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Methods of airway resistance assessment

The authors declare no financial disclosure

Abstract

Airway resistance is the ratio of driving pressure to the rate of the airflow in the airways. The most frequent methods used to measure airway resistance are whole-body plethysmography, the interrupter technique and the forced oscillation technique. All these methods allow to measure resistance during respiration at the level close to tidal volume, they do not require forced breathing manoeuvres or deep breathing during measurement. The most popular method for measuring airway resistance is whole-body plethysmography. The results of plethysmography include among others the following parameters: airway resistance (R_{aw}), airway conductance (G_{aw}), specific airway resistance (sR_{aw}) and specific airway conductance (sG_{aw}). The interrupter technique is based on the assumption that at the moment of airway occlusion, air pressure in the mouth is equal to the alveolar pressure . In the forced oscillation technique (FOT), airway resistance is calculated basing on the changes in pressure and flow caused by air vibration. The methods for measurement of airway resistance that are described in the present paper seem to be a useful alternative to the most common lung function test — spirometry. The target group in which these methods may be widely used are particularly the patients who are unable to perform spirometry.

Pneumonol Alergol Pol 2016; 84: 134–141

Key words: lung function tests, airway resistance, plethysmography

Introduction

Airway resistance is defined as the ratio of driving pressure to the rate of the airflow in the airways [1, 2]. According to Poiseuille law (assuming that airflow in the airways is laminar and the airways are stiff), the pressure difference, so resistance too, is directly proportional to the airway lenght and inversely proportional to the fourth power of their radius [1]. Another factor affecting resistance in such conditions is the viscosity of the respiratory gas [1]. Whereas for turbulent flow, the pressure-flow resistance ceases to be linear, and the resistance depends on the density of the respiratory gas [1]. In natural conditions, humans have both laminar and turbulent flow in the airways [1]. Furthermore, the airways are flexible and there are numerous connections between them [1]. Therefore, a real correlation between resistance and the gas flow, its characteristics and shape of the airways is complex [1]. Figure 1 illustrates contribution of separate components to total airway resistance. The most common methods for measurement of airway resistance are whole-body plethysmography, the forced oscillation technique and the interrupter technique. All these methods have certain features in common, among others measurement during breathing at the level close to tidal volume (TV), lack of necessity of performing forced respiratory manoeuvres and deep breathing during measurement. Moreover, all the above described techniques require less cooperation from the patient and less physical effort in comparison with the standard lung function test — spirometry. There are attempts to apply the studies assessing airway resistance, among others in patients unable to perform spirometry or in those with contraindication for spirometry.

Components of total airway resistance

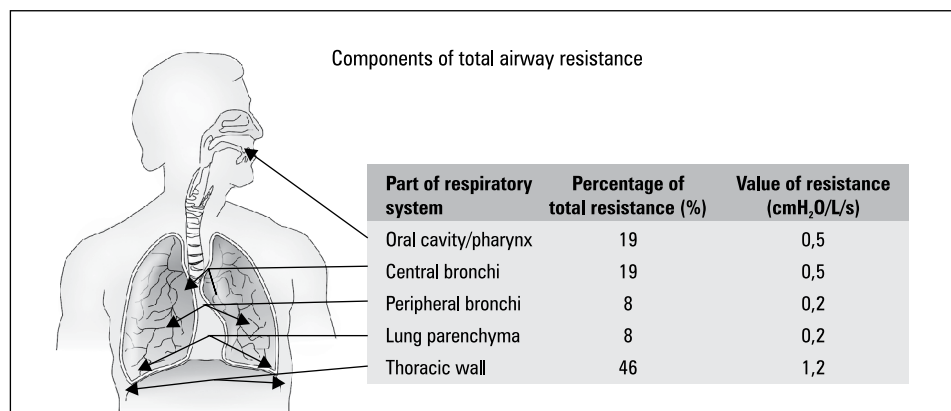| Part of respiratory system	Percentage of total resistance (%)	Value of resistance (cmH₂O/L/s)
Oral cavity/pharynx	19	0,5
Central bronchi	19	0,5
Peripheral bronchi	8	0,2
Lung parenchyma	8	0,2
Thoracic wall	46	1,2

Figure 1. Contribution of separate components to total airway resistance

Figure 1 illustrates a contribution of airway resistance from the mouth to the level of peripheral bronchi, the lung parenchyma resistance and the chest wall resistance to total airway resistance. It is worth highlighting that during tidal breathing through the nose , more than half of total airway resistance constitutes the resistance of the nasal cavity [3]. The nasal cavity as the part of the upper airways, which have direct contact with the environment, fulfils many vital functions, including humidification and warming the inspired air [3]. The present paper is going to present two methods of measurement of airway resistance that use physical phenomena analogous to the methods for measuring resistance of the bronchi — rhinomanometry and acoustic rhinometry.

