Pressure-Flow Characteristics of /m/ and /p/ Production in Speakers Without Cleft Palate: Developmental Findings

DAVID J. ZAJAC, PH.D.

Objective: **The purpose of this study was to describe the pressure-flow characteristics of a large sample of speakers without cleft palate ranging in age from early childhood to young adulthood.**

Method: **Speakers consisted of 223 children, teens, and adults without cleft palate categorized into five age groups: 6 through 8 years, 9 through 10, 11 through 12, 13 through 16, and 18 through 37 years. Speakers produced the syllables /mi/, /pi/, and /pʌ/, the word "hamper," and the sentence "Peep into the hamper." The pressure-flow method was used to determine oral air pressure, nasal airflow, and estimates of velopharyngeal (VP) orifice size associated with /m/ and /p/ production. Descriptive statistics were computed for each age group and speech sample. Analysis of variance (ANOVA) procedures were used to determine the effects of age, sex, and production level (word versus sentence) on the aerodynamic variables.**

Results: **ANOVA procedures indicated significant main effects ($p < .01$) of age on most of the aerodynamic variables during production of /m/ and /p/. No significant main effects or interactions involving sex were found for any variable. Regardless of age, approximately 95% to 99% of the speakers exhibited airtight VP closure during /p/ at syllable level, depending upon the selected nasal airflow criterion. ANOVA procedures also indicated significant main effects of production level (word versus sentence) on each of the aerodynamic variables during the /mp/ sequence. These effects appeared to be related to speaking rate.**

Conclusions: **The study suggests that speakers without cleft palate exhibit essentially complete VP closure during production of oral pressure consonants in isolated syllables, and developmental aspects of speech aerodynamics be considered during pressure-flow testing.**

KEY WORDS: *nasal airflow, oral air pressure, pressure-flow method, speech aerodynamics, speech development*

The pressure-flow technique, originally described by Warren and DuBois (1964), is an objective method for the evaluation of velopharyngeal (VP) function during speech production. The technique provides information on oral and nasal air pressure levels, the rate of nasal airflow, timing relationships between and among pressure-flow events, and estimates of VP orifice size (Warren et al., 1985). To determine VP orifice size, hydrokinetic principles are applied via the "orifice equation." Essentially, this equation is derived from Bernoulli's principle and assumes steady or laminar airflow conditions. Warren and DuBois (1964) introduced a dimensionless coefficient, $k = 0.65$, to account for differences between theoretical and actual (i.e., turbulent) flow conditions found in an analog model of the upper vocal tract. Subsequent studies employing both analog models (e.g., Warren and Devereux, 1966; Lubker, 1969; Smith and Weinberg, 1980; Yates et al., 1990) and human speakers (e.g., Guyette and Carpenter, 1988; Zajac and Yates, 1991) have confirmed the essential validity of the hydrokinetic approach to estimates of VP orifice size. As noted by Yates et al. (1990), however, the actual value of the flow coefficient relative to the human anatomy cannot be determined with certainty and, therefore, is an issue of controversy.

Because of the controversy involving the orifice equation, the importance of oral air pressure and nasal airflow measurements *per se* in the evaluation of VP function is often overlooked. Indeed, Barlow (1999) has described a clinical protocol that uses air pressure and airflow measures to calculate VP resistance as an alternative to area. Although interpretation of a resistance measure may be less intuitive than an area measure, this approach effectively eliminates the controversy involving the value of k in the orifice equation. A relative disadvantage of the Barlow approach, however, is the necessity

---

Dr. Zajac is Assistant Professor, University of North Carolina at Chapel Hill, Chapel Hill, North Carolina.

Submitted July 1999; Accepted December 1999.

Portions of this research were presented at the Annual Convention of the American Speech-Language-Hearing Association, Boston, Massachusetts, November 21, 1997.

Work supported by NIH Grant R29-DE10175.

Reprint requests: Dr. David J. Zajac, UNC Craniofacial Center, CB# 7450, Chapel Hill, NC 27599. E-mail David_Zajac@Dentistry.unc.edu.

of first determining nasal airway resistance during quiet breathing and subtracting this component from the VP resistance measure. Regardless of one's preference for a unit that reflects status of the VP mechanism (area or resistance), the usefulness of the pressure-flow method as a diagnostic or research tool is dependent upon adequate norms for comparison purposes. As noted by Vig and Zajac (1993), normative standards relative to respiratory function—which includes speech aerodynamics—must be appropriate for an individual's age and sex. There are no large-scale studies, however, that have used the pressure-flow method to describe VP function in speakers without cleft palate as a function of age and sex. This is surprising given the noninvasive and objective nature of the procedure; the findings from studies on laryngeal resistance, which have shown robust age differences relative to oral air pressure levels (e.g., Netsell et al., 1994); the findings from kinematic and acoustic studies, which have suggested sex differences in various aspects of VP function (e.g., McKerns and Bzoch, 1970; Kuehn, 1976; Seaver et al., 1991); and the findings from aerodynamic studies, which have suggested age and sex differences in some aspects of VP function (e.g., Thompson and Hixon, 1979). Although Thompson and Hixon studied a relatively large sample of normal speakers, their protocol did not include the determination of oral air pressure or VP area/resistance. Other studies that have included simultaneous pressure-flow measures assessed relatively small samples of either children (e.g., Leeper et al., 1998) or adults (e.g., Andreassen et al., 1992; Zajac and Mayo, 1996).

The purpose of the present study was to describe the pressure-flow characteristics of a large sample of speakers without cleft palate ranging in age from early childhood to young adulthood. Specifically, simultaneous measures of oral air pressure, nasal air pressure, nasal airflow, and estimates of VP orifice size were obtained as a function of age and sex during production of the nasal consonant /m/ and the oral consonant /p/ in syllables, words, and sentences.

METHOD

Participants

Participants consisted of 159 children, 22 teenagers, and 42 adults without cleft palate ranging in age from 6 to 37 years; total sample size was 223 speakers. They were grouped according to five age categories: 6 through 8, 9 through 10, 11 through 12, 13 through 16, and 18 through 37 years. Table 1 shows the distribution of men and boys and women and girls per age category. Ages were rounded to the nearest year. All participants spoke English as a first language. The majority of the children aged 6 through 12 years (n = 152) were recruited from two public schools near Pittsburgh, Pennsylvania. All adults (n = 42) were recruited from the same geographic area. All teens (n = 22) were recruited from Chapel Hill, North Carolina. Seven of the children aged 11 through 12 years were also recruited from North Carolina. Recruitment of some speakers from North Carolina occurred because of the relocation of the investigator during the course of the study. The overall racial composition of the speakers was 83% Caucasian (n = 186), 15% African American (n = 33), and 2% Asian American (n = 4). These proportions reflected primarily the children aged 6 through 12 years recruited from the public schools in Pittsburgh (i.e., 119 Caucasians, 32 African Americans, and 1 Asian American). The effects of possible dialectical differences between Caucasian and African American speakers and between speakers from Pennsylvania and North Carolina are addressed below and in the Results.

