Role of Impulse Oscillometry for Assessment of Lung Functions in Pediatric Bronchial Asthma

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ABSTRACT

Background: Impulse oscillometry (IOS) is a simple, noninvasive method using the forced oscillation technique, requires minimal patient cooperation and is suitable for use in both children and adults. This method can be used to assess obstruction in the large and small peripheral airways and has been used to measure bronchodilator response and bronchoprovocation testing. New data suggest that IOS may be useful in predicting loss of asthma control in the pediatric population. IOS has been introduced as an alternative technique to assess lung function with particular application to younger children with asthma. This is because IOS is noninvasive, easy to perform, and requires only minimal patient cooperation.

Keywords: Impulse oscillometry (IOS), bronchial asthma.

Introduction

Breathing problems caused by asthma are known as bronchial asthma, and it is a worldwide complex respiratory disorder characterised primarily by inflammations. IOS uses small pressure oscillations applied at the mouth to measure the resistance and respiratory system's reaction to impedance during spontaneous quiet breathing, providing an indirect assessment of lung function (1).

Spirometry may be underutilised because of the difficulties in performing it on young children, particularly those between the ages of 2 and 5 years, as well as the child's capacity to follow directions and make maximum, repeatable attempts (2).

Impulse oscillometry (IOS)

When using Impulse Oscillometry (IOS), no effort is required from the patient and just normal tidal breathing is required to identify airway alterations. IOS gives numerous measurements of respiratory mechanics such as respiratory resistance (R), reactance (X), and impedance (Z). Small external pressure signals are superimposed on the patient's spontaneous breaths to measure pulmonary mechanics (3).

(R) is the amount of resistance a sound wave has to go through the lungs and into the heart. In order to reach the distal airways, sound waves with a frequency of 5 Hz have longer wavelengths. Because of this, a sound wave pulse at 5 Hz is used to determine the resistance in the distal airways. Because sound waves travel a shorter distance at 20 Hz (a shorter wavelength), the resistance to sound waves reflects the upper airway's mechanics more clearly. The inverse of compliance, (X) represents lung elastance as a proxy. Obesity, interstitial lung disease, and small-airway disease all diminish lung compliance, therefore they should all have a detrimental impact on (X). (Z) is a less common clinically used combination of (R) and (X) (1).

Similarly to spirometry, IOS values are linked to clinical symptoms and asthma management, but a benefit of IOS may be the early detection of small changes in a patient's airway function compared to conventional spirometry. Evidence suggests that IOS can detect impaired distal airway function even when spirometry is normal, according to several studies (6).
A major advantage of IOS is that it requires little participation from the child and that measurements are taken during tidal breathing. Even children who are unable to conduct spirometry have been able to accurately and consistently complete the test. Another study of inner-city children at risk for asthma reported that of the 485 children who tried lung function testing, a larger percentage were capable of doing satisfactory spirometry than IOS at the ages of 3, 4, and 5 years (8). In determining acceptable and reproducible spirometry, the researchers employed forced expiratory volume in 0.5 seconds (FEV0.5) rather than the more often used forced expiratory volume in 1 second (FEV1). Although this is the case, they and other researchers have demonstrated that IOS is more sensitive than spirometry in detecting small-airway obstruction and differentiating children with asthma from those who did not (4).

Aside from helping to identify patients with asthma control issues, IOS has also been demonstrated to be useful in forecasting future control issues and asthma attacks. Spirometry and body plethysmography can't both measure airway resistance, but IOS can. IOS is a variation of Dubois and colleagues' forced oscillation technique, first described in 1956 (5) By superimposing pressure waves on the subject's tidal breathing, forced oscillation evaluates the mechanics of the airways. This device measures pressure and flow across a wide range of frequencies by transmitting pressure and flow through sound waves into the airways. The resistance of the airway can be computed once the pressure and flow have been determined. Low-frequency sound waves (15 Hz) go further into the lungs and can be used to examine the characteristics of the small lungs. Sound waves with a higher frequency have a greater amplitude and travel farther in less time (7).

