Some Characteristics of Oral and Nasal Air Flow During Plosive Consonant Production

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There are little available data concerning the oral and nasal air flow rates that occur in plosive consonants. Isshiki and Ringel (*11*) reported mean measures of combined oral and nasal air volume expended in the production of normal plosives while Van Hattum and Worth (*18*) described the total oral air volume used by normal speakers in selected plosive consonants. Subtelny and associates (*17*) reported peak oral flow rates for a single plosive, /p/. Yanagihara and Hyde (*24*) describe the maximum nasal flow rate during production of bilabial plosives. These studies did not, however, report for a substantial number of normal-speaking subjects the peak oral and simultaneous nasal flow rates during plosives. Such data appear to be useful in understanding the aerodynamics of plosive production.

The present investigation was concerned with the measurement of oral and nasal air flows that are associated with the utterance of plosive consonants by normal speakers. This study was undertaken not only because such information is basic to an understanding of normal speech, but also because it is relevant to an understanding of articulation disturbances that result from deficiencies in oral breath stream regulation. It was anticipated that data derived from normal speakers would provide baseline information against which the performance of subjects with velar pathology might be compared.

Method

Subjects. Young normal adults, twenty-five male and twenty-five female, were selected as subjects from among volunteers locally available. Persons selected as subjects had no abnormality of speech or voice quality, presented no history or current evidence of respiratory problems, and had essentially normal hearing in at least one ear. All subjects were between twenty and thirty-six years of age.

Apparatus. Instrumentation utilized in data collection included two

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warm-wire anemometers (Flow Corporation, Model 53A-1) with a custom-built face mask housing the sensing elements and a dual-channel strip-chart recorder (Sanborn, Model 60-1300 B). The design and function of the warm-wire anemometer have been described previously (*13*). Briefly, this instrument is based on the principle that a stream of air will cool a heated wire with a known coefficient of resistivity at a rate proportional to the air velocity. Such a wire may be used, then, as the sensing element in the circuitry of air-flow-measuring instrumentation. An advantage of the instrument is a frequency response suitable for measuring velocities in flow fields with high gradients and fast variations. Disadvantages include a lack of sensitivity to the direction of flow and non-linearity of response.

For this investigation, the sensing elements (platinum-wollaston wire .0005″ diameter) of the anemometer units were contained in a short, metal tube, four inches in length and seven-eighths-inch internal diameter, attached to the face mask. One sensing wire was located above and one below a partition which extended throughout the length of the tube in its center. The partition served to separate the flow of air from the nose and mouth. The mask was attached firmly to the subject's face by means of two rubber straps so that its pneumatic rim formed an essentially airtight seal. The proximal edge of the mask partition was fitted with a rubber extension which contacted the face above the upper lip.

Calibration of each anemometer unit was accomplished by delivering air at known volume-velocities, as measured by a standard wet-test meter, through each half-tube of the divided face mask. The flow rates corresponding to each of fifty points at twenty-millivolt intervals within the one-volt output range of the anemometer were measured and a calibration curve relating output voltage to flow rate was derived. On the basis of repeated calibrations conducted during data collection, it was determined that the instrument remained in calibration throughout the experiment.

Speech Sample. The speech sample consisted of thirty-six consonant and vowel combinations. Each of the six plosive consonants, /p/, /b/, /t/, /d/, /k/, and /g/, were combined with each of two vowels, /i/ and /ɑ/, in consonant-vowel (CV), vowel-consonant-vowel (VCV), and vowel-consonant (VC) arrangements. Intersubject variability in releasing the final consonant in VC combinations did not allow a meaningful analysis of these data. For this reason, the twelve VC syllables were excluded from final data analysis. The vowels /i/ and /ɑ/ were selected to permit the study of the effect of different vowel contexts on plosive air flow.

Experimental Procedure. All experimental data were collected in a sound-treated test suite with a low ambient noise level. Prior to data collection, the subjects were individually practiced in the production of each item of the speech sample. Subjects were instructed to produce a series of three syllables (CV, VCV, VC) during a single exhalation, at a conversational level of intensity, and at a comfortable pitch level. Each item in the series was produced separately. To avoid air flow differences that might result from variations in the production of the consonant and vowel combinations, subjects were told to produce each syllable with uniform stress. To counterbalance possible order effects, the sequence in which the subject said each item in the series was randomized.

