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REVIEW ARTICLE

Review Series: Non-Invasive Monitoring of Airway Inflammation in Asthma

Forced Oscillation Technique and Childhood Asthma

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ABSTRACT

Most infants and preschool children are not able to voluntarily perform the physiological maneuvers required to complete the pulmonary function tests that are used in adults and older children. Recently, commercial devices using forced oscillation technique (FOT) suitable for young children have become available. In devices with FOT, an oscillation pressure wave is generated by a loud speaker, is applied to the respiratory system, usually at the mouth, and the resulting pressure-flow relationship is analyzed in terms of impedance (Zrs). Zrs encompasses both resistance (Rrs) and reactance (Xrs). Rrs is calculated from pressure and flow signals, and is a measure of central and peripheral airway caliber. Xrs is derived from the pressure in the phase with volume and is related to compliance (Crs) and inertance (Irs). These parameters individually indicate the condition of the small and large airways in each patient and indirectly suggest the presence of airway inflammation. It is agreed that the clinical diagnostic capacity of FOT is comparable to that of spirometry. One of the advantages of FOT is that minimal cooperation of the patient is needed and no respiratory maneuvers are required. The use of FOT should be considered in patients in whom spirometry or other pulmonary function tests cannot be performed or in cases where the results of other tests appear to be unreliable. In addition, this approach is effective in assessing bronchial hyperresponsiveness. Considering these qualities, FOT is a useful method to study pulmonary function in preschool children with asthma.

KEY WORDS

asthma, forced oscillation technique, impulse oscillometry, preschool children, pulmonary function test

ABBREVIATIONS

BHR, bronchial hyperresponsiveness; FOT, forced oscillation techniques; IOS, impulse oscillometry; MEFV, maximal forced expiratory flow-volume; Zrs, impedance; Rrs, resistance; Xrs, reactance; Crs, compliance; Irs, inertance; FRC, functional residual capacity; Rint, interrupter resistance; sRaw, specific airway resistance; Vpleth, plethysmographic volume; TGV, thoracic gas volume; eNO, exhaled nitric oxide; $tcPO_2$, transcutaneous oxygen tension; FVC, forced vital capacity; FEV_1, forced expiratory volume in one second; MMF, maximal midexpiratory flow; PEF, peak flow; $\dot{V}_{50}$, maximal expiratory flow at 50% vital capacity; $\dot{V}_{25}$/HT, maximal expiratory flow at 25% vital capacity per height; Dmin, minimal dose of methacholine; St, speed of bronchoconstriction in response to methacholine; PC_{20}, provocation concentration producing a 20% fall in FEV_1; ATS, American Thoracic Society; ERS, European Respiratory Society.

INTRODUCTION

Bronchial asthma is one of the most common chronic respiratory diseases.[1] During exacerbation of asthma, asthmatic children suffer from coughing, wheezing, and dyspnea that are induced by airway inflammation, which result in limitations in air flow. In addition, without asthma attacks, most asthmatic children show reversibility of airway narrowing following the use of inhaled β_2 agonists and bronchial hyperresponsiveness (BHR).[2]

BHR is an exaggerated constrictive response of the

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airways to a wide variety of specific and nonspecific stimuli.[3] BHR produces the characteristic pathological abnormalities seen in asthma and clearly plays a central role in the pathophysiology of the disease.[4] Evaluating the reversibility of airway narrowing and BHR is important, not only for the diagnosis of asthma, but also for the evaluation of disease severity and treatment efficacy.[5] Assessing individual pulmonary function is especially important in order to evaluate the level of asthma control.

The use of pulmonary function tests is well established in adults and older children.[6] However, most infants and preschool children less than six years of age are not able to voluntarily perform many of the physiological maneuvers required to complete pulmonary function tests. Recently, commercial devices using forced oscillation technique (FOT) and other non-invasive techniques are suitable for young children have become available. This review focuses on the importance of non-invasive pulmonary function tests, especially FOT, in the evaluation of childhood asthma.

CONSENSUS OF PULMONARY FUNCTION TESTS IN CHILDREN

Respiratory symptoms are frequently seen in childhood. In infants and preschool children in particular frequently present with recurrent coughing and wheezing. While many of these children will outgrow these symptoms as they age, others will have asthma that persists into adulthood.[7] It has been suggested that there exist some phenotypes of recurrent wheezing in infants.[8] The pathophysiology, prognosis, and treatment may differ for each phenotype. Objective assessments of pulmonary function help to distinguish between these phenotypes and are needed to determine suitable treatments and to improve patient education.

