Partitioning Model Nasal Airway Resistance Into Its Nasal Cavity and Velopharyngeal Components

BONNIE E. SMITH, PH.D.
KATHLEEN J. FIALA, M.A.
THOMAS W. GUYETTE, PH.D.

Nasal respiration may be assessed as part of the diagnosis and management of persons with orofacial growth disturbances. It is often evaluated by calculating nasal airway resistance. Traditional methods for measuring nasal airway resistance do not provide information about nasal cavity versus velopharyngeal resistance components. A method that partitions nasal airway resistance into its nasal cavity and velopharyngeal components would provide a localized measurement of airway obstruction useful in evaluating the effects of surgical reconstruction of the velopharynx, enlarged adenoids, adenoidectomy, and nasal cavity obstructions along the nasal airway. A modeling project is presented delineating a method for partitioning nasal airway resistance into its nasal cavity and velopharyngeal components.

KEY WORDS: *partitioning nasal airway resistance, velopharyngeal component, nasal cavity component*

Evaluation of nasal respiration has become an area of research and clinical focus in the management of persons with orofacial growth disturbances (Thurston et al, 1980; Warren, 1984; Smith et al, 1985; Hinton et al, 1986; Keall and Vig, 1987). Nasal respiration is frequently evaluated by calculating nasal airway resistance (Butler, 1960; Kern, 1973; Warren et al, 1974; Hamilton, 1979; Connell, 1982; Pallanch et al, 1985). Nasal resistance (R_n) is derived from measurements of transnasal airflow rate ($\dot{V}$) and pressure drop (ΔP) using the formula, $R_n = \Delta P/\dot{V}$ (Butler, 1960; Kern, 1973; Hamilton, 1979; Kumlien and Schiratzki, 1979; Connell, 1982).

Nasal respiration involves resistance to airflow by both the nasal cavities and velopharynx (Warren and DuBois, 1964; Netsell et al, 1982). Throughout this study, we use the term "nasal airway resistance" to refer to resistance provided by both the velopharynx and nasal cavities. Velopharyngeal resistance refers to resistance of the airway from the nasopharynx to the oropharynx. Nasal cavity resistance refers to resistance of the airway from the nasal vestibule to the entrance to the choanae, including right and left nasal passages. In the normal adult population, velopharyngeal resistance is negligible at low flow rates (Warren and DuBois, 1964). However, partial obstruction of the velopharynx could create a substantial velopharyngeal component as part of nasal airway resistance.

Traditional methods for measuring nasal airway resistance include both an anterior and posterior approach. In the anterior approach, pressure is measured from the nasal vestibule (Kern, 1973; Hamilton, 1979; Connell, 1982). This pressure, while reflecting nasopharyngeal pressure, may not reflect the pressure drop across the velopharynx. In the posterior approach, pressure drop across both the velopharynx and nasal cavities is measured (Kern, 1973; Hamilton, 1979; Connell, 1982), but information about the contribution of either region, alone, to the total nasal airway resistance is not provided.

An alternate method, one that partitions nasal airway resistance into both its nasal cavity and velopharyngeal components, would provide a more precise and localized measurement of airway obstruction. Partitioning involves consideration of the nasal cavity component, from the nasal vestibule to the entrance to the choanae, and the velopharyngeal component, from the nasopharynx to the oropharynx. This information would be useful when evaluating the effects of surgical reconstruction of the velopharynx, such as pharyngeal flap surgery. It would also be important when assessing the effects of enlarged adenoids and adenoidectomy on the nasal airway. The purpose of this project was to delineate a method for partitioning nasal airway resistance into its nasal cavity and velopharyngeal components in an experimental model.

METHOD

Modeling Apparatus

In partitioning the nasal airway into its resistance components, a model of the upper respiratory tract was used to

Bonnie E. Smith is Assistant Professor, Department of Pediatrics and Department of Otolaryngology–Head and Neck Surgery, University of Illinois College of Medicine, Chicago, Illinois. Kathleen J. Fiala is a Speech Pathologist, South Metropolitan Association, Flossmoor, Illinois. Thomas W. Guyette is Assistant Professor, Section of Communicative Disorders, Rush University, Chicago, Illinois.

