therapeutic stimuli options may be extended beyond vowel and humming elicitations to syllable and speech contexts and assist with generalization of voice therapy targets to conversational speech.

Key Words: Variable occlusion−Face mask−Aerodynamic analyses−SOVT−Voice therapy.

INTRODUCTION

Voice therapy techniques often involve semioccluded vocal tract (SOVT) exercises, which improve vocal economy, thereby reducing the potential for vocal fold injury.[1−3] Positive vocal improvements have been shown when a semiocclusion occurs in the oral cavity[2,4−6] or other locations along the supraglottal vocal tract,[1,7] in concert with an artificially extended vocal tract via tubes/straws submerged in[8−10] or out of water.[11−13] Moreover, both in vivo[14−16] and ex vivo and computer modeling research[1,17] have reported that phonation using an SOVT improves voice production.[10,18,19] A limiting factor in the use of SOVT exercises is the type of phonation that can be produced, namely, single vowel phonemes[1,20] that do not promote the transfer of efficient phonatory behaviors to connected speech.[21] Because production of target voice therapy techniques in conversational speech (ie, generalization) is the most difficult aspect of therapy,[21,22] a critical need exists to translate the benefits of SOVT exercises to connected speech. The purpose of the current study was to determine the immediate effects of a variably occluded face mask (VOFM) on connected speech in patients with and without voice disorders.

SOVT phonation improves voice production, at least in part, due to increased supraglottal pressure and impedance created in the vocal tract made possible by the semiocclusion.[1,19,23−25] These positive effects have been demonstrated in people with and without voice disorders immediately following production of traditional SOVT exercises consisting primarily of vowel productions.[6,10,18,26−29] Limited data exist on this technique in connected speech, likely due to the articulatory limitations of phonating into a straw or tube. Aderhold described a voice technique whereby actors partially covered their mouths while speaking,[30] and other authors have also described hand-over-mouth and cup phonation voice therapy exercises as a form of SOVT techniques that allow for connected speech.[31−34] More recently, Mills et al introduced a semioccluded face mask (SOFM) that allows for connected speech in an ex vivo experiment using a tube extension with and without an SOFM. The authors reported that similar improvements in vocal function were observed following SOFM phonation as with traditional tube phonation.[20] Likewise, Fantini et al reported an improvement in acoustic outcomes (jitter, shimmer, and singing power ratio) and singer's subjective reports (phonatory comfort, harmonic quality, and stability of voice) when singing an operatic passage following voice exercises into an SOFM.[35]

In summary, while promising as a therapeutic tool, traditional SOVT exercises can only be produced with single

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Dr. S. N. Awan licenses the algorithms that form the basis of the *Analysis of Dysphonia in Speech & Voice (ADSV)* program to Pentax Medical/KayPentax (Montvale, NJ).

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phonemes, which limit their ability to generalize the technique to connected speech. The immediate effects of SOVT exercise performed in connected speech are unknown. Moving the site of occlusion from inside the oral cavity (as with straw/tube phonation methods) to outside of the oral cavity may allow for natural speech production while still increasing vocal tract impedance and elicitation of improved aerodynamic and acoustic characteristics of voice. The purpose of the present study was to examine the immediate effects of a VOFM on (a) estimated subglottal pressure (P_{sub}) in normophonic participants and (b) aerodynamic and acoustic characteristics of voice in a group of dysphonic participants.

EXPERIMENT 1

Methods

Experimental Design

This study was a prospective design.

Participants

Ten vocally healthy participants (five male, five female; age range = 23−25 years) produced syllable repetitions using the Voicing Efficiency protocol of the Phonatory Aerodynamic System (PAS) (Pentax Medical, Inc., Montvale, NJ).

Face Mask

For each participant, a disposable adult face mask (Puritan Bennett, Lenexa, KS) (Figure 1) was sealed to the flow head of the PAS and a port was inserted into the side of the mask for the insertion of the pressure sensing tube. A rubber grommet (The Hillman Group, Cincinnati, OH) with an opening diameter like that of the pressure sensing tube was inserted into the pressure port to provide a seal against the pressure sensing tube. The output port of the face mask was occluded using plastic knockout seals (The Hillman Group, Cincinnati, OH) with drilled openings to result in a series of four variable mask openings (3/8 in. [9.6 mm], 1/4 in. [6.4 mm], 1/8 in. [3.2 mm], and 1/16 in. [1.6 mm]). The drilled opening sizes were made using standard, readily available drill bits and were chosen via preliminary experimentation by the first author (S.A.).

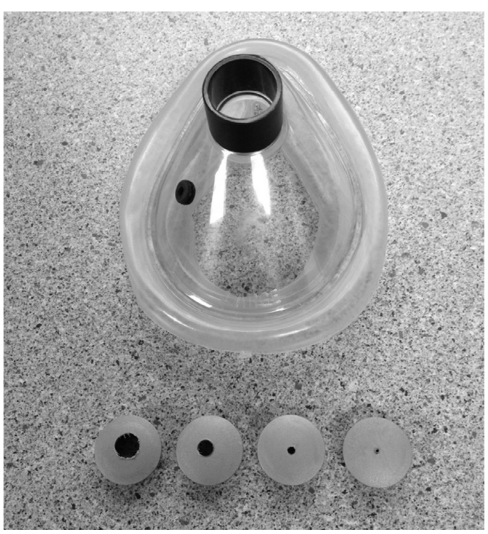

FIGURE 1. Disposable aerodynamic mask and plastic knockout seals with various diameter openings (from left to right: 3/8 in. (9.6 mm), 1/4 in. (6.4 mm), 1/8 in. (3.2 mm), and 1/16 in. (1.6 mm).

