

## **A Comparison of Two Methods for Assessment of Lung Mechanical Parameters**

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Comparison tests of the added compliance method and the standard method for the assessment of mechanical parameters of respiratory system are presented in this paper. In the added compliance method, an additional external mechanical chamber as the added compliance is periodically connected to the respirator-lungs system, to determine the values of the mechanical parameters of the respiratory system. The software application for the system control and data acquisition is written in the LabView Environment. The results confirm that the added compliance method is sufficient to be used for the calculation of the total compliance of respiratory system during the artificial ventilation.

**Key words:** mechanical parameters of respiratory system, total compliance, airway resistance, artificial ventilation

### **1. Introduction**

A transport of gases during respiration is supplying the lungs with oxygen from the inspired air and is removing the carbon dioxide in the expired waste. If a subject cannot breathe spontaneously then it requires to be supported by the artificial ventilation (e.g. mechanical ventilation). Mechanical ventilation provides the proper quantity of gas mixture containing oxygen and volatile anaesthetic agents to the ventilated subject. The respiratory mechanics can be described by the pressure, flow and volume relationships of the total respiratory system. It is well known that inspiratory phase of respiration is usually active, while expiratory phase may be passive, especially at its beginning. During passive expiration, the airflow is assumed approximately as exponential in character [1]. Therefore, the expiratory phase during the artificial

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*Received 12 March 2008; Accepted 13 March 2009*

ventilation can be used for assessment of the mechanical parameters. Monitoring of the mechanical parameters such as the total compliance of respiratory system ( $C_{rs}$ ) and the airway resistance ( $R_{aw}$ ) during the long-term artificial ventilation is the key problem of the patients' therapy with the severe acute respiratory distress syndrome as far as the optimization of the mechanical ventilation is concerned, and for this reason the selection of appropriate settings is needed.

It is necessary to comment problems arising when accuracy of measurements of lung mechanical parameters is considered. First of all, one should honestly say that present situation is a result of historical issues (medical diagnostic routines development) when the standard RC model has been assumed as a diagnostic basis for lungs parameters identification. It is well known that it is a very imperfect model of lungs not taking into account its complexity however widely used and still "alive". Until now there are no other proposed models of lungs so widely accepted by physicians as the standard RC model and able to replace the old one. However, there is a number of models (Otis, DuBois, Mead, Bates etc.) better describing the mechanical properties of lung. For sure, possible results of the lungs parameters identification of any new model should be convertible into parameters of the old model, otherwise could arise doubts about correctness of the new one. So, at present, it will be dealing with medically accepted standard method based on the RC model of lungs. A comparison of these methods should be performed *in vitro* using the well-identified model of lungs to avoid problems of its structural errors. In this case a problem of pressure and flow measurements errors is of less importance as they are generally small (about 1%) and negligible if compared to the possible lungs model errors what would inevitably occur while *in vivo* measurements of the lungs RC parameters are realized.

The aim of the work is to develop and test the modified measuring model system based on the added compliance method suitable for the clinical investigations with improved accuracy and simplified measurement process as well.

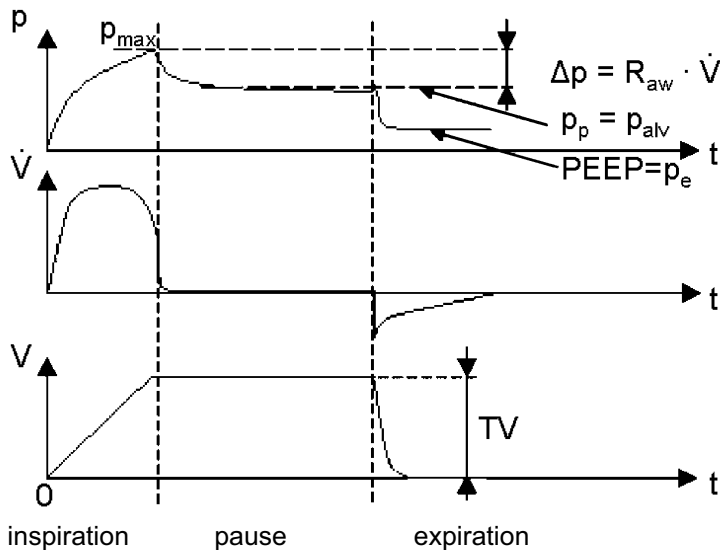
The added compliance method elaborated by Darowski and Kozarski (national patent no. 194694) [2], and then tested at the IBBE [3, 4] as an interesting alternative method for the mechanical parameters calculation, is compared with the clinically used conventional method i.e. the end-inspiratory pause (EIP) method (called also end-inspiratory airway occlusion method). In tests of both methods, the mechanical model of lungs is connected to the measurement set-up to check mentioned above parameters of the model's mechanics ( $C_{rs}$  and  $R_{aw}$ ).

## 2. Material and Methods

### 2.1. The EIP Method

The standard EIP method described by von Neergard and Wirz in 1927, known also as an interrupter method or end-inspiratory airway occlusion method for measuring

of respiratory mechanics, when the air is hold in the lungs with no air flow taken from the respirator (by the occlusion maneuver), is based on the measurements of the pressure and flow signals during the ventilation to estimate respiratory resistance and respiratory elastance [5]. The airflow is rapidly interrupted at the end of the inspiration by a computer-driven occlusion pneumatic valve. The airway occlusion usually is maintained for 0.5 to 1 s. When in practice the airway occlusion is longer than 1s, the pressure signal can get stable state. Basing on airway pressure records (Fig. 1), various characteristic pressure values are obtained. In this method, the pressures in alveolars  $p_{alv}$  and in the airways at the end-inspiratory pause (occlusion)  $p_p$  are assumed to be equal.



**Fig. 1.** Time records of pressure  $p$ , flow  $\dot{V}$ , and volume  $V$  respectively, where:  $p_{\max}$  – maximum value of the pressure (end-inspiratory pressure),  $p_p$  – the airways at the end-inspiratory pause (occlusion),  $PEEP = p_e$  – positive end-expiratory pressure,  $\Delta p = R_{aw} \cdot \dot{V} = p_{\max} - p_p$  – pressure drop,  $TV$  – tidal volume

The method of calculations of the total compliance of respiratory system  $C_{rs}$  and airway resistance  $R_{aw}$  is presented as follows:

$$C_{rs} = \frac{TV}{p_p - p_e} \quad (1)$$

where:  $TV$  – tidal volume,  $p_p$  – occlusion pressure (equal to the alveolar pressure),  $p_e$  – positive end-expiratory pause pressure (PEEP).

$$R_{aw} = \frac{p_{\max} - p_p}{\dot{V}} \quad (2)$$

where:  $\dot{V}$  – flow,  $p_{\max}$  – maximum value of the pressure (end-inspiratory pressure). Since the additional pause time is needed to perform lungs parameters measurements, the EIP method considerably influences the ventilation process.

## 2.2. The Added Compliance Method

In this work, the added compliance method [6, 7] is tested in comparison with the EIP method. The principle of this method presented in this subchapter (Fig. 2) is based on measurements of two basic mechanical parameters mentioned in the introduction by using the extra-added pneumatic capacitance ( $C_a$ ) (chamber or bellows) connected to the lung-respirator circuit at the expiratory phase of the respiratory cycle. The gas mixture flows from the OUTLET of respirator to the model of lungs. When the chambers of the model are filled at the end of the inspiratory phase of the respiratory cycle, then the added compliance valve ( $AV$ ) is opened and the expiratory valve in the respirator is still closed, and for a short time (about 200 ms) the extra-added pneumatic chamber or bellows ( $C_a$ ) is connected to the lung-respirator circuit. After that time, the expiratory valve in the respirator is opened and the gas flows into the INLET of the respirator, and then to the atmosphere (ATM.) through the respirator. The measurement set-up presented in Fig. 2, consists of four main parts: the respirator, the model of lungs where the airway resistance  $R_{aw}$  is connected in series with the total compliance of respiratory system  $C_{rs}$ , the added compliance part, and the computer system (PC). The acquisition board is installed into PC.