The use of pulmonary function tests in older children, adolescents and adults is well established. The same pulmonary function tests have been attempted in infants and young children; however, most infants and young children are not able to perform these tests. Consequently, serious problems in the accuracy of measurements of pulmonary function obtained from these tests in infants and young children have been presented.

First, it is impossible to use the standardized procedure of pulmonary function tests in infants and young children because significant cooperation and perseverance is required of them during the test.[9] Second, previous devices were originally developed for adults and it has been suggested that dead spaces in equipment and/or the diameter of mouthpieces are not adequately corrected to accommodate the size of young children.[10] Additionally, the software programs used to interpret the test results are designed to evaluate the parameters for adults, not for young children, and sometimes there exist no standard values for use in infants and young children. Furthermore, regarding the techniques used to test airway responsiveness to inhaled agonists or antagonists, it has been suggested that the inhaled dosage regimens are not adequately corrected for the size of children.[11] Of course, methods for measuring pulmonary function in younger children should be effortless and must be safe and painless.

Recently, some pulmonary function tests that are easy to perform in young children have become commercially available. The combined statement of the American Thoracic Society (ATS) and the European Respiratory Society (ERS) on the use of pulmonary function tests in preschool children summarizes current knowledge on the suitability of different pulmonary function tests for use in infants and young children and recommends the use of certain tests in preschool children.[12] These include the following standard spirometry,[13] maximal flow referenced to functional residual capacity ($\dot{V}$maxFRC),[14] interrupter resistance (Rint),[15,16] specific airway resistance (sRaw) measured in a plethysmograph[17] and FOT.[18,19] These recommendations are based on reliable scientific evidence, documented by references, and validated by subcommittee experts. Additionally, in many situations, insufficient data exist to make any definitive recommendations.

PROBLEMS OF PULMONARY FUNCTION TESTS IN CHILDREN

In school-age children and adolescents, pulmonary function tests have been administered prior to starting asthma therapy. However, regarding the use of these tests in infants and young children, much work remains to be done to standardize how these tests are performed and to understand the most appropriate role for these tests in relation to diagnosis and clinical management. Problems associated with the use of pulmonary function tests other than FOT in infants and young children are as follows:

Spirometry is commonly performed in adults and school-age children and recent reports have confirmed that preschool children are also able to perform the maneuvers required for this test.[13,20,21] By contrast, it has been demonstrated that both preschool and school-age children have difficulty meeting some of the quality-control criteria outlined in the ATS/ERS guidelines.[21-23] There are some problems with the reliability of data obtained from the use of spirometry in infants and young children. Efforts to obtain a MEFV curve in two to five year-old children have a low success rate, with few curves meeting the American Thoracic Society criteria.[24] If a forced expiratory measurement is to be obtained after several training attempts, the sequence of forced respirations may change the bronchial tone in children with asthma.

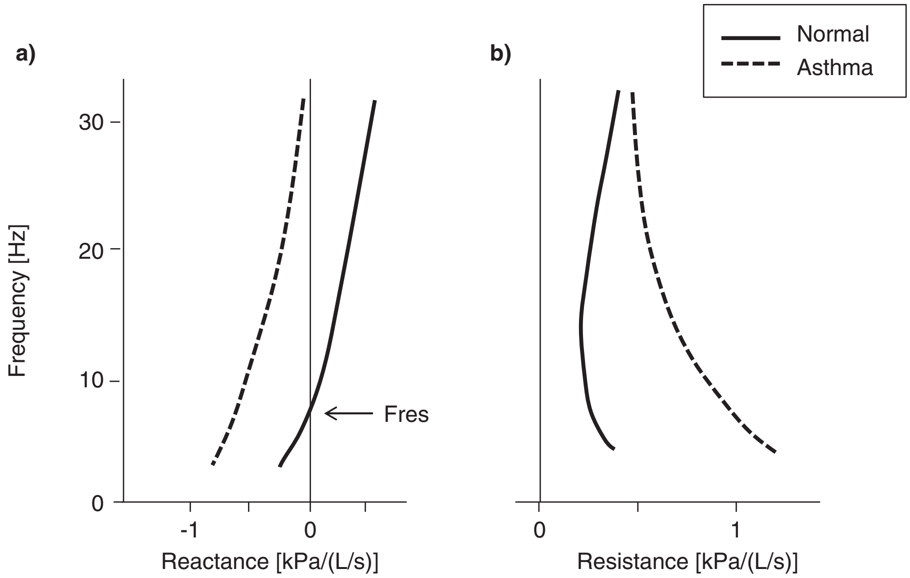

Fig. 1 A schematic illustration of the frequency dependence of respiratory impedance. Reactance (Xrs) in patients with asthma (—) is lower than that seen in normal control patients (---) (**a**). Respiratory reactance (Rrs) in patients with asthma is higher and negatively frequency-dependent (**b**). The arrow indicates resonant frequency.