Task

Participants produced three trials of /i:pipipipipipipi/ at comfortable pitch and loudness (elicitation rate = 1.5 bps) in each of five randomized conditions: (1) no occlusion, (2) 3/8 in. (9.6 mm) opening, (3) 1/4 in. (6.4 mm) opening, (4) 1/8 in. (3.2 mm) opening, and (5) 1/16 in. (1.6 mm) opening. Recordings of sound pressure level (SPL), intraoral pressure, and phonatory airflow were obtained during use of the mask in the various conditions to ascertain the immediate effect of a face mask with variable openings on phonatory aerodynamic parameters with a particular focus on estimated subglottal pressure (P_{sub}).

Results

Measures of mean estimated subglottal pressure (P_{sub}) were obtained from the central three syllables produced during production of /i:pipipipipipipi/ during each of the tested conditions (baseline [no occlusion], 9.6, 6.4, 3.2, and 1.6 mm occlusion). Because of the extreme restriction to transglottal airflow during the 1.6 mm occlusion condition, most participants were not able to initiate or maintain syllable production. Therefore, the 1.6 mm condition was removed from statistical analysis.

A series of paired comparisons was conducted using a nonparametric Wilcoxon signed rank test to determine the presence of significant differences between the remaining conditions. Due to the preliminary nature of this investigation, a type I error rate of $P < 0.10$ was utilized. Results showed that estimated P_{sub} was observed to decrease in all occlusion conditions versus nonocclusion (Table 1), with a significant reduction in P_{sub} observed between the baseline and 6.4 mm conditions (7.40 cm H_2O vs. 6.58 cm H_2O; $Z = -1.68$; $P = 0.092$).

EXPERIMENT 2

Methods

Experimental design

This study was a prospective, randomized cohort study.

TABLE 1.
Measures of Mean P_{Sub} Obtained During Productions of /i:pipipipipipipi/ Using a VOFM

	No Occlusion (n = 10)	9.6 mm (n = 10)	6.4 mm (n = 10)	3.2 mm (n = 9)[†]
Mean P_{Sub} (cm H_2O)	7.40	6.97	6.58*	6.65
Standard deviation	1.66	1.69	1.61	1.28

[†] One subject was unable to complete the syllable production task at the 3.2 mm occlusion condition.
Wilcoxon signed rank test (*$P < 0.10$), 6.4 mm versus no occlusion.

Participants

Twenty-one male and female participants with a primary diagnosis of either benign vocal fold lesion(s) (n = 5), muscle tension dysphonia (MTD; n = 5), vocal fold atrophy (atrophy; n = 5), or unilateral vocal fold immobility (UVFI; n = 6) were recruited for study participation. Additional inclusion/exclusion criteria were as follows: 18−85 years old, chief complaint of a voice problem, Voice Handicap Index-10 score of > 11,[36] no presence of a confounding voice disorder (eg, vocal fold cancer, scar, papilloma, paradoxical vocal fold movement disorder, progressive neurological voice disorders, etc.). All participants were referred for treatment for their voice problem (surgery, therapy, or both). Prior treatment did not exclude participation if the participant had an ongoing voice complaint for which additional treatment was recommended; however, participation in the study had to occur prior to beginning the recommended treatment. All diagnoses were determined by a multidisciplinary team of laryngologist and voice-specialized speech-language pathologist. Participants were recruited at the time of their clinic appointment or following a clinic appointment and prior to their return to the center for treatment. Participants were recruited consecutively based on diagnosis until at least five participants with each diagnosis were recruited. Recruitment and completion of the study for all participants were completed over the course of three months. Participants received monetary compensation for participation.

Intervention

The aim of the study was to determine the immediate effects of phonation through a VOFM on acoustic and aerodynamic voice outcomes. Based on the results of Study 1 in typical participants, the occlusion diameters of 9.6, 6.4, and 3.2 mm were chosen for trials with the disordered participants in experiment 2. Participants first completed baseline testing, followed by phonation training with the VOFM, then post-training data collection. These procedures are described in detail in the following sections.

Baseline

Acoustic and aerodynamic data were collected for baseline comparisons. For acoustic data collection, each participant was seated and a head-mounted microphone (Beta-54 WBH54, Shure Incorporated, Niles, IL) was placed at a mouth-to-microphone distance of approximately 10 cm. The participant repeated the sentence "Where is my paper puppy now?" and sustained an /a/ vowel at most comfortable pitch and loudness level. The sentence "Where is my paper puppy now?" was designed to include a variety of phoneme types, including a series of voiceless stop-plosive + vowel syllables that could be used for the estimation of P_{sub} in a sentence context. Sentence and vowel samples were captured using the Analysis of Dysphonia in Speech and Voice software of the Computerized Speech Laboratory (CSL) (Pentax Medical, Inc., Montvale, NJ). Various acoustic measures were obtained for the recorded samples but, for the purposes of this study, the primary focus was on measures of mean cepstral peak prominence (CPP) and the Cepstral Spectral Index of Dysphonia (CSID).

