Multidimensional Analysis of Bilabial Stop and Nasal Consonants—Cineradiographic and Pressure-Flow Analysis

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Palatopharyngeal valving during speech serves to control the direction of airflow and to modify intraoral air pressure, thereby influencing the acoustical characteristics of the speech signals generated. The complex nature of inter-relationships existing among physiological valving, pressure-flow dynamics, and spectral features of speech, has remained a focal point of research interest and effort for many years. Unquestionably, the need for more definitive information pertinent to surgical treatment of palatopharyngeal incompetence has served to maintain interest in study.

As might be expected from the nature of the parameters involved, various techniques have been used to study the physio-acoustic conversions of speech specifically as related to palatopharyngeal function. Techniques have also been combined. In this regard, cineradiography has been combined with spectrography (*1, 17*); with electromyography (*11*); and with pneumotachography for study of airflow (*12, 13*). Mechanical and electrical analogues of the vocal tract (*4, 5, 6, 15, 26, 28*) have also been developed to study the nature of existing relationships. More recently, parameters of oropharyngeal air pressure, nasal pressure, and nasal airflow have been recorded for the purpose of calculating palatopharyngeal orifice areas (*23, 24, 25, 27*).

The work reported here represents a continuation of the combined instrumental approach to study palatopharyngeal valving, pressure-flow dynamics, and speech output. Physiologic features have been recorded cineradiographically at 240 frames per second with simultaneous re-

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cordings of sound, intraoral-intranasal air pressure, and oral-nasal airflow. Since parameters of pressure and flow are related to both acoustical and physiological aspects of speech, these parameters were recorded to supplement radiographic information and thereby to facilitate interpretation.

To a degree, the study represents a departure from other investigations in the sense that the purpose is to describe physiological details within references of both time and the aerodynamics of the breath stream. In other words, the physiological description has been focused upon what happens, when it happens, and the associated effect upon air pressure and flow. Since some of the parameters recorded could be used to calculate palatopharyngeal orifice areas, such calculations were made to compare results with data reported by Warren (*23, 24*).

The fundamental question motivating this work concerns the extent of palatopharyngeal closure required for satisfactory speech production. Pertinent to this major area of inquiry, study of non-nasal and nasal consonants produced by normal speakers was undertaken. Some of the specific questions posed for study are as follows: a) What is the degree and duration of palatopharyngeal opening associated with nasal consonant production? b) What are the characteristics of nasal flow correlated with nasal resonance? c) How are palatopharyngeal and bilabial valving related in time? d) What are the physiological and pressure-flow differentiations between non-nasal and nasal sounds /p/, /b/, and /m/? These questions posed relative to normal speech production are considered basic to understanding and continued study of pathological speech resulting from palatopharyngeal incompetence.

Procedures

In broad aspect, data were accumulated for ten normal adult female speakers to describe /p/, /b/, and /m/ articulated in simple vowel-consonant-vowel sequences. The constant vowel context was used to control the influence of phonetic context upon pressure-flow and physiological parameters of the consonants studied. Vowel /i/ was selected for context because this vowel is produced with firm palatopharyngeal closure (*11, 14*).

All subjects had normal speech with no apparent deviation in structure. In sequence, the samples /ipi/, /ibi/, and /imi/ were produced with equal stress at a comfortable loudness level. Sequences were rehearsed with experimenter and test write-outs made before recording.

INSTRUMENTATION. The instrumentation system (*19*) and the integrating flowmeter (*29*) utilized in data accumulation have been described fully and need not be repeated. In overview, the cineradiographic equipment includes: the x-ray generator, image intensifier, high speed 16 mm motion picture camera, synchronizing circuits, a TV vidicon monitor system, and a modified Wehmer Cephalostat. A pulse generator located within the motion camera is used to synchronize the cine film with graphical recording.

Intraoral air pressure is recorded by a small silicone strain gauge pressure transducer pasted to the roof of the mouth. A catheter attached to a similar transducer is inserted into the nose for nasal pressure recording. Both transducers adequately record pressure modifications caused by articulatory movements as well as very rapid pressure fluctuations caused by vocal fold vibration.

The integrating flowmeter, designed to record oral and nasal flow in free field, consists of a series of short warm-wires arranged in oral and nasal sections. The oral section, consisting of 24 warm-wires, is separated from the nasal section by a thin metal plate which is padded with foam rubber to provide for tight contact with the upper lip just above the vermilion border. Above the plate, 4 additional warm-wires are linearly arranged to sample nasal flow.

Humans were used rather than mechanically controlled flow sources to calibrate the flowmeter. This source was considered desirable to approximate a number of potentially significant variables influencing flow measurements; such as, area of aperture, velocity, air temperature, and relative humidity. For calibration, measures of vital capacity were made with the flowmeter and a wet spirometer for 16 adult subjects. Comparative study of the results has shown that the integrating flowmeter is acceptable for measuring oral airflow during speech over the normal range of flow (0 to 1200 ml/sec). Nasal flow, however, is measured with less accuracy since only four sampling points were provided (*29*).

Data Recording and Write-Out. Signals from the various transducers including a microphone are appropriately amplified and recorded on five channels of a data tape recorder. A sixth channel carries a synchronizing pulse chain generated by the cine camera.

By playing the data tape back into a multichanneled oscillograph (Visicorder, Honeywell 1108), a completely synchronized graphical record is obtained. However, before graphical recording, the audio signal recorded on the data tape is converted to sound power as described by Peterson and McKinney (*18*). Rate of oral and nasal flow (volume velocity) is also electronically integrated over time to yield volume. To illustrate the type of data, a synchronized graphical record is reproduced in Figure 1.

Cine Analysis. Before measurement, the first and last closures of the oral and palatopharyngeal ports were identified by repeated forward and backward projection on the Kodak Film Analyzer with frame counter. After preliminary identification of relevant frame numbers, films were analyzed on the Benson-Lehner Oscar Model F3 (Optical Chart Reader and Scanner) equipped with a Vanguard 16 mm motion projector head (*19*).

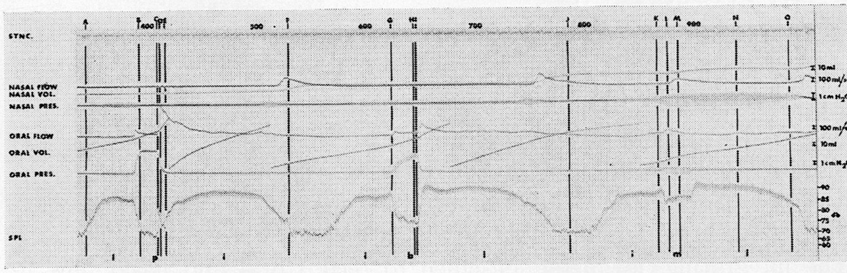


FIGURE 1. Points selected for measures of pressure and airflow are identified by lines: A, onset of voicing; B, cessation of voicing; C, auditory burst; D, maximum oral flow; E, resumption of voicing; F, termination of voicing; G, onset of oral pressure rise; H, earliest point of maximum oral pressure; I, terminal point of maximum oral pressure; J, palatopharyngeal closure; K, palatopharyngeal release; L, onset nasal flow; M, maximum nasal flow; N, palatopharyngeal reclosure; O, palatopharyngeal release.

In analysis, the palatal plane and pterygomaxillary fissure line, constructed perpendicular to the palatal plane, were used for reference. Manually operated cross bars are positioned for location of specific points. Point locations are converted to digital values and an automatic write-out obtained. The output of the converter is also fed into an IBM printing card punch (IBM 26). The punched cards are then processed by a larger computer (IBM S/360) to give direct measurements in millimeters.

Oral and palatopharyngeal port measurements were checked against identification of opening and closing of the articulatory ports as determined by the initial film viewing. Thus, the two procedures of measurement and inspection were employed to assure accuracy in frame identification of port opening and closing.

The primary purpose in analysis was to define valving activity; but a secondary purpose was to investigate possible differences in articulation of the three sounds relative to tongue and velar height, lip protrusion, and degree of tissue contact. The specific measures made to fulfill these purposes during open and closed conditions of the oral and palatopharyngeal valves are identified and illustrated in Figures 2 and 3.

