Intraoral Pressure and Its Relationship to Velopharyngeal Inadequacy

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Intraoral pressure measurements were made during multiple productions of the word "hamper" by each of 267 patients who manifested differing degrees of velopharyngeal inadequacy. The results indicate that intraoral pressure diminishes as the extent of velopharyngeal impairment increases. However, pressure remained above 3 cm H_2O in the majority of subjects, even when the impairment was such that intraoral and intranasal pressures were essentially equal. Comparison of these results with model simulations suggests that speakers make adjustments to velopharyngeal impairment that tend to maintain pressures at levels thought to be necessary for obstruent consonant production. Variations in pressure as a function of gender and age parallel those observed in normal children and adults.

KEY WORDS: *regulation/control, intraoral pressure, speech, velopharyngeal inadequacy, cleft palate.*

Several studies have reported the magnitude of intraoral pressure during production of pressure consonants by normal speakers. These pressures have varied somewhat as a function of speaker age (e.g., Bernthal and Beukelman, 1978; Stathopoulous and Weismer, 1985) and gender (e.g., Subtelny et al, 1966; Bernthal and Beukelman, 1978; Lotz and Netsell, 1986). In addition, they have been found to vary by word position (e.g., Arkebauer et al, 1967; Malecot, 1968; Brown et al, 1970; Malecot, 1955), voicing characteristics (e.g., Black, 1950; Malecot, 1966; Lisker, 1971; Netsell, 1969; Lubker and Parris, 1970; Warren and Hall, 1973; Weismer and Longstreth, 1980, Stathopoulos, 1986), vowel context (e.g., Klich, 1982; Brown et al, 1973; Karnell and Willis, 1982), utterance length (e.g., Brown and McGlone, 1969; Prosek and House, 1975; Flege, 1983), and syllable stress (e.g., Malecot, 1970; Flege, 1983). However, in none of these comparisons have the mean intraoral pressure values of an individual speaker's productions of voiceless plosive consonants been reported to fall below 3 cm H_2O. This latter value has been described by Warren (1982) as the minimal level of pressure necessary for the production of voiceless plosives. This agrees well with the suggestion by Flanagan (1972) that minimal requisite pressures for voiced sounds are on the order of 4 cm H_2O.

Although much has been written about intraoral pressures accompanying the speech of normal subjects, comparable information is not available for individuals manifesting velopharyngeal inadequacy. Certainly, one would expect these individuals to have difficulty in developing intraoral pressure for the production of

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consonants that involve partial or total obstruction of airflow through the vocal tract. As noted by Hutters and Brondsted (1987), ''velopharyngeal . . . (inadequacy) is presumed to prevent any considerable increase in the intraoral pressure'' (p. 127). However, they made no statement concerning what constitutes a ''considerable'' increase, and virtually no quantitative data exist in the current literature. One notable exception is a paper by Warren (1985a).

In a recent preliminary report (Warren, 1985a), it was suggested that, in most cases, intraoral pressures are maintained at levels adequate for consonant production even in the presence of velopharyngeal inadequacy. Approximately 70 percent of patients with velopharyngeal areas greater than 0.20 cm^2 were able to achieve pressures greater than 3 cm H_2O during plosive consonant productions. Warren postulated that maintenance of speech-driving pressures may be of primary importance in speech-motor control and that the speech system follows regulation/control strategies (1986a; 1986b). That is, he suggested that the speech system responds to structural deficits in ways that ensure aerodynamic stability.

The purpose of the present study was threefold and involved both vocal-tract model simulations and observations of clinical patients. First, intraoral pressures were assessed in a large population of patients seen for evaluation at the Oral-Facial and Communicative Disorders Program (OFCDP) clinic. If Warren is correct in assuming that the speech system follows regulation/control strategies, intraoral pressures during speech should be maintained across varying degrees of velopharyngeal impairment—within the physiologic limits of the system (Warren, 1986b). Next, a model study was conducted to determine the extent to which intraoral pressure generation in an inanimate system differs from that observed among patients who are presumed to be capable of actively compensating for their velophyarngeal impairment. Finally, the clinical subjects were investigated further to determine whether their oral pressures varied across ages and gender in a manner comparable to that which has been observed in the normal population.

MATERIALS AND METHODS

Subjects

All patients seen at the OFCDP clinic between April, 1982 and May, 1987 were included in this study if they (1) manifested a congenital structural abnormality that might be expected to affect velopharyngeal closure; (2) did not have nasal congestion or obstruction to the extent that would invalidate testing; and (3) were capable of cooperating sufficiently to perform the tasks required of them. The resultant group of 116 females and 151 males ranged in age from 4 years, 2 months to 58 years, 3 months with a median age of exactly 13 years. The age and gender distributions of these 267 subjects are summarized in Table 1.

The diagnostic categories and number of patients in each are listed in Table 2. With one possible exception, all of these diagnostic categories include an abnormality involving the secondary palate. The category labeled ''velopharyngeal inadequacy without evidence of overt, submucous, or occult submucous cleft'' may or may not include persons who had structural abnormalities of the palate that simply went undetected. By design, this category did include those patients who were judged to have a deep nasopharynx (''megapharynx'') with or without concomitant cervical vertebra abnormalities.