The subject was seated in an examining chair, the headrest of which was adjusted to maintain a comfortable and stable position. To ensure the stability of the face mask during data collection, the mask was mounted on a horizontal metal bar attached at either end to an adjustable stand. This arrangement permitted an easy adjustment of mask height and position.

The subject was then asked: a) to produce and sustain the nasal consonant /m/; and b) to blow through his mouth. Chart recordings of oral and nasal air flow were made during both of these trials. If the production of the /m/ sound resulted in no registration of oral air flow and if blowing through the mouth resulted in no registration of nasal air flow, the partition of the mask separating the oral and nasal sections was judged to be tightly fit. During data collection, each subject's productions were carefully monitored. If a subject violated the instructions he had been given, the trial in which the error occurred was repeated until an acceptable performance was obtained.

MEASURES. The maximum or peak oral air flow and nasal air flow occurring at the instant of peak oral flow were measured. The oral measurement point was selected for a number of reasons. First, the point at which peak oral air flow occurred was clearly identifiable as being within the consonant phoneme and could be measured reliably; second, this point served as a reference to which measurements of nasal air flow could be related; third, if changes in the syllable and/or vowel environment affected consonant flow, it was likely that peak oral flow would be sensitive to such effects; and fourth, it could be assumed that oral flows were egressive at this point. The nasal measurement was selected to provide an estimate of nasal air emission during the release phase of the consonant. All measurements of chart records were made to the nearest one-half millimeter of stylus excursion. These data were converted to anemometer output voltages and, subsequently, to equivalent flow-rates in accordance with the calibration curve of each instrument. All measurements were made twice; a third measurement was made to resolve differences between the first two.

Results and Discussion

The oral and nasal air flow measurements for male and for female subjects were analyzed statistically by means of a split-plot-design analysis of variance with a factorial arrangement of treatments. The significance level was set at .05. Data for the two sexes were not compared statistically. Table 1 presents the mean peak oral air flow (OAF) and nasal air flow (NAF) for each of the six plosives in each of the syllable and vowel contexts in which they were tested. The means represent average values obtained separately for the twenty-five male and the twenty-five female subjects.

Oral Air Flow. Examination of the analysis of variance for the OAF data indicated that, for both male and female subjects, the consonant, vowel, and syllable main effects and the vowel-by-consonant, vowel-by-syllable, and consonant-by-syllable interactions were significant.

TABLE 1. Mean peak oral and simultaneous nasal air flow volume velocities for twenty-five male and twenty-five female adults.

syllable	*vowel*	*consonant*	*flow rates (liters/min)*			
			male (N = 25)		*female (N = 25)*	
			oral	*nasal*	*oral*	*nasal*
CV	/i/	T	62.67	.30	47.87	.94
		P	56.17	1.03	41.41	1.54
		K	38.66	.12	34.58	.48
		D	26.24	.38	19.42	.63
		B	22.21	.86	12.93	.88
		G	17.59	.39	12.99	.25
	/ɑ/	T	79.46	.35	69.74	.96
		P	66.19	1.55	52.80	1.11
		K	68.62	.44	54.25	.31
		D	35.87	.49	20.79	.44
		B	25.51	1.36	13.95	1.01
		G	24.90	.55	15.49	.28
VCV	/i/	T	20.52	.23	16.55	.42
		P	18.26	.62	14.22	1.19
		K	13.26	.19	11.36	.24
		D	9.96	.46	6.15	.30
		B	6.74	.70	3.95	.59
		G	6.98	.59	5.10	.39
	/ɑ/	T	26.46	.42	25.21	.29
		P	21.42	1.00	16.21	.83
		K	21.78	.46	18.57	.34
		D	13.07	.69	6.57	.37
		B	8.87	1.09	4.60	.68
		G	7.08	.53	4.92	.25

Voicing Effects. When considered in the same syllable-vowel context, the OAFs for voiceless plosives always exceeded those for their voiced cognates for both sexes. To illustrate the effect of voicing on the mean oral flow rates for male and female speakers, Table 2 presents the ratio of voiced to voiceless plosive flow rates in both syllable and vowel contexts.

