

# Oscillometry: A Toolkit for Healthcare Professionals

"Oscillometry has become one of the most valuable additions to my respiratory assessment toolkit. Its ability to detect small airway dysfunction with just quiet tidal breathing has transformed how I evaluate patients—especially children, older adults, and anyone who struggles with forced maneuvers. In asthma and COPD, it often highlights impairment long before spirometry changes appear, helping me tailor treatment with greater precision.

For research and clinical care alike, oscillometry offers a sensitive, patient friendly way to understand airway behavior and monitor disease over time. It has become an essential complement to spirometry and a powerful tool in advancing the mission we share through the American Lung Association: improving lung health and delivering earlier, more personalized care."

**Charlene E. McEvoy, MD, MPH**

Physician, Pulmonary, Sleep and Critical Care | St. Paul, MN  
Investigator, HealthPartners Institute | Bloomington, MN

This toolkit is designed to help healthcare professionals better understand respiratory oscillometry, also referred to as forced oscillation technique (FOT). Impulse oscillometry (IOS) is a sub-technique of respiratory oscillometry. You can review the sections below on clinical perspectives and mechanics, as well as various tools and attachments. While this toolkit does not go into the details of oscillometry interpretation, it does provide a brief overview.

This oscillometry toolkit includes:

## Clinical Perspectives

1. What is oscillometry? A simple overview
2. How does oscillometry work?
3. What are the key terms in oscillometry?
4. How does oscillometry compare to spirometry?
5. What is the clinical usefulness of oscillometry in the assessment and management of lung disease?
  - a. Can oscillometry assist with early detection of lung disease?
  - b. How can oscillometry lead to improved health outcomes?
6. When should oscillometry be used? A clinician decision guide

7. What are the challenges and limitations of oscillometry

## **The Mechanics of Oscillometry**

1. How does oscillometry use sound waves to measure lung function?
2. How do I conduct an oscillometry test?
3. How do I interpret oscillometry results?
4. What factors should be considered when selecting an oscillometer?
5. How is oscillometry coded for legal and appropriate reimbursement?

## **Attachments and Tools**

1. References
2. Breathing artifacts in oscillometry
3. Patient-facing educational fact sheet
4. Healthcare professional educational slide deck

## Clinical Perspectives

Oscillometry has been invaluable in my research studies to understand lung function and bronchodilator responses in patient populations where spirometry is difficult or impossible to obtain because of age developmental stage, or current disease status. This includes toddlers with recurrent wheeze and other complex airway conditions like dysphagia and tracheomalacia, children with Trisomy 21, children with neuromuscular disorders, and children who are presenting to the emergency department with an acute asthma exacerbation. I believe that oscillometry is an important quantitative outcome measure to consider in clinical trials of respiratory treatments because it allows inclusion of people who may be excluded from research study participation because of inability to perform the forced maneuvers of spirometry. Oscillometry also provides complementary information to other objective lung function tests to provide a holistic picture of lung health.

**Kate Hamlington Smith, PhD**

Assistant Professor of Pediatrics

Breathing Institute, Children's Hospital Colorado

Pediatric Pulmonary and Sleep Medicine, University of Colorado

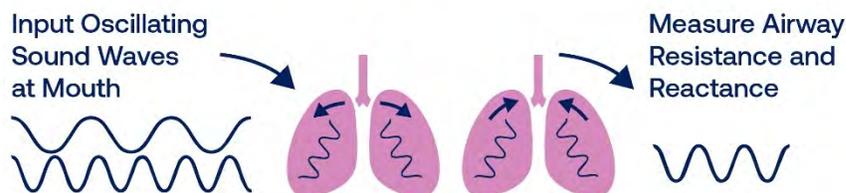
School of Medicine

### What is oscillometry? A simple overview

Respiratory oscillometry, also called forced oscillation technique (FOT), impulse oscillometry (IOS) or airwave oscillometry (AOS) is an objective lung function test that provides different information about the respiratory system that complements traditional lung function tests like spirometry and body plethysmography. Oscillometry is a non-invasive method for assessing the respiratory mechanics of the lung tissue (elasticity/stiffness), airways, and chest wall (compliance) during normal tidal breathing.

An oscillometry device generates sound waves, which are superimposed on a patient's passive tidal breathing, to measure respiratory resistance (degree of airway obstruction) and reactance (elastance or stiffness).

### How Oscillometry Works



Adapted from Dr. Kate Hamlington Smith, Children's Hospital Colorado, 2023.

This effort-independent lung function test is different from spirometry. Oscillometry requires:

- Passive breathing only – no forced maneuvers
- Minimal cooperation or coordination from the patient

Therefore, oscillometry is useful for young children, those who cannot perform acceptable spirometry maneuvers and, in many situations, where spirometry is contraindicated, such as during acute presentation of cardiac events (e.g. heart failure) or post cardiothoracic/abdominal/eye surgery.

## How Does Oscillometry Work?

Oscillometers apply different frequencies of airflow or gentle, small-amplitude pressure, through sound waves, at the mouth during passive tidal breathing. The frequency of the waves is usually in the range of 5 to 40 Hertz in clinical practice. This is a higher frequency than normal breathing to avoid interference between the breathing rate and measurement frequency. The device measures the response of the respiratory system to these waves.

Oscillometers use different techniques to generate these waves. The forced oscillation technique (FOT) delivers multi-frequency sinusoidal waves whereas the impulse oscillometry systems (IOS) deliver square waves as trains of individual frequencies.

Oscillometry provides the measurement of **respiratory system impedance**, which indicates how hard it is for air to move through the lungs during regular tidal breathing. Impedance is computed from the relationship between the input and output oscillating waves, which are pressure and flow signals. The respiratory impedance result that is measured by oscillometry depends on the frequency of the wave.

**Respiratory system impedance (total opposition to airflow) has two components:**

1. **Resistance (R)**: Reflects the degree of **airway obstruction** in the lungs (aka openness of airways).
2. **Reactance (X)**: Reflects elastic and inertial properties of the lungs. The **elastance** part of reactance (which is the inverse of **compliance**) reflects **stiffness** of the respiratory system (stiffness/elastance) of the lung tissue (aka expandability of airways and lung tissue).

## What are key terms in oscillometry?

### Impedance $\approx$ Resistance + Reactance

- **Impedance:** The total **opposition** to airflow. Impedance is calculated from the relationship between pressure and flow and expressed in units of pressure divided by flow rate.

cmH<sub>2</sub>O/L/s or kPa/L/s

- **Resistance (R):** Reflects the degree of **airway obstruction** in the lungs.
- **Reactance (X):** Reflects **elastic (stiffness) and inertial properties of the lungs**. Mainly reflects how much the lungs can stretch and recoil.
- **Frequency:** is usually measured at multiple frequencies simultaneously, between 5 and 40 Hertz in clinical settings. For example, R and X measured at 5 Hz are represented as R5 and X5.