The PAS 6600 (Pentax Medical, Inc.) was used for aerodynamic data collection. For this procedure, participants held the PAS hardware, which consisted of a face mask with integral intraoral pressure tube connected to a pneumotach. Once the mask was placed securely around the participant's nose and mouth, they repeated the seven-syllable string (syllable task) (/i: pipipipipipipi/) at a rate of 1.5 syllables per second (90 bpm),[37] maintained by following a lighted metronome (eg, flutetunes.com/metronome). This syllable string was repeated three times. Next, the participant again spoke the sentence, "Where is my paper puppy now?" three times (sentence task). Various measures were obtained for the syllable and sentence tasks but, for the purposes of this study, the primary focus was on measures of mean estimated P_{sub}, mean phonatory airflow (L/s), glottal resistance, and mean SPL.

Protocol for Use of the VOFM

The experimental protocol consisted of pre- and postintervention acoustic and aerodynamic data collection and three VOFM training conditions utilizing different diameter occlusions. Fifteen-minute rest periods were included between each condition to ensure condition washout and to reduce the possibility of carryover effects from one condition to the next. The entire procedure took approximately 60 minutes to complete. The outline of the experimental protocol is provided in Figure 2, and Figure 3 provides an example of a subject utilizing the VOFM.

The order in which participants completed the three mask training conditions was randomized within each disorder group. A randomization table organized by disorder, created prior to recruitment, was used to determine condition order for each participant.

Data management and reduction

Research Electronic Data Capture, hosted by the University of Pittsburgh, was used to manage all participant data. A research assistant reviewed all PAS and CSL files. Files were edited to remove any unnecessary parts of the recording such as throat clears. Syllable productions were considered appropriate for analysis if pressure and airflow equaled zero at appropriate time

BASELINE Pre-Tx Acoustic & Aerodynamic measures	CONDITION 1 Mask training with occlusion 1	POST-TX 1 Acoustic & Aerodynamic measures	15 minute rest	CONDITION 2 Mask training with occlusion 2	POST-TX 2 Acoustic & Aerodynamic measures	15 minute rest	CONDITION 3 Mask training with occlusion 3	POST-TX 3 Acoustic & Aerodynamic measures

FIGURE 2. Outline for the experiment 2 protocol to evaluate the effects of a VOFM on the aerodynamic and acoustic characteristics of voice.

FIGURE 3. Subject using the VOFM held firmly over nose and mouth. In this example, the mask is occluded with a plastic knockout seal drilled with a 9.6 mm opening.

points (pressure should equal zero during vowel production and airflow should equal zero during occlusion for /p/)[38] and if the productions were similar to other productions by the same participant within that condition (eg, if a participant with UVFI inhaled in the middle of the syllable train production, a central syllable could look more like an initial or final syllable production than a central production). If the three central /pi/ syllables were not appropriate for analysis, other central /pi/ productions were selected for analysis (ie, not the first or last /pi/ production within a syllable train). Like the syllable productions, "paper puppy" productions were considered appropriate for analysis if pressure and airflow equaled zero at appropriate time points. The airflow and pressure morphology of "paper puppy" was not as clean as in the syllable trains due to the nature of running speech (ie, speech rate and coarticulation affected the signal morphology). It was decided *a priori* that if pressure dropped below 0.10 cm H_2O and airflow dropped to 0.03 L or below, the data generated by the PAS software were analyzed. If airflow did not drop to 0.03 L or below during /p/ occlusion, that production was not included in aerodynamic analyses. If pressure did not drop below 0.10 cm H_2O, pressure, resistance, and efficiency were manually calculated and the floating pressure was subtracted.

Results

Data collected in experiment 2 were affected by key issues: (1) extreme variability due to inclusion of multiple disorder types and severities and (2) in the case of aerodynamic data, instances of missing data due to problems with the morphology of the airflow signal. These issues made traditional statistical analyses inappropriate for this type of within-subject treatment data. Instead, *standard mean differences* were calculated for each subject as measures of the magnitude of gain from treatment. The standard mean difference used in this study is a variation on Cohen's *d* in which the difference between the mean baseline and generalization is divided by the pooled standard deviation (SD)[39]:

$$d_2 = \frac{Mean_{Baseline} - Mean_{Generalization}}{S_{pooled}}$$

The standard mean difference is a form of effect size (ES) reported in SD units.[40,41] For the purposes of this study, indication of a beneficial treatment effect will be demonstrated via a positive (+) ES. Positive ESs will be automatically generated when the beneficial effect is a reduction in postocclusion performance (eg, for aerodynamic measures of estimated subglottal pressure, resistance, and SPL and for the multivariate acoustic CSID). For those variables in which an increase in postocclusion performance would reflect a beneficial change (eg, for the aerodynamic measure of mean airflow and for the acoustic measure of CPP), the computed sign of the ES was reversed.[42]

In computing the standard mean differences between baseline (ie, the no occlusion condition) and each of the three postocclusion conditions (ie, post-2 minutes of speech elicitation using a mask with restricted openings at 9.6, 6.4, and 3.2 mm), the following were computed:

1. The mean of the three baseline trials.
2. The mean of the postocclusion trials for each of the 9.6, 6.4, and 3.2 mm conditions. At least two trials were required in this computation.
3. The pooled SD across all participants for the baseline trials was computed as the square root of the weighted average of the variances.[40]

Aerodynamic analyses

Baseline (no occlusion) and postocclusion aerodynamic measures of voice were obtained in two contexts: (a) three central syllables of the seven-syllable train /i:pipipipipipipi/, and (b) the four /p/ initiated syllables in the sentence "Where is my paper puppy now." For the purposes of this study, analyses were focused on measures of mean peak pressure (cm H_2O), mean airflow (L/s), glottal resistance (cm H_2O/[L/s]), and mean SPL (dB).

