

Measurement of nasal airway resistance

W. R. Solomon, M.D., J. A. McLean, M.D., C. Cookingham, M.D.,
G. Ahronheim, A.B.,* and George R. DeMuth, M.D., Ann Arbor, Mich.

A measure of nasal airway resistance can be obtained by simultaneously relating transnasal pressure drop and the rate of nasal air flow. Resistance varies continuously throughout the range of attainable flows, and it has meaning only in relationship to specified rates of flow at which it is measured. The procedure described appears to provide a usable objective parameter for evaluating nasal response to controlled allergenic challenge and to other test situations.

Numerous means have been proposed to document changes in nasal patency. None of these, however, has provided an objective parameter entirely suitable for provocative testing with allergens under controlled conditions. Interest in the nasal effects of allergenic challenge has led us to review critically these methods and to devise, in accord with the characteristics of nasal air flow, a procedure directly measuring variations in airway resistance.

Early in this century, "anterior rhinometric" methods¹ were described in which nasopharyngeal pressure was estimated by attaching one nostril to a water manometer while the subject breathed through the contralateral airway. Others² have proposed that the nares be connected to diaphragm-type manometers so that maximum respiratory pressures might be recorded. Air-tight connections have required the use of nasal adapters which necessarily distort

From the Section of Allergy, Department of Internal Medicine, and the Department of Pediatrics, University of Michigan Medical Center, Ann Arbor, Mich.

This work was supported by United States Public Health Service Research Grant E-1379.

Presented in part at the Twentieth Annual Meeting of the American Academy of Allergy, San Francisco, Calif., February, 1964.

Received for publication May 19, 1964.

*Work done as Summer Student Fellow of the Allergy Foundation of America (1963).

the nares and mucocutaneous ostia interna. Although these adapters tend to reduce the changes in resistance due to nasal alar motion, because of small internal diameters, they often impose a significant impedance to air flow. The contribution to nasal resistance of transient mucosal changes is then proportionately reduced. This problem and the suggested reactivity of even normal noses to mechanical stimulation have directed attention toward methods which obviate nasal manipulation.

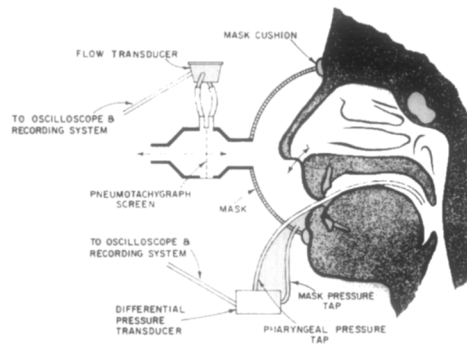
Zwaardemaker's principle³ of measuring the size and persistence of condensation patterns produced by expiring onto a cold metal plate has been utilized by numerous workers. Proetz⁴ substituted a cold calibrated tube for the original planar surface. A straightforward comparison between the two nasal passages is thus afforded; variations occurring in time, however, are readily obscured by changes in ambient air properties and variation in the respiratory pattern. Similarly, reliance on the subject's pattern of breathing has limited the usefulness of Uddströmer's⁵ technique of comparing the volumes of nasal and oral respiration during exercise-induced hyperpnea as an index of nasal patency.

Seeböhm and Hamilton⁶ placed, perorally, a double-lumened tube into their subjects' pharynges. While warmed moist oxygen passed at 10 L. per minute from one orifice to leave through the nose, pressure developing in the pharynx was transmitted by a second lumen to a differential pressure manometer and strain gauge. Significant errors may attend incomplete closure of the glottis or movement of oropharyngeal structures during the period of voluntary apnea. These difficulties were partially retained in the modifications suggested by McLaurin and his associates⁷ in which the pressure developed in a nasal mask is measured as moist oxygen is passed into the nose and through the oropharyngeal space during apnea. Methods using such defined gases, it should be noted, are not entirely suited to studies where characteristics of respired air are test variables. Earlier, attempts by Sternstein⁸ had employed measurement of pharyngeal pressures while ambient air was sucked through the nose, but these attempts were technically unsatisfactory.

Spiess,⁹ in 1900, recorded pharyngeal pressures during normal respiration using a tube passed between the closed lips. Such "posterior rhinometry" is relatively simple, avoids nasal instrumentation, and preserves spontaneous respiration. Unfortunately, an exact repetition of volume and flow pattern in succeeding breaths would be required to afford a measure of nasal patency from pressure determinations alone. The concurrent recording of volume flow and transnasal pressure drop, as described subsequently, allows precise determination of airway resistance throughout any normal respiratory cycle using ambient air.