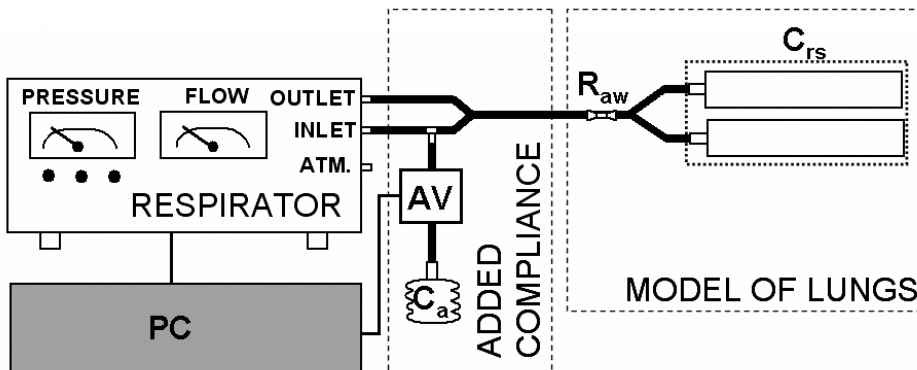
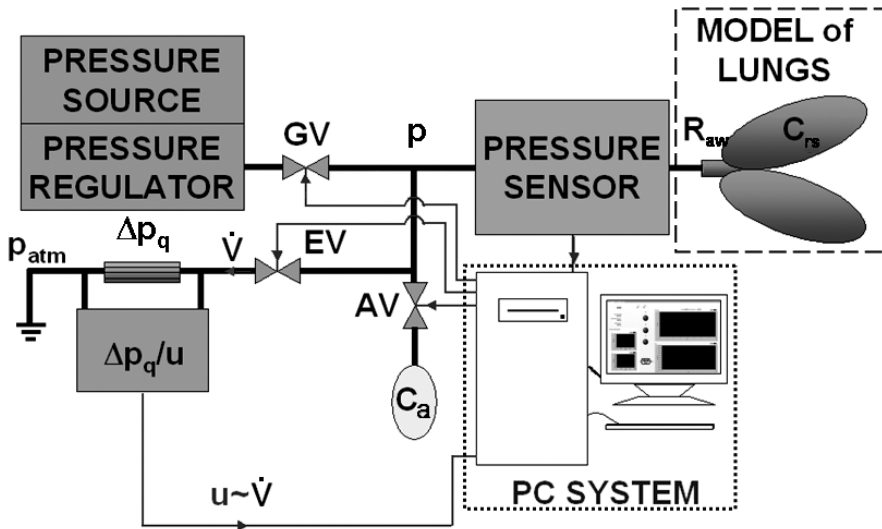


Fig. 2. Measurement set-up of the added compliance method, where:  $C_{rs}$  – total compliance of respiratory system,  $R_{aw}$  – airway resistance,  $C_a$  – added compliance,  $AV$  – added compliance valve

The first experimental setup of the tested method is presented in Fig. 3. Its model of lungs is filled with air. The air pressure  $p$  is changing up to the maximum value of the pressure  $p_{max}$ . Generator valve  $GV$  is open. Then, the generator valve  $GV$  is closed and the added compliance valve  $AV$  is opened and the pressure drop needed to calculate the  $C_{rs}$  is measured. After the measurement of the pressure drop, the expiratory valve  $EV$  is opened and at the end of expiration the pressure drop  $\Delta p_q$  proportional to the voltage  $u$  is measured for calculation of flow  $\dot{V}$ , and finally the  $R_{aw}$ . The pressure  $p$  equalizes to atmospheric pressure  $p_{atm}$  (to level zero). The results of the measurement are shown in Fig. 9.



**Fig. 3.** The first experimental measurement set-up of the added compliance method, where:  $C_{rs}$  – total compliance of respiratory system,  $R_{aw}$  – airway resistance,  $C_a$  – added compliance,  $GV$ ,  $AV$ ,  $EV$  – generator, added compliance, expiratory valves respectively,  $\dot{V}$  – flow,  $p$  – pressure,  $u$  – voltage,  $p_{atm}$  – atmospheric pressure,  $\Delta p_q$  – pressure drop to measure the flow that is proportional to the voltage  $u$ . The results are shown in Fig. 9

The procedure of calculations of the total compliance of respiratory system ( $C_{rs}$ ) and of the airway resistance ( $R_{aw}$ ), provided that the pressure drop  $\Delta p$  on the airway resistance produced by end-inspiratory flow is negligible, is presented as follows:

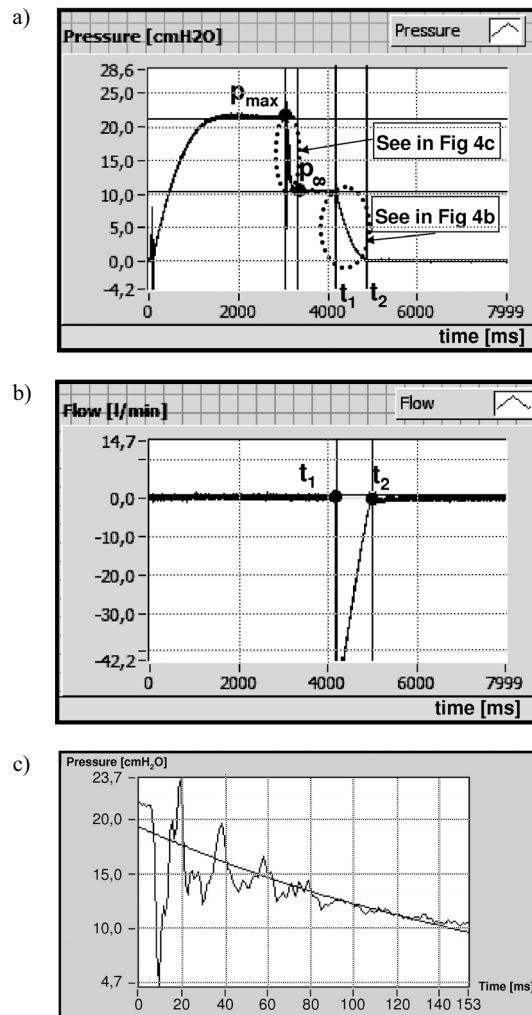
$$C_{rs} = C_a \frac{p_{\infty}}{\Delta p} \tag{3}$$

where:  $p_{\infty}$  – pressure of the steady state after the  $AV$  opening;  $\Delta p$  – pressure drop;  $\Delta p = p_{max} - p_{\infty}$ ;  $p_{max}$  – pressure at the end of the inspiratory phase of the respiratory cycle.

$$R_{aw} = \frac{\tau}{C_{rs} + C_r} \quad (4)$$

where:  $\tau$  – time constant,  $C_r$  – compliance of the respirator.

Time constant  $\tau$  is calculated either from the expiratory pressure or the flow records using the software application written in LabView Environment that is also used for the data acquisition, the process of valves control and the data analysis.



**Fig. 4.** The data analysis; a) time course of pressure drop  $\Delta p$ , where  $\Delta p = p_{max} - p_{\infty}$ ; b) time constant  $\tau$  measurement – linear approximation of the flow-time course between points  $t_1$  and  $t_2$ , where  $t_1$  and  $t_2$  – initial and end points of the  $\tau$ -measurement, respectively, c)  $\Delta p$  exponential approximation; the marked part of  $\Delta p$  between points  $p_{max}$  and  $p_{\infty}$  as shown in the pressure-time trace (Fig. 4a) and its regression curve

Using the software application, the acquisition of the pressure and flow signals can be done. The time constant  $\tau$  is found to be the time when, the expiratory flow plot, fitted to experimental data by the least squares method, falls to 36.79% of the chosen initial value (not necessarily the maximum value). The same result may be calculated from the pressure trace (Fig. 4). The values of the added compliance ( $C_a$ ) and the total compliance of respiratory system ( $C_{rs}$ ) required in the model are experimentally evaluated by using the syringe and the manometer. On-line signals (*On-line Measurement*) of the pressure and flow, respectively, can be observed on the charts  $p$  and  $\dot{V}$  in the panel. The *Start* button initiates the application. The appropriate diodes inform about the states of the generator, added compliance and expiratory valves. There is also the additional information about times and measurement numbers.

At the end of each measurement process, the pressure and flow signals are shown in the main charts called *Flow* and *Pressure*, respectively. The software application gives a possibility to store the results of measurement in the txt-files that are easy to be imported to another applications (i.e. Microsoft Excel). Moreover, there is also data analysis application, presented in Fig. 4 (a, b).

The part of the pressure-time trace obtained by the least-squares approximation is useful also for exponential approximation shown in Fig. 4c.