Measuring Raw by using an interrupter technique, Rint, requires relaxed tidal breathing through a mouthpiece-shutter-pneumotachograph system. This makes Rint an attractive technique for assessing respiratory function in young children with a limited ability to cooperate.[25] However, Rint does require some specific techniques, such as avoiding leaks at the mouthpiece and not allowing the following to occur: extreme flexion or extension of the child's neck, vocal cord closure, an irregular breathing pattern, movement during shutter closure, or incompletely relaxed breathing.[26] Indeed, success rates of this technique have been reported to be 56%, 81%, and 95% in children ages two to three, ages three to four, and ages four to five, respectively.[27] In a study of 3-year-old children with a history of wheezing, Phagoo *et al.* demonstrated that Rint appeared to be less sensitive in documenting the bronchoconstriction that occurs with the administration of methacholine, compared to that found in 5-year-old children.[28]

The standard method of body plethysmography may be too difficult for infants and young children to undergo. In order to measure sRaw, patients need to sit inside a closed, constant-volume, whole-body plethysmograph for several minutes. They must wear a nose clip, and breathe quietly through a pneumotachograph while maintaining a good lip seal without occluding the mouthpiece.[25] To obtain accurate measurements, infants and young children must be made to feel comfortable during lung function tests. Additionally, purchasing specialized equipment and employing special technicians for young children is expensive.[25]

FOT AND CHILDHOOD ASTHMA

FOT AND PARAMETERS

Recently, devices that use FOT have become clinically available. Impulse oscillometry (IOS) is one type of FOT. The methodology of this technique involves the generation of an oscillation pressure wave by a loud speaker that is applied to the respiratory system, usually at the mouth. The resulting pressure-flow relationship is analyzed in terms of impedance (Zrs).[6] An extensive methodological article covering the use of FOT has been published[29] and a specific chapter regarding FOT is included in the ATS/ERS statement.[30]

The key concept of FOT is Zrs, the spectral (frequency domain) relationship between pressure (P) and airflow ($\dot{V}$) generalization of resistance.[29] Zrs encompasses resistance (Rrs) and reactance (Xrs) (Fig. 1a, b). Rrs is calculated from pressure and flow signals.[31] Rrs is a measure of central and peripheral airway caliber, which induces resistance from the oropharynx to lung and chest wall tissue.[32] Xrs is derived from the pressure in phase with volume (near-zero flow, or out of phase) and is related to compliance (Crs) and inertance (Irs). The frequency at which there is a transition in the lungs from passive distention to active stretch is the point when the inflation pressure and elastic recoil cancel each other out and Irs equals Crs, resulting in a reactance equal to zero. This point is referred to as the resonant frequency (Fres) (Fig. 1a). At Fres (5-7 Hz in children[33]), flow

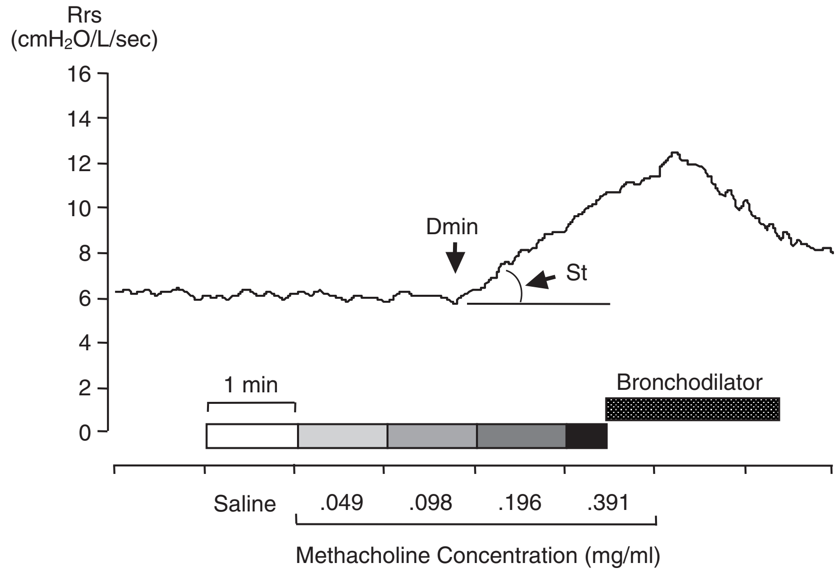

Fig. 2 The result of the methacholine inhalation challenge using the continuous oscillation method (Astograph®). Dmin, minimal dose of methacholine; St, speed of bronchoconstriction in response to methacholine.

and pressure are in phase and Zrs equals Rrs.

