Velopharyngeal Orifice Area Prediction During Aerodynamic Simulation of Fricative Consonants

BONNIE E. SMITH, Ph.D.
BERND WEINBERG, Ph.D.
Chicago, Illinois 60680.

The present work examined the predictive nature of modeled velopharyngeal orifice area calculations obtained using the hydrokinetic equation (Warren and DuBois, 1964) during conditions simulating voiceless fricative production. Results indicated that accurate estimates of velopharyngeal orifice area can be obtained during aerodynamic events like those known to exist during fricative production. These findings were interpreted to lend support to the view that aerodynamic assessment incorporating hydrokinetic principles provides a useful, non-invasive method for clinical testing and research investigation of velopharyngeal function.

KEY WORDS: accuracy, modeled velopharyngeal orifice area estimates, simulated fricative production

In recent papers, we provided information about the accuracy of estimating modeled velopharyngeal orifice areas (Smith and Weinberg, 1980, 1982). Estimations were made using the hydrokinetic method (Warren and DuBois, 1964) during steady airflow conditions and during non-steady airflow conditions simulating voiceless, stop consonant production. The results of our work, coupled with those of earlier investigators (Warren and DuBois, 1964; Lubker, 1969), provide support for the view that accurate estimation of velopharyngeal area (around five percent error in prediction) can be made during voiceless, stop consonant production, particularly when measurements of orifice differential pressure and nasal airflow are made at nasal airflow peak loci (Smith and Weinberg, 1982).

It is well known that fricative consonants are also misarticulated as a result of velopharyngeal incompetence (Morris, Spriestersbach, and Darley, 1961; Warren and Devereux, 1966; Morris, 1968). Several investigators (McWilliams, 1958; Subtelny and Subtelny, 1959; Morris, Spriestersbach, and Darley, 1961) reported that fricative consonants are more frequently misarticulated than stop consonants by persons with cleft palate. On the basis of pressure/flow studies, Warren (1979) demonstrated that individuals with adequate velopharyngeal closure during stop consonant production may demonstrate inadequate closure during fricative production. Hence, estimation of velopharyngeal orifice area during the production of fricative consonants would be expected to provide additional important indices of impairment.

Unfortunately, there is limited information about the accuracy of estimation of velopharyngeal orifice areas under conditions known to exist during fricative production (Warren and DuBois, 1964). Therefore, the purpose of the present project was to quantify the predictive nature of modeled velopharyngeal orifice area calculations using the hydrokinetic equation under conditions simulating voiceless, fricative consonant production.

Dr. Smith is Instructor, Center for Craniofacial Anomalies and Department of Otolaryngology, Abraham Lincoln School of Medicine, University of Illinois Medical Center, Chicago Illinois 60680. D. Weinberg is Professor and Head, Department of Audiology & Speech Sciences, Purdue University, West Lafayette, Indiana 47906. Address correspondence to Dr. Smith.

This investigation was supported in part by a grant from the National Institute of Dental Research, BE-02872.

Method

MODELING APPARATUS. The vocal tract model used in this project was provided by Warren. The velopharyngeal orifice of the model is constructed so that its dimensions can be varied by moving cover plates over the fully open velopharyngeal port. In this study, seven cover plates were constructed for insertion into the model. A circular opening was made in each cover plate to provide known velopharyngeal port openings ranging from 2–8 mm, inner diameter. The approximate areas of these openings were 3.12, 7.29, 12.48, 19.46, 31.65, 40.06, and 49.46 mm^2. These circular areas were calculated using the known diameter of bores used to create the openings. Orifice areas were chosen to sample a wide range of portal openings known to exist during speech production. The oral port opening of the model was open approximately 10 mm^2 throughout this investigation to simulate conditions known to exist during fricative consonant production (Hixon, 1966; Warren, Hall, and Davis, 1981).

ORIFICE AIRFLOW AND DIFFERENTIAL PRESSURE MEASUREMENTS. The volume rate of airflow through the velopharyngeal orifice of the model was sensed by a Silverman-type pneumotachometer. This device was coupled to the right nostril of the model. The pressure differential across the screen of the pneumotachometer was sensed by a Statham PM 197 pressure transducer. The signal of this transducer was amplified and fed into a Honeywell Visicorder (Model 1108). The airflow measurement system was calibrated with a Fisher Porter flowmeter (Model 10A1027).

The pressure drop across the modeled velopharyngeal orifice was transmitted directly to a differential pressure transducer (Statham PM 6) using two catheters, one inserted into the left nostril of the model, and the second into the oral floor of the model. A water manometer was used to calibrate these pressure measurements. The signal from this differential pressure transducer was amplified and fed into a second channel of the Honeywell visicorder. Flow and pressure measurements were calibrated to provide full scale deflection of 519 cc/sec for flow (1 cm = 51.9 cc/sec) and full scale deflection of 10 cm H_2O for pressure (1 cm = 1 cm H_2O).