### 3. Experimental Tests and Results

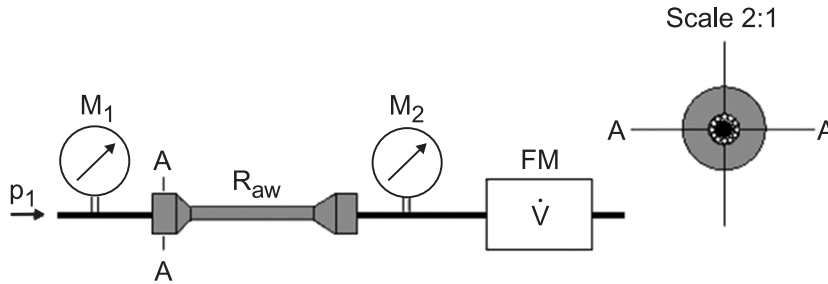
In the experimental tests, the mechanical volume-controlled ventilation mode of the ventilator (Fig. 8a) was used. Different types of capacitance  $C_{rs}$  were applied in the lung models: rigid chambers (volume: 25 l and 50 l) or a standard elastic lung model (Test Lung 190 Maquet, which the volume is equal to 1 l). A laminar capillary resistor was used as resistance  $R_{aw}$  (Fig. 2).

#### 3.1. The Way of the Model Parameters Measurement

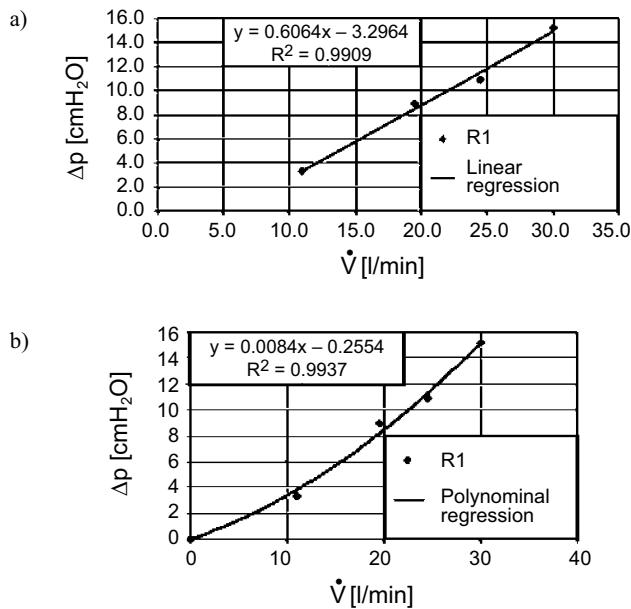
Resistance  $R_{aw}$  of the model was measured by using two manometers  $M_1$ ,  $M_2$  (Jumo dTRANS pO2, type 404385) and a mass flowmeter  $FM$  for gases with measurement range 1-100 l/min (Cole-Parmer, Wz-32908-75) (Fig. 5).

**Table 1.** Results of the model resistance measurement;  $\Delta p_R = p_1 - p_2$  – pressure drop on the model resistance

$p_1$ [cmH <sub>2</sub> O]	$p_2$ [cmH <sub>2</sub> O]	$\Delta p_R$ [cmH <sub>2</sub> O]	$\dot{V}$ [l · min <sup>-1</sup> ]	$R_{aw}$ [cmH <sub>2</sub> O · s · l <sup>-1</sup> ]
8.1	4.8	3.3	10.9	18
17.5	8.6	8.9	19.5	27
22.0	11.1	10.9	24.5	27
28.9	13.7	15.2	30	30



**Fig. 5.** Measurement set of the model airway resistance  $R_{aw}$ . The cross-section A-A in scale 2:1 explained the construction of the resistor which characterized the airway resistance  $R_{aw}$  of the model.  $M_1, M_2$  – manometers,  $FM$  – flowmeter,  $p_1, p_2$  – inlet and outlet pressures



**Fig. 6.** The model resistance time courses: a) linear part of the model resistance characteristic for the working conditions, b) total range of the model resistance changes

The obtained results are presented in Table 1 and Fig. 6. Ratio of the pressure drop  $\Delta p_R = p_1 - p_2$  and the flow  $\dot{V}$  represents the airway resistance  $R_{aw}$ .

