

Acoustic rhinometry in nasal allergen challenge study: which dimensional measures are meaningful?

D. Y. Wang*, M. T. Raza*, D. Y. T. Goh†, B. W. Lee† and Y. H. Chan‡

Departments of *Otolaryngology, †Paediatrics, Faculty of Medicine and ‡Clinical Trial & Epidemiology Research Unit, The National University of Singapore, Singapore

Summary

Background Acoustic rhinometry (AR) is commonly used as a quantitative assessment of nasal response to nasal allergen challenge (NAC). However, sources of error and physical limitations of various AR area–distance measurements have not been adequately evaluated.

Objective To investigate the clinical value of AR measurements, and the relationship between subjective sensation and objective AR measurements in the NAC study.

Methods Nasal challenge using increasing concentrations of crude *Blomia tropicalis* (Bt) extracts (0.6, 6, and 60 µg/mL) was performed in 15 adult patients (eight males and seven females) with ongoing persistent allergic rhinitis. Subjective symptom scores of nasal obstruction were recorded together with the objective AR measurements of the minimum cross-sectional area (MCA), distance to MCA and cross-sectional area (CSA) at 3.3, 4.0 and 6.4 cm from the nostril, during the 7 h after the last challenge.

Results The dose–response increase in nasal obstruction score was significantly ($P < 0.001$ for all) associated with decreases in mean MCA ($r = 0.75$), mean CSA3.3 ($r = 0.54$), mean CSA4.0 ($r = 0.53$) and mean CSA6.4 ($r = 0.20$). The mean MCA ($\pm$ SD) for each subjective symptom score 0, 1, 2 and 3 was found to be $0.73 (\pm 0.22) \text{ cm}^2$, $0.63 (\pm 0.29) \text{ cm}^2$, $0.33 (\pm 0.17) \text{ cm}^2$ and $0.21 (\pm 0.14) \text{ cm}^2$, respectively. When the MCA (left and right separately) reached an area $< 0.2 \text{ cm}^2$, measurements of CSA3.3 and CSA4.0 were significantly reduced by 60–70%.

Conclusion This study demonstrates that AR is a useful and objective investigational tool, which correlates well with the sensation of nasal obstruction. MCA, CSA3.3 and CSA4.0 are more reliable measurements than CSA6.4 due to physical limitations. It is important to note that when the MCA is smaller than 0.2 cm^2 , a common condition in the early-phase reaction, area–distance measurements beyond this point can be misinterpreted and should be considered with caution.

Keywords acoustic rhinometry, *Blomia tropicalis*, cross-sectional area, nasal allergen challenge, nasal obstruction, persistent allergic rhinitis

Submitted 3 June 2003; revised 19 January 2004; accepted 24 March 2004

Introduction

Nasal allergen challenge (NAC) is a valid and reliable tool for studying the pathophysiological mechanisms involved in allergic inflammation [1]. Nasal obstruction is one of the cardinal symptoms of allergic rhinitis. Therefore, subjective and objective measurements of nasal obstruction are essential in the assessment of quantitative nasal responses to allergens.

Acoustic rhinometry (AR) measures cross-sectional areas (CSAs) and the volume of the internal nasal cavity, which helps to define objectively the structural pathologies of the nasal passage [2]. In the literature, AR has been commonly used in nasal challenge studies with allergens or mediators (i.e., histamine) [3–9]. Several topographical measurements of the AR area– or volume–distance have been introduced, such

as minimal cross-sectional area (MCA), distance to MCA, CSA at 3.3, 4.0 and 6.4 cm from the nostril. Although each measurement is suggested to represent a distal dimension of the nasal cavity, there is no uniform agreement among experts on the value and significance of each measurement in respect to nasal cavity dimension. In addition, possible errors and physical limitations of AR measurement due to the natural structure of nasal cavity and sinuses, and constriction in the nasal valve area have been observed in laboratory nose models, but not in the human nose [10–12].

