Measurement of Respiratory Resistance in the Emergency Department*

Feasibility in Young Children With Acute Asthma

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**Objectives:** To assess, in acutely ill asthmatic children, the feasibility of obtaining reproducible measurements of two independent lung function tests, namely spirometry and respiratory resistance, using the forced oscillation technique (Rfo).

**Design/setting:** A prospective observational study of 150 previously untrained children, aged 2 to 17 years, treated for acute asthma in a tertiary-care pediatric emergency department.

**Measurements:** Following a standardized physical examination, three measurements of respiratory resistance by forced oscillation were attempted at 8 Hz (Rfo₈) and at 16 Hz (Rfo₁₆), followed by spirometry, all using the same instrument (Custo Vit R; Custo Med; Munich, Germany).

**Results:** On the initial assessment, 98 (65%) children, aged 2 to 17 years, were able to reproducibly perform the Rfo₈ measurement, 77 (51%) were able to reproducibly perform the Rfo₁₆ measurement, while only 65 (43%) subjects managed to reliably perform spirometry. A notable proportion of preschool-aged children cooperated with the Rfo₈ technique: 19% of 3-year-olds, 40% of 4-year-olds, and 83% of 5-year-olds. The superior success rate with Rfo₈ as compared with spirometry was seen in all age groups but was most striking both in preschoolers (relative risk [RR]=10.5; 95% confidence interval [CI], 8.0 to 13.8) and in children aged 6 to 9 years (RR=1.28; 95% CI, 1.18 to 1.39). Rfo₈ values correlated significantly with clinical markers of asthma severity such as respiratory rate (r=0.38) and heart rate (r=0.23) as well as with FEV₁ values (r²=0.73).

**Conclusions:** This study demonstrates the feasibility of obtaining reproducible measurements of respiratory resistance in a notable proportion of untrained, acutely ill, asthmatic children. The forced oscillation technique appears as an attractive alternative to objectively assess lung function in children too young or too ill to cooperate with spirometry. *(CHEST 1997; 111:1519-25)*

**Key words:** asthma; child; emergency care; oscillatory resistance; respiratory resistance; spirometry

**Abbreviations:** CI=confidence interval; ED=emergency department; PEF=peak expiratory flow; Rfo=respiratory resistance measured by forced oscillation; RR=relative risk

One of the major challenges for physicians caring for young children with asthma is how to measure objectively the severity of pulmonary dysfunction. In therapeutic trials in which the severity of the disease process needs to be appraised, the identification of a valid and objective means of assessing the lung function is critical.¹⁻³ Spirometry is the standard measurement technique used for school-aged children.⁴ Younger children, however, are frequently excluded from therapeutic studies, largely because of their inability to reliably perform reproducible spirometry or peak expiratory flows (PEFs).⁵⁻⁹ It is questionable whether the study results obtained in older children can be extrapolated to preschool-aged children without direct confirmation of findings. Yet preschool-aged children typically constitute over half of asthmatics presenting to a pediatric emergency department (ED).¹⁰ Therefore, an objective means of assessing asthma severity in young children would allow intervention studies to focus on this important subgroup.

A number of tests for measuring lung function in infants and young children has been developed. These include static mechanics using Hering-Breuer...
reflex, forced expiratory flows with rapid compression technique, analyses of tidal flow patterns, gas mixing indexes, and the interrupter technique.\textsuperscript{11-14} Most of these techniques remain technically difficult and require heavy sedation, which is a major inconvenience in the study of acute asthma in the ED. An alternative, noninvasive, effort-independent technique, the measurement of respiratory system resistance by forced oscillation (Rfo), can be obtained at bedside in children as young as 3 years old.\textsuperscript{15-18} The oscillatory technique is easier to perform than spirometry or PEFs inasmuch as only quiet breathing is required for the measurements. There is a strong correlation (r=0.81 to 0.83) between the Rfo measured at 6 to 8 Hz and airway resistance measured by whole body plethysmography.\textsuperscript{19-21} The Rfo is reported to be as sensitive as FEV, FVC, and midexpiratory flow rate in detecting airway obstruction.\textsuperscript{22-24} Rfo measurements have been successfully used in bronchial challenge testing in children as young as 3 years of age\textsuperscript{25-26} and in adults.\textsuperscript{19-21} Although the validity of this technique has been clearly established, to our knowledge, there are as yet no data on the success rate of obtaining Rfo measurements in untrained, acutely ill children.

