A Pressure-Flow Technique for Measuring Velopharyngeal Orifice Area During Continuous Speech

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The need for methods which measure adequacy of velopharyngeal closure arises from the requirements for assessing this function in certain speech defective individuals, notably those with cleft palates. Many techniques have been described for studying the velopharyngeal mechanism (*2–5*, *7*, *8*, *10*, *13–15*), the most recent of which is Björk's radiographic and spectrographic method for relating isthmus area to the acoustical characteristics of speech (*1*).

With the development of instruments capable of faithfully measuring pressure and airflow in the mouth and nose (*9*), the possibility of calculating velopharyngeal orifice area using hydrokinetic principles (*6*) became feasible.

Described in this paper is a method based on those principles; certain preliminary results obtained using normal subjects are also reported. Studies of surgically and prosthetically treated cleft palate patients will be reported in subsequent papers (*16*, *17*).

Description of Technique

This method is based upon a modification of the Theoretical Hydraulic Principle and assumes that the area of an orifice can be determined if the differential pressure across the orifice is measured simultaneously with rate of airflow through it.

Thus,

$$\text{Orifice Area} = \frac{\text{Rate of Airflow through Orifice}}{\sqrt{2\left(\dfrac{\text{Orifice Differential Pressure}}{\text{Density of Air}}\right)}}$$

Since production of speech involves an acoustic disturbance superim-

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posed upon respiratory airflow, the aerodynamic phase of phonation can be used to obtain the necessary parameters for application of this theoretical equation (see Appendix for derivation of equation).

Since even in the simplest cases, an equation cannot be developed which takes into account all of the details of turbulent, non-uniform and rotational flow, the derivation was adapted to a fictitious average steady motion. The theoretical equation, therefore, neglects several fundamental considerations and is only an approximation to actual flow conditions in the oropharynx, i.e., airflow is actually unsteady, non-uniform and rotational. The actual area of the orifice will differ from the theoretical area because of these factors. Hence, to obtain the actual area from this "rational approximation" a correction factor k must be introduced.

Experimental Model

It is impossible to measure this constant k for the velopharyngeal orifice, so a simple model was used instead. Furthermore, most orifice equations either assume that pressure is measured in the narrow area of the orifice, or that pressure just past the orifice is equal to pressure in the orifice. This assumption is valid if the kinetic energy of the gas passing through the orifice is lost due to turbulence on the nasal side of the orifice. Again, although unable to verify this in the nasopharynx, the model was used to measure pressure on the nasal side of the orifice in deriving the correction constant. To the extent that airflow in the artificial nose simulated airflow in the nose, the above assumption of turbulence would be valid. The model of the upper respiratory tract was constructed from plastic tubing and joints. This prototype of the upper speech mechanism was designed so that the area of the model velopharyngeal orifice could be varied by a series of interchangeable orifices of different size. The model mouth could be opened or closed thereby allowing for simulation of flow patterns in the pharynx during speech.

METHOD USED WITH MODEL. A series of 24 experiments were carried out on the model. These include 16 in which the model mouth was closed and eight in which it was open. This comparison was deemed necessary to ascertain whether the open mouth, acting as a "sink", affects the equation.

The apparatus used is shown diagrammatically in Figure 1. Differential pressure across the model velopharyngeal orifice was measured with a sensitive Lilly capacitance manometer.[1] Connected to the transducer were two catheters[2] which were placed above and below the orifice. Side holes were drilled in the catheters and the catheter end openings were plugged with wax so that only the lateral or the "static" pressure component was measured. Flow through the orifice was measured by a

[1] Lilly capacitance manometer, with venous pressure head. Technitrol Engineering Co., Philadelphia, Pa. A strain gauge manometer (differential pressure type) with small air displacement is also suitable.

[2] Polyethylene tubing PE 200.

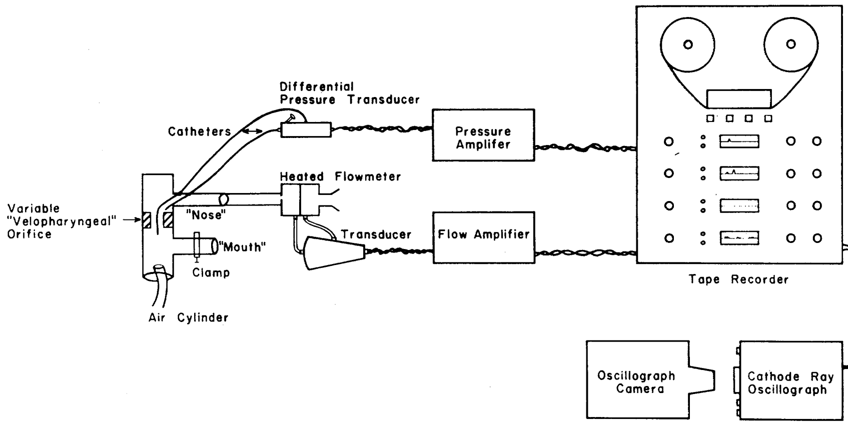

FIGURE 1. Diagrammatic representation of the apparatus used for measuring the coefficient k on the model "velopharyngeal orifice".

pneumotachograph[3] connected to the model nose. An air cylinder supplied the flow necessary to simulate the aerodynamics of speech. Both pressure and flow were recorded on a four channel magnetic tape recorder[4] which contains oscilloscopes for monitoring each parameter. An oscilloscope recording camera[5] was utilized to photograph on paper[6] the data which was replayed from the tape recorder into a cathode ray oscillograph.[7]

RESULTS OF EXPERIMENTS WITH THE MODEL TO DETERMINE COEFFICIENT k. The results of the experiments with the model are shown in Table 1. The coefficient k was computed from the equation

$$k = \frac{\dot{V}}{A\sqrt{2\left(\frac{P_1 - P_3}{D}\right)}} \tag{1}$$

where P_1 is the pressure below the orifice (oral side) and P_3 is the pressure above the orifice (nasal side). (See Appendix for definition of other symbols and for derivation of equations 1 and 2.) Although k theoretically varies with orifice size, the differences found in the 16 experiments with the "mouth" closed were so slight that it was decided that the constant k could be averaged and treated as a constant. Figure 2 illustrates how little k changes as the area is increased from 2.4 mm^2 to 120.4 mm^2.

