Review Article

Forced Oscillation Technique and Impulse Oscillometry: An Update on Current Understanding

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Abstract

Forced oscillation technique (FOT) and impulse oscillometry (IOS) are newer modality used for objective assessment of lung function in children with asthma and other respiratory diseases. The major benefit of FOT/IOS is that it requires a tidal breathing compared to forced exhalation in spirometry which makes it easier to perform for young children. This article briefly reviews the basic concepts, parameters, interpretation, clinical utility, and limitations of FOT/IOS. There is a need for a better theoretical and practical understanding of this method by pediatricians before the modality is used in routine practice.

Keywords: *Children, forced oscillation, impedance, pulmonary function test, reactance*

Introduction

Forced oscillation technique (FOT) is a newer lung function modality that is especially useful in children. Many new companies have recently brought their equipment into the market, including portable forms. This article briefly updates on the principles, technical aspects, interpretation, advantages, and limitations of FOT in the pediatric context.

Spirometry has been used for diagnosis and monitoring of various respiratory diseases in children. The most common utility remains for children with obstructive airway diseases like asthma. Despite the availability of spirometry for many years, it has been underused due to various reasons. Need for a good quality forced expiratory maneuver is the main limitation, especially in young children. In addition, many children with asthma can have a normal spirometry.[1] Hence, there was a need for a test that is effort independent without the need for a special breathing maneuver.

Comparison of Spirometry and Forced Oscillation Technique/Impulse Oscillometry System

Spirometry and FOT/impulse oscillometry system (IOS) are important tests for objective assessment of asthma and monitoring of asthma patients. Each one of these tests has its own advantages and limitations. Spirometry assessed the airflow limitation associated with obstructive lung disease and is considered the gold standard investigation. Spirometry has limited variability, short learning curve for providers, international reference equations, established definition of normality/disease, and low cost. FOT/IOS, on the other hand, has the advantage of tidal breathing compared to forced expiration and can be used in lower age groups. IOS is also more sensitive for the assessment of peripheral airways in asthma. Table 1 briefly summarizes the comparison between spirometry and FOT/IOS. The technical standards laid down by the European Respiratory Society taskforce are discussed in Table 2.

Background

In 1956, Dubois introduced the FOT for measuring lung function using sound waves that are transmitted at different frequencies in the lung.[3] IOS is a modified method, developed by Michaelson in 1976.

Principle of Forced Oscillation Technique and Impulse Oscillometry System

The FOT determines breathing mechanics by superimposing small external pressure signals on the spontaneous breathing of the subjects. The external pressure signals are sound waves that cause changes in pressure

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and this change in pressure causes change in airflow. The resultant flows of the externally applied pressure signals on tidal breathing determine the lung mechanical parameters.

IOS is based on principles of FOT where multiple sound waves of different frequencies are applied within a single burst against sequential sound waves of different frequencies in FOT, which is then mathematically decomposed into different frequencies. This reduces the time of test and also provides high signal-to-noise reduction.

IOS is performed by the child in a sitting position with a nose clip in place and the cheeks firmly supported to prevent shunting of applied impulse in the upper airway. Child breathes at tidal volume for the desired period of time (usually 15–20 s) as the sound waves are generated by a loudspeaker and passed into the respiratory system. Sound waves of different frequencies are produced from 5 to 40 Hz. Waves of lower frequencies (5 Hz) travel deep into the lungs till the alveoli before they are reflected back, while high-frequency waves (20 Hz) are reflected back from larger airways.[4,5] The superimposed external pressure signals on spontaneous tidal breathing are measured by a pneumochromatograph present at the mouthpiece to measure the pressure and flow [Figure 1]. The magnitude of change in pressure and flow is measured to determine the mechanical properties of the lung, namely, resistance (R), reactance (X), and impedance (I) [Figure 2]. FOT/IOS results require only the passive cooperation of the subject. Table 3 compares different types of FOT/IOS equipment currently available in the market.

Parameters in Impulse Oscillometry System

Impedance

Respiratory impedance is the sum of all forces that oppose the impulse generated. Pressure difference measured at any two points within the respiratory tract gives the impedance of the airway between these two points. For example, the pressure difference at the mouth and in the alveoli gives the impedance of the airway, and pressure difference at the mouth and pleural pressure gives the total impedance of the lung. In IOS, pressure at the mouth is compared to atmospheric pressure, i.e., pressure outside the chest wall defined as Zrs. This includes the in-phase component, which is resistance (Rrs) and out-of-phase component, which is reactance (Xrs).