The objective of this study was to determine the feasibility of obtaining reproducible Rfo measurements in untrained children during an asthma exacerbation. More specifically, we wished to (1) compare the proportions of acutely ill children in whom reproducible measurements were obtained with the Rfo and the spirometry techniques and (2) describe the relationship between Rfo and other indexes of asthma severity. The study was designed to simulate the context in which patients would be recruited for a clinical trial of asthma management in the emergency setting.

\section*{Materials and Methods}

\subsection*{Design}

We conducted a cross-sectional study of children aged 2 to 17 years presenting with an asthma exacerbation to the ED of the Montreal Children’s Hospital from April to November 1991. The protocol was reviewed and approved by the Institutional Review Board, and informed consent for participation in the study was obtained from parents or guardians.

\subsection*{Subjects}

Patients were eligible to participate if they had a clinical diagnosis of asthma confirmed by an emergency physician in accordance with the criteria of the American Thoracic Society,\textsuperscript{27} the need for at least one treatment with nebulized salbutamol, and were available for two successive assessments, presalbutamol and postsalbutamol, in the ED. The requirement for the two successive assessments was an essential element of the evaluation of the ability of Rfo to detect changes over time (the object of another report). Patients were excluded if they had one or more of the following: another chronic pulmonary disease (such as cystic fibrosis or bronchopulmonary dysplasia), cardiac dysrhythmia or anatomic abnormalities, neuromuscular disease, acute laryngitis, radiologically proved pneumonia, or history of premature birth. Furthermore, patients could be enrolled only once in the study to avoid nonindependence of subjects.

\subsection*{Procedures}

Baseline data, including age, sex, race, height, asthma history, and clinical assessments were ascertained for each participant by a trained research nurse. The initial assessment was usually obtained on arrival in the ED before any nebulized treatment. Each assessment consisted of a standardized clinical examination including the following: the measurement of respiratory and heart rates; the scoring of accessory muscle use (0=absent, 1=present, or 2=prominent), wheezing (0=absent, 1=expiratory only, 2=inspiratory and expiratory, and 3=audible without stethoscope), and air entry (0=normal, 1=decreased at bases, 2=widespread decrease, and 3=minimal/absent); a severity rating of the exacerbation, by the research nurse, on a Likert\textsuperscript{28} scale of 1 to 5; the measurement of transcutaneous oxygen saturation (Nellcor N10; Nellcor Inc; Hayward, Calif); three consecutive measurements of Rfo at 8 Hz (Rfo8) and at 16 Hz (Rfo16); and routine spirometry obtained on a portable device (Custo Vit B; Custo Med; Munich, Germany), permitting both Rfo at fixed frequencies and spirometry measurements.

Respiratory resistance measurements were obtained by imposing a sinusoidal pressure wave at two fixed frequencies (8 Hz and 16 Hz) on the airflow during quiet tidal breathing. For the measurements, the child was seated comfortably (sometimes on the parent’s lap), positioned with the head in a slightly extended position, and instructed to breathe quietly through an appropriately sized mouthpiece connected to a tube with known resistance. The child’s cheeks were supported and the nose occluded with standard nose clips to minimize the upper airway artifact. Fixed sinusoidal pressure oscillations were applied at the mouth by a piston pump that developed less than 0.02 kPa differential during normal tidal breathing. Each recording yielded the average respiratory resistance measured over the entire respiratory cycle during a 15- to 20-s period. The visual display of the tidal volume trace allowed rapid recognition of an irregular breathing pattern caused by partial airway obstruction from glottic narrowing or malposition of the tongue or an air leak through the nostrils or mouth. Following recognition of an irregular breathing pattern or air leak, the recording was stopped and measurements discarded. Three technically valid measurements of respiratory resistance were sequentially obtained at 8 and 16 Hz. Spirometry was then attempted using the same device and position. The best results for FVC, FEV, and PEF from three flow-volume curves were recorded.\textsuperscript{4} A maximum of six measurements were attempted to document reproducibility with Rfo\textsubscript{8}, Rfo\textsubscript{16}, and spirometry, irrespective of the success or failure with the preceding technique. Because of the reflex changes in airway smooth muscle tone occasionally induced by forced expiratory maneuver, respiratory resistance was systematically obtained before spirometry.\textsuperscript{29-31}

\subsection*{Forced Oscillation Technique}

The forced oscillation technique was previously described in detail by Simm.\textsuperscript{21} Briefly, the sinusoidal pressure oscillations superimposed on the spontaneous breathing of subjects enter the
respiratory tract via the mouthpiece. Depending on the level of respiratory resistance, the reflected airflow generates an oscillatory pressure. The pressure and flow are registered at the mouth with differential pressure transducers and pneumotachograph. By dividing pressure by flow (Z=[(Pos-Vos)]), the system calculates an impedance value. All measurements obtained over the 15- to 20-s sampling period are averaged without filtering. For the respiratory system, R represents the effective resistance of airways, lungs, and thorax and X represents the net effect of two opposite (a compliant and an inertial) components. The estimation of R depends on the phase angle θ between pressure and flow. A simple model (R=Z×cos θ) allows the conversion of the impedance's information (Z) to the respiratory resistance (R).