This project was supported in part by NINCDS grant NS23795.

Reprint requests: Bonnie E. Smith, Illinois Eye and Ear Infirmary, 1855 W. Taylor-B.46, Chicago, IL 60612

simulate nasal and velopharyngeal regions. This model was similar to that described by Warren (1984). The plastic model has been used in previous breathing research (Warren, 1984; Warren et al, 1984). The model approximates the oral and pharyngeal dimensions of the adult vocal tract, and the cross-sectional area of the model nose offers resistance to airflow comparable to established values for normal individuals. Its dimensions are described by Warren and Devereux (1966).

Experimental Procedure

Various degrees of nasal obstruction (mild, moderate, and severe) were simulated by inserting plugs into the model nostrils (approximate combined nasal cross-sectional areas, 36.58 mm^2, 16.60 mm^2, and 11.70 mm^2, respectively). Various degrees of velopharyngeal obstruction were also simulated by using three different cover plates in the model velopharynx (approximate areas, 38.12 mm^2, mild; 19.72 mm^2, moderate; and 6.96 mm^2, severe). These conditions were combined to create a total of nine different measurement conditions (Table 1).

Under each of the nine conditions, six resistance values were calculated: (1) right-sided nasal cavity resistance (RNCR), (2) left-sided nasal cavity resistance (LNCR), (3) total nasal cavity resistance (TNCR) obtained from the combination of conditions 1 and 2, (4) velopharyngeal resistance (VPR), (5) total nasal airway resistance obtained from the sum of components 3 and 4 (TNAR–C), and (6) total nasal airway resistance obtained using a posterior approach (TNAR–P). Resistance 1 to 5 were calculated as part of partitioning the nasal airway, while resistance 6 was obtained to validate these findings.

In determining nasal airway resistance, the nasal cavities have traditionally been viewed as two resistors in a parallel circuit (Hamilton, 1979; Connell, 1982). For partitioning the nasal airway, we extended this analogy by viewing the nasal cavities and velopharynx as two resistors in a combination electric circuit. That is, the velopharynx was considered combined with the nose in a simple series-parallel circuit. Ohm's law governing electric circuits states that series circuits have the same current (in our analogy, airflow) through all members, and the sum of all voltage drops (here, pressure drops) is equal to the source voltage (or pressure). In parallel circuits, the sum of all currents in all members equals the total current, while the voltage across any member equals that across any other member as well as the source voltage (Ryder, 1977). We proposed using these principles to derive nasal cavity, velopharyngeal, and total nasal airway resistance in the nasal airway "circuits" and undertook the modeling study to test this.

For all pressure-flow calculations, the model's airflow was supplied by an air cylinder. Resistance for each nasal cavity (RNCR and LNCR, above) was calculated using a anterior approach (Kern, 1973; Pallanch et al, 1985). The volume rate of nasal airflow ($\dot{V}$) through the right nasal chamber was coupled to the model's right nasal chamber, while a pressure transducer was coupled to the left model nostril to sense nasal pressure. This pressure was compared to room pressure to derive right nasal cavity pressure drop (ΔP). Specific pressure-flow instrumentation and calibration procedures have been described previously (Smith and Guyette, 1988). Resistance for the right nasal chamber was calculated using the formula: $RNCR = \Delta P/\dot{V}$. Pressure-flow measuring devices were then reversed to obtain measurements for the left nasal cavity. The mean resistance for three trials was obtained for each side at pressures ranging from 0.5 to 2.5 cm H_2O under each condition. Following application of Ohm's law, right- and left-sided resistances were calculated at the same pressure, and these values were combined to obtain the total nasal cavity resistance using the formula $TNCR = RNCR \times LNCR/RNCR + LNCR$ (Kern, 1973; Pallanch et al, 1985).