Table 2 shows that the effect of voicing was to reduce the mean flow rate for a voiced plosive to a level that was 53% to 26% of the rate for its voiceless cognate. The relationship of flow rates for voiced and voiceless plosives can be seen to vary somewhat for different consonant pairs according to both syllable and vowel context. The greatest reduction of flow with voicing occurs for female subjects in /ɑ/ contexts. The similarity of ratios for females in /ɑ/ contexts (from .26 to .30) across cognate pairs and syllable contexts stands in contrast to the greater variation evident in the male data and in that for females in /i/ contexts.

These data are consistent with intraoral air pressure and flow rate data for voiced and voiceless consonants reported by Black (*3*), Arkebauer and associates (*1*), Subtelny and associates (*17*), and Isshiki and Ringel (*11*). The cited studies indicate that voiceless plosives are characterized by greater OAFs and greater intraoral air pressures than their voiced cognates. It has been suggested (*1, 11*) that air flow differences between voiced and voiceless productions may be largely attributable to the flow resistance imposed by vocal fold action in voicing.

Differences in findings among studies reporting oral flow rates for consonants are of interest. Subtelny and associates (*17*) reported smaller mean flow rate values for consonants than those reported by Isshiki and Ringel (*11*) and speculate that the greater flow rates noted in the latter study might result from the increased effort required to overcome the resistance imposed by a face mask. A face mask was used in the present study, but the mean peak oral flow for each of the plosives did not always exceed flow rates averaged over the duration of the same plosives as reported by Isshiki and Ringel (*11*). Subtelny and associates (*17*), who

TABLE 2. Ratio of voiced to voiceless oral air flow means for plosive cognate pairs grouped according to sex of speaker and vowel and syllable context.

		/i/		/ɑ/	
		male	*female*	*male*	*female*
CV	D/T	.42	.41	.45	.30
	B/P	.40	.31	.38	.26
	G/K	.46	.38	.36	.28
VCV	D/T	.48	.37	.49	.26
	B/P	.37	.28	.41	.28
	G/K	.53	.45	.32	.26

did not use a face mask, report an average peak flow rate for /p/ produced by twenty adult speakers (ten male, ten female) in CV paradigms with /i/ equivalent to 55.98 liters per minute. This is somewhat larger than the average of 48.79 liters/min peak flow for /p/ with /i/ for the fifty adult speakers used in the present study. It appears difficult, therefore, to account for differences among findings of these studies solely on the basis of mask use.

It has been suggested that oral pressure and/or flow are influenced by such variables as vocal pitch and intensity (*8, 9, 10, 17, 19*), vital capacity (*6, 17, 25*), vocal tract dimensions (*5, 11, 17*), duration of phonemes (*17, 24, 25*), syllabic stress (*17, 12*), oral orifice size (*8, 17, 11, 21, 23*), repetition rate (*1*), and the speed of release of articulatory structures (*11, 17*). These variables, together with those associated with differences in instrumentation design and calibration, might singly or in combination effect data differences across studies. It seems premature, therefore, to ascribe differences in findings across studies to any one of these variables.

Vowel Effects. For both sexes, when OAFs were averaged over CV and VCV environments, plosives combined with the vowel /ɑ/ were associated with greater OAFs than the same plosives combined with /i/. This relationship held for plosives in both CV and VCV environments for both sexes. The only exception to this trend in Table 1 occurs for the plosive /g/ in VCV contexts for females where the value for /g/ with /i/ exceeds slightly that for /g/ with /ɑ/.

The statistical analysis revealed that the OAFs for individual plosives were not affected to a similar extent by changes in vowel context. The primary source of this interaction between consonants and vowel environments appears to lie in the greater increase in flow rates for /t/ and /k/ than for other plosives when the vowel context is changed from /i/ to /ɑ/. Voiced plosives as a group evidence little change in flow rate between the vowel contexts in either CV or VCV syllables. Of the voiceless plosives, /p/ was least affected by changes in the vowel with which it was combined.