MATERIALS AND METHOD

A face mask covers the nose and mouth, as shown in Fig. 1. Care is taken that the application is airtight, especially below the zygomas, and that pressure is not exerted upon the tissue overlying the nasal bones. A clinical pneumotachograph¹⁰ receives the tidal air, and develops across its 400 mesh screen

**Fig. 1**

Arrangement of apparatus for measurement of nasal air flow and transnasal pressure drop.

a pressure drop proportional to air flow. This pressure differential, which increases linearly to a flow of 180 L. per minute, is transmitted with the use of 3 mm. internal diameter Tygon tubing to the entry ports of a No. 270B Sanborn* bidirectional pressure transducer which, in turn, generates the flow signal. Calibration is best accomplished by connecting the pneumotachygraph in series between an appropriate rotameter and a flow source. However, a Tissot spirometer may be substituted if its filling is accurately timed with a stopwatch.

The plastic body of the mask has two perforations through which Tygon tubes of equal length and 2 mm. (i.d.) pass. That tube opening at the inner surface of the mask transmits, essentially, pressure variations at the nares. The second tube pierces the mask, passes between the subject's closed lips, and lies on the tongue, its end open to pressure variations in the posterior buccal cavity and oropharynx. A Sanborn No. 268B physiological pressure transducer receives these tubes and generates an electrical impulse proportional to the difference between pharyngeal and mask pressure (the pressure drop across the nasal airway). This transducer is readily calibrated with a water manometer, and its output is linear up to pressure differences of 150 mm. of mercury (204 cm. of water). The flow and pressure signals produced are amplified using Sanborn carrier preamplifiers (No. 350-3000), and they may be inscribed individually on channels of a recording system. Concurrently, the signals are projected on precalibrated axes of an oscilloscope using a Sanborn respiratory adapter (Model 461-175A).

The subject, seated unless other positions are being tested, is asked to breathe entirely through his nose while rolling his closed lips gently inward about the catheter, a maneuver that retards adventitious motion of the oral structures. The end of this tube is adjusted to a level at which optimal pressure tracings are inscribed, usually 90 mm. from the lips. During all tests on an individual this catheter position is maintained. Several minutes may be required to effect relaxation of the uvula and pharyngeal muscles. Thereafter, the oral and

*Sanborn Company (Medical Division), Waltham 54, Mass.

pharyngeal cavities communicate adequately, provided that the chin is raised, and excellent pressure tracings are obtained from well-tolerated catheter positions.

Measurements are most readily made from the image (Fig. 2) of the nasal flow-pressure drop relationship projected continuously onto the axes of the oscilloscope. Note that pressure drop (P) is written here as the horizontal axis, while the vertical axis is flow ($\dot{V}$). For interval determinations, a reference flow rate in excess of 0.5 L. per second (usually 35 L. per minute) is chosen and marked on the vertical axis. As the subject breathes, an overlying transparent disc is rotated until its closely spaced parallel lines are just tangent to the curve at the flow rate chosen. The slope of these lines ($d\dot{V}/dP$) is then proportional to $1/\text{resistance}$, and the slope of a line perpendicular to these lines will be a function of resistance (R) at the reference flow rate since R is $dP/d\dot{V}$. Bordering the left upper quadrant of the oscilloscope is a scale of degrees measuring the angle alpha made by that perpendicular and the oscilloscope's horizontal axis. Clearly, the tangent of angle alpha equals the slope of the perpendicular mentioned. It may be seen that R (in centimeters of water per liter per second) is, therefore, equal to K times the tangent of angle alpha, where K is an empirical constant expressing the calibration values of spaces on the flow and pressures axes of the oscilloscope: (P in centimeters of water)/space divided by $\dot{V}$ (in liters per second) per space.

