Estimation of Transpalatal Nasalance During Production of Voiced Stop Consonants by Noncleft Speakers Using an Oral-Nasal Mask

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Objective: **Our objective was to estimate nasalance due to transpalatal transfer of acoustic energy during production of voiced stop consonants by noncleft speakers. We also determined the relationship between the transpalatal nasalance and fundamental frequency (F0) of the speakers.**

Method: **Participants were 8 men and 10 women (mean age = 21.9 years, SD = 4.0) without cleft palate who produced voiced stop (/b d g/) and nasal (/m n ŋ/) consonants in syllables embedded in a carrier phrase. Participants also read the Zoo Passage. A divided OroNasal Nasality System mask was used to simultaneously obtain acoustic nasalance and airflow during production of the consonants. Both F0-derived and first formant (F1)–derived nasalance were computed.**

Results: **F0-derived and F1-derived peak nasalance across all speakers ranged from a low of 20% to a high of 80% during production of stop consonants. An estimate of error from the combined sources of transoral transfer of energy (5%) and acoustic crossover between microphones (15%) was no greater than 20%. Analysis of variance revealed no significant effects of the sex of the speakers for either F0-derived or F1-derived nasalance of stops. There was a significant effect of the place of stop production for F0-derived nasalance ($p < .05$). Nonsignificant but positive correlations were found between the F0 of the speakers and F0-derived ($r = .25$) and F1-derived ($r = .45$) nasalance.**

Conclusions: **Transpalatal transfer of oral acoustic energy accounts for most nasalance obtained during production of voiced stop consonants by noncleft speakers. F1-derived nasalance appears to better reflect transpalatal effects. Clinical implications are discussed.**

KEY WORDS: *nasalance, transpalatal nasalance, velopharyngeal closure, voiced stop consonants*

Nasalance is an acoustic measure that has gained widespread acceptance as a diagnostic correlate of perceived oral-nasal resonance balance (e.g., Dalston et al., 1991; Hardin et al., 1992; Watterson et al., 1996). The term *nasalance* was coined by Fletcher (1978) to represent the output of a dual-microphone device called TONAR II. Nasalance was defined as the ratio of nasal to oral-plus-nasal acoustic energy in a specific frequency range of speech. This range approximated the energy region of the first formant (F1) of most vowels (350 to 750 Hz). Currently, nasalance scores are usually obtained with a commercially available instrument, the Nasometer. Typically, nasalance scores are relatively high during production of nasal consonants that require some degree of velopharyngeal (VP) opening. Conversely, nasalance scores are relatively low during production of nonnasal sounds (e.g., vowels) that require closure of the VP mechanism. Nasalance scores also have been reported to be affected by variables such as gender, dialect, and phonetic context (Leeper et al., 1992; Seaver et al., 1992; MacKay and Kummer, 1994; Lewis et al., 2000).

Gildersleeve-Neumann and Dalston (2001) noted that nasalance scores are never zero during production of nonnasal sounds. They attributed this to a combination of (1) limited acoustic separation (25 dB) of the Nasometer's oral and nasal microphones (i.e., crossover error) and (2) vibration of palatal structures that transfers acoustic energy to the nasal cavity (i.e., ''transpalatal nasalance''). They attempted to separate the effects of acoustic crossover and transpalatal nasalance by instructing noncleft speakers to produce vowels and read the Zoo Passage under normal conditions and then with the nares occluded. The latter condition resulted in a significant reduction

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of nasalance. They attributed the decrease in nasalance to reduced detection of the transpalatal transfer of acoustic energy due to occlusion of the nares. For the vowels /i/, /a/, and /u/, the reduction in nasalance was greatest for /i/, suggesting that transpalatal nasalance was greatest for this vowel. Gildersleeve-Neumann and Dalston attributed this finding to increased dampening of acoustic energy by a more retro-positioned tongue for the vowels /u/ and /a/.

As indicated by Gildersleeve-Neumann and Dalston (2001), the phenomenon of transpalatal transfer of acoustic energy is not new. Indeed, Fletcher et al. (1989) noted that ‘‘even in the presence of a closed velopharyngeal port, nasal resonance may be instigated by vibrations from surrounding bony and soft tissue structures’’ (p. 246). Hoit et al. (1994) attributed the increase in nasalance reported among older speakers in part to ‘‘sympathetic transfer of acoustic energy from the oral cavity to the nasal pathways’’ (p. 302). Hoit and colleagues noted that such transfer would be more likely to occur in palatal structures that were less dense because of aging and atrophy. Rothenberg (2006) identified vibration of the soft palate as one source of ‘‘error’’ associated with the measurement of nasalance. The term ‘‘error’’ was used to denote nasalance that resulted from sources other than direct oral-nasal coupling. Rothenberg noted that vibration of the soft palate was ‘‘highly variable’’ and depended upon factors that included the F0 of the speaker and the ‘‘acoustic compliance of the soft palate’’ (p. 6).

Guildersleeve-Neumann and Dalston (2001) also highlighted the clinical importance of transpalatal nasalance. They stated: ‘‘It is conceivable that some patients with repaired clefts of the secondary palate may achieve complete velopharyngeal closure and yet still be unable to eliminate oral-nasal resonance imbalance in their speech because of the acoustic transmission characteristics of their soft palate’’ (p. 110).

Gildersleeve-Neumann and Dalston further noted that because of surgical scarring of the soft palate, speakers with repaired cleft palate may have different acoustic transmission characteristics than noncleft speakers.

Given the implications of transpalatal nasalance, it is surprising that few studies have attempted to quantify its magnitude or investigate contributing factors. Although Gildersleeve-Neumann and Dalston (2001) did not directly report an estimate of transpalatal nasalance, it can be determined from the data reported in table 1 of their study (p. 108). For example, the difference in nasalance between the unoccluded (31%) and occluded (6%) conditions was 25% for the vowel /i/. This means that approximately 80% of nasalance for /i/ can be attributed to transpalatal effects and 20% to acoustic crossover. A limitation of their study, however, involved methodology. Because they did not monitor actual VP status, they could not rule out the possibility that incomplete closure occurred, even transiently, for some speakers. Although most of the speakers likely achieved and maintained VP closure, there have been reported cases of some noncleft speakers who exhibited atypical nasal airflow during production of nonnasal sounds (e.g., Thompson and Hixon, 1979; Andreassen et al., 1992; Zajac, 2000).