The experimental data of flow and pressure measurements (Table 1) have been processed and the resultant regression plots (fitted by the least squares approximation) are presented in Fig. 6(a, b). For the linear regression (Fig. 6a) a zero point was omitted as in further comparison tests a region of small flows insignificantly participates in time constant calculations. However, this simplification leads to an



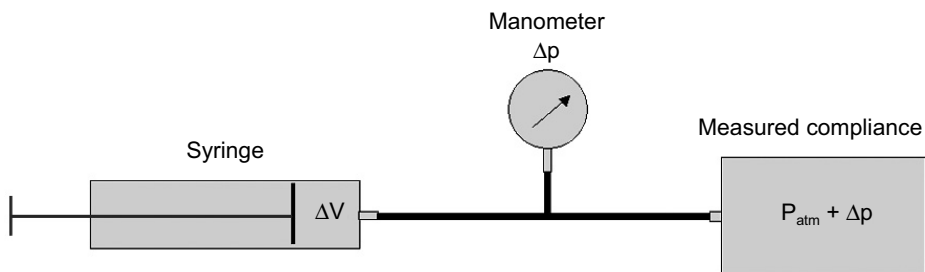
unrealistic approximation of the flow-pressure plot in the region of small flows (negative pressure drop for  $\dot{V} = 0$ ). A parabolic regression (including zero-point) gives much better approximation (Fig. 6b) in the whole range of the flow  $\dot{V}$  and pressure drop  $\Delta p$  values but in both cases the correlation coefficient  $R^2$  for the limited variables zone important for comparison tests remains practically the same. There is still the physically unrealistic approximation in the small-flow zone giving non-zero flow for zero pressure drop but measurement of lung parameter never occur in that wrongly approximated range of the pressure-flow curve. From this point of view the Rohrer-like equation (e.g.  $\Delta p = k_1 \cdot \dot{V} + k_2 \cdot |\dot{V}| \cdot \dot{V}$ ) seems to be better but less convenient for numerical applications.

The measurement set-up of the model compliance is presented in Fig. 7 where a standard syringe with the manometer is used to inject known volume  $\Delta V$  of air into the chamber. The measurements results are shown in Table 2.

The pressure was measured with accuracy  $\pm 0.1\%$  while flow and volume with accuracy  $\pm 1\%$ . The resultant accuracy was practically determined by the flow measurement error.

**Table 2.** Airway pressure  $\Delta p_{av}$ , volume  $\Delta V_{av}$  and total compliance of respiratory system  $C_{rs}$  in different types of lungs

	$\Delta p_{av}$ [cmH <sub>2</sub> O]	$\Delta V_{av}$ [ml]	$C_{rs}$ [ml · cmH <sub>2</sub> O <sup>-1</sup> ]
Lung model (25l)	3	60	20
Lung model (25l)	3.1	60	19
Maquet Test Lung 190 (max. 1l)	3.8	60	16

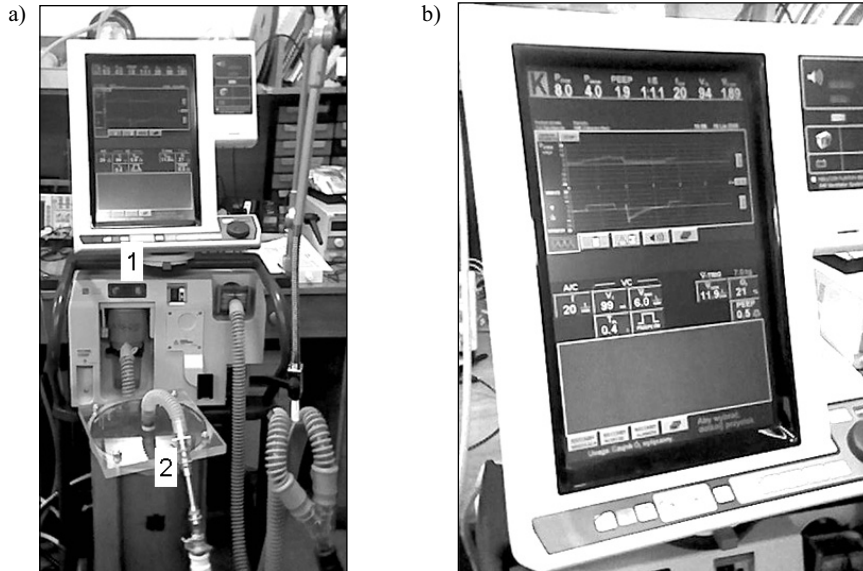


**Fig. 7.** The model compliance measurement set-up

### 3.2. The Comparison Tests of Both Methods

In the comparison tests, the ventilator (type Nellcor Puritan Bennett Bird 840 Ventilator System, Tyco Healthcare) equipped with integrated monitor, graphical user panel and touch panel for the easy changing of the setting and measuring control, working in the volume-controlled mode (controlling the pressure and flow signals) is

connected to the model of lungs which parameters were comparatively measured by the added compliance method and the end-inspiratory pause method of the ventilator. The measurement using the standard method is shown in Fig. 8.



