Screening of Velopharyngeal Closure Based on Nasal Airflow Rate Measurements

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Although sophisticated techniques for estimating velopharyngeal port area during speech are available, clinicians continue to seek approaches for screening patients with suspected velar inadequacy. The aim of the present study is to determine the sensitivity and specificity of predicting velopharyngeal dysfunction based on nasal airflow measurements. The pressure-flow technique was used to measure velopharyngeal orifice area and nasal airflow rate in 211 subjects with cleft palate or velar dysfunction, or both. The data demonstrate that nasal airflow rates above 125 cc/sec are almost always associated with velar dysfunction. Sensitivity and specificity of this index were high (0.85 and 0.96, respectively). A correct diagnosis was made in 93% of the cases. As expected, errors in judgment occurred most frequently in subjects with borderline velopharyngeal inadequacy.

KEY WORD: *velopharyngeal closure.*

Although sophisticated techniques for estimating velopharyngeal port area during speech are available (Warren, 1979), clinicians continue to seek approaches for screening patients with suspected velar inadequacy (Dalston and Warren, 1985). Measurements of nasal emission of air have been used as an index of velar activity for decades (Moser, 1942; Hess and McDonald, 1960; Quigley et al, 1964; Warren, 1975). In 1967, Warren reported a correlation of 0.77 between nasal emission and velopharyngeal orifice size in a group of 28 individuals with cleft palate. He also noted that the correlation varies considerably with degree of closure. Those with a port size less than 0.20 cm^2 demonstrated a correlation of 0.93, whereas those with a port size greater than 0.20 cm^2 had a correlation of 0.43. He concluded that nasal emission of air was not an accurate predictor of velar function because the strength of the relationship decreased significantly as degree of inadequacy increased.

The present study reassesses the relationship between nasal airflow rate and velopharyngeal orifice size in a larger group of subjects categorized according to degree of inadequacy. The aims were to develop a predictive index based on area and airflow measurements and to determine the sensitivity and specificity of the predictions.

MATERIAL AND METHODS

The pressure-flow technique (Warren, 1964, 1979) was used to estimate velopharyngeal orifice size and measure airflow rate in 211 subjects with cleft palate or velar dysfunction (Table 1). The age range of the subjects was 4

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TABLE 1 Primary Diagnosis of the 211 Subjects Employed in the Present Investigation

Diagnosis	*Frequency*	*%*
Right unilateral complete cleft of primary and secondary palate	14	7
Left unilateral complete cleft of primary and secondary palate	47	23
Bilateral complete cleft of primary and secondary palate	43	20
Cleft of soft palate only	16	8
Cleft of secondary palate, involving hard palate as well as velum	33	16
Submucous cleft	18	8
Occult submucous cleft	15	7
Incomplete cleft, involving both primary and secondary palate	3	1
Velopharyngeal inadequacy without evidence of overt, submucous, or occult submucous cleft	22	10

to 66 years with a mean of 16.0 years. There were 90 females and 121 males in the sample. The only criterion used in subject selection was that the patient have the intellectual capacity and neuromuscular integrity to perform the required tasks.

Briefly, the pressure drop across the velopharyngeal orifice (oral pressure minus nasal pressure) was measured by placing one catheter within the mouth and another in one nostril. The nasal catheter was secured by a cork that occluded the nostril, thereby creating a stagnant column of air. Both catheters measured static air pressures and transmitted those pressures to pressure transducers. Nasal airflow was measured by a heated pneumotachograph connected by plastic tubing to the subject's other nostril. The area of the constriction was then calculated from the following equation:

$$A = \mathring{V}/k\,(2\,\Delta P/d)\ ^{1}\!/_{2}$$

where A = area of orifice
$\mathring{V}$ = nasal airflow
k = 0.65
ΔP = oral-nasal pressure
d = density of air

Figure 1 illustrates catheter placement and instrumentation for estimating velopharyngeal orifice size and measuring nasal airflow.

The subjects were asked to produce a series of bilabial plosive consonants by repeating the word "hamper." The nasal-plosive blend "mp" was used to stress the velopharyngeal mechanism, because this phonetic combination more nearly approximates the degree of closure that occurs during continuous speech (Warren, 1979). Mean airflow rate and area of the velopharyngeal orifice were calculated during the production of "p" from a series of five utterances from each subject. The subjects were then divided into four groups according to velopharyngeal orifice size. The sample consisted of 137 subjects with adequate closure (orifice open $< 0.05\ cm^2$), 22 subjects with adequate/borderline closure ($0.05 - 0.09\ cm^2$), 21 subjects with borderline/inadequate closure ($0.10 - 0.19\ cm^2$), and 31 subjects with inadequate closure ($\geq 0.20\ cm^2$). Categorization according to the area criteria mentioned above was based on studies by Warren and his colleagues (1964, 1979, 1982).