Table 1 Number of Speakers in Each Age and Gender Group

Age (years)/Sex	*Number*
6–8	47
Male	21
Female	26
9–10	71
Male	26
Female	45
11–12	41
Male	24
Female	17
13–16	22
Male	11
Female	11
18–37	42
Male	21
Female	21
Grand Total =	223

Speakers were excluded from the study if they reported a history of cleft palate, hearing loss, tonsillectomy or adenoidectomy within a year of the study, or upper respiratory infections at the time of the study. In addition, all children recruited from the public schools passed a hearing screening administered by school personnel and also underwent a visual examination of the oral cavity performed by either the investigator, a trained graduate student in communication disorders, or both. The oral examinations revealed no evidence of undetected submucous cleft palate (i.e., bifid uvula or midline palatal translucence) in any of the children included in the study. One child exhibited a bifid uvula, mild hypernasality, and inaudible nasal air emission. This child was referred to a craniofacial team for evaluation and was not included in the study. It must be noted that speakers were excluded only for the above reasons. Voice, resonance, and articulation were not considered, except for the fact that all speakers were required to exhibit the neuromuscular ability to perform the articulatory tasks described below. Finally, informed parental and adult consents were obtained for all participants.

Speech Samples

The /m/ and /p/ phonemes were selected as the focus of study because they can be articulated with minimal interference from the oral catheter used to detect pressure, and placement and orientation of the pressure catheter are inconsequential because of stagnation-like flow conditions in the oral cavity. The speakers repeated the syllables /mi/, /pi/, and /pʌ/, the word ''hamper,'' and the sentence ''Peep into the hamper.'' The syllables were selected to provide contrasts between the nasal and oral consonant using the same vowel and the relatively high and low vowels using the oral consonant. The word ''hamper'' was selected because the /mp/ sequence requires dynamic adjustment of the VP mechanism. The sentence was selected to embed the /mp/ sequence in a continuous utterance.

Procedures

Oral air pressure was detected using a polyethylene catheter (1.67 mm internal diameter) placed in the speaker's mouth behind the upper incisors. Nasal air pressure was detected using a cork/catheter assembly that occluded the least patent nostril of the subject. Each catheter was connected to the high ports of separate pressure transducers referenced to atmosphere (Setra, Model 239, Acton, MA). Nasal airflow was detected using a plastic tube fitted snugly to the speaker's most patent nostril. The flow tube was connected in series to a heated pneumotachograph (Fleisch, #1, Switzerland) coupled to a third pressure transducer (Setra, Model 239). Patency of the nostrils was determined by either perceptual evaluation (i.e., observation of condensation on a detail reflector during exhalation with the mouth closed) or rhinomanometric testing. Calibration of the oral and nasal air pressure transducers was performed on a daily basis using a well-type manometer. The pressure transducers were shown to be linear over the range of 0 cm to 30 cm H_2O. Calibration of the pneumotachograph-pressure transducer was also performed on a daily basis using a compressed air supply and rotameter. The pneumotachograph-pressure transducer was shown to be linear over the range of 0 mL/s to 500 mL/s. The nominal frequency response of the pressure transducers was flat within 1% over the range of interest from 0 Hz to 20 Hz.

After the pressure catheters and airflow tubing were comfortably in place, the speakers repeated the syllables and the word ''hamper'' approximately five times on continuous exhalation using self-determined rate, pitch, and loudness levels. The sentence, ''Peep into the hamper,'' was repeated three times on continuous exhalation also using self-determined rate, pitch, and loudness levels. The children from Pittsburgh were tested in a quiet room in their schools. All equipment, including calibration devices, was transported to the school setting. Adults from Pittsburgh were tested in an aerodynamic laboratory at the University of Pittsburgh. The children and teens from Chapel Hill were tested in an aerodynamic laboratory at the University of North Carolina.

The pressure-flow signals were low-pass filtered at a cutoff of 15 Hz and digitized to a computer at a rate of 200 samples per second with 12-bit resolution for 5 seconds using PERCI-PSCOPE software, Version 1.1 (Microtronics, Chapel Hill, NC). PERCI-SARS software, Version 2.0, was used to acquire data at the University of North Carolina. This software essentially performs the same tasks as PSCOPE software but operates in a Windows environment. Production of each speech sample was monitored online by the investigator. Speakers, however, did not have visual access to the computer monitor. If intermittent problems such as occlusion of the oral pressure catheter occurred during data collection, then the sample was repeated. An attempt was made to collect multiple trials of each speech sample. It must be noted, however, that because of time constraints associated with testing children in a school setting, not all speakers produced all speech samples, multiple trials of a given speech sample, or both. The actual numbers of speakers that produced each speech sample are presented in Tables 2 through 7 in the Results.

Table 2 Oral Air Pressure as a Function of Age During Production of /m/ and /p/ in Syllables

Consonant/ Age Group (y)	*Oral Air Pressure (cm H_2O)**				
	M	*SD*	*Range*	*95% CI*	*n*
/mi/					
6–8	0.7	0.3	0.2–1.5	0.6–0.8	44
9–10	0.8	0.5	0.2–2.6	0.7–1.0	51
11–12	0.8	0.4	0.2–1.7	0.6–1.0	26
13–16	0.4	0.2	0.2–0.8	0.3–0.5	20
18–37	0.5	0.2	0.1–1.0	0.4–0.6	34
/pi/					
6–8	8.0	2.2	5.1–13.3	7.3–8.6	46
9–10	7.9	2.0	4.9–14.9	7.4–8.4	71
11–12	7.2	2.2	4.1–13.6	6.5–8.0	41
13–16	6.3	1.3	4.1–9.0	5.7–6.9	22
18–37	6.0	1.4	3.5–9.5	5.6–6.5	35
/pʌ/					
6–8	8.1	2.1	4.1–13.9	7.5–8.7	46
9–10	8.0	2.1	4.8–15.3	7.5–8.5	69
11–12	7.1	2.2	4.5–16.2	6.4–7.8	39
13–16	6.0	1.2	3.5–8.7	5.4–6.5	22
18–37	5.9	1.3	3.9–8.7	5.4–6.3	35

* M = mean; SD = standard deviation; CI = confidence interval.