The "theoretical equation" is thus modified by the correction coefficient to give the "working equation".

[3] Pneumotachograph, Technitrol Engineering Co., Philadelphia, Pa. (a strain gauge manometer and flowmeter is also suitable)

[4] Dacord Tape Recorder, Electro-Medi-Dyne, Farmingdale, N. Y.

[5] Grass Kymograph Camera, Grass Instrument Co., Quincy, Mass.

[6] Kodak linograph paper #44, Eastman Kodak Co., Rochester, N. Y.

[7] Dumont 322-A Cathode Ray Oscillograph, Allan E. Dumont Co., Clifton, N. J. This allowed recording two channels at a time; the tape was run through twice.

TABLE 1. Calculation of coefficient from k model of the velopharyngeal orifice.

Orifice (mm^2)	*Pressure* ($dynes/cm^2$)	*Flow* (cc/sec)	k
A	294	655	.71
120.4	294	662	.72
	333	698	.71
	215	555	.70
B	147	273	.66
76.1	176	297	.66
	166	273	.62
	147	285	.69
C	1411	185	.65
17.1	705	128	.63
	735	135	.66
	940	149	.64
D	1205	22	.60
2.4	1029	20	.61
	793	18	.59
	1381	24	.61
		Mean k = .65	

$$A = \frac{\dot{V}}{.65 \sqrt{2\left(\frac{P_1 - P_3}{D}\right)}} \tag{2}$$

This equation is similar to the hydrokinetic equation reported by Gorlin (*6*) for measuring area of the mitral valve.

EXPERIMENTAL ACCURACY. The accuracy of this method was also evaluated in the 24 additional experiments with the model. Table 2 discloses the overall errors which result when the coefficient .65 is used for all four orifice sizes. This also includes errors made in recording calibration of the differential pressure transducer and the pneumotachograph, and, in addition, the random errors inherent in measuring the parameters on the photographic paper. All measurements were made to the nearest 0.25 mm.

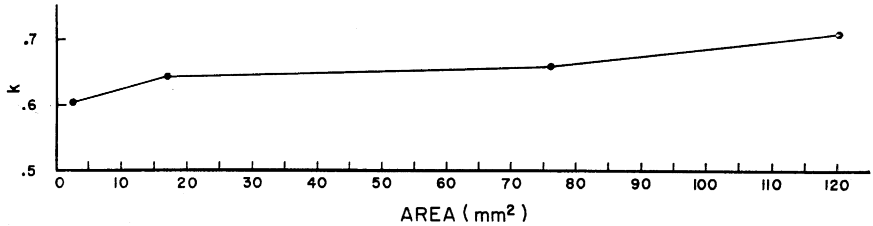

FIGURE 2. Relationship between orifice size and coefficient k. Since k varies so slightly with orifice size its average value (.65) is used as a constant for the orifice equation.

TABLE 2. Calculated size of model velopharyngeal orifice when using k as a constant value (model mouth closed).

Actual size (mm^2)	*Calculated size* (mm^2)	*Error* (mm^2)
A	131.5	+11.1
120.4	132.9	+12.5
	131.7	+11.3
	132.0	+11.6
B	77.7	+1.6
76.1	77.1	+1.0
	73.0	−3.1
	81.1	+5.0
C	17.0	−0.1
17.1	16.6	−0.5
	17.1	0.0
	16.8	−0.3
D	2.3	−0.1
2.4	2.2	−0.2
	2.2	−0.2
	2.3	−0.1

TABLE 3. Calculated size of model velopharyngeal orifice when using k as a constant value (model mouth open).

Actual size (mm^2)	*Calculated size* (mm^2)	*Error* (mm^2)
C	16.6	−0.5
17.1	18.4	+1.3
	14.7	−2.4
	15.4	−1.7
D	1.8	−0.6
2.4	1.6	−0.8
	1.8	−0.6
	1.8	−0.6

It should be noted that when the "mouth" was open the increased effect of turbulence did not appreciably affect the results (Table 3).

Procedure

Ten adult subjects with normal speech patterns and no gross dental deviations were selected for this phase of the study. The subjects were instructed to use a pitch level which seemed most natural for them during the phonation of two test sentences. A recording level meter on the tape recorder provided limited standardization for loudness level, but strict control was not considered necessary since the essential parameters of

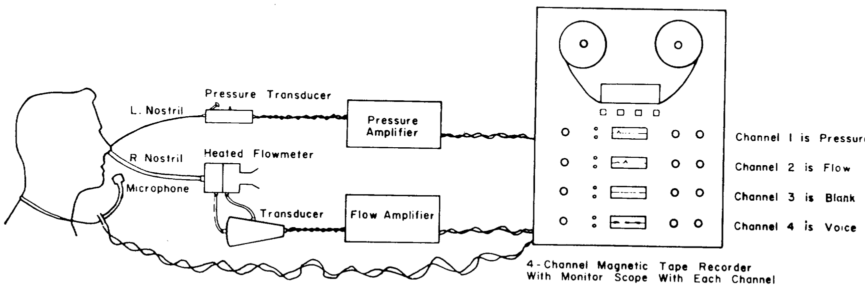

FIGURE 3. Diagrammatic representation of the apparatus used for recording pressure and flow in the upper pharynx during speech.

pressure and flow follow each other. The apparatus used is shown diagrammatically in Figure 3.[8] The pressure transducer formerly used in the model study to record differential pressure across the orifice now measures oropharyngeal pressure with respect to atmospheric pressure. The pneumotachograph is warmed by an electric current passing through a loop of nichrome wire. A microphone[9] positioned under the subject's chin is used for sound pick-up of the test sentences. Pressure, airflow, and the voiced sounds emitted are recorded on the four channel tape recorder, and the cathode ray oscillograph and oscillograph camera are utilized as previously mentioned for photographing the data.

Calibration. The apparatus was calibrated with each set of experiments. The pneumotachograph was calibrated by airflow into a rotameter[10] and the capacitance manometer was calibrated against a water manometer.

