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IDENTIFICATION OF THE HUMAN RESPIRATORY SYSTEM DURING EXPERIMENT WITH NEGATIVE PRESSURE IMPULSE EXCITATION

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Abstract

This article describes an innovative measurement method enabling one to identify mechanical parameters of the respiratory tract. The method is compared with traditional techniques such as the forced oscillation technique (FOT), forced expiration technique, and the interrupter technique (IT). The developed characteristics of the method were examined by simulation and experiments. The results confirmed its specificity and sensitivity.

Keywords: bio-measurement, respiratory tract, respiratory tract mechanical properties, diagnostic methods in medicine, respiratory tract models.

1. Introduction

The respiratory system along with the circulatory system constitute a basic system whose proper functioning determines an organism's survival. The basic respiratory system's function is to provide an organism with oxygen and to remove toxic carbon dioxide, which is a result of metabolism, from the organism. An acute failure of the respiratory system may have various reasons, but it always is an immediate threat to life. Hence, a lot of attention is paid to its diagnostics.

The article describes a new method to identify mechanical parameters of the respiratory system. The method is based on the assumption that from the identification point of view the respiratory system is a pneumatic, dynamic system and its properties are determined by parameters such as elastance, inertance as well as pneumatic resistance. If a transient state is generated in such a system by proper stimulation, transients of the object measurable signals will contain data sufficient to evaluate its parameters that is, conduct parametrical identification of the respiratory system. The object identification may be formulated as a solution of the inverse problem [21]. What is difficult in the process is to stimulate the object properly so that the data signals content is rich enough. The difficulty also lies in the fact that the data need be read and transformed into parameter estimates being the purpose of the research. The usefulness of the method is a derivative of the estimated parameter number and the uncertainty of the received estimates.

The measurement method presented in this article consists in stimulating the respiratory system with a short pressure impulse of 50 ms, generated at the outlet of the respiratory tract and recording the transitional state generated in this way in the flow signal of the exhaled air. An advantage of the method is the fact that it requires little cooperation on the examined person's side, which facilitates conducting research and renders the method objective. Another advantage is the simplicity of the measurement system. The process of obtaining diagnostic data has been moved to the stage of algorithmic processing of the recorded

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measurement signals. As significantly less time-consuming and troublesome for a patient, the presented method can successfully replace frequency methods, which are currently used [7, 35, 32, 33, 34, 23, 27].

Simultaneously it should be underlined that the problem of respiratory system measurements and analysis is not trivial. Such system is a multidimensional, non-linear object in which different phenomena occur, like gas flow in elastic ducts, accumulation and dissipation of mechanical energy etc. Its analysis and identification requires application of advanced signal analysis algorithms and designed experiment methods [13].

Looking for the identification methods of greater diagnostic resolution leads to the multi-method approach [5].

2. Electric models of lung mechanical properties

From the point of view of mechanical properties, the human respiratory system may be described as a system of connected pneumatic elements with flexible walls (Fig. 1), which are characterised by pneumatic resistance *R*, susceptibility *C* and inertance *L*.

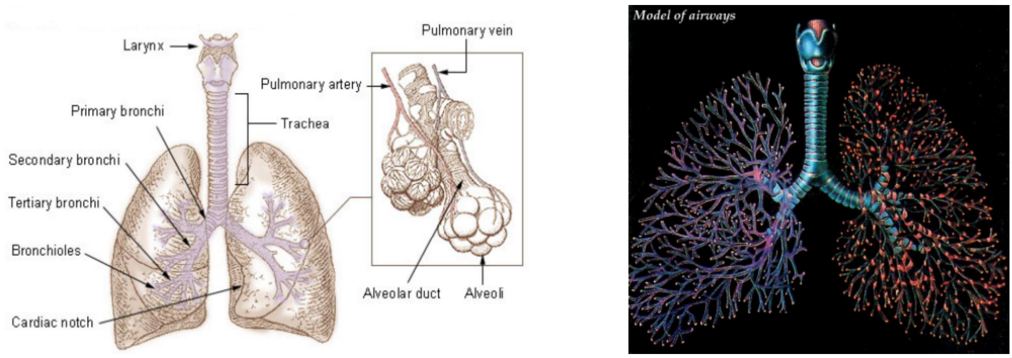

Fig. 1. The respiratory system anatomy [1, 2].

If this approach is accepted, an equivalent electric model, whose components are equivalents of the pneumatic parameters can be developed. In the literature, a number of such models, used to interpret the results of the respiratory system mechanical properties identification, may be encountered. The results are obtained with the frequency measurement methods. The level of complexity and the number of coefficients are different in the models [19, 22, 3, 31].

Among several models presented in [3, 34, 36] *e.g*. the six-element model described by the system of four differential equations was used. This model is most frequently employed to describe the mechanical properties of the respiratory system. It includes resistance and inertance of the respiratory tract, parameters of the tissue component and the functional residual capacity, *i.e.* the volume of gas remaining in the lungs at the end of passive expiration. The structure of this model is shown in Fig. 2.

The state equations representing the model shown in Fig. 2 are as follows (1a-1d):

$$\frac{d\dot{V}_1(t)}{dt}=\frac{1}{L_{aw}}\left[p(t)-R_{aw}\cdot\dot{V}_1(t)-p_g(t)\right], \tag{1a}$$

$$\frac{dp_g(t)}{dt}=\frac{1}{C_g}\left[\dot{V}_1(t)-\dot{V}_2(t)\right], \tag{1b}$$

$$\frac{d\dot{V}_2(t)}{dt} = \frac{1}{L_t}\left[p_g(t) - p_t(t) - R_t \cdot \dot{V}_2(t)\right], \tag{1c}$$

$$\frac{dp_t(t)}{dt} = \frac{1}{C_t}\dot{V}_2(t). \tag{1d}$$

This model is frequently used due to its structure, which is complex enough to include all the basic pneumatic and mechanical phenomena, and concurrently simple enough to make the estimation of its coefficients reliable. Models with more coefficients are basically extended six-element models, which additionally include the impact of the respiratory tract outside the toracal organs or the influence of the gastric tissue and chest. The tissue part of the model is developed resulting in a nine-element structure. Fig. 3 features a ten-element model of the respiratory system, which has been used among others in Peslin's and Roger's research works [31, 27]. Values of the model coefficients are in Table 1.

Table 1. Values of the coefficients characterising the model in Fig. 3.

coefficients	value [hPa·s·dm^{-3}]	coefficients	value [dm^3·hPa^{-1}]	coefficients	value [hPa·s^2·dm^{-3}]
R_p	0.0861	C_{aw}	0.005	L_l	0.002
R_l	0.213	C_g	0.0035	L_{aw}	0.021
R_t	0.5	C_l	0.124		
R_{aw}	1.42	C_t	0.21		

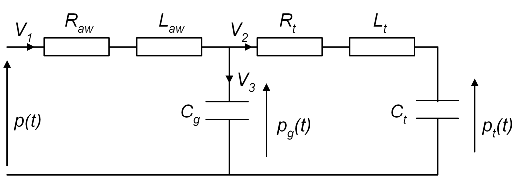

Fig. 2. A respiratory system model comprising six elements. R_{aw} –the respiratory tract resistance, L_{aw} – the respiratory tract inertance, R_t – the tissue resistance, L_t – the tissue inertance, C_t – the tissue susceptibility, C_g – the alveolar gas compressibility characteristic of functional residual capacity**,** the volume of gas remaining in the lungs at the end of passive expiration.

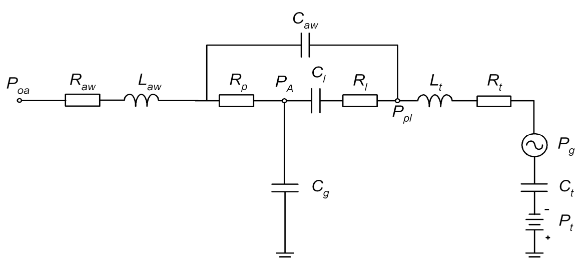

Fig. 3. The ten-element model of the respiratory system. R_c – the resistance of the central respiratory tract, L_c – the inertance of the central respiratory tract, R_p – the resistance of the peripheral respiratory tract, C_{aw} – the respiratory tract susceptibility, R_l – the tissue resistance, C_l – the tissue susceptibility, C_g – the alveolar gas susceptibility characteristic of the Functional Residual Capacity, R_t – the chest resistance, L_t – the chest inertance, C_t – the susceptibility of the chest and respiratory tract, P_g – the respiratory pressure generated by muscles during unrestrained respiration, P_t – the stress of the chest tissues, P_{oa} – the pressure at the outlet, P_A – alveolar pressure, P_{pl} – intrapleural pressure.

3. Methods of measuring respiratory system properties

A large variety of measurement methods is used to diagnose the respiratory system and their description, even a brief one, proceeds beyond the framework of this paper. Therefore, only selected, standard methods of evaluation of the respiratory system competence are discussed here. The methods are as follows:

- the spirometry method;
- the maximal flow-volume curve method applied during a forced expiration;
- the maximal expiratory pressure method and minimal inspiratory pressure method (MEP/ MIP);
- the frequency method (FOT) determining the transfer and input impedance of a respiratory system;
- the interrupter method (IT).