Data Analysis

Mean measurements of oral air pressure, nasal air pressure, nasal airflow, and estimated VP orifice size were determined for the /m/ and /p/ segments from the middle three productions of the syllables and the word ''hamper'' within a trial. The same measurements were determined from the three productions of ''hamper'' produced at sentence level within a trial. All measurements were obtained at peak oral pressure for /p/ and at peak nasal airflow for /m/. If multiple trials of a speech sample were available, only one trial (typically the last) was analyzed for this report. Mean measurements of oral air pressure and nasal airflow during /p/ production at word level, however, were calculated for each of three multiple trials produced by the teenage speakers. These data were used to estimate the reliability of the mean measurements reported below.

To evaluate the possibility of dialectical differences in aerodynamic characteristics between (1) the Caucasian and African American speakers from Pittsburgh and (2) the speakers from Pennsylvania and North Carolina, a measure of anticipatory nasal airflow was determined for all speakers during production of ''hamper.'' This measure consisted of a volume ratio

TABLE 3 Oral Air Pressure as a Function of Age During Production of /m/ and /p/ in "Hamper" at Word and Sentence Levels

Consonant/ Age Group (y)	*Oral Air Pressure (cm H_2O)∗*				
	M	*SD*	*Range*	*95% CI*	*n*
/m/ (word level)					
6–8	1.5	0.7	0.3–3.3	1.3–1.7	47
9–10	1.5	0.8	0.0–3.4	1.3–1.7	71
11–12	1.5	0.7	0.7–4.1	1.3–1.8	41
13–16	1.1	0.4	0.5–1.9	0.9–1.3	22
18–37	1.3	0.7	0.1–4.1	1.0–1.5	42
/m/ (sentence level)					
6–8	1.3	0.6	0.4–2.4	1.1–1.5	43
9–10	1.5	0.8	0.3–5.4	1.3–1.7	61
11–12	1.3	0.6	0.6–2.6	1.1–1.5	36
13–16	1.1	0.5	0.4–2.3	0.8–1.3	21
18–37	1.3	0.6	0.4–3.0	1.1–1.5	35
/p/ (word level)					
6–8	7.1	2.5	2.6–16.3	6.4–7.9	47
9–10	7.2	2.0	3.9–13.8	6.7–7.7	71
11–12	6.6	1.7	3.8–11.1	6.1–7.2	41
13–16	5.6	1.2	3.9–7.7	5.0–6.1	22
18–37	5.3	1.5	2.5–9.1	4.8–5.8	42
/p/ (sentence level)					
6–8	6.9	2.1	2.9–11.8	6.2–7.5	43
9–10	6.4	2.2	2.5–13.4	5.9–6.9	66
11–12	6.3	1.7	3.4–11.9	5.8–6.9	38
13–16	5.3	1.1	3.4–6.9	4.8–5.8	22
18–37	5.4	1.4	3.0–8.7	4.9–5.8	34

∗ M = mean; SD = standard deviation; CI = confidence interval. A value of 0.0 reflects pressures that were less than 0.05 cm H_2O.

of nasal airflow associated with the phonetic segments preceding /m/ to the nasal airflow associated with the entire word (Zajac and Mayo, 1996; Zajac, 1997). It was anticipated that dialectical differences, if extant, would most likely be reflected by a suprasegmental measure of nasal airflow.

TABLE 4 Nasal Air Flow as a Function of Age During Production of /m/ and /p/ in Syllables

Consonant/ Age Group (y)	*Nasal Airflow (ml/s)∗*				
	M	*SD*	*Range*	*95% CI*	*n*
/mi/					
6–8	76	27	15–161	67–84	46
9–10	90	31	38–178	83–98	70
11–12	95	42	31–205	81–108	38
13–16	113	40	45–200	96–131	22
18–37	120	46	55–252	104–136	34
/pi/					
6–8	1	1	0–6	1–2	46
9–10	1	1	0–5	1–2	71
11–12	2	2	0–13	1–3	41
13–16	5	8	0–34	1–8	22
18–37	4	7	0–27	2–7	35
/pʌ/					
6–8	1	1	0–6	1–2	46
9–10	1	2	0–9	1–2	69
11–12	1	1	0–5	1–2	39
13–16	5	14	0–69	0–11	22
18–37	3	4	0–19	2–4	35

∗ M = mean; SD = standard deviation; CI = confidence interval.

TABLE 5 Nasal Airflow as a Function of Age During Production of /m/ and /p/ in "Hamper" at Word and Sentence Levels

Consonant/ Age Group (y)	*Nasal Airflow (ml/s)∗*				
	M	*SD*	*Range*	*95% CI*	*n*
/m/ (word level)					
6–8	87	38	40–165	76–98	47
9–10	96	40	10–184	86–106	71
11–12	122	46	44–230	107–136	41
13–16	158	75	40–340	125–192	22
18–37	139	58	47–280	121–157	42
/m/ (sentence level)					
6–8	72	32	30–150	63–82	43
9–10	82	35	20–169	74–91	66
11–12	102	42	27–181	88–116	38
13–16	145	60	44–260	118–172	21
18–37	128	49	60–287	112–145	35
/p/ (word level)					
6–8	2	3	0–15	2–3	47
9–10	5	7	0–39	3–7	71
11–12	4	5	0–29	3–6	41
13–16	14	17	0–70	9–22	22
18–37	15	16	1–76	10–20	42
/p/ (sentence level)					
6–8	2	2	0–6	2–3	43
9–10	5	7	0–35	3–7	66
11–12	5	7	0–45	2–7	38
13–16	10	15	0–64	3–16	22
18–37	17	19	1–96	11–24	34

∗ M = mean; SD = standard deviation; CI = confidence interval.