During active valving, frame-by-frame analysis was made. At less active intervals, some two or three frames may have been skipped in analysis if no modification in position was observed (by inspection) from one frame to the next. Additional frames identifying pertinent features in the graphical record were included in analysis regardless of observable movement.

Since subtle shifts in articulatory positions were apparent on a frame to frame basis, an arbitrary decision was made to discount slight changes which were judged to be unassociated with movement per se. Structures were considered in stable position when movement

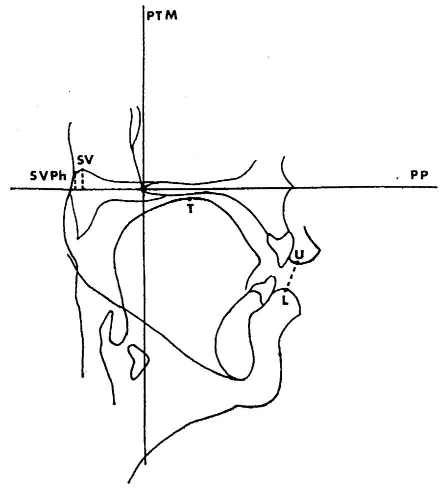


FIGURE 2. Tracing of cine frame reproduced to illustrate the ordinate-coordinate system used for analysis of oral and palatopharyngeal valving. As shown, the palatal plane (PP) and the pterygomaxillary fissure (PTM) are established as reference lines. Points labeled to illustrate analysis of an open oral port and closed palatopharyngeal valve are described as follows: U, inferior most point of upper lip; L, superior most point of lower lip; T, highest point of tongue; SV, highest point of velum; SVPH, highest point of palatopharyngeal contact. Measurements of successive frames or as a function of time included: U-L, lip aperture; T-PP and T-PTM, tongue position vertical and horizontal respectively; SV-PP, velar height; SVPh-PP, site of palatopharyngeal closure.

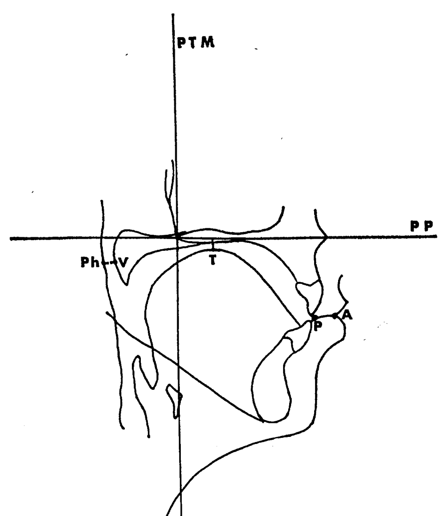


FIGURE 3. Reproduced tracing to illustrate additional measurements for the closed oral and open palatopharyngeal port status. Points labeled to illustrate measurement procedures include: A, anterior most point of lip contact; P, posterior most point of lip contact; T, highest point of tongue; Ph-V, point of closest approximation between velum and pharynx. Measurements included: A-PTM, degree of lip protrusion; A-P, degree of tissue contact; T-PP and T-PTM, tongue position; and PhV, palatopharyngeal aperture.

per frame was less than .5 mm. Structures were considered in motion (opening or closing) when movement equalled or exceeded .5 mm per frame. Application of this rule made it possible to establish onset of closing or termination of opening movements. These points and those defining initial and terminal contacts were used to determine the duration of opening and closing movements.

The degree of lip or velar movement occurring per frame during closing and opening was defined by the aperture dimension existing in the last frame before closure or in the first frame after contact was broken. Measures of movement per frame were thus limited to the frame interval (4.17 msec) immediately preceding or succeeding closure of the articulatory ports. This procedure was followed to restrict measures to comparable points in time for all speakers.

Pressure-Flow Analysis. To locate on each trace appropriate sites for measurement and to insure accuracy in frame number identification for cine analysis, vertical lines transecting the various traces were constructed and extended to the synchronizing pulse chain (Figure 1). Discrete features recorded in pressure, flow, or SPL traces, were used to locate points for line construction. The points defined from the intraoral pressure trace included: onset and cessation of voicing, onset of rise and return of pressure to zero level, initial and terminal points of maximum pressure. From the oral flow trace, the lowest point of flow during the interval of oral pressure modification and highest point after onset of oral pressure decay were identified. From the nasal flow trace, the onset of rise and the highest point were identified. To locate the middle of the first and second vowels, the fully elevated sound power level trace was bisected.

All analyses were done by the same individual. Accuracy and consistency in point location, line construction and measurement were evaluated by independently processing and measuring duplicate write-outs for ten subjects. Comparative study of measures derived from the duplicate records showed that procedures for analysis and the analyst were satisfactorily reliable.

Temporal Analysis. The synchronized system of recording permits study of both physiological and physical events within the reference of time. By film viewing with a frame counter, a specific event is identified. The associated frame is then related in time to other events recorded either on the film or the graphical recording. To illustrate, the opening of the palatopharyngeal port has been specified relative to closure of the oral port and relative to the point of maximum nasal flow. Time factors are determined simply by subtracting one frame number from another and multiplying the number of frames by 4.17 msec. This procedure was used to define intervals of: lip closure, palatopharyngeal opening, voicing, and a variety of other time relationships between valving and selective features of the pressure-flow data.

All data were card punched and processed on the IBM S/360 computer. Means, standard deviations and 95% confidence intervals were derived for each data set. In most instances, a data set consisted of measures for the three consonants. All analyses were made on the basis of paired differences within individual subjects.

Confidence intervals at the 95% level were computed for each measure to permit three way comparisons of /p/, /b/, and /m/, and in order to determine whether or not statistically significant differences were present. If the confidence intervals for any two sounds being compared do not overlap, there is a statistically significant difference at the .01 level. This method of analysis yields results identical to those obtained when standard *t* tests are computed.

Results

In accordance with the questions posed for study, results are reported for: physiological (Table 1), temporal, and flow analyses. Since marked variability in certain measurements was observed, some results are reported in terms of individual measures as well as means.

Palatopharyngeal Valving. Complete closure of the palatopharyngeal port before and during voicing of the first vowel was observed in all subjects. All subjects also showed complete closure during articulations of /ipi/ and /ibi/.

During production of /imi/, all subjects registered complete closure during initial voicing of the first vowel and all subjects showed a break in palatopharyngeal contact during phonation of the first vowel. Eight of the ten subjects re-established firm closure after articulation of /m/. One subject showed an intermittent opening and closing throughout phonation of the second vowel. A second subject failed completely in reclosure after the /m/. The average duration of palatopharyngeal opening for the eight speakers who reclosed the port was 242.75 msec with a large standard deviation of 72.86 msec (Table 1).

Degree of Opening. The maximum degree of palatopharyngeal opening averaged 4.38 mm with a standard deviation of 1.80 mm. Maximum opening for five of the ten subjects was less than 5 mm. In general, the degree of opening was small during production of the nasal consonant; however, one subject had an opening as large as 8 mm. The degree of opening as well as the duration of opening varied from one speaker to the next. In order to illustrate the variation noted, palatopharyngeal measures for the ten subjects are graphed individually as a function of time in Figure 4.