**Fig. 8.** The measurement using the standard method. a) measurement system, where: 1 – Nellcor Puritan Bennett 840 Ventilator System (Tyco Healthcare), 2 – the RC model of lungs applied; b) the monitor with the touch panel showing the example of results

**Table 3.** Results of the comparison tests

Pressure $p_{max}$ [cmH <sub>2</sub> O]	$C_{rs}$ [ml · cmH <sub>2</sub> O <sup>-1</sup> ]		$R_{aw}$ [cmH <sub>2</sub> O · l <sup>-1</sup> · s]	
	Method no. 1	Method no. 2	Method no. 1	Method no. 2
10	37±1	38±1	39±2	26±1
20	37±1	38±1	40±2	27±1
30	38±1	39±1	40±2	27±1

where: method no. 1 – the added compliance method, method no. 2 – the end-inspiratory pause method (EIP) in which the respiratory frequency is equal to 1 lresp./min. Data were obtained for the model of lungs – composed of two 25 l chambers (total volume of 50 l). In the table, the mean ± SD ( $n = 10$ ) values of the results are presented.

The results shown in Table 3 confirm a good agreement of two compared methods concerning compliance  $C_{rs}$  measurements. However, results of resistance  $R_{aw}$  measurements point out a high measurements error of the added compliance method.

On the other hand, the results obtained by method 2 (EIP) well correspond to the resistance measurements presented in Table 1. The results from the first experimental measurement set up of the added compliance method (Fig. 3) are presented on the software user panel as the numbers and curves in Fig. 9.

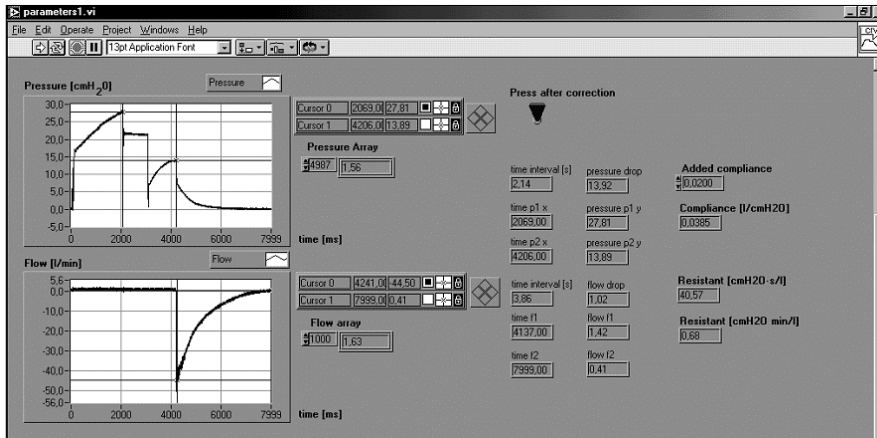


Fig. 9. The measurement using the first experimental set up of the added compliance method (Fig. 3)

#### 4. Conclusions

The results of the comparison tests prove that the added compliance method is sufficient to be used for estimation of the total compliance of a respiratory system during artificial ventilation. The results of the airway resistance measurements are significantly different for two compared methods. These differences appear as a result of a contribution of the dynamically and statically variable nonlinear resistance of the expiratory valve to the whole measured resistance what is difficult to be taken into account. This is why the airway resistance measured by the added compliance method is considerably bigger than the same measured by the reference method not influenced by the valve resistance. This measurement error can be decreased by the proper compensative procedure now under development. This method may be used after improvement of the resistance measurements and development of the related measurement diagnostic procedures suitable for co-operating research subjects or clinical patients.

#### Acknowledgement

Work financed partially by the State Committee for Science Research (MEiN, MNiI) as the grant no. 3 T11E 008 28, and partially from the Statutory Tasks at the IBBE PAS.

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