For the aerodynamic tasks, a positive treatment outcome for mean P_{Sub} would be a decrease in P_{Sub} postocclusion (a positive ES). Results for the /i:pipi/ task provided in Table 2 showed that across all participants in whom acceptable aerodynamic measures could be obtained, the mean ES from no occlusion versus restricted occlusion conditions was positive in occlusion conditions. When focused on the subset of participants that showed positive ESs (10/18 [55.55%] participants following the 9.6 mm occlusion, 9/17 [52.94%] participants following the 6.4 mm occlusion, and 9/15 [60.00%] participants following the 3.2 mm occlusion), the mean ESs from no occlusion versus restricted occlusion conditions were all positive and averaged >1 SD in post-6.4 and post-3.2 mm occlusions, with the greatest mean post-treatment ES observed for the 6.4 mm occlusion. For those participants that showed positive ESs, the mean ESs from no occlusion versus restricted occlusion conditions corresponded to mean reductions in P_{Sub} of 1.22 cm H_2O in the 9.6 mm condition, 1.97 cm H_2O in the 6.4 mm condition, and 1.74 cm H_2O in the 3.2 mm condition. A review of the

TABLE 2.
Mean Effect Size Measures (Standard Mean Differences) Representative of the Magnitude of Effect of Variable Mask Outlet Occlusion Sizes on Aerodynamic Measures Obtained From Productions of /i:pipipipipipipi/

Aerodynamic Measure	Participants With Beneficial Change	No Occlusion Versus 9.6 mm Occlusion	No Occlusion Versus 6.4 mm Occlusion	No Occlusion Versus 3.2 mm Occlusion
Mean Peak Pressure	All subjects*	0.03 (1.00); n = 18	0.36 (1.15); n = 17	0.29 (1.29); n = 15
	Participants with beneficial change	0.74 (0.58); n = 10	1.19 (0.78); n = 9	1.05 (0.92); n = 9
Mean Airflow	All subjects*	0.33 (1.63); n = 20	0.20 (1.45); N = 21	0.42 (1.93); n = 20
	Participants with beneficial change	1.51 (1.40); n = 11	1.22 (1.24); n = 11	1.64 (1.80); n = 11
Resistance	All subjects*	0.21 (0.48); n = 17	−0.09 (1.46); n = 17	0.38 (1.22); n = 14
	Participants with beneficial change	0.42 (0.53); n = 9	0.45 (0.53); n = 10	0.83 (1.25); n = 9
Mean SPL	All subjects*	−0.20 (1.26); n = 21	0.23 (1.73); n = 21	−0.06 (1.93); n = 21
	Participants with beneficial change	0.78 (0.49); n = 11	1.34 (1.05); n = 13	1.31 (1.18); n = 11

* Participants for whom acceptable aerodynamic data were obtained.

individual disorder groups showed that one of five participants with atrophy (mean ES = 0.99; ES SD = 0.39), four of five participants with lesion (mean ES = 1.17; ES SD = 0.89), three of five participants with MTD (mean ES = 0.77; ES SD = 0.55), and five of six participants with UVFI (mean ES = 1.02; ES SD = 0.90) demonstrated a positive ES for P_{Sub} in at least one of the three occlusion conditions (13/21 participants; 61.90%). Similar positive ES results were observed for measures of post-occlusion mean P_{Sub} obtained from the sentence "Where is my paper puppy now," although the number of participants in which acceptable measures of peak pressure could be obtained was greatly reduced (Table 3).

For postocclusion measures of mean airflow, an increase in airflow was considered a positive treatment outcome (computed ES sign was reversed). Results for the /i:pipi/ task provided in Table 2 show that across all participants in whom acceptable measures of peak pressure could be obtained, the mean ES from no occlusion versus restricted occlusion conditions was positive in all cases. When focused on the subset of participants that showed positive ESs (11/20 [55.00%] participants following the 9.6 mm occlusion, 11/21 [52.38%] participants following the 6.4 mm occlusion, and 11/20 [55.00%] participants following the 3.2 mm occlusion), the mean ESs from no occlusion versus restricted occlusion conditions were positive and averaged >1 SD following all occlusions. The greatest mean post-treatment ES was observed for the 3.2 mm occlusion. For those participants that showed positive ESs, the mean ESs from no occlusion versus restricted occlusion conditions corresponded to mean increases in airflow of 44 mL/s in the 9.6 mm condition, 36 mL/s in the 6.4 mm condition, and 48 mL/s in the 3.2 mm condition. A review of the individual disorder groups showed that four of five participants with atrophy (mean ES = 2.07; ES SD = 1.44), three of five participants with lesion (mean ES = 0.41; ES SD = 0.37), four of five participants with MTD (mean ES = 1.48; ES SD = 1.56), and five of six participants with UVFI (mean ES = 1.33; ES SD = 1.59) demonstrated a positive ES for mean airflow in at least one of the three occlusion conditions (16/21 participants; 76.19%). Similar positive ES results were observed for measures of post-9.6 and post-3.2 mm occlusion mean airflow obtained from the sentence "Where is my paper puppy now" (Table 3). When focused on the subset of participants who showed beneficial increases in mean airflow following occlusion, strength of ES was observed to be >1 SD in all conditions and >3 SD following use of the 3.2 mm occlusion (Table 3).

