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A STATION FOR THE RESPIRATORY MECHANICS MEASUREMENT BY OCCLUSION TECHNIQUES

In the paper, the stage for the evaluation of the respiratory mechanics by occlusion techniques is described. It consists of the hardware-software module of post-interrupter data acquisition, numerical procedures of the collected signal analysis and computational models, enabling a quantitative/qualitative verification of the relations between the lung structure, pathology and measurement results. Flexibility of the designed set-up guarantees the possibility to test the classical versions of the interrupter technique, its modified author's variant – enhanced interrupter technique and also the future developmental work in the appointed research area.

Keywords: pulmonary mechanics, occlusion techniques, interrupter technique, enhanced interrupter technique, indirect measurement

1. INTRODUCTION

The respiratory system is one of the main subsystems of the human body which ensures its vital functions. The fundamental role of the respiratory system consists in transport of a gas mixture through the bronchial tree, and finally in alveolar ventilation and gas exchange with the capillary blood. The research interests concentrate on each of the mentioned areas and concern both object cognition and the ability of its diagnose and control.

The structural complexity of the system makes the inference on the respiratory mechanics difficult. The bifurcating structure of elastic tubes with varying geometrical and mechanical characteristics forms about 24 generations of the bronchial tree in a simplified, symmetrical description by Weibel [1], but it is known that the physiological structure is not fully symmetrical [2].

The typical methods of the respiratory mechanics evaluation are based on provocative tests [3–7] where, depending on a chosen mechanical excitation, a system output manifests varied interactions at various structural levels (geometrical and material). Thus, considering the previous level of knowledge, the dissemination of the conception of data fusion in multi-method configuration seems to be justified. Nevertheless, some techniques, e.g. the forced oscillation technique (FOT) [8, 9], limit the application of future measurement tools to laboratory conditions, mainly for the sake of structural demands of the methods. Meanwhile, there is a need to provide the medical community with fast, cheap, not very invasive, simple in operation, reliable and repeating tests, possible to be exploited in mobile conditions.

Undoubtedly, the interrupter technique (IT) [10, 11] and its evolutionary version – enhanced interrupter technique (EIT) [12, 13] are the methods which possess the above-mentioned features. In [14] there is tentatively shown the potential to propose a time-frequency EIT algorithm which would be competitive in relation to the techniques grouping the regime of the analysis separately in the time or frequency domains (IT, the time method of the negative pressure impulse [15], FOT, NEP – negative expiratory pressure [16, 17], impulse oscillometry [18]). The results of investigations presented in [19–21] are the additional premises to this fact. The important advantage of the occlusion methods, i.e. IT, EIT, are minimal requirements regarding patient co-operation, which make them attractive in the sense of non-trivial test of infants, preschool and early-school children.

The stage for the respiratory mechanics evaluation by the occlusion techniques is a hardware-software unit enabling acquisition, processing and data analysis in accordance with the guidelines recorded in [22, 23]. An additional advantage is the possibility to test and compare the available IT versions with the author's evolutionary solutions. Thus, flexibility of a constructed set first of all concerns the acquisitive alternativeness of the signals and the selection of a physical-mathematical representation of the respiratory system. The commercial propositions of the device (for laboratory and common use) in the above-mentioned algorithmic group cannot offer such extensive measurement possibilities as the measurement system constructed at the Chair of Electronic and Photonic Metrology (KMEIF).

2. OCCLUSION TECHNIQUES

Many proposals of the occlusion algorithms for the evaluation of the respiratory mechanics can be found in literature [10, 11, 24–28]. Their common feature is the fact of unbalancing the system by the short-term (single-time or multiple, partial or complete) airflow limitation at the mouth by the various technical means (mechanical valve, pneumatic resistance, rotating disc). There are applied different acquisitive configurations of the signals for analysis (pressure P_{ao} and flow Q_{ao} at the mouth) and the algorithms for postocclusional data analysis during the described experiments.

In the light of constructional assumptions, the most attractive among occlusion methods is the airflow interrupter technique (IT), introduced by von Neergard and Wirtz [10]. It consists in short-term airflow interruption by the valve closure at the mouth and the simultaneous measurement of flow Q_{ao} decreasing to zero and rising pressure

P_{ao}. Using a valve as quick as possible [29, 30] is a question of great importance; typically, closure time ranges between 1 and 20 ms.