### What Does Resistance (R) Show?

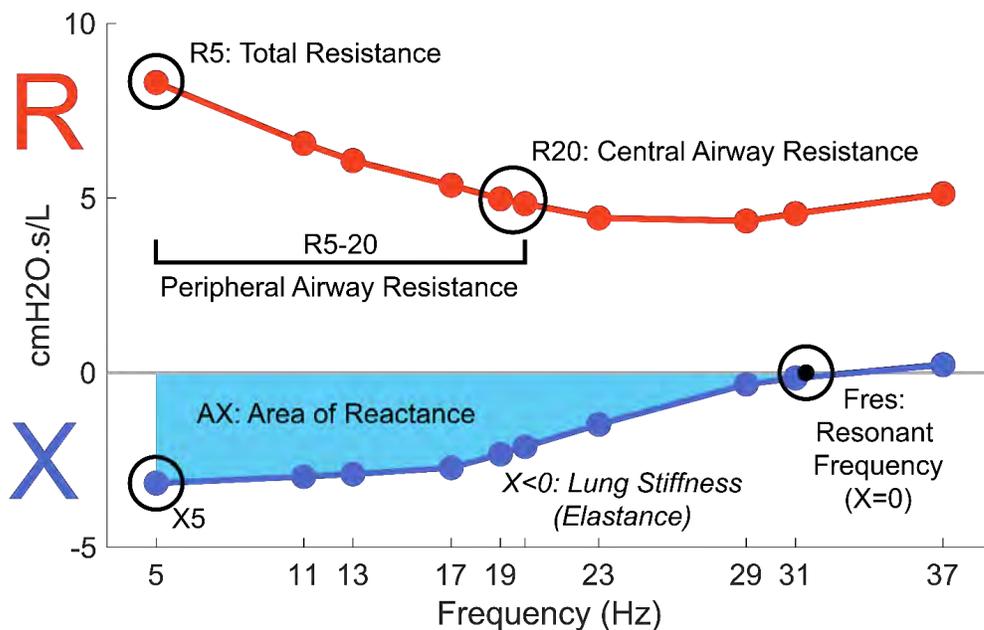
- **Airway Resistance:** Resistance to air moving through the airways
  - R increases with increased airway obstruction
  - Small changes in the diameter of an airway significantly affect resistance (degree of airway obstruction)
- **Frequency Dependence of Resistance:** Difference between total airway resistance measured at low frequency (5 or 7 Hz, e.g., R5) and central airway resistance measured at high frequency (19 or 20 Hz, e.g., R20)
- **R5-20 or R5-19:** Typical metric of frequency dependence of resistance
  - Resistance does not change very much across the frequency range measured in oscillometry because of numerous parallel peripheral airways, so R5-20 is usually small in adults (less frequency dependence in resistance)
  - R5-20 is increased in children (smaller lungs and fewer/smaller diameter peripheral airways) and with increased peripheral airway obstruction in disease

### What Does Reactance (X) Show?

- **Frequency dependence of Reactance:** Reactance (X) does normally increase from negative to positive with increasing frequency.
- **Elastance:** The elasticity (stiffness) of the respiratory system.
  - Shows how much the lungs can stretch and recoil.
  - Lung elastance is the inverse of lung compliance.
  - X is negative at lower frequencies where elastic properties dominate

- X (e.g., X5) becomes more negative with increased elastance (decreased compliance)
- **Inertance:** Opposition to acceleration forces in the larger airways
  - X is positive at higher frequencies where inertial properties dominate
  - X = 0: Elastic and Inertial properties are balanced.
- **Resonant Frequency (Fres):** The frequency where X = 0.
  - Fres is a larger frequency when elastic properties dominate (stiffer lungs)
  - Fres is a smaller frequency when inertial properties dominate (more air flow)
- **Area of Reactance (AX):** On the test results, the triangular area where X is negative, bounded by the lowest frequency and the resonant frequency (Fres).
  - AX is an integrative measure of the elastance component of reactance
  - AX increases with stiffer lungs and lung heterogeneity

A typical oscillogram is shown below with the Y-axis indicating the impedance and the X-axis indicating the frequencies at which the measurements are made.



Used with permission Dr. Kate Hamlington Smith, Children's Hospital Colorado

## Other Key Factors and Terms:

- **Airflow velocity/turbulence:** Turbulent flow (larger airways, high speed) creates more resistance than smooth laminar (smooth) flow (smaller airways, lower speed).
- **Air viscosity and length:** Thicker air (viscosity) and longer airways increase resistance.
- **Peripheral Airways:** The tiny, cartilage-free air passages deep within the lungs, ending in the alveoli, and play a key role in diseases like asthma and COPD.
- **Lung Heterogeneity:** The uneven, or non-uniform structure or function within the lungs, where different areas ventilate differently.
- **Lung Volume/Chest Wall:** Changes during breathing affect airway diameter and tissue elasticity. Changes in lung volume can affect the impedance measurements.
- **Frequency Waveform:** Oscillometry devices have different frequency waveforms at which impedance is measured.
  - **Impulse Oscillometry (IOS)** uses a loudspeaker to generate frequencies at multiples of the fundamental frequency, usually 5 Hz: 5, 10, 15, 20, 25, 30, 35 Hz.
  - **Spectral Oscillometry/Airwave Oscillometry (AOS)** uses a vibrating mesh to generate sinusoidal waveforms consisting of mutually prime frequencies.
    - 5-37 Hz waveform: 5, 11, 13, 17, 19, 23, 29, 31, 37 Hz
    - 7-41 Hz waveform: 7, 11, 13, 17, 19, 23, 29, 31, 37, 41 Hz
  - **Sparse waveform:** Typically consists of 5 or 7, 11, and 19 or 20 Hz.
  - **Mono-frequency:** Impedance generated a single frequency only.

## How does oscillometry compare to spirometry?

Oscillometry, like spirometry, is an objective lung function test. Spirometry measures volumes and flow rates during forced inspiratory and expiratory maneuvers. On the other hand, oscillometry measures the impedance to air flow throughout the respiratory system during tidal breathing. The two methods provide different information about lung mechanics.

The table below provides a comparison between these two objective lung function tests.

### Spirometry and Oscillometry: Evidence Based Comparison

| Feature                                       | Spirometry  | Oscillometry  |
|---|---|---|
| What this objective test measures <b>best</b> | Large airway dynamics (Krishnan, 2025)  | Peripheral / small airway dynamics (Krishnan, 2025)   |
| Key measures                                  | Measures <b>lung volumes and airflow</b> : <ul style="list-style-type: none"> <li>• FVC (Forced Vital Capacity)</li> <li>• FEV1 (Forced expiratory flow in 1<sup>st</sup> second)</li> <li>• Ratio for FEV1/FVC</li> </ul> (Krishnan, 2025) | Measures <b>respiratory impedance</b> using small amplitude oscillatory multi-frequency waves delivered at the mouth to measure respiratory: <ul style="list-style-type: none"> <li>• Resistance</li> <li>• Reactance</li> </ul> (Bates, 2011; Mou, 2024) |
| Primary use                                   | Gold-standard for the diagnosis of <b>airflow obstruction</b> (asthma, COPD) (Krishnan, 2025)   | Highly sensitive to <b>small-airway dysfunction</b> , therefore useful across asthma, COPD, and other conditions for early detection or response to treatment (Kaminsky 2022; Krishnan 2025)  |
| Level of patient effort required              | Requires <b>forceful, maximal effort</b> , often difficult for young children, elderly, or patient with illness (Krishnan, 2025; Patel, 2024)   | <b>Effort-independent</b> , requiring only tidal breathing – easier for young children and elderly and can be used in situations where spirometry is contra-indicated (Krishnan 2025; Morgan 2026)  |
| Sensitivity to small-airway disease           | Limited; FEF 25-75 may correlate but inconsistently (Mou, 2024)   | Superior sensitivity to small airway dysfunction, early detection of COPD symptoms and airway abnormalities (Mou, 2024)   |
| Measured dynamically or at rest               | Challenges airways through forced expiratory flow which reveals abnormalities   | Measures airways during normal breathing conditions (Gochicoa-Rangel, 2025)   |
| Bronchodilator response detection             | Changes in FEV1/FVC used to assess responsiveness (Krishnan, 2025)  | Changes in Resistance (R) and Reactance (X) used to assess responsiveness (King, 2020; Krishnan, 2025; Morgan, 2026; Thamrin, 2007)<br><br>More sensitive to detect bronchodilator responsiveness (Mondal, 2019)  |
| Test duration                                 | Longer- requires repeated coached maneuvers and rest periods (Patel, 2024)  | Shorter, quick to perform (30-60 second maneuvers) (EPR Guidelines, 2007; Morgan, 2026 Patel, 2024;   |

|   |  |  |
|---|--|--|
| Key metric to aid in medication therapy | FEV1 guides medication therapy in asthma (NHLBI, 2007)<br><br>FEV1, along with patient's symptoms and exacerbation risk, guide COPD therapy (GOLD, 2025) | No established metric to guide medication therapy (Adbo, 2023)   |
| Patient burden                          | May provoke cough, breathlessness, and fatigue (e.g. IPF) (Patel, 2024)  | Associated with less symptom burden (Patel, 2024)  |
| Ideal populations                       | Older children and adults who can follow instructions  | Anyone but particularly the very young children ( $\geq 3$ years), patients with cognitive or language barriers through lifespan (ATS, 2023) |

## What is the clinical usefulness of oscillometry in the assessment and management of lung disease?

Oscillometry may be clinically useful to:

1. **Be used across the lifespan.** "To date, there is no evidence that impedance measurements in infants contribute to clinical decision-making. However, oscillometric studies have contributed to the pathophysiological understanding of respiratory disease in infants, particularly those with wheezing disorders." (Kaminsky, 2022).
2. **Assessment of young children.** Oscillometry may be useful in pediatric practices because it is easier to perform with small children. This test can assist to predict airway disease and diagnose lung dysfunction at an earlier age, leading to decreased short-acting bronchodilator use, symptoms, exacerbations, airway remodeling, emergency department visits, and hospitalizations (Corazalla, 2026).
3. **Identification of co-existing lung disease in adults where respiratory symptoms can be masked by underlying comorbidity.** Oscillometry may be useful in settings such as congestive heart failure (CHF), underlying chronic rheumatologic (e.g. chronic myositis, myopathies) where symptoms of dyspnea are inappropriately attributed to non-respiratory cause. Oscillometry could be used for example in the setting of acute exacerbations of CHF in the emergency room to rule out co-existing lung disease.
4. **Monitor an individual's environmental or occupational exposures over time** by detecting **subclinical changes in airway resistance and reactance**, particularly in the small airways, that may occur before spirometric abnormalities appear. Because oscillometry requires only quiet tidal breathing, it is well suited for **repeated longitudinal testing**, allowing clinicians to track trends in lung mechanics associated with ongoing or intermittent exposures (e.g., dust, fumes, smoke). Studies have shown oscillometry abnormalities in exposed individuals with persistent respiratory symptoms despite normal spirometry, supporting its role in exposure surveillance (Berger 2013; King 2020).
5. **Assess reduced lung compliance** (meaning the lungs are stiff and difficult to inflate, requiring more pressure to expand, a hallmark of restrictive lung disease) (Ishikawa 2024; Oostveen 2003; O'Rourke 2025; Wu 2022; Wu 2025)
6. **Detect small-airway dysfunction**, which may appear before it can be detected in spirometry test results. This makes it valuable for assessing and phenotyping asthma, COPD and other obstructive or post-infectious airway diseases (Brashier 2015; Kaminsky 2022; King 2020; Ribeiro, 2018; Singh 2020; Usmani 2021;)
7. **Track treatment response after bronchodilator or anti-inflammatory therapy** (Cottee 2020; Donohue 2024; Navanandan 2020; Shing Takahask 2023)

8. **Predict COPD exacerbations.** A clinical study using daily home oscillometry found significant physiological changes 5-7 days before the COPD exacerbations. This may require home oscillometry for monitoring, something that is likely cost prohibitive. (ATS, 2023)
9. **Manage disease long-term** because oscillometry can detect small airway dysfunction and physiological deterioration earlier than spirometry, even when forced expiratory measures remain stable (King, 2020).

## How can oscillometry lead to improved health outcomes?

Oscillometry may lead to improved health outcomes by:

1. Objectively **evaluate early changes in respiratory health and response** to medication therapy in populations when other methods are not available (Desormeau 2023; Elias 2026).
2. **Predicting COPD exacerbations.** This prognostic value provides a window for prevention. (ATS, 2023 Conference report; Huang 2025; Park, 2024; Zhang 2022; Zimmermann, 2020).
3. **Informing treatment responsiveness and treatment plans during an asthma exacerbation** (Navanandan, 2020; Navanandan, 2025; Takahask, 2023)
4. Reactance parameters were found to be **more sensitive in identifying poor asthma control than spirometry**, supporting the use of oscillometry to complement spirometry in the clinical management of asthma (Cottee, 2020).
5. By assessing lung abnormalities early, **oscillometry may then reduce the need for medications** which could then **reduce healthcare costs** and the **long-term effects** of high-dose inhaled corticosteroids. (Bhattarai, 2020; Pisi, 2021; Qvarnstorm, 2023; Veneroni, 2023)

## When Should Oscillometry Be Used: A clinician decision guide

The current gold standard test used to diagnosis asthma and COPD is spirometry. For this reason, most experts recommend that oscillometry should not be used as a standalone diagnostic tool but rather in conjunction with spirometry, plethysmography, and clinical history and other investigations such as chest imaging and appropriate blood work.

However, oscillometry can be clinically useful as outlined in the “*What Is the Clinical Usefulness of Oscillometry in the Assessment and Management of Lung Disease*” section above.

Below are some suggested uses for oscillometry in the clinical setting.

### Indications for oscillometry use:

1. If the patient is unable to perform spirometry, oscillometry is recommended (i.e. too young, too old or situations where patient is unable to follow instructions to perform spirometry, presence of contraindication to forced expiratory maneuvers but at risk for undiagnosed lung disease) (ATS, 2023). Normal oscillometry can rule out underlying lung disease. Abnormal oscillometry indicates the need for further assessment.
2. If results from spirometry are normal, but the patient remains symptomatic, oscillometry is recommended (Kaminsky, 2022) and subsequent follow up is indicated.
3. Oscillometry can be helpful in early detection and diagnosis of lung disease as it is more sensitive than spirometry at assessing small airway dysfunction (Kaminsky 2022; Ribeiro 2018; Usmani, 2021).
4. Oscillometry can be used to monitor medication treatment response (Abdo, 2023; Cottee, 2020; Donohue, 2024; GOLD 2025; Navanandan, 2020; NHLBI, 2027; Shing Takahask, 2023).
5. Monitor an individual’s environmental or occupational exposures over time. (Berger, 2013; King, 2020).
6. Oscillometry can also help predict COPD exacerbations and can be used during an exacerbation to inform treatment plans (Navanandan, 2020; Shingo Takahashi, 2023; Zimmermann, 2020).
7. Assess bronchodilator responses and airway hyperresponsiveness when spirometry is not possible or in addition to spirometry (discordant responses could reveal otherwise missed reactive airways) (Mondal, 2019).

## Considerations When Implementing an Oscillometry Test

### Creating a Process for Conducting Oscillometry Tests

When implementing oscillometry in clinical practice, consider the following:

1. Have at least one clinic staff adequately trained in performing the procedure.
2. Establish written protocols and procedures to match the intended use and audience (e.g. infants, preschool- and school-aged children, elderly, occupational screening and home monitoring).
3. Testing can be performed in an exam or procedure room, the portability of some devices allow for testing at the bedside.
4. Oscillometry should be conducted first, if other lung function tests such as spirometry are planned during the same clinic visit. This ensures that oscillometry is evaluated at FRC. Tests that require deep breaths and forced maneuvers will change the lung volume (King, 2020).
5. Testing generally takes 15 minutes when measuring a patient’s baseline lung function. If obtaining a pre- and post-bronchodilator response, 30 minutes should be allocated.
6. See *How to Conduct an Oscillometry Test* section for more information.

### Challenges and Limitations in Oscillometry

1. **Lack of standardization and validation.** There are few accepted reference values for certain age groups and populations (Zhu-Quan Su, 2018). Also different oscillometry devices often produce non-interchangeable results. “Differences in methodologies across laboratories or manufacturers can lead to inconsistencies in results. While efforts are being made to establish standardized guidelines, variations in testing procedures continue to pose challenges in ensuring uniformity.” (Krishnan, 2025).
2. **Limited guideline support** – Oscillometry is not routinely recommended by international clinical guidelines, which limits its adoption and insurance reimbursement (Krishnan, 2025). However recent ERS and GINA guidelines have mentioned oscillometry, in particular for preschool-aged children in diagnostics with asthma (GINA, 2025; Makrinioti, 2024).
3. **Interpretation challenges** – Interpretating oscillometry data is more complex than interpreting standard spirometry results (Krishnan, 2025; Sarkar, 2023). This demands additional training for healthcare providers.
4. **Technical limitations** – Oscillometry tests can be affected by breathing patterns, requires the patient to hold still, and can be inaccurate in certain patient populations (Kaminsky 2022; Krishnan 2025).

5. **Clinical efficacy evidence** – There is limited evidence demonstrating that routine oscillometry monitoring improves clinical outcomes (Krishnan 2025).
6. **Cost and equipment availability** – The cost of high-quality oscillometry devices can be expensive, limiting access across healthcare settings. (Krishnan 2025; Saadeh 2015).
7. **Lack of integration with electronic health records** – Like most pulmonary function test equipment, oscillometry device integration with electronic health records is a challenge. However, many oscillometry device manufacturers emphasize smartphone or cloud connectivity for clinician review and remote monitoring rather than direct electronic health record synchronization.