Definitions

Reproducibility with Rfo was classified as follows: good in children who performed at least two measurements with a coefficient of variation of ≤0.15,²⁰,²³,²⁴ poor in children with a coefficient of variation of repeated measurements >0.15; or absent in patients who refused, or were unable, to breathe without a leak in the mouthpiece. For spirometry, reproducibility was rated as good in children who fulfilled the American Thoracic Society’s criteria, or absent.² Success with either technique referred exclusively to patients who demonstrated good reproducibility.

Statistical Analysis

We performed bivariate analyses to identify the determinants of success with each technique, using the unpaired Student’s t test for continuous variables and the χ² test for categorical variables. A multivariate logistic regression was performed to examine the relative contribution of various factors to the children’s ability to successfully perform the measurements. After stratifying for age, we then used proportions to describe the success rate with each technique. McNemar relative risk (RR) and confidence intervals (CIs) were used to compare the success rates with spirometry and Rfo. The relationship between Rfo and other indexes of asthma severity was described with the Pearson correlation coefficient. A value of p<0.05 was accepted as indicating statistical significance. Results are expressed as the median (interquartile range [D1,D3], that is, the values of the 25% and the 75% percentiles).

Results

Of the 208 patients approached, 44 children were excluded because of the following: (1) the inability to perform the second assessment before discharge in 14 children, all of whom cooperated with Rfo; (2) exclusion criteria in 19 patients; and (3) the previous participation in this study of 11 subjects. The participation rate was 92% (150 subjects) for the remaining 164 eligible patients (Table 1). The median percent height-adjusted FEV₁ and Rfo₈ values were indicative of moderate obstruction at baseline. Half of participants (n=77) were preschoolers, that is, between the ages of 2 and 6 years.

On the initial assessment in the ED, 24% (n=36) of patients were unable to breathe regularly without a leak at, or partial obstruction of, the mouthpiece during the Rfo₈ measurements; the median age of these uncooperative patients was 3 years, significantly younger than those who were unable to cooperate with Rfo₁₆ and spirometry (Table 2). Ninety-eight (65%) of 150 children demonstrated good reproducibility with Rfo₈ measurements, while 77 (51%) could also reproducibly perform the Rfo₁₆. However, only 65 (43%) were able to perform both the oscillatory (Rfo) and spirometric (FEV₁, FVC, PEF) measurements. All children who reproducibly performed spirometry also cooperated with Rfo. Because the Rfo values are of clinical use when reproducible, the following data refer only to patients with good reproducibility with Rfo measurements.

The single most important predictor of reproducibility with the measurements of Rfo₈ and Rfo₁₆ was age. Once age was considered in the logistic model, other variables, such as sex, race, heart and respiratory rates, severity rating, initial oxygen saturation, percent predicted FEV₁, and Rfo₈ were not significant factors. Figure 1 depicts the age-stratified success rate for each technique. As might be expected, none of the 2-year-olds were able to cooperate with

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<th>Table 1—Characteristics of the 150 Participants*</th>
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*Data are presented as median (25%, 75%) unless indicated otherwise.

1Air entry score ranges from 0 (normal) to 3 (minimal/absent).
2Wheezing score ranges from 0 (none) to 3 (audible without a stethoscope).
3Severity rating measured on a Likert scale of 1 (mildest) to 5 (most severe).
4Height-adjusted percent predicted Rfo₈ are based on normative values for Rfo16. This approximation of Rfo₈ slightly overestimates the severity of the airway dysfunction.
any method of measurement. However, the rate of success with Rfo₈ measurement reached 83% for the 5-year-olds. The superior cooperation with Rfo₈ as compared with spirometry was seen in all age groups, but was most striking both in the preschool-aged patients (RR=10.5; 95% CI, 8.01 to 13.76) and the children aged 6 to 9 years (RR=1.28; 95% CI, 1.18 to 1.39), than in those aged 10 years or older (RR=1.18; 95% CI, 1.09 to 1.25). The success rate with Rfo₁₆ measurement did not significantly exceed that with spirometry in any age group.