Whole-body plethysmography

The most common method for measurement of airway resistance is whole-body plethysmography. A plethysmograph consists of a rigid chamber, in which the subject breathes through a head measuring flow and volume (pneumotachograph) [4]. It also includes transducers that measure the pressure difference between the interior of the plethysmograph and the room and register pressure from the mouth [4]. Plethysmographic measurement of lung volume and airway resistance is based on the assumption that the change in air pressure in the cabin of the plethysmograph (P_p) correlates with the change in alveolar pressure (P_A) [4]. The next component of the measuring set is a shutter that is placed close to a pneumotachograph [4]. To measure resistance and volume using a plethysmograph, the patient needs to breathe quickly and shallowly. The above breathing technique allows to reduce narrowing of the

airways at the glottis and limit turbulences of airflow and changes in its volume [1]. During free breathing, airflow at the mouth (V) and volume changes inside the chamber (P_p) are registered. Furthermore, during the examination, airflow is stopped several times in the airways by closing a shutter mechanism in the measuring system. During manoeuvres, when there is no airflow, change in P_p and pressure changes at the mouth (P_m) are measured using a transducer positioned next to a pneumotachograph [4]. Basing on the latter value, it is possible to estimate change in P_A [1, 4]. Lung volume is measured in accordance with Boyle-Mariotte law (i.e. constancy of the product of pressure and volume of gas under isothermal conditions) basing on the following: constant volume of a chamber, estimate change in P_A and simultaneously measured change in P_p [4]. Whereas airway resistance is computed basing on the proportion of gradient of the curve P_A/P_p registered during breathing manoeuvres when there is no airflow and the gradient of the curve V/P_p registered during free breathing manoeuvres [1, 5, 6]. The results of plethysmography include among others the following parameters: airway resistance (R_{aw}), specific airway resistance (sR_{aw}) and specific airway conductance (sG_{aw}). Figure 2 illustrates a graphic diagram of plethysmographic measurement of lung volume and airway resistance and the most crucial relationships between the measured parameters.

The resistance value expressed as R_{aw} depends on lung volume, contrary to the parameters sR_{aw} and sG_{aw}, which are relatively independent from the changes in lung volume [1]. R_{aw} is the quotient of sR_{aw} and thoracic gas volume (TGV, volume of the air in the lungs at the moment of measurement) measured during breathing manoeuvres with a closed shutter in the measuring
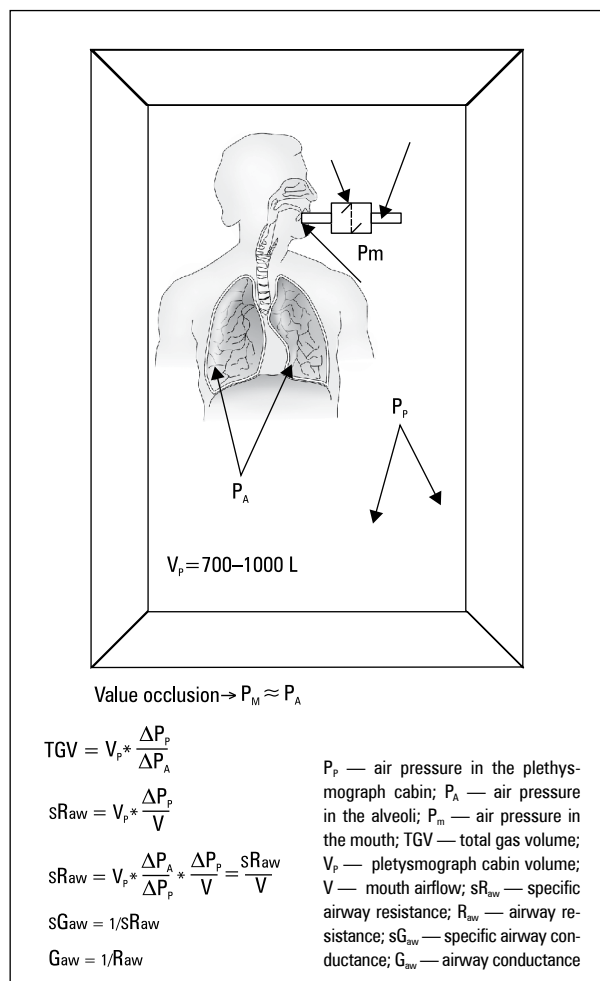
Value occlusion → $P_M \approx P_A$