Velar Stability and Position during Closure. Measures of maximum velar height during closure showed, in general, that the velum did not remain in stable or in fixed firm contact with the posterior pharyngeal wall. Subtle shifts in vertical position and in the vertical extent or degree of contact with the posterior pharyngeal wall were

TABLE 1. Means, standard deviations and 95% confidence intervals (CI) for cine measures describing articulations of /p/, /b/, and /m/ in VCV context. Measures report time intervals in msec and movements in mm. Ten subjects were used.

measurement	*mean*	*SD*	*95% CI*
velum			
max. height (interval lip closure)			
/p/	8.52 mm	1.89	7.19–9.85
/b/	9.21 mm	1.62	7.99–10.44
maximum opening			
/m/	4.38 mm	1.80	3.11–5.65
movement per frame: opening			
/m/	.78 mm	.47	.45–1.12
movement per frame: closing			
/m/	.97 mm	.79	.38–1.56
duration of opening (n, 8)			
/m/	242.75 msec	72.86	183.35–302.15
lips			
duration of closing			
/p/	47.12 msec	9.64	40.33–53.91
/b/	53.79 msec	23.38	37.32–70.27
/m/	47.54 msec	14.88	37.06–58.01
duration of opening			
/p/	50.87 msec	24.62	33.53–68.22
/b/	45.45 msec	12.96	36.32–54.58
/m/	48.37 msec	7.41	43.15–53.59
movement per frame: closing			
/p/	1.87 mm	1.33	.93–2.80
/b/	1.85 mm	1.38	.87–2.82
/m/	1.74 mm	1.14	.94–2.54
movement per frame: opening			
/p/	1.70 mm	1.03	.98–2.43
/b/	2.04 mm	.98	1.34–2.73
/m/	2.13 mm	1.69	.94–3.31
duration of closure			
/p/	95.08 msec	15.20	84.37–105.79
/b/	94.66 msec	14.98	84.11–105.21
/m/	101.17 msec	14.67	90.83–111.50
protrusion			
/p/	57.59 mm	4.02	54.76–60.42
/b/	57.03 mm	5.08	53.45–60.61
/m/	57.28 mm	5.10	53.69–60.88
tissue contact			
/p/	6.18 mm	1.02	5.46–6.90
/b/	5.59 mm	1.07	4.84–6.34
/m/	5.77 mm	1.13	4.97–6.57
tongue			
max. height (interval lip closure)			
/p/	4.97 mm	2.71	3.06–6.88
/b/	5.20 mm	3.02	3.08–7.32
/m/	4.67 mm	2.24	3.09–6.25

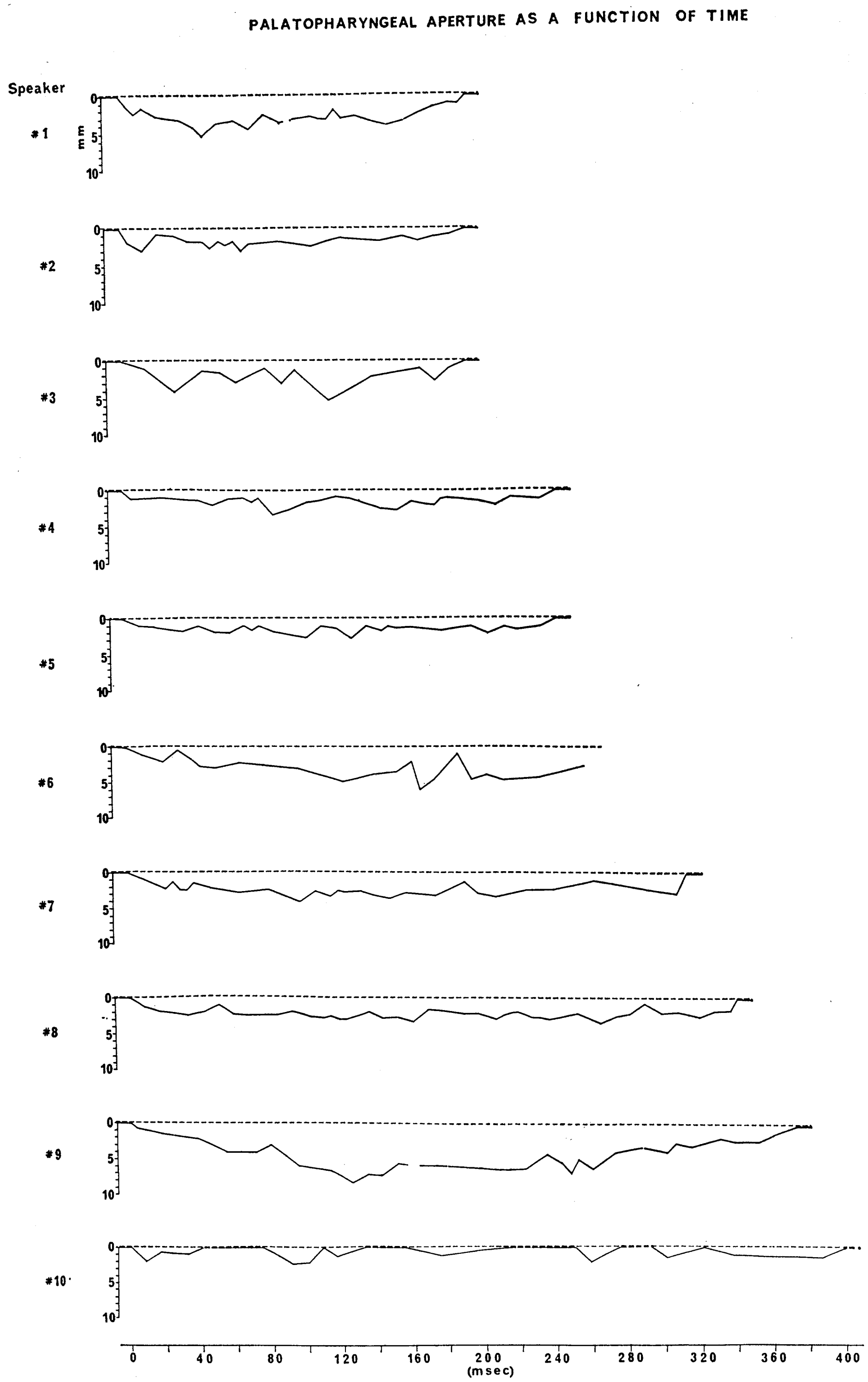


FIGURE 4. The extent and duration of palatopharyngeal opening during articulation of /imi/ are graphed in millimeters and milliseconds for ten speakers. As illustrated, speaker #6 failed to reestablish closure for production of the second vowel /i/. Speaker #10 showed intermittent opening and closing of the palatopharyngeal port.

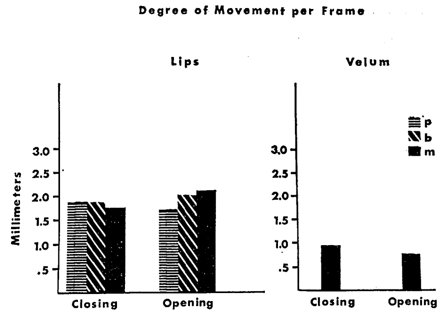


FIGURE 5. Graph of averaged data defining the degree of lip and velar movements occurring in one frame immediately preceding or succeeding tissue contact to achieve closure or release of the articulatory valve.

evident. This was true despite the fact that the port remained, by measurement, technically closed. These modifications in velar position provide radiographic evidence that the degree of firmness or the tightness of the palatopharyngeal seal varied during periods of closure.

The confidence intervals for measures of maximum velar height during articulation of /p/ and /b/ indicated no difference of statistical significance (Table 1). Velar height measures averaged, individually, for all frames analyzed during lip closure also failed to indicate a significant difference in velar position as a function of the stop consonant produced.

VELAR AND LIP MOVEMENT DURING VALVING. Velar movement per frame in opening and closing, immediately succeeding and preceding closure, averaged .78 mm and .97 mm respectively, with corresponding SDs of .47 and .79 (Table 1). Lip movement, immediately succeeding and preceding closure averaged about 2 mm per frame with large SDs approximating 1 mm.[1] Thus, numerically, velar movement was found to be less than half the movement recorded for the lips. On the basis of these findings, lip movements or the dynamics of oral valving appear to be considerably faster than velar movements associated with palatopharyngeal valving (Figure 5).

TEMPORAL DATA. Means and SDs for measures of temporal relationships are reported in Table 2. As indicated by the standard deviations, marked variability in the timing of palatopharyngeal valving was apparent. Palatopharyngeal closure was effected 135 msec before voicing for /ipi/; 88 msec before /ibi/; and 76 msec before /imi/. These results suggest that duration of closure before voicing may be longer at the

[1] These measures are in agreement with Fujimura's data derived from high speed photographic study (240 f.p.s.) of one speaker (*2*). Fujimura's measures of lip separation 5 msec after explosion of /p/, /b/, and /m/ (when preceded by a schwa vowel) are a fraction of a millimeter larger than the means reported for lip opening in the first frame (4.17 msec) after lip release. Fujimura also reported a 54 msec interval between the instant of lip separation and onset of glottal vibration when /p/ appeared in similar phonetic context. The comparable interval in this study averaged 62.99 msec, SD 20.36 (Table 2). Considering the variability encountered, present findings again appear to be in basic agreement with those reported by Fujimura.

