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Cross-sectional area as a measure of nasal resistance

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SUMMARY

The possibility of using cross-sectional area as a measure of nasal resistance was investigated with an equation based on hydraulic principles that link the area of a constriction in an airway to the pressure gradient and flow rate of air passing through it.

Experiments with anatomical models of the nasal cavity confirmed the area of the nasal valve could be measured from simple pressure and flow data with a mean error of 3.5 mm^2 *(SD=2.2). The software of a clinical rhinomanometer was then modified to incorporate this equation. Initial tests with a series of substitute airway constrictions of known area indicated the rhinomanometer could then use pressure and flow data to derive the area of each constriction with a mean error of 1.4* mm^2 *(SD=0.9). Using this modification during rhinomanometry on 18 adults with subjectively clear nasal airways, a mean value for the narrowest area of the combined nasal cavities was found to be 48* mm^2 *(SD=13.7) and results from 17 subjects complaining of nasal obstruction produced a mean narrowest area of 27* mm^2 *(SD=11.8). Thus, this system can accurately derive area from data normally gathered from rhinomanometry and the value is constant over a range of pressure gradients and flow rates. The advantages of considering nasal obstruction in terms of area are discussed.*

INTRODUCTION

After many decades in which numerous methods of measuring nasal airflow resistance have been described, Clement (1984) published the Committee Report on standardisation of rhinomanometry in an attempt to define a common system of measuring and presenting data. Despite this, papers still appear on different ways to quantify nasal resistance. Ullmer and Enzmann (1988) describe the oscillation method and Naito et al. (1989) have used computer averaged nasal resistance with head out body plethysmography. One recurring objection to the use of the simple relationship of pressure gradient over the air flow to give a measure of resistance, as recommended by Clement, is that the value so obtained is not constant over a range of flow rates or pressure gradients because the relationship between these two parameters is not linear. Raising the flow rate to a power, termed by some the coefficient of non-laminar flow, does give a more linear relationship but the suggested magnitude of this power varies (Miles-Foxen et al., 1971; Dallimore and Eccles, 1977; Naito et al., 1989).

The use of the cross-sectional area of the nose as a measure of resistance has made sporadic appearances in the literature and offers the possibility of a constant value to represent the degree of airway obstruction (Connell, 1966; Miles-Foxen et al., 1971).

Modification of hydraulic principles to form an equation that links the area of a constriction to the pressure gradient and flow rate of air passing through it has been used by Warren (1964, 1984, 1987) to measure the velopharyngeal orifice as it relates to orthodontic practice.

The equation takes the form:

$$\text{narrowest cross-sectional area} = \frac{\text{flow rate}}{k\sqrt{\dfrac{2 \times \text{pressure gradient}}{\text{density of air}}}} \qquad (1)$$

The constant *k* has be found empirically and Warren (1964, 1984) constructed a "model nose" with a series of plastic tubes which allowed pressure and flow data to be gathered for various constriction sizes. He was able to demonstrate the equation could then be used to find the area of an unknown airway constriction by simply measuring pressure gradient across it and flow rate through it.

As well as the interesting possibility of quantifying "resistance" in terms of size of airway constriction, the equation allows this to be done at any flow rate or pressure gradient thus obviating the usual need for a standard pressure or flow reference point.

This study was undertaken to further explore the possibility of using the cross-sectional area, as calculated by the above equation, as a measure of nasal obstruction and to incorporate this concept into a clinical rhinomanometer.

METHODS

To derive a value for the constant *k* for incorporation into the modified hydrokinetic equation, an anatomical model system was developed which allowed pressure and flow data to be gathered for a range of airway constriction sizes. A silastic foam cast of one nasal cavity of a hemisected head was used as a template for an acrylic cast.

For this study, the "nasal valve area" was selected as the site to be varied and its size was altered with modelling clay to create eight different cross-sectional areas. The narrowest site of each was found from serial sections of new silastic foam casts. The area of the remaining nasal cavity was demonstrated to be larger than each modelled valve area by similar foam cast sectioning.

Airflow through the model was generated with a simple air pump and the flow rate was measured with a pneumotachograph. The pressure gradient across the nasal valve was measured with a microanenometer. The results were used to calculate a mean value for the constant k and thus assess the validity of the modified hydrokinetic equation for the anatomical model system.