PROCEDURE. The model was driven by airflow supplied by an air cylinder. Flow rates were selected to simulate aerodynamic events known to exist during fricative consonant production. A large number of simultaneous nasal flow and differential pressure measurements were used to calculate velopharyngeal orifice area using Warren's hydrokinetic equation:

$$A = \frac{\dot{V}}{0.65\sqrt{2\left(\frac{P_1 - P_3}{D}\right)}}$$

where A is orifice area (cm^2), $\dot{V}$ is volume rate of airflow through the orifice, P_1 is measured pressure below the orifice, P_3 is measured pressure above the orifice, D is the density of air, and 0.65 is a correction factor or constant term (Warren and DuBois, 1964). In addition, percent error in calculated orifice area was determined.

$$\text{Percent Error} = \frac{\text{known area} - \text{calculated area}}{\text{known area}} \times 100$$

Three measures, (1) mean orifice area, (2) standard deviation of orifice area, and (3) mean percent error were obtained for each of the seven known orifice openings under each of two measurement approaches. The first measurement approach involved obtaining orifice estimates when flow through the model was not varied (steady flow condition). Under this condition, 105 orifice estimate and percent error values were obtained (7 orifice areas × 15 estimates at each area). For the other measurement strategy, flow through the model was varied at a rate of approximately 3–4 variations per second to provide dynamically changing pressure/flow events such as those found during voiceless, fricative consonant production. In this approach, simultaneous flow and pressure measurements were made at airflow peak loci (Smith and Weinberg, 1982). Under these dynamic modeling conditions, 280 measurements of orifice area and percent error were made (7 orifice areas × 40 orifice estimates at each area).

Results and Discussion

An initial appraisal of the accuracy of velopharyngeal orifice area estimation was obtained by calculating descriptive statistical measures, that is, average and standard deviation values for velopharyngeal orifice areas. These values for measurements made during the simulation of voiceless fricatives are tabulated in Table 1. These descriptive measures are compared with those obtained under conditions simulating production of voiceless stops (Smith and Weinberg, 1982). Comparable data for relative errors in prediction are summarized in Table 2.

Several major effects are evident in this body of data. First, the variation (standard deviation) in predicted orifice areas was small for all known orifice openings, measurement approaches and consonant simulations. Second, average calculated orifice areas corresponded favorably (error in prediction was about 10 percent or less) with orifice areas known to be present in the model. Third, accuracy of velopharyngeal orifice area estimation decreased somewhat during fricative simulation.

A three factor (ABC) analysis of variance was used to assess whether significant differences in mean percent error were present as a function of three main effects: (1) known orifice area (factor A), (2) consonant simulation (factor B), and (3) measurement approach (factor C). Percent error calculations were transformed into angles, and the transformed data were then used in the analysis of variance (Winer, 1971). The results of the analysis of variance are summarized in Table 3. These analyses revealed significant ($p \leq .01$) main effects for known orifice area, consonant simulation, and measurement approach. In addition, interactions between and among the main effects (that is, AB; AC, BC, ABC interactions) were all significant. These findings indicated that significant differences in average percent error were present as a function of (1) orifice area known to be present in the model, (2) consonant simulation (fricative versus stop), and (3) measurement approach

TABLE 1. Calculated Orifice Area Means (mm^2) and Standard Deviations (mm^2) for Known Orifice Openings During Conditions Simulating Voiceless Fricative and Stop Consonants Using Two Measurement Approaches