TABLE 2. Summary of data defining in msec the temporal relationships between physiological events and specific features in pressure flow recording.

interval	*/ipi/*	*/ibi/*	*/imi/*
		msec	
palatopharyngeal closure to onset of voicing			
M	135.00	88.14	75.83
SD	35.60	53.37	31.43
onset pressure rise to lip closure			
M	8.00	7.00	−1.73
SD	7.63	4.11	8.55
lip closure to cessation of voicing			
M	22.20		
SD	5.35		
pressure rise			
M	63.75	103.50	11.68
SD	20.35	18.75	8.29
pressure decay			
M	69.25	29.75	8.33
SD	23.51	13.25	4.68
total duration pressure elevation			
M	186.00	148.50	139.00
SD	35.60	17.33	29.28
onset pressure decay to maximum oral flow			
M	53.50	20.75	
SD	27.59	7.55	
lip release to maximum oral flow			
M	53.80	25.60	
SD	19.78	10.41	
lip release to resumption of voicing			
M	62.99		
SD	20.36		
voiceless interval			
M	149.50		
SD	28.06		
palatopharyngeal release to lip closure			
M			67.90
SD			43.19
palatopharyngeal release to maximum nasal flow			
M			125.33
SD			39.55
lip closure to maximum nasal flow			
M			57.20
SD			35.48
lip release to palatopharyngeal closure			
M			70.88
SD			70.39

onset of speech utterances or when closure is effected from a status of rest rather than from a status of partial or incomplete rest as might be anticipated during continuous speech.

On the basis of averaged data for the articulation of /m/, the initial break of palatopharyngeal contact occurred 68 msec before lip closure. Palatopharyngeal reclosure occurred approximately 71 msec after lip release. Compositely, these findings indicate palatopharyngeal valving is anticipatory in some contexts, but not in others. Closing was effected before voicing and opening occurred before lip closure. However, reclosure of the palatopharyngeal valve after articulation of /m/ lagged rather than preceded lip release. In this latter respect, the velar adjustment cannot be considered anticipatory. These observations serve simply to emphasize the importance of specifying phonetic context when describing temporal features of articulatory valving.

As indicated in Table 1, the duration of palatopharyngeal opening (243 msec) was much longer than the duration of lip closure (101 msec) for the /m/ in /imi/. The interval of lip closure was about equidistant between palatopharyngeal opening and closing with maximum velocity of nasal flow recorded about the midpoint of the lip closure interval. These and other relationships in time are graphically displayed on the basis of averaged data in Figure 6.

ORAL VALVING. Data summarizing lip meaurements are included in Table 1. Closing and opening movements averaged about 50 msec for all three consonants. Only slight differences in duration of movement as a function of the consonant were revealed with none of the differences significant as indicated by 95% confidence intervals.[2]

Similarity in lip activity during production of the three sounds was also shown by measures of closure duration (Figure 7). Lip closure averaged 95 msec for /p/ and /b/, and 101 msec for /m/ with SDs of 15 msec for all three measures. During intervals of lip closure, measures of maximum tissue contact and maximum protrusion were made. The results, reported in Table 1, indicate no significant difference in bilabial valving as a function of the consonant.

Further analysis to define relative degree of tissue contact or protrusion involved averaging respective measures for all frames analyzed during the lip closure. The results, yielding an average index of tissue contact and protrusion for each phoneme, are similar to the results de-

[2] Comparison of data defining opening as opposed to closing shows the interval of closing (47 msec) for /p/ was slightly shorter than opening (51 msec). During articulation of /b/, the opposite was observed—closing occupied a longer interval (54 msec) than opening (45 msec). For /m/, opening and closing durations were the same with slightly greater variation identified with closing gesture. Variability in measures identified with explosion of /p/ and implosion of /b/ is particularly prominent. Theoretically, spectral shifts, termed transitions, are caused by movements. The duration of transitions for bilabial stops and nasal consonants have been described as approximating 50 msec (*8*, *9*, *15*). Thus closing and opening gestures described here appear to be in general agreement with other data.

Measures of tissue contact between lips were made to explore the tense-lax differentiation between consonants. If it is assumed that a firmer articulatory closure or a more forcible contraction of lip musculature results in a broader extent of contact, a broader contact for /p/ than for /b/ would be expected. A greater extent of lip protrusion might also be anticipated. The cine findings relative to tissue contact and lip protrusion fail to support a tense-lax differentiation between consonants. In this respect, the data agree with recent electromyographic studies of lip activity reported by Harris, Lysaught, and Schvey (*3*).

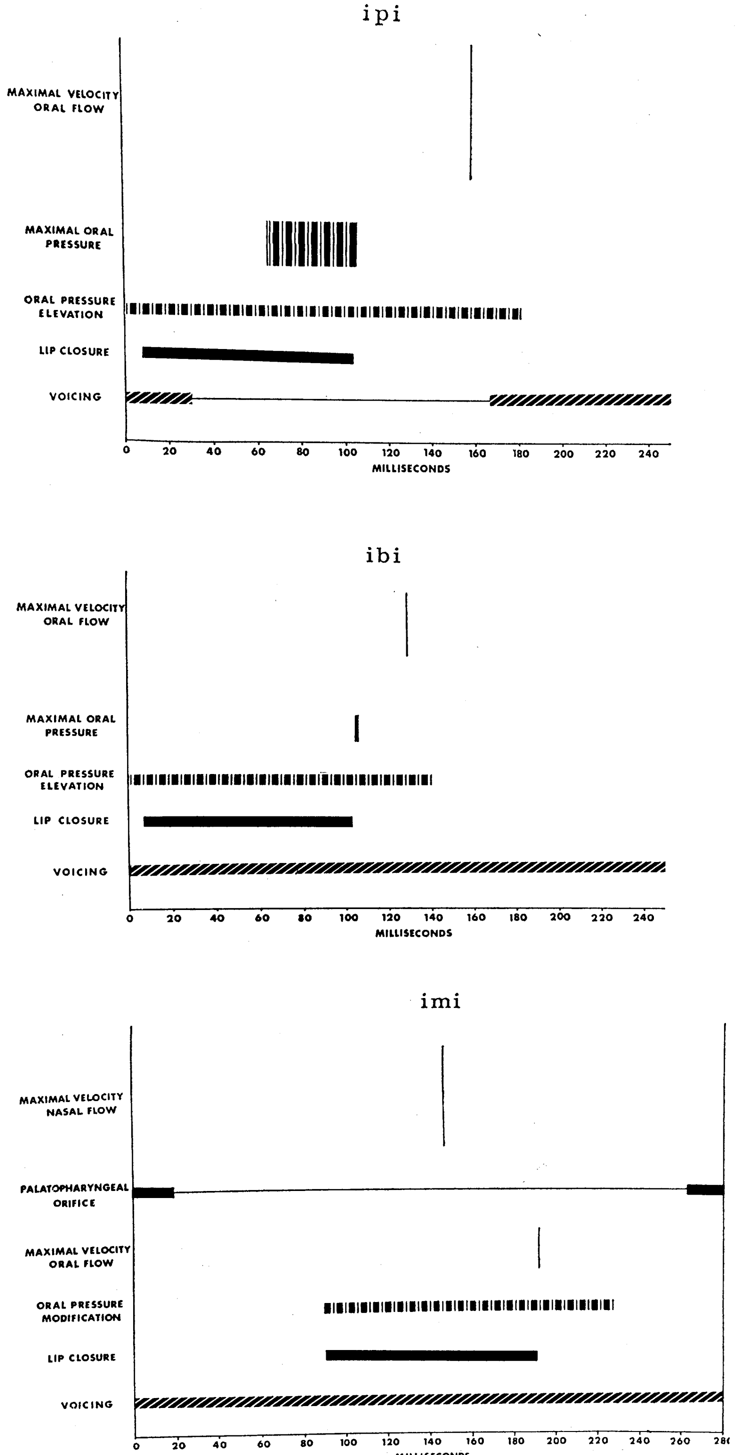


FIGURE 6. Graphs of averaged data summarizing the temporal analysis of laryngeal, oral, and palatopharyngeal valving and associated parameters of: duration of oral pressure elevation, duration of maximum oral pressure, the site of maximum oral and/or nasal flow. The vertical length of lines locating in time maximum velocities of flow are proportionally graphed to illustrate relative difference in flow velocities as a function of the phoneme.