Statistical Analysis

Descriptive statistics including means (M), standard deviation (SD), ranges, and 95% confidence intervals (CI) were computed for oral air pressure, nasal airflow, and estimated

TABLE 6 Estimated Velopharyngeal Orifice Area as a Function of Age During Production of /m/ and /p/ in Syllables

Consonant/ Age Group (y)	*VP Orifice Area (mm^2)∗*				
	M	*SD*	*Range*	*95% CI*	*n*
/mi/					
6–8	19.6	9.6	2.3–35.2	14.5–24.7	16
9–10	23.8	13.6	5.3–59.1	19.1–28.4	36
11–12	25.3	16.0	4.6–67.5	18.4–32.2	23
13–16	49.8	25.0	10.6–111.1	37.4–62.2	18
18–37	37.7	22.2	14.5–103.9	29.2–46.1	29
/pi/					
6–8	0.1	0.1	0.0–0.3	0.0–0.1	46
9–10	0.0	0.1	0.0–0.2	0.0–0.1	71
11–12	0.1	0.1	0.0–0.6	0.0–0.1	41
13–16	0.2	0.4	0.0–1.5	0.1–0.4	22
18–37	0.2	0.4	0.0–1.5	0.1–0.4	35
/pʌ/					
6–8	0.0	0.1	0.0–0.3	0.0–0.1	46
9–10	0.1	0.1	0.0–0.4	0.0–0.1	69
11–12	0.0	0.1	0.0–0.2	0.0–0.1	39
13–16	0.2	0.7	0.0–3.2	0.0–0.5	22
18–37	0.1	0.2	0.0–0.9	0.1–0.2	35

∗ M = mean; CI = confidence interval; VP = velopharyngeal. Values of 0.0 reflect areas that were less than 0.05 mm^2.

TABLE 7 Estimated Velopharyngeal Orifice Area as a Function of Age During Production of /m/ and /p/ in "Hamper" at Word and Sentence Levels

Consonant/ Age Group (y)	*VP Orifice Area (mm²)**				*n*
	M	*SD*	*Range*	*95% CI*	
/m/ (word level)					
6–8	15.9	10.7	4.0–50.3	12.8–19.1	46
9–10	15.3	9.4	2.6–54.9	13.0–17.6	68
11–12	19.7	11.9	3.4–57.9	16.0–23.5	41
13–16	27.0	13.2	8.8–63.4	21.2–32.8	22
18–37	19.8	10.2	4.5–42.7	16.7–23.0	42
/m/ (sentence level)					
6–8	13.8	8.9	3.3–39.8	11.0–16.7	40
9–10	13.2	7.4	2.7–36.4	11.3–15.1	61
11–12	16.0	9.0	2.5–34.5	12.9–19.0	36
13–16	25.5	9.9	6.5–47.7	21.0–30.1	21
18–37	17.6	8.3	8.3–43.4	14.6–20.5	34
/p/ (word level)					
6–8	0.1	0.2	0.0–0.7	0.1–0.2	47
9–10	0.2	0.3	0.0–2.2	0.2–0.3	68
11–12	0.2	0.3	0.0–1.6	0.1–0.3	41
13–16	0.6	0.6	0.0–2.1	0.3–0.8	22
18–37	0.7	0.8	0.0–3.4	0.5–1.0	42
/p/ (sentence level)					
6–8	0.1	0.2	0.0–1.0	0.1–0.2	43
9–10	0.3	0.5	0.0–2.9	0.2–0.4	66
11–12	0.2	0.4	0.0–2.5	0.1–0.3	38
13–16	0.6	1.1	0.0–4.8	0.1–1.1	22
18–37	0.9	0.9	0.0–4.8	0.6–1.2	34

* M = mean; SD = standard deviation; CI = confidence intervals; VP = velopharyngeal Values of 0.0 reflect areas that were less than 0.05 mm².

VP orifice area for /m/ and /p/ as a function of age and sex of the speakers. Although nasal air pressure is required to estimate VP orifice area, nasal pressure data *per se* are not presented in this report. ANOVA procedures were used to determine possible age and sex effects on selected data sets. Post hoc differences among groups were determined using Bonferroni tests. Probability levels were set at $p < .01$ for all statistical tests.

RESULTS

The mean measurements of oral air pressure and nasal airflow during /p/ production from the three multiple trials by the teenage speakers were assessed using ANOVA procedures with trials as a repeated measure. Results indicated no significant differences among the three means for oral air pressure (F = 0.70, df = 2, 42, $p = .502$) or nasal airflow (F = 0.03, df = 2, 42, $p = .969$). These findings, therefore, suggest that the mean data reported below are reliable indicators of the aerodynamic variables of interest.

The volume ratios of anticipatory nasal airflow associated with the Caucasian (n = 116) and African American (n = 32) children recruited from the public schools in Pittsburgh were analyzed by an independent *t* test. Data were not available for three of the Caucasian children. The result indicated no significant racial difference between the children (t = −0.38, df = 146, $p = .703$). This analysis, however, should not be interpreted to imply that dialectical differences in other aspects of speech might not exist.

The volume ratios of anticipatory nasal airflow for all of the speakers were further analyzed by a one-way ANOVA using age as the independent variable. The results indicated no significant differences among any of the age groups (F = 1.07, df = 4, 212, $p = .371$). This finding, therefore, suggests that the teenage speakers who were recruited from North Carolina did not exhibit regional differences relative to the other speakers. Indeed, as described below, the teenagers and adults exhibited highly similar pressure-flow characteristics overall. This analysis also should not be interpreted to imply that dialectical differences in speech aerodynamics or other aspects of speech might not exist. The lack of aerodynamic differences in the present study may have occurred because the majority of the speakers from North Carolina exhibited no identifiable regional dialect.

Descriptive statistics for oral air pressure, nasal airflow, and estimated VP orifice area during /m/ and /p/ production as a function of age of the speakers are presented in Tables 2 through 7. Because results of the ANOVA procedures (described below) indicated no significant main effects or interactions involving sex, the data in the tables are collapsed across male and female speakers. In general, age effects were most apparent relative to oral air pressure generated during /p/ and nasal airflow generated during /m/ production. Younger children tended to exhibit higher oral air pressure during /p/ and lower nasal airflow during /m/ in all speech samples. In addition, regardless of age, speakers exhibited a level of production effect involving "hamper." Specifically, the speakers used higher oral air pressure during /p/ and greater nasal airflow during /m/ at word versus sentence levels. Results specific to each pressure-flow variable and speech sample are summarized below.