The primary purpose of the present study was to estimate nasalance associated with the transfer of energy across palatal structures during production of voiced stop consonants by noncleft speakers. In theory, during production of oral stop consonants, deviations from 0% nasalance can be attributed to (1) the oral transfer of acoustic energy into the nasal cavity (i.e., transpalatal nasalance) and (2) the oral transfer of acoustic energy across the lips and/or tongue with subsequent crossover to the nasal microphone. To estimate error due to the transfer of energy across the lips and/or tongue, we also instructed the speakers to produce the nasal consonants. Because of the need to confirm VP closure during production of stop consonants, we used an oral-nasal mask to simultaneously determine acoustic nasalance and oral and nasal airflows. A secondary purpose of the study was to determine the relationship between the transpalatal nasalance and F0 of the speaker. This objective was motivated by acoustic theory. It is well known, for example, that sympathetic vibration of a structure depends upon an imposed sound source.

METHOD

Participants

Initially, 10 men and 10 women without cleft palate or other known craniofacial anomalies were recruited to participate in the study. The mean age of the men was 21.6 years, with a standard deviation (SD) of 3.9. The mean age of the women was 22.4 years, with a SD of 4.1. All subjects were screened to ensure that they met the five criteria for inclusion: (1) English as their first (i.e., native) language; (2) the absence of colds and upper respiratory infections at the time of the study; (3) no oral or nasal surgeries within the previous year; (4) normal speech, voice, resonance, and nasal emission characteristics, as judged by both investigators (E.B. and D.Z.); and (5) hearing within normal limits, as determined by pure-tone screening at a hearing level of 25-dB at 0.5, 1, 2, and 4 kHz in the better ear. Potential participants were screened for any recent surgeries of either the mouth or nose to eliminate possible acoustic impedance effects due to localized tissue swelling. The racial composition of the participants comprised 10 Caucasian women, 6 Caucasian men, 3 African American men, and 1 Asian American man. Once potential participants passed the above screening procedures, participants reviewed a consent form, and any questions they had were addressed. The consent form and the study plan were approved by an institutional review board at the University of North Carolina at Chapel Hill.

Speech Sample

The speech sample consisted of syllables with voiced stops (/eb/, /ed/, /eg/) and nasal consonants (/em/, /en/, /eη/) embedded in the carrier phrase ‘‘Say ——— again.’’ Voiced stops were selected for the following reasons. First, the production of these sounds, in theory, should generate relatively high levels of transpalatal nasalance compared with other nonnasal sounds because of closure of the oral cavity during the stop phase (Krakow and Huffman, 1993). Indeed, oral cavity impedance has been reported to affect nasalance associated with different vowels (e.g., Lewis et al., 2000). Second, because obstruent consonants have been reported to be produced with maximal VP closure (Bell-Berti, 1993), the confounding effects of transient VP openings should be minimized. Third, because of oral cavity closure, the effects of acoustic crossover (i.e., sound from the oral cavity reaching the nasal microphone) would be reduced. Fourth, stop consonants are relatively easy to identify by the presence of gaps in both the acoustic and airflow signals.

Place of production of the voiced stop consonants was studied because we speculated that oral cavity impedance might affect transpalatal nasalance, directly and/or indirectly. Direct effects might occur, given the findings of Gildersleeve-Neumann and Dalston (2001). They suggested that a more retropositioned tongue might dampen transpalatal vibrations. Indirect effects might occur because of differences in the transfer of acoustic energy across the lips and/or tongue, with subsequent crossover to the nasal microphone. Because of these possible effects, we also studied the nasal consonants. We anticipated that a comparison of oral and nasal consonants might help to estimate the magnitude of energy transfer across the lips and/or tongue. Finally, given that we were not interested in vowel effects per se, we selected /e/ to be paired with the target consonants because it resulted in real words or relatively easy to produce nonsense syllables.

Each carrier phrase was repeated five consecutive times. The order in which speakers produced the five carrier phrases was randomized for each speaker. An exclusion criterion was used to eliminate orders that consisted of three consecutive oral or nasal consonants. This was done to help eliminate possible learning and preservative effects that might result from three consecutive oral or nasal targets. Following production of the carrier phrases, the participants read the Zoo Passage (Fletcher, 1972) a single time. As described later, this was done to provide some evidence of concurrent validity of nasalance derived using an oral-nasal mask.

Instrumentation

An OroNasal Nasality System mask (Model O/N-MA1, Glottal Enterprises, Inc., Syracuse, NY) was used to simultaneously obtain acoustic nasalance and oral and nasal airflows during production of the speech sample (Fig. 1). The OroNasal mask is similar to the Nasometer (Kay Elemetrics, Inc., Lincoln Park, NJ) in that two microphones are used to detect oral and nasal sound energies during speech production. The microphones, however, are embedded in the base of a circumferentially vented (CV) divided mask that can also be used to detect oral and nasal airflows. All face masks distort the acoustic speech signal to some degree. The manufacturer of the OroNasal mask states that the mask is designed to provide minimal acoustic distortion. Although frequency response characteristics are not provided by the manufacturer, Rothenberg (1973) reported that the response of a single-chamber CV mask was relatively flat up to 1.6 kHz. Given the relatively low–bandpass filter settings (limited to frequencies below 750 Hz, as described later), we anticipated negligible effects of the mask on derived nasalance scores.

The signals from each microphone were digitized (22.05-kHz sampling rate) and bandpass filtered with a computer running OroNasal Nasality Software (Version 1.5, Glottal Enterprises, Inc., Syracuse, NY). The software provides options to digitally filter the acoustic signals with settings that either approximate the Nasometer (i.e., 350 to 750 Hz) or are specific to expected F0 (i.e., 80 to 160 Hz for men and 120 to 240 Hz for women). Rothenberg (2006) claims that nasalance calculated from settings based upon the F0 (F0-derived) is less dependent on a particular vowel or pitch of a speaker than nasalance derived from the first formant (F1) energy region (F1-derived). Rothenberg notes that the nasal signal contains a relatively stronger F0 component and a weaker F1 component than the oral signal. As the F0 of a speaker approaches the lower limit of a 350-to-750-Hz passband filter, more energy will pass the nasal channel relative to the oral channel, and nasalance will increase. Similarly, nasalance for a vowel will increase as the F0 approaches the F1 (e.g., /i/). The extent of these effects will depend upon the steepness of the slope of the filter used to analyze the signals. For example, a filter with a less steep slope will pass relatively more energy beyond the nominal cutoff points than a filter with a steeper slope. For the present study, we calculated nasalance with digital filter settings both specific to the expected F0 and approximant to the F1 energy region. This was done to obtain preliminary evidence relative to (1) the concurrent validity of the OroNasal mask for F1-derived nasalance and (2) the claimed advantages of F0-derived nasalance (Rothenberg, 2006). We anticipated that the latter might be accomplished given that the slope characteristics of the OroNasal software digital filters are the same for either analysis mode (Glottal Enterprises, personal communication).