Values of Rfo₈ and Rfo₁₆, obtained on the initial assessment, correlated significantly with respiratory rate (r=0.38 and 0.33, respectively; p<0.002) and heart rate (r=0.23 and 0.27; p<0.01). Applying the reference values of Lebecque et al.²² the percent predicted Rfo₈ values also correlated significantly with the air entry score (r=0.28; p<0.005), intercostal retractions (r=0.23; p<0.05), nurse’s severity rating of the exacerbation (r=0.41; p<0.001), and oxygen saturation (r=−0.20; p<0.05), but not with wheezing. We observed a significant logarithmic inverse relationship between Rfo₈ and FEV₁ values (r²=0.73), as illustrated in Figure 2, top. Logarithmic inverse relationships of similar magnitude were also observed between Rfo₈ and both FVC and PEF (r²=0.69 to 0.71), as well as between Rfo₁₆ and FEV₁ (Fig 2, bottom), FVC, and PEF (r²=0.58 to 0.67).

**DISCUSSION**

Our study demonstrates that the technique of forced oscillation can be successfully used to measure respiratory resistance in previously untrained preschool children, aged 3 years and older, with an asthma exacerbation. In children aged 4 and 5 years, we observed the noticeable success rates of 40% and 83%, respectively, with the Rfo₈ measurement, but only 0% and 17%, respectively, with spirometry. The high level of cooperation for Rfo₈ was sustained in the 6- to 9-year-olds (76%) and the ≥10-year-olds (89%), which compares again favorably to those observed with spirometry (59% and 76%, respectively).

The Rfo technique requires at least minimal cooperation on the part of the child, inasmuch as a regular pattern of breathing with a constant tidal volume is required for the measurements. The two most frequent reasons for noncooperation with Rfo₈ in our youngest children were refusal to use a mouthpiece and inability to breathe without a leak at the mouthpiece. Only rarely were data not recorded because of an irregular breathing pattern. The assessment of acutely ill children aged 2 to 3 years remains difficult. In contrast, it was possible to measure the Rfo₈ in a substantial proportion of 4- and 5-year-old acutely ill children—a group in whom cooperation with spirometry or peak flowmeter measurement is extremely difficult to obtain. This cooperation is even more remarkable in that none of our patients had had experience with the measurement of respiratory resistance by forced oscillation prior to the index exacerbation.

We speculate that the difference between the
cooperation rates for the Rfo, and Rfo, measurements, as depicted in Table 2, can be attributed to the frequency difference. The preschool-aged children had more difficulty breathing against the imposed 16-Hz oscillations, possibly because of a decrease in elastic recoil pressure gradient with incomplete expiration and dynamic hyperinflation of the lung. Dynamic hyperinflation was suggested by an upward drift of the tidal volume signal on the machine (Custo Vit R). Many of the young children could not tolerate the imposed 16-Hz oscillations. The measurements were spontaneously terminated by the child coughing or removing the mouthpiece, or by the technician noticing a change in breathing pattern. The presence of deterioration in subsequent lung function measurements suggest a transient nature of the postulated phenomenon. Such phenomenon was not observed, however, at the 8-Hz frequency. Although the inability to obtain respiratory measurements at 16 Hz in some preschool-aged children may appear inconsequential, the possibility of a transient deterioration in lung function cannot be excluded. We therefore advise caution in performing respiratory measurements at higher frequencies in preschool-aged children during an exacerbation, until this phenomenon is further clarified.

To our surprise, children aged 6 years and older were also significantly more likely to cooperate with the measurement of Rfo, than with spirometry. In reviewing recent therapeutic trials conducted in asthmatic children, we could not determine the proportion of otherwise eligible patients excluded because of their inability to perform reproducible spirometric measurements. Based on our study, it is reasonable to estimate, however, that approximately 40% of children aged 6 to 9 years and 25% of those aged 10 years and older would be excluded from participation in a clinical trial in which spirometry served as the objective measure of asthma severity. Thus, the use of the oscillatory resistance as an outcome variable would present a distinct advantage over spirometry. This technique allows not only for the recruitment of preschool-aged children, but also for the evaluation of a more representative sample of children aged 6 years and older.