With care, the same information is derivable from the written record (Fig. 3). Since the individual $\dot{V}$ and P tracings share a horizontal time axis, a vertical line defines an instant in time. If tangents are drawn to the flow and pressure curves at the time point when $\dot{V}$ is 35 L. per minute, then the slope of a tangent to the pressure curve divided by the slope of a tangent to the flow curve equals dP over $d\dot{V}$, since $d \text{ Time}$ is constant. $dP/d\dot{V}$ is the tangent of angle alpha, described on the oscilloscope, and R equals K times this value, as above. In practice, the instantaneous point flow is approximated by

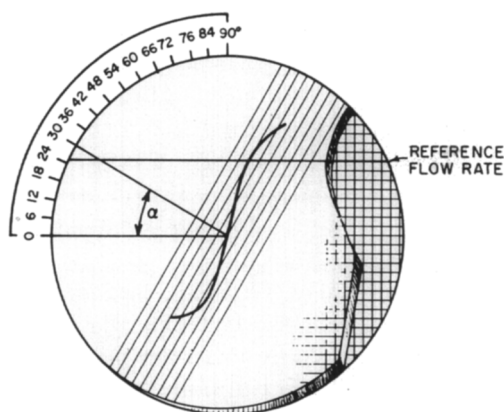
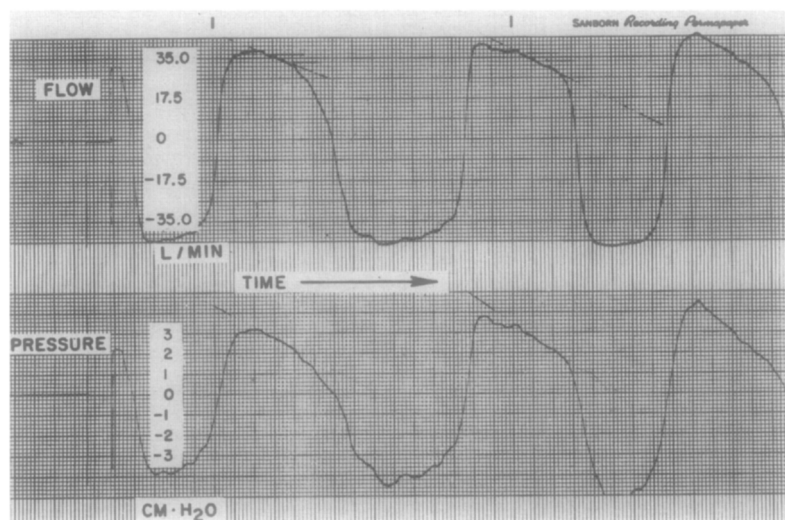


Fig. 2

Schematic representation of the oscilloscope with its overlying disc rotated to indicate resistance at the reference flow rate. Pressure drop is projected on the horizontal axis.

**Fig. 3**

Simultaneous flow rate and pressure drop curves for nasal respiration. Positive values refer to expiration; negative values denote inspiration.

a flow range (e.g., 33.5 to 36.5 L. per minute) to increase the precision with which tangents are drawn. Noninstantaneous values for dV , dP , and $dTime$, of course, result. Despite the inexactness of visually fitting the tangent to a curve, practice permits this with a small relative error. In 80 test periods involving 30 subjects, the angle α , calculated from the tracings and that read from the oscilloscope, corresponded within 5.5 degrees. In 72 of the 80, less than 3 degrees separated these values. The permanent tracings are especially valuable in provocative testing where, after challenge, the nasal maximal expiratory flow rate may dip below the reference flow rate used in base-line measurements. Comparison of the curves can then be made at some lower reference flow rate which has been attained throughout. While quiet breathing is preferred, a subject may be asked to increase his respiratory rate to allow him to reach a reference flow or to increase the smoothness of breathing. For reasons to be discussed, our practice has been to make all interval measurements during the second half of expiration. The average of 5 determinations has provided the measure of nasal resistance during a single test period. However, the variation of single readings about this mean seldom exceeds ± 2 degrees.

RESULTS

The characteristic relationship of flow rate and transnasal pressure drop during a complete respiratory cycle is shown in Fig. 4, A. Although volume flow in normal breathing seldom exceeds 35 L. per minute (0.58 L. per second), the V-P curve approaches linearity during only a short portion of this range, (generally below 0.2 L. per second). In 10 ostensibly normal adult males examined, nasal airway resistance at these lowest flow rates was 0.7 to 2.2 cm. of water per liter per second. In magnitude, these figures are comparable to re-

sistance values determined with the body plethysmograph for the lower airway¹¹ during mouth breathing at considerably higher rates of flow (0.5 L. per second). As nasal patency decreases, this quasilinear portion representing the lower rates of flow becomes frankly curved, making measurements of its "slope" unfeasible. At progressively higher flow rates, resistance always increases continuously, and it is apparent that much nasal ventilation is accomplished against forces far in excess of the values mentioned above. For valid comparisons involving the nose, therefore, resistances must be related to a common rate of flow. At 35 L. per minute (0.58 L. per second), nasal airway resistance in our 10 normal subjects had risen to between 2.5 and 6.2 cm. of water per liter per second.