Measurement of Oropharyngeal Pressure. A small partially collapsed balloon was passed through the left nostril and orifice into the oropharynx (Figure 4). The balloon, made of thin latex, measured approximately 0.8 cm long and 0.4 cm wide. A balloon of these dimensions was found to be tolerated easily without causing a gag reflex and was found to give more reliable readings than one of a smaller size. Best positioning of the balloon could be determined by monitoring the pressure record as the subject phonated. If the balloon was correctly placed at the level of the resting uvula, the contracting soft palate moved upward and backward away from it (Figure 5). A cork was then inserted into the left nostril to prevent air leakage and to secure the balloon in position. The heated pneumotachograph was connected to the right nostril by a large snugly-fitting tube.

Technique for Relating Oropharyngeal Pressure to Orifice Differential Pressure. In order to use the area equation, it is necessary to

[8] The Lilly manometers and tubing have a response time of 1/100 sec. (*9*) which is approximately twice as fast as the rise time of pressure or flow during speech.
[9] Turner crystal microphone, The Turner Co., Cedar Rapids, Iowa.
[10] Flowrater Meter, Fischer & Porter Co., Warminster, Pa.

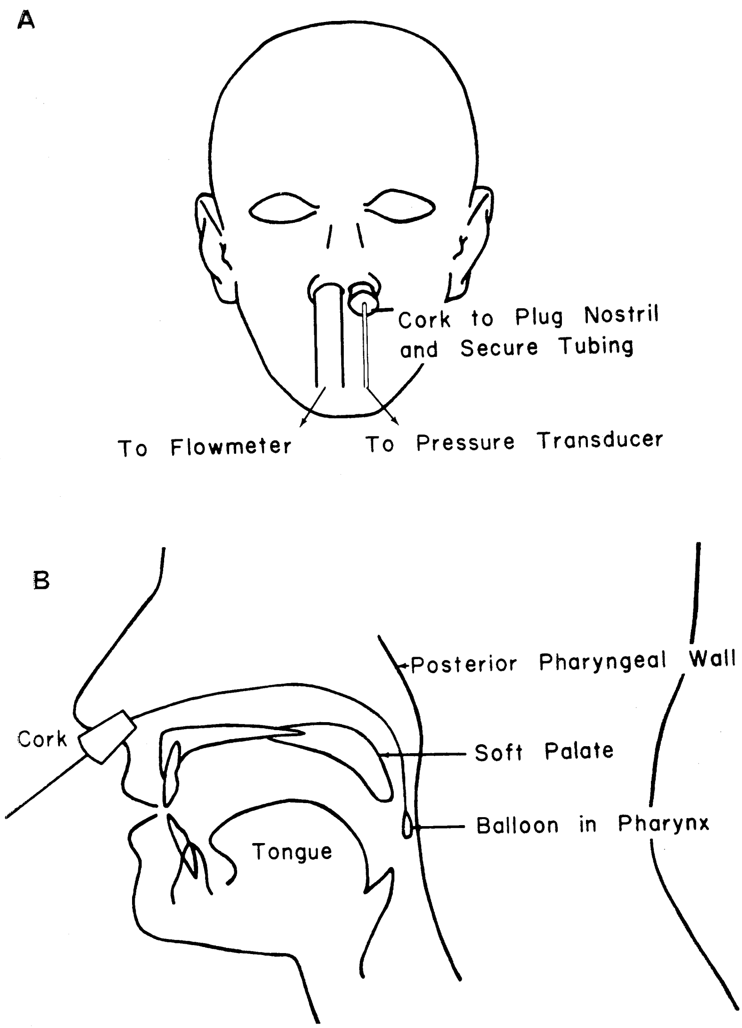

FIGURE 4. Technique for recording oropharyngeal pressure and orifice airflow in normal subjects. In A, the flowmeter is connected to the right nostril, and a cork plugs the left nostril and secures the balloon in position. In B, the balloon is placed in the oropharynx slightly below the uvula.

relate the oropharyngeal pressure obtained during speech to differential pressure in the velopharyngeal orifice (hereafter referred to as orifice). Since oropharyngeal pressure is equal to the pressure drop across the orifice and the nasal pathway, then orifice differential pressure can be obtained by subtracting the nasal pressure component from oropharyngeal pressure. To do this the following procedure is performed. A record is made while the subject, with lips closed, breathes lightly through his nose. Cineradiographic studies have shown that during expiration the soft palate remains in its resting position and the orifice is wide open (*18*).

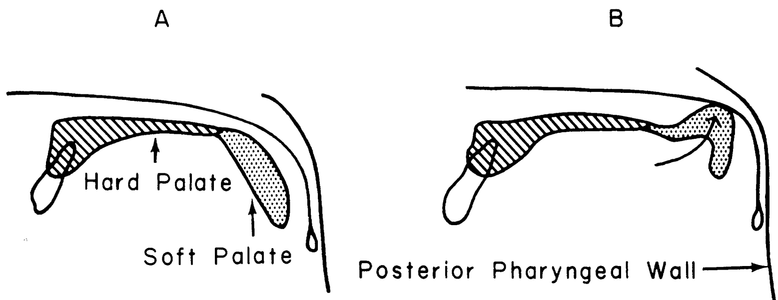

FIGURE 5. Correct balloon placement in oropharynx. In A, the balloon is placed at tip of resting uvula. In B, the soft palate elevates away from the balloon during speech.

The values obtained for oropharyngeal pressure and nasal airflow are then plotted on graph paper. Theoretically oropharyngeal pressure measurements during expiration contain both orifice and nasal pressure components, but in reality, at low nasal flow rates comparable to those encountered during speech, the orifice component is too small to be recorded.[11] Figure 6 illustrates that the pressure-flow graph obtained during expiration actually is a measure of nasal resistance at low nasal flow rates. The wide open orifice pressure component can be measured only at flow rates above approximately 200 cc/sec. Therefore, during expiration with the orifice wide open, oropharyngeal pressure can be considered equal to the nasal pressure drop.