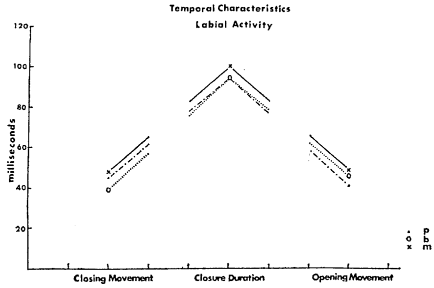


FIGURE 7. Means for closing and opening movements of the lips and for the duration of closure graphed for sounds /p/, /b/, and /m/.

rived from measures of maximum values. The averaged index of lip contact was 4.47 mm, 4.02 mm, and 3.82 mm for /p/, /b/, and /m/. These figures indicate a tendency for contact to be greater for /p/; however, relative differences are very small. Only two subjects showed appreciably greater contact (exceeding 1 mm) for /p/ than /b/. In general, cine analysis failed to reveal significant differences in oral valving as a function of the bilabial consonants when produced in VCV context.

Tongue Position. Since tongue position can influence the direction and pattern of airflow and the resonance characteristics of the vocal tract, measures of maximum tongue height during intervals of lip closure were made. Statistical comparison of measures (Table 1) failed to suggest significant differences in tongue height as a function of the sound produced. The high point of the tongue was found to be about 5 mm below the palatal plane for all three sounds. A different tongue position to direct airflow through the nose during articulation of /m/ was not indicated.

Four speakers showed the same vertical position of the tongue for /p/ and /b/. Four showed a slightly lower tongue position during implosion for /p/ than for /b/. Two subjects showed the opposite situation, in that the tongue was higher during implosion for /p/ than for /b/. Compositely, measures of tongue height and velar height failed to support the concept that a larger oral cavity dimension exists during periods of high intraoral pressure or during implosion for the voiceless stop.

To assess tongue position on the basis of individual speakers, vertical and horizontal measures of the tongue were plotted for each frame analyzed during the interval of lip closure. By superimposing graphs for each of the three sounds, differences in stability and in relative position of the tongue were studied.

Tongue position was found to be most stable during articulation of /m/. Subtle changes in the vertical and horizontal position were apparent during production of both /p/ and /b/; however, no consistent

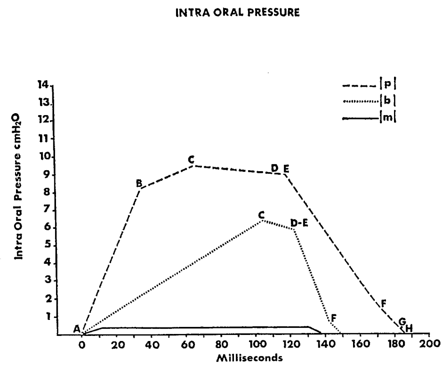


FIGURE 8. Averaged intraoral pressure measures for sounds /p/, /b/, and /m/ are graphed in proper time order for the following points: A, onset of pressure elevation; B, cessation of voicing /ipi/; C, maximum oral pressure; D, minimum oral flow; G, resumption of voicing /ipi/; H, return to base pressure.

pattern of movement could be identified with lip closure, termination of closure, or the interval immediately succeeding articulatory release.[3]

INTRAORAL AIR PRESSURE. In general, air pressure measures from this study were derived to facilitate temporal descriptions of valving at the larynx, lips, and palatopharyngeal port; and to provide data necessary to calculate palatopharyngeal orifices. These purposes do not require an elaborate reporting of air pressure per se. The measures, graphically presented in Figure 8, are in basic agreement with data reported previously for adult female speakers (*21*).

The amplitude of pressure for /p/ (M, 9.50 cm H_2O; SD, 1.99) was considerably higher than for /b/ (M, 6.35 cm H_2O; SD, 2.02). Despite this fact, the interval of rise to attain a higher pressure for /p/ was much shorter than for /b/. Resistance to flow created by vocal fold vibration probably explains the longer period of rise as well as the lower amplitude of pressure characteristic of /b/.

During production of /m/ when the palatopharyngeal port is open, slight elevation in intraoral pressure (M, .40 cm H_2O; SD, 39) and very slight elevation in intranasal pressure was observed.

ORAL AIRFLOW. The velocities of oral and nasal airflow associated with the features of oral and palatopharyngeal valving described are graphically presented in Figure 9. The graph was prepared to illustrate patterns of oral and nasal airflow and to differentiate volume velocities as a function of the consonant produced. For this purpose, flow measures at

[3] Phonetic context is known to have an appreciable effect upon physiological and pressure flow dynamics of consonants. For this reason, the essential parameters of the consonants were studied within a constant and controlled phonetic context. The results obtained indicate considerable stability in tongue position during lip closure for all three consonants, when the sounds were stripped of the influence of a variable phonetic context. Similar analyses of tongue stability during lip closure within variable phonetic context have shown considerable shifts in lingual position can and do occur (*16*).

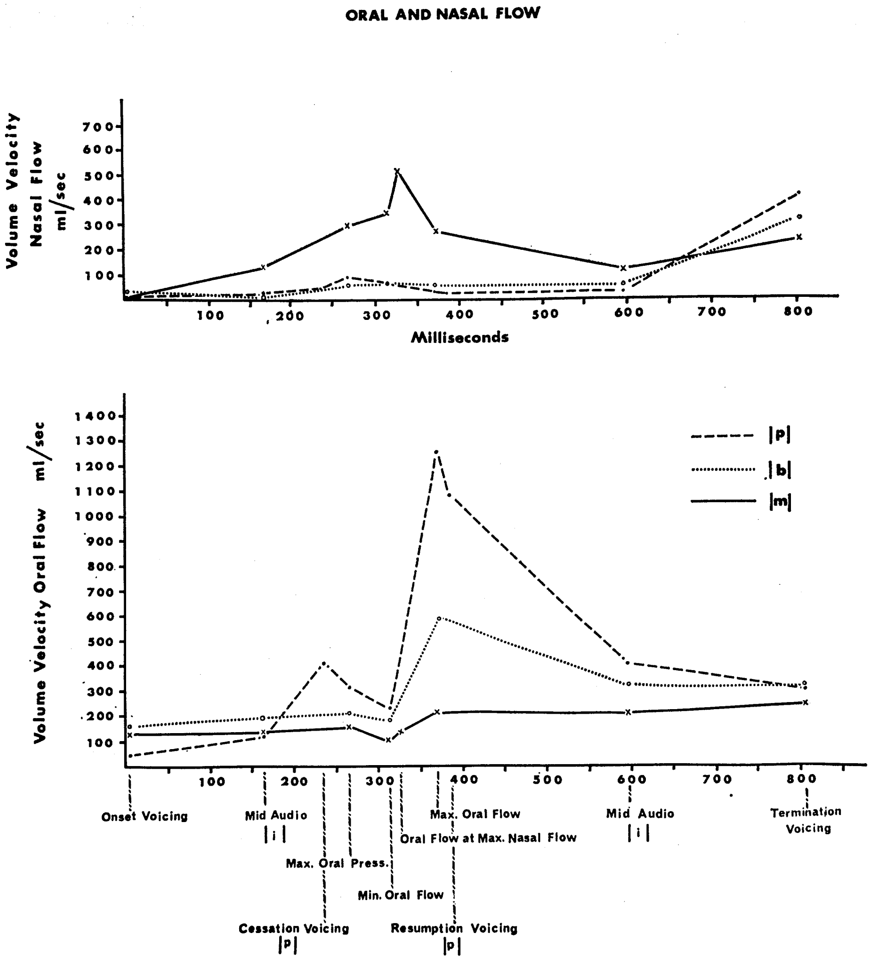


FIGURE 9. Averaged measures of nasal (above) and oral flow are graphed for selective points defined from graphical recordings of utterances /ipi/, /ibi/, and /imi/. The respective sites of flow measurement are identified in the lower graph.

specific points in time were averaged for the ten speakers (Table 3) and plotted within the appropriate time sequence. Points selected for flow measurement are identified in the legend.