The big airway features can be seen in data produced from sound waves with a frequency greater than 20 Hz. IOS can show how well the proximal and distal airways are working by taking measurements at high and low frequencies. Commercially available IOS systems have a loudspeaker that produces sound waves between 2 and 35 Hz, on average. A mouthpiece connects the loudspeaker to the oropharynx, the glottis, and the lower airways, allowing the sound oscillations and pressure fluctuations to be transferred. The tubing between the loudspeaker and the mouthpiece is coupled to a pneumotachograph and transducer, allowing pressure and flow to be measured during inspiration and expiration. Using a signal filter, the externally created oscillations are separated from the child's natural breathing rhythm while the generated sound waves are superimposed. Respiratory impedance is calculated via computer analysis of pressure and flow amplitude and phase changes during inspiration and expiration. The respiratory system's impedance includes all of the factors that limit airflow (7).

**Concepts in impulse oscillometry:**

Several concepts, including impedance, are important in understanding IOS. Total respiratory system impedance, represented as Zrs, is composed of resistance (Rrs) 206 McDowell and reactance (Xrs). Resistance can be conceptualized as the energy a sound wave requires to travel through the airways and inflate the lung. The resistance of the entire respiratory system (Rrs) includes that found in the extrathoracic airways, intrathoracic airways, lung parenchyma, and the chest wall. The resistance at low frequencies, such as 5 Hz (R5), is that of both the central and the distal airways, whereas resistance at higher frequencies such as 20 Hz (R20) represents that of the large airways. Resistance of the peripheral airways can be determined by subtracting resistance of the large airways from that of the respiratory system, or R5 R20. This value is commonly referred to as the R5-R20. Peripheral airway obstruction results in more resistance in the lower-frequency sound waves (R5), which travel deeper into the lungs than the higher-frequency waves (R20) representing the large airways (1).
Thus, \( R_5 \) will be disproportionately elevated relative to \( R_{20} \) in peripheral airway obstruction, and consequently, a higher value for \( R_5-R_{20} \) is obtained under such circumstances. This disproportionate effect on low-frequency resistance compared with high-frequency resistance in small-airway obstruction is called frequency dependence of resistance, which is an alternate term for \( R_5-R_{20} \). In small-airway obstruction, the value of both \( R_5 \) (resistance at low frequencies representing large and small airways) and \( R_{5-R_{20}} \) (resistance of more peripheral airways) will be elevated. Reactance of the respiratory system, represented as \( X_{rs} \), is composed of the inert and elastic properties of the respiratory system. The elastic properties of the pulmonary system are manifested as the elastic recoil of the airways and lung parenchyma in response to distension. Reactance is the energy generated by the elastic recoil of the lung parenchyma and the airways added to the inertance of the system. Inertance is the force opposing movement of the sound wave through the respiratory system. Reactance can also be thought of as the “stored energy” of the respiratory system or rebound energy that is generated in response to the sound wave moving through the lungs. In contrast, Resistance is the pressure opposing the forward movement of the sound wave and is a force occurring in front of and in phase with the sound wave. Reactance occurs in response to the sound wave and therefore is the energy echoed back to the system after, and out of phase with, the sound wave. The sum of the forces ahead of the sound wave (resistance) and those generated behind the sound wave in response to the pressure of the wave (reactance) equal the impedance of the entire respiratory system. In other words, \( R_{rs} = R_5 + X_{rs} \). Inertance is the force opposing movement of the sound wave through the respiratory system. At low frequencies where sound waves have reached the more distal airways, elastic recoil (reactance) will be high compared with inertance. At higher frequencies, where sound waves travel only as far as the larger, more proximal, airways, elastic recoil (reactance) will be low compared with the inertive properties of the airways. (1).