Known Orifice Area (mm^2)	*Fricative Simulation*		*Stop Simulation*	
	Steady Flow	*Alternative Flow, Airflow Peak*	*Steady Flow*	*Alternating Flow, Airflow Peak*
3.12	$\bar{X}$ = 3.39 s.d. = 0.27 n = 15	$\bar{X}$ = 3.48 s.d. = 0.08 n = 40	$\bar{X}$ = 3.29 s.d. = 0.16 n = 8	$\bar{X}$ = 3.36 s.d. = 0.11 n = 40
7.29	$\bar{X}$ = 7.39 s.d. = 0.37 n = 15	$\bar{X}$ = 7.20 s.d. = 0.38 n = 40	$\bar{X}$ = 7.24 s.d. = 0.53 n = 15	$\bar{X}$ = 7.45 s.d. = 0.26 n = 40
12.48	$\bar{X}$ = 12.21 s.d. = 0.44 n = 15	$\bar{X}$ = 1.88 s.d. = 0.21 n = 40	$\bar{X}$ = 12.13 s.d. = 0.48 n = 18	$\bar{X}$ = 12.69 s.d. = 0.73 n = 40
19.46	$\bar{X}$ = 18.72 s.d. = 0.39 n = 15	$\bar{X}$ = 18.18 s.d. = 0.34 n = 40	$\bar{X}$ = 18.40 s.d. = 0.83 n = 18	$\bar{X}$ = 19.08 s.d. = 1.34 n = 60
31.65	$\bar{X}$ = 30.14 s.d. = 0.10 n = 15	$\bar{X}$ = 28.74 s.d. = 0.31 n = 40	$\bar{X}$ = 31.29 s.d. = 1.45 n = 19	$\bar{X}$ = 29.62 s.d. = 0.76 n = 40
40.06	$\bar{X}$ = 39.01 s.d. = 1.69 n = 15	$\bar{X}$ = 35.94 s.d. = 0.43 n = 40	$\bar{X}$ = 39.94 s.d. = 1.94 n = 18	$\bar{X}$ = 36.59 s.d. = 1.11 n = 40
49.46	$\bar{X}$ = 52.16 s.d. = 4.33 n = 15	$\bar{X}$ = 44.27 s.d. = 0.83 n = 40	$\bar{X}$ = 49.76 s.d. = 2.06 n = 18	$\bar{X}$ = 46.97 s.d. = 1.47 n = 40

(steady flow versus alternating flow, $\dot{V}$ peak measurement). The finding of significant interactions among these factors indicated that variation in prediction of the known velopharyngeal orifice area was not the same across consonant types and measurement approaches. We interpreted the results for consonant type and measurement approach factors to suggest that acceleration effects are present in dynamic modeling data and that the presence of such effects does occasion variation in orifice area estimation (Smith and Weinberg, 1982).

As we have outlined in an earlier paper (Smith and Weinberg, 1982), the hydrokinetic equation proposed by Warren was suggested by physical equations for steady, ideal fluid flow motion, that is, conditions in which volume rate of airflow is unchanged and a constant pressure is maintained across the orifice (Warren and DuBois, 1964; Shapiro, 1953). Such conditions only approximate those actually occurring during speech production. As noted by Warren and DuBois, flow motion under these circumstances is often unsteady, nonuniform and rotational, and acceleration of airflow is present because of variations in differential pressure across the orifice. In our earlier paper (Smith and Weinberg, 1982) we noted that, in theory, determination of velopharyngeal orifice area in situations where flow is non-steady requires the addition of acceleration terms to the hydrokinetic equation and that these acceleration terms are proportional to $\Delta\dot{V}/\Delta t$, the time rate of change of volume velocity or $\dot{V}$ (Shapiro, 1953; Tubis, 1981). In theory, acceleration terms are equal to zero (1) in conditions where flow rate is steady and, (2) in non-steady flow conditions where $\Delta\dot{V}/\Delta t$ equals zero; for example, at airflow rate peaks.

In view of the theoretical considerations outlined above, the accuracy for orifice area estimations made under steady flow conditions and under alternating flow conditions at $\dot{V}$ peaks should be similar. The discrepancy between steady flow and airflow peak calculations (see Tables 1 and 2) may, in part, be explained by the fact that airflow peak measurements were made under conditions in which input flow rate, and, therefore, measured nasal flow rate varied. Measurements of nasal flow maxima made on the basis of visual inspection may not have been precise; that is, such measurement may not have identified points where the acceleration of nasal airflow was zero. Such measurement artifact may account for the observed increases in relative error in prediction for orifice area calculations made at airflow peak loci.

As we have indicated, one of the principle reasons for completing the present work was that there are limited data concerning the accuracy of velopharyngeal area estimation during fricative consonant production. For example, Warren and DuBois (1964) have provided information about area estimation for a small number of conditions (2 modeled orifice areas and 8 orifice differential pressure/nasal airflow measurements) sampled during fricative simulation. The average relative estimation error for these orifice area calculations was about 17.81 percent, a value substantially higher than those (5.22 percent for steady flow and 8.21 percent for non-steady flow conditions) established in the present project. The discrepancy between the degree of accuracy obtained for our orifice area

TABLE 2. Mean Percent Errors in Prediction for Known Orifice Openings During Conditions Simulating Voiceless Fricative and Stop Consonants Using Two Measurement Approaches

Known Orifice Area (mm^2)	*Fricative Simulation*		*Stop Simulation*	
	Steady Flow	*Alternating Flow, Airflow Peak*	*Steady Flow*	*Alternating Flow, Airflow peak*
3.12	9.10	10.98	6.30	7.69
7.29	3.87	4.67	4.49	3.29
12.48	3.48	4.81	4.29	4.92
19.46	3.91	6.60	6.24	5.02
31.65	5.13	9.20	3.34	6.42
40.06	4.46	10.28	3.61	8.67
49.46	6.60	10.50	3.33	5.17
	$\bar{X} = 5.52$	$\bar{X} = 8.21$	$\bar{X} = 4.43$	$\bar{X} = 5.82$

TABLE 3. Analysis of Variance Summary Table for Mean Percent Error Data

Source of Variation	*Mean Square*	*DF*	*F*
Known Orifice Area (A)	0.3690	6	15.3750**
Consonant Simulation (B)	0.6633	1	27.6375**
Measurement Approach (C)	1.7175	1	71.5625**
AB Interaction	0.1018	6	4.2417**
AC Interaction	0.1720	6	7.1667**
BC Interaction	0.3163	1	13.1792**
ABC Interaction	0.1197	6	4.1276**
Within Cell	0.0240	771	

** $F_{.99}(6,771) = 2.80$
** $F_{.99}(1,771) = 6.63$

calculations and the degree of accuracy obtained for those calculations reported by Warren and DuBois may be explained, in part, by the fact that our prediction errors were based on large numbers of orifice estimates (see Table 1), with a total of 385 orifice area samples, while prediction error for the Warren and DuBois data was derived for a total of only 8 orifice area samples.

The results of the present investigation revealed that the overall accuracy in modeled velopharyngeal orifice area prediction was diminished when measurements were made under conditions simulating voiceless fricative production (5–8 percent overall error in prediction) in comparison with measurement made under conditions simulating voiceless stop production (4–6 percent error in prediction). These results were interpreted to suggest that the hydrokinetic equation may account to a lesser degree for airflow characteristics which existed during fricative consonant simulation. This is not totally unexpected given consideration of the derivation of the hydrokinetic equation (Warren and DuBois, 1964; Smith and Weinberg, 1982) and consideration of the different pressure-flow relationships which exist during stop versus fricative production (Warren and DuBois, 1964; Warren and Ryon, 1967; Warren and Devereux, 1968). Although the results of this study revealed increased errors in prediction of velopharyngeal orifice areas during fricative simulation in comparison with those evident during stop simulation, we believe that the relative magnitudes of orifice estimation errors associated with fricative simulation (about 10 percent or less) were not sufficient to preclude direct application of the hydrokinetic equation to human experimentation during fricative consonant production.

It is important to note that variations in orifice area prediction can result from a variety of instrumental and procedural factors. For example, consideration needs to be given to validation of pressure/flow instrumentation (Smith and Weinberg, 1982). In addition, further consideration needs to be given to the selection of speech samples to be included during aerodynamic assessment of velopharyngeal function (Thompson and Hixon, 1979; Warren, 1979, 1982; McWilliams, 1982 a, b; Netsell, 1982). The number of repetitions of these samples is also important, given that the accuracy of orifice area prediction may be substantially increased by obtaining multiple estimates of velopharyngeal orifice area under each condition or for each utterance tested (Smith and Weinberg, 1980, 1982).

Finally, we caution that additional variation in velopharyngeal orifice area estimation may occur when the hydrokinetic method is applied to human experimentation. For example, variation in orifice area estimation may result from spurious oral pressure readings. Such readings may occur during production of compensatory articulations (e.g., glottal stops and pharyngeal fricatives) by persons with palatopharyngeal incompetence. Compensatory articulations may be substituted for stop as well as fricative and affricate consonant sounds. Since compensatory strategies often involve posterior shifts in lingual place targets (Trost, 1981), it may be difficult/impossible to obtain valid measurements of pressure build up below the velopharyngeal orifice. This would, in turn, lead to invalid orifice differential pressure measurement and affect velopharyngeal orifice area estimation. Even in the absence of compensatory lingual maneuvers, oral catheter placement during fricative production requires additional monitoring. This is due to the presence of oral airflow during fricative production, which is accompanied by regions of higher pressure (e.g., behind the tongue contact or site of major articulatory constriction) and regions of lower or atmospheric pressure (e.g., in front of the tongue contact or site of major articulatory constriction). Placement of the oral catheter posterior to the site of major articulatory constriction may prevent the measurement of spuriously low or negative orifice differential pressures.

The results of the present project, coupled with those of previous investigations (Warren and DuBois, 1964; Smith and Weinberg, 1980, 1982), indicate that the hydrokinetic equation proposed by Warren can be used to obtain accurate estimates of modeled velopharyngeal orifice areas during conditions simulating both voiceless stop and fricative consonants. Taking into consideration the factors mentioned above when applying the hydrokinetic method to human experimentation, we interpret our findings to lend support to the view that aerodynamic assessment incorporating hydrokinetic principles provides a useful, noninvasive method for clinical testing and research investigation of velopharyngeal function.

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