According to the manufacturer, calibration of the OroNasal mask microphones is not necessary because the sensitivity and frequency response of the microphones are closely matched (Glottal Enterprises, personal communication). We evaluated this statement by performing a calibration check of the microphones. A function generator and amplified loudspeaker were used to deliver sine and square waves to the OroNasal mask microphones from a distance of approximately 5 inches. Sine wave frequencies of 120 and 180 Hz were selected to represent typical F0s for men and women, respectively. A 105-Hz square wave was selected because this type of signal produces harmonics in the F1 range and it is used to calibrate the Nasometer. F0-derived nasalance scores obtained with the bandpass filter settings for men and women were 49.7% and 49.6%, respectively. F1—derived nasalance scores obtained with the bandpass filter settings that approximate the Nasometer was

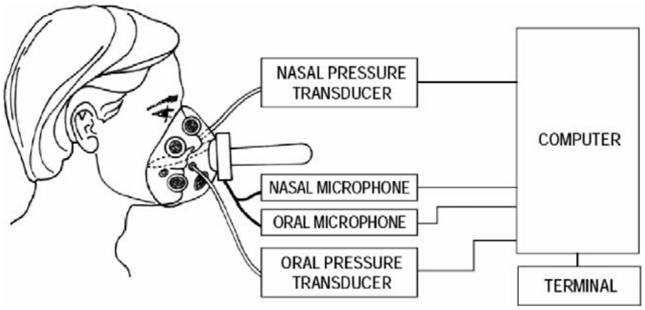

FIGURE 1 Illustration of OroNasal Nasality System mask (Glottal Enterprises, Inc.). A divided circumferentially vented mask is used to obtain nasal and oral airflows. Two microphones embedded in the base of the mask handle (not visible) transduce the nasal and oral acoustic signals.

50.0%. These values indicate satisfactory calibration of the microphones. Calibration checks, periodically during the course of the study, revealed similar nasalance values.

The OroNasal Nasality System requires that the threshold value for silence discrimination be set to the specific audio characteristics of the user's computer sound card. When the threshold (expressed in dB) is set properly, the program should indicate no nasalance during intervals containing silence or unvoiced speech sounds. In addition, ''no gaps should be seen in the display of continuously voiced speech sounds with the possible exception of the closed interval of a voiced stop, e.g. /b/'' (p. 6, OroNasal Nasality System, User Manual, 2002). For the present study, a silence threshold of 50 dB was selected because this reference value enabled a nasalance signal to be detected during the intervals of the voiced stop gaps associated with /b/, /d/, and /g/ but not during nonspeech silence intervals, such as pauses between words. We need to note that the OroNasal Nasality System User Manual states that the reference value ''is an arbitrary level within the system'' and will vary from system to system depending on the characteristics of the sound card in the computer. Finally, as with all nasalance systems, some crossover of acoustic energy between oral and nasal microphones is inevitable. The manufacturer of the OroNasal mask states that crossover from all sources results in a nasalance ratio reading of about 0.1 to 0.15 (Glottal Enterprises, personal communication). We estimated crossover effects, expressed in percent nasalance, as follows. A headphone speaker was used to alternately seal the chambers of the OroNasal mask. A 105-Hz square wave was then delivered to the speaker, and the F1-derived nasalance was recorded. Crossover from the nasal to the oral microphone was approximately 5%, and crossover from the oral to the nasal microphone was approximately 15%. Given that the chambers of the mask are not identical in design (Fig. 1), this difference was not unexpected.

Oral and nasal airflows during production of the speech samples were simultaneously detected by inserting air pressure taps into the oral and nasal chambers of the mask (Fig. 1). These taps were connected to two separate differential air pressure transducers (Setra, Model 239, Boxborough, MA). Oral and nasal airflow signals were low-pass filtered (80 Hz) and digitized (1-kHz sampling rate) to a computer using PERCI-SARS hardware and software (Version 3.21, Microtronics, Inc., Chapel Hill, NC). The acronym ''PERCI-SARS'' represents the names of the original system (Palatal Efficiency Ratings Computed Instantaneously) and the updated system (Speech Aeromechanics Research System). The oral and nasal portions of the mask were calibrated with a compressed air supply and rotometer that delivered an airflow of 250 mL/s. Finally, an external microphone was positioned approximately 3 inches in front of the oral portion of the mask to record the audio signal. The audio signal was low-pass filtered (9 kHz) and digitized (20-kHz sampling rate) to the computer using PERCI-SARS hardware and software. This additional audio signal was used to obtain the F0 of the speakers and to help determine the stop segments during production of the phrases.

Procedures

All participants practiced saying the target syllables within the carrier phrase at least one time before data were recorded. All phrases were said at self-determined conversational pitch, rate, and loudness levels. Once the mask was in place, the participants were asked to sustain /m/ and then to sustain /i/ so the investigators could verify the mask was adequately sealed around the nose and mouth, respectively, without the occurrence of crossover airflow. If crossover airflow was detected, the participants were instructed to remove the mask, reposition it, and repeat the sustained utterances. Once an adequate mask seal was confirmed, the participants were asked to say the randomly ordered carrier phrases. Following completion of the carrier phrases, the participants were asked to read the Zoo Passage a single time after a practice reading.

Data Analysis

OroNasal Nasality software was used to determine the mean nasalance during reading of the Zoo Passage for each speaker. The software also was used to determine peak nasalance during each voiced stop and nasal consonant produced in the carrier phrases. These segments were identified by replaying the audio signal and were marked with the software's cursors. The duration of the segments typically averaged 100 to 150 ms. Once marked, the segments were automatically analyzed by the software in 40-ms consecutive blocks with 50% overlap. Descriptive statistics, including peak nasalance expressed in percentage, were generated by the software. Mean peak nasalance was then calculated for each speaker and each consonant based upon the five productions. PERCI-SARS software was then used to determine the peak nasal airflow that occurred during each stop and nasal consonant produced in the carrier phrases. These segments also were identified by replaying the audio signal. Although oral airflow also was obtained as part of the procedures, this signal was used to help identify phonetic segments, so these values are not reported.

Because normal velar movement (i.e., velar bounce) during production of high pressure stop consonants might create artifact nasal airflow, a flow rate of 30 mL/s or less was selected as a criterion to indicate VP closure. This criterion was selected based on evidence reported by Fisher and Swank (1997) that artifact airflow as high as 30 mL/s could be generated in a divided oral-nasal mask. We need to note that Zajac (2000) previously suggested that a nasal airflow criterion of 20 mL/s or less might account for artifact effects. That study, however, measured nasal airflow with a tube inserted into a single nostril rather than with a face mask that covered the entire nose. Given that a face mask will detect displaced air volume from both nasal passages, the use of the 30-mL/s flow rate was deemed appropriate.

Finally, PERCI-SARS software was used to obtain the mean F0 of each speaker. This was done by analyzing the audio signal obtained with the microphone positioned outside the oral portion of the mask with a pitch subroutine to determine the F0 during a midportion of the vowel /e/ in the target syllable of the stop consonants.

Reliability

Intrajudge reliability of the nasalance scores was estimated by randomly selecting two participants (one man and one woman) and having the original scorer repeat all measurements. For the man, the scorer obtained 30 of 30 (100%) exact agreements for repeated measurements of the consonants (i.e., 3 stops and 3 nasals each produced 5 times). For the woman, the scorer obtained 29 of 30 (97%) exact agreements. The 1 disagreement resulted in nasalance scores that differed by only 4%. Interjudge reliability was also estimated by having a second scorer independently obtain nasalance for both speakers. For the man, the second scorer obtained 29 of 30 (97%) exact agreements with the original scorer. The 1 disagreement resulted in nasalance scores that differed by 9%. For the woman, the second scorer obtained 28 of 30 (93%) exact agreements with the original scorer. The 2 disagreements resulted in nasalance scores that differed by only 2% and 3%, respectively. These data indicated good reliability for the nasalance measurements.

Statistical Analysis

Paired *t* tests were used to determine whether any significant differences existed between F0-derived and F1-derived nasalance scores. Analysis of variance (ANOVA) procedures were used to evaluate the mean peak nasalance data. Given that we expected differences between the stop and nasal consonants, separate three-by-two ANOVAs were performed, with the place of articulation as a repeated factor and the speaker's sex as a between factor. Sex was evaluated because at least one previous study has reported a small but significant nasalance difference between men and women (e.g., Seaver et al., 1992). Tukey HSD (honestly significant different) tests were used to determine post hoc differences among consonants when place effects were found. Independent *t* tests were used to evaluate possible sex differences for the Zoo Passage. Finally, linear regression methods were employed to determine the relationship between the transpalatal nasalance levels and F0 of the speakers. Alpha levels were set at .05 for all statistical tests.

RESULTS

VP Closure During Stop Consonant Production

The extent of VP closure during production of the stop consonants was assessed among all speakers by examining the magnitude of peak nasal airflow. Overall, by collapsing across sex and place of articulation, 285 of 300 (95%) stops were produced with VP closure, as defined by the 30-mL/s nasal airflow criterion. Of the 15 stops that were produced with nonartifact nasal airflow, 9 were produced by 2 men (5 and 4 stops, respectively). Because these speakers tended to exhibit nasal airflow primarily during a particular stop (/g/ and /d/, respectively), they were excluded from the following data analysis. This resulted in a total of 18 speakers (10 women, 8 men) who produced 264 of 270 (98%) stops with complete VP closure, as indicated by the lack of nasal airflow.

Peak Nasalance of Stop and Nasal Consonants

Figure 2 illustrates data from a woman producing ''Say /eb/ again.'' The middle and bottom graphs are the audio and nasal airflow signals, respectively, obtained with PERCI-SARS software. The F0-derived nasalance signal, obtained with Oro-Nasal Nasality System software, is superimposed at the top. The speaker produced the phrase with a slight pause after the word ''say,'' as indicated by the gaps in both the audio and nasalance signals. The duration of the pause, however, was not long enough to result in VP opening, as indicated by the stable nasal airflow signal. As expected, the figure reveals a peak in nasalance associated with the /n/ segment at the end of the phrase. In addition, two relatively high peaks in nasalance are associated with the /b/ and /g/ segments in the target syllable /eb/ and the word ''again,'' respectively. As seen in the audio signal, both of these nasalance peaks are associated with voiced stop gaps. As further seen in the nasal airflow signal, the target segment /b/ was produced with VP closure, as indicated by airflow that did not exceed the 30-mL/s artifact criterion (dotted horizontal line). Indeed, each of the other obstruent consonants (/s/ and /g/) in the phrase is also associated with artifact nasal airflow that occurred because of velar bounce. We support this interpretation by noting that (1) actual VP openings associated with utterance onset and offset are clearly evidenced by nasal airflow that exceeds the 30-mL/s criterion and (2) the small negative airflows that occur following the stop segments are characteristic of velar bounce. Finally, we need to note that a peak in nasalance does not occur during the fricative /s/. Most likely, differences in voicing and manner of production (i.e., a relatively open oral cavity) contributed to this finding.

Table 1 presents individual speaker and group means and standard deviations of peak F0-derived nasalance scores for the

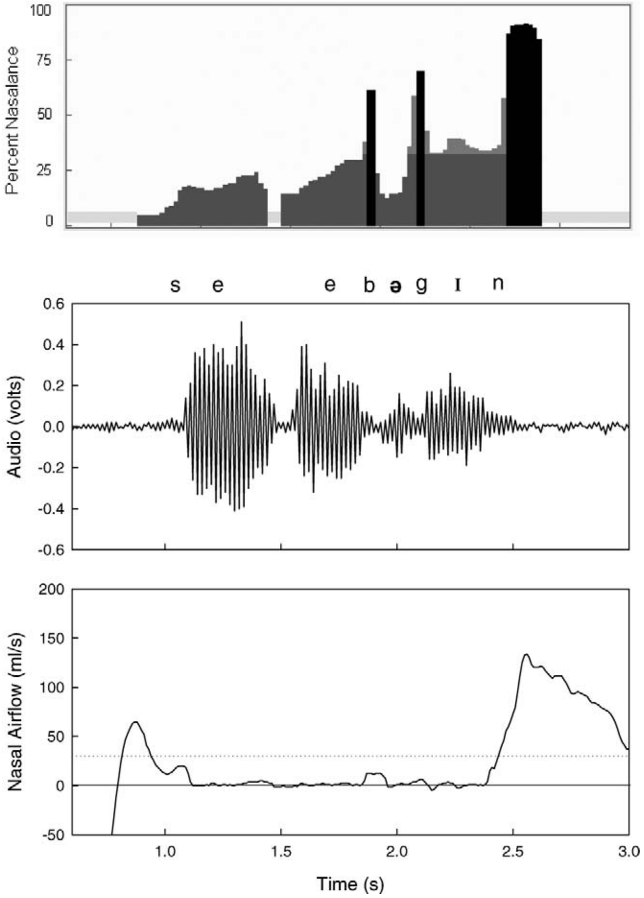

FIGURE 2 Data from a woman producing "Say /eb/ again." Middle and bottom graphs are the audio and nasal airflow signals, respectively. Top graph has superimposed F0-derived nasalance signal. Horizontal dotted line on the airflow graph indicates the 30-mL/s artifact criterion. Horizontal bar on the nasalance graph indicates intervals of silence.

stop and nasal consonants as a function of the sex of the speakers (N = 18). As revealed by the table, individual speakers exhibited large variability during production of voiced stops, as indicated by nasalance means ranging from a low of 17.0% to a high of 82.1% across all stops. The nasal consonants were produced with substantially less variability, as indicated by a low nasalance mean of 80.0% and a high mean of 94.5%. For all speakers, higher nasalance was associated with the nasal consonants, as expected (i.e., /m/ was higher than /b/, /n/ was higher than /d/, and /η/ was higher than /g/ for each speaker). Both women and men tended to exhibit an increase in nasalance as the place of stop production moved from labial to alveolar to velar. Nine of 10 women and 6 of 8 men, for example, demonstrated greater nasalance for /g/ than for /b/.

Table 2 presents F1-derived nasalance scores for the speakers. Within-speaker standard deviations are not shown because the relative dispersions of scores are the same as for F0-derived nasalance. Although some speakers exhibited substantial F1-derived values for stops compared with F0-derived values (e.g., woman #1), there were little overall group differences between F0-derived and F1-derived nasalance. For example, collapsing across the sex of the speakers, the mean peak F0-derived nasalance for /b/, /d/, and /g/ were 51.6% (SD = 10.5), 54.0% (SD = 18.7), and 59.0% (SD = 17.0), respectively (Table 1). Mean peak F1-derived nasalance for /b/, /d/, and /g/ were 54.6% (SD = 7.6), 54.6% (SD = 16.8), and 57.2% (SD = 15.9), respectively (Table 2). Paired *t* tests revealed no significant differences between F0-derived and F1-derived nasalance for the three stop consonants ($p > .05$).

For the nasal consonants, F0-derived and F1-derived nasalance also were similar. Mean peak F0-derived nasalance for /m/, /n/, and /η/ were 88.2% (SD = 3.0), 91.0% (SD = 3.2), and 92.1% (SD = 2.4), respectively (Table 1). Mean peak F1-derived nasalance for /m/, /n/, and /η/ were 85.8% (SD = 5.2), 89.3% (SD = 3.6), and 88.7% (SD = 4.0), respectively (Table 2). Although differences among the nasal consonants were similar in magnitude to differences among the stop consonants, paired *t* tests revealed significant differences between F0-derived and F1-derived nasalance for all three nasal consonants ($p < .05$). Most likely, this occurred because of the substantially smaller standard deviations associated with the nasal consonants.

Focusing on the F0-derived nasalance in Table 1, results of an ANOVA with stops as a repeated factor and sex as a between factor indicated that the sphercity assumption for repeated measures was achieved (Max and Onghena, 1999) and that the main effect for stops was significant (F[2,32] = 3.60, $p < .05$, eta squared = .184). The main effect of sex and the sex-by-stop interaction was not significant. A multivariate ANOVA, which does not require the sphercity assumption, also indicated a significant effect of stops (Hotellings F[2] = 4.72, $p < .05$, effect size = .386). Post hoc Tukey tests indicated a significant difference between /b/ (mean nasalance = 51.6%) and /g/ (mean nasalance = 59.0%).

Results of a second ANOVA with nasals as a repeated factor and sex as a between factor indicated that the sphercity assumption was achieved and that the main effect for nasals was significant (F[2,32] = 16.16, $p < .001$, eta squared = .503). The main effect of sex was also significant (F[1,16] = 5.43, $p < .05$, eta squared = .253). The sex-by-nasal interaction was not significant. A multivariate ANOVA also indicated a significant effect of nasals (Hotellings F[2] = 12.93, $p < .05$, effect size = .633). Post hoc Tukey tests indicated significant differences between /m/ (mean nasalance = 88.2%) and /η/ (mean nasalance = 92.1%) and between /m/ and /n/ (mean nasalance = 91.0%). Relative to sex, men produced the nasal consonants with significantly greater nasalance than women. Given the primary focus of the study, this effect is not discussed. Significantly higher nasalance during production of nasal consonants by men, however, may be related to increased oral impedance (i.e., greater mass of lips and/or tongue) compared with women.

Focusing next on the F1-derived nasalance in Table 2, results of univariate and/or multivariate ANOVA procedures indicated no significant main effects of the place of articulation or the sex of the speakers and no significant interactions for either the stop or nasal consonants ($p > .05$).