# The Mechanics of Oscillometry

## How Does Oscillometry Use Sound Waves to Measure Lung Function?

In oscillometry, sound waves are artificially generated pressure oscillations that ride on top of a person's normal breathing (tidal breathing).

1. A loudspeaker (or a piston or a vibrating mesh) inside the oscillometry device is used to generate sound waves.

- The speaker diaphragm moves back and forth.
- This motion creates small pressure fluctuations in the air—basically sound waves.

2. Oscillations enter the lungs

- The patient breathes normally through a mouthpiece.
- While the patient breathes, the device superimposes these sound waves into the airflow.
- The oscillations are low-amplitude (gentle) and usually low frequency (about 5–35 Hz).

3. As the sound waves travel inside of the airways

- Some energy is resisted by airway narrowing and friction.
- Some energy is stored and released by the elastic tissues of the lungs.
- Some energy is reflected due to changes in airway size.

This interaction changes the phase and amplitude of the sound waves.

4. Sensitive sensors measure:

- **Pressure** changes
- **Flow** changes

From these pressure and flow changes, the oscillometry device calculates **respiratory impedance (total opposition)**, which includes:

- **Resistance (R)** (airway obstruction)
- **Reactance (X)** (stiffness/elastance)

5. Sound waves are perfect for lung function measurement because they:

- Travel easily through air
- Can probe different airway sizes depending on frequency
- Do not require forced breathing

By measuring how these waves change as they travel through the airways, the device can calculate respiratory impedance (total opposition), separating airway resistance (airway obstruction) and reactance (stiffness/elastance). Using different frequencies helps the system assess both large and small airways.

## How To Conduct an Oscillometry Test

### Equipment, Materials, and Software Preparation

1. Refer to the manufacturer's instruction manual for specific device instructions.
2. Select New Patient, if appropriate, and enter the patient's information such as first and last names, date of birth, birth sex, height, weight and smoking history.
3. Ensure that the correct waveform is selected depending on the device.
4. King (2020) recommends performing regular biological controls as part of your clinic's procedures.
5. Ensure that the appropriate set of reference values is selected (Deprato, 2022). Chang (2022) recommends the following reference values: Oostveen or Brown for adults and Nowowiejska for children ages 3 to 17. However, newer reference equations for pediatrics are now available (Ducharme, 2025).  
NOTE: The preferred and availability of reference values may differ depending on the patient population and oscillometry device manufacturer. **It is ideal to use the reference equations developed with the specific device that is being used.**

### Patient Screening and Preparation

1. Follow the normal screening procedures for the pulmonary function lab or clinic. There is no evidence that oscillometry transmits respiratory pathogens (Wu, 2021).
2. Ensure that the patient has not had any recent dental or facial surgeries, such as tooth extractions, and can form a proper tight seal around the mouthpiece.
3. Ensure that the patient is as relaxed as possible, is not wearing tight-fitting clothing and withholds from tobacco use and vigorous exercise at least 1 hour prior to testing.
4. Perform oscillometry prior to other pulmonary function tests, such as spirometry or exhaled nitric oxide (FeNo) testing.

5. Withhold bronchodilators prior to testing, unless otherwise instructed by a referring provider. Record patient's usage of bronchodilators, dosage, time/date of last administration and any medication allergies.
6. Verify the patient's information: first and last names, date of birth, birth sex and height.
7. Measure the patient's height without shoes, with feet together, standing as tall as possible with the eyes level and looking straight ahead, and the back flush against a wall or flat surface.
  - NOTE: For patients unable to stand erect, height may be estimated using arm span. For patients aged 25 years or older, where height measurements have been made previously in the same laboratory, remeasuring height at subsequent visits within 1 year may not be necessary.

### Preparing the Patient and Starting the Test

1. Attach a single-patient-use bacterial/viral filter to the oscillometry device.
2. Ensure that the oscillometry device is ready in the testing mode.
3. Explain the test to the patient.
  - Describe the sensation generated by oscillations such as 'vibrations' or 'fluttering.'
  - Instruct the patient to breathe normally while holding their cheeks with their palm and fingers and using their thumbs to support the soft tissue of the jaw during measurements. If they are unable to hold their cheeks themselves, you may hold it for them.
  - Explain to the patient that swallowing should be avoided and the tongue must be below the mouthpiece during the test.
  - It can be helpful for younger children to first handle and put on the nose clips and practice putting the oval end of the filter in their mouth.
4. **Positioning:**
  - **Device:** If holding the device, the operator should sit or stand in front of the patient and be able to view both the patient and the computer screen showing the measurement recording.
    - If using a support arm, make sure the device is positioned so the mouthpiece is directly in front of the participant's mouth and the participant's torso is upright without slouching down or reaching up.
  - **Patient:** The patient should sit upright in a chair with feet on the floor, or they may sit in their caregiver's lap.
    - The operator can stand behind the participant to hold cheeks while watching the screen and checking for mouth seal.

5. **Cheek Support:** The patient (if able) should gently support their cheeks with their hands with thumbs under jawbone (not too tight). If unable, another person can stand behind the patient and apply very gentle pressure to the patient's cheeks. If a patient is sitting in a caregiver's lap, a caregiver can hold cheeks.
6. **Nose clip:** Nose clip should completely seal the nasal passages. Use tissue paper if the nose clip is slipping. If a child is not tolerating, another person can gently pinch the child's nose shut. If
7. **Mouth Seal:** Mouth should completely seal around the filter opening so that there is no air leak
8. **Tongue:** Tongue should not occlude filter opening and can be positioned under the filter opening
9. **Head Tilt:** Gently position the device such that the participant faces approximately 15 degrees upwards from the horizontal plane to ensure there is no compression on the upper airways that could lead to elevated resistance readings.
10. For young children, a video may provide a needed distraction. Ensure the video screen is directly in front of participant or slightly above eye level during the test.
11. Ask the patient to wet his/her lips before wrapping them around the mouthpiece to form a proper, tight seal.
12. Instruct the patient to continue steady, quiet breathing through the filter. NOTE: Supplementary oxygen must be turned off during measurements to avoid any drift into the oscillometry device.
13. Remind the patient of the 30 second test duration and the minimum requirement of three measurements.
14. Before starting the test, watch for at least 3 steady breaths on the testing screen to ensure that the patient is breathing at their normal resting respiratory rate. It is helpful to take a baseline respiratory rate before doing the test for reference. Coach patients to slow breathing rate if they are breathing faster than normal.
15. **Start recording.** Continue watching patient and screen, **coach gentle steady breathing** with consistent tidal volume and respiratory rate, and make sure mouth is sealed around the filter. NOTE: During the test, inform the patient of the time remaining during each measurement.

## Quality Control During the Test and Determining Acceptable Measurements

1. Ensure that the patient's breathing during the test is representative of their resting breathing state before they start the test.
2. During the measurement recordings, watch the breathing traces and patient behavior. Things to observe and correct:
  - Leak around the mouthpiece
  - Nasal passages not fully occluded
  - Rapid breathing that was not present before the test started
  - Very slow or deep breathing that was not present before the test started
  - Irregular/variable breathing or combinations of rapid/deep/shallow breathing
  - Breath holding or glottis closure
  - Tongue occluding the mouthpiece opening
  - Swallowing, coughing, laughing, talking, or humming
3. **Measurement Acceptability:** At least 3 (ideally at least 5) breaths that are free from artifact in each recording.
  - Oscillometry device software programs may have algorithms that automatically exclude breaths with artifacts, and manual exclusions may be possible.
  - **Note:** Children normally have a higher respiratory rate and will have many breaths over a 20–30 second recording. Adults will have a slower respiratory rate and the recording time may need to be extended to have 3–5 breaths in one recording.
  - The R and X values that are reported for each individual recording are averaged from the non-excluded data collected over that recording period.
4. After obtaining the first 1-2 measurements, review the results and the breathing traces and coach the patient if needed. Looking for steady breathing in the time traces – there should be minimal variation in tidal volume and respiratory rate during the recording. Impedance measurements are sensitive to the breathing volume and rate. It is important for the breathing volume and rate to reflect the patient's resting state.
5. Review the plots of R and X across the spectrum of frequencies measured.
  - Typically, R at the lowest frequency (e.g., R5) will be greater than or similar to R at the next highest frequency (e.g., R10 or R11). The R curve should not bend significantly towards zero.
  - Similarly, X at the lowest frequency (e.g., X5) should be less than X at the next highest frequency (e.g., X10 or X11). The X curve should not bend significantly towards zero.
  - If these paradoxical curved bends are present, this could indicate leaking and/or panting into the device. Check that the patient has a proper mouth seal and is breathing at their resting rate.