In this study NAC using house dust mite *Blomia tropicalis* (Bt) was performed in patients with persistent allergic rhinitis (PAR). AR was performed, and the subjective sensation of nasal obstruction was recorded, during the early- and late-phase reactions after NAC. The aim of this study was to investigate the quantitative value and possible errors of various AR distance–area measurements in patients who experienced subjective symptoms varying from no obstruction to a maximal nasal obstruction caused by NAC. We assessed the

Correspondence: De-Yun Wang, Department of Otolaryngology, The National University of Singapore, 5 Lower Kent Ridge Road, Singapore 119074, Singapore. E-mail: entwdy@nus.edu.sg

relationship between the patient's subjective sensation and objective AR measurements in various nasal conditions.

Methodology

Study patients

Fifteen adult patients (eight males and seven females) between 21 and 44 years of age (mean age of 28.4 years) with ongoing PAR were recruited. Their sensitization to *Bt* was confirmed by a positive skin prick reaction. The patients had no acute nasal symptoms and had not taken any medication during the previous 2 weeks (at least 30 days for any nasal or systemic corticosteroids). A written informed consent was obtained from each subject. Approval to conduct this study was granted by the National Medical Research Council of Singapore and the Institutional Review Board of the Medical Faculty of The National University of Singapore.

Crude extract of *Bt*

Crude extract of *Bt* was prepared from cultured mites, as described previously [13]. In brief, the mites were harvested when the culture was approximately 4 weeks old. The mite culture was separated through a series of 500 and 125 µm sieves, by using a mechanical sieve shaker. Mites with sizes greater than 120 µm were transferred to a modified Tullgren, which was built up of five layers of gauze on a funnel that was attached to a 15 mL Falcon tube. A 60 W bulb was applied at a distance of 15 cm from the culture medium for 4 h. Most of the mites in the medium crawled through the gauze and down into the tube. Mites that remained in the funnel were then swept into the tube using a tiny soft brush after the gauze was removed. One gram of frozen or lyophilized mites was homogenized using a pestle and mortar in the presence of liquid nitrogen. Twenty-five millilitres of phosphate-buffered saline (PBS), 2 mM phenylmethyl-sulphonyl fluoride (PMSF) and 1 mM EDTA was used for protein extraction at 4 °C overnight. After centrifugation at 15 000 *g* for 15 min, the supernatant of the extract was dialyzed overnight at 4 °C against PBS.

Nasal allergen challenge

The NAC was carried out in a double-blind manner using nasal spray, one puff (0.04 mL of allergen solution) per nostril [14, 15]. The study subject was asked to be in complete apnea during spraying. This precaution would prevent the provocation extract from entering the lower airway. The NAC was started by using PBS (diluent of allergen extract) and then subsequently increasing concentrations of *Bt* extracts; 0.6 µg/mL (low), 6 µg/mL (medium) and 60 µg/mL (high) at intervals of 15 min. Subjective and objective symptoms were collected as a baseline, 15 min after each nasal challenge and at 30 min, 1, 3, 5 and 7 h after the last challenge in order to study the early- and late-phase reactions. After a washout period of at least 2 weeks, six of the patients underwent an identical challenging procedure with only PBS as a control.

Subjective symptoms of nasal obstruction

Nasal obstruction was recorded using a symptom severity scale: 0 = none: no obstruction evident; 1 = mild: symptom

clearly present but minimal awareness; 2 = moderate: definite awareness of symptom which is bothersome but tolerable; 3 = severe: symptom is hard to tolerate and interferes with activities of daily life/sleeping.

Measurement of AR

A SRE 2100 acoustic rhinometer (Rhinometrics A/S, Lynge, Denmark) was used to measure the nasal geometry. It was performed according to the standard procedure as described in our previous reports [16, 17]. Briefly, the subjects sat upright in an armchair, with the head properly supported, and breathed quietly through the mouth. An appropriately sized adapter was selected according to the shape of the subject's nostril. Every test consisted of three consecutive measurements of each side of the nasal cavity. The following CSA measurements were recorded:

- MCA: the minimal CSA at 1–5 cm from the nostril.
- Distance (cm) to MCA from the nostril.
- CSA at 3.3, 4.0 and 6.4 cm from the nostril, representing the anterior end of the inferior turbinate, the mid-portion of the inferior turbinate that has the most abundant erectile tissue component, and the posterior nasal cavity [2, 18, 19].