$$TGV = V_P * \frac{\Delta P_P}{\Delta P_A}$$

$$sRaw = V_P * \frac{\Delta P_P}{V}$$

$$sRaw = V_P * \frac{\Delta P_A}{\Delta P_P} * \frac{\Delta P_P}{V} = \frac{sRaw}{V}$$

$$sGaw = 1/sRaw$$

$$Gaw = 1/Raw$$

P_P — air pressure in the plethysmograph cabin; P_A — air pressure in the alveoli; P_m — air pressure in the mouth; TGV — total gas volume; V_P — pletysmograph cabin volume; V — mouth airflow; sR_{aw} — specific airway resistance; R_{aw} — airway resistance; sG_{aw} — specific airway conductance; G_{aw} — airway conductance

Figure 2. Graphic presentation of plethysmographic measurement of lung volume and airway resistance

system [4]. Therefore, in case of increase in TGV, R_{aw} may remain within the norm, despite elevated specific airway resistance [4]. Such a situation is observed in many patients with chronic obstructive pulmonary disease, in whom pulmonary emphysema was found [4]. Moreover, when there is no airflow, breathing manoeuvres are difficult to perform for some patients, among others for those with obstruction of the airways [4].

Specific airway resistance (sR_{aw}) is calculated from the gas pressure and the proportion of the change in thoracic volume to the flow in the mouth [4]. sR_{aw} is usually applied to measure resistance in children, for it does not require the measurement of lung volume using a breathing manoeuvre against a closed shutter, which is difficult to perform in this group of patients [5]. There are various methods for calculating the value of specific airway resistance. Depending on the applied method, sR_{aw} may be expressed as total specific resistance (sR_{tot}), effective specific resistance (sR_{eff}) and specific resistance at the

flow of 0.5 l/s ($sR_{0.5}$) [4]. To calculate sR_{tot}, change in air volume between total inspiration and total expiration is used [4]. Resistance expressed as sR_{tot} is very sensitive in diagnostics of partial obstruction of peripheral airway [4]. However, as calculations use extreme values of change in volume during breathing manoeuvres, repeatability of sR_{tot} may be lower in relation to other methods [4]. Whereas specific airway resistance — sR_{eff} is calculated basing on the relationship of the surface area under the curve of volume change-volume and flow-volume [4]. The advantage of sR_{eff} is that it takes into account respiratory function during the whole respiratory cycle (including among others changeability of flow and deviation from linear nature of the curve flow — volume change) [4]. In comparison with total specific resistance, sR_{eff} reflects to a larger degree resistance of larger proximal airways [4]. Furthermore, diagnostic value of $sR_{0.5}$, i.e. specific resistance at the flow of 0.5 L per second is elevated [4]. The above rate was used as a result of observation that the gradient of specific resistance in the graph of flow-volume change is relatively constant between inspiratory and expiratory flow at 0.5 L/s [4]. Due to dependence of airway resistance on the flow rate, the appliance of $sR_{0.5}$ would increase repeatability and comparability of measurements [4]. However, $sR_{0.5}$ reflects mainly resistance of the large bronchi and has much less sensitivity to peripheral airway abnormalities [4].

Specific conductance (sG_{aw}) is the reciprocal of sR_{aw} [4]. sG_{aw}, which does not depend on volume change, is a repeatable and sensitive method for assessment of airway resistance [1]. Specific conductance is used for reliable evaluation of the respiratory system in patients with severe obstruction of the airways, in whom emphysema may occur [4]. sG_{aw} has a great sensitivity to changes causing increase in resistance in the central parts of the bronchial tree, but much less to diagnostics of obstruction of peripheral airways [1].

It was proved that in patients with reversible airway obstruction, in whom clinical improvement after administration of a bronchodilator occurred, sG_{aw} is more sensitive to recognition of response to a bronchodilator than spirometry [7]. Moreover, the measurement of sG_{aw} is not dependent on relaxation of the muscular coat of the airways after taking a deep breath, which occurs in some patients — the examination does not require performance of forced breathing manoeuvre [8]. This phenomenon may affect the results of examinations that involve forced breathing manoeuvre, including the measurement of FEV_1

during spirometry. There are also reports of high sensitivity of sG_{aw} to response of the airways to a factor inducing bronchospasm in hyperreactivity tests using methacholine and histamine [9, 10]. The standard method for assessment of response of the airways to methacholine in the above tests is spirometry. However, spirometry involves hard effort of the patient and the results depend on motivation and cooperation of the subject. Therefore, plethysmographic measurement of resistance could be a potential alternative to assessing obstruction after administration of methacholine using spirometry.

According to the guidelines of the American Thoracic Society (ATS), measurement of resistance using a plethysmograph may be an alternative to evaluate the response of the airways to methacholine in hyperreactivity test in patients unable to perform acceptable spirometric manoeuvres [11]. It was found that in patients with asthma and COPD, changes in resistance measured with this method in response to methacholine correlate with the changes in FEV_1, however, plethysmographic parameters are characterised by less repeatability [11].

Assessment of resistance using the interrupter technique

During measurement of airway resistance with the interrupter technique, the patient breathes calmly [1, 12, 13]. To calculate resistance, the following values are necessary: airflow in the airways and alveolar pressure [13]. However, the second parameter cannot be measured in a noninvasive way [13]. Thus, the interrupter technique is based on the assumption that at the moment of transient occlusion of the airways of the calmly breathing patient, air pressure in his mouth equals alveolar pressure [2, 12−15]. During examination, the measuring system causes periodic, rapid, short-term (duration 100 ms) occlusion of flow in the airways [1, 12, 16]. Airway resistance is estimated basing on the measurement of pressure in the mouth directly after occlusion of the airways and the airflow measured directly prior to occlusion (Fig. 3) [1, 12, 13]. It was proved that resistance measured using this method (R_{int}) reaches repeatable values in the subsequent measurements in short intervals (i.e. during one visit) [17]. However, repeatability of R_{int} measurements in more distant points in time is lower [17]. Therefore, examination using this technique is more efficient in assessment of response of the airways during short-term interventions (e.g. bronchial reversibility testing) than
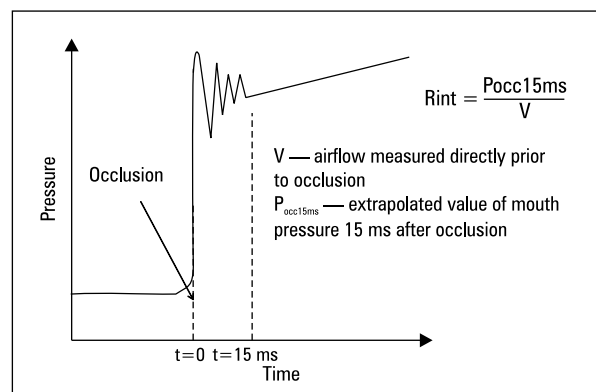

Figure 3. Measurement of airway resistance by interrupter technique

in long-term evaluation of lung function in a given patient [17].

Similarly to the forced oscillation technique, the interrupter technique is noninvasive and requires only calm breathing and minimal cooperation of the patient — examinations using this method may be performed in little children [1, 12, 13, 18]. It was proved that this method is useful for preschool children (2−5 years of age), giving effective performance measurement in 56%, 81% and 95% of children at the age of 2−3 years, 3−4 years and 4−5 years respectively [19].

Compared to the assessment of airway resistance with the plethysmograph, the interrupter technique necessitates less cooperation of the patient [14]. Furthermore, contrary to the plethysmograph, the equipment that measures airway resistance using the interrupter technique is inexpensive and portable [20]. Another advantage of the examination using the interrupter technique is short duration of measurement [18].

There were attempts to use the interrupter technique for assessment of lung function in adults, including patients unable to perform examinations involving cooperation. The interrupter technique may be applied in patients with intellectual disabilities, in whom diagnostics of respiratory diseases usually relies merely on physical symptoms [21].

However, there were reports of certain limitations of precise measurement with the help of the interrupter technique — related to sensibility of the upper airways and to delayed pressure compensation between the alveoli and the mouth in the case of pathologically changed airways [13].

Until now the assessment of airway resistance using the interrupter technique has been widely used in the paediatric population, and the commonly available predicted values are determined for this group of patients [2, 22].
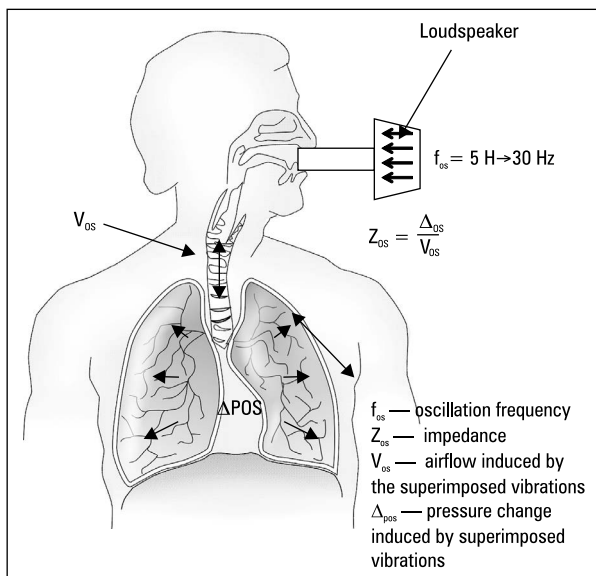
Figure 4. Measurement of airway resistance by forced oscillation technique

Similarly to the above mentioned methods of airway resistance, the interrupter technique is described in the guidelines of ATS as alternative to spirometry in the evaluation of hyperreactivity testing in patients unable to perform spirometry [11].

Forced oscillation technique

In the forced oscillation technique (FOT), when the patient breathes normally, a membrane of a loudspeaker emits to the airways sinusoidal vibrations (forced oscillations) [23−25]. Airway resistance is calculated basing on changes in pressure and the airflow induced by the vibrations (Fig. 4) [8]. The pattern of relationship between airflow and changes in pressure induced by forced oscillations is significantly different from the pattern of relationship between airflow and changes in pressure related to respiratory movements of the subject [8]. Therefore, the value of resistance measured with FOT is to a large degree independent from breathing pattern of the patient [8]. FOT is a noninvasive method that necessitates only minimal, passive cooperation of the patient [8, 23]. The parameter analysed in FOT is impedance with its components: respiratory resistance (R_{rs}) and reactance [24]. The use of changeable frequency of the emitted vibrations allows to diagnose different parts of the respiratory system [24]. To diagnose the lung parenchyma, a low frequency range is utilised (< 1 Hz) [24]. Whereas airway resistance is assessed using higher frequencies [24]. Respiratory resistance

measured with the forced oscillation technique reflects a total value of airway resistance and the chest wall, and its value largely depends on the patency of the bronchial tree [1]. Measurement is usually made in a frequency range between 5 and 30 Hz [8]. FOT is a very sensitive tool in diagnosis of spasm of the bronchial muscular coat, however, it is much less specific for particular diseases [1]. Nevertheless, the technique allows to differ to a certain extent central airway obstructions from the peripheral ones. In the case of central obstruction, increase in R_{rs} is found, irrespective of oscillation frequency [8]. Whereas in peripheral obstruction, negative relationship between R_{rs} and frequency of vibrations of measurement is observed [8]. Reactance (X_{rs}) largely depends on the ability of the airways to gather energy related to distortion of the airways tissue [8]. This ability is lower in case of increased lung rigidity (e.g. in interstitial diseases with fibrosis) or emphysema (e.g. in COPD with advanced emphysema) [8]. In the above conditions, lower reactance (more negative) measured during oscillation of low frequencies is found [8]. X_{rs} allows to assess elasticity of the respiratory system in a way that does not require the appliance of invasive procedures (e.g. insertion of a tube to the oesophagus during measurement of the lung sensibility).