- Caution should be used in interpreting the 5 Hz values in these cases as they may be artificially closer to zero due to breathing and/or signal processing artifact.
  - If available, choice of a pediatric waveform starting at a higher frequency (e.g., 7 or 8 Hz) may improve results in the preschool age group who naturally have a higher respiratory rate.
6. Continue taking 3-4 more measurements and reviewing results.
- Unlike spirometry, where the single “best” maneuver is selected for reporting, the current convention is to report the average of each R and X value from at least 3 acceptable measurements.
  - It is advisable to take more than the minimum of three measurements to ensure the possibility of including at least 3 acceptable measurements on average.
7. **Measurement Exclusion:**
- Measurements with breathing artifacts/abnormal patterns or obvious abnormalities, or that do not include at least 3 whole breaths, should be excluded from the test average.
  - R and X curves that fall significantly out of the cluster of the other measurement curves (clear outliers) and are accompanied by breathing artifact or evidence of non-resting breathing patterns should be excluded from the test average.
  - Coherence is a statistical measure that shows how reliable the signal is between the pressure oscillations sent into the airway and the airflow measured coming out. High coherence (close to 1) means there is a good signal, little noise and a reliable measurement. Low coherence means the signal is contaminated by noise, irregular breathing, coughing, swallowing, leaks or movement. In the past, coherence was used to judge if a test was good quality. However, current guidelines indicate that you should not rely on coherence as a standalone criterion for measurements of acceptability.
8. **Measurement Repeatability:**
- An acceptable test has at least 3 repeatable measurement recordings that each have 3-5 acceptable breaths.
  - Per current guidelines repeatability means that the coefficient of variation (CoV = standard deviation/mean) in R5 (or the lowest frequency resistance) is:
    - $CoV \leq 15\%$  in children
    - $CoV \leq 10\%$  in adults.
  - In addition, the R and X curves should not show significant variability across the frequency spectrum

## To Evaluate Airway Response Post-Bronchodilator Administration – optional

1. Administer bronchodilator via a valved-holding chamber. Ensure acceptable technique.
2. Record the method and number of doses administered.
3. Wait for at least 15 minutes.
4. Repeat above testing steps assess post-bronchodilator response

## Disinfection

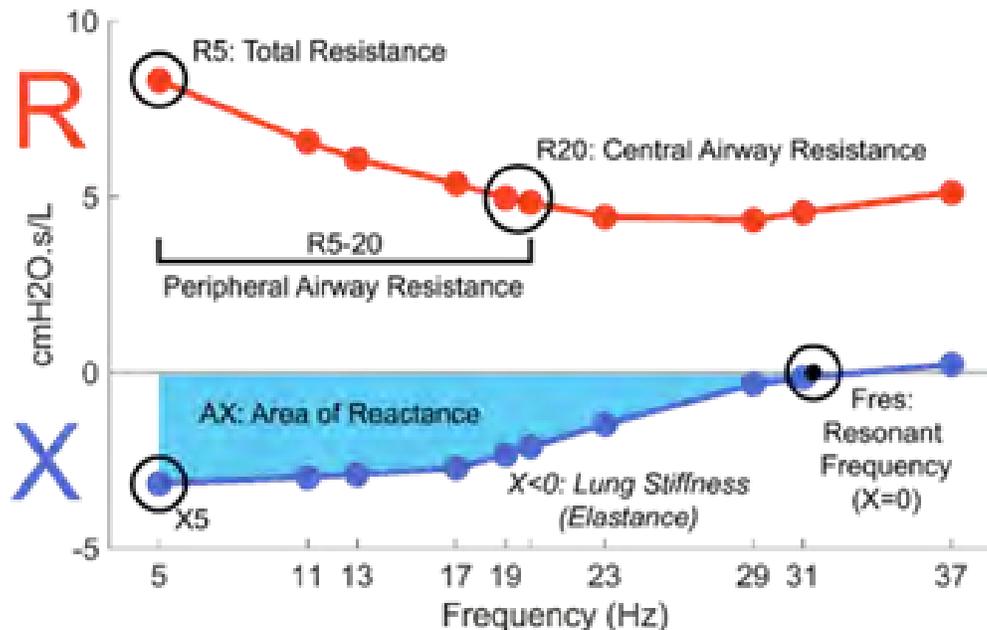
1. Discard patient's mouthpiece and nose clip.
2. Use disinfectant wipes to clean the oscillometry device and patient chair.

## Reporting test results (Chang, 2022)

1. Include patient's first and last names, height, age, and birth sex.
2. Include input signal frequencies and duration of individual recordings.
3. Report on the mean of acceptable and reproducible measurements and the CoV for these reported measurements.
4. Report the reference equations used and report z-scores from these equations.
5. Include impedance graph demonstrating Rrs and Xrs versus oscillation frequency.
6. Include post-bronchodilator response with dosage and method of administration including z-scores and absolute percentage change – optional

## How to Interpret Oscillometry Results

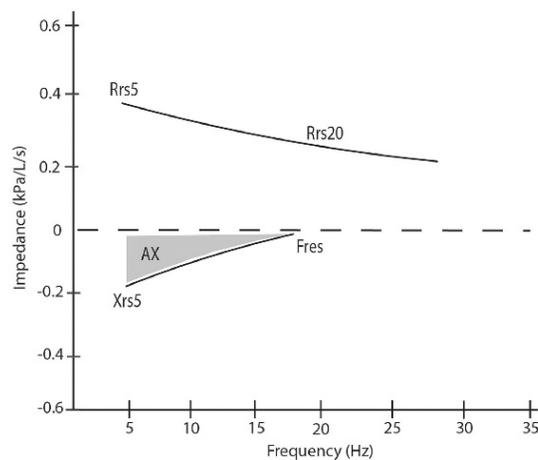
While the goal of this toolkit is not to provide in-depth instruction on oscillometry interpretation, the following provides a brief overview (Biswas, 2025; Brashier, 2015; Gochicoa-Rangel, 2025; Gupta, 2021; King, 2020; Liang, 2022).



### Steps to Oscillometry Interpretation:

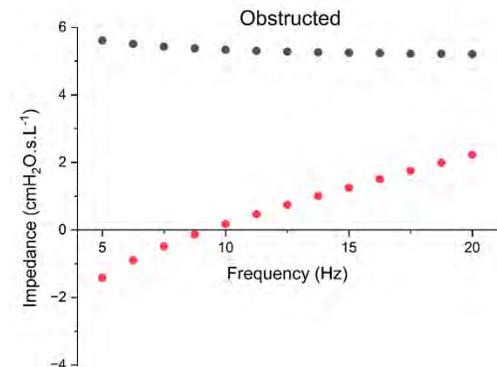
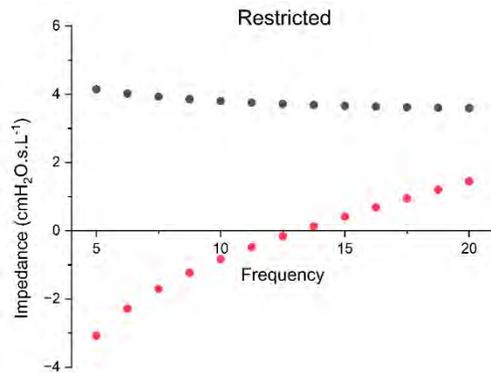
1. Check quality metrics (COV1 coherence)
  - Coefficient of Variation: <10% for adults, <15% for children (R5 parameter).
  - Repeat at least 3 tests for a valid session.
  - Coherence: 0.85 ensure signal reliability (coherence is not recommended for quality assessment on its own).
2. Review R5, total resistance
  - R5 (resistance at 5Hz) reflects the total respiratory system resistance from central and peripheral airways.
  - Increased R5 suggests overall airway narrowing, as in asthma, COPD or acute bronchoconstriction.
  - Normal R5 means total airway resistance is within expected limits.
3. Review R5-R20, small airway resistance
  - R20 (resistance at 20 Hz) primarily reflects large/central airways.
  - R5-R20 means small airway narrowing, often the earliest sign of obstructive lung disease.