Rrs and Xrs at 5 Hz are designated as R5 and X5, respectively. Lower-frequency oscillations, such as 5 Hz, generally travel farther to the lung periphery and provide an indication of the condition of the entire pulmonary system. Therefore, when either proximal or distal airway obstruction occurs, R5 and X5 may be increased. Komarow *et al.* explained that higher-frequency oscillations, such as 20 Hz, transmit signals more proximally and provide information primarily concerning the central airways.[31] Therefore, central airway obstruction will be reflected in an increased R20, and disease isolated to the distal airways will increase R5 to a greater extent than R20. This is because the increase in proximal resistance measured by R20 makes up only a small percentage of the total change in the system's resistance that is measured by R5. This is referred to as frequency-dependent change and the resistance is routinely measured as a differential change (R5-R20).[31] In the terminology of IOS, total resistance (R5), central resistance (R20), small airway resistance (R5-R20), distal reactance (X5), and reactance area (AX) are conventionally used.

CONTINUOUS MONITORING SYSTEM OF Rrs

Since the 1980's, we have been using the airway hyper reactivity test system, Astograph® (Chest Co., Tokyo, Japan) to complete childhood methacholine inhalation challenges[34,35] according to the procedure described by Takishima.[36] The aerosol generator in Astograph® delivers increasing doses of methacholine from 12 serially arranged nebulizers. Bronchial responsiveness is displayed in the form of a continuous record of the Rrs, measured by the oscillation technique. When applied in children, a constant-amplitude pressure generator is connected to a mouthpiece and produces a constant-amplitude sinusoidal pressure wave of 2 cm of H_2O of 7 Hz at the mouth. For the parameters of the methacholine inhalation challenge, Rrs by continuous monitoring of respiratory resistance was calculated exactly from the dose-response curve (Fig. 2).[35]

The minimum dose of methacholine that causes bronchoconstriction, which is the cumulative methacholine dose at the inflection point of the Rrs tracing, represents the degree of bronchial sensitivity (Dmin). The linear rate of increase in Rrs indicates the speed of bronchoconstriction in response to methacholine and represents the degree of bronchial reactivity (St) (Fig. 2).[35]

PRACTICAL MEASUREMENT

The FOT/IOS apparatus consists of a measuring head, a resistor, a pneumotachograph, and pressure and flow transducers (Fig. 3). The transducer attached to the pneumotachograph measures total pressure and flow during tidal breathing. The pressure and flow signals are obtained during tidal breathing and the pressure oscillations pass though the pneumotachograph and are measured by the transducer.

Data are collected during several rounds of breathing, more than three or five breaths are required for one acquisition round which lasts 10 seconds or more. The results of the IOS testing are then graphically displayed on a computer monitor. In order to identify acceptable measurements, the devices dis-

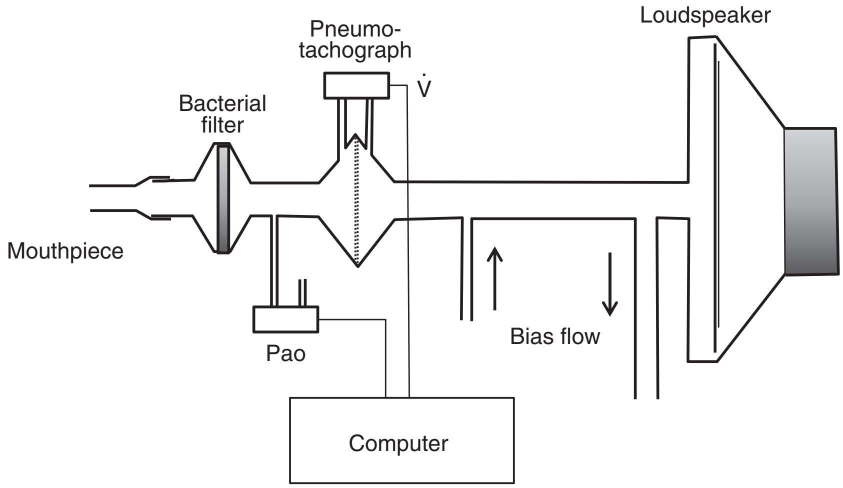

Fig. 3 A schematic arrangement of the forced oscillatory impedance (Zrs) measurement. Pao, airway opening pressure; $\dot{V}$, airflow.