Flow rates were observed to vary during phonation and to vary considerably among subjects. For these reasons, large standard deviations for measures made at specific points in time were anticipated and realized (Table 3).[4]

[4] If, for each subject, a mean flow rate for vowels had been derived by dividing total air volume by duration of phonation, variability in measures would be less prominent. Considering differences in measurement procedure, phonetic context, and instrumentation, it seems remarkable that oral flow measures for vowel /i/ at mid-audio are in general agreement with mean flow rates for normal female subjects (M, 119 cc/sec; SD, 25) reported by Isshiki and von Leden (7) and by Yanagihara, Koike, and

TABLE 3. Summary of means and standard deviations for volume velocity measures of oral and nasal flow in ml/sec made at selective points during articulations of /ipi/, /ibi/, and /imi/ (n, 10).

points of flow measurement	*/ipi/*		*/ibi/*		*/imi/*	
	mean	*SD*	*mean*	*SD*	*mean*	*SD*
onset of voicing						
oral	45.	55.	155.	107.	125.	121.
nasal	5.	16.	30.	26.	10.	21.
mid-audio first vowel						
oral	115.	111.	185.	133.	130.	121.
nasal	20.	35.	10.	21.	125.	170.
cessation of voicing /ipi/						
oral	405.	152.				
nasal	45.	64.				
maximum oral pressure						
oral	310.	124.	205.	76.	150.	122.
nasal	85.	127.	55.	93.	290.	232.
minimum oral flow						
oral	225.	111.	175.	72.	100.	97.
nasal	60.	81.	60.	107.	340.	179.
maximum nasal flow /imi/						
oral					135.	106.
nasal					510.	299.
maximum oral flow						
oral	1250.	118.	585.	113.	205.	136.
nasal	35.	47.	50.	78.	270.	292.
resumption voicing /ipi/						
oral	1070.	109.				
nasal	20.	26.				
mid-audio second vowel						
oral	400.	160.	315.	165.	200.	172.
nasal	25.	26.	5.	16.	110.	105.
termination of voicing						
oral	300.	158.	310.	178.	240.	184.
nasal	405.	498.	310.	567.	225.	373.

By comparison of the superimposed graphs for the three consonants, gross differences in oral and nasal airflow are effectively displayed. In general, an oral flow velocity approximating 100 ml/sec was identified with the initiation of voicing with a slightly higher velocity recorded at mid-audio of the first vowel.

When voicing ceased during implosion of /p/, a rather high velocity of flow was recorded. This point in time is closely related to: lip closure, relaxation of glottal resistance, and rapid rise in intraoral pressure. These factors in combination may account for the higher rate of flow recorded at that point.

von Leden (M, 100 cc/sec; SD, 22.8) (*31*). In the former study, a pneumotachograph with tube inserted into the mouth was used. In the latter study, a "pneumotachmask" was used. Sustained phonations of vowel /a/ were studied in both investigations.

As shown in Figure 9, oral flow for /p/ tended to be higher than for /b/ at most points of measurement including the point of maximum oral pressure, which occurs earlier for /p/ than for /b/. The major difference between /p/ and /b/ is related to explosion. Volume velocity for /p/ exceeded twice that recorded for /b/.

NASAL AIRFLOW. At the onset of voicing for the three sequences, minimal nasal flow (5 to 30 ml/sec) was recorded. At the mid-audio of the first vowel, nasal flow averaged 20 ml/sec before /p/, and 10 ml/sec before /b/.

Slightly higher velocities of nasal flow, averaging 85 ml/sec for /p/ and 55 ml/sec for /b/, were recorded at the point of maximum oral pressure. At maximum pressure for /p/, four speakers had no nasal flow, three had minimal flow (50 ml/sec), and three had flow velocities of 100, 200, and 400 ml/sec. Thus, the majority of subjects did not register appreciable nasal leakage during implosion when the consonant appeared in VCV context. However, variable and appreciable nasal flow can and did occur during periods of palatopharyngeal closure (cineradiographically defined) in some subjects with normal articulation.

In general, the averaged data show that higher velocities of nasal as well as oral flow are associated with the higher pressure characteristic of /p/. At the point of maximum oral flow and at mid-audio of the second vowel, when oral pressure is reduced, nasal flow diminished from about 40 ml/sec to 15 ml/sec. At the termination of voicing for all three sequences, nasal flow was observed to increase as palatopharyngeal relaxation occurred.

During articulation of the /imi/ sequence, a comparatively high nasal airflow (125 ml/sec) was recorded at the mid-audio of the initial vowel. This finding is explained by the opening of the palatopharyngeal port during vowel phonation well in advance of lip closure. A comparatively high nasal flow (110 ml/sec) was also recorded at the mid-audio of the second vowel. This may be accounted for by the lag in palatopharyngeal reclosure.

In general, the onset of nasal flow was observed to coincide with the timing of the palatopharyngeal break. At the earliest point of stable oral pressure modification, nasal flow averaged 290 ml/sec with peak velocity recorded 57 msec after lip closure. Thus, when resistance to oral flow was introduced by lip closure, a marked rise in nasal flow to maximum velocity was observed. The shift to nasal resonance as indicated by the sound power and intraoral pressure traces was more closely related in time to lip closure than to palatopharyngeal opening.

TEMPORAL ANALYSIS. The temporal relationships described above and others derived by combined analysis of data are illustrated in Figure 10. Measures of palatopharyngeal and oral openings have been superimposed upon measures of pressure and flow for all three sounds /p/, /b/, and /m/.

Variability in valving and in the timing of events was marked. With this fact in mind, averaged data defining temporal relationships are presented to serve as a general frame of reference (Figure 6). The physiologic events selected define valving at the lips, palatopharyngeal port, and larynx. Closing and opening of respective valves are plotted in time relative to points of maximum pressure and flow recording.

For the /ipi/ sequence, intraoral pressure begins elevation 8 msec before lip closure is effected or while the lips are in the process of closing. Vocal fold vibration continues for a short period (22 msec) after lip closure has been attained. Intraoral pressure decay from maximum amplitude coincides in time with the release of the lip contact. The peak velocity of oral flow (1250 ml/sec) is recorded 53.8 msec after lip release. Voicing is resumed within 10 msec after peak oral flow.

In general, total duration of pressure elevation, including periods of rise and decay, was considerably longer than the corresponding interval of lip closure. This may be explained by the fact that intraoral pressure begins to rise before lip closure and continues to decay after lip release.

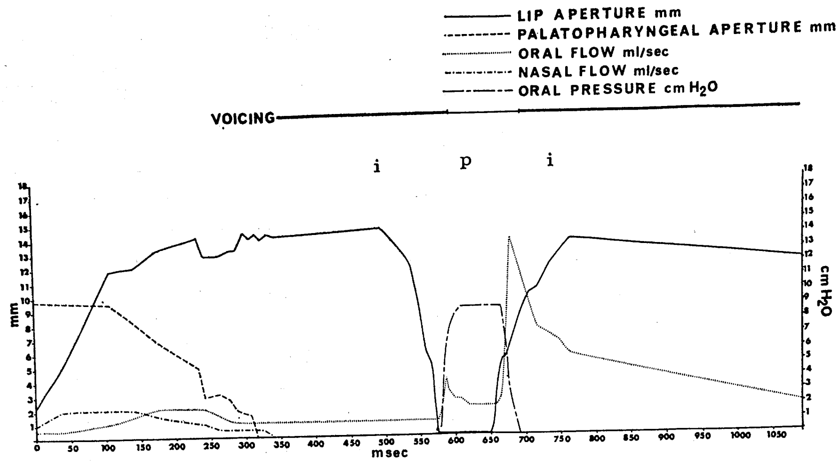
The voiceless interval during articulation of /p/ averaged 149.5 msec which is also longer than the interval of lip closure (95.1 msec). This observation is explained by the fact that lip closure occurs before laryngeal vibration ceases. Thus, during implosion, bilabial and laryngeal valving overlap by approximately 22 msec. During explosion, no overlap occurs. Voicing is resumed 63 msec after lip release. In combination, these factors indicate that the voiceless interval[5] should exceed the interval of lip closure as the data show.