- A normal R20 but elevated R5-R20 can indicate isolated small airway disease.
  - R19 and R5-19 can be interpreted in the same way as R20 and R5-20.
4. Review X5: Small airway reactance
- X5 (reactance at 5 Hz) reflects the elastic and inertial properties of peripheral airways.
  - More negatively increased X5 values means stiffer, less compliant small airways.
  - This is seen in restriction, such as fibrosis or interstitial lung disease) and in severe small airway obstruction, such as asthma and COPD.
5. Review AX: Area under the Reactance Curve
- AX is the integrated area under the reactance curve from 5 Hz to Fres (resonant frequency or zero-crossing).
  - Increased AX indicates greater small airway dysfunction and can amplify findings from X5.
  - AX is highly sensitive to early changes in small airways.



Reprinted from Ducharme, F. M., & Chan, R. (2025). *Oscillometry in the diagnosis, assessment, and monitoring of asthma in children and adults*. *Annals of Allergy, Asthma and Immunology*, 134(2), 135–143. <https://doi.org/10.1016/j.anaai.2024.11.013>, with permission from Elsevier.

6. Identify the pattern (peripheral, restrictive, obstructive).



7. Add within-breath analysis, expiratory flow limitation or inspiratory flow limitation detection.

#### Expiratory Flow Limitation (EFL)

- Defined as markedly higher expiratory resistance/reactance compared to inspiration.
- EFL is a hallmark of COPD, severe asthma, and other obstructive diseases.
- Mechanism: During expiration, small airways collapse prematurely, trapping air.
- Oscillometry signal:
  - R5 (expiratory) markedly higher than R5 (inspiratory)
  - More negative X5 (exp) than X5 (inspiratory)
  - Often seen with dynamic hyperinflation.

#### Inspiratory Flow Limitation (IFL)

- Characterized by higher inspiratory resistance/reactance compared to expiration.
- Suggestive of restrictive mechanics, including upper airway restriction, interstitial lung disease, and chest wall disorders.
- Mechanism: Increased stiffness or structural limitation reduces inspiratory compliance.
- Oscillometry signal:
  - R5 (inspiratory) markedly higher than R5 (expiratory)
  - X5 more negative during inspiration.

#### Why It Matters:

- Whole-breath results may appear borderline or normal, but within-breath analysis can reveal dynamic airway behavior that guides diagnosis and therapy.

- Expiratory flow limitation (EFL) detection can prompt earlier COPD intervention.
  - Inspiratory flow limitation (IFL) patterns can push work-up toward restrictive or neuromuscular causes rather than obstructive disease.
8. Consider reversibility, pre- and post-bronchodilator
- According to technical standards supported by the American Thoracic Society (ATS) and European Respiratory Society (ERS), oscillometry is used to detect asthma through measures of increased respiratory resistance (R) and reactance (X). Recommended bronchodilator responsiveness (BDR) thresholds for asthma, based on the 95<sup>th</sup> percentile in healthy individuals, are defined as:
    - R5 ↓ by ≥40%
    - X5 ↑ by ≥50%
    - AX ↓ by ≥80%

## What Factors Should Be Considered When Selecting an Oscillometer?

The following factors should be considered when selecting an oscillometer for a clinic setting:

1. FDA approval for intended clinical use
2. Clinical validation data demonstrating accuracy, repeatability, and sensitivity
3. Measurement parameters available (e.g., R5, R20, X5, AX, Fres)
4. Quality control algorithms (coherence, leak detection, artifact rejection)
5. Reference equations included and appropriateness for patient population
6. Age range and feasibility (pediatric, adult, elderly)
7. Ease of operation and consistency between operators
8. Patient coaching aids (real-time feedback, animations, visual cues)
9. Turnaround time per test for busy clinic workflows
10. Report clarity to aid clinical interpretability
11. Data connectivity (electronic health record integration, export formats)
12. Physical footprint and portability within clinic spaces
13. Consumables and infection control compatibility
14. Calibration procedures and ongoing maintenance needs
15. Total cost of ownership (device, software, disposables, service)
16. Vendor support, software updates
17. Training availability

## How Is Oscillometry Coded for Legal and Appropriate Reimbursement?

Oscillometry is a reimbursable lung function test.

### CPT Codes for Oscillometry

- **94728:** Airway resistance by impulse oscillometry.
- **94060:** Evaluation of wheezing – performance is measured before and after the administration of a bronchodilator drug
- **94070:** A provider deliberately induces bronchospasm by controlled and measurable exposure to a specific stimulant. They test lung function multiple times to evaluate the lung function under induced bronchospasm.

### Coding considerations

1. **Bundling:** Code 94728 cannot be reported with certain other pulmonary function tests, such as spirometry (94010) or bronchodilator response (94060).
2. **Specificity:** Always check the specific type of test performed to ensure the correct code is used, as there may be other codes for different types of airway resistance or lung volume measurements.
3. **Modifiers:** Modifiers may be needed in certain situations. For example, Modifier 26 (Professional Component used when billing only the provider's professional work, but not the equipment, supplies, or technical side) and TC (Technical Component when the provider bills only the technical portion of a service and not the provider's interpretation) can be used when the professional and technical components of the service are provided by different entities.

## Attachments and Tools

1. References
2. Breathing artifacts in oscillometry
3. Patient-facing educational fact sheet
4. Healthcare professional educational slide deck

## References

1. Abdo, M., et al. (2023). Minimal clinically important differences in asthma outcomes. *European Respiratory Journal*, 61(3), 2201793. <https://doi.org/10.1183/13993003.01793-202>
2. Bates, J. H. T., Irvin, C. G., Farré, R., & Hantos, Z. (2011). Oscillation mechanics of the respiratory system. *Comprehensive Physiology*, 1(3), 1233–1272. <https://doi.org/10.1002/cphy.c100058>
3. Berger, K. I., Wohlleber, M., Goldring, R. M., Reibman, J., Farfel, M. R., Friedman, S. M., ... Shao, Y. (2021). *Respiratory impedance measured using impulse oscillometry in a healthy urban population. ERJ Open Research*, 7(1). <https://doi.org/10.1183/23120541.00560-2020>
4. Bhattarai, P., et al. (2020). Clinical application of forced oscillation technique (FOT) in early detection of airway changes in smokers. *Journal of Clinical Medicine*, 9(9), 2778. <https://doi.org/10.3390/jcm9092778>
5. Biswas, R. (2025, July 16). *How to Interpret PulmoScan oscillometry data*. PulmoScan. Retrieved Feb 1, 2026 from <https://pulmoscan.cognitalabs.com/how-to-interpret-pulmoscan-oscillometry-data/>
6. Brown, N. J., Xuan, W., Salome, C. M., Berend, N., Hunter, M. L., Musk, A. W., James, A. L., & King, G. G. (2010). Reference equations for respiratory system resistance and reactance in adults. *Respiratory Physiology & Neurobiology*, 172(3), 162–168. <https://doi.org/10.1016/j.resp.2010.05.013>
7. Brashier, B., & Salvi, S. (2015). Measuring lung function using sound waves: Role of the forced oscillation technique and impulse oscillometry system. *Breathe*, 11(1), 57–65. <https://doi.org/10.1183/20734735.020514>
8. Chang, E., Vasileva, A., Nohra, C., Ryan, C. M., Chow, C.-W., & Wu, J. K. Y. (2022). *Conducting respiratory oscillometry in an outpatient setting. Journal of Visualized Experiments*, (182), Article e63243. <https://doi.org/10.3791/63243>
9. Children's Colorado Pediatric Professionals. (2023, January 27). *Measuring lung function with oscillometry* [Video]. YouTube. [https://www.youtube.com/watch?v=70C\\_etF84aA](https://www.youtube.com/watch?v=70C_etF84aA)
10. Corazalla, Edward O. Personal communication. January 28, 2026.
11. Cottee, AM, Seccombe, LM, Thamrin C, King GG, Peters MJ, Farah CS.. (2020). Bronchodilator response assessed by the forced oscillation technique identifies poor asthma control with greater sensitivity than spirometry. *Chest*, 157(6), 1435–1441. <https://doi.org/10.1016/j.chest.2019.12.035>
12. Dellacà, R. L., et al. (2004). Detection of expiratory flow limitation in COPD using the forced oscillation technique. *European Respiratory Journal*, 23(2), 232–240. <https://doi.org/10.1183/09031936.04.00046804>
13. Deprato, A., Ferrara, G., Bhutani, M., et al. (2022). Reference equations for oscillometry and their differences among populations: A systematic scoping review. *European Respiratory Review*, 31(165). <https://doi.org/10.1183/16000617.0021-202>
14. Desormeau, B., Smyrnova, A., Drouin, O., & Ducharme, F. M. (2023). Real-life impact of oscillometry in clinical assessment of preschoolers with asthma. *Respiratory Medicine*, 209, 107148. <https://doi.org/10.1016/j.rmed.2023.107148>
15. Donohue, P. A., & Kaminsky, D. A. (2024). The role of oscillometry in asthma. *Current Opinion in Pulmonary Medicine*, 30(3), 268–275. <https://doi.org/10.1097/MCP.0000000000001057>
16. Ducharme, F. M., & Chan, R. (2025). Oscillometry in the diagnosis, assessment, and monitoring of asthma in children and adults. *Annals of Allergy, Asthma & Immunology*, 134, 135–143. <https://doi.org/10.1016/j.anai.2024.11.013>