Mean values of the above measurements (right and left); MCA (mMCA), distance to MCA and CSA (mCSA3.3, mCSA4.0, mCSA6.4) were calculated.

Statistical analysis

A repeated measurement analysis was performed to assess the time trend of the responses and mean differences between the mite-challenge subjects and controls taking into account the group $\times$ time interactions. Coefficient of variation (CV) was used to compare the variability of the area–distance measurements at each CSA over time.

Spearman's correlation was applied to investigate the relationship between variables of AR area–distance measurements and subjective symptom scores.

Results

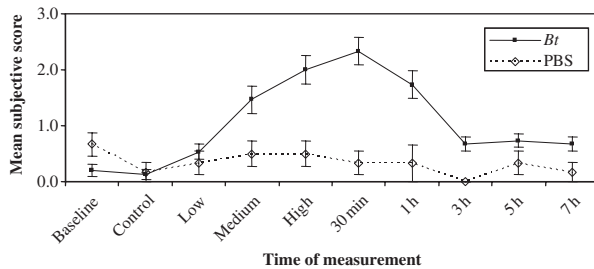
All study subjects completed the study.

Subjective nasal symptoms

Figure 1 shows the mean nasal ($\pm$ SD) symptom scores before and after NAC with control solution (PBS) and *Bt*. There was a dose–response increase in nasal obstruction score after *Bt* challenges with a maximal blockage (mean score of 2.33 ± 0.25) at 30 min after challenge. There was a significant difference ($P = 0.025$) between the two groups with the study subjects experiencing a significant change over time ($P = 0.011$) but not the controls (time $\times$ group interactions, $P = 0.002$).

AR area–distance measurements

Figure 2 shows the mean ($\pm$ SD) of MCA, distance to MCA, CSA3.3, CSA4.0 and CSA6.4 measurements at different time-points after nasal challenge with *Bt* and control solution. For mMCA, mCSA3.3 and mCSA4.0, reduction of CSAs after



Differences between case and control: $P = 0.025$
 Time trend: $P = 0.011$
 Time & group interaction: $P = 0.002$.

Fig. 1. Mean subjective symptom score of nasal obstruction before and after *Blomia tropicalis* (Bt, $n = 15$) and control (phosphate-buffered saline (PBS), $n = 6$) challenge.