The mobility of the alae nasi suggested that, for identical flow rates in inspiration and expiration, resistances might differ. Our initial studies amply confirmed such differences and showed a greater inherent variability in inspiratory resistances during succeeding breaths compared to values obtained in expiration. Maximum dilatation of the nasal vestibules with short Tygon tubes rendered the inspiratory and expiratory curves interchangeable. This suggests that observed variations had arisen in and superficial to the mucocutaneous ring. For actual testing, however, no such control of capricious alar motion is possible without inducing artifacts due to manipulation. Therefore, we have chosen to make all our measurements during the second half of expiration, the region of greatest stability in consecutive measurements.

Fig. 4, *A* and *B*, shows representative oscilloscope images in one subject before and 10 minutes after nasal inhalation of 0.1 c.c. of histamine acid phosphate (0.275 mg. per cubic centimeter) as an aerosol. It has been common to ob-

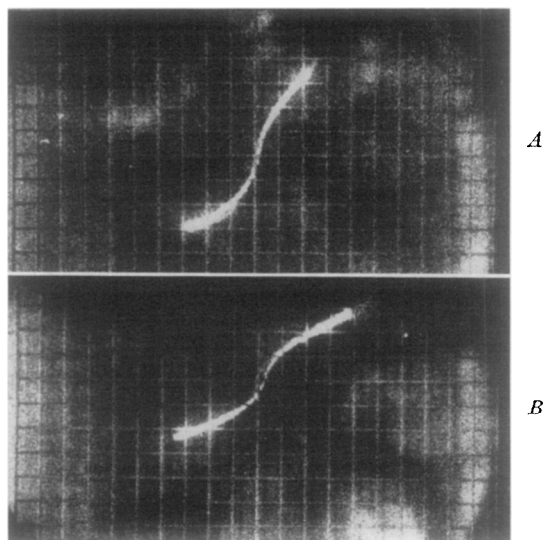


Fig. 4

Oscilloscope flow-pressure drop tracings before and after histamine inhalation. *A*, Quiet respiration base line. *B*, Ten minutes after histamine aerosol. Hysteresis is apparent at low flow rates with induced nasal obstruction.

serve the induction of striking objective decreases in nasal patency in subjects who have perceived little or no change in airway conductance. Periodic intrinsic changes in mucosal swelling have been described^{12, 13} in each half of the nose. Since these cyclic variations are thought to alternate between the two airways, total nasal resistance need not change with time. Our tracings only occasionally show small short term resistance changes occurring, without obvious cause, under constant environmental conditions. Such variations are seen especially with nasal obstruction in habitual mouth breathers. An investigation of the factors promoting these changes is in progress.

DISCUSSION

Röhrer,¹⁴ in 1921, calculated that the nose would contribute approximately 47 per cent of respiratory passage impedance to airflow. More recently, Butler,¹⁵ with the use of the body plethysmograph, has observed the striking increase in total airway resistance imposed by nasal breathing. A mean increase of 168 per cent in the work of breathing occurred when nasal was substituted for oral respiration in his normal subjects. His values for nasal resistance, indirectly calculated as total airway resistance (nasal) minus the total airway resistance (oral), were 1.1 to 4.3 cm. of water per liter per second at flows of 30 L. per minute, and they approximate our own data.

The very magnitude of nasal resistance, in comparison to that of the intrathoracic airways, is a prolific source of difficulties opposing its accurate measurement. Familiar indices of airway patency, such as the maximum ventilatory volume and maximum expiratory flow rate, have proved unfeasible by the nasal route because of effort dependence and the distressing otalgia which occurs at high intrapharyngeal pressures. The curvilinearity of the nasal P-V curve, at even very modest flows, requires emphasis (Figs. 2 and 4). It implies that, for the nose, there is no consistently encountered flow range in which the terms in the P-V relationship having an order greater than one, may be neglected (i.e., a linear Resistance equals Pressure/Flow relationship, analogous to Ohm's law, is not a characteristic of nasal breathing). The importance of recognizing this complex relationship has been stressed by Tonndorf¹⁶ in evaluating the work of Semerak and others who have sought to relate flow and pharyngeal pressure change as an index of nasal patency. In view of the numerous expansions, compressions, and angular accelerations which air must undergo while transversing the arched and highly irregular nasal passages, additional pressure head losses are to be expected. A range of uncomplicated laminar flow, such as occurs in straight circular conduits, is apparently not seen in nasal respiration; the extent to which full turbulence develops is, however, unknown. Our choice of 35 L. per minute as a reference standard is empiric, and it is based on the greater observed consistency in succeeding breaths of P-V values above flows of 20 L. per minute than below.