Two assumptions are made. a) During speech, any change in oropharyngeal pressure for a given flow rate is caused by a decrease in orifice size. b) Nasal resistance does not change during phonation of the sentence. The latter assumption can be tested by measuring nasal resistance from the subject's expiration record prior to and immediately following each sentence. The measured flow rate for each specific speech element is then used to determine the nasal pressure component from the pressure-flow graph. This nasal component is subtracted from the oropharyngeal pressure measurement to give orifice differential pressure. Any back pressures from having one nostril occluded should be cancelled out with this procedure.

Validity of the Balloon Technique. It was necessary to determine whether the balloon or its tubing altered the completeness of velopharyn-

[11] This is shown by directly measuring the pressure drop across the resting orifice in the following way (Figure 7). One catheter is inserted into the subject's left nostril, secured by a cork which plugs the nostril and creates a stagnant column of air above the orifice. A second catheter, placed in the subject's mouth, is held in position by closing the lips together. Both catheters, closed at their tips but open laterally for static pressure measurement, are connected to the differential pressure transducer. With the heated flowmeter connected to the right nostril, the subject is asked to breathe out through his nose. The result is a differential pressure and nasal flow record across the resting, open orifice. When this orifice pressure component is subtracted from the previously discussed pressure-flow curve at corresponding flow rates, it becomes apparent that orifice differential pressure is so small that it can be ignored during expiration (Figure 6).

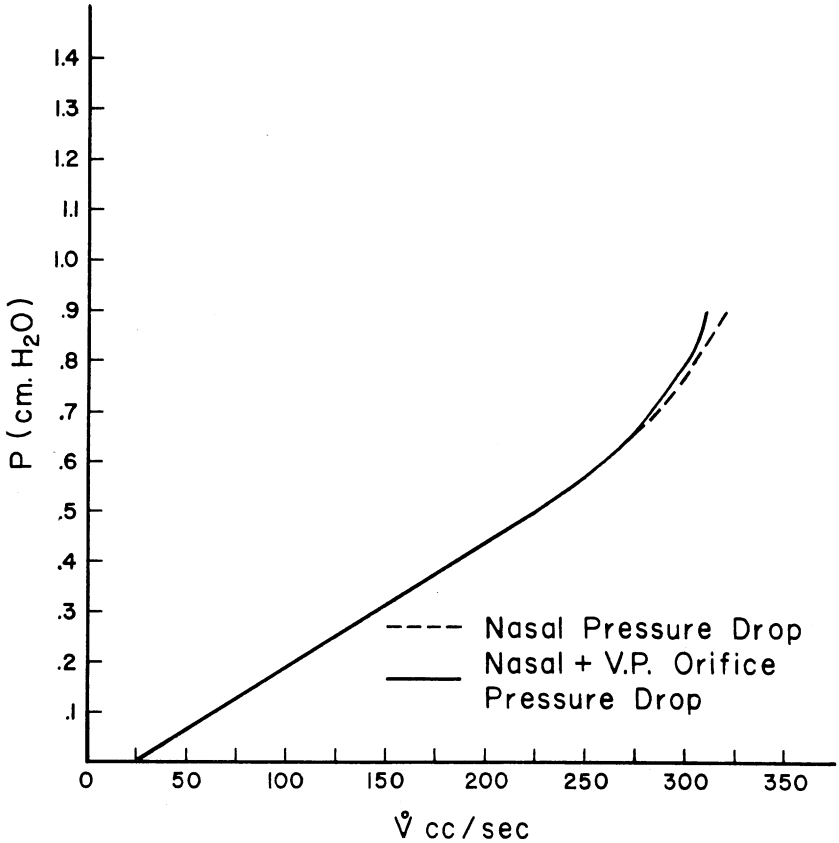

FIGURE 6. Pressure-flow graph of expiration to determine nasal and orifice pressure components. At flow rates less than approximately 200 cc/sec the pressure drop across the resting open orifice is too small to be recorded. The graph, therefore, is actually a measure of nasal resistance up to this point.

geal closure during speech. Since closure is most complete when phonating plosive consonants it was assumed that if the balloon did have an effect it would be demonstrated most clearly with these sounds. A preliminary study was undertaken which involved two procedures performed by eight normal adult subjects. Using the test sentence *Bessie stayed all summer* peak nasal flow rates were compared for the consonant *b* under the following two experimental conditions: a) the pneumotachograph was connected to the right nostril and balloon inserted into the oropharynx by way of the plugged left nostril, and b) the pneumotachograph was connected to the right nostril and a cork stopper placed in the left nostril. In this procedure, the balloon was eliminated leaving the orifice in a normal empty state.

The peak nasal flow rates obtained during phonation of the consonant *b* were compared statistically using a *t* test, and no significant difference