For both sexes, the vowel effect was greater for both voiced and voiceless plosives in CV than in VCV syllables. For the male data, when means were taken over the six plosives in each of four syllable-vowel contexts, a change in vowel from /i/ to /ɑ/ in VCV syllables was accompanied by a change in mean OAF from 12.62 liters/min to 16.45 liters/min, a difference of 3.83 liters/min. When means over the six plosives were compared in CV syllables, however, this change in vowel context was accompanied by a change in mean OAF from 37.26 liters/min to 50.09 liters/min, a difference of 12.83 liters/min. Similar relationships can be derived from the female data.

It may be noted, however, that while there was a greater absolute increase in plosive flow rates with a change of vowel context from /i/ to

/ɑ/ in CV than in VCV syllables, the proportional increase in flow was similar in the two syllable types. This appeared to be true not only for plosives as a group but for individual plosives as well.

Regarding the possible source of the plosive flow rate differences associated with differences in the vowel context, it is perhaps relevant that the vowel /ɑ/ tends to be produced with greater intensity than /i/ (*4*). Because of lower tongue position and larger mouth opening in its articulation, /ɑ/ also offers less impedance to oral flow than /i/. The present data suggest that differences in the driving pressures and impedances among vowels affect the peak flow rates of the plosive with which they are combined. These data lend support to the Isshiki and Ringel (*11*) generalization that the flow rate for plosives is influenced by the following vowel.

Syllable Effects. For both sexes, the plosive consonants as a group produced in CV syllables were characterized by greater OAFs than those same consonants in VCV syllables, regardless of vowel context. For both sexes, however, there was a tendency for the voiceless plosives to be more markedly affected by differences in syllable context than voiced plosives. For both sexes, one or more of the OAFs for the voiced plosives in CV syllables was equal to or greater than the largest OAF for a voiceless consonant in VCV syllables. It appears, therefore, that while voiceless plosives involve greater OAFs than voiced plosives when the sounds were tested in the same type of syllable, this relationship may not hold when the voiced plosive is tested in a CV syllable and the voiceless plosive is tested in a VCV syllable.

It may be seen in Table 1 that, when vowel context is held constant, the OAF for plosives in CV environments is about three times that for the same plosive in a VCV context. Although variations occur, this CV/VCV ratio appears generally consistent throughout the data for both sexes. In view of the limited controls imposed on the production of the syllables in this investigation, the regularity of this relationship suggests that the pressures and impedances for plosives in CV syllables tend to vary in a lawful manner with respect to those for plosives in VCV syllables.

The effect of syllable context on the OAF for plosives varied as a function of the vowel with which the plosive is combined. For both sexes, there was a greater difference in OAF for plosives as a group between CV and VCV contexts when plosives were combined with /ɑ/ than when they were combined with /i/. These findings suggest that the effects of syllable context on the OAF for plosives are not independent of the vowel environment.

A consistent relationship observed for plosives produced in all syllable-vowel environments, for both sexes, was the tendency for /t/ to exceed the other voiceless consonants and /d/ to exceed the other voiced consonants in OAF. This relationship within voiced and voiceless categories suggests that the lingua-alveolar plosives might be characterized by greater driving pressure during the release phase of their production and/or by lower impedance to flow than are the other plosives in each category studied.

Sex Effects. While the OAF data were not analyzed statistically for differences between the sexes, inspection of Table 1 indicated that female OAFs tended to be smaller than those for male subjects in all syllable-vowel contexts. On the average, the ratio of male to female OAFs for plosives produced in the same syllable-vowel contexts was 1.42 over all contexts studied. For CV syllables, the mean male/female ratio was 1.40; for VCV syllables it was 1.44. Generally, plosives associated with relatively large OAFs for males were those characterized by relatively large flows for females. Moreover, the effect of vowel and syllable contexts on male and female OAFs was similar.

The greater OAFs for male than for female subjects found in the present study are of interest in view of intraoral pressure data reported by Subtelny and associates (*17*). These authors report greater pressures for consonants produced by adult females than by adult males. It appears, therefore, that adult females achieve greater intraoral pressures for plosives but lower peak flows than males. Further study of this difference in pressure-flow relationship between the sexes would appear useful.