It is not surprising then that reactance at low frequencies has been shown to correlate with peripheral airway obstruction. (14) When reactance is zero (\( X = 0 \)), the elastic recoil of the airways and lungs is equal and opposite to the inertance of the system, and all of the impedance in the system is created by the forward movement of the sound wave. At this frequency, known as resonant frequency or \( F_{res} \), low-frequency and high-frequency reactance can be discriminated. At frequencies above \( F_{res} \), inertance is greater than elastic recoil as is seen in the large airways. Frequencies below \( F_{res} \) will be those at which elastic recoil is greater than inertance, a property of the small airways. Therefore, \( F_{res} \) is the dividing point between large and small airways based on the mechanical properties of the airways. It is important to realize that the distinction between large and small airways based on \( F_{res} \) is determined by the airway mechanics rather than the size or generation of the airway. The value of \( F_{res} \) is higher in children than in adults and decreases with age. \( F_{res} \) is also increased in airway obstruction (1).

During IOS testing, curves for the resistance and reactance at all frequencies between 5 and 20 Hz are generated. Both curves are then plotted against frequency and displayed on a single graph called a Goldman graph (4). The area under the reactance curve between the values at 5 Hz (\( X_5 \)) and at \( F_{res} \) is called the area of reactance (\( AX \)). Both \( AX \) and \( X_5 \) provide information about distal airway obstruction because reactance (elastic recoil) is greatest in the small airways, where low-frequency sound waves can reach. Obstruction of the small airways results in lower (more negative) values for \( X_5 \) (reduced reactance or elastic recoil). Similarly, the \( F_{res} \) is higher in airway obstruction because the point in the airways where reactance (elastic recoil) is zero is more proximal, and the more proximal, larger airways are represented by values obtained at higher frequencies. Lower \( X_5 \) and/or higher \( F_{res} \) will increase the area under the reactance curve, and therefore, the value of \( AX \). It follows then that \( AX \) is elevated in proportion to small-airway obstruction. (9). \( AX \) has been reported to be the most sensitive measure in discriminating between asthmatics and healthy controls. (4).
Fig. 1. A Goldman graph displaying reactance (X) (blue line) and resistance (R) (red line) plotted as a function of frequency. Fres is the frequency where X = 0. X5 and R5 are reactance at 5 Hz and resistance at 5 Hz, respectively. The AX is the shaded triangle represented by the area under the reactance curve between Fres and 0 Hz. R5, Fres, and AX will be increased in peripheral airway obstruction. X5 will be more negative in peripheral airway obstruction. (1)

Obtaining impulse oscillometry measurements:

IOS may be performed with the child seated in a chair or seated on the parent’s lap. Legs must be uncrossed to prevent contraction of the abdominal muscles, which can result in lower-end expiratory lung volumes. Nose clips are used to prevent leakage of pressure through the nose. With the head in neutral position, the child places the mouthpiece into his or her mouth and makes a seal with the lips. The cheeks are supported by an adult to prevent shifting of impulses to the upper airway and to limit the compliance of the cheeks (10).

Sound waves are generated by the loudspeaker while the child performs tidal breathing for 20 to 30 seconds. Rrs and Xrs are measured and displayed in real time for inspection by the operator. Rrs and Xrs for all frequencies between 5 and 20 Hz are derived and stored for each trial. A minimum of 3 acceptable trials with less than 10% variation among trials are performed. All equipment calibration and testing should be done in accordance with American Thoracic Society (ATS)/European Respiratory Society standards. The performance of the test takes only a few minutes; however, in young children, additional time should be allowed for acclimation to the equipment and testing environment before the IOS procedure is performed (11).

Reference Values For Impulse Oscillometry:

Reference values in spirometry are affected predominantly by height, but also by age, gender, race, and ethnicity, and predicted normal values are accessible for diverse racial and ethnic groups. In contrast, predicted values in IOS are also based principally on height but are derived from an ethnically homogeneous sample, which is largely white. The equations are based almost exclusively on data obtained from white children of European descent (12). However, a literature review by Galant and colleagues26 and subsequent comparison of values obtained from diverse populations and commercially available regression equations revealed that normative values for R5 and X5 in healthy children and adults are comparable despite differences in geographic and ethnic origin, and these values correlate with the values obtained from regression equations programmed.
into commercially available software. Thus, predicted values programmed into commercially available software should be considered reasonable reference values for R5 and X5. Unfortunately, because of a paucity of data, there is still a need to establish reference values for other important IOS parameters, such as AX (12).