Pre β_2 agonist inhalation

Z5	[kPa/(L/s)]	1.12
R5	[kPa/(L/s)]	1.06
R20	[kPa/(L/s)]	0.78
R5-R20	[kPa/(L/s)]	0.28
X5	[kPa/(L/s)]	-0.34
Fres	[L/s]	23.94
AX	[kPa/L]	2.49

Post β_2 agonist inhalation

Z5	[kPa/(L/s)]	0.56
R5	[kPa/(L/s)]	0.55
R20	[kPa/(L/s)]	0.47
R5-R20	[kPa/(L/s)]	0.08
X5	[kPa/(L/s)]	-0.08
Fres	[L/s]	15.67
AX	[kPa/L]	0.35

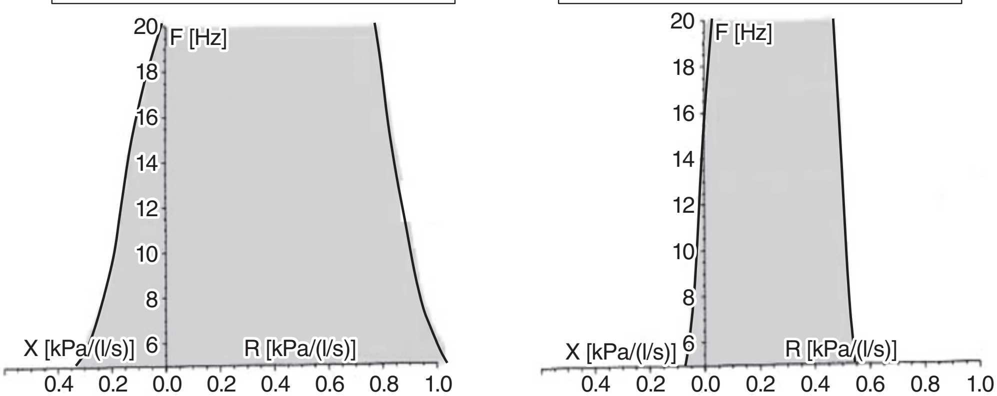

Fig. 4 The results of testing a three-year-old male with suspected asthma before and after inhalation of a β_2 agonist. After inhalation of the β_2 agonist, the values of R5, R20, R5-R20, and X5 decreased and the area of Rrs and Xrs also decreased.

play tidal flow and/or volume in real time. Rrs is related to both height and age, but not sex, in preschool children.[30,37] Figure 4 shows the results of testing a three-year-old boy, who was suspected to have asthma, both before and after inhalation of a β_2 agonist. The values of R5, R20, R5-R20, and X5 decreased more than 40%, and the area of Rrs and Xrs also significantly decreased.

During the examination, the child must sit upright, with the neck in a neutral or slightly extended position.[31] The head should be in a neutral position or in slight extension, not in rotation or flexion, and the cheeks must be supported with the hands in order to avoid the "upper airway shunt"[38,39] (Fig. 5). There must be no leaks around the mouthpiece. To avoid the presence of artifacts in the mouth chamber, the lips must be firmly closed around the mouthpiece and a nose-clip must be worn.

In the methacholine provocation tests with continuous measurement using Astograph®, patients are also examined during tidal breathing while in a sitting position and with a nose clip attached and two air-filled balloons placed at both sides of the cheeks (Fig. 6a, b).[34] During tidal breathing, doses of inhaled methacholine are doubled every minute and Rrs is continuously measured.[34] When Rrs reachs double the baseline value, methacholine inhalation is stopped and salbutamol solution is inhaled for two minutes. On the graphical display of the computer monitor, the parameters of Dmin and St in the dose-response curve are calculated.

Fig. 5 A four-year-old female performing IOS. The patient is using a nose-clip, and is supporting the cheeks. The results of the IOS testing are graphically displayed on a monitor.

ADVANTAGES OF FOT

FOT is very easy to perform and more than 80% of young children are able to achieve reliable measurements on the first attempt.[6] FOT has been able to detect real-time airway narrowing, both in symptomatic asthmatic children and in non-symptomatic asthmatic children in testing of airway responsiveness. The reproducibility of this technique does not seem to be influenced by bronchial diseases.[40,41] Therefore, due to its advantages, FOT has been applied in young populations, including in the emergency management of asthmatic patients. Additionally, this approach does not expose patients to the risk of bronchospasm, as is sometimes seen during the spirometry maneuver.