Yanagihara and associates (*25*) have previously reported that the volume of air subjects expend in production of sustained vowels is related to their vital capacities. Since the average ratio of male to female vital capacities is approximately 1.25 (*2*), it appears possible that the observed differences between sexes with regard to plosive OAFs may be related to sex differences in vital capacity.

Nasal Air Flow. Nasal air flow was measured in this study at the instant of peak oral air flow. An inspection of individual chart records revealed that, while at least some NAF was often recorded during the release of oral air in plosive production, the oral peak flow did not necessarily correspond to a peak in nasal flow. In some instances, for example, no NAF was registered at the instant of the peak oral flow, but nasal flows were registered before or after the oral peak. Generally, subjects evidencing relatively large NAFs for some plosives evidenced a measurable NAF for all of the plosives.

The reason for these nasal flows may be questioned. There is the possibility that the NAFs reflected a leak between the oral and nasal sections of the face mask. Table 1 reveals that greatest NAFs were associated with /p/ and /b/, bilabial sounds produced with relatively large lip and mandibular movements. It may be that mask leaks occurred because of facial movements during production of /p/ and /b/ even though great care was taken to assure a tight mask fit and to test for separation of flows through the oral and nasal mask sections.

Other explanations of the NAFs may also be suggested. If it is assumed that there was no mask leak and measured nasal flows were at all times egressive, then they may reflect an open velopharyngeal valve during the oral release of the plosive. A further possibility is that the nasal flows reflect an elevation of the velum into the pharyngeal space and a consequent displacement of nasal air. Lubker and Moll (*14*), on the basis of nasal air flow measurements and simultaneous cineradiographic observation of velopharyngeal valving, noted an upward displacement of the velum during the initiation of stop production. It is also possible that the nasal flows were, at least at times, ingressive rather than egressive. Lubker and Moll (*14*) noted inconstant ingressive nasal flows for plosive and other consonants using instrumentation sensitive to flow direction. They noted also that ingressive nasal flows may be recorded both when the velar port is open and when it is closed.

Examination of the analysis of variance for the NAF data indicated that, for male subjects, the consonant and vowel main effects and the consonant-by-syllable and vowel-by-consonant-by-syllable interactions were significant. For female subjects, only the consonant and syllable main effects were significant.

Consonant Effects. When mean nasal air flows for individual plosives were taken over both syllable and vowel contexts, male subjects evidenced greatest nasal flow for /p/ with progressively smaller mean flow rates for /b/, /g/, /d/, /t/, and /k/. For females, the order from largest to smallest means was /p/, /b/, /t/, /d/, /k/, and /g/. For both sexes, greatest mean nasal flows were recorded in production of the bilabial plosives and least in production of the lingua-velar plosives. The magnitude of the mean nasal flows was, as expected, small. For males, the consonant NAF means ranged from .12 liters/min for /ki/ to 1.55 liters/min for /pɑ/. For females, mean nasal flow rates ranged from .24 liters/min for /iki/ to 1.54 liters/min for /pi/. Lubker and Moll (*14*), using simultaneous cineradiographic and air flow measures, report a slight increase in velopharyngeal opening and a decrease in velar height at the instant of peak oral flow during the production of /p/ in the phrase /se pɪn/. While the Lubker and Moll data appear consistent with the present finding that small nasal flows occur at the instant of peak oral flow, their data are based on the study of a single subject. It is possible that the dynamics of velar valving may vary considerably from subject to subject and also according to the particular vowels and consonants preceding and following the plosive.

The examination of individual subject records revealed that the present nasal flow rates never exceeded 72 cc/sec (4.32 liters/min) for any of the plosives in any of the contexts studied. These flow rates appear to be generally consistent with the limited NAF data that is available from other studies. Warren (*20*), for example, has reported that two subjects classified as having adequate velopharyngeal closure produced the plosive /p/ in /papa/ with less than 155 cc/sec (9.3 liters/min) maximum nasal air flow. In contrast, his subjects classified as having velopharyngeal insufficiency exhibited peak nasal emission rates greater than 175 cc/sec (10.5 liters/min) for the consonant /p/. Data reported by Van Hattum and Worth (*18*) suggest that at the instant of peak oral flow, plosive NAFs approximating 100 cc/sec (6 liters/min) in /ipi/ constructions and less than 50 cc/sec (3 liters/min) in /ibi/ constructions occurred in their study of oral and nasal air flow rates. Yanagihara and Hyde (*24*) report maximum NAF rates for /p/ and /b/ ranging from 20 cc/sec to 100 cc/sec regardless of the succeeding vowel. Thus, the mean NAF rates for the bilabials in this study seem compatible with the data from other studies.

The present findings suggest that measurable NAFs generally not exceeding 72 cc/sec at the instant of peak oral flow characterize plosives produced by subjects with normal velopharyngeal valving. Because it may not be assumed, however, that subjects always utilize similar oral articulator postures or expiratory efforts in speech, the differentiation of individuals with velopharyngeal incompetence from those with normal velopharyngeal valving probably should not be predicated solely on NAF differences.

Vowel and Syllable Effects. The effect of vowel context on nasal air flow means differed for the male and female groups. Males evidenced greater NAFs for consonants produced with /ɑ/ than with /i/ when the NAFs were averaged over both types of syllable. For males, therefore, consonants combined with /ɑ/, a vowel produced with a relatively lax velar seal (*15*), low tongue position, and wide mouth opening, are associated with greater NAFs. These findings are consistent with those of Vaughn (*19*), who reported greater NAFs for /ɑ/ than for /i/ when these vowels were produced in isolation by adult male subjects.

The lack of a significant vowel effect for the females is also of interest. It appears that these female subjects produced the plosives with similar NAF means when the consonants were combined with /ɑ/ and with /i/. These data might suggest a vowel-related sex difference in velopharyngeal valving during plosive consonant production.

With regard to syllable effects, females evidenced greater nasal flows for plosives in CV than in VCV syllables, and this tendency was most evident for /p/ and /b/. For the females, interactions involving the vowel-syllable elements of the context and the plosives were not significant. For males, the NAF means for individual plosives averaged over both vowels were not equally affected by a change in syllable context. The means for /p/ and, to a lesser extent, for /b/ were reduced in VCV as compared to CV syllables. This marked syllable effect did not obtain for the other plosives. For the males, however, the plosives /p/ and /b/ were associated with the largest nasal air flow means and the means for /g/ and /d/ exceeded those for /k/ and /t/, regardless of the syllable-vowel context.

Generally, the differences among NAF means for the individual plosives produced by males were greater when the consonants were combined with /ɑ/ than with /i/, regardless of the syllable context. Vowel contexts, however, did not affect all the plosives produced by males in the same way in the two types of syllable. For example, in CV contexts, the mean NAF for /g/ tended to decrease when the syllabic vowel was changed from /ɑ/ to /i/. In VCV contexts, however, the mean NAF for /g/ tended to increase when the syllabic vowel was changed from /ɑ/ to /i/.

It appears that, for males at least, complex relationships may exist between NAF means for some plosive consonants and the components of the context in which these consonants are produced. Further research may be profitably concerned with investigation of the interactive effects of vowel and syllable contexts on consonant NAFs.

Summary

This study investigated air flow differences among the six plosive consonants in selected syllable-vowel environments. Twenty-five male and twenty-five female normal-speaking young adults were utilized as subjects. The speech sample consisted of the plosives /p/, /b/, /t/, /d/, /k/, and /g/ combined with the vowels /i/ and /ɑ/ in CV and VCV contexts. Oral and nasal air flows were assessed by means of a warm-wire anemometer permitting simultaneous but separate measurements of air flow from the nose and mouth during speech. The chart records of these flows were analyzed to determine the maximum volume-velocity of oral air flow and the nasal air flow concurrent with the oral peak during production of the consonants in each syllable. In general, the findings indicated that differences existed among the plosive consonants with respect to both oral and nasal air flow, and that the oral and nasal volume-velocities for the plosives were affected by the differences in the vowel-syllable environments. Some problems in interpretation of the data were discussed and some questions meriting further study were suggested.

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