Oral Air Pressure

Syllable Production

As shown in Table 2, the results of a 5 (age group) × 2 (sex) × 3 (syllable) ANOVA with syllable type (/mi/, /pi/, /pʌ/) as a repeated measure indicated a significant interaction effect between syllable type and age (F = 6.86, df = 8, 328, $p < .001$). Post hoc analyses of the simple effects of syllable type by age revealed the following significant ($p < .01$) pressure differences: (1) during /mi/ among 9- to 10-year-olds and adults, 9- to 10-year-olds and teenagers, and 11- to 12-year-olds and teenagers; (2) during /pi/ between 6- to 8-year-olds and adults and between 9- to 10-year-olds and adults; and (3) during /pʌ/ between 6- to 8-year-olds and adults, between 9- to 10-year-olds and adults, between 6- to 8-year-olds and teenagers, and between 9- to 10-year-olds and teenagers. Post hoc analyses of the simple effects of age group by syllable type revealed significant ($p < .01$) pressure differences between /mi/ and /pi/ and between /mi/ and /pʌ/ for every age group. No significant pressure differences occurred between /pi/ and /pʌ/ for any of the age groups.

Word and Sentence Production (Table 3)

For /m/, the results of a 5 (age group) × 2 (sex) × 2 (production level) ANOVA with production level (word and sentence) as a repeated measure revealed no significant oral air pressure effects of age, sex, production level, or interactions.

For /p/, the results of the ANOVA indicated a significant main effect of age (F = 6.47, df = 4, 193, $p < .001$) and production level (F = 8.01, df = 1, 193, $p < .01$). Regardless of level of production, post hoc analysis of the age effect revealed significant ($p < .01$) pressure differences between 6- to 8-year-olds (M = 7.0, SD = 2.1 cm H_2O) and adults (M = 5.4, SD = 1.3 cm H_2O), and between 9- to 10-year-olds (M = 6.8, SD = 2.0 cm H_2O) and adults. Regardless of age, oral pressure during /p/ was significantly ($p < .01$) higher at word (M = 6.6, SD = 2.1 cm H_2O) than at sentence (M = 6.2, SD = 1.9 cm H_2O) level of production.

Nasal Airflow

Syllable Production (Table 4)

Teenagers and adults generally exhibited greater nasal airflow than the younger children during production of /mi/. The results of a 5 (age group) × 2 (sex) ANOVA indicated a significant main effect of age (F = 8.20, df = 4, 209, $p < .001$). Data for /p/ were not included in the ANOVA because of the essential absence of airflow. Post hoc analysis indicated significant ($p < .01$) differences in nasal airflow between 6- and 8-year-olds and teenagers; 6- to 8-year-olds and adults; and 9- to 10-year-olds and adults.

As noted above, production of the syllables /pi/ and /pʌ/ was generally associated with little if any nasal airflow, especially for children aged 6 through 12 years. Thompson and Hixon (1979) noted that ‘‘small magnitudes’’ of either positive or negative nasal airflow may be detected in the presence of air-tight VP closure due to muscular contractions of the velum which displace small volumes of air. Hoit et al. (1994) suggested that a criterion of 10 mL/s or less of nasal airflow be considered artifact. Applying this criterion to the data of the present study, 95.3% (205/215) and 98.6% (208/211) of the speakers exhibited essentially complete VP closure during /pi/ and /pʌ/, respectively. Using a criterion of 20 mL/s or less of nasal airflow, the percentages increase to 98.6% (212/215) and 99.5% (210/211) for /pi/ and /pʌ/, respectively. Use of the 20 mL/s criterion seems reasonable given that some recent studies have suggested that oral airflow artifact as high as 30 mL/s may occur for adults due to articulator movement within a mask (e.g., Fisher and Swank, 1997; Zajac et al., 1998). In the present study, only two speakers (both teenagers) exhibited nasal airflow greater than 30 mL/s during production of /p/ at syllable level, one speaker during /pi/ (34 mL/s) and one speaker during /pʌ/ (69 mL/s).

Word and Sentence Production (Table 5)

In general, teenagers and adults produced greater nasal airflow than the children during /m/ at word and sentence levels. The results of a 5 (age group) × 2 (sex) × 2 (production level) ANOVA with production level as a repeated measure indicated significant main effects of age (F = 17.17, df = 4, 193, $p < .001$) and production level (F = 36.24, df = 1, 193, $p < .001$). Regardless of level of production, post hoc analysis of the age effect revealed significant ($p < .01$) airflow differences during /m/ between 6- to 8-year-olds (M = 80, SD = 32 mL/s) and 11- to 12-year-olds (M = 112, SD = 42 mL/s), between 6- to 8-year-olds and teenagers (M = 153, SD = 63 mL/s), between 6- to 8-year-olds and adults (M = 135, SD = 51 mL/s), between 9- to 10-year-olds (M = 90, SD = 33 mL/s) and teenagers, between 9- to 10-year-olds and adults, and between 11- to 12-year-olds and teenagers. Regardless of age, speakers exhibited greater nasal airflow during /m/ at word (M = 114, SD = 54 mL/s) than at sentence (M = 98, SD = 48 mL/s) level of production.

VP Orifice Area

Syllable Production (Table 6)

In general, the findings for VP orifice area parallel the findings for nasal airflow. Teenagers and adults typically exhibited larger VP orifice areas than the younger children during production of /mi/. The results of a 5 (age group) × 2 (sex) ANOVA indicated a significant main effect of age (F = 9.32, df = 4, 121, $p < .001$). Post hoc analysis indicated significant ($p < .01$) differences in VP area during /mi/ between 6- to 8-year-olds and teenagers, between 9- to 10-year-olds and teenagers, and between 11- to 12-year-olds and teenagers.

Regardless of age, estimated VP orifice areas were typically under 1 mm^2 during production of /pi/ and /pʌ/. Every speaker who exhibited an area of 1 mm^2 or less also exhibited nasal airflow of 20 mL/s or less. An area criterion of 1 mm^2 or less, therefore, may be considered to reflect complete VP closure. Using this criterion, 98.6% (212/215) and 99.5% (210/211) of the speakers again were classified as exhibiting complete VP closure during /pi/ and /pʌ/, respectively. The largest VP area associated with /pi/ was 1.5 mm^2; the rate of nasal airflow was 34 mL/s. The largest VP area associated with /pʌ/ was 3.2 mm^2; the rate of nasal airflow was 69 mL/s.