VOLUME (TOTAL FLOW). In preceding pages, marked variability in palatopharyngeal valving and in velocity of nasal flow has been reported. On the basis of these observations, considerable variability in volume measures should be anticipated and was realized (Table 4).

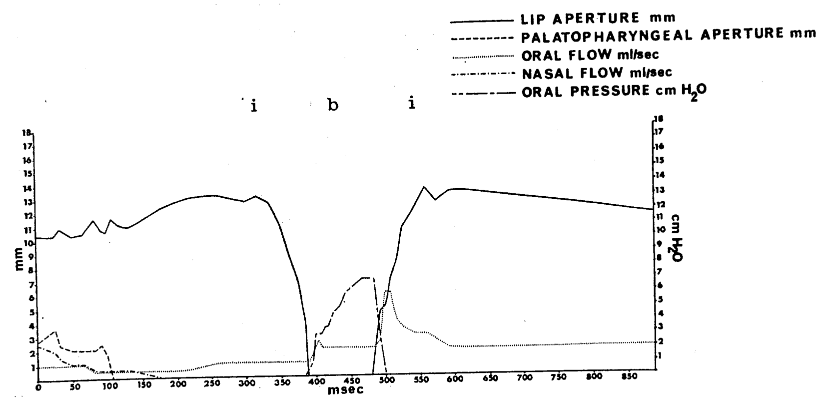
To facilitate measuring, the trace for oral and nasal volume was transected at points of lip closure and release and at points of palatopharyngeal opening and closing. The gradient of the curve between points of closure and release was then measured. Total flow volume for the respective physiologic intervals was determined by simply adding oral and nasal volumes. This latter step permitted study of total flow values and nasal flow as a ratio of total flow. The purpose of the latter ratio was to overcome, in part, individual differences in respiratory capacity and function.

In general, a higher volume of total flow (53.70 cc) during lip closure was associated with the production of /m/ or under circumstances when

[5] The voiceless interval is longer than the closure duration or interval for the /p/ in intervocalic position (about 120 msec) defined from spectrographs (*10*). This may be explained by the fact that the auditory burst associated with pressure release may represent the termination of silence. The burst which precedes resumption of voicing therefore establishes a shorter period of silence than would be indicated by recording of pressure fluctuations caused by vocal fold activity.



LIP APERTURE mm
PALATOPHARYNGEAL APERTURE mm
ORAL FLOW ml/sec
NASAL FLOW ml/sec
ORAL PRESSURE cm H_2O
VOICING
i p i
mm
cm H_2O
msec



LIP APERTURE mm
PALATOPHARYNGEAL APERTURE mm
ORAL FLOW ml/sec
NASAL FLOW ml/sec
ORAL PRESSURE cm H_2O
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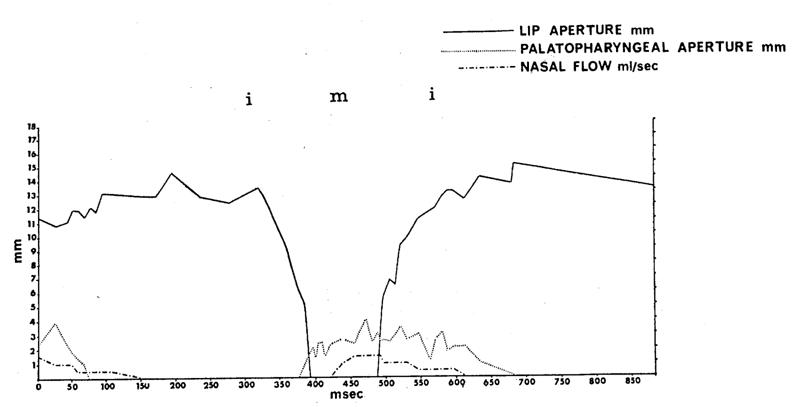

LIP APERTURE mm
PALATOPHARYNGEAL APERTURE mm
NASAL FLOW ml/sec
i m i
mm
msec

FIGURE 10

TABLE 4. Means, standard deviations and 95% confidence intervals for measures of volume in cc and in ratios for intervals of lip closure and palatopharyngeal opening (n, 10).

interval and measurement	*mean*	*SD*	*95% CI*
lip closure			
oral volume			
/ipi/	35.30 cc	17.39	23.05–47.55
/ibi/	24.50 cc	7.84	18.98–30.02
/imi/	15.10 cc	12.70	6.15–24.05
nasal volume			
/ipi/	7.10 cc	13.30	0 –16.47
/ibi/	3.80 cc	7.73	0 –9.25
/imi/	38.60 cc	26.78	19.73–57.47
total volume			
/ipi/	42.40 cc	22.70	26.41–58.39
/ibi/	28.30 cc	11.95	19.88–36.72
/imi/	53.70 cc	31.44	31.55–75.85
ratio: nasal/total			
/ipi/	.14	.19	0 –.28
/ibi/	.09	.17	0 –.21
/imi/	.67	.23	.51–.84
palatopharyngeal opening			
oral volume			
/imi/	42.50 cc	32.36	16.11–68.89
nasal volume			
/imi/	73.63 cc	54.41	29.27–117.98
total volume			
/imi/	116.13 cc	73.79	55.96–176.29
ratio: nasal/total			
/imi/	.64	.22	.47–.82

the palatopharyngeal valve was open. Since the interval of lip closure (101 msec) was considerably shorter than the interval of palatopharyngeal opening (243 msec), the latter period was associated with a larger total volume of flow (116.13 cc). In addition to the longer interval of palatopharyngeal opening, the larger total flow would be anticipated since the oral port remained open for some time after the palatopharyngeal break and for some time before the palatopharyngeal port reclosed.

VOLUME (NASAL FLOW). The volume of air expired through the nose during intervals of lip closure was found to average: 7.10 cc for /p/,

FIGURE 10. Physiological data defining oral (solid) and palatopharyngeal (dashed) valving are plotted in proper temporal relationships for one speaker during utterance of /ipi/. The heavy solid line graphs associated voiced and voiceless intervals. Data specifying oral and nasal flow and intraoral pressure are superimposed in proper temporal relationship to illustrate the aerodynamics associated with physiological valving. In other graphs, pertinent physiological and physical parameters are plotted for /ibi/ and /imi/ utterances produced by the same adult female speaker. Differentially considered, the three graphs illustrate essential differences in physiological valving and aerodynamics as a function of the phoneme.

3.80 cc for /b/, and 38.60 cc for /m/.[6] These nasal volumes calculated as ratios of total volume averaged: .14, .09, and .67 for /p/, /b/, and /m/ respectively. Despite marked variability, the larger volume and ratio of nasal flow for /m/ were statistically significant, as indicated by the 95% confidence intervals reported.

During articulation of /imi/, nasal volume for the interval of lip closure was about half (38.60 cc) the nasal volume recorded during palatopharyngeal opening (73.63 cc). Although the latter defines the interval in which nasal flow can occur, the shift in nasal resonance was found to be most closely related to lip valving. Hence, nasal flow volume approximating 40 cc seems to provide a reasonable estimate of flow associated with the period of bilabial nasal consonant production.

Volume measures obviously will be influenced by the specific procedure employed to define the interval in which flow occurs. In accordance with major objectives of this investigation, volume measures were made for intervals physiologically defined. Traditionally, stop consonant production has been subdivided in terms of implosion and explosion. Hence, a second procedure was used to define intervals of implosion and explosion for a group of five subjects. Implosion was defined as the period from onset of pressure rise to the terminal point of elevated pressure. Explosion was defined as the period from onset of pressure decay to zero pressure level.