Velopharyngeal areas less than $0.05\ cm^2$ were considered to be adequate because normal, noncleft speakers do not manifest areas greater than this value (Warren, 1979). Conversely, the definition of inadequate closure was based on aerodynamic data, demonstrating that oronasal differential pressure during speech is essentially zero at or above this level (Warren and Dubois, 1964). In addition, our unpublished clinical observations have led us to con-

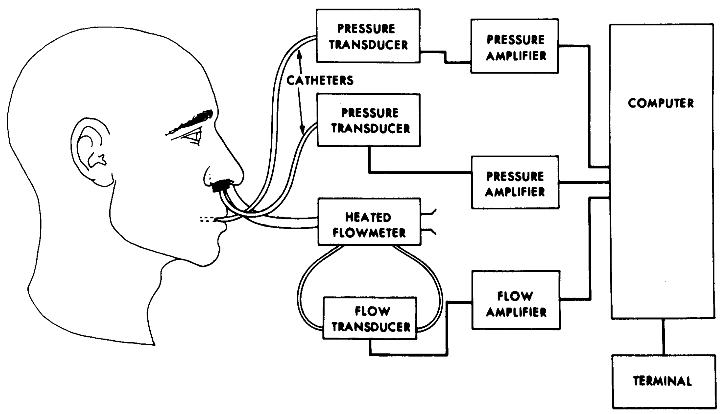

Figure 1 Equipment used to record test sounds, airflow rates, and pressures.

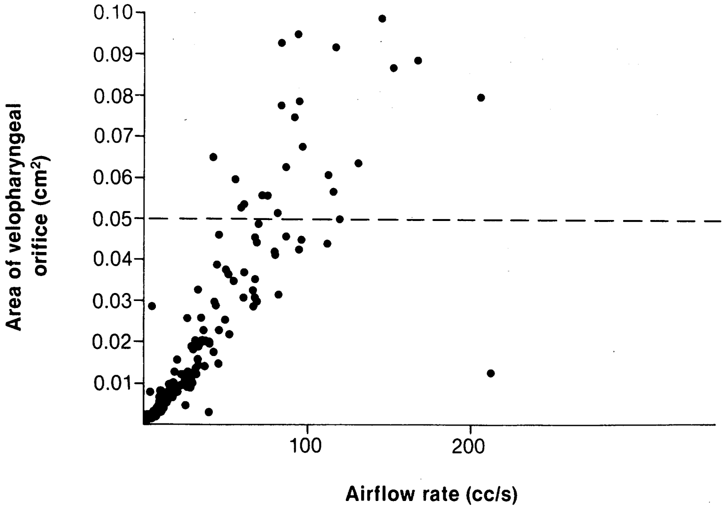

Figure 2 Relationship between orifice size and nasal airflow for subjects with velopharyngeal orifice areas <0.10 cm².

clude that speakers with velopharyngeal areas in the inadequate range invariably manifest hypernasality, nasal emission, or both (Warren, 1979).

The intermediate categories of adequate/borderline closure (0.05–0.09 cm^2) and borderline/inadequate closure (0.10–0.19 cm^2) are more arbitrary. Nevertheless, there is both aerodynamic and perceptual evidence to suggest these groups (Warren, 1979).

Results

The relationship between orifice size and nasal airflow for subjects with adequate and adequate/borderline closure is illustrated in Figure 2. A fairly linear pattern is apparent. Subjects with borderline/inadequate and inadequate closure are shown in Figure 3. The data show a nonlinear pattern with a great degree of scatter. Mean airflow rates according to group are listed in Table 2. As expected, airflow rate increased substantially with increased degree of inadequacy.

Spearman correlation coefficients based on the relationship between velopharyngeal orifice size and airflow rate were calculated for the entire sample and for each group (see Table 2). Although the correlation for the entire sample was 0.94, only the adequate group demonstrated a strong relationship between the two variables.

A mathematical model based on statistical analysis was developed to describe the relationship between airflow rate and area of velopharyngeal closure. The model led to the following prediction equation:[1]

$$3\sqrt{\text{area}} = -0.0797 + 0.1142\,(3\sqrt{\text{flow} + 1})$$

[1] Details on the development of the model are available from the authors.