TABLE 1 Individual Speaker and Group Means (SDs) of Peak F0-Derived Nasalance Scores (%) for Stop and Nasal Consonants as a Function of the Sex of the Speakers (N = 18) and Mean F0-Derived Nasalance Scores (%) for the Zoo Passage

		F0-Derived Nasalance (%)						
Speaker Sex	*No.*	*/b/*	*/d/*	*/g/*	*/m/*	*/n/*	*/ŋ/*	*Zoo*
Female	1	38.9 (4.3)	46.0 (10.1)	48.6 (12.1)	88.7 (0.1)	91.4 (0.6)	91.8 (0.3)	11.1
	2	59.8 (11.0)	79.0 (2.3)	82.1 (1.3)	86.1 (4.7)	91.1 (0.3)	91.8 (0.5)	25.8
	3	61.5 (2.4)	72.4 (0.7)	77.6 (1.5)	90.2 (0.4)	92.0 (0.3)	93.9 (0.1)	19.0
	4	54.7 (9.6)	71.9 (5.9)	63.6 (12.8)	86.0 (1.3)	89.1 (0.5)	89.9 (1.2)	15.9
	5	56.1 (10.5)	63.1 (14.7)	61.6 (17.8)	89.5 (0.5)	93.0 (0.3)	94.1 (0.2)	18.1
	6	45.7 (13.3)	17.0 (3.6)	39.1 (11.8)	80.0 (4.3)	84.7 (6.7)	90.6 (1.2)	13.4
	7	28.9 (11.1)	30.7 (3.7)	38.0 (5.2)	89.2 (1.8)	90.6 (1.3)	92.2 (0.4)	†
	8	62.3 (11.2)	64.0 (11.8)	73.0 (7.1)	84.1 (3.4)	92.7 (0.4)	93.5 (0.4)	18.0
	9	50.5 (14.3)	58.2 (10.5)	77.6 (2.6)	85.6 (4.6)	90.5 (1.2)	92.6 (0.2)	20.8
	10	60.3 (1.7)	68.2 (0.5)	66.8 (1.2)	87.8 (0.7)	81.3 (2.7)	89.2 (0.6)	19.4
Group mean (SD)		51.9 (11.0)	57.0 (19.9)	62.8 (16.0)	86.7 (3.1)	89.6 (3.8)	92.0 (1.7)	18.0 (4.3)
Male	2	47.9 (9.5)	50.9 (6.0)	64.9 (17.8)	89.7 (0.7)	93.6 (0.3)	92.6 (2.4)	16.4
	3	60.5 (3.1)	67.6 (10.0)	69.1 (2.2)	92.0 (0.4)	93.9 (0.8)	94.4 (0.3)	21.9
	4	29.4 (14.1)	31.3 (8.9)	35.2 (20.6)	87.7 (3.4)	91.7 (3.2)	93.5 (1.6)	13.8
	5	45.3 (3.1)	26.5 (6.7)	20.7 (3.5)	90.0 (0.2)	91.5 (3.0)	85.7 (11.3)	15.9
	6	58.1 (1.7)	63.8 (6.1)	58.3 (14.4)	88.9 (0.2)	91.9 (0.6)	89.5 (2.7)	13.0
	7	57.1 (4.7)	74.2 (3.6)	70.7 (3.1)	89.3 (0.3)	93.9 (0.3)	94.3 (0.3)	13.6
	8	59.8 (1.6)	51.5 (12.6)	65.8 (14.9)	90.0 (0.5)	91.7 (0.7)	94.5 (0.2)	20.1
	10	52.7 (15.0)	35.7 (18.2)	48.8 (15.6)	92.4 (1.2)	93.5 (1.4)	94.0 (1.1)	19.5
Group mean (SD)		51.4 (10.5)	50.2 (17.7)	54.2 (18.0)	90.0 (1.6)	92.7 (1.1)	92.3 (3.1)	16.8 (3.4)

† Missing data.

Mean Nasalance of the Zoo Passage

Tables 1 and 2 also present the mean nasalance score of each speaker during the reading of the Zoo Passage. A paired *t* test revealed no significant difference ($p > .05$) between F0-derived (17.4%, SD = 3.8) and F1-derived (17.9%, SD = 2.9) nasalance. Independent *t* tests indicated no significant differences between men and women for either F0-derived or F1-derived nasalance ($p > .05$). As indicated in Tables 1 and 2, nasalance scores for one woman were not obtained because of a recording error.

Overall, for either F0-derived or F1-derived nasalance, scores for the Zoo Passage were essentially similar to data derived from the Nasometer, as reported by Seaver et al. (1992). This finding provides concurrent validity for F1-derived nasalance using the OroNasal mask and indicates that distortion of acoustic signals was not a significant problem.

Relationship Between F0 and Nasalance of Stop Consonants

Figure 3A illustrates a linear regression between the F0 of the speakers and mean peak F0-derived nasalance of the stop consonants. Each data point in the figure represents mean nasalance across all three stops for a given speaker. As illustrated, there was a low and nonsignificant correlation ($p > .05$). Figure 3B illustrates a linear regression between the F0 of the speakers and F1-derived nasalance of the stop consonants. As illustrated, there was a higher but still nonsignificant correlation. Finally, Figure 3C illustrates the same data as Figure 3B but with one woman who appeared to be an outlier (F0 of 229 Hz and nasalance of 32%) omitted. As illustrated, there was a moderately high and significant ($p < .05$) correlation between the F0 of the speakers and F1-derived nasalance.

TABLE 2 Individual Speaker and Group Means (SDs) of Peak F1-Derived Nasalance Scores (%) for Stop and Nasal Consonants as a Function of the Sex of the Speakers (N = 18) and Mean F1-Derived Nasalance Scores (%) for the Zoo Passage