A positive treatment outcome for mean resistance would be a decrease in resistance following occlusion (resulting in a positive ES). When measured during the /i:pipi/ task, small, positive

TABLE 3.
Mean Effect Size Measures (Standard Mean Differences) Representative of the Magnitude of Effect of Variable Mask Outlet Occlusion Sizes on Aerodynamic Measures Obtained From Syllables Initiated With /p/ in the Sentence "Where Is My Paper Puppy Now"

Aerodynamic Measure	Included Participants	No Occlusion Versus 9.6 mm Occlusion	No Occlusion Versus 6.4 mm Occlusion	No Occlusion Versus 3.2 mm Occlusion
Mean peak pressure	All subjects*	0.09 (1.29); n = 9	1.14 (1.44); n = 9	0.83 (1.64); n = 11
	Participants with beneficial change	1.70 (0.25); n = 3	1.46 (1.17); n = 8	1.68 (0.88); n = 8
Mean airflow	All subjects*	0.69 (3.10); n = 20	−0.17 (2.43); n = 18	0.93 (3.52); n = 20
	Participants with beneficial change	2.47 (2.58); n = 12	1.26 (1.19); n = 11	3.09 (2.83); n = 11
Resistance	All subjects*	0.73 (1.85); n = 9	0.88 (2.21); n = 9	1.11 (2.09); n = 11
	Participants with beneficial change	1.50 (1.80); n = 6	2.62 (2.31); n = 4	1.50 (2.11); n = 9
Mean SPL	All subjects*	−0.38 (1.37); n = 20	−0.30 (1.74); n = 19	−0.04 (2.27); n = 20
	Participants with beneficial change	0.98 (0.50); n = 8	1.25 (1.19); n = 8	1.71 (1.52); n = 10

* Participants for whom acceptable aerodynamic data were obtained.