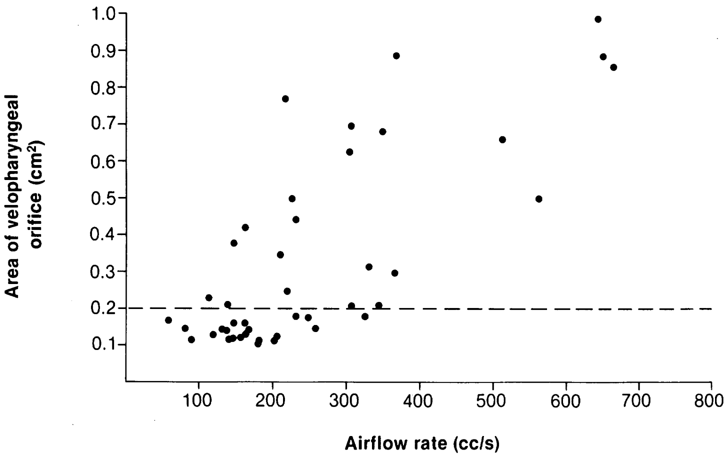

Figure 3 Relationship between orifice size and nasal airflow for subjects with velopharyngeal orifice areas ≥0.10 cm².

TABLE 2 Mean Airflow Rate and Correlation Coefficient for Airflow Rate and Velopharyngeal Orifice Area

Area of closure (cm^2)	*Airflow Rate (cc/sec) Mean SE*	*Spearman Correlation Coefficient Between Area and Airflow Rate*	*p-Value for Correlation Coefficient*
Adequate			
<0.05	26.8 (2.5)	0.92	0.0001
Adequate/borderline			
0.05–0.09	101.0 (9.4)	0.56	0.0066
Borderline/inadequate			
0.10–0.19	167.5 (13.4)	0.11	0.6298
Inadequate			
⩾0.20	308.2 (33.2)	0.16	0.3974
Total	*89.9 (8.8)*	*0.94*	*0.0001*

Table 3 compares the measured areas to the predicted areas based on the equation. Approximately 87% of the adequate group were predicted to be adequate, and 55% of the adequate/borderline group were predicted to be adequate/borderline. A similar percentage (57%) of the borderline/inadequate group was also predicted to be within the corresponding group; 71% of the inadequate subjects were correctly predicted.

Since there is evidence that the borderline/inadequate group has aerodynamic characteristics similar to the inadequate group and that the adequate/borderline group has characteristics similar to the adequate group (Warren, 1979; Warren et al, 1985), the data were then collapsed into areas <0.10 cm^2 and areas ⩾0.10 cm^2. A comparison of the predicted and measured areas for these two groups is shown in Table 4. Sensitivity for the cross table was 0.88. *Sensitivity* is the percentage of cases predicted to be inadequate based on airflow rates, compared with cases considered to be inadequate based on area measurements. *Specificity* is the percentage of cases predicted to be adequate on the basis of airflow rates, compared with cases considered to be adequate based on area measurements. The specificity value was 0.94. Thus, predictive accuracy improves when only two groups are used.

Table 5 summarizes the distribution of airflow in 25-cc increments compared with velopharyngeal orifice areas categorized by group. The data show that all but one of the subjects in the adequate group had flow rates less than 126 cc/sec. Similarly, all but one of the adequate/borderline groups had flow rates less than 176 cc/sec. Data from the borderline/inadequate and the inadequate groups were more widely distributed, with none having flow rates less than 51 cc/sec. Three subjects in the borderline/inadequate group and five subjects in the inadequate group demonstrated flow rates less than 126 cc/sec.

The data were again collapsed to < or ⩾ 0.10 cm^2 and < or ⩾ 125 cc/sec flow and are summarized in Table 6. Using this 2 × 2 distribution, only seven subjects were false-positives, whereas eight were false-negatives. Both the sensitivity and specificity values were high, 0.85 and 0.96, respectively.

Finally, to increase the accuracy of prediction by decreasing variance, the 2 × 2 table was redone, eliminating all subjects with gross in-

TABLE 3 Distribution of Subjects* According to Predicted and Measured Velopharyngeal Orifice Areas

	Measured Area (cm^2)			
Predicted Area (cm^2)	*<0.05*	*0.05–0.09*	*0.10–0.19*	*⩾0.20*
Adequate				
<0.05	119	2	1	1
Adequate/borderline				
0.05–0.09	16	12	2	2
Borderline/inadequate				
0.10–0.19	1	7	12	6
Inadequate				
⩾0.20	1	1	6	22
Total	*137*	22	*21*	*31*

* N = 211

TABLE 4 Distribution of Subjects* According to Predicted and Measured Area Categorized as Adequate (<0.10 cm^2) and Inadequate (≥0.10 cm^2)

Predicted Area (cm^2)	*Measured Area (cm^2)*	
—	<0.10	≥0.10
<0.10	149	6
≥0.10	10	46

* N = 211
Sensitivity = 0.88; specificity = 0.94

adequacy (>0.8 cm^2). Justification for this step is based on our knowledge that gross inadequacy is easy to recognize clinically. These data are presented in Table 7. Specificity remained high, and sensitivity increased to 0.90.