Similarly to the measurement of resistance with a plethysmograph, FOT does not involve forced breathing manoeuvre. Moreover, it does not use airway occlusion manoeuvre. Therefore, breathing manoeuvres that are necessary to assess resistance using FOT probably do not affect muscular coat tension of the bronchi [8]. Additionally, FOT may be carried out in people unable to perform standard lung function testing that require coordinated or forced breathing manoeuvres, i.e. in children, elderly people, patients with severe obstruction or diseases disturbing the function of the respiratory muscles [8].

So far, FOT has been used among others in diagnostics of the respiratory system diseases in children, in adults and elderly people [8]. FOT is applied in diagnostics of obstructive and restrictive disorders, monitoring of treatment, screening tests and assessment of reactivity of the airways and reversibility testing [1, 8].

Furthermore, FOT may serve as screening testing in detection of complications after lung transplantation [8]. In patients after transplantation, reliability of spirometric measurements may be questioned due to significant disorders of mobility of the chest, which hinder patients from

doing maximal forced breathing manoeuvre [8]. FOT also allows to identify changes in peripheral parts of the lungs, which are undetectable in spirometry [8].

There were attempts to utilise FOT for assessment of response of the airways to methacholine in hyperreactivity of the bronchi. Vink *et al*. in the study on the paediatric population observed that changes in resistance and reactance measured with FOT correlated significantly with the changes in FEV_1 [26]. The authors observed that increase in resistance occurred prior to the decline in FEV_1 in response to methacholine [26].

In contrast to standard methods of assessment of the airways such as spirometry or measurement of peak expiratory flow, FOT does not involve active cooperation of the patient [26]. Moreover, the examination is very easy to perform. It may be applied in examining the youngest children, elderly people and subjects ventilated mechanically [1].

The profiles of changes typical of certain respiratory disorders found during FOT were determined. Obstruction of peripheral airways is characterised by increase in resistance and decline in reactance [8, 27]. Whereas in the case of interstitial diseases and emphysema, reactance is lower [8]. In interstitial diseases, the decline is related to greater lung rigidity, whereas in the case of emphysema, it is caused by the loss of the lung ability to distort, which is related to hyperinflation [8].

Similarly to plethysmographic measurement of airway resistance, FOT is recommended by the ATS guidelines for hyperreactivity testing with methacholine in patients who are unable to perform correct spirometric manoeuvres [11]. However, provocation tests using this technique should be assessed only in the laboratories that are experienced in applying the forced oscillation technique and interpretation of the results obtained with this method [11].

Rhinomanometry

Rhinomanometry consists of measurement of nasal airway resistance (NAR) in the nasal cavity basing on the airflow in the nasal canal and the pressure difference along the long axis of the nasal cavity [28, 29]. NAR is evaluated in order to objectively assess obstruction in the nasal cavity [29]. The most popular type of rhinomanometry is active anterior rhinomanometry [28−30]. The method measures the pressure difference between the anterior nares and the nasopharynx using a measuring tool placed in one nasal cavity during normal breathing of the patient with patency of the second nasal cavity [28−30]. In passive anterior rhinomanometry, pressure is measured at a defined airflow [28]. A weak point of the method is its poor precision [30]. Whereas in active posterior rhinomanometry, pressure is measured in the posterior nares, and the airflow is registered in both nasal cavities [28, 30]. The main disadvantage of active posterior rhinomanometry is pharyngeal reflex which is induced by measuring instruments [30]. It was shown that there is correlation between the results obtained using rhinomanometry and the results of the nasal cavity assessment using the methods that are usually used for lung function testing — plethysmography and FOT [3, 31, 32]. Limitations of rhinomanometry are related to small repeatability of the outcome, slight correlation of the results with subjective symptoms of restricted patency of the nasal cavity and poor availability of the method [3].

Acoustic rhinometry

Acoustic rhinometry consist in emission of sound waves to the interior of the nasal cavity and the evaluation of sound waves reflected from its inner area [3, 28]. These data allow to determine volume and shape of the nasal cavity [28]. The amplitude of reflected sound waves and change in the amplitude in time unit are analysed. These parameters allow to calculate the area and to determine changes in the cross-sectional area depending on the distance from the place where reflected waves were registered [3, 30]. With known dimensions of the anterior nares, the change in the amplitude of reflected rays compared to the amplitude of the emitted wave allows to estimate changes in the cross-section of the airways in the nasal cavity [3]. On the other hand, knowing the velocity of wave propagation, time between recording subsequent reflections of the emitted wave allows to estimate the distance between the sites of change in cross-section of the nasal cavity [3]. Acoustic rhinometry permits determination of cross-sectional area of the nasal cavity and identification of its narrowest part [28, 30]. In clinical practice, acoustic rhinometry is used among others in diagnostics of various types of nasal mucosal inflammation, objective verification of sensation of nasal patency, assessment of provocation testing and anatomy of the nasal cavity [3].

Table 1. Characteristics of the most crucial parameters assessed by plethysmography, the interrupter technique and the forced oscillation technique.

	Parameter	Characteristics/utility	Advantages		Disadvantages
PLETH	R_{aw}	proximal airways TGV-dependent (nonlinearly)	high sensitivity in diagnosing upper airway obstruction		hyperinflation decreases its value low sensitivity in mild obstruction
	G_{aw}	TGV-dependent (linearly) reciprocal of R_{aw}			hyperinflation increases its value
sR_{aw}	sR_{tot}	peripheral airways	TGV-independent	high sensitivity in diagnosing mild peripheral airway obstruction	low repeatability
	sR_{eff}	proximal airways		takes into account respiratory function during the whole respiratory cycle	
	$sR_{0.5}$	proximal airways		high repeatability	low sensitivity in diagnosis peripheral obstruction
	sG_{aw}	proximal airway bronchial reactivity	TGV-independent, reliable despite presence of severe obstruction and/or hyperinflation high sensitivity in diagnosing obstruction, including upper airway obstruction		low specificity
IT	R_{int}	useful in non-cooperating patients bronchial reactivity	high short-term repeatability		low long-term repeatability
FOT	R_{rs}	peripheral airway bronchial reactivity	independent assessment of central and peripheral obstruction measurement does not affect airway function		despite having acceptable repeatability, it is more variable compared to spirometry
	X_{rs}	lung elastic properties assessment	non-invasive ($\neq$lung compliance measurement)		low repeatability

TGV — thoracic gas volume; IT — interrupter technique; FOT– forced oscillation technique; R_{aw} — airway resistance; G_{aw} — airway conductance; PLETH - plethysmography; sR_{aw} — specific airway resistance; sR_{tot} — total specific airway resistance; sR_{eff} — effective specific airway resistance; $sR_{0.5}$ — specific airway resistance at 0,5 L/s flow; sG_{aw} — specific airway conductance; R_{int} — interrupter resistance; R_{rs} — forced oscillation airway resistance; X_{rs} — forced oscillation airway reactance

Conclusions

Table 1 illustrates characteristics, clinical utility and limitations of the most crucial parameters assessed using the three methods of airway resistance — plethysmography, FOT and the interrupter technique. The methods for measurement of airway resistance that were presented in the present paper seem to be a useful alternative to the most common lung function test — spirometry. These methods should be commonly used in patients unable to perform examination with standard methods — i.e. children, elderly people, people with intellectual disabilities and those with limited physical efficiency. In clinical practice, these methods could be particularly useful for procedures requiring the assessment of the airways for several times in the short term, e.g. in hyperreactivity or exercise-induced bronchospasm provocation testing. Furthermore, the evaluation of airway resistance is independent from the phenomenon of transient airway relaxation, which is related to a deep inspiration preceding a forced breathing manoeuvre, and which occurs in some patients during spirometry — this phenomenon hinders clinical interpretation among others of bronchial hyperreactivity test [11, 33−35]. Moreover, methods for assessment of airway resistance in the nasal cavity allow among others to evaluate condition of the nasal mucosa, objective evaluation of patency and anatomy of the nasal cavity, which is applied e.g. in diagnostics of nasal mucosal inflammations and qualifications of patients for laryngology procedures.

Conflict of interest

The authors declare no conflict of interest.

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