The tenuity of the nasal passages allows small changes in airway lumen to induce relatively significant changes in resistance. Thus, the scarcely perceptible distention of the nasal vestibules brought about by the air stream in early expiration, can introduce measurable variations in the P-V curve. Present concepts

of bronchial resistance generally regard the inertia of intrathoracic airway gas as being insignificantly small. There is reason to suspect, however, that for the nasal passages significant portions of total pharyngeal pressure may operate to induce volume accelerations during tachypnea and times when, during quiet breathing, the normally narrow passage is further compromised. Such inertial forces may contribute generously to the hysteresis which is seen in our P-V curves under these conditions.

The authors acknowledge the help and encouragement of Dr. John M. Sheldon.

REFERENCES

1. Courtade, A.: Étude clinique et physiologique de l'obstruction nasale, *Arch. Internat. Laryng.* **16**: 320, 598, and 884, 1903.
2. Stoksted, P., and Nielson, J. Z.: Rhinomanometric Measurement of the Nasal Passage, *Ann. Otol. Rhin. & Laryng.* **66**: 187, 1957.
3. Zwaardemaker, H.: *Arch. f. Laryng.* **1**: 174, 1894 (quoted by Uddströmer, M.: *Acta oto-laryng.*, suppl. 42, p. 69, 1940).
4. Proetz, A. W.: *Essays on the Applied Physiology of the Nose*, ed. 2, St. Louis, 1953, Annals Publishing Co., p. 147.
5. Uddströmer, M.: Nasal Respiration: A Critical Survey of Some Current Physiological and Clinical Aspects of the Respiratory Mechanism With a Description of a New Method of Diagnosis, *Acta oto-laryng.*, suppl. 42, pp. 3-146, 1940.
6. Seeböhm, P. M., and Hamilton, W. K.: A Method for Measuring Nasal Resistance Without Intranasal Instrumentation, *J. ALLERGY* **29**: 56, 1958.
7. McLaurin, M. D., Shipman, W. F., and Kirkley, D. E., Jr.: A Modified Technique of Rhinometry With a Preliminary Note on the Effect of Nasal Decongestants Administered Orally, *Laryngoscope* **70**: 155, 1960.
8. Sternstein, H. J., and Schur, M. O.: Quantitative Study of Nasal Obstruction, *Arch. Otolaryng.* **23**: 475, 1936.
9. Spiess, G.: Die Untersuchungsmethode der Nase und ihre Nebenhöhlen, *Heymann's Handb. Laryng. u. Rhin.*, ed. 3, 1900 (quoted by Stoksted, P., and Nielsen, J. Z.: *Ann. Otol. Rhin. & Laryng.* **66**: 187, 1957).
10. Silverman, L., and Whittenberger, J. L.: *Clinical Pneumotachograph* in Comroe, J. H., Jr., editor: *Methods in Medical Research*, Chicago, 1950, The Year Book Publishers, Inc., vol. 2, p. 104.
11. Comroe, J. H., Forster, R. E., Dubois, A. B., Briscoe, W. A. and Carl'sen, E.: *The Lung*, ed. 2, Chicago, 1962, Yearbook Medical Publishers, Inc.
12. Heetdeerks, Dewey, R.: Observations on the Reaction of Normal Nasal Mucous Membrane, *Am. J. M. Sc.* **174**: 231, 1927.
13. Stoksted, P.: The Physiological Cycle of the Nose Under Normal and Pathological Conditions, *Acta oto-laryng.* **42**: 175, 1952.
14. Rohrer, F.: *Arch. ges. Physiol.* **162**: 225, 1915 (quoted by Mead, J.: *Mechanical Properties of Lungs*, *Physiol. Rev.* **41**: 315, 1961).
15. Butler, J.: The Work of Breathing Through the Nose, *Clin. Sc.* **19**: 55, 1960.
16. Tonndorf, J.: *Ann. Otol. Rhin. & Laryng.* **67**: 984, 1958.