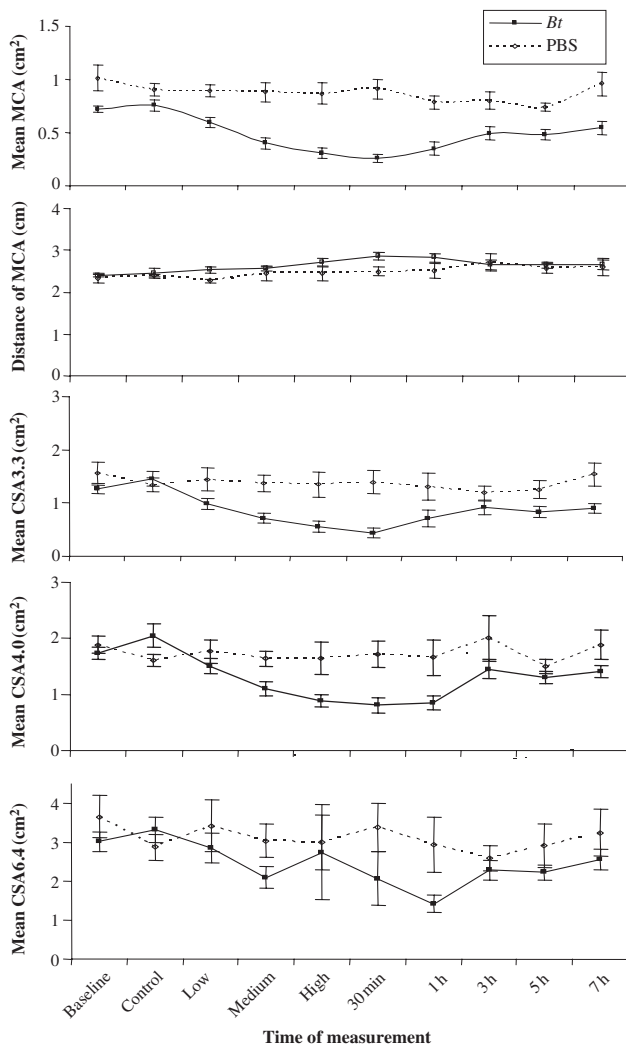


Fig. 2. Mean values ($\pm$ SD) of minimum cross-sectional area (MCA), cross-sectional area (CSA)3.3, CSA4.0 and CSA6.4 after nasal challenge with house dust mite *Blomia tropicalis* (Bt, $n = 15$) and control solution (phosphate-buffered saline (PBS), $n = 6$).

nasal challenges with Bt are confirmed by statistically significant differences as compared with control challenge, as well as time trend and time $\times$ group interactions (Table 1). Maximal reduction of mean MCA (0.26 cm^2) is associated with the

maximal increase of mean distance to MCA (2.86 cm) at 30 min after NAC.

CV at different CSAs is shown in Table 2. The variation at mCSA6.4 is more varied as compared with the other area measurements as shown by the larger mean CV with a twice as large standard error and wider range (minimal and maximal values).

Relationship between nasal symptom scores and AR area-distances

Spearman's correlation was performed to investigate the relationship between the subjective symptom score of nasal obstruction and objective measurements of AR; see Fig. 3. There is an inverse relationship between symptoms score and MCA ($r = -0.568$, $P < 0.001$). Although there are significant correlations between nasal obstruction scores and all four area-distance measurements, it appears that the strongest relationship is found between nasal symptom score and mMCA ($r = 0.75$), and followed by mCSA3.3 ($r = 0.54$), mCSA4.0 ($r = 0.53$) and mCSA6.4 ($r = 0.20$). The correlations between MCA and the other three area-distance measurements are shown in Table 3. Once again, the CSA6.4 measurement differs largely from other area measurements in terms of their relationship with nasal obstruction score and MCA.

Influence of constriction of MCA ($< 0.2 \text{ cm}^2$) on area-distances beyond MCA

It was reported that in normal adults the CSA of the nasal valve is $0.2\text{--}0.6 \text{ cm}^2$. As the constriction narrows ($< 0.2 \text{ cm}^2$) the area and volume measurements beyond this point are often underestimated [12]. To test this hypothesis, we divided MCA (left and right separately) into two groups; < 0.2 and $\geq 0.2 \text{ cm}^2$ as measured during the time course of NAC (Table 4), and compared the corresponding area measurements (CSA3.3, CSA4.0 and CSA6.4) beyond the MCA. Results showed that when the MCA reached an area $< 0.2 \text{ cm}^2$, measurements of CSA3.3 and CSA4.0 were reduced by 60–70%.

Discussion

Nasal obstruction is one of the predominant symptoms of allergic rhinitis that can be registered subjectively and objectively [20]. It can be measured by sensation of nasal obstruction, nasal airflow and resistance induced by airflow, and CSA at various distances. AR is a static test of nasal luminal dimensions, which is independent of airflow [21]. Given the area-distance variation, different parameters can be determined; the common AR measurements are MCA, CSA at distances of 3.3, 4.0 and 6.4 cm from the nostril, which represent nasal valve, the anterior end of inferior turbinate, mid-portion of the inferior turbinate (or the anterior end of the middle turbinate) and the posterior nasal cavity, respectively [2–7, 18, 19, 22, 23]. However, standardization of measurements, sources of error and physical limitations of AR measurements have not been adequately evaluated.