As indicated earlier, the velopharynx was considered a single resistor in series with the parallel nasal cavity resistors. Velopharyngeal resistance was calculated from measurements of pressure drop across the velopharynx and airflow rate through the velopharynx following the procedure outlined by Warren and DuBois (1964). Specifically, airflow rate was sensed by a pneumotachograph coupled to the least obstructed nostril (Smith et al, 1985), and pressure drop was sensed by a pressure transducer with one side coupled to the model mouth and other side coupled to the opposite model nostril. Velopharyngeal resistances were calculated at flow rates equal to the sum of the average right- and left-sided nasal cavity flow rates measured in the calculation of total nasal cavity resistance. The mean velopharyngeal resistance for three trials at each flow rate under each condition was obtained.

In partitioning the nasal airway, Ohm's law governing series-parallel circuits was used to derive the total nasal airway resistance (TNAR–C, above) for the nine conditions. This was accomplished by adding total nasal cavity resistance and velopharyngeal resistance at the same flow rates (those flow rates at which total nasal cavity and velopharyngeal resistances were previously calculated). Resistances were reported at five flow rates for conditions 1 to 3, and three flow rates for the remaining conditions. Sampling

TABLE 1 Conditions Under Which Nasal Airway Resistance Was Calculated

	Velopharyngeal Obstruction		
Mild (area = 38.12 mm^2)	*Moderate (area = 19.72 mm^2)*		*Severe (area = 6.96 mm^2)*
Nasal Obstruction			
Mild (cross-sectional area = 36.58 mm^2)	*Condition 1* nose: mild velopharynx: mild	*Condition 2* nose: mild velopharynx: moderate	*Condition 3* nose: mild velopharynx: severe
Moderate (cross-sectional area = 16.60 mm^2)	*Condition 4* nose: moderate velopharynx: mild	*Condition 5* nose: moderate velopharynx: moderate	*Condition 6* nose: moderate velopharynx: severe
Severe (cross-sectional area = 11.70 mm^2)	*Condition 7* nose: severe velopharynx: mild	*Condition 8* nose: severe velopharynx: moderate	*Condition 9* nose: severe velopharynx: severe

TABLE 2 Mean Total Nasal Cavity Resistances (cm H_2O/LPS), (TNCR)

Nasal Obstruction	$\dot{V}$ *(LPS)*	*Velopharyngeal Obstruction* *Mild*	*Moderate*	*Severe*
Mild	.17	3.04	3.00	3.15
	.27	3.73	3.79	3.75
	.33	4.37	4.48	4.69
	.37	4.95	5.07	5.62
	.43	5.44	5.69	6.01
Moderate	.21	7.51	7.50	7.36
	.24	8.63	8.08	8.50
	.27	9.43	9.66	9.31
Severe	.07	7.53	7.68	7.95
	.12	12.26	12.68	12.37
	.16	15.26	15.85	16.14

TABLE 4 Mean Nasal Airway Resistances (cmH_2O/LPS) Obtained Using the Component Approach (TNAR–C)

Nasal Obstruction	$\dot{V}$ *(LPS)*	*Velopharyngeal Obstruction* *Mild*	*Moderate*	*Severe*
Mild	.17	4.63	9.51	41.04
	.27	5.93	14.12	56.13
	.33	7.45	17.75	64.45
	.37	8.41	20.98	73.62
	.43	9.65	22.70	82.35
Moderate	.21	9.02	14.05	55.46
	.24	10.30	16.52	63.32
	.27	11.33	18.39	66.79
Severe	.07	8.58	8.79	20.54
	.12	13.47	15.92	37.37
	.16	16.62	20.93	44.64

was limited due to creation of high model head pressures under some conditions.

Nasal airway resistance for each of the nine conditions was also derived directly, using a posterior approach (Kern, 1973). For this approach, nasal airflow rate was sensed by a pneumotachograph coupled to both nostrils using a Y-section interface (Smith and Guyette, 1988). The pressure differential across the model nose and velopharynx was sensed by a differential pressure transducer coupled to the oral cavity of the model. These pressures were compared to room pressure to derive nasal pressure drop. Nasal airway resistance was calculated from these measurements using the equation $\text{TNAR–P} = \Delta P/\dot{V}$. For comparison, resistances were obtained at the same airflow rates as the total nasal airway resistances under the partitioning or component approach. The mean resistance for three trials at each flow rate under each condition was calculated.