Resistance

Resistance reflects airway caliber at different regions of the airway – central airway, peripheral airway, and alveoli. Resistance at higher frequency waves (R20) represents large airway resistance while that at a lower frequency (R5) represents total airway. The difference between the two (R5-R20) represents resistance contributed by small peripheral airways to the total airway resistance. In children, the contribution of small airways is higher than in adults.

Reactance

Reactance represents the energy stored or dissipated by

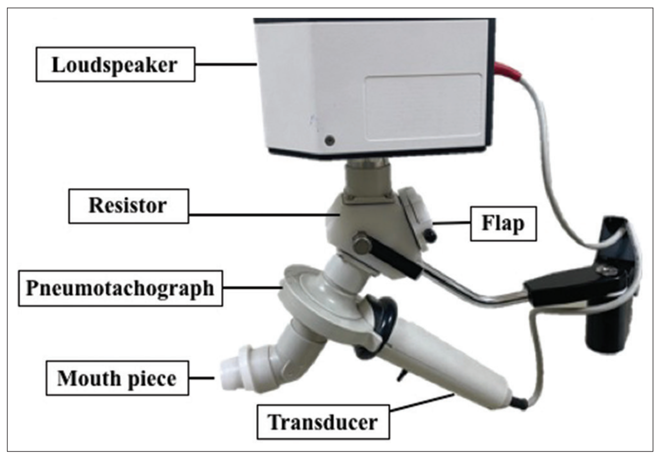

Figure 1: Components of impulse oscillometry apparatus

Table 1: Comparison of spirometry and forced oscillation technique/impulse oscillometry

	Spirometry	FOT/IOS
Main principle	Flow sensor/volume displacement helps measure flow rates and lung volumes	Sound waves transmitted into the respiratory system help measure resistance and reactance of the airway
Maneuver	Forced expiratory maneuver	Tidal breathing
Patient cooperation required	+++	+
Parameters measured	FEV_1, FVC, FEV_1/FVC, FEF_{25-75}	Rrs, Xrs, Ax, Fres
Availability	Easily available	Only in tertiary centers
Cost (lakhs)	1–8	10–14
Technical standardization	Well established	Not well established
Reference values	Normative data available for all races and demographic variables	Normative data scanty
Reliability for diagnosis of restrictive lung disease	++	+
Reliability of diagnosis of obstructive lung disease	++	++

Xrs: Reactance, Rrs: Resistance, Fres: Resonant frequency, Ax: Area of reactance, FOT: Forced oscillation technique, IOS: Impulse oscillometry system, FEV_1: Forced expiratory volume in 1 s, FVC: Forced vital capacity, FEF: Forced expiratory flow, +: Positive the airways in response to airwaves passed through them that allows the airway to stretch. It is a combination of inertance (force of moving air column in the airway) and compliance (elastic properties of the peripheral parts of the respiratory system). Compliance is defined as volume change that could be achieved per unit pressure change in the lungs. Elastance is the reciprocal of compliance, i.e., pressure change required to bring about a unit volume change. Because reactance is volume dependent, it is a good indicator of lung volume changes in diseased states such as interstitial lung disease, impaired elastic recoil of the parenchyma, and air trapping. Reactance becomes more negative in lung diseases, indicating the respiratory system becomes stiffer.

Resonant frequency (Fres)

Resonant frequency is defined as the point where capacitance is equal to inertance, i.e., total reactance is zero. It separates the low frequency, where capacitance predominates (small airways) and high frequency, where inertial component predominates (large airways). In both obstructive and restrictive lung diseases, Fres increases as the reactance becomes more negative at low frequencies.

Area of reactance (Ax)

Area under the reactance curve from lowest frequency to the Fres [Figure 2]. It reflects the elastic properties of the lung and increases in diseases of the peripheral lung.

Interpretation of Impulse Oscillometry

In peripheral airway obstruction, the increase in airway resistance is frequency dependent. Resistance at lower frequencies (R5) is affected more than that at higher frequencies (R20) because the pressure wave traveling to the distal part encounters greater resistance. The reactance in peripheral airway disease also decreases. Whereas, in central airway disease, the increase in airway resistance is frequency independent. The resistance at lower frequencies (R5) and higher frequencies (R20) is equally affected [Figure 3]. Restrictive airway disease leads to decrease reactance as the elastic recoil of the lungs is affected. There is no change in airway resistance in restrictive lung diseases. Bronchodilator reversibility is a sensitive indicator of airway hyperresponsiveness in IOS. A postbronchodilator fall in R5 value by 20%–40% and Ax by 40% is considered statistically significant.[6]