The nasal valve region (the primary airway resistor) is considered to be a site of major pathophysiological concern [21]. However, the location and nature of the nasal valve is still not

Table 1. Statistical comparisons between nasal challenge with *Bt* ($n = 15$) and control solutions (PBS, $n = 6$) in different time of measurements

	Mean CSAs in distance									
	MCA (cm ²)		<i>D</i> (cm)		CSA3.3 (cm ²)		CSA4.0 (cm ²)		CSA6.4 (cm ²)	
	<i>Bt</i>	PBS	<i>Bt</i>	PBS	<i>Bt</i>	PBS	<i>Bt</i>	PBS	<i>Bt</i>	PBS
Time of measurements										
Baseline	0.72	1.01	2.39	2.33	1.26	1.57	1.74	1.88	3.02	3.65
Control	0.76	0.90	2.47	2.39	1.45	1.34	2.04	1.61	3.32	2.88
Low*	0.60	0.89	2.53	2.27	0.99	1.45	1.51	1.77	2.85	3.42
Medium*	0.40	0.88	2.58	2.44	0.72	1.37	1.10	1.64	2.10	3.04
High*	0.31	0.87	2.73	2.44	0.55	1.35	0.89	1.64	2.75	2.99
30 min	0.26	0.91	2.86	2.49	0.44	1.39	0.81	1.72	2.07	3.38
1 h	0.35	0.79	2.82	2.51	0.71	1.30	0.85	1.65	1.43	2.94
3 h	0.49	0.80	2.66	2.72	0.91	1.19	1.45	2.00	2.28	2.59
5 h	0.48	0.74	2.64	2.57	0.83	1.25	1.31	1.50	2.23	2.91
7 h	0.54	0.96	2.67	2.60	0.90	1.54	1.41	1.88	2.56	3.25
Statistical comparisons (<i>P</i> -value)										
Between groups	<0.001		0.184		0.008		0.038		0.281	
Time trend	<0.001		<0.001		<0.001		<0.001		0.45	
Time × group interaction	<0.001		0.306		<0.001		<0.001		0.757	

*Nasal challenge with increasing concentrations of *Bt*. *Bt*, *Blomia tropicalis*; PBS, phosphate-buffered saline; CSA, cross-sectional area; MCA, minimum cross-sectional area.

Table 2. Coefficient of variation at different CSAs (cm²)

Area in distance (cm)	Coefficient of variation				
	Mean	Standard error	Minimum	Maximum	Median
MCA	0.47	0.06	0.23	0.76	0.45
CSA3.3	0.52	0.06	0.28	0.82	0.47
CSA4.0	0.42	0.05	0.24	0.64	0.39
CSA6.4	0.61	0.11	0.35	1.45	0.46

Calculations were based on a total of 420 measurements; nasal challenges with *Blomia tropicalis* ($n = 15$) and control solution ($n = 6$) at 10 different time of measurements, right and left sides. $P = 0.533$ (Kruskal–Wallis test). CSA, cross-sectional area; MCA, minimum cross-sectional area.

Table 3. Interrelationships of acoustic rhinometry area–distance measurements, and their relationship with the subjective nasal obstruction scores

Area in distance (cm)	Coefficient correlation	
	MCA	Nasal obstruction scores
MCA*	–	0.75 ($P < 0.001$)
CSA3.3	0.807 ($P < 0.001$)	0.54 ($P < 0.001$)
CSA4.0	0.631 ($P < 0.001$)	0.53 ($P < 0.001$)
CSA6.4	0.359 ($P < 0.001$)	0.20 ($P < 0.001$)

Calculations were based on a total of 420 measurements; nasal challenges with *Blomia tropicalis* ($n = 15$) and control solution ($n = 6$) at 10 different time of measurements, right and left sides. MCA, minimum cross-sectional area; CSA, cross-sectional area.