**Interpretation of impulse oscillometry:**

The most commonly used parameters in interpretation of IOS are R5, R20, X5, Fres, and AX. Values for R5 and R20 that are greater than 150% of predicted should be considered abnormal and are consistent with increased airway resistance. An R5-R20 value is considered elevated, and consistent with peripheral airway obstruction, if it is greater than 30% in children and greater than 20% in adults. The within-individual variability of airway resistance when measured by IOS is approximately 16% for children and 10% for adults, which is comparable to the 5% to 15% individual variability in airway resistance obtained by body plethysmography (13). Recent Diagnosis Techniques in Pediatric Asthma 209 Decreasing values for X5 indicate a loss of elastic recoil to the system at 5 Hz as would be present in peripheral airway obstruction. X5 is abnormal if the value is greater than 150% of predicted. The Fres (where reactance is zero), is abnormal if it is greater than 25 Hz in children or greater than 20 Hz in adults (13).

A higher value for Fres indicates increased resistance. Fres naturally decreases with age. There are no accepted reference values for AX. IOS measurements are considered accurate when coherence at 5 Hz is greater than 0.8 and coherence at 20 Hz is between 0.9 and 1 (14). Causes of decreased coherence include swallowing, glottis closure, coughing, mouthpiece obstruction by the tongue, or irregular respiratory pattern (14).

**Impulse oscillometry and asthma:**

One of the most useful areas of application for IOS is pediatric asthma. IOS can provide objective measures of lung function even in children who cannot perform spirometry, allowing earlier detection of airway obstruction and response to treatment. IOS has been studied extensively in asthma, including during acute exacerbations. Children with asthma have elevated resistance, specifically R5, as well as decreased Xrs at baseline compared with children without asthma, (15) and Fres have also been shown to be increased in asthmatics compared with healthy controls. Response to bronchodilator is the hallmark of bronchial hyperreactivity and a diagnostic criterion for asthma (15)

Following administration of a bronchodilator, children with asthma demonstrate a decrease in resistance, both R5 and R5-R20, and in Xrs and AX. However, the degree of response to bronchodilator reported has varied widely, anywhere from 8.6% to more than 40%. A review of pediatric studies revealed that when change greater than the upper limit of the 95% confidence interval for R5 is used, the mean bronchodilator response (BDR) in healthy children was 39% (16). Thus, a decrease in R5 or X5 greater than or equal to 40% following administration of a bronchodilator should be considered a positive response in pediatric asthma. Even lower BDR cutoff values have been shown to distinguish between children with asthma and healthy controls. A BDR decrease of 20% in R5 or R10 differentiated asthmatic preschoolers from those without asthma (17).

Similarly, decreases of 8.6% at R10 and 29.1% in AX were found to identify asthma in school-aged children. These same studies demonstrated changes in IOS parameters even without concomitant change in spirometry, indicating that IOS may be more sensitive than spirometry in distinguishing asthma from healthy controls. This increased sensitivity is most likely because IOS reflects changes in the caliber of the small airways where changes of asthma occur earlier, before the abnormalities in the larger airways characterized by spirometry (5).
Schulze et al. (5) evaluated IOS and spirometry during methacholine challenge in 48 children with recurrent wheezing. In the 28 children who had significant changes in both FEV1 and R5 during the challenge, a lower provocation dose was needed to attain a decrease in R5 than to achieve a 20% decrease in FEV1, implying that IOS may be more sensitive than spirometry in detecting response to methacholine. The investigators also noted that a 45% increase in R5 and/or a decrease in X5 of 0.69 kPa s L−1 predicted a 20% decrease in FEV1 with adequate sensitivity and specificity. Peripheral airway resistance measurements after methacholine, especially R5-R20, have also been shown to significantly correlate with asthma severity. IOS may be more helpful than spirometry in identifying children with more severe disease.