Word and Sentence Production (Table 7)

The teenage and adult speakers also exhibited larger VP orifice areas during /m/ production at word and sentence levels. The results of a 5 (age group) × 2 (sex) × 2 (production level) ANOVA with production level as a repeated measure indicated significant main effects of age (F = 7.98, df = 4, 178, $p < .001$) and production level (F = 13.37, df = 1, 178, $p < .001$). Regardless of level of production, post hoc analysis of the age effect revealed significant ($p < .01$) orifice area differences during /m/ between the teenagers and each of the other age groups. Means were 15.0 (SD = 9.0), 14.4 (SD = 7.5), 18.0 (SD = 10.1), 26.7 (SD = 10.3), and 18.1 mm^2 (SD = 7.7) for the youngest to the oldest age group, respectively. Regardless of age, speakers exhibited larger orifice areas during /m/ at word (M = 18.5, SD = 11.4 mm^2) than at sentence (M = 16.0, SD = 9.3 mm^2) level of production.

Finally, during production of /p/ in the /mp/ sequence, estimated VP orifice areas did not exceed 5 mm^2 as an upper limit for any age group of speakers. This finding is in agreement with the limits of VP adequacy as suggested by Warren and his colleagues (e.g., Warren et al., 1989).

DISCUSSION

The results of this study provide developmental information on aerodynamic aspects of /m/ and /p/ production in a relatively large sample of speakers without cleft palate ranging in age from early childhood to young adulthood. Because speakers with repaired cleft palate in this age range are most likely to benefit from instrumental assessment of VP function, these data should be useful to clinicians and researchers who use the pressure-flow technique in particular or aerodynamic procedures in general. As discussed below, the data may also provide some insights into the role of the respiratory system in determining oral air pressure levels and VP motor control strategies during speech production. To facilitate discussion of the data, the following section is organized by oral air pressure findings, nasal airflow findings, VP orifice area findings, level of production effects, and clinical implications.

Oral Air Pressure

Overall, the results confirm that oral air pressure levels are greater in younger children than adults during production of the oral stop /p/ at self-determined loudness levels. These findings are consistent with previous reports involving laryngeal resistance measurements in children and adults (e.g., Netsell et al., 1994). The difference between the 6- to 8-year-old children and adults in the present study averaged approximately 2 cm H_20 during production of syllables, words, and sentences. In addition, children in the age range of 6 to 12 years typically exhibited a higher upper range of mean oral pressures (i.e., 11 cm to 16 cm H_2O) than the teenagers and adults (i.e., approximately 9 cm H_2O).

Several explanations may account for the relationship between age and oral air pressure. Because of the known inverse relation between pressure and volume (i.e., Boyle's Law), some researchers suggested that the absolute size of the vocal tract was the key determinant of peak oral air pressure. Brown and McGlone (1969), however, reported no direct relationship between the magnitude of oral air pressure and vocal tract size as measured from lateral cephalograms of adult male speakers. They suggested physiologic factors such as respiration, voicing, and articulation were responsible for differences in oral air pressure among speakers. Müller and Brown (1980) suggested that the mechanical impedance to airflow was largely responsible for oral air pressure variations among speakers of different ages. Because children have smaller pharyngeal and oral surface areas, greater pressure is required to overcome the resistance of the vocal tract. Indeed, as noted by Müller and Brown, it requires more effort to inflate a smaller than a larger balloon because less surface area is exposed to the respiratory force.

Differences in respiratory mechanics *per se* may also affect oral air pressure levels as a function of age. Because children are known to have less compliant (i.e., more stiff) respiratory systems than adults, elastic recoil may generate higher relaxation pressures. In this regard, it is interesting to note that Zajac (1997) reported that older adult speakers (68 to 83 years) exhibited higher oral air pressures than younger adult speakers. This finding may be attributed in part to the fact that older individuals also exhibit increased respiratory stiffness due to aging (Kahane, 1990). In addition, older speakers have been shown to initiate utterances at higher lung volume levels (Hoit and Hixon, 1987). The combined results from the present study and those from Zajac (1997), therefore, suggest that respiratory mechanics may also play a significant role in the generation of habitual or self-determined oral air pressure levels of children.

Finally, it should be noted that a trend was apparent in the data for male speakers to exhibit slightly higher oral air pressures than female speakers during production of /p/ regardless of age. This trend was consistent with previous studies that reported sex-specific findings (e.g., Netsell et al., 1994; Zajac, 1997). The sex effects associated with the speakers in the present study, however, did not reach statistical significance.

Nasal Airflow

The findings relative to nasal airflow suggest that noncleft speakers exhibit essentially airtight VP closure during production of /p/ at syllable level regardless of age. The data associated with /pi/ and /pʌ/ are consistent with the findings of Thompson and Hixon (1979) and Hoit et al. (1994). Thompson and Hixon reported that 111 of 112 speakers aged 3 to 37 years exhibited essentially zero flow during production of /ti/, /di/, /si/, and /zi/. In the present study, only 3 of 215 speakers exhibited nasal airflow greater than 20 mL/s during /pi/; only one speaker exhibited airflow greater than 30 mL/s. During production of /pʌ/, one additional speaker exhibited nasal airflow greater than 30 mL/s. It must be noted that both of these speakers were female and in the 13- to 16-year-old age group. Neither speaker exhibited a distinct regional dialect. The speaker who produced the highest nasal airflow, however, also reported a history of tonsillectomy and adenoidectomy in the first grade. It is of interest to note that the only speaker in the study by Thompson and Hixon (1979) who exhibited nasal airflow was also a female teenager. She was reported to exhibit nasal airflow in the range of 20 mL/s to 80 mL/s during /t/, /d/, /s/, and /z/, similar to the levels of the two female teenagers in the present study. It is tempting to speculate, therefore, that some teenage speakers may fail to undergo the motor control reorganization of VP function that typically occurs due to structural change resulting from the pubescent growth spurt and the involution of the adenoids. This may be especially likely for speakers who have had tonsillectomy, adenoidectomy, or both. Obviously, longitudinal studies of speakers during the period of adenoid involution are required to test this hypothesis.

All speakers, but especially the teenagers and adults, exhibited relatively greater nasal airflow during production of /p/ in the /mp/ sequence at both word and sentence levels. Because of the phonetic context, these results were not unexpected. Although statistical analysis was not performed on these data, inspection of Table 5 indicates relatively increased nasal airflow beginning in the teenage years. The 95% confidence intervals of the mean, for example, suggest that nonartifact nasal airflow (i.e., greater than 20 mL/s) occurred for both the teenagers (except at sentence level) and adults. The increased nasal airflow may be explained by greater tolerance by the teenagers and adults for carryover nasal airflow—perhaps because their habitual pitch and/or loudness levels may mask the perceptual consequences of nasal air loss—and VP structural differences between the younger children and teenagers/adults due to the loss of adenoid tissue.