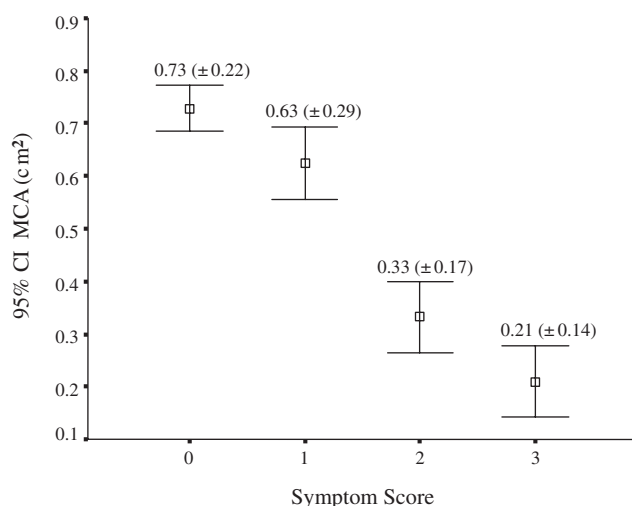


Fig. 3. Correlation between minimum cross-sectional area (MCA) and symptom score. Spearman's correlation: $r = -0.568$ ($P < 0.001$). Values shown on the graph are mean ($\pm$ SD) of minimum cross-sectional area (MCA). Calculations were based on a total of 420 measurements; nasal challenges with *Blomia tropicalis* ($n = 15$) and control solution ($n = 6$) at 10 different times of measurements, right and left sides.

clear. The nasal cavity conforms to a slit-like shape due to three turbinates. This structure is physiologically important since it creates a turbulent inspiratory air stream and provides two-thirds of the total respiratory resistance. Some authors suggest that the nasal valve consists of the slit-like opening between the caudal end of the upper lateral cartilage and nasal septum, while others suggest it is composed of the caudal nasal septum, the caudal end of the upper lateral cartilage, the head of the inferior turbinate, and the remaining tissues surrounding the piriform aperture [22, 24]. It would appear that the nasal valve is a functional region rather than an area [21].

MCA is the most frequently used AR determinant. In some subjects the MCA is located at the nasal valve while in others, especially in cases of turbinate hypertrophy, it is the anterior part of the inferior turbinate [9]. Our data showed a mean ($\pm$ SD) baseline MCA of 0.72 ± 0.12 cm² at a distance of 2.39 ± 0.16 cm that decreased rapidly to a minimum value of 0.26 ± 0.14 cm² at a distance of 2.86 ± 0.31 cm 30 min after NAC. Under normal conditions, the MCA represents a narrow lumen of the functional valve, which is anterior

Table 4. Frequency of MCA (right and left, $n = 30$) less than 0.2 cm^2 at different time of measurements and its influence on the measurements of CSA (3.3, 4.0 and 6.4 cm) beyond this point

		MCA $< 0.2 \text{ cm}^2$					MCA $\geq 0.2 \text{ cm}^2$		
		Distance–area (cm^2)					Distance–area (cm^2)		
	n	CSA3.3	CSA4.0	CSA6.4	n	CSA3.3	CSA4.0	CSA6.4	
Baseline	0	–	–	–	30	–	–	–	
Control	0	–	–	–	30	–	–	–	
Low†	1	0.08	0.13	2.21	29	1.02	1.55	2.87	
Middle†	6	0.25*	0.58*	2.05	24	0.83	1.23	2.11	
High†	15	0.26**	0.6**	3.64*	15	0.85	1.18	1.86	
30 min	13	0.19**	0.52**	2.34*	17	0.64	1.02	1.86	
1 h	11	0.35**	0.37**	0.78**	19	0.92	1.13	1.80	
3 h	4	0.25**	0.57*	1.02*	26	1.02	1.59	2.48	
5 h	5	0.35*	0.76*	1.47	25	0.93	1.42	2.39	
7 h	5	0.25**	0.67**	1.23*	25	1.03	1.56	2.82	

* $P < 0.05$, ** $P < 0.01$. †Nasal challenge with increasing concentrations of *Blomia tropicalis* (Bt).

(approximate 0.91 cm) to the anterior end of the inferior turbinate (at the distance of CSA3.3 cm). During allergic reactions, it moves more posteriorly to the anterior end of the inferior turbinate due to the dilative reaction of the capacitance vessels of the erectile tissue. There is an inverse relationship between symptoms score and MCA. With subjective symptom scores of zero and one, there was a wider range of MCA that corresponded well with a wide variation of normal nasal cavity dimensions. Interestingly, MCA range is more specific with pathological conditions causing severe nasal obstruction (scores 2 and 3) (Fig. 3).