Table 2: Technical standards for impulse oscillometry[2]

Technical parameter	Recommendation
Technically acceptable and repeatable maneuvers	Minimum of three maneuvers required The three replicates should have CoV of R5 at lowest oscillation frequency of <15% in children Free of artifacts – artifact detection by machine has to be standardized
Minimum acquisition time	30 s for >12 years, 16 s for <12 years
Reporting of results	Flexibility in formulation of reports should be offered by all softwares. Oscillometry parameter included in a report should be determined by the end user
Reference values in children	Standing height is the dominant predictor of R_{rs} There is a large scatter in the prediction of R_{rs} and Xrs at low frequency in young children Use of the reference equations from studies in which the devices and population most closely approximate the local situation is recommended
BDR	Threshold for significant BDR in children is a change in R5 of −40% X5 of +50% Ax of −80%

Rrs: Resistance, Xrs: Reactance, CoV: Coefficient of variability, Ax: Area of reactance, BDR: Bronchodilator response

Table 3: Comparison of different forced oscillation technique and impulse oscillometry equipment

	Vyntus IOS	Resmon pro V3	Tremoflo C100	Pulmoscan
Manufacturer	Jaeger	MGC diagnostics	Thorasys	Cognita labs
Technology	IOS	FOT	FOT	FOT
Flow measurement type	Pneumotach	Mesh	Mesh	Mesh
Volume accuracy	±3% or 0.05 L	<±3.5% or 0.1 L		<3% or 0.05 L
Mouth pressure	±15 mmHg	±25 cm of H_2O		Up to 5 cm H_2O
Frequency range	0–100 Hz (multiple frequency sound waves)	5–37 Hz (pseudo random noise stimulus)	Pseudo random noise stimulus	4–32 Hz (pseudo random noise stimulus)
Parameters measured	R5, R20, X5, X20, Ax	R5, R19, R5–R19, X5, X19, R5–19, Ax	R5, R5–20, Ax	R5, R20, X5, X20, Fres, Ax
Portability	Fixed system, can be connected to PC	Fixed system, can be connected to PC	Portable, handheld	Portable, wireless

FOT: Forced oscillation technique, IOS: Impulse oscillometry system, Ax: Area of reactance, Fres: Resonant frequency, PC: Personal computer

Reference Values

Height is considered the dominant predictor of Rrs and Xrs, while there is no effect of sex, weight, race, or age. Various reference values are available which can be used in clinical practice, although there is a need to obtain normative data in different geographical regions and races, including from India.

Clinical Application of Impulse Oscillometry System in Pediatric Practice

Asthma

The major utility of IOS has been in the diagnosis and monitoring of asthma, especially in young children who are unable to perform spirometry. Many clinical trials have compared spirometry with IOS and shown IOS to be equally sensitive,[7-10] while some have shown IOS to be more sensitive than spirometry.[7] IOS is a suitable option for children who fail to perform spirometry.[8] Recent evidence shows that 25%–40% of children with asthma have small airway dysfunction. IOS is considered a sensitive marker of small airway disease in children with asthma.[8,11] There is increasing evidence to suggest that IOS is a useful parameter to assess control and follow-up in children. Children with controlled asthma who have increased peripheral airway resistance are at risk of losing asthma control.[12,13] Few studies have used sequential Ax values and found that Ax independently can be useful to assess asthma control in children.[8]

Preschool wheezing

IOS can be easily performed by preschooler children in the age group of 3–6 years. It is a useful method for documenting obstruction and assessing control.[14]

Bronchiectasis (including cystic fibrosis)

Spirometry is the gold standard pulmonary function for monitoring lung function in children with cystic fibrosis (CF). Recent studies have shown the utility of IOS in monitoring lung functions during stable state and exacerbations but require more data.[9] There is recent evidence to suggest that IOS can be useful for assessing the disease severity of “non-CF bronchiectasis” in children.

Bronchiolitis obliterans

Since IOS is a sensitive modality to detect small airway disease, it has been used to study children with bronchiolitis obliterans (BO). Postinfectious BO in children can be detected by greater changes in Xrs compared to spirometry. In adults, posttransplant BO can be detected early using oscillometry.