After these initial experiments, the concept was developed for use with the NR6 rhinomanometer (Mercury Electronics, Glasgow) which measures pressure gradient across the nasal cavity and flow rate through it as the subject breathes through an anaesthetic type mask. The software was modified by the manufacturers to use the following form of equation (1):

$$\text{area} = \frac{\text{flow rate}}{k\sqrt{1.55 \times \text{pressure}}} \qquad (2)$$

area $=\text{mm}^2$ (narrowest cross-sectional area)
flow rate = cc/second
pressure = pascals
k = constant
[1.55 is the result of 2/density of air (1.29 kg/m^3)]

To confirm the value for the constant k was valid during clinical rhinomanometry, with the normal oscillations of respiration, the system illustrated in Figure 1 was used. During respiration the pressure gradient was derived from the mask pressure and the intra-oral pressure which was measured via a small catheter passed through the flange of the tracheostomy tube. Thus the mouth was a substitute for the nasal cavity and the tracheostomy tubes, with a known cross-section, substituted for the nasal valve area. The cross-sectional area derived from the rhinomanometer was then compared with the true area of the tubes.

Finally, a series of 35 subjects were selected from patients, staff and students in the hospital and rhinomanometry performed in a standard manner.

There were 18 subjects who described their nasal airway as subjectively clear and 17 who felt it was blocked to some extent. Each nose was examined and a note made of the internal anatomy. Posterior rhinomanometry was used if possible but those unable to achieve this used the anterior method. The traditional resistance values in pascals. s/cc and the derived narrowest cross-sectional area in mm^2 were recorded simultaneously.

RESULTS

The values for k derived from the eight nasal valve models were combined to give the mean value for k as 0.64 (SD = 0.07, $n=24$).

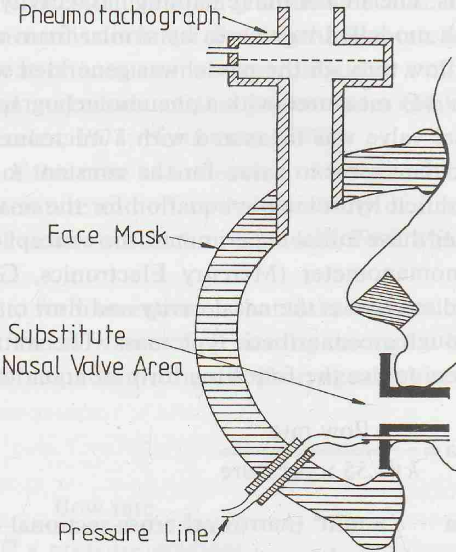

Figure 1. Schematic diagram of system developed to test validity of modified hydrokinetic equation as a means of calculating cross-sectional area from pressure and flow data. The nose is closed with tape and the mouth held shortened tracheostomy tubes of known area substitute for constrictions in the airway. The oral pressure is measured via the fine catheter passing through the flange of the tracheostomy tube.
"Rhinomanometry" is then performed with airflow through the mouth only.

Table 1. Results of 10 area estimations, each of four shortened tracheostomy tubes substituting as nasal airway constrictions. Area derived by the rhinomanometer software from pressure and flow data with value for $k = 0.64$. (Pressure reference point = 75 Pascals.)

tube diameter (mm^2)	6	7	8	9
tube true area (mm^2)	28.3	38.5	50.3	63.6
estimated area (mm^2)				
mean	30.5	38.1	50.9	64.1
SD	2.0	1.3	1.0	1.4

Overall mean of difference between true and each estimated area = 1.41 mm^2 (SD = 1.3, n = 40).

Table 2. Results of area estimations of four shortened tracheostomy tubes substituting as nasal Airway Constrictions at Different Pressure Reference Points. Area derived by the rhinomanometer from pressure and flow data with value for $k = 0.64$. (Each result is mean and standard deviation (SD) of four readings.)

tube diameter (mm)	6	7	8	9
tube true area (mm^2)	28.3	38.5	50.3	63.6
50 Pascals	28.4 (0.6)	35.9 (1.3)	49.5 (0.9)	64.8 (1.7)
100 Pascals	29.2 (0.6)	37.4 (2.0)	49.7 (1.5)	65.6 (0.6)
150 Pascals	29.0 (1.5)	37.0 (1.5)	49.5 (0.5)	64.2 (0.9)
200 Pascals	29.1 (0.4)	37.1 (0.6)	48.8 (0.3)	*

* Resistance of this tube too small to record at 200 Pascals pressure gradient.
Overall mean difference between true and estimated area for each reading = 1.3 mm^2 (SD = 0.9, n = 60).