As indicated in Table 4, there was a clear increase in nasal airflow during production of /mi/ as a function of age. Based upon the known dimensions of the vocal tract as a function of age, this finding was not unexpected. Warren et al. (1990), for example, have reported an increase of approximately 3 mm^2 per year in the cross-sectional area of the nasal airway in children. In addition, because the oral cavity is closed and voicing occurs during the /m/ segment, nasal airflow should also reflect laryngeal function. Indeed, the present nasal airflow findings are consistent with developmental patterns of laryngeal airflow during vowel production reported by Netsell et al. (1994). They reported, for example, that laryngeal airflow during production of /pi/ increased as a function of age from preschool-aged children to adults.

Nasal airflow during production of /m/ in ‘‘hamper’’ also showed the expected age effect as revealed in Table 5. The teenagers, however, actually exhibited higher nasal airflow than the adults at both word and sentence levels. Although difficult to explain, this finding should not be attributed to a regional variation in nasalization for the following reasons. First, as indicated above, during production of /mi/, the teenagers exhibited a level of nasal airflow consistent with an age effect. Second, as indicated in the Results, there were no significant differences in anticipatory nasal airflow among any of the age groups. A possible explanation may have to do with relative differences in habitual loudness of the teenagers. The teens, for example, may have produced the word and sentence stimuli with reduced intensity as compared with the syllables. Some recent studies have reported an inverse relationship between intensity and nasal airflow (e.g., Zajac et al., 1998). Unfortunately, because a calibrated audio signal was not obtained as part of the procedures, this assumption cannot be evaluated.

VP Orifice Area

The area data reported were calculated using a k value of 0.65 as originally suggested by Warren and DuBois (1964). As indicated by Yates et al. (1990), a constant k value is expected to result in estimations of VP orifice area that have relative accuracy among speakers who exhibit similarity in orifice geometry. Examination of the VP orifice area data during /mi/ production in Table 6 illustrates a generally consistent increase with age except for the teenage speakers. The teenagers exhibited VP areas that were larger than expected based upon airflow data as revealed in Table 4. The VP areas, therefore, may have been overestimated due to a relative difference in orifice geometry during production of /mi/. As indicated by Yates et al. (1990), the effect of increasing the value of k (i.e., assuming less turbulence and pressure loss at the orifice) would be to reduce the estimated area. Conversely, if the value of k is constant but turbulence and pressure loss are reduced—as would occur in theory with the involution of adenoids—then estimated areas would tend to be inflated. Indeed, as noted by Yates et al. (1990) and others, caution should be used in the interpretation of orifice area data when similarity of VP geometry cannot be confirmed.

Levels of Production

Regardless of age, speakers exhibited higher rates of nasal airflow and larger VP orifice areas during production of /m/ in the /mp/ sequence at word versus sentence levels. Speakers also exhibited greater oral air pressures during production of /p/ at word level. These findings appear to be best explained by differences in speaking rates. Although speakers were instructed to produce all speech samples at a self-determined rate, they were additionally instructed to use a single breath group. Because of the difference in the number of syllables per breath group between the word and sentence stimuli (i.e., 10 and 18 syllables, respectively), it was anticipated that rate differences may occur. To test this assumption, a post hoc analysis was conducted to determine the number of syllables produced per second by the teenage speakers. This analysis indicated that the teenagers produced more syllables per second at sentence ($M = 5.2$, $SD = 0.8$) than at word ($M = 3.8$, $SD = 0.6$) levels. The difference was statistically significant ($t = 10.39$, $df = 21$, $p < .001$).

As noted by Kent et al. (1974), speakers may ‘‘undershoot’’ a velar target when speaking rate is increased. Because the VP port must be open to achieve production of /m/, speakers may reduce the extent of VP opening when speaking at a faster rate in order to achieve VP closure in a timely manner for subsequent oral segments. The aerodynamic effect of this reduced articulatory movement during /m/ may be a reduction in nasal airflow. Aerodynamic evidence of a similar articulatory ‘‘undershoot’’ during VP closure associated with /p/ was also present in the study. Speakers in each of the age groups, for example, exhibited the largest range of VP orifice areas during /p/ production at sentence versus word levels. In addition, the reduced oral air pressures at sentence level further suggest that an articulatory undershoot of VP closure may have occurred during /p/ production. These findings are consistent with data recently reported by Samlan and Barlow (1999). They demonstrated that female speakers exhibited significantly decreased VP resistance during production of /p/ at a compressed (fast) speaking rate.

Finally, it must be noted that the relative positions of the target sequence /mp/ within the breath groups at the word and sentence levels also may have influenced the results. Oral air pressure, for example, has been shown to decline from the beginning to the end of a breath group (Zajac, 1997). Further study that controls target position within the breath group, therefore, is warranted.

Clinical Implications

The above findings suggest useful aerodynamic criteria for the evaluation of VP function during pressure-flow testing. Relative to /p/ production at syllable level, it is suggested that nasal airflow rates of 20 mL/s or less be considered as complete or air-tight VP closure regardless of age. The use of a 10 mL/s or less criterion, as suggested by Hoit et al. (1994), may be appropriate for children in the age range of 6 to 12 years. Because children typically have smaller airway dimensions than teens and adults, the magnitude of artifact displacements of nasal air volume would be less. Relative to /m/ production at syllable level, it is suggested that the means and standard deviations for nasal airflow as a function of age be used to assess the adequacy of VP opening. These data may prove especially useful in the evaluation of speakers following secondary palatal surgery for VP inadequacy. Often, the evaluation of VP function during production of nasal consonants is neglected relative to oral speech segments. A successful surgical technique, however, should promote VP function for both oral and nasal speech segments. The use of developmentally based nasal airflow criteria, therefore, may facilitate clinical decisions.

Recognition of age-specific oral air pressure levels during speech production also has important clinical implications. To illustrate, the reader may wish to consider the following three outcomes for an individual with repaired cleft palate following secondary palatal surgery. In each example, the hypothetical speaker demonstrates normal resonance and nasal emission characteristics with oral air pressures within the expected age range, oral air pressures two standard deviations above the expected age mean, or oral air pressures two standard deviations below the expected age mean. The second and third outcomes may warrant concern, but for different reasons. The second outcome may suggest the continued use of increased respiratory effort as a learned compensatory strategy. A vocal hygiene program, therefore, may be warranted. The third outcome, however, may suggest a VP mechanism that is still compromised. The reduced oral air pressures may reflect an attempt to mask hypernasality or audible nasal emission that might occur at normal effort levels. Clearly, additional diagnostic testing and, perhaps, trial behavioral therapy may be an option.