Finally, nasal airway resistance calculated from the nasal cavity and velopharyngeal components was compared to the nasal airway resistance derived directly using the posterior approach. Comparisons were made using the formula,

$$\text{percent difference} = \frac{\text{TNAR–P} - \text{TNAR–C}}{\text{TNAR–P}} \times 100.$$

RESULTS

The mean total nasal cavity resistance obtained from combined left- and right-sided nasal cavity resistances are shown in Table 2. These data illustrate that nasal cavity resistance is minimally affected by velopharyngeal obstruction. The increase in nasal cavity resistance reflects known decreases in area of nasal cavity openings.

Mean velopharyngeal resistances are shown in Table 3. These data illustrate that estimates of velopharyngeal resistance using the component approach are minimally affected by changes in nasal cavity resistance (i.e., using this approach, nasal cavity resistance and velopharyngeal resistance can be determined independently). Also, as with nasal cavity resistance, velopharyngeal resistance reflects known changes in orifice size and varies as a function of airflow rate.

Table 4 presents the mean nasal airway resistances for the component approach. These data were derived by simple addition of the total nasal cavity resistance (see Table 2) and the velopharyngeal resistance (see Table 3) at each flow rate under each condition. In an attempt to determine the validity of nasal airway resistances obtained using the component approach, nasal airway resistance was measured using posterior rhinomanometry. These data are presented in Table 5. The comparison of the two nasal airway resistance values (TNAR–C versus TNAR–P) for each condition are shown in Table 6. The data in Tables 4, 5, and 6 show general agreement between nasal airway resistances derived from nasal cavity and velopharyngeal components and those obtained using a posterior approach.

TABLE 3 Mean Velopharyngeal Resistances (cmH_2O/LPS), (VPR)

Nasal Obstruction	$\dot{V}$ *(LPS)*	*Velopharyngeal Obstruction* *Mild*	*Moderate*	*Severe*
Mild	.17	1.59	6.50	37.89
	.27	2.19	10.33	52.39
	.33	3.00	13.27	59.76
	.37	3.46	15.91	68.01
	.43	4.21	17.01	76.35
Moderate	.21	1.51	6.55	48.10
	.24	1.67	8.44	54.82
	.27	1.90	8.73	57.48
Severe	.07	1.05	1.11	12.59
	.12	1.21	3.24	25.00
	.16	1.36	5.00	28.50

TABLE 5 Mean Nasal Airway Resistances (cmH_2O/LPS) Obtained Using a Posterior Approach (TNAR–P)

Nasal Obstruction	$\dot{V}$ *(LPS)*	*Velopharyngeal Obstruction* *Mild*	*Moderate*	*Severe*
Mild	.17	4.49	9.51	40.62
	.27	6.44	13.52	55.32
	.33	7.84	17.54	62.69
	.37	8.52	19.98	70.82
	.43	9.73	23.04	78.20
Moderate	.21	9.81	14.94	55.54
	.24	11.22	18.33	62.14
	.27	12.76	20.20	68.19
Severe	.07	9.11	10.00	21.11
	.12	15.15	16.87	38.96
	.16	18.33	22.71	44.17

TABLE 6 Mean Percent Differences Between Nasal Airway Resistance Calculated Using the Component Approach (TNAR–C) and Using a Posterior Approach (TNAR–P)

Nasal Obstruction	$\dot{V}$ *(LPS)*	*Velopharyngeal Obstruction*		
		Mild	*Moderate*	*Severe*
Mild	.17	3.03	0.02	1.02
	.27	8.02	4.37	1.47
	.33	4.97	2.36	4.47
	.37	1.30	4.98	3.95
	.43	0.82	1.51	5.32
Moderate	.21	8.01	5.93	0.15
	.24	8.25	9.88	1.86
	.27	11.17	8.97	2.10
Severe	.07	5.87	12.00	2.68
	.12	11.12	5.66	4.07
	.16	9.35	7.84	1.07

Discussion

The approach we have described provides the examiner with information about each nasal chamber, the total nasal cavity, the velopharynx, as well as the total nasal airway. The observation that TNAR–C and TNAR–P values are roughly equivalent indicates that the component approach provides valid resistance measurements. It is apparent that this method provides more information than that obtained using either anterior or posterior rhinomanometry alone, as indicated earlier.