In children unable to complete spirometry testing, the FOT is comparable with the signs in assessing response. Ducharme *et al.* have reported that, of children aged two to 17 with acute asthma, 65% were able to reproduce Rrs at 8 Hz, whereas only 43% were able to perform spirometry on the initial assessment. They also reported that a notable proportion of preschool-age children cooperated with Rrs at 8 Hz: 19% of 3-year-olds, 40% of 4-year-olds, and 83% of 5-year-olds.[42] Additionally, it has been reported that, in healthy children aged three to 18 years, children less than 6 years of age had no difficulty performing the FOT maneuver, and that healthy children aged two to 7 years performed the tests effectively approximately 90% of the time.[43,44]

Mansur *et al.* have studied the relationships between methacholine-induced asthma symptom scores, IOS, and spirometry in adult asthmatics, and

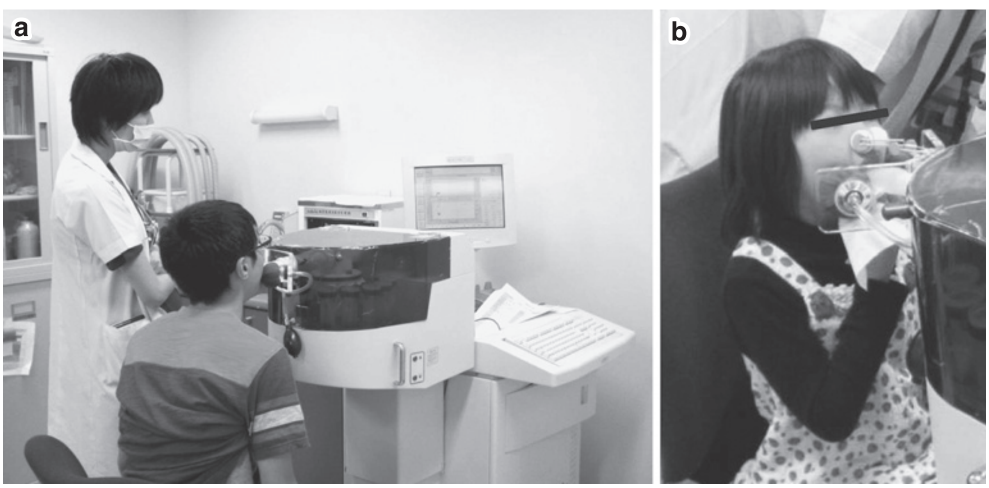

Fig. 6 (**a**) shows a methacholine inhalation challenge using the continuous oscillation method (Astograph®). The patients are also examined during tidal breathing while in a sitting position with a nose clip attached and two air-filled balloons placed at both sides of the cheeks (**b**). During tidal breathing, the doses of inhaled methacholine are doubled every minute and Rrs is continuously measured.

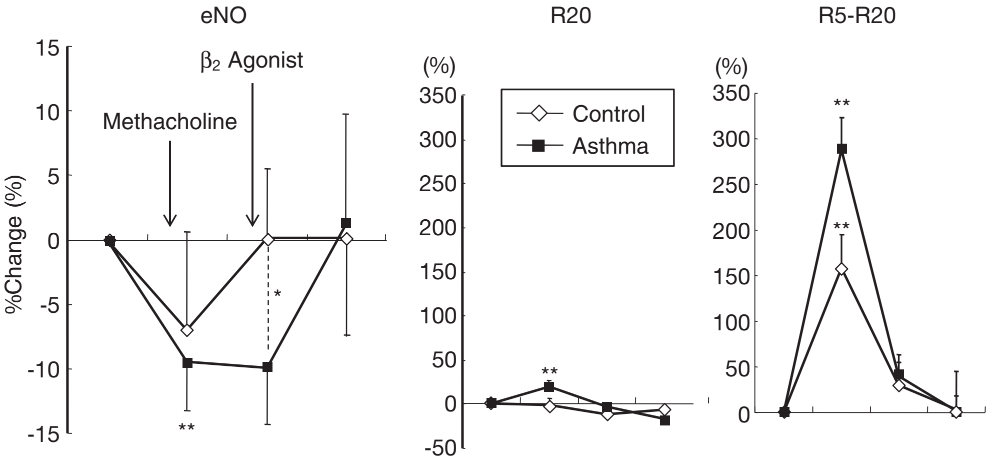

Fig. 7 The eNO level and a methacholine inhalation challenge. A significant decrease occurred in the eNO level after the methacholine inhalation challenge in both normal and asthmatic children. This decrease did not correlate with the percentage decrease seen in FEV_1 or R20; however, it did correlate with the small airway resistance, R5-R20. $^{**}p < 0.01$, $^{*}p < 0.05$.

suggested that the symptom of wheezing showed a correlation between IOS and spirometry and that the Rrs measured during a methacholine challenge correlated better with asthma symptoms than with spirometric measures.[45] In children, the study of spirometry and IOS demonstrated that FEV_1 and PEFR were significantly correlated with the IOS parameters, R5, R10, and R20 in patients with asthma and in controls.[46] Additionally, in a study of the utility of IOS in young children with asthma aged three to six years, significant correlations between the bronchodilator responses of spirometric parameters and the IOS parameters, R5, R10, and R20 were found.[47]

In a clinical trial including children with asthma aged six to 14 years, XA was found to be unique and reflected an ongoing improvement compared with spirometry that occurred during the latter part of the trial.[25] In particular, the pattern of improvement seen in XA, small airway function, over the course of therapy suggested that this test might detect alterations in airway mechanics that are not reflected by spirometry.[25] Also, in a study of exercise-induced responses using IOS in children with wheezing and age-matched controls, the children with wheezing showed significantly larger responses in R5, X5, and Fres after exercise than the controls.[48]

In studies to evaluate bronchodilator response, FOT was well accepted by young asthmatic children, and R5 was reproducible and correlated with the results of spirometry and plethysmography.[49] Additionally, the bronchodilator responses of IOS were found to be remarkably abnormal in 4-year-old children with persistent asthma, whereas spirometry did not establish similar statistically significant findings.[50] In measuring the response of inhaled methacholine in healthy and asthmatic children using IOS and spirometry, the R5 level was found to be significantly different between the asthmatic and healthy children, and Xrs may therefore be a suitable replacement for PC_{20} in methacholine challenge testing.[51] FOT is a useful tool in the diagnosis of the early development of asthma and its use might be helpful to objectively measure the outcome of early interventions.

ASTHMA AND AIRWAY INFLAMMATION

FOT is not able to measure the amount of airway inflammation directly. However, the existence of acute/chronic airway narrowing and BHR, both of which are directly induced by airway inflammation, is demonstrated by extraordinary pulmonary function during FOT.

The measurement of the exhaled nitric oxide (eNO) level has been proposed to be used as a noninvasive marker of airway inflammation in asthmatic patients.[52,53] We evaluated the relationships between the eNO level, spirometry, and FOT by minimizing the effects of aging and height. A Jaeger Master-Screen-Impulse Oscillometry System® (Jaeger CO, Wurzburg, Germany) was used in accordance with the techniques recommended by the manufacturer. Although FEV_1 and other parameters of central airway resistance did not correlate with the eNO level, the small airway parameters of R5-R20 did inversely correlate with the eNO level in younger asthmatic children.[54] Furthermore, to evaluate the effect of bronchoconstriction on eNO levels, we performed spirometry, IOS, and eNO level measurement at three points, before and after a methacholine inhalation challenge and after the inhalation of a β_2 agonist. We reported that a significant decrease occurred in the eNO level after the methacholine inhalation challenge was conducted.[55] This decrease did not correlate with the percentage decrease in FEV_1 or R20; however, it did correlate with the small airway resistance parameter, R5-R20 (Fig. 7).[55]

In a clinical trial to study the effects of anti-inflammatory drugs on pulmonary function in adult asthmatics, spirometry and IOS were used to compare the effects of ciclesonide with the effects of fluticasone propionate, and to compare the effects of a salmeterol and fluticasone propionate combination with the effects of fluticasone propionate. The IOS parameters, R5-R20, X5, and AX, were significantly more improved compared to the spirometry parameters.[56,57] In a study to evaluate the effects of montelukast on Rrs in children with asthma, the IOS parameters, Z5, R5, R20, R5-R20, X5 and Fres, were significantly improved, and were found to be more sensitive than the spirometric parameters.[58] The FOT results found in asthmatic patients are clearly distinguishable from those found in healthy subjects and FOT is a feasible method to detect airway disturbance induced by airway inflammation in asthmatics.

MEASUREMENT OF BHR WITH FOT

The measurement of BHR may provide additional information regarding symptoms and lung function in children with asthma. FOT has been used to quantify the responses to methacholine[59] and histamine[60] in young asthmatic patients who are clinically stable.

To evaluate the influence of aging on BHR during childhood, we studied age-related changes in bronchial reactivity to the administration of methacholine in children from two to 13 years of age using transcutaneous oxygen pressure ($tcPO_2$) monitoring and FOT with the Astograph®.[34] In children aged two to 7 years old, bronchial sensitivity, Dmin, decreased significantly; however, after age eight years of age, the values gradually increased. On the other hand, bronchial reactivity (St), in seven to 16 year-old children with asthma, decreased after age 13, while the St values in the controls showed no significant changes between ages seven and 16.[61]

In children with atopic and nonatopic asthma, BHR induced by a methacholine inhalation challenge using FOT has been studied, and a remarkable difference in the bronchial response to methacholine between the children with atopic asthma and those with non-atopic asthma was reported.[62,63] Additionally, we have reported the effects of height and age on BHR in childhood asthma[64] and the age-dependent relationship between Dmin and the total serum IgE level by the examination with FOT.[65]