Of course, physical abnormality does not necessarily indicate velopharyngeal impairment. However, the fact that each of the subjects was referred for evaluation suggests that at least each of them was thought to have an impairment at the time of referral.

The pressure-flow technique (Warren, 1975, 1979, 1982) was used to estimate velopharyngeal orifice size and intraoral pressures in the

TABLE 1 Age and Gender Distribution of Subjects Included for Investigation in this Study

Age	*Male*	*Female*	*Total*	*Male (%)*	*Total Sample (%)*
<07 yrs.	13	11	24	54	9
7 yr–9 yr, 11 mo	36	22	58	62	22
10 yr–12 yr, 11 mo	25	17	42	60	16
13 yr–15 yr, 11 mo	30	25	55	55	21
16 yr–18 yr, 11 mo	15	15	30	50	11
>18 yr, 11 mo	32	26	58	55	22
Total	*151*	*116*	*267*	*57*	*100*

TABLE 2 Primary Diagnosis of the 267 Subjects Employed in the Present Investigation

Diagnosis	*Frequency*	*%*
Right unilateral complete cleft of primary and secondary palate	20	7.5
Left unilateral complete cleft of primary and secondary palate	61	22.8
Bilateral complete cleft of primary and secondary palate	53	19.9
Cleft of soft palate only	25	9.4
Cleft of secondary palate, involving hard palate as well as velum	49	18.4
Submucous cleft	20	7.5
Occult submucous cleft	18	6.7
Velopharyngeal inadequacy without evidence of overt, submucous, or occult submucous cleft	18	6.7
Incomplete cleft, involving both primary and secondary palate	3	1.1

267 subjects. This technique was discussed in detail previously (Warren and Dubois, 1964; Warren, 1979; Warren, 1982; Warren et al, 1985). Briefly, the pressure drop across the palatopharyngeal orifice (oral pressure minus nasal pressure) was measured during speech by placing one catheter within the mouth and another in one nostril. The nasal catheter was secured by a cork that blocked the nostril, creating a stagnant column of air. Both catheters measured static air pressures and transmitted these pressures to pressure tranducers. Nasal airflow was measured by a heated pneumotachograph connected by plastic tubing to the subject's other nostril. The area of the constriction was then calculated from the following equation:

$$A = \mathring{V}/k\ (2\Delta P/d)\ ½$$

where A = area of orifice in cm^2; $\mathring{V}$ = nasal airflow in cc/sec; k = 0.65; ΔP = oral-nasal pressure in cm H_2O; d = density of air in cm^3. Figure 1 shows catheter placement and instrumentation for estimating velopharyngeal orifice size and measuring intraoral pressure, nasal pressure, and nasal airflow.

During pressure-flow testing, each subject was asked to produce a series of voiceless plosive consonant /p/'s in the word "hamper" (hæ´mpr). Most subjects were asked to produce another series in the word "papa" (pápə). The latter word has been used in much of the research performed in this laboratory and reported in the literature. The former word has been employed more recently because production of the nasal-plosive blend /mp/ in the word "hamper" is thought to stress the palatal mechanism, thereby aiding in the identification of those individuals with velopharyngeal inadequacy. More importantly, velopharyngeal activity during production of this word is felt to approximate that which occurs during continuous speech. Simulation of ongoing speech is necessary because some individuals demonstrate adequate closure on isolated plosive-vowel syllables but not during conversation.

Between four and six productions of /p/ in each word were analyzed for each subject. The velopharyngeal areas and intraoral pressures reported here represent the average values across these multiple productions.

The 267 subjects were placed into one of five groups based on pressure-flow estimates of

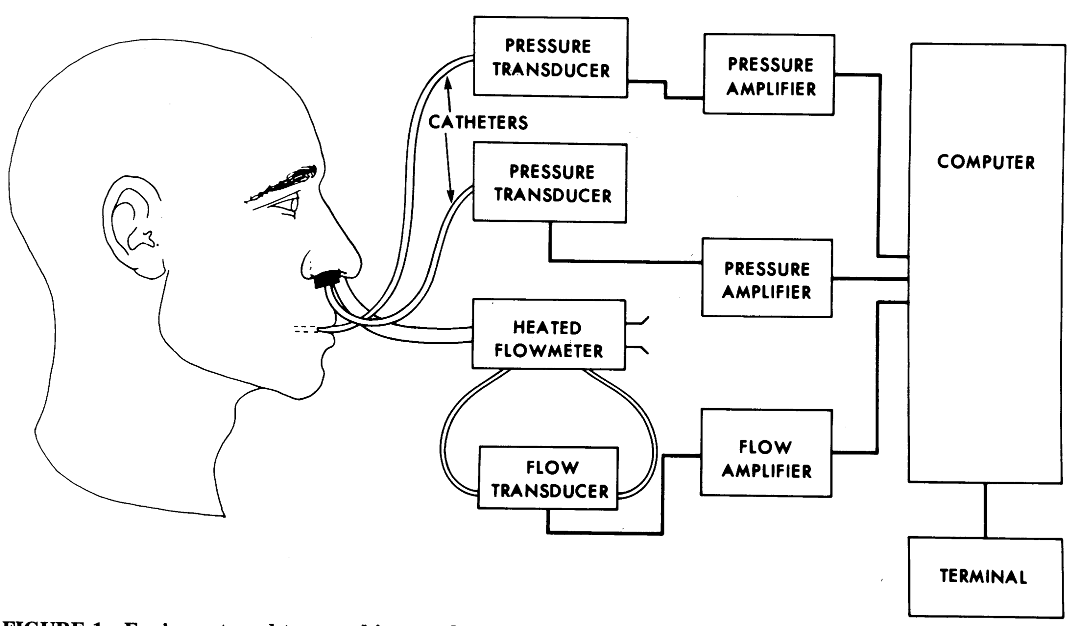

FIGURE 1 Equipment used to record intraoral pressures.

velopharyngeal orifice size made by averaging their productions of the word "hamper." Group I consisted of 70 female and 111 male subjects (N = 181) categorized as having adequate velopharyngeal closure. Orifice size in this group ranged from 0.0 to 0.049 cm^2. Group II comprised 14 female and 13 male patients (N = 27) classified as having adequate/borderline closure. Velopharyngeal size for this group ranged from 0.05 to 0.09 cm^2. The borderline/inadequate closure group, Group III, consisted of 14 female and 9 male subjects (N = 23) whose velopharyngeal areas ranged from 0.10 to 0.19 cm^2. Group IV was comprised of 13 females and 13 males (N = 26) who were considered to have inadequate closure. Their velopharyngeal areas were between 0.20 cm^2 and 0.80 cm^2. The 5 female and 5 male subjects (N = 10) with grossly incompetent velopharyngeal closure were placed in Group V. Their inadequacy was so great that differential pressure could not be measured accurately.

Categorization according to the area criteria mentioned above was operational and was based on previous studies by Warren and his colleagues. Velopharyngeal areas less than 0.05 cm^2 were considered to be adequate because normal non-cleft speakers do not manifest areas greater than this value (Warren, 1979). Conversely, the definition of inadequate closure was based on aerodynamic data demonstrating that velopharyngeal openings greater than 0.20 cm^2 are inadequate for normal speech (Warren, 1975). Unpublished clinical observations have led us to conclude that speakers with velopharyngeal areas in the inadequate range invariably manifest hypernasality, nasal emission, or both. Gross inadequacy (Group V) was reserved for patients whose oral-differential pressure during speech was zero. The intermediate categories of adequate/borderline closure (0.05–0.09 cm^2) and borderline/inadequate closure (0.10–0.19 cm^2) are somewhat more arbitrary. Nevertheless, there is both aerodynamic and perceptual evidence to support these groupings (Warren, 1979).

Modeling Study

The prototype for the plastic model employed in this study has been described in detail elsewhere (Warren and Devereux, 1966). Since that time, similar models have been used in numerous studies (Warren and Ryon, 1967; Lubker, 1969; Smith and Weinberg, 1980; Smith and Weinberg, 1982; Smith and Weinberg, 1983; Smith, Moon and Weinberg, 1984; Warren et al, 1984a). The only modification employed in the current investigation was that a stopper was placed in the left nare of the model. As a consequence, the effective cross-sectional area of the model nose was reduced to 0.30 cm^2. Recent work by Warren (1985b) suggests that this is a reasonable approximation to the nasal cross-sectional area found in children with cleft palate. Over three fourths (76%) of the patients studied here were children under 18 years of age.

Respiratory activity was simulated by a pump that produced airflow in the form of sine waves. The airflow was adjusted to generate a maximum pressure comparable to that which might be expected among human speakers.

The pressure created in a completely closed model could not be measured without damaging the model. Therefore, it was not possible to test directly whether the pressure generated by the pump was comparable to pressures generated by normal speakers producing stop consonants. However, an attempt was made to adjust the lowest model velopharyngeal aperture to an area equivalent to that observed in the adequate/borderline patient group described below. The average velopharyngeal area for this group was found to be 0.071 cm^2, and their average peak oral pressure was 4.5 cm H_2O (Table 3). As shown in Table 4, the lowest model aperture achieved was 0.075 cm^2, and the peak oral pressure generated by the pump under this condition was 4.87 cm H_2O.

Peak oral-cavity pressure was measured at several velopharyngeal apertures to define the relationship between velopharyngeal aperture size and intraoral pressures in this passive system. Oral pressures were sensed by a catheter in the oral cavity of the model and relayed to a dedicated IBM PC AT computer via a Validyne Model MP45-24-871 pressure transducer. Velopharyngeal aperture settings were verified

TABLE 3 Intraoral Pressures (in cm H_2O) Obtained from Subjects During Production of /p/ in the Word "Hamper"*

Velopharyngeal Adequacy Group	*N*	*Mean Intraoral Pressure*	*Standard Deviation*
I (Adequate)	181	6.7	2.4
II (Adequate/ borderline)	27	4.5	1.9
III (Borderline/ inadequate)	23	4.1	1.7
IV (Inadequate)	26	3.5	2.0
V (Grossly inadequate)	10	3.0	1.3

* Subjects are grouped according to velopharyngeal adequacy as determined aerodynamically.

TABLE 4 Relationship Between Velopharyngeal Area and Peak Intraoral Pressure in Passive Vocal-Tract Model in Which Oral Cavity is Closed at Lips*

Velopharyngeal Area (cm^2)	*Peak Intraoral Pressure (cm H_2O)*
0.075	4.87
0.14	3.12
0.15	2.95
0.21	2.37
0.31	2.01

* Air pressure was provided by a sinusoidal pump whose output was adjusted to correspond to patient data obtained during the current investigation.

using the pressure-flow technique previously described.

Results

Table 4 presents the measurement values illustrating the relationship between velopharyngeal apertures and intraoral pressures in a passive vocal tract whose oral cavity is closed to simulate bilabial approximation for obstruent consonant production. In this experiment, intraoral pressure dropped below 3 cm H_2O when the velopharyngeal opening exceeded 0.14 cm^2. This size opening is in the middle of the operationally defined borderline/inadequate category already described.

Among the 267 patients, 46 (17%) manifested velopharyngeal areas greater than 0.14 cm^2. Of the 27 females and 19 males in this group, 25/46 (54%) produced intraoral pressures above 3.0 cm H_2O. Of the 21 who did not, 17 (81%) had velopharyngeal apertures $\geqslant$0.20 cm^2.

Table 3 lists mean intraoral pressures and standard deviations (SD) for the clinical patients grouped according to degree of velopharyngeal impairment. Across groups, pressure levels fell as the degree of inadequacy increased. Nevertheless, even in the group whose inadequacy was so great that differential pressure could not be measured accurately (Group V), the average pressure was 3.0 cm H_2O.

The clinical data also were analyzed to determine how many subjects achieved intraoral pressures $\geqslant$3 cm H_2O during production of the plosive /p/ in the word "hamper." This analysis revealed that 232 of the 267 subjects (87%) achieved intraoral pressures $\geqslant$3 cm H_2O. The percentages, according to group, were as follows:

I. 97% of the adequate group (175/181);
II. 74% of the adequate/borderline group (20/27);
III. 78% of the borderline/inadequate group (18/23);
IV. 50% of the inadequate group (13/26);
V. 60% of the grossly inadequate group (6/10).

Warren previously suggested that patients with velopharyngeal apertures $\geqslant$0.10 cm^2 (groups III, IV, and V) manifest varying degrees of velopharyngeal inadequacy (Warren, 1979). Considered in this way, 63% (37/59) of patients in this study with velopharyngeal inadequacy demonstrated pressures of 3 cm H_2O or more during plosive consonant productions. Conversely, 6% (13/208) of patients with varying degrees of adequacy (Groups I and II) did not produce peak pressures of this magnitude during testing.

The relationship between intraoral pressure and speaker gender and age was investigated for the entire group of clinical subjects studied here. As can be seen in Table 5, males consistently produced greater pressures than females. In addition, intraoral pressure tended to diminish with increasing speaker age. These relationships also tended to persist for each of the five

TABLE 5 Relationship among Gender, Age, and Intraoral Pressures During Production of /p/ in the Word "Hamper" Spoken by all 267 Subjects

Age Group	*N*	*Male Mean (SD)*		*N*	*Female Mean (SD)*		*N*	*Total Mean (SD)*	
<07 yr	13	8.3	(3.3)	11	5.8	(2.2)	24	7.1	(3.1)
7 yr–9 yr, 11 mo	36	6.9	(2.9)	22	5.8	(3.0)	58	6.5	(3.0)
10 yr–12 yr, 11 mo	25	6.6	(2.4)	17	6.2	(2.4)	42	6.4	(2.7)
13 yr–15 yr, 11 mo	30	6.3	(2.8)	25	5.5	(1.7)	55	5.9	(2.4)
16 yr–18 yr, 11 mo	15	5.7	(2.1)	15	3.6	(1.7)	30	4.6	(2.2)
>18 yr, 11 mo	32	4.9	(1.8)	26	4.0	(1.7)	58	4.5	(1.8)
Total	*151*	*6.3**	*(2.7)*	*116*	*5.1**	*(2.3)*	*267*	*5.8*	*(2.6)*

* Statistical comparison of these overall means, utilizing the Student's *t* test, indicated a significant difference in pressures produced by the males and females ($p < 0.05$).

subgroups studied. That is, within each velopharyngeal category, males and younger children tended to produce higher peak pressures (Tables 6 and 7). However, extreme caution should be exercised in interpreting the information in Table 7 since some of the cell sizes are very small.

Finally, some authors have suggested that intraoral pressures during productions of pressure consonants by normal speakers vary somewhat as a function of word position and vowel context. Therefore, the pressures obtained during analysis of repeated /p/ productions in the words "papa" and "hamper" were compared across all subjects for whom both sets of data were collected at the same sitting. Across the 156 subjects investigated, the average intraoral pressure for /p/ in the word "papa" was 5.3 cm H_2O (SD 3.0), while the intraoral pressure for /p/ in the word "hamper" was 5.5 cm H_2O (SD 2.9). A student t-test revealed no statistically significant difference between the intraoral pressures obtained using these two utterances.

DISCUSSION

The fact that no consistent difference in intraoral pressure was obtained for /p/ productions in the word "papa" versus those in the word "hamper" in this retrospective study should not necessarily be construed as evidence that the individuals studied did not manifest contextual differences in their voiceless bilabial plosive productions. The lack of difference may be because both the initial and intervocalic /p/ productions in the word "papa" typically were measured and used in the analyses reported here. Thus, potential contextual effects may have been masked. Nevertheless, it is reasonable to conclude that, at least for the 156 subjects in this aspect of the study, intraoral pressures recorded from productions of "papa" were comparable to those values obtained during productions of the word "hamper."

While insufficient information is available to make meaningful statistical comparisons with other published reports (e.g., Subtelny et al, 1966; Bernthal and Beukelman, 1978; Stathopoulous and Weismer, 1985; Lotz and Netsell, 1986), it would appear that the pressure values manifested by the patients in this study were similar to those reported in the literature for normal speakers in that pressures were lower for females and for older subjects in both cases.

For example, Lotz and Netsell (1986) studied the pressures generated by 70 children and 30 adults during repeated productions of /pi/ syllables. They found pressures averaging 9.1 cm H_2O for males and 8.8 cm H_2O for females between 4 and 8 years of age. For children between 10 and 12 years of age, males averaged 8.3 cm H_2O and females averaged 8.0 cm H_2O. The adult males manifested average pressure of 6.4 cm H_2O, while the adult females averaged 5.8 cm H_2O.

Although the directional trend across gender and age groups appears to be similar among normal subjects and the patients studied here (see Table 5), comparison of the current data with those presented in Lotz and Netsell (1986) suggests that the pressure magnitudes are lower in the current group. Since 32% of the patients studied here manifested inadequate velopharyngeal closure, this finding was to be expected.

The relationship between intraoral pressures and speaker gender and age reported among normal speakers was observed for all experimental groups studied. That is, within each velopharyngeal category, males and younger children tended to produce higher peak pressures (see Tables 6 and 7). However, as already noted, extreme caution should be exercised in interpreting the information in Table 7 since some of the cell sizes are very small.

Several possible reasons have been put forward to explain the fact that intraoral air pressure (Po) varies as a function of age (see Stathopoulos, 1986 for a review). In her study of 40

TABLE 6 Relationship among Gender, Velopharyngeal Adequacy Group, and Intraoral Pressures During Production of /p/ in the Word "Hamper" Spoken by all 267 Subjects

	Males		*Females*	
Velopharyngeal Adequacy Group	*N*	*Pressure Mean (SD)*	*N*	*Pressure Mean (SD)*
I (Adequate)	111	7.0 (2.6)	70	6.1 (2.1)
II (Adequate/ borderline)	13	5.5 (4.4)	14	4.1 (1.7)
III (Borderline/ inadequate)	9	4.6 (1.4)	14	3.8 (1.8)
IV (Inadequate)	13	4.0 (2.3)	13	2.9 (1.4)
V (Grossly inadequate)	5	3.3 (1.1)	5	2.8 (1.6)

TABLE 7 Relationship among Gender, Age, and Intraoral Pressures During Production of /p/ in the Word "Hamper" Spoken by 59 Subjects Whose Velopharyngeal Areas Were Greater than 0.099 cm^2

Age Group	Male N	Male Pressure Mean	(SD)	Female N	Female Pressure Mean	(SD)	Total N	Total Pressure Mean	(SD)
<07 yrs.	1	6.7	(—)	2	2.8	(1.9)	3	3.9	(2.4)
7 yr–9 yr, 11 mo	5	5.6	(2.1)	5	3.6	(2.8)	10	4.6	(2.5)
10 yr–12 yr, 11 mo	4	4.3	(3.0)	1	3.9	(—)	5	4.2	(2.6)
13 yr–15 yr, 11 mo	2	2.4	(0.4)	4	3.4	(0.7)	6	3.0	(0.8)
16 yr–18 yr, 11 mo	4	3.8	(1.8)	4	1.9	(1.2)	8	2.8	(1.7)
>18 yr, 11 mo	11	3.6	(1.1)	16	3.5	(1.5)	27	3.5	(1.3)
Total	*27*	*4.1*	*(1.9)*	*32*	*3.3*	*(1.7)*	*59*	*3.6*	*(1.8)*

normal subjects, Stathopoulos (1986) concluded that "children and adults produce comparable Po values when speaking at the same intensity levels" (p. 74). Normal children may simply speak at higher intensity levels when they are asked to speak normally. The age difference evident in the current data may also be explained in this way. However, this cannot be verified since no information concerning speaking loudness level was obtained on these subjects.

Apparently no explanation of observed gender differences in intraoral pressures during speech has been postulated in the literature. It may well be that males habitually speak more forcefully, i.e., at a greater intensity. Whatever the reason, the difference between the sexes apparently occurs regardless of the presence or extent of velopharyngeal inadequacy.

The data from all 267 subjects show that, across ages and gender, intraoral pressures during voiceless plosive consonant productions are influenced by the degree of velopharyngeal competency, as one might expect. Compared to the adequate group, pressure was approximately 33% lower in the adequate/borderline groups, 39% lower in the borderline/inadequate groups, 48% lower in the inadequate group, and 55% lower in the grossly inadequate group. However, data obtained from the model simulations suggest that more substantial drops in intraoral pressure should have occurred if the aerodynamic response to increasing velopharyngeal impairment were a totally passive event.

In the analog study reported here, airflow sufficient to generate 4.87 cm H_2O intraoral pressure in a system with a 0.075 cm^2 velopharyngeal aperture was held constant as the aperture was varied in successive steps to simulate increasing degrees of velopharyngeal impairment. Under these controlled conditions, intraoral pressures fell below 3 cm H_2O once the velopharyngeal aperture exceeded 0.14 cm^2.

The fact that the clinical findings in this study do not parallel the modeling data suggests that at least some of the subjects investigated adopted an active means of maintaining pressures in the face of decreased airway resistance, resulting from velopharyngeal inadequacy. Whatever the strategy adopted, it appears to have worked fairly effectively since pressures remained above 3 cm H_2O in the majority of subjects (see Table 3). This was true even when the velopharyngeal impairment was so great that intraoral and intranasal pressures were essentially equal (Group V).

The assumption that 3 cm H_2O is the minimal intraoral pressure necessary to produce pressure consonants is based upon empirical evidence provided by a number of researchers (e.g., Warren, 1979; Warren et al, 1981; Putnam et al, 1986). This value actually is more conservative than the 4 cm H_2O cited by Flanagan (1972) as the minimal pressure necessary to sustain vocal-fold vibration. Regardless of the particular pressure value assumed to be minimally acceptable, the present investigation suggests that, in the face of velopharyngeal impairment, speech pressures tend to be maintained at a level greater than that achieved by a passive vocal-tract model driven to simulate the aerodynamic conditions observed during speech.

Two questions arise from the observation that human speakers may compensate for velopharyngeal inadequacy so as to keep intraoral pressures above that which might be expected in a passive system. The first concerns how such compensation might be effected. Warren (1986a) has stated that patients frequently increase respiratory effort to effect increased pressure. Respiratory output usually increases with increased velopharyngeal inadequacy to a limit of about 600 to 800 cc/sec (Warren, 1967; Warren et al, 1969). When nasal resistance is sufficiently high, the increase in airflow rate enables the speaker to generate pressures associated with normal speech.

If pressure cannot be maintained by increasing airflow rate, other responses may occur. Warren (1986a) has suggested that structural adaptations may occur if increased airflow rate cannot maintain intraoral pressures for speech. Structural responses may include adjustments such as the nasal grimace, high lingual carriage, and increased glottal resistance. In a recent report, Paynter (1987) provides some circumstantial support for this hypothesis. She studied listener preferences for various forms of speech produced by children with velopharyngeal inadequacy, and reported what she felt was evidence "compatible with Warren's theory that . . . compensatory articulation patterns occur . . . in order to maintain aerodynamic stability" (p. 118).

Regardless of how adjustments are made to maintain intraoral pressure, it is reasonable to ask *why* these pressures are maintained. Is their maintenance a primary goal, a secondary goal, or merely a coincidental by-product of some other system activity. Warren (1986a; 1986b) and his colleagues (Warren et al, 1980; 1981; 1984b) have suggested that pressure maintenance may be a primary goal of the system. In support of this view, a comparison can be made between the present findings and several studies that have observed subject response to system perturbations.

Putnam et al (1986) used translabial bleed valves to perturb the upper airway during consonant productions. As the bleed-valve opening increased, intraoral pressure fell and airflow rate increased proportionally. Their translabial perturbations simulated adequate, borderline, and inadequate closure of the oral port. Despite the decline in pressure in the Putnam et al study, levels always remained above 4 cm H_2O. The changes in pressure level in relation to size of the perturbation are remarkably similar to those revealed by data from the present study.

Bite-block and natural open-bite studies (Klechak et al, 1976; Warren et al, 1980; Warren et al, 1981; Warren et al, 1984b) also have demonstrated that speech pressures are maintained at adequate levels in the presence of perturbations to the system. Even when anterior open bites as large as 6 mm were artificially imposed, spontaneous adaptations occurred that resulted in maintenance of an appropriate aerodynamic environment. This occurred even though listeners perceived that speech accuracy deteriorated.

While such studies support the data presented here, demonstrating that speakers are able to maintain intraoral pressures in the face of either transient or persistent system disturbances, it might be argued that the maintenance of pressure in such circumstances is merely required so that speakers can generate the acoustic power necessary to generate perceptually acceptable pressure consonants. In such a case, pressure maintenance would not necessarily indicate that speech aerodynamics follow regulation and control strategies. It would merely reflect the fact that pressure is a necessary requisite to achieve the primary goal of impounding air for pressure-consonant productions. However, the fact that listeners perceived a deterioration in speech during the experimentally induced anterior open-bite conditions suggests one or more of the following: (1) pressure maintenance took precedence over perceptual accuracy; (2) pressure maintenance does not have a one-to-one relationship with perceived speech normality; (3) pressure maintenance was necessary but not sufficient for production of accurate speech, and speakers were able to maintain pressure but not able to produce all the requisites for acceptable speech; (4) speakers may adopt a minimum competency strategy leading to adjustments that do not fully compensate for experimentally imposed perturbations; or (5) the speakers perceived that their own speech remained acceptable under the various experimental conditions. None of the studies mentioned above obtained information concerning the speakers' perceptions of their own speech. This clearly would be the easiest of the five alternatives to test experimentally.

It would be interesting to compare subject performance under varying conditions of anterior open-bite and auditory masking. If speakers maintain equivalent pressures and perceive themselves as having comparable speech proficiency with and without auditory masking under identical open-bite conditions, it might suggest that pressure maintenance is a primary goal of the speaking mechanism and not secondary to acoustic and perceptual accuracy. The relative importance of auditory feedback in the maintenance of speech acceptability might be reflected in the extent to which speech accuracy deteriorates under masking. Among currently published studies, one by Warren et al (1984b) comes closest to examining this question.

Warren et al (1984b) reported studying the speech of the normal individuals under auditory masking and varying conditions of imposed anterior open bite. They found that these subjects tended to maintain oral port sizes appropriate for the production of fricative consonants even though the perceptual quality of these phonemes deteriorated noticeably. Although intraoral pressure measurements were not reported in that study, unpublished data from that investigation do show that these pressures were consistently maintained above 3 cm H_2O.

Finally, it should be noted that 13 of the 208 subjects in Groups I and II manifested average intraoral pressures <3 cm H_2O during production of the plosive /p/ in the word "hamper." It seems reasonable to assume that individuals in those two groups were physiologically capable of producing pressures greater than 3 cm H_2O. If so, one might argue that pressure maintenance is not under strict regulation/control since at least some individuals capable of producing "adequate" pressures do not routinely do so. One explanation that would be in keeping with Warren's regulation/control hypothesis is that those individuals who manifested low intraoral pressures had previously received speech therapy that trained them to speak using "light articulatory contacts." This technique involves teaching patients to produce pressure consonants with reduced intraoral pressures. We have yet to determine whether any of the subjects investigated here received such training.

As a conservative conclusion, it appears reasonable to state that the present findings are not at variance with the hypothesis that speech aerodynamics follow regulation and control strategies. This is true even though intraoral pressures did decrease with increasing degrees of velopharyngeal inadequacy. The essence of Warren's regulation/control hypothesis is that an *attempt* is made to maintain intraoral pressures during speech. The extent to which the pressures observed in this study exceed those measured in the passive simulation system may be considered to be a rough estimate of the success of that effort. The extent to which these pressures were not maintained constant across the experimental groups studied here may simply reflect the physiologic limits of this compensatory response.

Although the findings may be construed as support for the concept that the speech system follows regulation/control strategies, many significant questions remain unanswered. For example, a pressure value of 3 cm H_2O was adopted here as an operational definition of adequate consonant pressure. The validity of this definition has not been tested rigorously, even though it is based upon long-term observations of data generated from aerodynamic studies. The relationship between consonant pressure and the perceptual acceptability of its acoustic analog also must be investigated. In addition, the hypothesis that speech pressures are maintained by controlling airflow and structural movements implies that articulatory gestures may be made in an attempt to maintain vocal-tract pressures even if those gestures compromise overall speech intelligibility. One of several questions raised by such a hypothesis concerns the relationship among compensatory articulations, intraoral speech pressures, and overall vocal-tract resistance. This is being investigated at the present time.

References

Arkebauer H, Hixon T, Hardy J. (1967). Peak intraoral air pressure during speech. J Speech Hear Res 10:196–208.

Bernthal JE, Beukelman DR. (1978). Intraoral air pressure during the production of /p/ and /b/ by children, youths, and adults. J Speech Hear Res; 21:361–371.

Black J. (1950). The pressure component in the production of consonants. J Speech Hear Dis 15:207–210.

Brown W, McGlone R. (1969). Constancy of intraoral air pressure. Folia Phoniatrica 21:332–339.

Brown W, McGlone R, Tarlow A, Shipp T. (1970). Intraoral air pressure associated with specific phonetic positions. Phonetica 22:202–212.

Brown W, McGlone R, Proffit W. (1973). Relationship of lingual and intraoral air pressure during syllable production. J Speech Hear Res 16:141–151.

Flanagan JL. (1972). Speech analysis, synthesis and perception (2nd ed). New York: Springer-Verlag.

Flege JE. (1983). The influence of stress, position, and utterance length on the pressure characteristics of English /p/ and /b/. J Speech Hear Res 26:111–118.

Hutters B, Brondsted K. (1987). Strategies in cleft palate speech—with special reference to Danish. Cleft Palate J 24:126–136.

Karnell M, Willis C. (1982). The effect of vowel context on consonantal intraoral air pressure. Folia Phoniatrica 34:1–8.

Klechak TL, Bradley DP, Warren DW. (1976). Anterior open bite and oral port constriction. Angle Orthodont 46:232–242.

Klich RJ. (1982). Effects of speech level and vowel context on intraoral air pressure in vocal and whispered speech. Folia Phoniatrica 34:33–40.

Lisker L. (1971). Supraglottal air pressure in the production of English stops. Language and Speech 13:215–230.

Lotz WK, Netsell R. (1986). Developmental patterns of laryngeal aerodynamics for speech. Paper presented at the midwinter meeting of the Association for Research in Otolaryngology.

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

Lubker J, Parris P. (1970). Simultaneous measurements of intraoral air pressure, force of labial contact, and labial electromyographic activity during production of the stop cognates /p/ and /b/. J Acoust Soc Am 47:625–633.

Malecot A. (1955). An experimental study of force of articulation. Studia Linguistica 9:35–44.

Malecot A. (1966). The effectiveness of intraoral air pressure pulse parameters in distinguishing between stop cognates. Phonetica 14:65–81.

Malecot A. (1968). The force of articulation of American stops and fricatives as a function of position. Phonetica 19:95–102.

Malecot A. (1970). The lenis-fortis opposition: its physiological parameters. J Acoust Soc America 47:1588–1592.

Netsell R. (1969). Subglottal and intraoral air pressure during intervocalic contrast of /t/ and /d/. Phonetica 20:68–73.

Paynter ET. (1987). Parental and child preference for speech produced by children with velopharyngeal incompetence. Cleft Palate J 24:112–118.

Prosek RA, House A. (1975). Intraoral air pressure as a feedback cue in consonant production. J Speech Hear Res 18:133–147.

Putnam AHB, Shelton RL, Kastner CV. (1986). Intraoral air pressure and oral air flow under different bleed and bite-block conditions. J Speech Hear Res 29:37–49.

Smith BE, Weinberg B. (1980). Prediction of velopharyngeal orifice area: A reexamination of model experimentation. Cleft Palate J 17:277–282.

Smith BE, Weinberg B. (1982). Prediction of modeled velopharyngeal orifice areas during steady flow conditions and during aerodynamic simulation of voiceless stop consonants. Cleft Palate J 19:172–180.

Smith BE, Weinberg B. (1983). Velopharyngeal orifice area prediction during aerodynamic simulation of fricative consonants. Cleft Palate J 20:1–7.

Smith BE, Moon JB, Weinberg B. (1984). The effects of increased nasal airway resistance on modeled velopharyngeal orifice area estimation. Cleft Palate J 21:172–180.

Stathopoulos ET, Weismer G. (1985). Oral air flow and intraoral air pressure: a comparative study of children, youths and adults. Folia Phoniatrica 37:152–159.

Stathopoulos ET. (1986). Relationship between intraoral air pressure and vocal intensity in children and adults. J Speech Hear Res 29:71–74.

Subtelny J, Worth J, Sakuda M. (1966). Intraoral pressure and rate of flow during speech. J Speech and Hear Res 9:498–518.

Warren DW. (1967). Nasal emission of air and velopharyngeal function. Cleft Palate J 4:148–156.

Warren DW. (1975). The determination of velopharyngeal incompetency by aerodynamic and acoustical techniques. Clin Plast Surg 2:299–304.

Warren DW. (1979). Perci: a method for rating palatal efficiency. Cleft Palate J 16:279–285.

Warren DW. (1982). Aerodynamics of speech. In: Lass NJ, McReynolds LV, Northern JL, Yoder DE eds. Speech; language and hearing. Philadelphia: WB Saunders Co.:219–245.

Warren DW. (1985a). Regulation/control of speech aerodynamics in cleft palate. Asha 27:111.

Warren DW. (1985b). Respiratory significance of the nasal grimace. Asha 27:82.

Warren DW. (1986a). Compensatory speech behaviors in individuals with cleft palate: a regulation/control phenomenon? Cleft Plate J 23:251–260.

Warren DW. (1986b). Regulation/control of speech aerodynamics. Folia Phoniatrica 38:368.

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

Warren DW, Devereaux JL. (1966). An analog study of cleft palate speech. Cleft Palate J 3:103–114.

Warren DW, Ryon WE. (1967). Oral port constriction, nasal resistance and respiratory aspects of cleft palate speech: an analog study. Cleft Palate J 4:38–46.

Warren D, Hall D. (1973). Glottal activity and intraoral pressure during stop consonant productions. Folia Phoniatrica 25:121–129.

Warren DW, Wood MT, Bradley DF. (1969). Respiratory volumes in normal and cleft palate speech. Cleft Palate J 6:449–469.

Warren DW, Nelson G, Allen GD. (1980). Effects of increased vertical dimensions on oral port size and fricative intelligibility. Am J Acoust Soc Am 67(5):1828–1831.

Warren DW, Hall DJ, Davis J. (1981). Oral port constriction and pressure airflow relationships during sibilant productions. Folia Phoniatrica 33:380–394.

Warren DW, Lehman MD, Hinton VA. (1984a). Analysis of simulated upper airway breathing. Am J Orthod 86:197–206.

Warren DW, Allen G, King HA. (1984b). Physiologic and perceptual effects of induced anterior open bite. Folia Phoniatrica 36:164–173.

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

Weismer G, Longstreth D. (1980). Segmental gestures at the laryngeal level in whispered speech: evidence from an aerodynamic study. J Speech Hear Res 23:383–392.