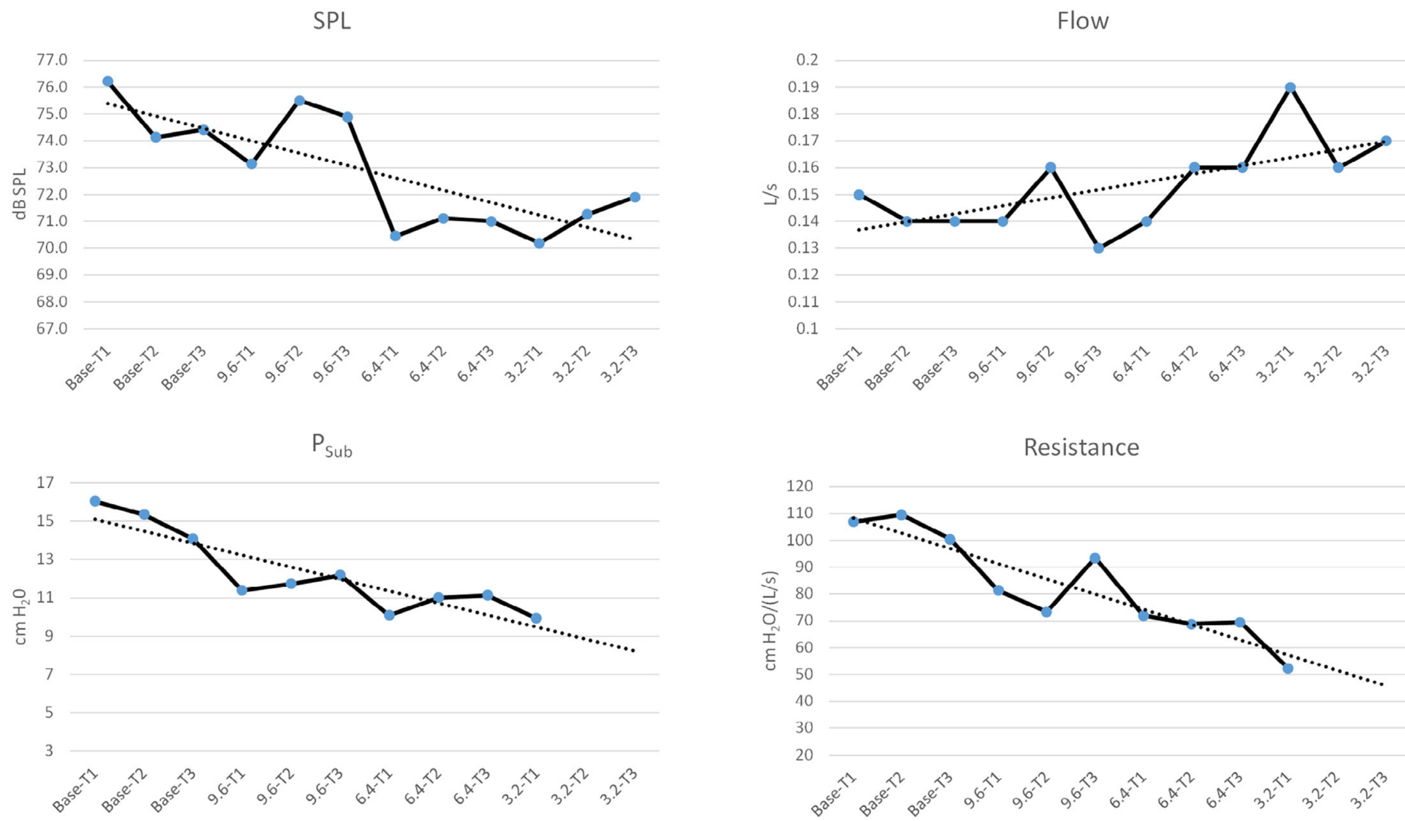

FIGURE 4. Examples of beneficial changes in aerodynamic characteristics of voice (SPL, P_{sub}, flow, and glottal resistance) for a patient with vocal fold lesions following use of a VOFM (syllable repetition task). Three trials (T1, T2, and T3) were obtained at baseline (base [no occlusion]) and post-9.6, post-6.4, and post-3.2 mm occlusions. In this patient, acceptable measures of P_{sub} and resistance were obtained for only the first of three trials using the smallest (3.2 mm) occlusion. Trend lines across the multiple trial and condition data are also provided.

ESs were observed post-9.6 and post-3.2 mm occlusions. When focused on the subset of participants who showed the expected positive treatment outcome for resistance, the greatest ES was observed in the 3.2 mm condition (Table 2). For those participants that showed positive ESs, the mean ESs from no occlusion versus restricted occlusion conditions corresponded to mean reductions in glottal resistance of 42.81 cm H_2O/(mL/s) in the 9.6 mm condition, 40.33 cm H_2O/(mL/s) in the 6.4 mm condition, and 74.72 cm H_2O/(mL/s) in the 3.2 mm condition. A review of the individual disorder groups showed that two of five participants with atrophy (mean ES = 1.23; ES SD = 1.16), three of five participants with lesion (mean ES = 0.18; ES SD = 0.18), four of five participants with MTD (mean ES = 0.39; ES SD = 0.54), and five of six participants with UVFI (mean ES = 0.58; ES SD = 0.89) demonstrated a positive ES for resistance in at least one of the three occlusion conditions (14/21 participants; 66.66%). Similar positive ES results for resistance were also observed when measured after occlusion in the sentence context, although the number of participants in which measures of resistance could be obtained was limited (Table 3).

A positive treatment outcome for mean SPL would be a decrease in SPL postocclusion (resulting in a positive ES). When measured during the /i:pipi/ task, a small, positive ES was observed across all subjects only for the post-6.4 mm occlusion. When focused on the subset of participants who showed the expected positive treatment outcome for SPL, the greatest ES was also observed in the 6.4 mm condition (Table 2). For those participants that showed positive ESs, the mean ESs from no occlusion versus restricted occlusion conditions corresponded to mean reductions in SPL of 0.75 dB in the 9.6 mm condition, 1.30 dB in the 6.4 mm condition, and 1.27 dB in the 3.2 mm condition. A review of the individual disorder groups showed that four of five participants with atrophy (mean ES = 0.90; ES SD = 0.63), four of five participants with lesion (mean ES = 1.73; ES SD = 1.60), three of five participants with MTD (mean ES = 0.87; ES SD = 0.64), and five of six participants with UVFI (mean ES = 1.02; ES SD = 0.62) demonstrated a positive ES for SPL in at least one of the three occlusion conditions (16/21 participants; 76.19%). In the sentence context, there was no observation of positive ESs for change in SPL when measured across all subjects. While the subset of participants in which positive ESs were observed was reduced in the sentence context versus the syllable context, the magnitude of the observed positive ES was particularly strong for the 3.2 mm occlusion (Table 3).

Figure 4 provides an example of a patient with lesion who was observed to display the aforementioned beneficial trends on aerodynamic characteristics following use of the VOFM.

Acoustic analyses

For the purposes of this study, acoustic analyses were focused on measures of CPP and CSID computed from the sentence

TABLE 4.
Mean Effect Size Measures (Standard Mean Differences) Representative of the Magnitude of Effect of Variable Mask Outlet Occlusion Sizes on Acoustic Measures of CPP and the CSID

Acoustic Measure	Included Participants	No Occlusion Versus 9.6 mm Occlusion	No Occlusion Versus 6.4 mm Occlusion	No Occlusion Versus 3.2 mm Occlusion
CPP	All subjects (N = 21)	0.29 (1.66)	0.16 (1.89)	0.48 (1.15)
	Participants with beneficial change	1.17 (0.93); n = 14	1.49 (1.18); n = 12	1.05 (0.71); n = 15
CSID	All subjects (N = 21)	0.72 (1.41)	0.72 (1.92)	0.75 (1.33)
	Participants with beneficial change	1.21 (1.20); n = 16	1.61 (1.65); n = 14	1.28 (0.95); n = 16