17. Elias, D. B., Amin, R., et al. (2026). Reversible airway obstruction on impulse oscillometry in preschool children with bronchopulmonary dysplasia. *The Journal of Pediatrics*. <https://doi.org/10.1016/j.jpeds.2026.115013>
18. Global Initiative for Asthma. (2025). Global Strategy for Asthma Management and Prevention. <https://ginaasthma.org>
19. Gochicoa-Rangel, L., & Vargas, M. H. (2025). How best to choose an oscillometer and reference equations for your patients with asthma. *Annals of Allergy, Asthma & Immunology*, 134, 159–164. [https://www.annallergy.org/article/S1081-1206\(24\)01681-8/fulltext](https://www.annallergy.org/article/S1081-1206(24)01681-8/fulltext)
20. Global Initiative for Chronic Obstructive Lung Disease. (2025). *Global strategy for prevention, diagnosis and management of chronic obstructive pulmonary disease (2025 report)*. Retrieved from <https://goldcopd.org/2025-gold-report/>
21. Gupta, N., Sachdev, A., Gupta, D., & Gupta, S. (2021). Oscillometry–The future of estimating pulmonary functions. *Karnataka Pediatric Journal*, 35(2), 79–87. [https://doi.org/10.25259/KPJ\\_25\\_2020](https://doi.org/10.25259/KPJ_25_2020)
22. Hellinckx, J., De Boeck, K., Bande-Knops, J., et al. (1998). Bronchodilator response in 3–6.5-year-old healthy and stable asthmatic children. *European Respiratory Journal*, 12, 438–443. <https://doi.org/10.1183/09031936.98.12020438>
23. Hellyer, N., et al. (2017). Comparison of diaphragm thickness measurements among postures via ultrasound imaging. *PM&R*, 9(1), 21–25. <https://doi.org/10.1016/j.pmrj.2016.06.001>
24. Hickman, N., Hughes, A. L., Biswas, P., et al. (2023). Early detection of acute exacerbation of chronic obstructive pulmonary disease (AECOPD) using at-home lung oscillometry. *American Journal of Respiratory and Critical Care Medicine*, 207(Suppl.), A4499. [https://doi.org/10.1164/ajrccm-conference.2023.207.1\\_MeetingAbstracts.A4499](https://doi.org/10.1164/ajrccm-conference.2023.207.1_MeetingAbstracts.A4499)
25. Huang, Y., Zhang, X., Wang, J., et al. (2025). Role of impulse oscillometry in chronic obstructive pulmonary disease and asthma–chronic obstructive pulmonary disease overlap. *Clinical and Translational Allergy*, e70057. <https://doi.org/10.1002/ct2.70057>
26. Ishikawa, T., Nishikiori, H., Mori, Y., Fujino, K., Saito, A., Takahashi, M., Kuronuma, K., Hinotsu, S., & Chiba, H. (2024). The impact of respiratory reactance in oscillometry on survival in patients with idiopathic pulmonary fibrosis. *BMC Pulmonary Medicine*, 24, 10. <https://doi.org/10.1186/s12890-023-02776-y>
27. Kaminsky, D. A., Simpson, S. J., Berger, K. I., et al. (2022). Clinical significance and applications of oscillometry. *European Respiratory Review*, 31(163), 210208. <https://doi.org/10.1183/16000617.0208-2021>
28. King, G. G., Bates, J., Berger, K. I., et al. (2020). Technical standards for respiratory oscillometry. *European Respiratory Journal*, 55(2), 1900753. <https://doi.org/10.1183/13993003.00753-2019>
29. Krishnan, B., Kannukettiyil, N. J., & Gopal, A. (2025). Oscillometry versus spirometry: Initial insights. *International Journal of Clinical Studies & Medical Case Reports*. <https://ijclinmedcasereports.com/pdf/IJCMCR-RW-01278.pdf>
30. Liang, X., Zheng, J., Gao, Y., et al. (2022). Clinical application of oscillometry in respiratory diseases: An impulse oscillometry registry. *ERJ Open Research*, 8(4), 000802022. <https://doi.org/10.1183/23120541.00080-2022>
31. Makrinioti, H., Fainardi, V., Bønnelykke, K., et al. (2024). ERS statement on preschool wheezing disorders. *European Respiratory Journal*, 64(3). <https://doi.org/10.1183/13993003.00257-2024>
32. Malmberg, L. P., Pelkonen, A. S., Haahtela, T., et al. (2003). Exhaled nitric oxide rather than lung function distinguishes preschool children with probable asthma. *Thorax*, 58, 494–499. <https://doi.org/10.1136/thorax.58.6.494>