Relative to the above examples, the clinical findings reported by Dalston et al. (1988) reinforce the need to consider age-specific oral air pressure norms. Dalston et al. reported generally lower but similar developmental patterns of oral air pressure in a large group of speakers diagnosed with varying degrees of VP inadequacy. The relative consistency of the age-related oral air pressure findings highlights the diagnostic potential of comparison to established age norms.

Finally, the present results suggest that speaking rate may affect VP function, at least in a nasal-plosive phonetic context. Because of the possibility of reduced articulatory movement associated with an increase in speaking rate, it is suggested that speakers be constrained to a conversational rate of approximately three to four syllables per second during pressure-flow testing.

Acknowledgments. The investigator wishes to thank Wendy Kubancsek, Liz McVay, Amy Sauder, and Jennifer Thomas for their assistance with the project. Special appreciation is extended to the children and parents of the Woodland Hills School District (Churchill, Pennsylvania) who participated in the study, Mr. Stanley Ohrin, Principal of Wilkins Primary School, and Mrs. Roslynn Wilson, Principal of Fairless Intermediate School.

REFERENCES

Andreassen ML, Smith BE, Guyette TW. Pressure-flow measurements for selected oral and nasal sound segments produced by normal adults. *Cleft Palate Craniofac J.* 1992;29:1–9.

Barlow SM. *Handbook of Clinical Speech Physiology.* San Diego: Singular Publishing; 1999.

Brown WS, McGlone RE. Relation of intraoral air pressure to oral cavity size. *Folia Phoniatr.* 1969;21:321–331.

Dalston RM, Warren DW, Morr KE, Smith LR. Intraoral pressure and its relationship to velopharyngeal inadequacy. *Cleft Palate J.* 1988;25:210–219.

Fisher KV, Swank PR. Estimating phonation threshold pressure. *J Speech Lang Hear Res.* 1997;40:1122–1129.

Guyette TW, Carpenter MA. Accuracy of pressure-flow estimates of velopharyngeal orifice size in an analog model and human subjects. *J Speech Hear Res.* 1988;31:537–548.

Hoit JD, Hixon TJ. Age and speech breathing. *J Speech Hear Res.* 1987;30: 351–366.

Hoit JD, Watson PJ, Hixon KE, McMahon P, Johnson CL. Age and velopharyngeal function during speech production. *J Speech Hear Res.* 1994;37: 295–302.

Kahane J. Age-related changes in the peripheral speech mechanism: structural and physiological changes. *ASHA Rep.* 1990;19:75–87.

Kent R, Carney P, Severeid L. Velar movement and timing: evaluation of a model for binary control. *J Speech Hear Res.* 1974;17:470–488.

Kuehn DP. A cineradiographic investigation of velar movement variables in two normals. *Cleft Palate J.* 1976;13:88–103.

Leeper HA, Tissington ML, Munhall KG. Temporal characteristics of velopharyngeal function in children. *Cleft Palate Craniofac J.* 1998;35:215–221.

Lubker JF. Velopharyngeal orifice area: a replication of analog experimentation. *J Speech Hear Res.* 1969;12:218–222.

McKerns D, Bzoch KR. Variations in velopharyngeal valving: the factor of sex. *Cleft Palate J.* 1970;7:652–662.

Müller EM, Brown WS. Variations in the supraglottic air pressure waveform and their articulatory interpretation. In: Lass N, ed. *Speech and Language: Advances in Basic Research and Practice*. Vol. 4. New York: Academic Press; 1980:318–389.

Netsell R, Lotz WK, Peters JE, Schulte L. Developmental patterns of laryngeal and respiratory function for speech production. *J Voice*. 1994;8:123–131.

Samlan RA, Barlow SM. The effects of transition rate and vowel height on velopharyngeal airway resistance. In: Barlow SM, ed. *Handbook of Clinical Speech Physiology*. San Diego: Singular Publishing; 1999:247–264.

Seaver EJ, Dalston RM, Leeper HA, Adams LE. A study of nasometric values for normal nasal resonance. *J Speech Hear Res*. 1991;34:715–721.

Smith BE, Weinberg B. Prediction of velopharyngeal orifice area: a re-examination of model experimentation. *Cleft Palate J*. 1980;17:277–282.

Thompson AE, Hixon TJ. Nasal air flow during normal speech production. *Cleft Palate J*. 1979;16:412–420.

Vig P, Zajac DJ. Age and gender effects on nasorespiratory function in normal subjects. *Cleft Palate Craniofac J*. 1993;30:279–284.

Warren DW, Dalston RM, Trier WC, Holder MB. A pressure-flow technique for quantifying temporal patterns of palatopharyngeal closure. *Cleft Palate J*. 1985;22:11–19.

Warren DW, Dalston RM, Morr KE, Hairfield WM, Smith LR. The speech regulating system: temporal and aerodynamic responses to velopharyngeal inadequacy. *J Speech Hear Res*. 1989;32:566–575.

Warren DW, Devereux JL. An analog study of cleft palate speech. *Cleft Palate J*. 1966;3:103–114.

Warren DW, DuBois AB. A pressure-flow technique for measuring velopharyngeal orifice area during continuous speech. *Cleft Palate J*. 1964;1:52–71.

Warren DW, Hairfield WM, Dalston ET. Effect of age on nasal cross-sectional area and respiratory mode in children. *Laryngoscope*. 1990;100:89–93.

Yates CC, McWilliams BJ, Vallino L. The pressure-flow method: some fundamental concepts. *Cleft Palate J*. 1990;27:193–198.

Zajac DJ. Velopharyngeal function in young and older adult speakers: evidence from aerodynamic studies. *J Acoust Soc Am*. 1997;102:1846–1852.

Zajac DJ, Mayo R. Aerodynamic and temporal aspects of velopharyngeal function in normal speakers. *J Speech Hear Res*. 1996;39:1199–1207.

Zajac DJ, Mayo R, Kataoka R. Nasal coarticulation in normal speakers: a re-examination of the effects of gender. *J Speech Lang Hear Res*. 1998;41:503–510.

Zajac DJ, Yates CC. Accuracy of the pressure-flow method in estimating induced velopharyngeal orifice area: effects of the flow coefficient. *J Speech Hear Res*. 1991;34:1073–1078.