Table 3. Results of area estimation by rhinomanometry of three shortened tracheostomy tubes substituting as nasal airway constrictions at different pressure reference points (mean of four results) with the equivalent conventional resistance value in brackets; to demonstrate increasing resistance but constant area estimation with increasing pressure gradient ($k=0.64$).

tube diameter (mm)	6	7	8
tube true area (mm^3)	28.2	38.5	50.3
reference pressure	estimated areas by rhinomanometry mm^2 (resistance: pascal s/cc)		
50	28.4 (0.312)	35.9 (0.247)	49.5 (0.180)
100	29.4 (0.430)	37.4 (0.341)	49.1 (0.255)
150	29.0 (0.539)	37.0 (0.416)	49.5 (0.311)
200	29.1 (0.610)	37.1 (0.478)	48.8 (0.364)

The results of area estimation of the four tracheostomy tubes used to represent a constriction in an airway are shown in Table 1 (the constant *k* was set at 0.64). The overall mean difference between actual and estimated areas was only 1.41 mm^2 ($SD=1.3$, $n=40$). These were at a reference pressure value of 75 pascals and the results of similar tests at different pressure reference points are shown in Table 2. Despite the range of pressure reference points, there is a mean error of only 1.3 mm^2 ($SD=0.9$, $n=60$) between the actual and the rhinomanometrically estimated area of each tube.

Table 3 compares the derived area with the standard value for resistance over a range of reference pressure points for the shortened tracheostomy tube system. Between 50 and 200 pascals, the area value is seen to vary by a mean of 1.2 mm^2 ($SD=0.58$) yet the resistance values in pascals. s/cc almost doubles in each case.

The system was then used for clinical rhinomanometry. A total of 36 adult subjects were selected, 18 with a subjectively clear nasal airway and 17 with a subjectively blocked nasal airway when rhinomanometry was performed. In all, 19 (53%) were successful with the posterior method; the remainder used the anterior method.

Figure 2 shows the means (± 2 SD) for the narrowest cross-sectional area derived from rhinomanometry for these two groups; unblocked = 48.4 mm^2, blocked = 27.4 mm^2. The difference was highly significant (t test, $p<0.0001$).

Figure 3, derived from data for the unblocked group, shows five examples of the total area, the area for each nasal cavity assessed separately (posterior method) and the simple sum of these areas (R + L). Figure 4 shows similar data from five subjects in the blocked group, with the clinically observed pathology. This indicates the way area can be summed without recourse to reciprocal values and how it reflects clinical findings.

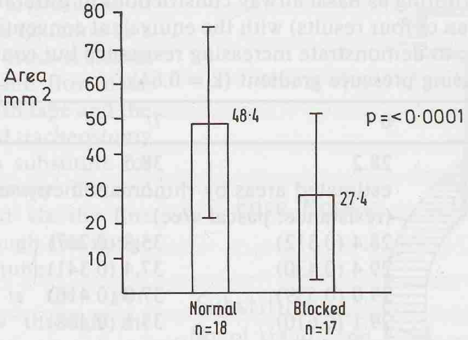

Figure 2. Narrowest cross-sectional area as derived by rhinomanometry for 18 subjects with a "normal" nasal airway and 17 subjects with nasal obstruction. Bars show mean value and ± 2 standard deviations. Students t test.

Area estimation mm^2

Total	Right	Left	(R + L)
64.6	20.9	41.7	(62.6)
45.0	16.6	27.8	(44.4)
49.1	7	34.0	(41.0)
48.9	22.4	24.4	(46.8)
53.4	36.8	22.5	(59.3)

Figure 3. Narrowest cross-sectional area as derived by posterior rhinomanometry for 5 subjects in the unblocked group. "Total" refers to area of both nasal cavities measured simultaneously, "Right" and "Left" refers to each side measured separately, R + L shows the simple sum of area for the 2 sides for comparison with the derived value.

Area estimation mm^2

Total	Right	Left	(R + L)	Pathology
34.4	23.2	10	(33.2)	Left deviated septum
30.7	4	29.8	(33.8)	Right Adhesion
31.1	20.6	11.2	(31.8)	Congested
10.0	6	5	(11.0)	Very Congested
30.7	13.9	8	(21.9)	Large inferior Turbinates

Figure 4. As for Figure 3 but data refers to 5 subjects in the blocked group. Also shown is the clinical finding in each case.

DISCUSSION

These experiments clearly indicate the modified version of the hydrokinetic equation can be used to measure the cross-sectional area of constrictions in anatomical models of the nasal airway and that it can be incorporated into the software of a commercially available rhinomanometer. In a situation where a single constriction exists in an airway, the equation gives a very good estimate of its true area over a range of flow rates and pressure gradients without the problem of non-linearity when using resistance calculated from the more usual relationship of pressure gradient over flow rate. The small variability in the constant *k* has been discussed by Gorlin (1951) and Warren (1984) who stress *k* must be found experimentally for the system in which it is to be used.