"Where is my paper puppy now." In the case of CPP, a positive treatment outcome would be an increase in CPP (computed ES sign was reversed). Results provided in Table 4 show that across all participants (N = 21), the mean ES from no occlusion versus restricted occlusion conditions was positive in all cases (ie, increased CPP) but relatively small in magnitude. However, when focused on the subset of participants that showed positive ESs (14/21 [66.67%] participants following the 9.6 mm occlusion, 12/21 [57.14%] participants following the 6.4 mm occlusion, and 15/21 [71.43%] participants following the 3.2 mm occlusion), the mean ESs from no occlusion versus restricted occlusion conditions were positive and averaged >1 SD in all cases. The greatest mean post-treatment ES was observed for the 6.4 mm occlusion. For those participants who showed positive ESs, the mean ESs from no occlusion versus restricted occlusion conditions corresponded to mean increases in CPP of 0.55 dB in the 9.6 mm condition, 0.71 dB in the 6.4 mm condition, and 0.50 dB in the 3.2 mm condition. A review of the individual disorder groups showed that four of five participants with atrophy (mean ES = 1.37; ES SD = 1.31), five of five participants with lesion (mean ES = 1.16; ES SD = 0.70), three of five participants with MTD (mean ES = 0.80; ERS SD = 0.55), and five of six participants with UVFI (mean ES = 1.23; ES SD = 1.00) demonstrated a positive ES for CPP in at least one of the three occlusion conditions (17/21 participants; 80.95%).

The CSID is a multivariate estimate of dysphonia[43,44] that has been reported to be a strong correlate of dysphonia severity as reported using the Consensus Audiory Perceptual Evaluation of Voice (CAPE-V) perceptual rating scale. In the case of the CSID, a positive treatment outcome would be a decrease in CSID (resulting in a positive ES). As shown in Table 4, across all participants the mean ES from no occlusion versus restricted occlusion conditions was positive in all cases (ie, decreased CSID). When focused on the subset of participants that showed positive ESs (16/21 [76.19%] participants following the 9.6 mm occlusion, 14/21 [66.67%] participants following the 6.4 mm occlusion, and 16/21 [76.19%] participants following the 3.2 mm occlusion), the mean ESs from no occlusion versus restricted occlusion conditions averaged >1 SD in all cases. The greatest mean post-treatment ES was again observed for the 6.4 mm occlusion. For those participants that showed positive ESs, the mean ESs from no occlusion versus restricted occlusion conditions corresponded to mean reductions in the CSID of 6.78 in the 9.6 mm condition, 9.01 in the 6.4 mm condition, and 7.17 in the 3.2 mm condition. A review of the individual disorder groups showed that four of five participants with atrophy (mean ES = 2.40; ES SD = 1.73), five of five participants with lesion (mean ES = 1.08; ES SD = 0.90), four of five participants with MTD (mean ES = 0.96; ES SD = 0.99), and six of six participants with UVFI (mean ES = 1.13; ES SD = 1.18) demonstrated a positive ES for CSID in at least one of the three occlusion conditions (19/21 participants; 90.48%).

DISCUSSION

This manuscript has provided the results of two studies examining the potential effects of a VOFM on selected aerodynamic and acoustic characteristics of voice obtained during both syllable and speech tasks. Experiment 1 demonstrated that in typical participants without voice problems, the immediate effects of phonation into a VOFM on syllable production was a reduction in estimated subglottal pressure (P_{sub}) in all variably occluded conditions as compared to a baseline (no occlusion) condition. In particular, estimated P_{sub} was significantly reduced with the 6.4 mm mask opening condition. This tendency for syllable production with reduced P_{sub} was also observed in experiment 2 in both syllable and sentence productions produced by a majority of participants with voice disorders following 2-minute speech/syllable repetition tasks with the VOFM. In addition to beneficial reductions in P_{sub}, favorable changes in glottal resistance, mean airflow, mean SPL, and acoustic characteristics of voice were also observed for a majority of participants with voice disorders following phonation using the VOFM. The results of experiment 2 show that beneficial changes in both aerodynamic and acoustic characteristics of voice may be obtained for people with voice disorders using a VOFM that (a) extends therapeutic target stimuli options beyond standard vowel and humming elicitations to connected speech productions and (b) may be assembled at extremely low cost.

Aerodynamic changes

A key finding of both experiment 1 (measures collected with a VOFM on) and experiment 2 (measures collected with the VOFM off following speech/syllable trials using a VOFM on) was that a majority of participants were observed to produce speech and syllable productions with a reduced subglottal pressure. When attempting to phonate into a sealed mask with small diameter mask outlet openings, high subglottal pressures and high flow rates can result in substantial intraoral back pressures that limit transglottal airflow and may make phonation impossible (as observed in experiment 1 with the smallest opening of 1.6 mm). When the mask is sealed around the nose and mouth region, "forcing" against the occluded mask opening results in either (a) uncomfortably effortful voice or (b) an inability to phonate. Therefore, to phonate comfortably with the mask on, the speaker is obliged to reduce subglottal pressure and allow flow rates that can escape via the small diameter mask opening without preventing or severely limiting transglottal flow rates.

Our observations of reduced mean P_{sub} while using a VOFM in experiment 1 is contrary to the previously reported expectation of increased intraoral pressures using various types of tube or straw phonations. This may be due to the placement of the occlusion outside of the mouth in the present study versus directly within the oral cavity in the alveolar region in straw/tube phonation techniques. We intend future studies to elucidate the mechanisms underlying the observation both peri- and post-face mask use as observed in this study. However, the reductions in P_{sub} observed in both experiments 1 and 2 of this study in our various typical and disordered participants are intuitively beneficial and often used as a positive outcome to be achieved by voice therapy.