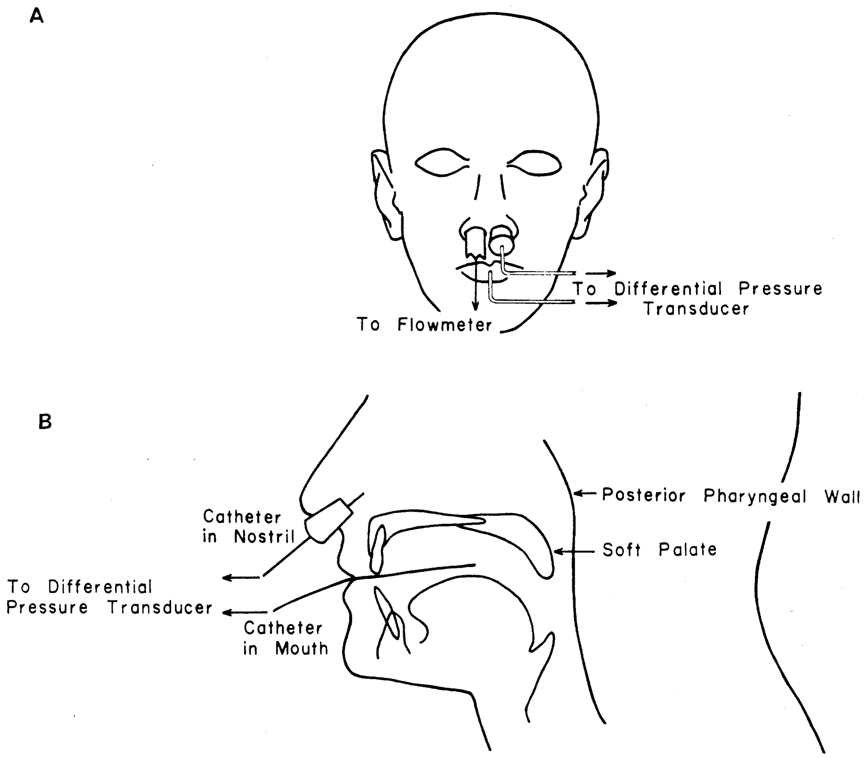

FIGURE 7. Technique for measuring the pressure drop across the resting open orifice. The frontal view is shown in A. The sagittal view, in B, shows how one catheter is placed into the subject's left nostril, is secured by a cork which plugs the nostril, and creates a stagnant air column above the orifice. The second catheter is placed in the subject's mouth. Both catheters are connected to a differential pressure transducer. The subject is requested to breathe out through his nose with his lips closed; air flow is measured by the flowmeter connected to the right nostril.

was found between the two procedures. It may be assumed from this that competency of closure is not altered by the balloon technique for measuring oropharyngeal pressure. Calibration of the balloon against an open tipped catheter did reveal, however, a slight discrepancy (3%) in pressure amplitude measurement, probably due to the slight stiffness of the thin walled balloon. The balloon was used to keep saliva out of the catheter.

Experimental Technique. Each of the 10 subjects was instructed to perform the following procedures: First, to breathe lightly through his nose with lips closed. (This gives a record for measurement of nasal resistance in the normal subject.) Second, to repeat the sentences *Are you home papa* and *My tent is very clean.*

The transitions between various sounds in continuous speech often are so indistinct that boundaries between speech elements are difficult to identify, if judged by criteria such as where a consonant ends and a vowel begins. For this reason, a method based on pressure, airflow, and sound

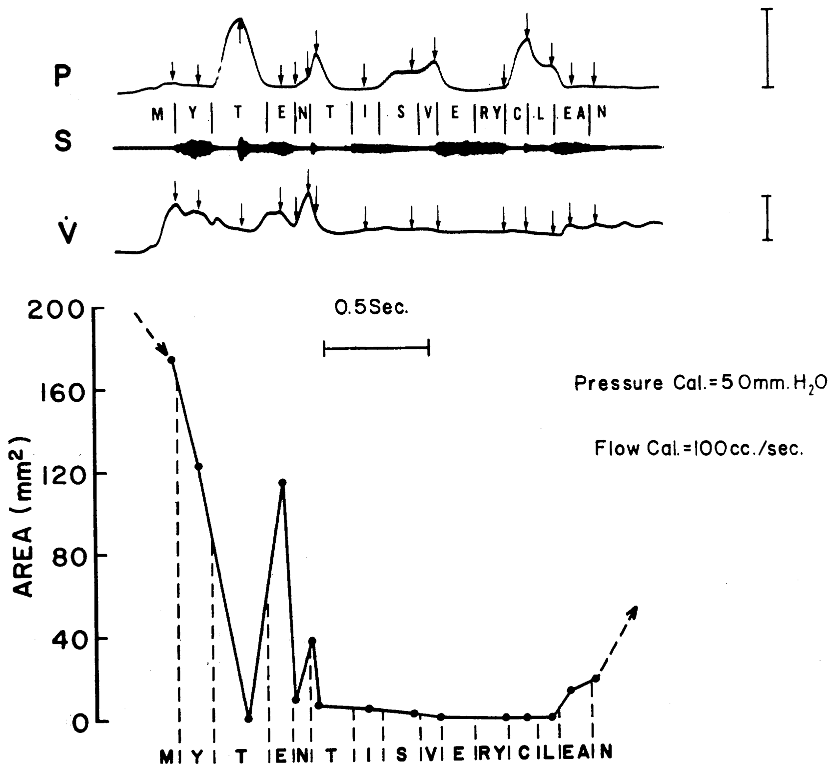

FIGURE 8. Normal oropharyngeal pressure, sound, orifice airflow and orifice area record of *My tent is very clean.* Arrows point to where measurements were made. Sound element boundaries are established according to physiological and acoustical events.

patterns was developed for determining speech element limits. Figures 8 and 9 illustrate sentences separated into such segments. For example, the articulation of an occlusive consonant is considered to begin with the initiation of the pressure rise. Although the consonant actually ends somewhere on the descending slope of the pressure deflection, its terminal limit cannot be positively identified. Therefore, the terminal boundary of the consonant may be arbitrarily placed at the point on the downward slope of the pressure deflection where the voice record changes. This is then considered to be the beginning of the next speech element, defined "physiologically" rather than phonetically. If elements could not be separated they were treated jointly as one element.

Temporal comparison of orifice areas during continuous speech is not feasible because sentence phonation time varies for each subject. For this reason, it was necessary to devise a sampling technique which permitted comparison of specific speech sounds among subjects. For consonants, measurements were made at the point of highest pressure within the boundary of the specific sound. For vowels, measurements were made at