The modification of the NR6 rhinomanometer software to include equation (2) was undertaken by the manufacturers (Mercury Electronics, Glasgow, UK). Data normally gathered in the course of clinical rhinomanometry was used to calculate both area and the conventional resistance value. The very low mean error of 1.41 mm^2 (SD 1.3, $n = 40$) when the system was used to calculate the area of a series of mouth held tubes illustrates the system's high level of accuracy.

The clinical results show the ease of use of the system as well as the way area can reflect the effects of obstructive pathology in the nose which, in most cases, involved structures in or around the nasal valve area.

Warren (1984) found an effective area of 40 mm^2 to be a watershed below which subjective sensation of obstruction was more likely. Above this value the flow rate seemed less dependent on area. The mean areas for the data in the present study 48 mm^2 (SD = 13.78) for the unblocked group and 27 mm^2 (SD = 11.8) for the blocked group are in reasonable agreement with this.

The problem of deciding the site of maximum constriction in any given nose still exists but the nasal valve is the principle site in the normal nose and is the site of much obstructive pathology. This can be confirmed clinically by a positive Cottle's sign; if the narrowest site were more posterior, the resulting enlargement at the valve area would not be expected to significantly increase airflow. (This can be confirmed with rhinomanometry during retraction of the cheek with adhesive tape). If Cottle's sign is negative then factors further back in the nasal cavity are responsible for most of the resistance and, although the area estimation from rhinomanometry may still be expected to give the narrowest point, its precise location would be less certain.

The use of small plastic tubes passed along the floor of the nasal cavity is currently being evaluated as a means of obtaining pressure gradient data from specific sites but the necessary invasion of the sensitive nasal cavity, with possible reflex changes in turbinate congestion and the inevitable area taken up by such a tube needs to be addressed. These preliminary results using nasal models and clinical rhinomanometry indicate the potential advantages of considering area as a measure of resistance. This can be summarised as:

1. The area value so derived is constant over a range of pressure gradients and flow rates for a given constriction and there is no need for a standard pressure reference point.
2. During clinical rhinomanometry the area of, for example, the nasal valve can be measured during respiration when it adopts its functional dimensions.
3. Clinicians considering surgery to the nose to relieve obstruction are necessarily dealing with concepts of changing cross-sectional area and to be able to visualise resistance in these terms has interesting possibilities for planning operations.
4. The modified hydrokinetic equation as applied in this study is, above all, a practical working system that can make use of data already gathered in the course of clinical rhinomanometry with simple modifications to existing software.

REFERENCES

1. Bridger GP. Physiology of the nasal valve. Arch Otolaryngol 1970; 92: 543–553.
2. Clement PAR. Committee report on standardisation of rhinomanometry. Rhinology 1984; 22: 151–155.
3. Connell JT. An instrument for measuring the effective cross-sectional airway. J Allergy 1966; 37: 127–134.
4. Daltimore NS, Eccles R. Changes in human nasal resistance associated exercise hyperventilation and rebreathing. Acta Otolaryngol (Stockh) 1977; 84: 416–421.
5. Gorlin R, Gorlin SG. Hydraulic formula for calculation of the area of the stenotic mitral valve, other cardiac valves and central circulatory shunts. Am Heart 1951; 41: 1–29.
6. Kern EB. Surgical approaches to abnormalities of the nasal valve. Rhinology 1978; 16: 165–189.
7. Mann DG, Sasaki CT, Suzuki M, Fukuda H, Hernandez JR. Diator naris muscle. Ann Otol 1977; 86: 362–370.
8. Miles–Foxen EH, Preston TD, Lack JA. The assessment of nasal airflow: A review of past and present methods. J Lar Otol 1971; 85: 811–825.
9. Naito K, Cole P, Chaban R, Humphrey D. Computer averaged nasal resistance. Rhinology 1989; 27: 45–52.
10. Ullmer S, Enzmann H. Exact measurements of nasal resistance with the oscillation method. Rhinology 1988; 26: 263–272.
11. Van Dishoeck HAE. The part of the nasal valve and turbinates in total nasal resistance. Rhinology 1965; 3: 19–26.
12. Warren DW. A quantitative technique for assessing nasal airway impairment. Am J Orthod 1984; 86: 306–314.
13. Warren DW, Du Bois P.A pressure flow technique for measuring velopharyngeal orifice area during continuous speech. Cleft Palate J 1964; 52–71.
14. Warren DW, Hinton VA, Pillsbury HC, Hairfield WM. Effects of size of the nasal airway on nasal airflow rate. Archs Otolar Head Neck Surg 1987; 113: 405–408.

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