Oral volumes during imposion were similar for /p/ (M, 28.0 cc; SD, 8.4), and for /b/ (M, 25.0 cc; SD, 7.9). However, a much larger volume was expired during explosion for /p/ (M, 61.0 cc; SD, 19.8) than for /b/ (M, 11.0 cc; SD, 4.2). Thus measures for combined periods of implosion and explosion revealed a much larger total volume for /p/ (M, 92.0 cc; SD, 40.4) than for /b/ (M, 39.0 cc; SD, 11.4). Total volume for /m/ averaged M, 46.0 cc; SD, 23.8.

PALATOPHARYNGEAL ORIFICE AREAS. Palatopharyngeal orifice areas were calculated by substituting intraoral pressure, intranasal pressure, and nasal airflow measurements in the Warren equation.[7] To facilitate full comparison, means and SDs were calculated from Warren's reported orifice areas, individually stated for /p/, articulated in three different phonetic contexts, by ten normal speakers. The analysis showed orifice areas for /p/ varied as follows: M, .48 mm^2, SD, .47; M, .94 mm^2, SD,

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[6] Nasal volumes during articulation of /p/ and /b/ (7.10 cc and 3.80 cc) definitely fall within Yanagihara and Hyde's (*30*) estimation that less than 20 cc of air escapes through the nose during the production of bilabial stop consonants. Means reported for nasal flow rate measured at the point of maximum intraoral pressure (85 ml/sec for /p/ and 55 ml/sec for /b/) are also in general agreement with Yanagihara and Hyde's statement that maximum nasal flow rate during syllable repetition fluctuates between 20 cc and 100 cc regardless of voicing.

[7]
$$A = \frac{V}{k\sqrt{2\frac{\Delta P}{D}}}$$

1.56; and M, 1.79 mm^2, SD, 2.51. On the basis of these measures, orifice size appears to differ as a function of the phonetic context.

Orifice areas calculated for /p/ in VCV context used in this investigation averaged M, 1.65 mm^2; SD, 2.38. Standard t tests to evaluate differences between this calculated orifice area and those reported by Warren were made. Because of variability in areas related to phonetic context, the significance of t values obtained depended upon which comparisons were made. Two of the three ts were not significant, whereas the third t indicated the present orifice areas were significantly larger than Warren's orifice area which averaged .48 mm^2.

Further analysis of variance confirmed variability in orifice areas as a function of phonetic context. The F values indicated, furthermore, that the variability existing between Warren's orifice areas for the three different articulations of /p/ does not exceed the variability existing between Warren's area measures and those described here.

Measures reported by Warren as an example for /m/ were also in general agreement with averaged measures of analogous parameters recorded during the /imi/ articulation. Thus, despite differences in instrumentation, calculated orifice areas were found to agree essentially with Warren's data pertaining to orifice size in normal speakers, when the oral port is closed and the palatopharyngeal port is either open or closed.

Further study is needed to learn more about the relationship existing between calculated orifice areas as determined by the pressure-flow technique and radiographic measures of the orifice. Preliminary results suggest that a positive correlation may exist *over the range of orifice areas described here, with associated oral port closure.* However, before the strength of the relationship can be estimated with confidence, further study of a larger sample providing greater variation in palatopharyngeal and oral port dimensions is needed.

Discussion

FLOW-PORT CLOSURE. One feature in the data effectively displayed in Figure 9 requires discussion. At the lowest point of oral flow during lip closure, low but positive flow values were recorded for all three sounds. The average volume velocity (166 ml/sec) is not high; nonetheless, the fact remains that oral flow was recorded when the cine film indicated that none should be noted since the bilabial port was closed. Similarly, minimal nasal flow was recorded in some speakers when the palatopharyngeal port was shown by cine to be closed.

No fully satisfactory explanation for these perplexing observations can be made but possibilities should be considered. If oral flow and nasal flow during port closures were unique in these data, the findings might reasonably be attributed to some basic limitation in the flow recording system. Although such an explanation may be relevant, similar findings are indicated in flow recordings presented by other investigators (*22*) who used different flow recording instruments to study stop consonants produced in VCV context. For this reason, flow recorded during port closures probably should not be attributed *exclusively* to some limitation in the warm-wire free field flow measuring apparatus.

A second possible explanation could be related to limitations in lateral films which may not provide an adequate index of palatopharyngeal or bilabial closure in *all* subjects. That is, closure may appear firm in the midline while minimal openings in the elliptical apertures exist laterally, especially during initial and terminal phases of contact. Individual measures of oral flow during lip closure provide some support for this possibility.

Whatever the explanation for flow occurring during port closure, present data suggest that airtight articulatory port closures are not consistent nor requisite to normal speech production. That is, minimal oral or nasal flow may escape during bilabial or palatopharyngeal closure without creating a deleterious effect upon the pressure-flow features required for satisfactory spectral output.

Support for this suggestion can be drawn from the data reported. For example, one speaker showing complete palatopharyngeal closure had an associated nasal flow rate of 400 ml/sec during implosion of /p/. Intraoral pressure was not reduced as a result of nasal escapage. To the contrary, intraoral pressure was above average and oral flow generated at explosion was average. In combination, these findings may be explained by an excessively large expiratory flow associated with an incomplete and probably varying palatopharyngeal seal. Certainly, the results do not indicate that nasal airflow per se, during stop consonant production, is inevitably related to defective sound production.

Additional support for the hypothesis that articulatory closures need not be airtight, especially for the full duration of the consonant, can be found in Björk's study (*1*). After combining cineradiographic and spectrographic data, Björk reported that the great majority of normal subjects completely closed the velopharyngeal port during production of /p/ when the /p/ initiated the first word of a sentence. However, the /b/, within a vowel context during sentence articulation, was produced with an open palatopharyngeal valve in 4% of his subjects. An additional 4% had the palatopharyngeal valve open during the first part of the /b/.

The results, reported by Björk, show that subtle variations in palatopharyngeal closure occur as a function of time and phonetic context. Complete palatopharyngeal closure was not always observed during plosive production. Studies of palatopharyngeal function and speech in cleft palate speakers have also shown that complete closure of the palatopharyngeal port was not required for intelligible plosive production (*20*).

The subtle shifts in horizontal and vertical position of the velum observed during periods of port closure may be interpreted as evidence that the extent of closure varies slightly with time. Since a functional relationship exists between velar movement (elevation and retraction) and pharyngeal movement (constriction), the changes observed in velar position may reasonably be associated with subtle shifts in the lateral pharyngeal walls. In combination, these features could modify orifice areas sufficiently to explain minimal and variable nasal airflow during periods of port closure as visualized cineradiographically.

One clinical implication of these varied observations seems justified. Nasal flow during plosive production should not be considered dichotomously: absent or present, normal or abnormal. A realistic appraisal of nasal airflow measures at the present time might better be stated in relative, rather than in absolute, terms. This applies simply because a number of variables, such as expiratory effort, nasal pathway resistance, and associated details of oral valving, will influence nasal flow (*28*).

Intelligent clinical interpretation of nasal airflow can best be made when some additional information is provided concerning the effect of nasal airflow upon the character of sound produced or upon associated parameters of intraoral pressure and oral flow, both of which may be more critical to spectral features of the sound. Such interpretation would seem to require continued study of several significant parameters simultaneously recorded so that the nature of the inter-relationship can be understood more adequately.

Summary

To study non-nasal and nasal consonants, high speed cineradiographs and pressure flow recordings were obtained simultaneously for ten normal adult female subjects articulating /p/, /b/, and /m/ in VCV context. Subtle shifting in velar position during periods of complete palatopharyngeal closure was observed for all subjects during articulation of /ipi/ and /ibi/. In some speakers, minimal nasal flow occurred during periods of closure. These observations suggest that the extent of closure as visualized in the lateral film varies slightly with time and that airtight closure does not always occur and is not requisite for satisfactory production of plosives in VCV context. These results suggest that clinical interpretation of nasal airflow can best be made when additional information is provided relative to the effect of nasal flow upon the character of speech produced; or upon associated parameters of pressure and oral flow, both of which may be more critical to spectral features of the sound. Small palatopharyngeal openings, averaging 4 mm, were identified with nasal consonant production. The duration of palatopharyngeal opening exceeded twice that of lip closure. Resistance to oral flow introduced by lip closure resulted in nasal flow acceleration. The shift to nasal resonance was more closely related in time to lip closure rather than to palatopharyngeal opening.

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