The results of experiment 2 indicate that reductions in P_{sub} that may occur while the VOFM is on are maintained in many speakers when the VOFM is taken off. One of the ways in which reduced P_{sub} may be achieved is via increased glottal opening during phonation. The results of experiment 2 indicate that, following mask use, many of the participants in this study produced increased mean airflow rates and decreased overall glottal resistance. This combination of reduced P_{sub}, increased airflow, decreased overall resistance, and reduced SPL is potentially beneficial not only for vocally hyperfunctional participants, but also for "unloading" the laryngeal mechanism in participants with glottal incompetence who may have acquired compensatory secondary MTD.[45] This unloading effect may be the reason why beneficial reductions in P_{sub} were observed across MTD, lesion, and UVFI groups. The only group in which reduction in P_{sub} was limited (observed in one of five participants) was the atrophy group. A possible explanation for this finding is that the patients with atrophy may not have had glottal incompetence (gap) but rather decreased tonicity of the vocal folds resulting in a diagnosis of atrophy. In the latter case, patients with atrophy may not have had high estimated P_{sub} at baseline.

In experiment 2, beneficial aerodynamic changes were observed in all occlusion conditions, with the greatest ES for reduction in P_{sub} observed for the 6.4 mm condition (similar to that observed during mask use in experiment 1). Since P_{sub} is a key determinant of SPL, it was not surprising that this condition also resulted in the greatest ES reduction in mean SPL. However, depending upon the participant, beneficial aerodynamic changes may be observed in any of the occluded conditions. Therefore, it may be that prospective patients may be guided through a hierarchy of mask opening sizes, starting with the smallest occlusion possible without forcing (eg, 3.2 mm) and progressing through a series of larger mask openings until the completely open mask port is achieved to best simulate conversational speech.

Acoustic changes

While beneficial aerodynamic changes were observed in most of those participants from whom adequate aerodynamic data could be obtained, an even greater proportion of participants showed beneficial acoustic changes in the voice following VOFM use in experiment 2 (Table 4). A relatively high-amplitude CPP has been associated with both normophonic voice and with post-treatment voice in dysphonic speakers.[43,46,47] In addition, the CPP is a primary contributor to the CSID,[44] a multivariate acoustic estimate of dysphonia severity that has also been reported to decrease in post-treatment voice cases. In the current study, increased amplitude CPP and decreased CSID scores were observed following use of the VOFMs, with the greatest mean ESs for CPP and the CSID observed for the 6.4 mm condition. While the aforementioned beneficial aerodynamic changes may result in improved vocal quality and underlying periodicity, the overall necessity for relaxed phonation would appear to promote improved cepstral and spectral characteristics of the voice in many of our participants following mask use. While increases in CPP have been associated with increases in SPL,[48] a review of the ES for SPL data obtained for the sentence "Where is my paper puppy now" during our aerodynamic testing was very poorly and nonsignificantly correlated with the ESs observed for the CPP data obtained from acoustic analyses of the sentence (r's <0.15 in all three mask opening conditions).

LIMITATIONS AND FUTURE DIRECTIONS

Several limitations of this study should be noted. First, the results of experiment 2 indicate clearly that not all participants will benefit from this treatment technique. We observed some indication that, particularly for aerodynamic changes, certain disordered groups may be less amenable to voice change using a VOFM than others (eg, atrophy cases). Future studies with larger samples of typically observed dysphonia types will be able to provide more detail as to the potential benefits of this VOFM method. Second, for any potential patient, it is essential that the clinician fully instruct the patient to not push against the mask. It was clear from some of our P_{sub} data in experiment 1 that some participants had difficulty phonating against the VOFM, which resulted in increased subglottal pressures and difficulty achieving phonation. These increased pressures may then be maintained in speech situations with the mask off. These patients may need a longer duration of the treatment task than used in this study to acclimate to the mask before effective phonation with reduced subglottal pressure may be achieved. Future studies should examine whether the duration of task may influence the acquisition and maintenance of positive voice changes. Third, this study presented the variable diameter mask occlusions in a random order across participants. However, the possibility of either a sequencing or carryover effect of a particular occlusion condition to another cannot be ruled out. Future studies will examine whether any type of order effect may be present in eliciting voice change or whether similar results may be obtained using a single mask opening diameter. Fourth, although participants were not formally asked to report on subjective changes in the feel or sound of their voice, several participants commented that their voice production felt or sounded better after using the variably occluded mask as compared to baseline. Future studies will incorporate perceptual evaluation methods in addition to the objective aerodynamic and acoustic methods used in this study. Finally, experiment 2 of this study was focused on a single group of treatment-seeking individuals and a nontreatment control group was not utilized. It is our hope that our future work may be conducted within the context of a randomized, controlled study.

CONCLUSIONS

The results of this study demonstrate that beneficial changes in both aerodynamic and acoustic characteristics of voice may be obtained in a variety of dysphonic speakers using a VOFM. By moving the place of occlusion outside of the oral cavity, therapeutic target stimuli options may be extended beyond standard vowel and humming elicitations to syllable and connected speech productions, and thereby promote more effective and efficient results of voice treatment.

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