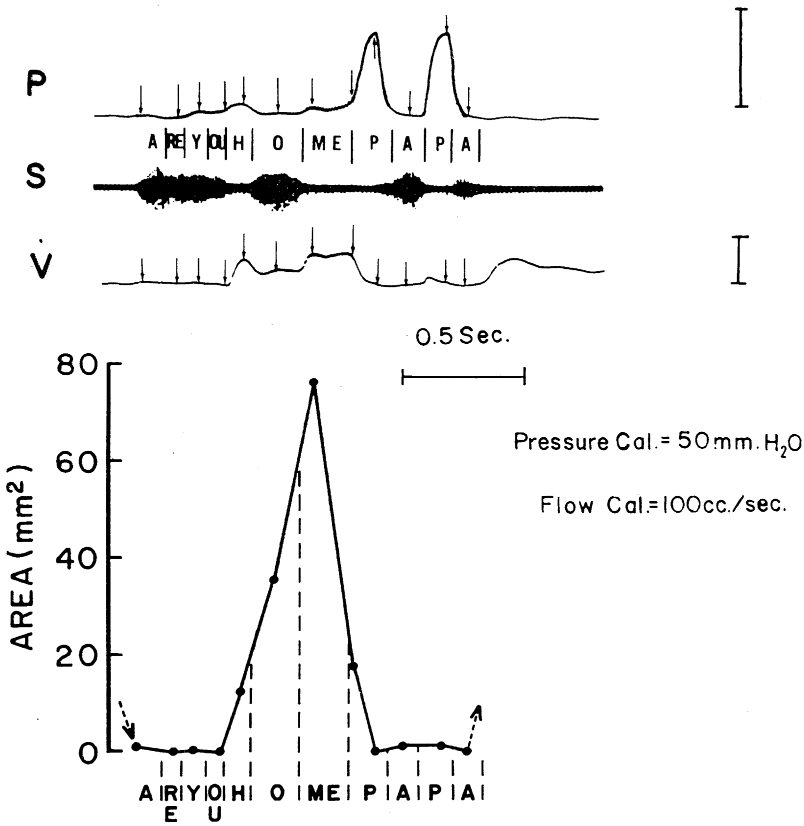

FIGURE 9. A normal oropharyngeal pressure, sound, orifice airflow and orifice area record of *Are you home papa.*

midpoint of the voiced sound interval except in the few cases where it was difficult to separate two speech elements. When this occurred the measurements were made at the beginning and end of the voiced sounds.

Since only one measurement was made for each vowel or consonant, the value obtained for orifice size is an instantaneous measure of area at the reference point used.

Results

Typical oropharyngeal pressure, voiced sound, orifice airflow, and orifice area patterns of the two test sentences are illustrated in Figures 8 and 9. Occlusive and continuant consonants characteristically are produced with high oropharyngeal pressure and little, if any, orifice flow. Nasal consonants, on the other hand, are produced with high orifice flow and very low oropharyngeal pressure.

The influence of phonetic content on the area of the velopharyngeal orifice is evident in the sentence *My tent is very clean* (Figure 10). This

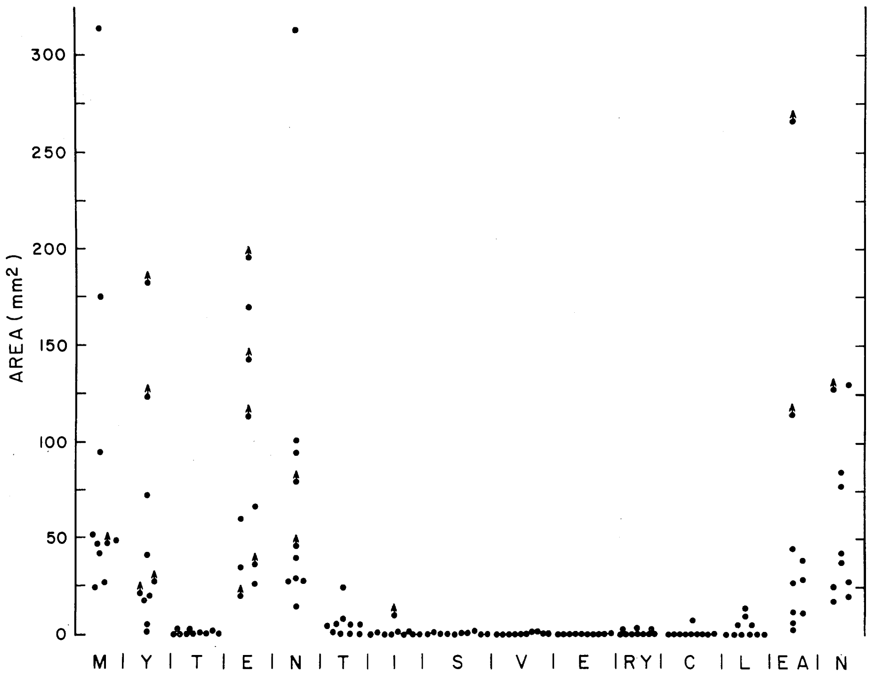

FIGURE 10. Summary of orifice area data from 10 normal subjects phonating *My tent is very clean.* Measurements are instantaneous values of orifice size at the reference point of each speech element. Arrows indicate that actual areas are greater than the values noted (as explained in text). Note the effect of phonetic content on orifice size.

effect was verified by statistical comparison of orifice size during production of the vowel *e* in the word *tent* and in the word *very*; the analysis by a nonparametric sign test revealed a highly significant difference in orifice size for this vowel in different phonetic contexts.

In certain cases, depending upon flow rate, the pressure component due to nasal resistance was equal to the oropharyngeal pressure recorded. This meant that the orifice was open too wide for differential pressure to be measured. When this occurred, an arbitrary value, equal to the lowest pressure which could be measured at the highest amplifier sensitivity, was used for the differential pressure value. Since the actual pressure was less than this amount the calculated area was less than the actual area. Thus if the calculated area, using the arbitrary value for differential pressure, equaled 124 mm^2 then it was written as > 124 mm^2.

That a nasal consonant also influences a closely associated occlusive consonant is evident from the analysis of the plosive *t* pair in the word *tent*. Using the *t* test, a significant difference in orifice size ($P < .02$) was found, the orifice being smaller for the initial *t* than for the terminal *t*.

These data indicate that both vowels and consonants are influenced by phonetic content, although the degree of effect is much greater for vowels.