The validity of the Rfo measurement in the assessment of airway function has been established previously in comparison with measurements obtained with body plethysmography and with spirometry. Moreover, the strong correlation between Rfo, and other clinical variables indicative of the severity of airway dysfunction, such as heart rates, air entry score, transcutaneous oxygen saturation, and severity rating, further supports the value of this measurement in acutely ill preschool-aged children. In school-aged subjects, we observed a significant logarithmic inverse relationship between the Rfo, and the FEV1 values at baseline. An important proportion of the variation in Rfo, (r = 0.73) and, to a lesser extent, in Rfo, (r = 0.64) was explained by the relationship with FEV1 (Fig 2). In other words, one could reasonably predict the Rfo, of a given patient from the FEV1 value. To our knowledge, the relationship between Rfo and FEV1 has not been reported previously in children during an acute asthma exacerbation. However, inverse linear relationships of similar magnitude (r = 0.49 to 0.76) between FEV1 and Rfo

**Figure 2.** Logarithmic inverse relationship between the Rfo (in kilopascals/liter/second) and FEV1 (in liters) measurements obtained on the initial assessment: top (A): Rfo, and FEV1 (n = 65; r = 0.73); bottom (B): Rfo, and FEV1 (n = 65; r = 0.64). In contrast with FEV1, Rfo values increase with severity.
measured at 6, 10, and 12 Hz have been described in healthy children and in patients with normal baseline FEV \(_1\) values.\textsuperscript{24,25,30,37} Our study appears, then, to be the first report of the relationship between Rf0\(_8\) and FEV \(_1\) in children with acute asthma and compares favorably with previous reports concerning healthy individuals and patients with stable asthma.

**Limitations**

The generalization of the results of this study to other populations is an important issue. There is no a priori reason to believe that children presenting to other emergency care facilities with asthma exacerbations of comparable severity would show markedly different cooperation rates with Rf0. In contrast, the cooperation rate with spirometry is likely to be influenced by the proportion of children who have performed the technique previously, a variable not documented in our patients. We recognize that the experience of the “technician” performing the test will also influence the success rate for both the Rf0 and spirometry.\textsuperscript{38} This experience may be particularly important when evaluating an acutely ill preschooler. In a recent trial involving children with acute asthma, we observed cooperation rates varying from 53% in the 3-year-olds to 98% in the 5-year-olds.\textsuperscript{39} These higher rates support the presumption that there is a learning curve in the ability of the technician to obtain the cooperation of young children.

Recognized limitations exist with the impedance measurement technique used in this study. The device we used (Custo Vit R) measures an input impedance by varying the pressure at the airway opening and measuring flow at the same site. An important problem with input impedance is upper airway artifact, which may lead to an underestimation of the respiratory impedance.\textsuperscript{40} Upper airway artifact results from the loss of part of airflow entering the mouth with movement of the upper airway wall, including the cheeks. The higher the respiratory impedance, the more flow will be shunted and lost through upper airway wall.\textsuperscript{41} Thus, the upper airway artifact increases with the severity of airway obstruction, particularly at high oscillatory frequencies. To minimize the artifact, the cheeks may be supported with the palms of the hands or forced oscillations may be applied around the head through a head generator rather than at the mouth.\textsuperscript{42}

An alternative approach is to apply pressure variations to the chest wall and measure airflow at the airway opening. This alternative approach, the respiratory transfer impedance, may provide a more accurate estimation of the respiratory system impedance than possible with the input impedance.\textsuperscript{43} However, neither the head generator technique nor the respiratory transfer impedance is suitable for the bedside evaluation of acutely ill children in the ED setting because of their cumbersome experimental design. In our study, we attempted to reduce the upper airway artifact by cheek compression but recognized that this may have been only partially effective.\textsuperscript{37} However, the respiratory resistance derived at 8 Hz, which was the most feasible oscillatory measurement frequency in our study, was also previously reported as the most discriminating frequency in assessing bronchial response to bronchoconstricting agents.\textsuperscript{44,45}

**Conclusion**

With a substantial proportion of children aged 3 years or older cooperating reproducibly with the measurement of respiratory resistance by forced oscillation at 8 Hz, this technique is advantageous for objectively studying preschool-aged children in whom spirometry can seldom be reliably performed. Moreover, the Rf0\(_8\) allows the safe and objective evaluation of a significant proportion of the school-aged patients who cannot reproducibly perform spirometry during an asthma exacerbation. Respiratory resistance measurement at 16 Hz was technically more difficult and must be applied with caution in preschool-aged children because of the possibility of transient deterioration in lung function. Because the context of this study was chosen to simulate that of a clinical therapeutic trial of acute asthma, we believe that respiratory resistance measured at 8 Hz using the forced oscillation technique may represent a significant advance in pediatric asthma research. It provides a feasible method to safely assess groups of children who are presently excluded from clinical trials because of their inability to cooperate with spirometry, thus leading to the inclusion of a more representative sample of patients than possible with the use of spirometry.

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Clinical Investigations


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