Discussion

In 1967, Warren reported that nasal emission of air increased with increased degree of inadequacy to an airflow rate of about 700 to 800 cc/sec. This finding was also observed in the present study. The correlation between airflow rate and velopharyngeal port area (0.94) is higher than the value reported earlier (0.77). This is apparently related to a change in our particular cleft population over the past 20 years. That is, the adequate group in the present study included about 75% of the subjects, whereas only 50% were adequate in the earlier study. Both studies demonstrate that the relationship between the two variables is strong at orifice areas less than 0.20 cm^2 and weak at larger orifice sizes.

The large variance in the inadequate range was moderated somewhat by the model equation, which used $(\text{flow} + 1)^{1/3}$ to help stabilize the variance of area. Although the model equation provided a good fit overall, it did not account for the variability among groups. Thus, if the equation is to be used, it must be used with caution. Collapsing the groups to adequate (<0.10 cm^2) and inadequate (≥0.10 cm^2) improved the accuracy of predictions. As Table 3 demonstrates, the equation is incorrect in only 16 of 211 subjects, or in 8% of the cases when only two groups were used.

TABLE 5 Distribution of Subjects* According to Airflow Rate and Measured Area of Velopharyngeal Orifice

Airflow Rate (cc/sec)	*Measured Area (cm^2)*			
	<0.05	*0.05–0.09*	*0.10–0.19*	*≥0.20*
0–25	80	1	0	0
26–50	34	0	0	0
51–75	15	4	1	2
76–100	6	9	2	0
101–125	1	2	0	3
126–150	0	3	6	3
151–175	0	2	5	1
176–200	0	0	1	0
201–225	1	1	2	4
226–250	0	0	2	1
251–275	0	0	1	1
276–300	0	0	0	0
301–325	0	0	1	3
326–350	0	0	0	3
>350	0	0	0	10

* N = 211

TABLE 6 Distribution of Subjects* According to Airflow Rate and Measured Velopharyngeal Orifice Area Categorized as Adequate (<10 cm^2) and Inadequate (≥10 cm^2)

Airflow Rate (cc/sec)	*Measured Area (cm^2)* *<0.10*	 *≥0.10*
<125	152	8
≥125	7	44

* N = 211
Sensitivity = 0.85; specificity = 0.96

The relationship between flow and area is such that it appears justifiable to use airflow measures to screen subjects with suspected velopharyngeal inadequacy. Thus, patients with nasal airflow above 125 cc/sec during repeated productions of the word "hamper" should be evaluated further for possible velopharyngeal inadequacy. The present study suggests that such screening would miss about 15% of all patients who did, in fact, have a velopharyngeal problem. Conversely, 4% of the patients would be regarded as inadequate even though more complete pressure-flow testing would reveal that their velopharyngeal function was adequate.

Predictive accuracy can be improved if individuals with inadequacy greater than 0.80 cm^2 are excluded, presumably, they are fairly easy to identify without elaborate testing. If such individuals are eliminated, the overall error rate is about 5%. Four percent will be screened as

TABLE 7 Distribution of Subjects According to Airflow Rate and Measured Velopharyngeal Orifice Area

Airflow Rate (cc/sec)	*Measured Area (cm^2)* *<0.10*	 *≥0.10*
<125	152	4
≥125	7	35

* N = 198; subjects with areas >0.8 cm^2 are excluded
Sensitivity = 0.90; specificity = 0.96

inadequate when they are adequate, and 10% will be screened as adequate when they are inadequate.

The present data, while similar to our previous findings, provide a better basis for clinical screening of persons with velopharyngeal inadequacy. A flow rate above 125 cc/sec appears to be a fairly accurate predictor of velar dysfunction. In an earlier report, Warren (1967) stated that a flow rate of >175 cc/sec during plosive consonant productions indicated inadequacy. Although, in the present study, the maximum airflow rate for a person with adequate closure was 200 cc/sec, very few subjects had airflow rates higher than 125 cc/sec. Thus, 125 cc/sec appears to be a logical point showing high specificity as well as reliable sensitivity for use as an index to screen patients with velopharyngeal inadequacy. Airflow rates above that level would increase specificity slightly but decrease sensitivity remarkably, resulting in almost no false positives but a rather high number of false negative findings. Although subjects with velopharyngeal inadequacy may have airflow rates <125 cc/sec and those with adequacy may have rates >125 cc/sec, the frequency of such occurrences is low.

Finally, although the findings indicate that useful clinical screening of velopharyngeal function can be done based on airflow measurements, the high degree of variance and low correlations emphasize the need for caution. That is, the prediction of velopharyngeal inadequacy based on airflow rates is intended for screening purposes only. When the data indicate the probability of velar dysfunction, a more definitive assessment utilizing either nasendoscopy (Pigott, 1969; Miyazaki et al, 1975), videofluoroscopy (Skolnick, 1970; Skolnick et al, 1975), or pressure-flow measurements (Warren, 1979) is indicated.

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