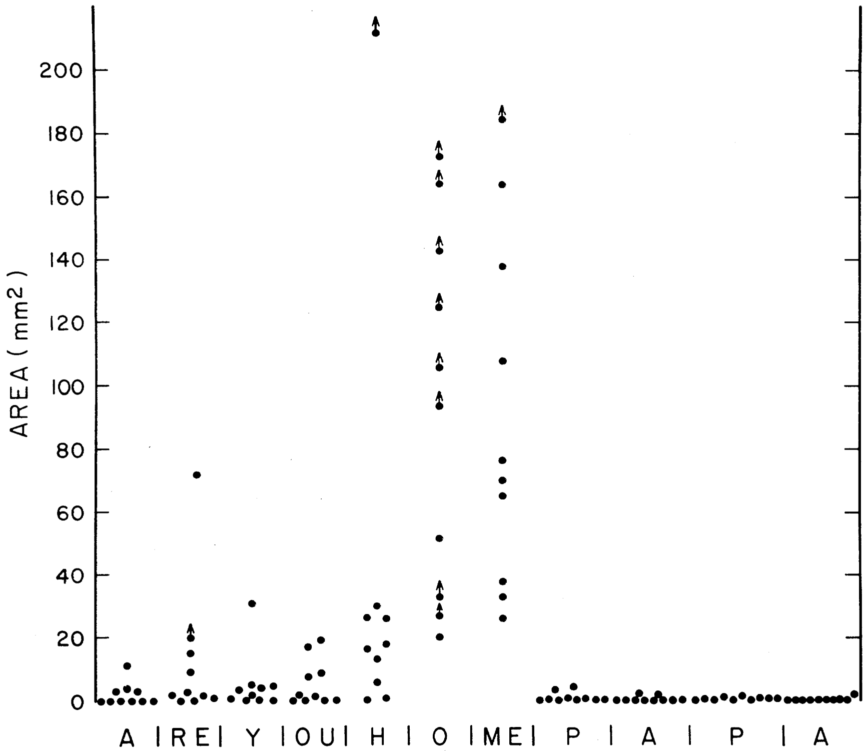

FIGURE 11. Summary of orifice area data from 10 normal subjects phonating *Are you home papa.* Measurements were made at the reference points and arrows indicate that actual area values are greater than the values noted. The area graph demonstrates the effect of a nasal consonant on closely connected speech elements. Note that the interval of preparation for the nasal consonant begins at *h*.

As expected, the greatest variation in orifice size occurred with nasal consonants and with the nasalized vowels which precede these consonants. Occlusive and continuant consonants which require high oropharyngeal pressure were made with the tightest closure and least variation in orifice size.

The effect of a nasal consonant upon closely associated speech sounds is also evident in the sentence *Are you home papa.* In Figure 11 it can be observed that the velopharyngeal orifice began to open as far in advance as the voiceless *h* in preparation for the nasal *m*. For example, the mean value of the *m* voiced interval was 120 millisec compared to a mean opening interval of 284 millisec prior to initiation of the sound. The orifice, therefore, was open an average of 404 millisec or nearly 3.5 times longer than the actual *m* voiced interval.

For comparison, in the sentence *My tent is very clean*, the orifice began to open 196 millisec (mean) in advance of the consonant *n* in *clean.* Since the nasal sound lasted only 127 millisec (mean) the orifice was open 2.5

times longer than the nasal voiced interval. The difference in open interval time between *m* in the word *home* in *Are you home papa* (404 millisec) and *n* in the word *clean* in *My tent is very clean* (323 millisec) can best be explained by differences in phonetic context. The word *clean* begins with an occlusive consonant which requires a certain degree of closure for its production. The voiceless *h* in *home*, however, not requiring high oropharyngeal pressure, can be produced with the orifice open. Thus, the discrepancy occurred because the orifice did not open until after the production of *c* in the word *clean* in *My tent is very clean*, whereas it opened during the production of *h* in the word *home* in *Are you home papa.*

Discussion and Conclusions

Technique. A method has been described for relating changes in velar structure to the acoustical characteristics of speech. The technique, based upon pressure and flow measurements, provides a means for estimating the functional area of the velopharyngeal orifice during continuous speech. Reproducibility of data for the model was good; reproducibility for normal subjects based on repeating the sentences several times was considered adequate by inspection, i.e., pressure and flow patterns are similar.

The distinct advantage of this method over other techniques is that all of the important parameters related to velopharyngeal function (pressure, airflow, orifice area and associated speech characteristics) can be assessed and evaluated together. A disadvantage already noted is that orifice size, when large, cannot be calculated if orifice airflow is small.

Presently, the only other technique available for evaluating orifice size involves the use of transversal tomography during the production of isolated sustained sounds. Björk reported in his excellent monograph (*1*) that transversal tomography, cineradiography, and sound spectrography can be used to determine orifice cross-sectional area during connected speech. The validity of projection of two-dimensional cineradiographic data to orifice area is dependent upon his suggestion that the sagittal axis of the coupling gate between the nasal and oral cavities is related to the area of the cross-section. Although he considers the relationship linear, the data he presents suggest a possible quadratic relation between the two parameters at small orifice sizes. It would be interesting to compare the functional areas measured with this technique to the anatomical areas measured by Björk's method.

Phonetic Content and Orifice Size. The data obtained in this study support the notion that the function of the velopharyngeal sphincter is primarily related to the production of consonants and only secondarily concerned with vowels, that is, the area of the orifice during pronunciation of vowels is dependent upon the type of consonant present in the phonetic segment. Björk (*1*) previously described nasalization of vowels which precede nasal consonants; the present results also confirm those findings.

Nusbaum, Foley and Wells (*12*) found that individuals may produce vowels with an open orifice, although this does not necessarily imply a noticeably nasal tone. Moll (*10*) suggests that velopharyngeal closure on vowels may vary systematically not only as a function of the vowel sound produced but also as a function of the phonetic context of the vowel. He reported that low vowels are made with greater velar opening than high vowels (*11*). Our related findings disclose that variations in vowel orifice size stem mainly from the sphincter's role in adequate consonant production. The degree of influence appears to depend upon the type of consonant and whether the vowel is contained within its interval of preparation. The preparation interval for nasal consonants was found to be approximately 2.5 to 3.5 times longer than the actual sound. However, interval length, in turn, was modified somewhat by the phonetic content of the preceding segment, that is, the interval is shortened by the presence of an occlusive consonant. Non-nasal consonants were affected similarly, but the degree varied with consonant type. Open consonants, not requiring high oropharyngeal pressure, were influenced to a greater degree than occlusive or continuant consonants.

The important new point resulting from this study is that a consonant influences the orifice size of all speech elements (vowels and consonants) contained within its interval of preparation. The effect is dependent upon both the type of consonant and the type of vowel involved. The preparation period for a nasal consonant, being an opening velar movement, increases the size of the orifice for preceding sounds. In contrast, this period is a closing movement for occlusive or continuant consonants, and orifice size is decreased for the preceding sounds. Because of these many interacting processes, absolute air-tight closure appears to occur only infrequently in continuous speech.

In a subsequent paper a technique will be described for use with cleft palate subjects, and a comparison of normal and abnormal pressure, flow, and orifice area patterns will be made (*17*).

Summary

A new technique which uses hydrokinetic principles has been described for studying velopharyngeal function during continuous speech. The principle is based upon a modification of the Theoretical Hydraulic Equation and assumes that the area of the velopharyngeal orifice can be determined if the differential pressure across the orifice is measured simultaneously with airflow through it. The distinct advantage of this new method is that parameters related to velopharyngeal closure (orifice size, oropharyngeal pressure, orifice airflow and acoustic characteristics) can be assessed and

evaluated simultaneously. Preliminary data obtained in a study of 10 normal adult subjects support the notion that the velopharyngeal sphincter is primarily concerned with consonant production and only secondarily concerned with vowel production. Variations found in vowel orifice size stem mainly from the sphincter's role in consonant production.

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APPENDIX: DERIVATION OF THE HYDROKINETIC EQUATION. The basic equations used to develop the "theoretical equation" are the equation of continuity and the energy equation combined in a special form. For developing and discussing the equation, the following symbols will be used:

A	= area	cm^2
P	= absolute static pressure	$dynes/cm^2$
Z_i	= internal energy	$ergs/cm^3$
Z_k	= kinetic energy	$ergs/cm^3$
S	= mean axial speed of fluid	cm/sec
V	= volume	cm^3
γ	= specific weight of the fluid	$dynes/cm^3$
D	= density of air (0.001)	gm/cm^3
$\dot{V}$	= volume rate of airflow	cm^3/sec

Consider a steady stream flowing along a channel with rigid, impervious walls, from section A_1 to a section A_2. According to the equation of continuity for steady flow, the mass of fluid passing any section A_1 per unit time is constant and equal to that passing a second section A_2 per unit time, thus

$$A_1S_1 = A_2S_2 \tag{3}$$

The general energy equation states that as each mass of fluid passes from A_1 to A_2, the increase of its total energy, kinetic plus internal, is equal to the work done on it plus the heat added to it. The work done upon the fluid due to the pressure change is

$$(P_1V_1 - P_2V_2) \tag{4}$$

Since the weight of air is negligible, the gravitational potential can be neglected. Thus the general energy equation becomes

$$(Z_{k2} + Z_{i2}) - (Z_{k1} + Z_{i1}) = (P_1V_1 - P_2V_2) \tag{5}$$

It is assumed in equation (5) that there is no heat transfer (adiabatic flow). Now ordinary subsonic aerodynamics is an example of incompressible flow so

$$V_1 = V_2 \tag{6}$$

Thus

$$(Z_{k2} + Z_{i2}) - (Z_{k1} + Z_{i1}) = (P_1 - P_2)V \tag{7}$$

Since practically no work of compression or expansion is done and no heat is transmitted to or from the walls, the internal energy Z_i cannot change from either of these causes. However, some heat is generated by wall resistance and in the continual damping out of eddy currents by viscosity. If Z_d represents the quantity of this dissipated energy, then

$$Z_{i2} - Z_{i1} = Z_d \tag{8}$$

and

$$Z_{k2} - Z_{k1} = (P_1 - P_2)V - Z_d \tag{9}$$

Since flow is actually non-uniform, the average kinetic energy may be represented by

$$Z_k = \frac{S^2}{2g} + \psi^2 \tag{10}$$

in which ψ^2 is the energy loss due to non-uniform flow.

Finally, in nearly all cases turbulent eddying flow occurs and this component has a kinetic energy of its own, in addition to that of the axial motion already present. Thus, if the average amount of this new kinetic energy be denoted by Z_t^2(Z_t for turbulence), the complete expression is

$$Z_k = \frac{S^2}{2g} + \psi^2 + Z_t^2 \tag{11}$$

By applying this equation to the sections A_1 and A_2 the following equation is obtained

$$Z_{k2} - Z_{k1} = \frac{S_2^2}{2g} - \frac{S_1^2}{2g} + (\psi_2^2 - \psi_1^2) + (Z_{t2}^2 - Z_{t1}^2) \tag{12}$$

Now replacing V with $1/\gamma$ in equation (9) and rearranging,

$$\frac{S_2^2}{2g} - \frac{S_1^2}{2g} = (P_1 - P_2)\frac{1}{\gamma} - x \tag{13}$$

where

$$x = Z_d + (\psi_2^2 - \psi_1^2) + (Z_{t2}^2 - Z_{t1}^2) \tag{14}$$

The term x represents the net effect of resistance, non-uniformity and turbulence. If, between A_1 and A_2, we neglect these factors represented by x, a simplified approximate equation can be written.

Thus

$$\frac{S_2^2}{2g} - \frac{S_1^2}{2g} = (P_1 - P_2)\frac{1}{\gamma} \tag{15}$$

so that

$$S_2^2 - S_1^2 = 2g\left(\frac{P_1 - P_2}{\gamma}\right) \tag{16}$$

If we let $\dot{V}$ be the volume rate of flow then

$$(\dot{V}/A) = S \tag{17}$$

according to the continuity equation and

$$A_1S_1 = A_2S_2 = \dot{V} \tag{18}$$

If we now assume A_2 to be very small compared to A_1 so that $A_2 \ll A_1$, then $S_2 \gg S_1$, we can neglect S_1^2 compared to S_2^2. Hence

$$S_2^2 = 2g\left(\frac{P_1 - P_2}{\gamma}\right) \tag{19}$$

and

$$S = \sqrt{2g\left(\frac{P_1 - P_2}{\gamma}\right)} \tag{20}$$

or rearranging

$$A_2 = \frac{\dot{V}}{\sqrt{2g\left(\frac{P_1 - P_2}{\gamma}\right)}} \tag{21}$$

since

$$\gamma = Dg \tag{22}$$

then

$$A_2 = \frac{\dot{V}}{\sqrt{2\left(\frac{P_1 - P_2}{D}\right)}} \tag{23}$$

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