		F1-Derived Nasalance (%)						
Speaker Sex	*No.*	*/b/*	*/d/*	*/g/*	*/m/*	*/n/*	*/ŋ/*	*Zoo*
Female	1	58.7	53.1	58.9	80.9	88.1	88.2	17.2
	2	59.5	74.9	77.7	79.3	90.1	87.6	22.4
	3	60.0	71.0	71.3	91.7	91.4	92.5	14.5
	4	54.3	66.6	66.1	90.3	87.8	87.1	23.2
	5	62.8	72.7	68.7	88.3	92.0	90.9	14.2
	6	48.4	17.7	32.6	77.4	81.6	87.3	15.3
	7	55.6	53.8	58.6	86.2	87.9	88.7	†
	8	63.7	62.8	77.9	82.5	92.4	93.1	19
	9	40.0	49.6	71.9	73.6	89.6	90.4	15.8
	10	59.2	67.9	62.0	88.5	82.5	89.3	17.4
Group mean		56.2	59.0	64.6	83.9	88.3	89.5	17.7
(SD)		(7.2)	(17.0)	(13.2)	(6.1)	(3.7)	(2.1)	(3.3)
Male	2	44.9	44.8	52.5	88.7	93.6	90.0	15.3
	3	51.7	71.3	53.8	90.2	92.1	91.2	22.9
	4	41.9	31.3	54.0	84.4	83.6	85.1	18.1
	5	49.3	29.9	20.4	89.2	89.1	76.4	19.2
	6	55.8	58.9	49.0	86.7	90.4	85.6	16.3
	7	54.2	69.0	60.2	85.0	92.3	91.0	15.7
	8	68.9	47.4	63.3	91.5	92.2	94.4	18.8
	10	54.6	39.5	31.4	91.0	91.3	88.2	19.5
Group mean		52.7	49.0	48.1	88.3	90.6	87.7	18.2
(SD)		(8.2)	(16.0)	(14.7)	(2.7)	(3.1)	(5.5)	(2.5)

† Missing data.

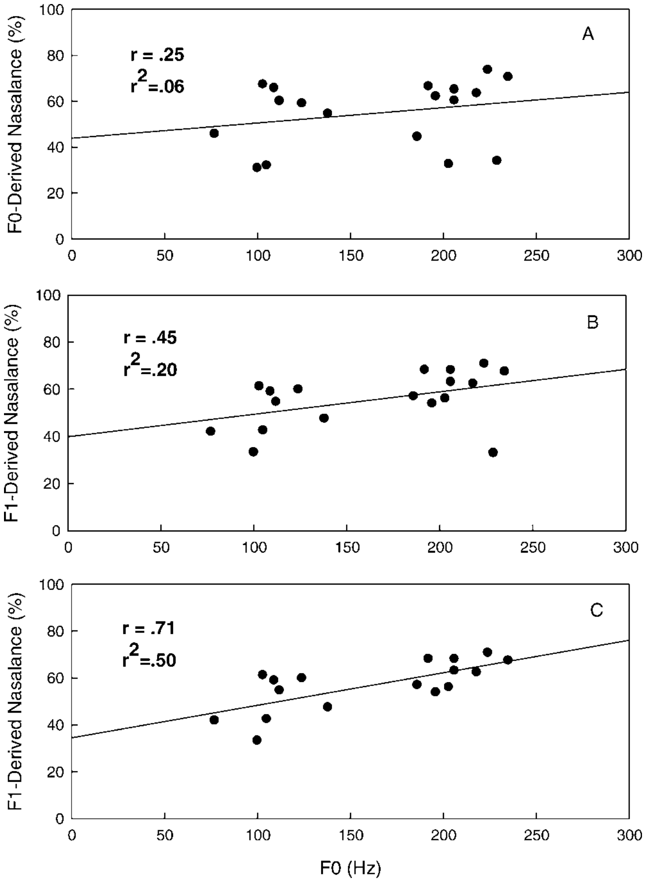

FIGURE 3 A: Linear regression of F0 and F0-derived nasalance of stop consonants (all speakers). B: Linear regression of F0 and F1-derived nasalance of stop consonants (all speakers). C: Linear regression of F0 and F1-derived nasalance of stop consonants (one apparent outlier omitted).

DISCUSSION

The primary purpose of the present study was to determine the transpalatal nasalance associated with voiced stop consonants produced by noncleft speakers using the OroNasal Nasality System mask. The aerodynamic data clearly indicated that the speakers achieved VP closure, as shown by the lack of nasal airflow. Peak nasalance levels, therefore, were not associated with direct oral-nasal coupling. In theory, deviations from 0% nasalance can be attributed to (1) oral transfer of acoustic energy into the nasal cavity (i.e., transpalatal nasalance) and (2) oral transfer of acoustic energy across the lips and/or tongue with subsequent crossover to the nasal microphone. Most likely, transoral effects would be relatively small. As discussed later, examination of the nasal consonants provides an estimate of transoral transfer of energy across the lips and/or tongue.

Relative to nasal consonants, deviations from 100% nasalance can be attributed to (1) crossover of acoustic energy from the nasal to the oral microphone and (2) oral transfer of acoustic energy across the lips and/or tongue. On average, F0-derived nasalance was approximately 90% across all speakers and places of articulation (Table 1), a finding consistent with previous results obtained with the Nasometer. Approximately 10% of nasalance, therefore, can be attributed to the combined effects of microphone crossover and oral transfer of acoustic energy. Because the *in vitro* (i.e., headphone) estimate of acoustic crossover from the nasal to oral chambers of the mask was approximately 5%, this means that another 5% was due to transoral transfer. Indeed, a similar estimate of oral transfer effects can be obtained by examining the place of articulation.

As indicated in Table 1, depending on sex, nasalance was approximately 2% to 5% higher during production of /η/ than /m/. Assuming that the VP opening was relatively constant across nasal consonants, this effect was caused by decreased energy at the oral microphone because of increased oral impedance as the place of articulation moved from anterior to posterior in the oral cavity. In essence, increased nasalance for /η/ occurred as a result of increased oral impedance. These findings, therefore, support the estimate of transoral transfer of energy as no more than 5% for the nasal consonants. We need to note that, as revealed in Table 2, men tended to produce /m/ and /η/ with approximately equal levels of F1-derived nasalance. Although the reason for this is not clear, we speculate that it may relate to lower F0 and transoral transfer effects.

Given that nasalance error due to oral transfer across the lips and/or tongue was no greater than 5% (based upon the nasal consonants) and acoustic crossover from the oral to nasal microphones was approximately 15% (based upon the headphone test), we estimate that at least 80% of nasalance for the oral stops listed in Tables 1 and 2 can be attributed to transpalatal transfer of energy. This estimate of nasalance due to transpalatal effects is consistent with the finding of Gildersleeve-Neumann and Dalston (2001) of 80% for the vowel /i/.