There are some physical limitations or errors associated with the algorithms used in AR: (1) sinus ostium size, sinus volume or CSA in the distal parts (approximately $5\text{--}10 \text{ cm}$ into the nasal cavity) of the nasal cavity [10]. (2) A significant constriction in the nasal valve area will affect the area and volume measurements beyond this point [11, 12]. (3) Distortion of the vestibule with the nasal tip adapter and anatomical variations of the columella, which changes the 0 reference points [22]. In addition, erectile tissue in the nose, especially the inferior turbinates, fluctuates greatly in size depending on physiological changes (e.g., nasal cycle, body temperature, posture and exercise) and response to inflammation. A spontaneous fluctuation in nasal patency can be documented every 10 min with irregular patterns, frequency and amplitude in healthy and allergic individuals [17]. All these factors have to be taken into account when using AR as an investigational tool in different studies.

Using nasal cavity models, two experimental studies have demonstrated that the measurement of both CSA and volume beyond a constriction area of less than 0.2 or 0.28 cm^2 will cause significant systemic errors [11, 12]. Following our data, a constriction of less than 0.2 cm^2 at the MCA caused a significant underestimation (60–70%) of the CSA measurements (Table 4). This is particularly important when using AR in a nasal challenge study, which may cause severe nasal obstruction during the early-phase reaction. In a previous report, Phipatanakul et al. [8] used the MCA and nasal cavity volumes measured at $0\text{--}5$ and $5\text{--}10 \text{ cm}$ from the nostril during the acute airway response to cat allergen exposure. The authors concluded that although AR does provide an objective

measure of nasal response to allergen exposure, it has significant limitations due to the lack of correlation with symptoms, the inability to measure a dose response, and the changes noted even among the control subjects. However, this unexpected result could be due to the uncorrected volume measurements since the MCA reported was very low ($< 0.1 \text{ cm}^2$) after cat allergen exposure.

Among all the measures of CSA in this study, CSA6.4 was found to be least reliable, with a high CV compared with the other measurements and did not show a significant difference between Bt and control groups. It was reported that the effects of paranasal sinuses and low-frequency acoustic resonances in the posterior part of the nasal cavity are not accounted for in the current AR algorithms [10]. Areas between 5 and 10 cm may be influenced by the sinuses and especially the ostia connecting them with the nasal cavity [25]. It is important to note that all possible sources of errors and physical limitations have to be considered when using AR as an investigational tool in the study of nasal physiology and pathophysiology in various clinical and experimental settings.

In conclusion, AR has proved to be a useful and objective investigational tool in the evaluation of nasal physiology and pathophysiology. Among the AR area–distance measurement parameters, MCA appears to be the most sensitive and correlates well with the sensation of nasal obstruction. When MCA is smaller than 0.2 cm^2 , a common condition especially in the early-phase reaction after NAC, other distal measurements beyond this point can be underestimated and should be ignored.

Acknowledgement

The authors thank Prof. James D. Smith for kindly reviewing the paper.

Reference

- 1 Bousquet J, Van Cauwenberge P, Khaltaev N. Allergic rhinitis and its impact on asthma (ARIA) (ARIA Workshop Report). *J Allergy Clin Immunol* 2001; 108:S147–334.

- 2 Hilberg O, Jackson AC, Swift DL, Pedersen OF. Acoustic rhinometry: evaluation of nasal cavity geometry by acoustic reflection. *J Appl Physiol* 1989; 66:295–303.
- 3 Hilberg O, Grymer LF, Pedersen OF. Nasal histamine challenge in nonallergic and allergic subjects evaluated by acoustic rhinometry. *Allergy* 1995; 50:166–73.
- 4 Malm L, Gerth van Wijk R, Bachert C. Guidelines for nasal provocations with aspects on nasal patency, airflow, and airflow resistance. International Committee on Objective Assessment of the Nasal Airways, International Rhinologic Society. *Rhinology* 2000; 38:1–6.
- 5 Ganslmayer M, Spertini F, Rahm F, Terrien MH, Mosimann B, Leimgruber A. Evaluation of acoustic rhinometry in a nasal provocation test with allergen. *Allergy* 1999; 54:974–9.
- 6 Terrien MH, Rahm F, Fellrath JM, Spertini F. Comparison of the effects of terfenadine with fexofenadine on nasal provocation tests with allergen. *J Allergy Clin Immunol* 1999; 103:1025–30.
- 7 Roithmann R, Shpirer I, Cole P, Chapnik J, Szalai JP, Zamel N. The role of acoustic rhinometry in nasal provocation testing. *Ear Nose Throat J* 1997; 76:747–50.
- 8 Phipatanakul W, Kesavanathan J, Eggleston PA, Johnson EF, Wood RA. The value of acoustic rhinometry in assessing nasal responses to cat exposure. *J Allergy Clin Immunol* 1998; 102:896–901.
- 9 Hilberg O. Objective measurement of nasal airway dimensions using acoustic rhinometry: methodological and clinical aspects. *Allergy* 2002; 57:5–39.
- 10 Cakmak O, Celik H, Cankurtaran M, Buyuklu F, Ozgirgin N, Ozluoglu LN. Effects of paranasal sinus ostia and volume on acoustic rhinometry measurements: a model study. *J Appl Physiol* 2003; 94:1527–35.
- 11 Cankurtaran M, Celik H, Cakmak O, Ozluoglu LN. Effects of the nasal valve on acoustic rhinometry measurements: a model study. *J Appl Physiol* 2003; 94:1527–35.
- 12 Hamilton JW, Cook JA, Phillips DE, Jones AS. Limitations of acoustic rhinometry determined by a simple model. *Acta Otolaryngol* 1995; 115:811–4.
- 13 Yi FC, Chew FT, Jimenez S, Chua KY, Lee BW. Culture of *Blomia tropicalis* and IgE immunoblot characterisation of its allergens. *Asian Pacific J Allergy Immunol* 1999; 17:189–94.
- 14 Wang DY, Goh DYT, Ho AKL, Chew FT, Yeoh KH, Lee BW. The upper and lower airway responses to nasal challenge with house dust mite *Blomia tropicalis*. *Allergy* 2003; 58:78–82.
- 15 Wang DY, Duyck F, Smits J, Clement P. Efficacy and onset of action of fluticasone propionate aqueous nasal spray on nasal symptoms, eosinophil count, and mediator release after nasal allergen challenge in patients with seasonal allergic rhinitis. *Allergy* 1998; 53:375–82.
- 16 Huang ZL, Wang DY, Zhang PC, Dong F, Yeoh KH. Evaluation of nasal cavity by acoustic rhinometry in Chinese, Malay and Indian ethnic groups. *Acta Otolaryngol* 2001; 121:844–8.
- 17 Huang ZL, Ong KL, Goh SY, Liew HL, Yeoh KH, Wang DY. Assessment of nasal cycle by acoustic rhinometry and rhinomanometry. *Otolaryngol Head Neck Surg* 2003; 128:510–6.
- 18 Grymer LF, Hilberg O, Pedersen OF, Rasmussen TR. Acoustic rhinometry: values from adults with subjective normal nasal patency. *Rhinology* 1991; 29:35–47.
- 19 Jang YJ, Lee JH, Jang JY. Acoustic rhinometric evaluation of the nasal response to exercise in patients with nasal septal deviation. *Clin Otolaryngol* 2000; 25:423–7.
- 20 Wang D, Clement P. Assessment of early and late phase nasal obstruction in atopic patients after nasal allergen challenge. *Clin Otolaryngol* 1995; 20:368–73.
- 21 Cole P. Acoustic rhinometry and rhinomanometry. *Rhinology* 2000; 16 (Suppl.):29–34.
- 22 Corey JP, Nalbone VP, Ng BA. Anatomic correlates of acoustic rhinometry as measured by rigid nasal endoscopy. *Otolaryngol Head Neck Surg* 1999; 121:572–6.
- 23 Corey JP, Gungor A, Nelson R, Fredberg J, Lai V. A comparison of the nasal cross-sectional areas and volumes obtained with acoustic rhinometry and magnetic resonance imaging. *Otolaryngol Head Neck Surg* 1997; 117:349–54.
- 24 Kasperbauer JL, Kern EB. Nasal valve physiology. Implications in nasal surgery. *Otolaryngol Clin North Am* 1987; 20:699–719.
- 25 Hilberg O, Pedersen OF. Acoustic rhinometry: recommendations for technical specifications and standard operating procedures. *Rhinology* 2000; 16 (Suppl.):3–17.