Neuromuscular disorders

Children with neuromuscular disorders such as spinal muscular atrophy, muscular dystrophies, and myopathies require lung function in follow-up. Spirometry has been used conventionally but cannot be done in young children and many older children. Studies have shown that *R* values

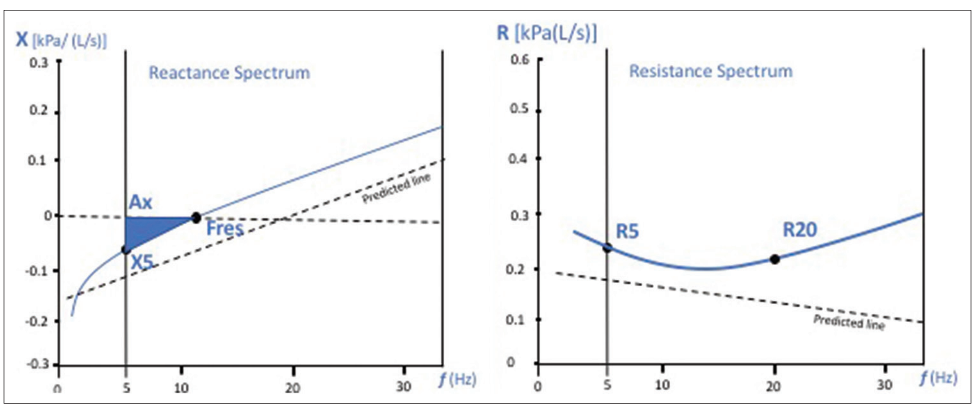

Figure 2: Impulse oscillometry graph pattern in “Normal state”

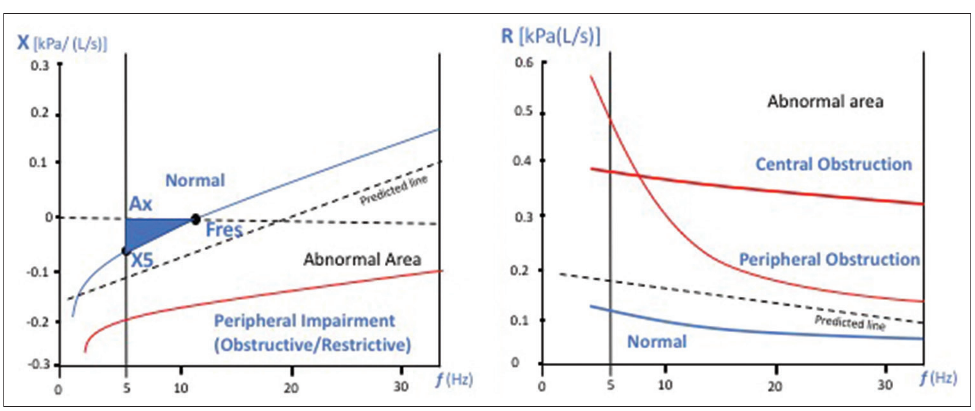

Figure 3: Impulse oscillometry graph pattern is “Disease states”

increase due to underinflation, secretions in the airways, and microatelectasis, and X values reduce due to reduced compliance of the chest wall and reduced lung volumes.[15]

Interstitial Lung Disease

In children with restrictive lung disease, the reactance values reduce with normal resistance values in IOS. Despite this theoretical concept, there is a paucity of evidence regarding the utility of IOS in follow-up of children with interstitial lung diseases.[5]

Limitations

Despite the benefits of the easy technique, FOT and IOS seem to have many limitations. Various FOT and IOS devices are available, but their harmonization of oscillometry devices seems to be a problem.[2] Trivial artifacts (glottic closure, tongue obstruction, variations in respiratory rate, and effort) lead to significant variations in FOT/IOS readings. Normative data in different geographical regions and races still need to be established. Large, multicenter studies are required to determine the multiethnic population's normal values across all ages, equivalent to Global Lung Function Initiative (GLI). There is a paucity of data on the repeatability of measurement, which makes the interpretation of any change difficult. There is also a lack of data on what is a significant deviation from normal, making definitions of obstruction and restriction difficult. Last but not least, the cost of the equipment is formidable.

Conclusions

Spirometry is the most useful pulmonary function test in children for the diagnosis and monitoring of various respiratory disorders. Various international authorities, such as the ERS and Global Initiative for Asthma, consider spirometry as the gold standard of investigation in children with asthma. FOT and IOS can be a useful complementary investigations for respiratory pediatricians in young children who are unable to perform spirometry and assessment of small airway disease in older children with asthma. Spirometry should remain the primary tool for pediatricians in secondary care, while FOT/IOS can be a useful add-on for pediatric pulmonology facilities.

Clinical Examples of Utility of Impulse Oscillometry System (These are Linked to Respective Figures)

Case 1

A 5-year-old boy with suspected asthma was subjected to spirometry but was unable to perform. IOS showed significantly raised R5 values with frequency dependence, suggestive of peripheral airway obstruction [Figure 4a].

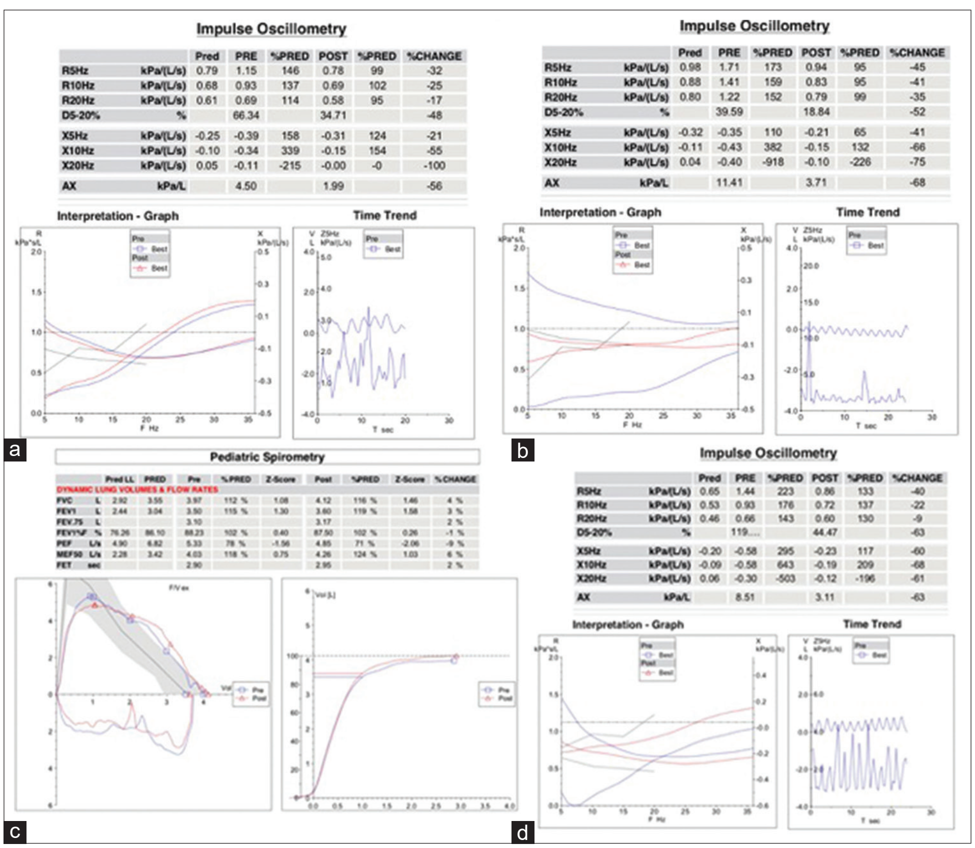

Figure 4: (a) Impulse oscillometry of Case 1 showing peripheral airway obstruction; Raised R5 value (>120) with postbronchodilator reversibility of −31% in R5 and −56% in Ax (b) Impulse oscillometry of Case 2 showing peripheral airway obstruction with bronchodilator reversibility; Raised R5 value (>150) with significant post bronchodilator reversibility of −45% in R5 and − 68% in Ax (c) Normal Spirometry of Case 3; (d) Impulse oscillometry of Case 3 showing significant obstruction with bronchodilator reversibility. Raised R5 value of 233 with −40% change in R5 and − 63% change in Ax postbronchodilator

Case 2

A 3-year-old girl with chronic cough without any wheeze. IOS shows significant obstruction with postbronchodilator reversibility in both R5 and Ax [Figure 4b].

Case 3

A 7-year-old boy with suspected asthma with frequent symptoms requiring nebulization with bronchodilators underwent lung function testing. His spirometry was normal (forced expiratory volume 1 [FEV1] and FEV1/forced vital capacity >−2SD), but IOS showed significant obstruction with reversibility (R5 >140, ΔR5 >20%, and ΔAX >40%) [Figure 4c and d].

Declaration of patient consent

The authors certify that they have obtained all appropriate patient consent forms. In the form, the patient(s) has/have given his/her/their consent for his/her/their images and other clinical information to be reported in the journal. The patients understand that their names and initials will not be published and due efforts will be made to conceal their identity, but anonymity cannot be guaranteed.

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Conflicts of interest

There are no conflicts of interest.

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