Shi et al. (7) studied lung function by spirometry and IOS in more than 100 healthy and asthmatic children. They demonstrated R5-R20 and AX to be useful and more sensitive than spirometry in identifying poorly controlled asthma. In a subsequent study of children with well-controlled asthma (based on clinical and spirometric measures), R5-R20 predicted loss of disease control within 8 to 12 weeks better than spirometry, even when including measurements of forced expiratory flow between the 25th and 75th percentile of forced vital capacity (FVC). A 1-year study of 4- to 7-year-old children with asthma revealed that R5 and R5-R20 were more predictive of asthma exacerbation than FEV1, FEV1/forced vital capacity, or methacholine challenge, and that IOS could identify with 80% accuracy which children would have exacerbations. (5).

### Table 1: Description, abbreviations, and normal values for common IOS.

<table>
<thead>
<tr>
<th>IOS Parameter</th>
<th>Symbol</th>
<th>Description</th>
<th>Reference Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Respiratory impedance</td>
<td>Zs</td>
<td>Impedance = resistance + reactivity</td>
<td>none established but increase suggestive of elevated small-airway resistance</td>
</tr>
<tr>
<td>Respiratory resistance</td>
<td>Rs</td>
<td>Airway + tissue + chest wall resistance</td>
<td>R5 normal if ≤150% predicted</td>
</tr>
<tr>
<td></td>
<td>R5</td>
<td>Resistance at frequency of 5 Hz = resistance of proximal and distal airways</td>
<td></td>
</tr>
<tr>
<td></td>
<td>R20</td>
<td>Resistance at frequency of 20 Hz = resistance of proximal airways</td>
<td>R20 normal if ≤150% predicted</td>
</tr>
<tr>
<td></td>
<td>R5-R20</td>
<td>Value at R5 – value at R20 = resistance of small airways</td>
<td>none established but increase suggestive of elevated small-airway resistance</td>
</tr>
<tr>
<td>Respiratory reactance</td>
<td>Xs</td>
<td>Elastic + inertive properties of airways + lung tissue</td>
<td>abnormal if X5 &gt;150% predicted</td>
</tr>
<tr>
<td></td>
<td>X5</td>
<td>Reactance at frequency of 5 Hz</td>
<td>increased value suggests small-airway obstruction</td>
</tr>
<tr>
<td>Resonant frequency</td>
<td>Freq</td>
<td>Frequency at which elastic forces = inertive forces; X = 0</td>
<td>adults: normal &lt;12 Hz abnormal &gt;20 Hz children: normal &lt;20-25 Hz abnormal &gt;25 Hz</td>
</tr>
<tr>
<td>Reactance area</td>
<td>AX</td>
<td>Area under the reactance curve bounded by Freq and X5</td>
<td>none established but increase suggestive of peripheral airway obstruction</td>
</tr>
<tr>
<td>Coherence</td>
<td>Co</td>
<td>Indicator of quality control</td>
<td>test acceptable if:</td>
</tr>
<tr>
<td></td>
<td>Co 5</td>
<td>Assessment of reproducibility</td>
<td>Co 5 Hz 0.7-0.9</td>
</tr>
<tr>
<td></td>
<td>Co 20</td>
<td>Coherence at 5 Hz</td>
<td>Co 20 Hz 0.9-1.0</td>
</tr>
<tr>
<td></td>
<td>Coherence at 20 Hz</td>
<td>Coherence at 20 Hz</td>
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</tbody>
</table>

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Conclusion:
IOS could help to better diagnose and predict the severity of bronchial asthma in children with good accuracy and allow to know which children would have exacerbations.

Conflicts of interest: None

References: