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TECHNICAL NOTE

Servocontrolled generator to measure respiratory impedance from 0.25 to 26 Hz in ventilated patients at different PEEP levels

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Servocontrolled generator to measure respiratory impedance from 0.25 to 26 Hz in ventilated patients at different PEEP levels. R. Farré, M. Ferrer, M. Rotger, D. Navajas. ©ERS Journals Ltd 1995.

ABSTRACT: Assessing respiratory impedance (Zrs) in ventilated patients over a wide frequency band, ranging from breathing rates to typical forced oscillation frequencies, during end-expiratory pauses at different positive end-expiratory pressures (PEEP) is of potential interest to assess a patient's respiratory mechanics. Zrs measurements under these conditions are not possible with the present variants of the forced oscillation technique. The aim of this work was to design a forced oscillation generator operating from spontaneous breathing frequencies whilst withstanding PEEP.

To this end, we constructed a generator based on a servocontrolled loudspeaker. This allowed the loudspeaker cone to remain at its resting position regardless of the external PEEP applied. The system was optimized by using a mechanical analogue. The clinical applicability of the servocontrolled generator was assessed by measuring Zrs in mechanically-ventilated chronic obstructive pulmonary disease (COPD) patients during end-expiratory pauses at different transrespiratory pressures.

The forced oscillation generator designed may be easily applicable in practice since it is small and light. The system is able to withstand transrespiratory pressures of up to 17 hPa and allows the application of forced oscillation of sufficient amplitude (>2 hPa peak-to-peak, 0.25–26 Hz) to obtain reliable respiratory resistance and reactance data.

The servocontrolled generator permits the assessment of respiratory mechanics over a wide frequency band ranging from breathing frequencies to the most typical forced oscillation frequencies during end-expiratory pauses at PEEPs within the conventional range.

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The measurement of respiratory impedance (Zrs) in artificially-ventilated patients by means of the forced oscillation technique is of interest since respiratory mechanics can be explored over a wide range of frequencies [1]. The frequency band investigated must be as wide as possible, since the influence of the different mechanical properties (airway resistance, tissue viscoelasticity, airway wall motion,...) play a different role depending on the frequency. Moreover, measurements of Zrs at different transrespiratory pressures could provide information about the changes of the resistive and elastic properties of the respiratory system when varying the lung inflation. Therefore, Zrs data obtained at frequencies down to typical breathing rates at different transrespiratory pressures may be helpful to optimize the ventilator settings, particularly the positive end-expiratory pressure (PEEP). Assessment of Zrs under these conditions requires the measurement to be performed during a ventilator pause lasting several seconds, to cover more than one period of forced oscillation, whilst keeping transrespiratory pressure constant. Despite its potential interest, the forced oscillation technique has not so far been used in this particular application, since neither the conventional nor the most recently proposed variants of the forced oscillation technique [2, 3] have been designed to operate at low frequencies while withstanding a transrespiratory pressure load.

Therefore, the aim of this work was to develop a clinically applicable system to measure the frequency dependence of Zrs in mechanically-ventilated patients for frequencies down to the typical breathing rates during end-expiratory pauses at different PEEP levels. To this end, we modified a loudspeaker-based forced oscillation system by implementing a closed-loop feedback control of the loudspeaker cone position. With this procedure, the cone remained at its resting position when subjected to the external PEEP load. The performance of the system was optimized by using a mechanical analogue.

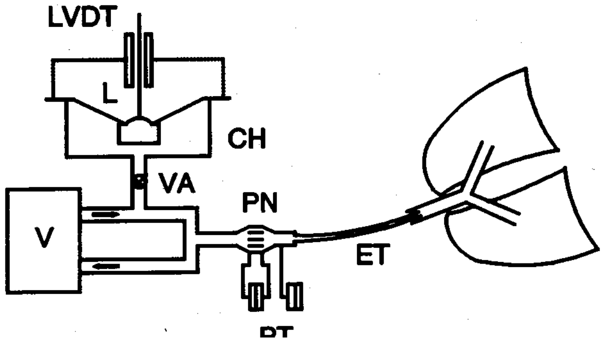

Fig. 1. – Diagram of the set-up: ventilator (V); pneumotachograph (PN); pressure transducers (PT); endotracheal tube (ET); loudspeaker (L); chamber (CH); valve (VA); positron transducer (linear variable differential transformer (LVDT)).

We assessed the clinical applicability of the set-up by measuring *Z*rs in mechanically-ventilated chronic obstructive pulmonary disease (COPD) patients.

Methods

Figure 1 shows a diagram of the servocontrolled system designed to measure *Z*rs in ventilated patients. An 8 inch subwoofer loudspeaker (Pioneer, TS-W201, 100 W, 219 cm^2 of moving area, 13 mm of excursion) was attached to a cylindrical chamber (10 cm in height, 20 cm in diameter). The loudspeaker coil was placed inside the chamber to minimize the gas enclosed in it and, thus, the compliance of the generator. The flexible junctions of the loudspeaker cone were sealed with latex. The chamber had an outlet tube with a valve to connect the system in parallel with the endotracheal tube in the inspiratory circuit. The position of the loudspeaker cone was measured with a linear variable differential transformer (LVDT) transducer (Sangamo, AC/15). The moving element of the position transducer was fixed to the external face of the loudspeaker cone. The difference between the driving signal, *i.e.* the desired position, and the actual cone position was fed to a conventional proportional-integral-differential (PID) circuit and then used to excite the loudspeaker.

To design the servocontrolled forced excitation generator under realistic operating conditions, the endotracheal tube (8 mm internal diameter (ID)) in figure 1 was connected to a resistance-inertance-elastance (*R-I-E*) mechanical analogue simulating the impedance of a human subject. This analogue was built with a wire-mesh screen resistor (R=2.2 hPa·s·L^{-1}), a cylindrical tube (I=1.2 Pa·s^2·L^{-1}), and an air chamber to provide the compliant component (E=18.2 hPa·L^{-1}). To determine the servocontrol settings, the attention was focused on the low frequency band (DC-5 Hz) typical of the pressure patterns used during mechanical ventilation. Therefore, the coefficients of the PID controller were set to achieve a good steady-state response when the forced excitation generator loaded with the mechanical analogue was subjected to a step input. To this end, the differential and integral components of the PID were firstly disconnected, and the proportional gain was progressively increased and set a little below the point where the system oscillated. Secondly, the derivative component of the PID was connected, and its time constant was increased to improve the transient response. Finally, the integral component was connected, and its time constant was reduced to improve the steady-state response to the step input whilst maintaining the system stable.

The clinical applicability of the generator designed was tested in two paralysed and mechanically-ventilated COPD patients at different PEEP levels. The study was approved by the Ethics Committee of the hospital and informed consent was obtained from the next of kin of the patients. The servocontrolled generator was placed in the inspiratory circuit in parallel with the ventilator (Siemens, 900-C) (fig. 1). The patient was intubated with a cuffed endotracheal tube (Portex, 7.5 mm ID) and mechanically ventilated with constant flow, as established by the attending physician. During the normal ventilator cycling, the valve connecting the forced oscillation generator was closed. To measure *Z*rs the expiratory outlet was occluded by pressing the corresponding button of the ventilator and the valve of the forced oscillation generator was manually opened. The forced excitation signal applied to the paralysed patient contained power at 0.25, 0.5, 1, 2, 4, ..., 24, 26 Hz. The amplitudes of the low-frequency components were enhanced. Flow was recorded at the entrance of the endotracheal tube by means of a Fleisch-type pneumotachograph and a differential pressure transducer (Celesco LVDT, 2 hPa). The common-mode rejection ratio of this differential pressure transducer and tubing connected to the pneumotachograph was greater than 60 dB (0.25–26 Hz). Pressure at the trachea was measured with a transducer (Honeywell 176) connected to a catheter (50 cm in length and 0.12 cm ID), with a lateral pressure port at its tip placed 2 cm beyond the outlet of the endotracheal tube. Pressure and flow signals were analogically low-pass filtered (Butterworth, 8 poles, 32 Hz) and sampled at 128 Hz. The frequency responses of the pressure and flow measuring devices were digitally corrected. The last 8 s of pressure and flow data from an end-expiratory occlusion lasting about 12 s were divided into three blocks of 4 s each (50% overlapping). After subtracting the mean value, each block was multiplied by a Hanning window and its Fast Fourier Transform was computed to estimate spectra and impedance. A minimum of 10 normal ventilator cycles were allowed before repeating a measurement.

Results

The results obtained using the respiratory impedance analogue showed that the servocontrol implemented in the generator maintained the loudspeaker cone at its resting position for external loading pressures of up to 17 hPa. This allows application of a forced oscillation of typical amplitude (1 hPa) at PEEP levels of up to 15 hPa. Figure 2 shows an example of the pressure at the entrance of the endotracheal tube and the loudspeaker cone position recorded when the system generated a

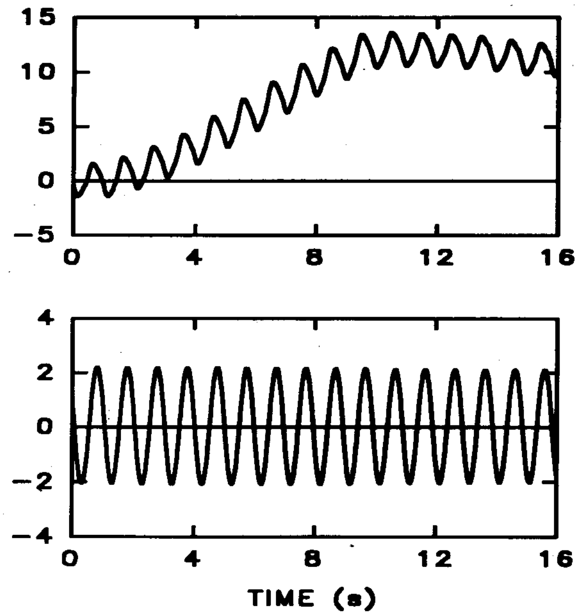

Fig. 2. – Pressure and position of the servocontrolled loudspeaker cone when generating a forced oscillation (1 Hz, ±1.5 hPa) under external pressure load.

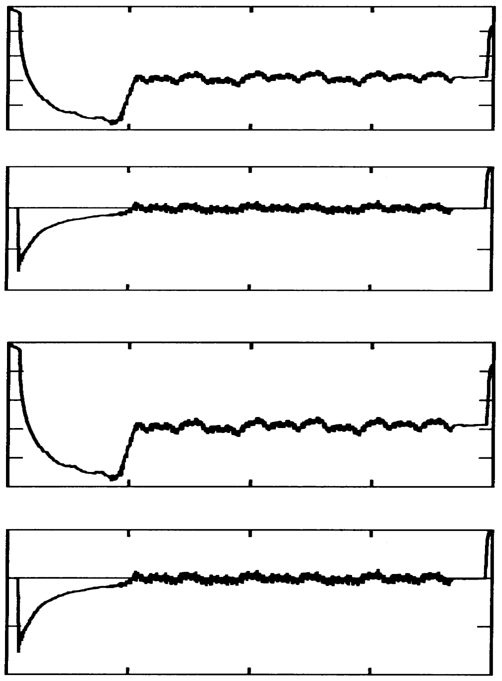

Fig. 3. – Pressure and flow recorded in the measurement of Zrs in a paralysed chronic obstructive pulmonary disease (COPD) patient during an end-expiratory pause.

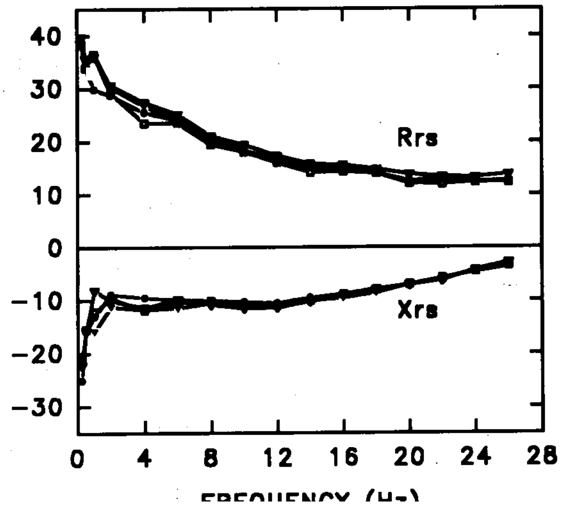

Fig. 4. – Respiratory impedances - resistance (*R*rs), reactance (*X*rs) - measured in a chronic obstructive pulmonary disease (COPD) patient during four end-expiratory pauses at intervals of 15 min.

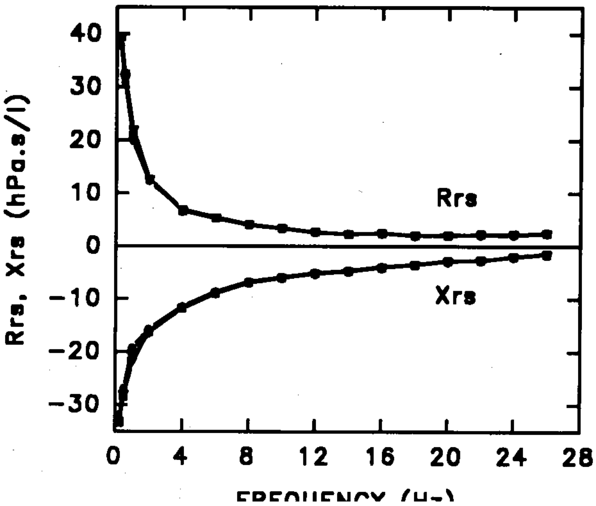

Fig. 5. – Respiratory impedances - resistance (*R*rs), reactance (*X*rs) - measured in a chronic obstructive pulmonary disease (COPD) patient during four consecutive end-expiratory pauses.

sinusoidal forced oscillation while an external pressure load was progressively being applied. The servocontrolled loudspeaker maintained its cone oscillating around its resting position regardless of the pressure load. It can be observed that although the position (*i.e.* volume) was sinusoidal, the associated pressure at the entrance of the endotracheal tube was not perfectly sinusoidal. This was due to the harmonic distortion produced by the nonlinear pressure-flow relationship in the endotracheal tube.

Figure 3 shows the typical pressure and flow signals recorded when measuring Zrs during an end-expiratory pause in a paralysed COPD patient. In this case, the forced excitation (3 hPa peak-to-peak) was applied at a transrespiratory pressure (intrinsic PEEP) of 10.2 hPa. Figures 4 and 5 show examples of the frequency dependence of Zrs and its reproducibility. Figure 4 plots the resistances (*R*rs) and reactances (*X*rs) (Zrs=*R*rs + j·*X*rs; $j=(-1)^{1/2}$) obtained from four end-expiratory pauses at intervals of 15 min. Figure 5 corresponds to *R*rs and *X*rs from four consecutive measurements in another patient. The reproducibility (coefficient of variation) of *R*rs and *X*rs measured from consecutive end-inspiratory pauses (fig. 5) was within 7% at all frequencies. The reproducibility of data in figure 4 obtained over a period of 1 h was within 15% at all frequencies, except at 1 Hz, owing to the cardiac noise interference in this patient. In both patients *R*rs exhibited a considerable frequency dependence from 0.25–32 Hz. *X*rs showed a rapid increase from 0.25 to 2 Hz and a less pronounced increase up to 26 Hz, always remaining negative (frequency of resonance out of the investigated frequency range).

Figures 6 and 7 are examples of the changes observed in *R*rs and *X*rs when modifying PEEP. Figure 6 corresponds to the same patient as in figure 4 when transrespiratory pressure was reduced from 10.2 to 8.1 hPa by prolonging the duration of expiration by 5 s. *Z*rs varied considerably: *R*rs increased by 27% and *X*rs decreased by 69% on average over the whole frequency band (data affected by cardiac noise (1 Hz) were discarded in this figure). Figure 7 shows the changes induced in *R*rs and *X*rs when extrinsic PEEP applied to the patient in figure 5 was modified from 0 to 10 hPa. The associated change in transrespiratory pressure during end-expiratory pauses, from 10.5 hPa (intrinsic PEEP) to 12.4 hPa, led to a decrease in *R*rs and an increase in *X*rs (29% over the whole frequency band both for *R*rs and *X*rs).

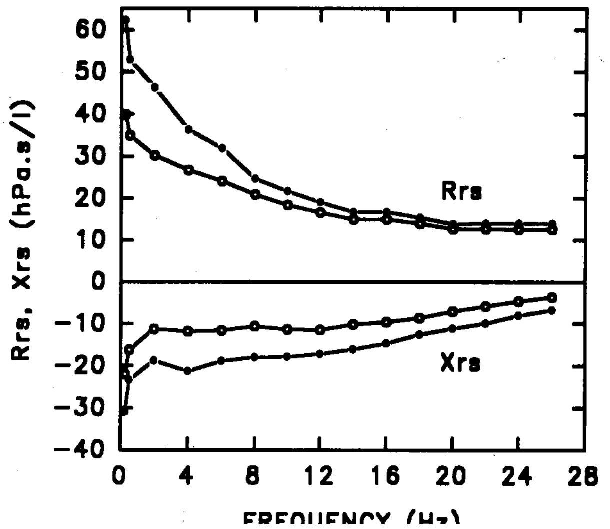

Fig. 6. – Respiratory impedances - resistance (*R*rs), reactance (*X*rs) - measured in the patient featured in figure 4, when reducing transrespiratory pressure from 10.2 hPa (○) to 8.1 hPa (●).

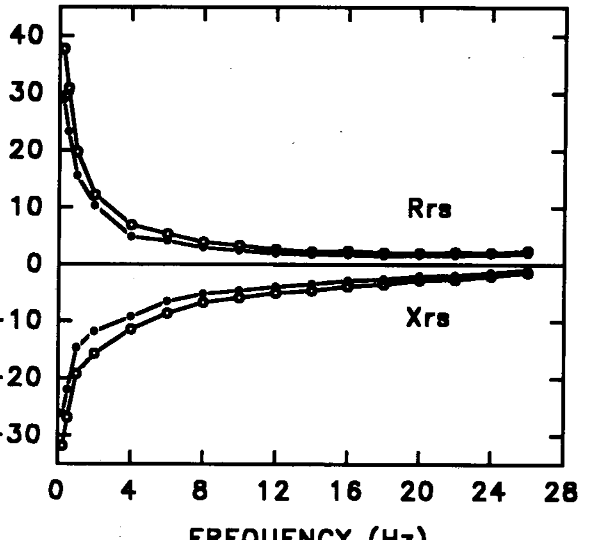

Fig. 7. – Respiratory impedances - resistance (*R*rs), reactance (*X*rs) - measured in the patient featured in figure 5, when extrinsic positive end-expiratory pressure (PEEP) was increased from 0 (○) to 10 hPa (●).

Discussion

In this work, we developed a clinically applicable system to measure the frequency dependence of *Z*rs in mechanically-ventilated patients over a wide frequency band ranging 0.25–26 Hz during end-expiratory pauses at different PEEP levels. Measuring in such conditions is not possible with conventional forced oscillation devices, since they are not designed to operate under external pressure load. In fact, disconnection of the ventilator from the patient was required in previous measurements in intubated-paralysed patients [4]. To overcome this difficulty, PESLIN *et al.* [2] used a set-up based on a loudspeaker separating two chambers connected by a high inertance tube acting as a low-pass mechanical filter. This generator obviates the need for the loudspeaker to withstand the high-amplitude low-frequency pressure due to the ventilator cycling, but the presence of the low-pass mechanical filter limits the lowest measuring frequency to 5 Hz [2]. A possible modification of this loudspeaker-in-box system to reduce the lowest measuring frequency would be to narrow the diameter of the tube in the low-pass mechanical filter, as HANTOS *et al.* [5] did in animal studies. This, however, would require the prolongation of the apnoea period to equilibrate pressure, which constitutes a drawback in patient studies. NAVAJAS *et al.* [3] proposed the measurement of *Z*rs in ventilated patients by connecting a conventional forced oscillation device to the expiratory outlet of the mechanical ventilator in order to avoid submitting the loudspeaker to the high-pressure generated by the ventilator during inspiration. This approach has the advantage of allowing the measurement of *Z*rs during artificial ventilation by using a conventional forced oscillation set-up, but *Z*rs can only be measured during expiration. Therefore, these variants of the forced oscillation technique are not suitable for measuring *Z*rs at low frequencies during external pressure load in patients. The servocontrol procedure that we implemented allows the loudspeaker to support PEEP. In contrast to other possible alternatives (using a linear motor or an oscillating pump), this approach has the advantage of providing a generator for multifrequency measurements with a reduced size and weight, which facilitates its clinical application.

To achieve an adequate performance, the electromechanical parameters of the different elements of the servocontrolled system should be carefully selected according to its specific requirements. Firstly, a powerful loudspeaker must be used to apply the large forces required to support PEEP. Secondly, as the system has to oscillate at low frequencies, the area of the loudspeaker cone must be large enough to produce adequate volume strokes with cone displacements within the normal excursion range. Thirdly, the generator placed in parallel with the ventilator should interfere minimally with the ventilation circuit. Therefore, its impedance, mainly due to the enclosed air compliance, must be as high as possible. Finally, the set-up must be of a reduced size to allow its clinical application during artificial ventilation. The commercially available loudspeaker used in this work and the reduced chamber size struck a balance between the conflicting requirements concerning power, area of the moving surface, excursion range and total size of the generator.

In addition to supporting PEEP, the generator designed was able to apply forced oscillation of sufficient amplitude to reliably measure Z_{rs}, since this required cone displacements within its nominal range. Indeed, given the excursion (±6.5 mm) and moving area (219 cm^2) of the cone, the volume oscillation that the loudspeaker can generate is of ±140 ml. At 0.25 Hz, which is the most demanding frequency, this corresponds to a flow oscillation of $\pm 0.22\ L \cdot s^{-1}$. As Z_{rs} modulus at 0.25 Hz is about $20\ hPa \cdot s \cdot L^{-1}$ in healthy subjects [4] and higher in patients (figs 4–7), the achievable flow oscillation of $\pm 0.22\ L \cdot s^{-1}$ would induce a forced oscillation pressure exceeding ±4 hPa, which is much greater than the one commonly applied in the measurements of Z_{rs} by forced oscillation (±1 hPa). Therefore, the servocontrolled generator would be able to operate at frequencies of less than 0.25 Hz. However, as this would increase the period of oscillations, in the patient measurements we restricted the lowest frequency to 0.25 Hz to avoid an excessive apnoeic period at each end-expiratory pause. The servocontrolled generator that we constructed was implemented with the specific aim of measuring Z_{rs} down to low frequencies during ventilator pauses. Nevertheless, it is possible to easily modify the design of the set-up if the objective is to assess Z_{rs} during the whole cycle of the ventilator. Taking into account that the coil-magnet system of the loudspeaker acts as a force generator, the loading pressure that the system may support can be increased by reducing the effective area of the moving surface. This, however, would limit the amplitude of forced excitation volume provided by the generator and, therefore, the lowest forced oscillation frequency would be increased.

The results obtained (figs. 3–7) confirm the clinical applicability of the system devised to assess respiratory mechanics in paralysed, mechanically-ventilated patients. Indeed, the system was able to apply a forced oscillation suitable for obtaining reproducible R_{rs} and X_{rs} over the whole frequency band (0.25–26 Hz) for PEEP values within the clinical range. In addition to the methodology specifically used in our measurements in patients, the servocontrolled generator can be used with the different variants of the forced oscillation technique proposed in the literature. For instance, those concerning the characteristics of the excitation signal (spectra enhancement to improve the signal-to-noise ratio, periodic or nonperiodic signals,...), data processing procedure (number of blocks, time or frequency domain averaging,...), or the method of solving the nonlinearity of the endotracheal tube (tracheal catheter, or correction of data when pressure is sampled at the entrance of the endotracheal tube). In addition to confirming the practical applicability of the system, our preliminary results in COPD patients suggest that assessing Z_{rs} down to 0.25 Hz by forced oscillation during end-expiratory pauses may provide useful information to improve understanding of respiratory mechanics in patients, which is of considerable interest in setting the mechanical ventilation parameters [6]. In particular, the frequency dependence of R_{rs} and X_{rs}, which was markedly different from the one observed in paralysed, mechanically-ventilated healthy subjects [4], could be interpreted in terms of system nonhomogeneities. Moreover, comparison of R_{rs} and X_{rs} at frequencies (0.25 Hz) close to breathing with the ones derived from the conventional ventilation signals could enable us to explore system nonlinearities. In this respect, Z_{rs} data measured at different PEEP levels may provide information concerning the dependence of the respiratory system load at different operating points.

The procedure of servocontrolling the position of the loudspeaker cone can also be of interest in the set-ups used to measure Z_{rs} in awake subjects; especially if the attention is focused on the low frequency range (<6 Hz), where the spontaneous breathing of the subject could induce bias errors. In this application, servocontrolling the loudspeaker may facilitate the use of unbiased estimators [7, 8], requiring the excitation device to remain linear and stationary over the whole breathing cycle. In this respect, we verified that when the servocontrolled excitation generator was connected to a typical bias tube (I=120 cm, ID=2 cm) as in conventional devices to measure Z_{rs} in spontaneously breathing subjects, the displacement of the loudspeaker cone was less than 0.15 mm when the generator was submitted, through the pneumotachograph, to sinusoidal flows of $\pm 0.4\ L \cdot s^{-1}$ (0.125–4 Hz) simulating the breathing of a subject. This implies that, when compared with the impedance of the bias tube placed in parallel, the loudspeaker offers an almost infinite impedance to breathing, which contrasts with the high compliance of conventional loudspeakers [9]. Consequently, the impedance of the measuring system depends only on the chamber and on the bias tube, which are precisely known, and the problem of possible loudspeaker nonlinearities is no longer present, which is of crucial importance for the correction of bias errors [7, 8]. In practice, the only components to be incorporated (fig. 1) into a conventional forced oscillation device would be a position transducer - LVDT, potentiometer or optical [10, 11] - and a conventional PID controller (implemented in hardware or in software). Therefore, in addition to the application in ventilated patients, for which it was designed, the loudspeaker servocontrol procedure can also be easily implemented in any conventional forced oscillation generator.

In conclusion, the servocontrolled generator that we designed allows assessment of respiratory mechanics in artificially-ventilated patients during expiratory pauses at different PEEP levels for a wide frequency band ranging from spontaneous breathing frequencies to typical forced oscillation frequencies. The system provides data concerning the mechanical load offered by the respiratory system as a function of frequency and of transrespiratory pressure. This may be of clinical interest to determine the mechanical status and progress of artificially-ventilated patients [6, 12]. Moreover, in addition to other clinical parameters Z_{rs} data at different transrespiratory pressures could be helpful for setting the optimum PEEP.

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