Although we chose to report resistance data for each location, pressure-flow data can also be used to calculate the cross-sectional areas for these regions (Warren, 1984). In addition, information provided by the component approach can be reported as a percent contribution to total nasal airway resistance. For example, Table 2 shows total nasal cavity resistance and Table 3 shows velopharyngeal resistance for each condition. Using condition 3 for illustration (nose, mild obstruction; velopharynx, severe obstruction; flow rate, 0.17 LPS), the percent contribution of the nasal cavities to nasal airway resistance can be calculated using the formula: (TNCR/TNAR–C)$\times$100. For this example, the nasal cavity contribution to nasal airway resistance is 7.7 percent. Likewise, the velopharyngeal contribution to nasal airway resistance is 92.3 percent.

The research and clinical applications of this approach are apparent. For example, this method can facilitate the study of the results of pharyngeal flap surgery given that it isolates the contribution of this region to nasal airway resistance at any given time following surgery. Likewise, any patient population for whom it becomes important to separate the nasal cavities from the velopharynx for diagnosis and management could benefit from partitioning of nasal airway resistance.

When obtaining resistance calculations in human subjects, consideration should be given to subject-to-instrumentation interfaces as well as to the possibility of palatal elevation while assessing the velopharyngeal region. These factors have been mentioned previously (Kern, 1973; Hamilton, 1979; Kumlien and Schiratzki, 1979; Connell, 1982; Netsell et al, 1982) and await further documentation. We are currently partitioning the nasal airway into its nasal cavity and velopharyngeal components to evaluate nasal respiration in human subjects.

Acknowledgement. The authors would like to thank Richard Holm for his suggestions in reviewing the manuscript.

References

Butler J. (1960). The work of breathing through the nose. Clin Sci 19:55–62.

Connell JT. (1982). Rhinomanometry: measurement of nasal patency. Ann Allergy 6:179–185.

Hamilton LH. (1979). Nasal airway resistance: its measurement and regulation. Physiologist 22:43–49.

Hinton VA, Warren DW, Hairfield WM. (1986). Upper airway pressures during breathing: a comparison of normal and nasally incompetent subjects with modeling studies. Am J Orthod 89:492–498.

Keale CL, Vig PS. (1987). An improved technique for the simultaneous measurement of oral and nasal respiration. Am J Orthod Dentofacial Orthop 91:207–212.

Kern EB. (1973). Rhinomanometry. Otolaryngol Clin North Am 6:863–874.

Kumlien J, Schiratzki H. (1979). Methodological aspects of rhinomanometry. Rhinology 10:107–114.

Netsell R, Lotz WK, Shaughnessy AL. (1982). Nasal cavity resistance estimates during vocalization. Read before the Association for Research in Otolaryngology Meeting, St. Petersburg Beach, Florida.

Pallanch JF, McCaffrey TV, Kern EB. (1985). Normal nasal resistance. Otolaryngol Head Neck Surg 93:778–785.

Ryder JD. (1977). Engineering electronics. New York: McGraw Hill.

Smith BE, Guyette TW. (1988). Estimation of nasal cross-sectional areas using oral versus nasal pressure measurements. Cleft Palate J 25:199–202.

Smith BE, Maddox CM, Kostinski AB. (1985). Modeled velopharyngeal orifice area prediction during simulated stop consonant production in the presence of increased nasal airway resistance. Cleft Palate J 22:149–153.

