Review
# Forced oscillation assessment of respiratory mechanics in ventilated patients

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## Abstract

The forced oscillation technique (FOT) is a method for non-invasively assessing respiratory mechanics that is applicable both in paralysed and non-paralysed patients. As the FOT requires a minimal modification of the conventional ventilation setting and does not interfere with the ventilation protocol, the technique is potentially useful to monitor patient mechanics during invasive and noninvasive ventilation. FOT allows the assessment of the respiratory system linearity by measuring resistance and reactance at different lung volumes or end-expiratory pressures. Moreover, FOT allows the physician to track the changes in patient mechanics along the ventilation cycle. Applying FOT at different frequencies may allow the physician to interpret patient mechanics in terms of models with patho-physiological interest. The current methodological and technical experience make possible the implementation of portable and compact computerised FOT systems specifically addressed to its application in the mechanical ventilation setting.

**Keywords:** forced oscillation technique, monitoring, respiratory impedance, respiratory resistance, airway mechanics

## Introduction

The mechanical properties of the respiratory system in paralysed and mechanically ventilated patients are commonly measured by means of occlusion techniques [1] or by multilinear regression analysis [2]. Respiratory resistance and elastance are computed from pressure and flow recorded at the airway opening under the assumption that the contribution of the patient's respiratory muscles is nil, so that airway pressure coincides with transpulmonary pressure. Although these measurements can readily be performed on paralysed patients, their application during assisted ventilation in patients with active inspiratory muscles is not possible. The only conventional procedure for assessing respiratory mechanics when the patient's respiratory muscles are active is to employ an oesophageal balloon catheter. However, the use of an oesophageal balloon is not practicable in applications during mechanical ventilation such as noninvasive ventilation or weaning.

FOT is a method for noninvasively assessing respiratory mechanics during mechanical ventilation [3] and is applicable both in paralysed [4–7] and nonparalysed patients [8–10]. FOT is based on the application of a small pressure oscillation (about 2 cmH$_2$O) at the airway opening by means of an external generator, and on recording the oscillation pressure and flow [11]. When employed in nonparalysed patients, forced oscillation is applied at a frequency (more than 2 Hz) that is much higher than the patient's breathing rate. At such high frequencies the activity of the muscle pump, which operates at the breathing frequency and its first harmonics, is negligible. Under

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COPD = chronic obstructive pulmonary disease; FOT = forced oscillation technique; PEEP = positive end-expiratory pressure.
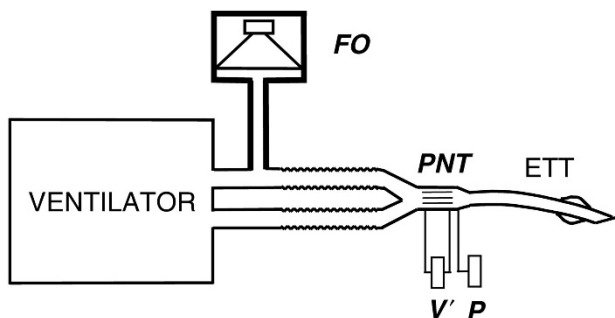
**Figure 1**



Diagram of the setting to apply the forced oscillation technique during mechanical ventilation. A forced oscillation generator (FO) is connected in parallel to the ventilator. Flow ($V'$) and pressure ($P$) are measured by means of a pneumotachograph (PNT) and a pressure transducer, respectively.

**Figure 2**



Example of the pressure and flow signals recorded during application of a 5 Hz forced oscillation during volume-controlled noninvasive mechanical ventilation in a patient with a chest wall restrictive defect. The 5 Hz forced oscillation technique component is superimposed on the pressure and flow ventilator waveforms.
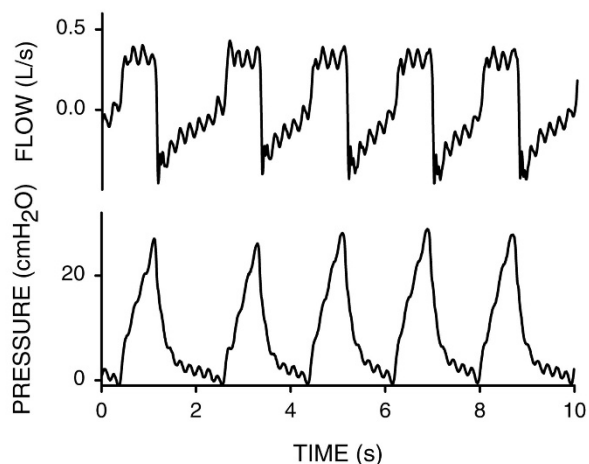
this assumption the only driving pressure at the forced oscillation frequency is the pressure applied at the mouth by the external generator. Consequently, FOT applied at a sufficiently high frequency allows the noninvasive assessment of respiratory mechanics in patients with artificial respiratory support regardless of the degree of activity of their respiratory muscles.

## Oscillatory resistance and reactance

Assessment of respiratory mechanics by the application of FOT requires a minimal modification of the conventional ventilation setting. As shown in Fig. 1, a forced oscillation generator is connected in parallel with the ventilator. Flow is recorded by a pneumotachograph placed at the inlet of the endotracheal tube and a differential pressure transducer. Pressure is recorded by a pressure transducer placed at the airway opening. When FOT is applied in nonintubated patients with ventilatory support, the endotracheal tube is replaced by a nasal or face mask. With the setting shown in Fig. 1, the forced oscillation pressure can be superimposed on the ventilator pressure waveform without modifying or interfering with the ventilation protocol. Figure 2 shows an example of the pressure and flow signals recorded during a FOT measurement at a frequency of 5 Hz during noninvasive mechanical ventilation.

To assess oscillatory mechanics by FOT, the recorded signals (Fig. 2) are filtered to isolate the 5 Hz oscillatory signals from the low-frequency breathing components. The patient's mechanics is characterised by means of his/her respiratory impedance, which quantifies the relationship between oscillatory pressure and flow. As explained elsewhere [11], respiratory impedance is a complex quantity represented by two components: respiratory resistance ($R_{rs}$) and reactance ($X_{rs}$). $R_{rs}$ is defined as the quotient between the oscillatory pressure component in phase with flow and the oscillatory flow amplitude.

Similarly, $X_{rs}$ is computed from the oscillatory pressure component out of phase with oscillatory flow and the oscillatory flow amplitude [11].

$R_{rs}$ and $X_{rs}$ measured by FOT can be interpreted by means of mechanistic models of the respiratory system mechanics. For instance, the respiratory system can be modelled by a simple resistance ($R$), an inertance ($I$) and an elastance ($E$), in an $R–I–E$ model. According to the definition of $R_{rs}$ and of $X_{rs}$, it follows [11] that for a given oscillation frequency (f) the oscillatory resistance coincides with the resistance value of the simple $R–I–E$ model ($R_{rs} = R$). Moreover, the reactance of the $R–I–E$ model is $X_{rs} = 2\pi f I – E/(2\pi f)$. Therefore, when applied to a homogeneous $R–I–E$ model, FOT results in a $R_{rs}$ value that is independent of frequency, whereas $X_{rs}$ depends on frequency and accounts for the elastic ($E$) and inertial ($I$) properties. Accordingly, measuring $R_{rs}$ and $X_{rs}$ at different frequencies and fitting the $R–I–E$ model to the data make it possible to derive the values of the parameters $R$, $I$ and $E$ that characterise the mechanical properties of the patient's respiratory system. The pattern of frequency dependence of $R_{rs}$ and $X_{rs}$ described by the $R–I–E$ homogeneous model is observed in healthy subjects [11]. Nevertheless, when FOT is applied in ventilated patients this simple model is no longer applicable owing to the complexity of the patient's respiratory system [5–7]. For this application, respiratory impedance data should be interpreted in terms of models that take into consideration the different mechanisms that determine the behaviour of the respiratory system at the oscillatory frequencies investigated [7,12,13]. In particular, modelling should include coefficients that

account for the expected serial and/or parallel inhomogeneities [5] and the viscoelasticity of respiratory tissues [14]. In this regard, FOT has the advantage that the frequency band explored can be modified depending on the pathophysiological aim of the measurement. For instance, if interest is focused on studying respiratory tissue properties, low-frequency (less than 2 Hz) impedance data would be more sensitive [7]. By contrast, measurements at higher frequency would afford more sensitive data on airway characteristics [5]. A frequency of 5 Hz or higher should be used when applying a simple sinusoidal oscillation (Fig. 1) for monitoring respiratory mechanics along the ventilation cycle [5,15,16].

## Equipment

The basic FOT set-up shown in Fig. 1 can be implemented by means of different technical approaches. The main practical issues are the type of oscillation generator, the procedure for measuring pressure and flow, and the type of oscillatory signal employed to measure $R_{rs}$ and $X_{rs}$.
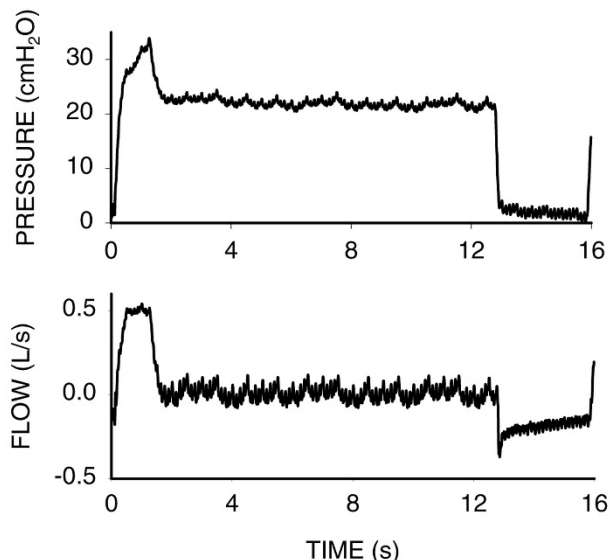
As shown in Fig. 1, the forced oscillation generator should be able to withstand the high positive ventilator pressure during inspiration and should be able to generate the forced oscillation pressure [17]. In the absence of a FOT generator specially designed to withstand high positive pressures, the technique was employed by disconnecting the patient from the ventilator for a few seconds and applying pressure oscillation with a loudspeaker attached to the inlet of the endotracheal tube [4]. Another method for applying FOT in ventilated patients with a simple loudspeaker-in-box system is to connect it to the expiratory outlet of the ventilator [18]. During the inspiratory phase the expiratory valve of the ventilator is occluded with the result that the loudspeaker is not subjected to the high pressures applied to the patient. During the expiratory phase the valve is opened and the pressure oscillation generated by the loudspeaker is transmitted to the patient through the expiratory tubing. This simple method, which can be applied to both paralysed and nonparalysed patients, allows measurements only during expiration. The application of FOT during all the ventilation cycle and for any external positive end-expiratory pressure (PEEP) applied is currently possible by means of two procedures. One of the generators employed [5] consists of a loudspeaker-in-box system including a pneumatic filter that allows the device to withstand positive pressures. This procedure has the advantage of being very simple but its main drawback is that forced oscillation can be applied only for frequencies greater than 5 Hz, which excludes the physiological frequency band close to the breathing rate. To overcome this limitation, a more complex FOT generator based on a servocontrolled loudspeaker-in-box system has been described [19]. This allows the extension of forced oscillation measurements to frequencies close to the breathing rate (0.25 Hz). It is of interest to note that

future technical developments could enable the ventilator to generate the oscillation signal superimposed on the ventilation waveform [10,20], which would considerably simplify the routine application of FOT.

An important issue in the assessment of respiratory mechanics by FOT in ventilated patients is the measurement of flow and pressure. For practical reasons the pressure transducers are placed at a certain distance from the inlet of the endotracheal tube. Consequently, the effects of the tubes connecting the transducers to the pneumotachograph, and the pneumotachograph to the airway opening, on the frequency response of the sensors [21] should be taken into consideration and corrected [22]. Although flow measurement is readily performed by a pneumotachograph, a good common-mode rejection ratio in the differential pressure transducer connected to the pneumotachograph should be ensured [23] or data should be corrected [24]. This requirement, which is general in FOT measurements, is particularly relevant in this application given that the impedance values characterising ventilated patients are high. Increasing the resistance of the pneumotachograph, which could reduce potential artefacts [23,24], is not practicable because this would promote auto-PEEP. Pressure measurement in ventilated patients is influenced by the nonlinear pressure–flow relationship in the endotracheal tube. The most direct way of rounding off the artefacts caused by tube nonlinearities is to measure pressure at the tracheal level instead of at the endotracheal tube inlet. This procedure can be performed by using a special tube incorporating a catheter [25] or by introducing a catheter into the trachea through the endotracheal tube. In both cases, the tube nonlinearity does not affect the measurements because the recorded pressure does not include the pressure drop across the tube. These two procedures for directly recording tracheal pressure suffer from the practical drawback that they require the use of a special endotracheal tube or the introduction of an extra catheter, respectively. For routine purposes, it is more practical to measure pressure at the inlet of the endotracheal tube and to correct for its nonlinear effects in the measured impedance [5].
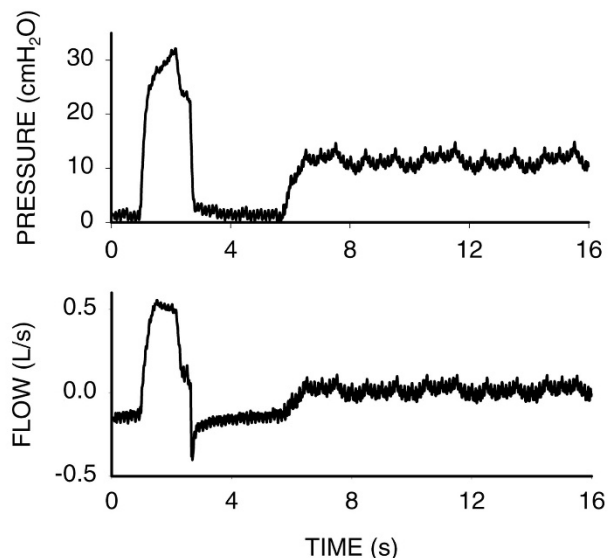
Assessment of the frequency dependence of $R_{rs}$ and $X_{rs}$ provides information for a better characterisation of the patient's respiratory mechanics. Determining $R_{rs}$ and $X_{rs}$ at several frequencies with sinusoidal oscillation (Fig. 2) would require several measurements at the different frequencies of interest, which would not be practicable in routine. Alternatively, it is possible to characterise respiratory mechanics in greater detail by measuring $R_{rs}$ and $X_{rs}$ at different frequencies simultaneously in a single measurement. For this purpose, a complex signal containing several frequencies is employed instead of a sinusoidal oscillation [11]. The multifrequency signal might consist of a random noise, of a fundamental frequency plus its harmonics (for

**Figure 3**



Pressure and flow signals recorded in a forced oscillation technique measurement (0.25–16 Hz) during an inspiratory pause in a paralysed and mechanically ventilated patient with chronic obstructive pulmonary disease.

**Figure 4**



Pressure and flow signals recorded in a forced oscillation technique measurement (0.25–16 Hz) during an expiratory pause in a paralysed and mechanically ventilated patient with chronic obstructive pulmonary disease.

example 2, 4, 6, 8 Hz) or of a more complex combination of optimised frequencies, which is particularly useful in the case of marked nonlinearities in the respiratory system [26]. The analysis of the complex multifrequency signals recorded and the computation of $R_{rs}$ and $X_{rs}$ at the different frequencies are performed automatically by means of a computer. Conventional data processing also provides an index of impedance reliability [27].
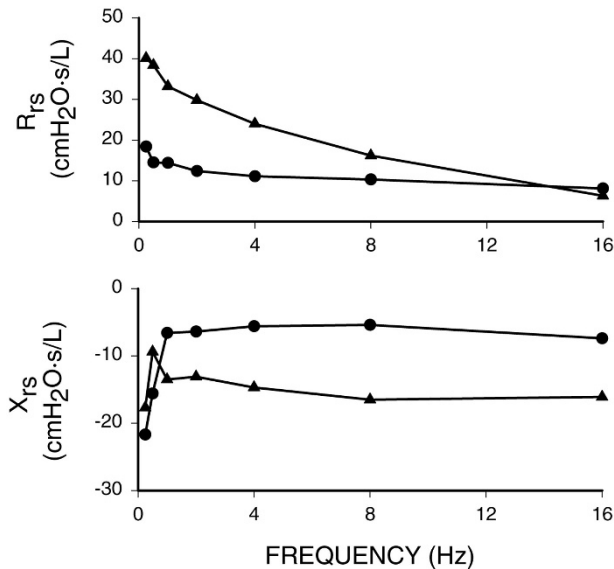
## Application of FOT in ventilated patients

The basic approach to the assessment of respiratory mechanics by FOT is the application of a sinusoidal oscillation (Fig. 2). This procedure is particularly suitable for computing an index of respiratory impedance to monitor the changes in the patient's respiratory mechanics within the ventilation cycle during invasive and noninvasive ventilation [5,8]. Moreover, sinusoidal oscillation is also useful for assessing patient mechanics during noninvasive ventilation with continuous positive airway pressure, pressure support, volume control or proportional assist ventilation [8–10,28]. Given its simplicity, sinusoidal oscillation is a potential tool for routinely determining the response to different pharmacological treatments or interventions during mechanical ventilation (such as postural change [28], aspiration, application of PEEP [19,28], weaning).

Extending the frequency band of FOT measurements down to low frequencies (about 0.25 Hz) allows the assessment of $R_{rs}$ and $X_{rs}$ over a wide band, including frequencies close to breathing rates. The advantage of such

a measurement is that it enables us to compare $R_{rs}$ and $X_{rs}$ measured by FOT with the results obtained by more conventional techniques in respiratory mechanics (such as airway occlusions or multilinear regression analysis) [6,7]. Using low frequencies (that is, long periods) to assess respiratory mechanics at a given lung volume requires the patient to be paralysed and the measurements to be performed during inspiratory (Fig. 3) or expiratory (Fig. 4) pauses so as to keep the respiratory system at a fixed operating point (in terms of volume or transpulmonary pressure) during a measurement lasting several seconds. A short pause is readily achieved by pushing the corresponding ventilator control buttons with minimum disturbance of the ventilation pattern.
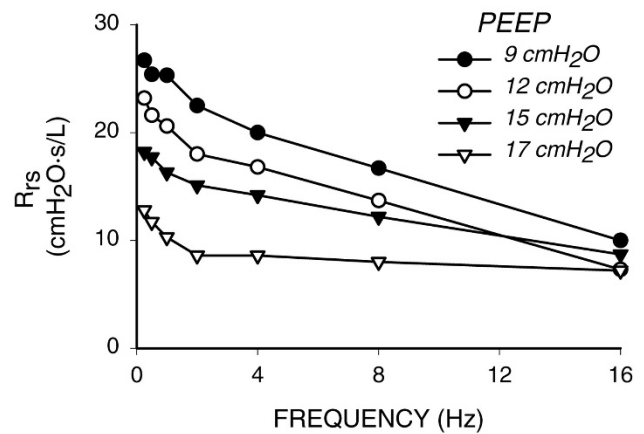
One advantage of measuring $R_{rs}$ and $X_{rs}$ during inspiratory and expiratory pauses in a given patient is to quantify the dependence of respiratory mechanics on lung volume or transpulmonary pressure. Indeed, as shown in Fig. 5, $R_{rs}$ and $X_{rs}$ computed from the measurements in Figs 3 and 4 show that in this patient with chronic obstructive pulmonary disease (COPD), impedance was considerably greater during expiratory than inspiratory pauses, particularly at the lower frequencies. $R_{rs}$ during the expiratory pause was considerably dependent on frequency over the whole frequency band. By contrast, $R_{rs}$ during the inspiratory pause was much less dependent on frequency (Fig. 5). $X_{rs}$ also was also different during inspiratory and expiratory pauses, particularly at more than 1 Hz. This pattern of frequency dependence has been interpreted in
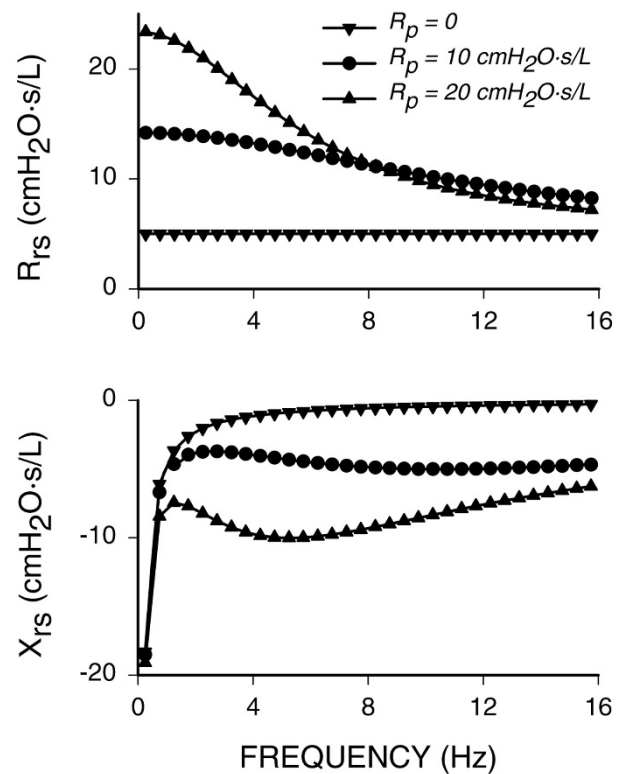
**Figure 5**



Respiratory resistance ($R_{rs}$) and reactance ($X_{rs}$) during inspiratory (●) and expiratory (▲) pauses (Figs 3 and 4) in a paralysed and mechanically ventilated patient with chronic obstructive pulmonary disease.

**Figure 6**



Respiratory resistance ($R_{rs}$) measured during expiratory pauses at different positive end-expiratory pressure levels in a paralysed and mechanically ventilated patient with chronic obstructive pulmonary disease.

**Figure 7**



Respiratory resistance ($R_{rs}$) and reactance ($X_{rs}$) in a model [7] consisting of a central airway resistance of 5 cmH$_2$O s L$^{-1}$ plus a bronchial wall elastance of 700 cmH$_2$O L$^{-1}$ in parallel with a peripheral airway resistance ($R_p$) and a tissue elastance of 30 cmH$_2$O L$^{-1}$. $R_{rs}$ and $X_{rs}$ are shown for three different values of $R_p$.

terms of increased peripheral resistance due to airway closure at end-expiration [5,7]. This interpretation is in keeping with the observations in Fig. 6, namely that $R_{rs}$ at end-expiration progressively and considerably decreased as transpulmonary pressure (PEEP) increased. The values of $R_{rs}$ and $X_{rs}$ provided by FOT can be compared with the resistance and elastance indices derived from the application of the airway occlusion technique, which has been used extensively to assess airway mechanics in ventilated patients [6,7]. Indeed, FOT data are obtained from small-amplitude oscillations at the extreme points of a conventional inflation (end-expiration and end-inspiration), whereas data from the occlusion manoeuvres are obtained from a high-amplitude excursion across those extreme points. Such a comparison sheds some light on the mechanisms determining the nonlinear properties of the respiratory system in patients and might be useful for predicting the relationship between pressure, flow and volume during mechanical ventilation.

The interpretation of $R_{rs}$ and $X_{rs}$ measured under nonlinear conditions (Figs 5 and 6) is difficult. However, the results obtained in analogue models, in animals and in patients suggest that FOT is useful for characterising the viscoelastic properties of respiratory tissues [7], for assessing inhomogeneities in the respiratory system [5–7] and for detecting expiratory flow limitation during mechanical ventilation [16,29]. The interpretation of measured $R_{rs}$ and $X_{rs}$ can be performed in terms of models with a pathophysiological interest. For instance, a simple model proposed to

analyse $R_{rs}$ and $X_{rs}$ in mechanically ventilated COPD patients consists of a central airway resistance plus a shunt elastance due to the bronchial wall, in parallel with peripheral airway resistance and tissue elastance [7]. As shown in Fig. 7, this simple model can mimic the pattern of frequency dependence of $R_{rs}$ and $X_{rs}$ during end-inspiratory and end-expiratory pauses (Fig. 5) by means of an increase in the peripheral resistance due to airway closure during expiration. Figure 7 shows that, in inhomogeneous models, a change in airway properties, for example an increase in peripheral resistance, modifies both $R_{rs}$ and $X_{rs}$. Nevertheless, it should be stressed that so far there is no solid evidence in favour of using a specific model to interpret FOT data in mechanically ventilated patients. Consequently, the values of $R_{rs}$ and $X_{rs}$ measured at certain frequencies are probably the best indices for monitoring the mechanical status and evolution of the ventilated patient in clinical practice.

## Conclusion

FOT is useful for characterising the respiratory mechanics in patients subjected to noninvasive or invasive mechanical ventilation. The main advantage of this technique is that it is readily and continuously applicable during mechanical ventilation, obviating the need for disturbing or modifying the ventilation pattern. Moreover, it allows automatic and on-line monitoring of $R_{rs}$ and $X_{rs}$ to assess the dependence of the patient's respiratory mechanics on pressure, flow and volume as well as to detect expiratory flow limitation. Continuous FOT monitoring of the status and evolution of the ventilated patient provides updated information that is potentially useful for resetting the ventilator. Although at present the application of FOT in ventilated patients has been mainly confined to research, current methodological and technical experience enables the application of portable and compact computerised FOT systems during mechanical ventilation [30,31].

## Acknowledgement

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