The method of negative pressure impulses developed by the authors is described against the above-mentioned measurements.

Measurements of the respiratory system parameters may enable one to formulate non-parametric characteristic of the respiratory mechanics or create parametric models of the respiratory system. The latter constitute a basis for the respiratory system diagnosis. The respiratory system parameters are estimated by calculating the model coefficient values and comparing them with the standard values (average values in the healthy population).

Spirometry is used to measure pressures and flows generated in a respiratory system allowing one to form non-parametric characteristics. Spirometry tests, whose results are recorded in the form of spirographs, are performed either during quiet respiration or a forced expiration maneuver. The former conditions allow to calculate vital capacity, VC, and its components (Fig. 4), whereas the latter enable one to determine the maximal expiratory flow-volume curve MEFVC (Fig. 5) and values related.

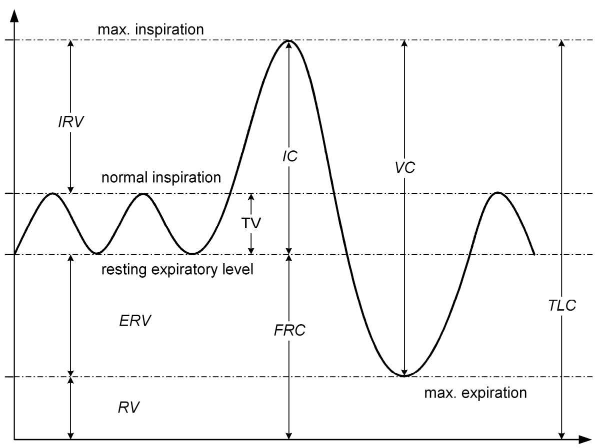

Fig. 4. Spirometry static quantities – volume and capacity. TV – tidal volume, *IRV* – inspiratory reserve volume, *ERV* – expiratory reserve volume, *RV* – residual volume, *TLC* – total lung capacity, *VC* – vital capacity, *IC* – inspiratory capacity, *FRC* – functional residual capacity.

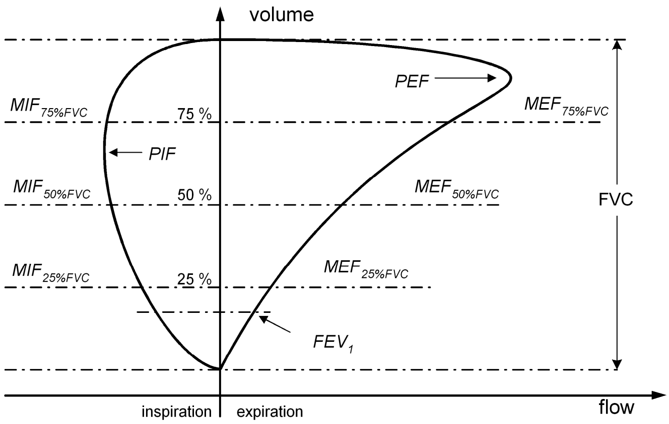

Fig. 5. The flow-volume curve and diagnostic parameters based on it: FVC – forced vital capacity, FEV_1 – forced expiratory volume in one second, FEV_1%VC – forced expiratory volume in one second % of vital capacity, $FEV_{1\%}FVC$ – forced expiratory volume in one second % of forced vital capacity, *PEF* – peak expiratory flow, *PIF* – peak inspiratory flow, $MEF\mathrm{x}_{\%}FVC$ – maximal expiratory flow at x% of *FVC*, $MIF\mathrm{x}_{\%}FVC$ – maximal inspiratory flow at x% of *FVC*.

Such measurements provide data on the patency of the central and peripheral respiratory tracts and on the strength of expiratory muscles. Although spirometry tests appear to be easy to perform, they are in fact quite complex and their results often uncertain. A considerable limitation of spirometry tests (especially in case of children) is the fact that they require patient's cooperation and effort. Thus, the accuracy of the data obtained and that of the diagnosis based on it is highly dependent on the quality of forced expiratory maneuver performance [10, 37, 8, 38].

This group also includes MIP/MEP tests [39, 4, 26]. Minimal inspiratory pressure tests and maximal expiratory pressure tests allow to assess the strength of respiratory muscles. This is done by measuring inspiratory or expiratory pressure during maximal inspiratory effort following an expiration reducing the amount of gas to its residual capacity or during maximal expiratory effort following a full inspiration. Both maneuvers are performed by closing the respiratory tract output. Also patients requiring the assistance of mechanical ventilation can be MIP/MEP tested. If MIP is lower than – 30 [hPa], the patient is likely to cease using the respirator, which is almost impossible if MIP is over – 20 [hPa].

Fig. 6 depicts two algorithms to calculate the maximal (minimal) expiratory (inspiratory) pressure.

The MEP test outcome is considered to be the value of the expiratory pressure measured as soon as (*e.g.* 1s later) the maximal value has been reached (Fig. 6a) or the average value of pressure kept for a given period of time (*e.g.* 3s) following the peak value (Fig. 6b). Both algorithms are designed to eliminate cases when the person examined is unable to keep the maximal pressure value for a longer period of time. In such a situation, the strength of respiratory muscles cannot be accurately assessed.

The Forced Oscillation Technique (FOT) is essential to identify the respiratory system parameters. The human respiratory system, which comprises the respiratory tract transporting air into the pulmonary alveoli, alveolar gas and tissues surrounding the pulmonary alveoli, can be treated as a dynamical system including two inputs and two outputs, the impedance of the respiratory tract, alveolar gas and tissues [6, 7, 30, 28] (Fig. 7).

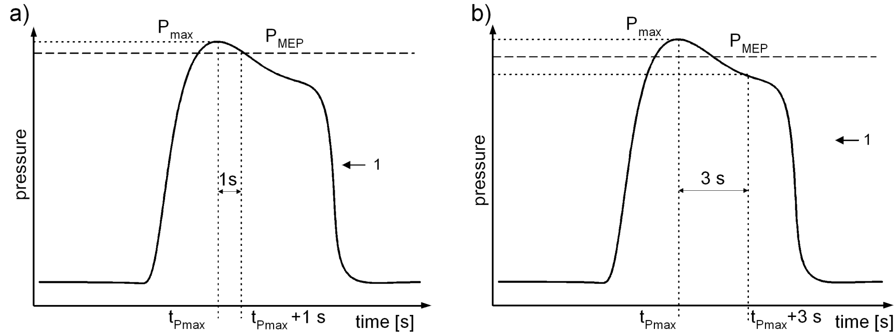

Fig. 6. A graphic representation of two algorithms to measure MEP.
1 – the time course of pressure during a respiratory maneuver, P_{max} – the maximal pressure value, P_{MEP} – the MEP test result.

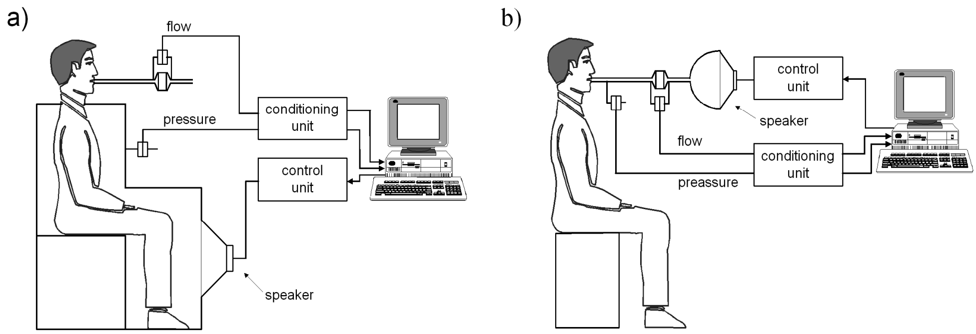

Fig. 7. The respiratory system impedance measured with the frequency method.
a) The cross impedance measurement, b) the input impedance measurement.

The input quantity is either the pressure change at the respiratory tract inlet or the pressure change around the chest. The output quantity is either the gas flow at the respiratory tract outlet or the gas flow around the chest respectively. The transfer impedance of the respiratory system is the ratio of the forced pressure to the respiratory system flow response when the input and output quantities are measured at different points. The input impedance is the ratio between the two quantities measured at one point, *e.g.* at the respiratory tract outlet. Nowadays, there are two measurement methods used for such identification [24, 32, 33, 34, 36, 8, 9]. The methods are as follows:

– The measurement of transfer impedance in a pressurized cabin made of inflexible walls with loudspeakers installed. A patient is placed inside the cabin (Fig. 7a) and a determined (monoharmonic, poliharmonic) or random pressure signal is produced. The patient’s head is outside the cabin, which is hermetically closed around the patient’s neck. The pressure changes generated in the cabin by operating the loudspeakers and the flow at the respiratory tract outlet are recorded. This method has a number of disadvantages, especially:

- the construction of the test cabin is problematic, as sufficient containment and inflexibility are difficult to achieve,

- the measurement range is constrained due to the fact that the cabin properties are dynamic and the pressure is distributed irregularly at the frequencies above 50-60 [Hz].

– During the input impedance measurement, only the patient's head is placed in the pressurized cabin (Fig. 7b). The pressure change in the cabin (corresponding with the pressure change at the respiratory tract outlet) and the flow at the respiratory tract outlet are measured. Providing the patient with comfortable breathing conditions is the greatest challenge, especially in case children are examined.

In addition to frequency methods, time methods stimulating the respiratory system with a non-periodic signal are successfully used. Some of them analyze and record the object variables in a fixed, permanent state and others do that in the induced transfer state. The interrupter technique and the negative pressure impulse method – described below – belong to the group.

The interrupter technique (IT) was introduced by von Neergaard and Wirz in 1927 [25] as one of the first non-invasive methods to investigate into mechanical properties of the respiratory system. Subsequently, in the 1950s, it was developed by Mead and Whittenberger [20]. The method is simple and relatively convenient for the patient. The expiratory airflow is briefly (from less than 20 to over 100 [ms]) broken by closing a valve at the respiratory tract outlet. On closing the decreasing and finally ceasing flow as well as the increasing pressure ΔP_{ao} are measured in the mouth. The collected data is used to calculate the interrupter resistance which is defined as (2):

$$R_{\text{int}} = \frac{\Delta P_{ao}}{\dot{V}_{\text{int}}}, \tag{2}$$

where:

– ΔP_{ao} – the pressure in the mouth following the occlusion (change of the occlusion pressure);

– $\dot{V}_{\text{int}}$ – the flow recorded just before the occlusion.

In order to clarify the character of the pressure signal flow following the occlusion and to find applications for the respiratory system models of various complexity (one-component models as well as two- or more-component models), further research into the technique was conducted. Its results were far from the expected ones. Thus, nowadays, the interrupter technique is used to compute the interrupter resistance R_{int}, which contains both the respiratory tract resistance and partly the tissue resistance.

In Poland, the research into the interrupter technique has been performed for a number of years in the Chair of Electronic and Photonic Metrology, Department of Electronics, Wroclaw University of Technology [14, 15, 16, 17, 18]. Attempts to improve this technique led to the development of a comprehensive model of the respiratory system, which is based on the 24 dichotomous bronchial tree model.

4. Negative pressure impulse method

The purpose of the measurement method described in this work is to record and analyze the input impedance of the respiratory system [12, 29]. Impulse pressure changes are forced at the respiratory tract outlet and thus the airflow caused as well as pressure excitation are measured. The duration of the produced pressure impulses is short, *i.e.* less than a hundred milliseconds. The measurement data obtained from the transient dynamical stages generated in the flow signal is used for diagnostic purposes. Measurements are conducted during normal breathing (Fig. 8), which does not affect the results in any significant manner due to the short measurement time. In comparison with the frequency method, the proposed one is simple and less time-consuming.

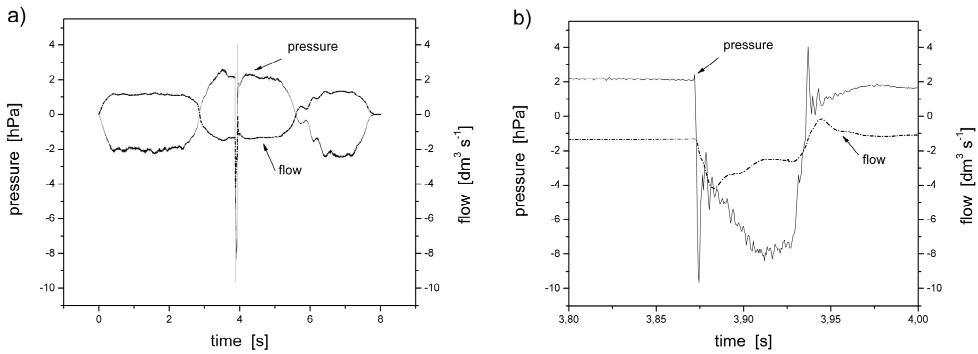

Fig. 8. The measurement signals registered at the respiratory tract outlet used to identify the respiratory system parameters: a) coercion in the form of a negative pressure impulse and the object response in the form of the airflow against calm breathing, b) the same signals in a different time scale.

The problem of the patient's condition variability (non-stationary objects) disappears during testing and the examination itself is less inconvenient for the patient. Furthermore, unconscious and artificially ventilated patients can be examined using the presented method.

5. Simulation research into negative pressure impulse method

In order to analyze and evaluate the essential properties of the proposed method used to identify mechanical properties of the respiratory tract, its mathematical and simulation models have been developed (Fig. 9) and a number of simulations have been performed. It was tested if models describing such properties can be erroneously designed due to the influence of the measurement method selected parameters and the effect of the identified object.

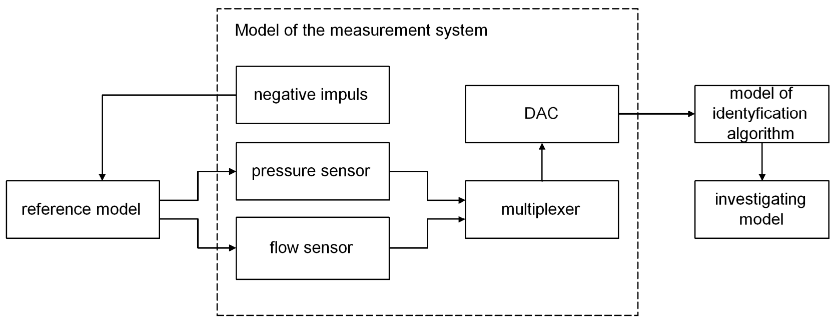

Fig. 9. A block diagram showing a simulation model of the method.

Simulations were conducted as follows. A certain model form of the respiratory system along with the values of its coefficients were determined. This model – called a forward model – replaced the measurement object in the simulation experiments. It was stimulated with simulated excitation (the respiratory pressure and the forced pressure impulse) to obtain the calculated response of the model (the respiratory flow), which is treated as a "measurement" signal allowing identification. Identification concerns a model whose structure is usually less complicated than that of the forward model. It is described as the inverse model. The coefficient values of the inverse model, which are computed during identification, are compared with the coefficient values of the forward model, which were assumed prior to the identification process. This allows to assess identification errors. The forward model structure accepted for this investigation is depicted in Fig. 3 and Table 1, whereas the inverse model, which was characterized by six coefficients, in Fig. 2. The force stimulating the forward model was a rectangular pressure impulse whose amplitude, duration, time of edge rise and fall were limited. The respiratory pressure course was described as a periodic signal whose edges were rising exponentially and whose frequency was 0.25 [Hz], inspiration phase 1.5 [s] and expiration phase 2.5 [s]. Thus, the whole respiration cycle duration is 4 [s].

Example results are shown in Fig. 10. They are in the form of characteristics illustrating the relationship between a relative r.m.s estimation error and the influence parameters such as pressure impulse duration, sampling frequency, the time of a forced impulse occurrence, changes in values of the selected parameters of the respiratory system when calculating each coefficient of a six-component model. The following conclusions can be drawn from the simulations performed:

– The respiratory tract parameters can be classified into three groups in terms of identification uncertainty. The most accurately estimated parameters of the respiratory tract are resistance R_{aw} and inertance L_{aw}. In their case, the relative r.m.s. estimation error does not exceed 10%. Tissue parameters L_t, R_t and C_t constitute the second group. When they are computed, the relative r.m.s. estimation error may range from 15% to 30%. The alveolar gas susceptibility parameter C_g is difficult to measure.
– The impact of the forced impulse occurrence time in the expiration phase, calculated from the beginning of the respiration cycle, is insignificant as far as errors in the respiratory system parameter identification are concerned. The results obtained reveal however that the optimal duration of a pressure impulse is approx. 100 [ms] (Fig. 10).

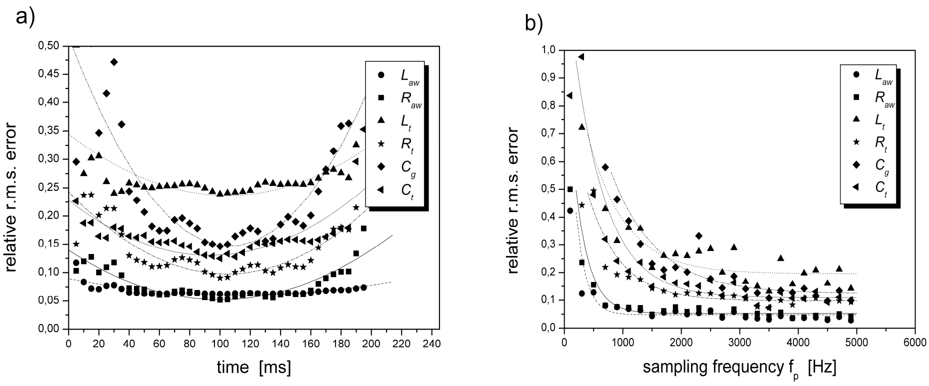

Fig. 10. The relative r.m.s. estimation error for the six model components: a) in relation to the forcing pressure impulse duration; b) in relation to the sampling frequency.

– The increase in sampling frequency results in the decrease in the number of measurement errors for all object parameters. If the sampling frequency is above 1500 [Hz], the measurement error for parameter R_{aw}, which is the most important parameter in diagnostics, remains at the same level not exceeding 5%.
– The increase in the value (more than the receivable value) of any of the respiratory system parameters (being a result of some disease) leads to the loss of accuracy of other parameter identification.

The above-mentioned conclusions, which were formulated on the basis of the conducted simulations, enabled us to select adequate parameters for measurement experiments.

6. Measurement experiments

The experimental research was conducted in the Institute of Tuberculosis and Lung Diseases in Rabka, which is equipped with the measurement system designed and constructed in the Department of Measurement and Instrumentation at the AGH University of Science and Technology in Krakow (Poland).

The system consists of two basic components (Fig. 10) [11]: the measurement channel for pressure and the measurement channel to record the respiratory flow volume. The former, *i.e.* the pressure measurement channel, is fitted with a differential (measurement in conjunction with the atmospheric pressure) pressure sensor of the MP45-871 series with a measurement range of 88.0 [hPa], manufactured by Validyne. The latter includes a pneumo-tachometer of the 3700A type, produced by Hans Rudolf Inc. and cooperating with a differential pressure sensor of the MP45-871 series with a measurement range of 2.25 [hPa].

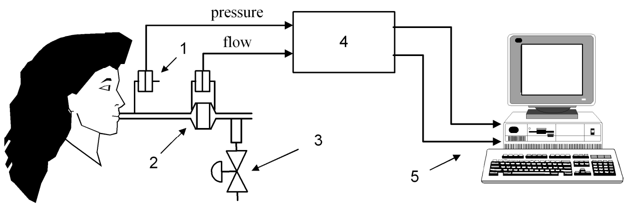

Fig. 11. A diagram of the system for measuring the respiratory tract mechanical parameters using the method of negative pressure impulses. 1 – the expiratory airflow pressure sensor, 2 – the flow measurement, 3 – the system enabling one to generate negative pressure impulses, 4 – systems conditioning measurement signals, 5 – a computer with its software and measurement card.

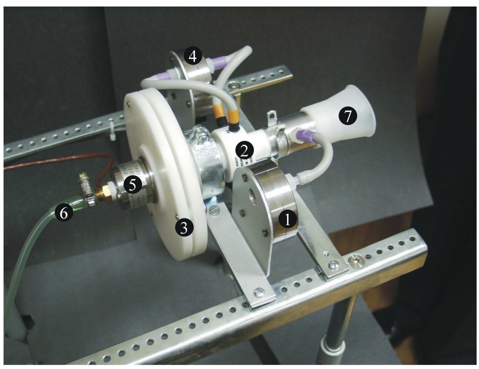

Fig. 12. The measurement station used to diagnose the respiratory system. 1 – the expiratory airflow pressure sensor, 2 – the flow measurement, 3 – the Venturi apparatus allowing to generate pressure impulses, 4 – the pressure sensor cooperating with the pneumo-tachometer, 5 – the electrical valve controlling the compressed air flow, 6 – providing compressed air, 7 – the mouthpiece.

In addition, there were Venturi apparatus installed allowing to generate negative pressure impulses, an electrical valve controlling the compressed air flow, systems for conditioning measurement signals and a computer with a measurement card and software for controlling the measurement process and recording the measurement data in the system. The measurement system diagram is shown in Fig. 10, whereas Fig. 11 features a photograph of the measurement station used for the experiments.

The measurement system allows to control the following experimental parameters:

– the time during which measurement signals are monitored, ranging from 4 [s] to 16 [s];
– the sampling frequency of measurement signals (from 4 [kHz] per channel to 1 [kHz] per channel);
– the duration of a negative pressure impulse, ranging from 5 [ms] to 2 [s];
– amplitudes of negative pressure impulses not exceeding 15 [hPa].

The impulse rising time depends on the type of electrical valve used and, in this system, can reach maximum 5 [ms].

First, the experiments were conducted on healthy volunteers. The examined responded well to an exciting pressure impulse provided that the amplitude value was less than 10 [hPa] and its duration approx. 50 [ms]. When an impulse lasts longer than 50 [ms] (see simulation results), muscle reaction can be noticed in some cases [29]. The experiments proved that the relationship between pressure and flow is non-linear (in accordance with Rohrer's equation), which results in the fact that the respiratory tract resistance value is dependent on the flow and, consequently, on the pressure impulse amplitude value. If this non-linearity is taken into account in a given model, the accuracy of the respiratory tract resistance identification is enhanced. The reproducibility of respiratory system parameter estimation results is higher for flows greater than 2 [dm^3s^{-1}]. Moreover, estimation errors for other system parameters can be decreased if susceptibility C_g is assumed to be known.

The results revealed that the respiratory tract inertance L_{aw} can be identified better than other parameters. The standard deviation of this parameter estimation ranges from 8% to 15%. Resistance R_{aw} and R_t form a parameter group which is second in terms of uncertainty. The standard deviation in their calculation is less than 30%. The standard deviation of the tissue susceptibility assessment C_t does not exceed 50%. The tissue part inertance L_t is the parameter most difficult to identify. The relative standard deviation of its values is over 70%.

Subsequently, in the second stage of the experimental research, the sensitivity and specificity of the method were tested.

7. Sensitivity and specificity of the proposed method

To test the sensitivity and specificity of the described method, the respiratory system parameters of both healthy and ill people were identified. The examined group consisted of thirteen individuals, including six healthy men in the 25-50 age bracket and seven patients of the Institute of Tuberculosis and Lung Diseases in Rabka. The patients (three women and four men), who were in their teens or twenties, suffered from a diagnosed respiratory tract disease.

Significant differences in the time series of flow signals among healthy and ill people were noticed (Fig. 13). It is worth emphasising that the flow signal shape is repeatable in both groups.

Values of the model coefficients were calculated using AMT (Adjusted Model Technique) on the basis of the registered pressure and flow signals. Since the model used is physical, they are interpreted as estimations of the respiratory system parameters.

The identification results show that the proposed measurement method allows to distinguish a healthy person from a patient unequivocally. All the examined volunteers were classified into the right category.

The high classification resolution can be obtained using two respiratory system parameters (Fig. 14): the mean resistance value R (being the sum of the respiratory tract resistance R_{aw} and the tissue resistance R_t) and susceptibility C_t.

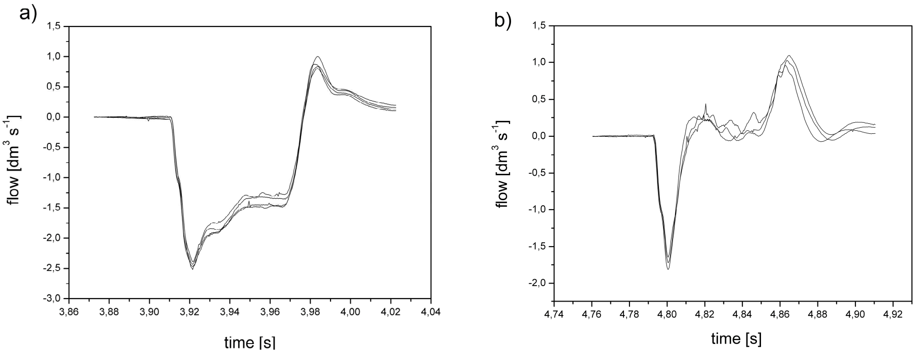

Fig. 13. The respiratory flow signal series in response to a forcing pressure impulse: a) in the group of healthy people, b) in the group of ill people.

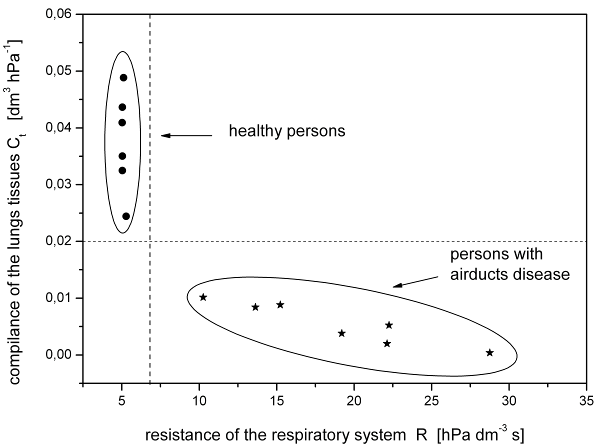

Fig. 14. The results of the susceptibility C_1 and accumulative respiratory system resistance identification in the group of healthy people and patients suffering from a diagnosed respiratory system disease.

8. Conclusions

The method of short-term, negative pressure impulses described in this article was developed in the Department of Measurement and Instrumentation at the AGH University of Science and Technology. The simple structure of the measurement system and the fact that it is convenient for a patient are two main advantages of the method. The investigation, encompassing simulations and experiments, was conducted in order to determine the properties of this measurement method.

The results obtained allow to formulate the general conclusion that this method of measuring respiratory system mechanical parameters enables one to detect lesions in the respiratory system and allows to distinguish the healthy from the ill. However it should be underlined that the respiratory system of the patients of the Institute of Tuberculosis and Lung Diseases who were examined with the method was considerably damaged due to their disease.

The detailed conclusions concern both the choice of the identification method parameters (duration time of the pressure impulse, its amplitude as well as occurrence time of this impulse) and estimation uncertainty of the respiratory system parameters. They have been formulated at the ends of successive chapters.

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