Fundamental Frequency and Transpalatal Nasalance

A secondary purpose of the study was to determine the relationship between the F0 of the speakers and transpalatal nasalance. Depending upon the type of nasalance computed (F0-derived or F1-derived), there was a positive-and-low to a positive-and-moderately-high relationship. Given that the phenomenon of sympathetic vibration (or resonance) of a structure depends upon an imposed sound source, this general trend was not unexpected. Perhaps somewhat surprising, however, was the finding that the relationship was stronger for F1-derived nasalance. Indeed, with one woman omitted (Fig. 3C), the correlation was significant, accounting for approximately 50% of the variance. This implies that the resonant frequency of the soft palate is higher than the F0 and is likely in the range of 350 to 750 Hz. These findings also support the claim of Rothenberg (2006) that F0-derived nasalance is less influenced by the F0 than F1-derived nasalance. Apparently, this occurs because the effects of transpalatal nasalance are eliminated to some extent by the lower passband filter settings. The use of F1-derived nasalance, however, might be preferred when using transpalatal nasalance as a diagnostic index for speakers with repaired cleft palate (discussed later). Finally, we need to note that the OroNasal Nasality System software, Version 1.5, requires the selection of either F0 or F1 filter settings. Because of this, we could not calculate nasalance with other passband settings or the unfiltered acoustic signals. Additional research using such an approach is required to determine the passband region that best reflects transpalatal nasalance.

Variability of Transpalatal Nasalance

As revealed in Tables 1 and 2, the mean peak nasalance of individual speakers tended to vary considerably from a low of approximately 20% to a high of approximately 80% during the production of stop consonants. As indicated above, Rothenberg (unpublished manuscript) noted that vibration of the soft palate is "highly variable" and depends upon several factors, including (1) the vowel or consonant that is produced, (2) the degree of VP coupling, (3) the F0 of the speaker, and (4) the "acoustic compliance of the soft palate." Given that VP closure was confirmed for all speakers, this factor can be eliminated as a source of variability. Of the remaining factors, acoustic compliance of the soft palate appears to contribute the most to variability of transpalatal nasalance. Our reasoning for this assumption is as follows: Relative to the first factor (i.e., the phonetic segment produced), approximately 18% of the variance of F0-derived nasalance was accounted for by the place of stop production, as revealed by an ANOVA. Relative to the third factor, results of the linear regression analysis indicated that 6% of the variance (Fig. 3A) was accounted for by the F0 of the speakers. Thus by default, approximately 75% of the variance of F0-derived nasalance can be attributed to acoustic compliance of the soft palate. Considering F1-derived nasalance (Table 2), although the relative contributions of the place of production and F0 do change, the contribution of the soft palate remains approximately the same. Specifically, an ANOVA ($F[2,32] = 0.30$, $p > .05$, eta squared = .019) indicated that only 2% of the variance was accounted for by the place of stop production, while the linear regression indicated that approximately 20% (Fig. 3B) was accounted for by F0. Thus, approximately 78% of the variance of F1-derived nasalance can be attributed to acoustic compliance of the soft palate. If the data from Figure 3C are used instead, then the relative proportion of variance attributed to compliance of the soft palate is reduced to approximately 50%. Regardless of the actual proportion, the above findings highlight that although multiple sources contribute to variability of transpalatal nasalance, acoustic compliance of the soft palate appears to be primary.

As revealed by the within-speaker standard deviations in Table 1, some speakers exhibited relatively high variability of nasalance across all stop consonants (e.g., woman #5, man #10). Given the above discussion of multiple sources of variance, this finding was not unexpected. In contrast, other speakers exhibited relatively high variability for only one of the stop consonants (e.g., woman #2, man #3). Because the place of production, VP coupling, and F0 were relatively constant, variability among these speakers might have occurred because of transient changes in the acoustic compliance of the soft palate. Given the methodology of the present study, we cannot determine the nature of compliance changes, if extant. We speculate, however, that drainage and/or pooling of normal nasal secretions might be responsible, in part, for these apparent transient changes in transpalatal nasalance.

Clinical Implications

Knowledge of the extent of acoustic nasalance that results from transfer of energy across palatal structures might be important when evaluating patients with repaired cleft palate and hypernasal speech. As indicated by Warren et al. (1993), ‘‘a speech language pathologist may judge an individual to be hypernasal even though the patient demonstrated adequate velopharyngeal closure on instrumental assessment’’ (p. 150). Warren and colleagues suggested that timing factors, such as the duration of VP port opening, might be responsible for the occurrence of hypernasality. On the basis of the current findings and those of Gildersleeve-Neumann and Dalston (2001), it is also likely that transpalatal nasalance might be a factor. For such patients, comparison of nasalance scores on vowels and/or voiced stops with established norms might promote clinical care by enabling clinicians to match behavioral treatment strategies to the underlying cause of perceptual symptoms. For example, in cases where transpalatal nasalance appears to be the primary cause of hypernasality, the use of strategies that increase oral opening (e.g., increased loudness and/or over articulation) might be beneficial. Although F0 appears to be related to transpalatal nasalance, we do not advocate manipulation of pitch as a behavioral strategy. However, because F0 will naturally decline with increasing age, clinicians may be justified in adopting a ‘‘wait and see’’ strategy for some children. Obviously, research involving patients with a repaired cleft palate that incorporates physiologic, nasometric, and perceptual methods is required to determine the usefulness of transpalatal nasalance as a diagnostic index. In the future, the clinical assessment of patients may also necessitate the nonsimultaneous determination of VP status and transpalatal nasalance scores, including use of the Nasometer.

Finally, we need to note that nasalance is typically obtained during the reading of extended passages rather than production of consonant segments. Clinical application of transpalatal nasalance, therefore, may also require the use of additional speech samples. As we suggested earlier, the use of prolonged vowels may facilitate the generation of reliable nasalance scores. The use of passages such as the Zoo Passage may also be needed, or at least the use of representative sentences of the passage.

CONCLUSIONS

Transpalatal transfer of acoustic energy accounts for most nasalance (i.e., approximately 80%) during production of voiced stop consonants by noncleft speakers using an oral-nasal mask. On the basis of F1-derived nasalance, it was estimated that the variance due to the F0 of the speakers accounted for at least 20% to possibly 50% of the obtained transpalatal nasalance. On the basis of these findings, we suggest that determination of transpalatal nasalance may be a useful diagnostic tool for some speakers with a repaired cleft palate. Given that speakers with repaired cleft palate may exhibit different levels of transpalatal nasalance because of inherent tissue deficits and/or effects of surgical scarring, clinical research is needed.

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