LIMITATION OF FOT IN CHILDREN

The ERS published a statement regarding FOT, in which they concluded that the method is sensitive to environmentally induced impairments in pulmonary function and is reliable in assessing airway responsiveness.[29] FOT may be more sensitive than spirometry, and has the potential to assess airway conditions in preschool children at risk for asthma. Many studies have suggested that the use of FOT in changes is feasible to evaluate responses to therapy and to follow the course of respiratory diseases.[32,66]

On the other hand, the main weakness of respiratory impedance determination is that it does not distinguish between obstructive and restrictive lung disorders.[29] Additionally, like interrupter techniques, FOT requires the minimum cooperation of patients. The patients must minimize movement and avoid chewing, vocalizing, swallowing, or placing their tongue inside the mouthpiece during the procedure. Furthermore, the patient must breathe calmly, regularly, and without glottis closure, at a normal or determined rate.[31] All measurements obtained during disturbed breathing cycles must be discarded. Infants less than three years of age and some older children may not be able to comply with these requirements.

Some reports have suggested that FOT is less sensitive compared with other pulmonary function tests. Rrs (frequency <10 Hz) must decrease 15% to 40% from its baseline or 27% of its predicted value to determine a positive response to bronchodilators.[67] An investigation involving four- to five-year old children enrolled in the Childhood Asthma Prevention Study demonstrated little differences in the baseline oscillation parameters between children with and those without clinically active asthma.[68] Thamrin *et al.* studied bronchodilator responsiveness in preschool children using FOT, and the response seen in children with cystic fibrosis, asthma or wheezing was not greater than that seen in healthy children.[67] Nielsen and Bisgaad have compared the change in sRaw seen in whole-body plethysmography, Rint, and R5, X5 by FOT in children aged two to five years, and reported that the bronchodilator response measured by sRaw allows for a separation of asthmatic children from healthy children.[69] Malmberg *et al.* studied the reliability of FOT and eNO levels in identifying asthma in preschool children and suggested that the eNO level is superior to FOT parameters in measuring bronchodilator responsiveness.[70]

Enlarged tonsils are frequently present in young children, which makes inspection of a child's throat prior to resistance measurement mandatory. With standard FOT, Zrs is affected by motion of the upper airway walls. This "upper airway shunt" increases an artificial frequency dependency of Rrs, and Xrs is decreased with increased Fres in the presence of a high Zrs.[29] Although it is not possible to eliminate this shunt effect completely, firm and uniform support of the upper airway walls should be applied.

Some reports have suggested that a discrepancy exists between FOT and other pulmonary function tests. However, to some extent, any discrepancy between FOT and spirometry is as a matter of course, since, methodologically, one is measured during tidal breathing and the other requires a perfect forced expiration.

SUMMARY

It has been suggested that the clinical diagnostic capacity of respiratory impedance measurements obtained from FOT is comparable to that obtained from spirometry. Many previous reports have concluded that FOT is a reliable technique for assessing pulmonary function in children with asthma. The advantages of FOT are that minimal cooperation of the patient is required and no respiratory maneuvers are needed. The use of FOT to measure respiratory impedance should be considered for patients in whom spirometry cannot be performed or appears to be unreliable.[29]

At any time, pediatricians think about the ideal pulmonary function test to use in preschool children. The test should be simple to perform, safe, reproducible, sufficiently sensitive to detect the changes in pulmonary function that occur with growth, able to distinguish clearly between health and disease, and applicable to any age so that longitudinal studies may be conducted to monitor individual children from infancy to adulthood.[71] Considering its mechanical qualities, FOT is an ideal method to study pulmonary function in preschool children.

In our institute, FOT is used to complete for childhood pulmonary function tests in children with asthma and other acute and chronic respiratory diseases where other techniques cannot be applied. In order to perform accurate pulmonary function tests on young children, we need devices with appropriate methods and easy handling maneuvers. Considering this clinical aspect, we realize that FOT is effective for measuring pulmonary function in preschool children.

It is also important to know the limitations of FOT. However, one advantage of FOT over interrupter techniques or plethysmography is that FOT partitions respiratory system mechanics into Rrs and Xrs,[25] and an abnormal Xrs might provide important information about reductions in small-airway conductance and increased lung elastance. The ability of FOT to evaluate the condition of small airways is admirable.

We studied the relationship between FOT parameters and eNO values,[72] and performed lung sound analyses to diagnosis asthma in preschool children.[73] Most pediatricians may profess that the most important period in which to measure pulmonary function is the infantile period, since this is the age of onset for childhood asthma. Further methodological improvements in FOT will increase our ability to make better use of this technique in clinical practice.

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