33. Matos, R. I., McEvoy, C. T., & Jensen, E. A. (2025). Reversible airway obstruction on impulse oscillometry in preschool children with bronchopulmonary dysplasia. *Pediatric Pulmonology*. Advance online publication. <https://pubmed.ncbi.nlm.nih.gov/41638357/>
34. Mondal P, Yirinec A, Midya V, et al. Diagnostic value of spirometry vs impulse oscillometry: A comparative study in children with sickle cell disease. *Pediatric Pulmonology*. 2019; 54: 1422-1430. <https://doi.org/10.1002/ppul.24382>
35. Mou, T., Wang, Y., Fu, Y., et al. (2024). Analysis of the correlations and inconsistencies between spirometry and impulse oscillometry in the diagnosis of small airway dysfunction. *BMC Pulmonary Medicine*, 24, 619. <https://doi.org/10.1186/s12890-024-03420-z>
36. National Asthma Education and Prevention Program, Third Expert Panel on the Diagnosis and Management of Asthma. (2007). *Expert Panel Report 3 (EPR-3): Guidelines for the diagnosis and management of asthma* (NIH Publication No. 07-4051). National Heart, Lung, and Blood Institute, National Institutes of Health. <https://www.nhlbi.nih.gov/health/pro/guidelines/current/asthma-guidelines>
37. Navanandan, N., Hamlington, K. L., Mistry, R. D., Szeffler, S. J., & Liu, A. H. (2020). Oscillometry for acute asthma in the pediatric emergency department: A feasibility study. *Annals of Allergy, Asthma & Immunology*, 125(5), 607–609. <https://doi.org/10.1016/j.anai.2020.07.002>
38. Navanandan, N., et al. (2025). *Clinical applications of impulse oscillometry in pediatric respiratory disease*. *Pediatric Pulmonology*. Advance online publication. <https://pubmed.ncbi.nlm.nih.gov/40705565/>
39. Navanandan, N., et al. (2025). Impulse oscillometry measures associated with asthma control and exacerbations in children. *Annals of the American Thoracic Society*. <https://doi.org/10.1513/AnnalsATS.202502-205OC>
40. Nowowiejska, B., et al. (2008). Transient reference values for impulse oscillometry for children aged 3–18 years. *Pediatric Pulmonology*, 43(12), 1193–1197.
41. O'Rourke, M. C., & Mendenhall, B. R. (2025). *Transesophageal echocardiogram (TEE)*. StatPearls Publishing. <https://www.ncbi.nlm.nih.gov/books/NBK430685/>
42. Oostveen, E., MacLeod, D., Lorino, H., et al. (2003). The forced oscillation technique in clinical practice: Methodology, recommendations and future developments. *European Respiratory Journal*, 22(6), 1026–1041. <https://doi.org/10.1183/09031936.03.00089403>
43. Oostveen, E., et al. (2013). Respiratory impedance in healthy subjects: Baseline values and bronchodilator response. *European Respiratory Journal*, 42(6), 1513–1523.
44. Ostridge, K. (2019). The peak index: Spirometry metric for airflow obstruction severity and heterogeneity. *Annals of the American Thoracic Society*, 16(8), 974–975. <https://doi.org/10.1513/AnnalsATS.201905-388ED>
45. Park, H., Lee, H. J., Lee, H. W., et al. (2024). Diagnosis and evaluation of small airway disease and COPD using impulse oscillometry. *Scientific Reports*, 14, Article 79818. <https://doi.org/10.1038/s41598-024-79818-w>
46. Patel, S., Sylvester, K. P., Wu, Z., Rhamie, S., Dickel, P., Maher, T. M., Molyneaux, P. L., Calverley, P. M. A., & Man, W. D.-C. (2024). A comparison of respiratory oscillometry and spirometry in idiopathic pulmonary fibrosis: Performance time, symptom burden and test-retest reliability. *ERJ Open Research*, 10(4), 00227-2024. <https://doi.org/10.1183/23120541.00227-2024>
47. Pisi, R., et al. (2021). Detection of small airway dysfunction in asymptomatic smokers with preserved spirometry: The value of the impulse oscillometry system. *International Journal of Chronic Obstructive Pulmonary Disease*, 16, 2585–2590. <https://doi.org/10.2147/COPD.S319972>
48. Qvarnström, B., Engström, G., Frantz, S., et al. (2023). Impulse oscillometry indices in relation to respiratory symptoms and spirometry in the Swedish Cardiopulmonary

- Bioimage Study. *ERJ Open Research*, 9(5), 00736-2022. <https://doi.org/10.1183/23120541.00736-2022>
49. Rangel, L., Vargas, M. (2024). How best to choose an oscillometer and reference equations for your patients with asthma. *Annals of Allergy, Asthma, and Immunology*, 134 (2), 159-164. <https://doi.org/10.1016/j.anai.2024.11.009>
  50. Ribeiro, C., Faria, A. C. D., Lopes, A. J., et al. (2018). Forced oscillation technique for early detection of the effects of smoking and COPD: Contribution of fractional order modeling. *International Journal of Chronic Obstructive Pulmonary Disease*, 13, 3281–3295. <https://doi.org/10.2147/COPD.S173686>
  51. Saadeh, C., Saadeh, C., Cross, B., Gaylor, M., & Griffith, M. (2015). Advantage of impulse oscillometry over spirometry to diagnose chronic obstructive pulmonary disease and monitor pulmonary responses to bronchodilators: An observational study. *SAGE Open Medicine*, 3, 2050312115578957. <https://doi.org/10.1177/2050312115578957>
  52. Safia, N., Mayuran, R., Merin, K. (2022). Asthma diagnosis using patient-reported outcome measures and objective diagnostic tests: Now and into the future. *Current Opinion in Pulmonary Medicine*, 28(3), 251–257. <https://doi.org/10.1097/MCP.0000000000000871>
  53. Sarkar, S., Jadhav, U., Ghewade, B., Sarkar, S., & Wagh, P. (2023). Oscillometry in lung function assessment: A comprehensive review of current insights and challenges. *Cureus*, 15(10), e47935. <https://doi.org/10.7759/cureus.47935>
  54. Singh, D., Long, G., Cançado, J. E. D., & Higham, A. (2020). Small airway disease in chronic obstructive pulmonary disease: Insights and implications for the clinician. *Current Opinion in Pulmonary Medicine*, 26(2), 162–168. <https://doi.org/10.1097/MCP.0000000000000637>
  55. Su, Z.-Q., Guan, W.-J., Li, S.-Y., Ding, M., Chen, Y., Jiang, M., Chen, X.-B., Zhong, C.-H., Tang, C.-L., & Zhong, N.-S. (2018). Significances of spirometry and impulse oscillometry for detecting small airway disorders in COPD and heavy smokers. *International Journal of Chronic Obstructive Pulmonary Disease*, 13, 3031–3044. <https://doi.org/10.2147/COPD.S172639>
  56. Takahashi, S., Shirai, T., & Akamatsu, T. (2023). Oscillometry helps assess treatment responsiveness in adults with asthma exacerbations. *Respiratory Physiology & Neurobiology*, 313, 104065. <https://doi.org/10.1016/j.resp.2023.104065>
  57. Thamrin, C., Gangell, C. L., Udomittipong, K., et al. (2007). Assessment of bronchodilator responsiveness in preschool children using forced oscillations. *Thorax*, 62, 814–819. <https://doi.org/10.1136/thx.2006.071290>
  58. Usmani, O. S., et al. (2021). Why we should target small airways disease in our management of chronic obstructive pulmonary disease. *Mayo Clinic Proceedings*, 96(9), 2448–2463. <https://doi.org/10.1016/j.mayocp.2021.03.016>
  59. Veneroni, C., Valach, C., Wouters, E. F. M., et al. (2024). Diagnostic potential of oscillometry: A population based approach. *American Journal of Respiratory and Critical Care Medicine*, 209(4), 444–453. <https://doi.org/10.1164/rccm.202306-0975OC>
  60. Wu, J. K. Y., Ma, J., Nguyen, L., Dehaas, E. L., Vasileva, A., Chang, E., Liang, J., Huang, Q. W., Cassano, A., Binnie, M., Shapera, S., Fisher, J., Ryan, C. M., McInnis, M. C., Hantos, Z., & Chow, C.-W. (2022). Correlation of respiratory oscillometry with CT image analysis in a prospective cohort of idiopathic pulmonary fibrosis. *BMJ Open Respiratory Research*, 9(1), e001163. <https://doi.org/10.1136/bmjresp-2021-001163>
  61. Wu, J. K. Y., Ryan, C. M., Hiebert, R. J., Han, Z., Liu, A., Jeong, C.-H., Mubareka, S., Evans, G. J., & Chow, C.-W. (2021). Aerosol generation during pulmonary function testing: Monitoring during different testing modalities. *Canadian Journal of Respiratory, Critical Care, and Sleep Medicine*, 6(2), 1–8. <https://doi.org/10.1080/24745332.2021.1965926>

62. Wu, J. K. Y., Xu, J. J.-N., Numakura, T., Ryan, C. M., McInnis, M. C., Binnie, M., Shapera, S., Fisher, J. H., Hantos, Z., & Chow, C.-W. (2025). Standard pulmonary function tests and respiratory oscillometry patterns in hypersensitivity pneumonitis and idiopathic pulmonary fibrosis. *BMJ Open Respiratory Research*, *12*(1), e003600. <https://doi.org/10.1136/bmjresp-2025-003600>
63. Zimmermann, S. C., et al. (2020). Day to day variability of forced oscillatory mechanics for early detection of acute exacerbations in COPD. *European Respiratory Journal*, *56*(3), 1901739. <https://doi.org/10.1183/13993003.01739-2019>
64. Zhang, Y., Tanabe, N., Shima, H., et al. (2022). Physiological impairments on respiratory oscillometry and future exacerbations in chronic obstructive pulmonary disease patients without a history of frequent exacerbations. *COPD: Journal of Chronic Obstructive Pulmonary Disease*, *19*(1), 149–157. <https://doi.org/10.1080/15412555.2022.2051005>