Smith BE, Skef Z, Cohen M, Dorf DS. (1985). Aerodynamic assessment of the results of pharyngeal flap surgery: a preliminary investigation. Plast Reconstr Surg 76:402–408.

Thurston JB, Larson DL, Shanks JC, Bennett JE, Parsons RW. (1980). Nasal obstruction as a complication of pharyngeal flap surgery. Cleft Palate J 17:148–154.

Warren DW. (1984). A quantitative technique for assessing nasal airway impairment. Am J Orthod 86:306–314.

Warren DW, Devereux JL. (1966). An anolog study of cleft palate speech. Cleft Palate J 3:103–314.

Warren DW, DuBois AB. (1964). A pressure-flow technique for measuring velopharyngeal orifice area during continuous speech. Cleft Palate J 1:52–71.

Warren DW, Lehman MD, Hinton VA. (1984). A study of simulated upper airway breathing. Am J Orthod 86:198–206.

Warren DW, Trier WC, Bevin AG. (1974). Effect of restorative procedures on the nasopharyngeal airway in cleft palate. Cleft Palate J 11:367–373.

Commentary

The potential for separating the nasal components (each individual nostril and both nostrils combined) of airway resistance from those of the velopharyngeal (VP) orifice would be of great value to those clinicians and researchers who are interested in determining the status of the airway or the best form of management for those individuals who suffer blockage of the upper airway. As the authors suggest, most investigation done heretofore has been to view the upper airway as a unit, without addressing the issue of the influence of the component parts of the airway. This may be due in part to the complexity of function of the upper airway as reflected in the many variations brought about by temperature, humidity, age, atmospheric pressure, and the influence of the nasal cycle.

It is apparent from the report of this "modeling project" that Smith, Fiala, and Guyette are in the initial building stages of research designed to give insight into the contribution of the component parts. They report that data from their component approach is within the range of acceptance (0.02 to 12.08 percent) of the data obtained by the posterior approach technique for evaluating total nasal airway resistance, thus indicating its validity.

It is important for the reader to put the words "nasal" and "velopharyngeal" in quotes as this testing was done on a plastic model and not on human subjects. To suggest, as the authors do, that this method "can facilitate the study of pharyngeal flap surgery . . ." is premature and could be misleading to those clinicians who are using pressure-flow methodology in the evaluation of this population. It will be most interesting to review the investigators' findings on "normal" human subjects, on individuals with known defects in the nose or region of the velopharyngeal orifice, and individuals who have undergone surgical or other physiologic change in the shape of the internal nose or in the area of the velopharyngeal orifice.

As the authors imply in their results, information obtained from the component approach can be reported as a percent contribution to total nasal airway resistance. If all data from the different air flow rates are averaged (Table 4 from Smith et al), interesting questions arise as to the information obtained and how this information might relate to the dynamics among component parts of the upper airway. For example, when nasal obstruction is mild, the nasal airway contribution to nasal resistance average 60.5 percent when the velopharyngeal obstruction is mild, and 7.7 percent when velopharyngeal obstruction is severe. However, when nasal obstruction is severe, the nasal airway contribution to nasal resistance averages 90.2 percent when the VP obstruction is mild and 36 percent when VP obstruction is severe. Of interest in the data is that with increase in nasal obstruction from mild to severe, the percent of nasal airway contribution to nasal resistance increases 29.7 percent in the presence of mild VP obstruction and 28.7 percent in the presence of severe VP obstruction. As might be expected, this indicates that, with increase in severity of nasal obstruction, the percent of nasal component would increase similarly. However, the data do not indicate as to why, when both nasal and VP obstruction are ranked the same severity, the percent that the nasal component plays average 60.6, 51.6, and 36 percent for mild, moderate, and severe, respectively. If these differences hold up in evaluating human populations then these questions should be addressed.

Because there are a multitude of factors involved in the function of the upper airway in humans, a reliable method to separate the component parts would be of value clinically. I look forward to following further research in this area.

Quinter C. Beery, Ph.D.
Associate Professor of Otolaryngology
University of Pittsburgh School of Medicine
Pittsburgh, Pennsylvania