Immediately on occlusion there is a rapid jump in pressure equal to the resistive pressure drop (ΔP_{ao}) across the airways just before the interruption, with a contribution from the chest wall, giving an assessment of the interrupter airway resistance (R_{int}) as a ratio of ΔP_{ao} and the flow value (Q_{ao}) measured just before interruption (1).

$$R_{int} = \frac{\Delta P_{ao}}{Q_{ao}}. \tag{1}$$

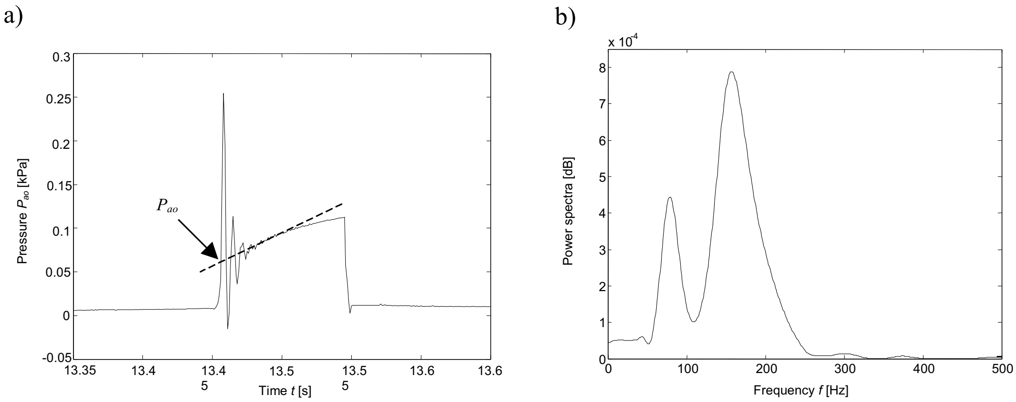

Fig. 1. a) Mouth pressure before, during and after occlusion in an infant; arrow – point where interruption pressure (P_{ao}) was measured; b) Power spectrum of P_{ao} calculated according to [31].

This is followed by a slower increase of the pressure reflecting stress recovery of lung and chest wall tissues, disrupted by highly dumped oscillations (Fig. 1A). The power spectrum of these oscillations exhibits two peaks (Fig. 1B). The larger peak reflects the quarter-wave resonance of the airway gas, and the second one reflects a tissue resonance [32].

2.1. IT algorithms of data analysis

The most popular algorithms of postocclusional data analysis are presented in this section.

In the first case, the well-known procedures described by Phagoo *et al.* [33] were applied as well as by Liistro *et al.* in [34]. The algorithm used by Phagoo to calculate R_{int} from the secondary pressure phase involves a simple, two-point linear regression of the postocclusional signal, which is back-extrapolated to an arbitrary time after valve closure (Fig. 2).

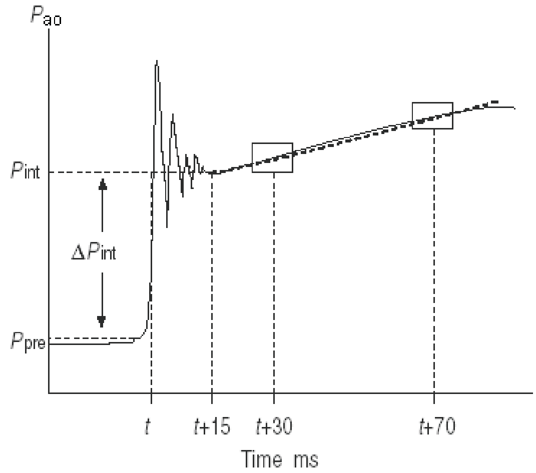

Fig. 2. Schematic diagram illustrating calculation of the interrupter pressure.

In accordance with Phagoo, the time of complete valve closure (t_{cl}) is taken as occurring at 25% of the peak value of the first oscillation upstroke. The points are based on the mean pressure values for two 10 ms portions of the data centered on t_{cl}+30 ms (range t_{cl}+25 to t_{cl}+35 ms) and t_{cl}+70 ms (range t_{cl}+65 to t_{cl}+75 ms), which are then linearly back-extrapolated to 15 ms after the valve closure time (i.e. t_{cl}+15 ms). The difference between this calculated pressure ($P_{int}A$) and the preocclusion mouth pressure (P_{pre}) (due to the apparatus resistance) is then divided by the preprogrammed value of flow (Q_{ao}) to give the interrupter resistance ($R_{int}A$). The second option – $P_{int}B$ is estimated as the intersection point of the drawn line with the rising slope of the first oscillation. Calculated with this value $R_{int}B = (P_{int}B - P_{pre})/Q_{ao}$.

To expand our future view on the precision of the enhanced interrupter algorithm (EIT) in comparison with techniques available so far of interrupter data processing, also the linear back-extrapolation algorithm prepared by the group of Liistro [34] was applied. It assumes $R_{int}C = (P_{int}C - P_{pre})/Q_{ao}$ estimation by indirect evaluation of $P_{int}C$ pressure. Originally, the measure of the parameter was the intersection point of the drawing line appointed at a subjective time 8 ms. However, Liistro *et al.* used in their work a shutter with occlusion time t_c equal to 6–7 ms, so it was decided to take 20 ms for our shutter as the end-point of the extrapolation process.

The next stage is using the Jackson et al. [28] idea, who used a curvilinear back-extrapolation to collected P_{ao} data. The purpose of the group was to find and eliminate the sources of the alveolar pressure (P_A) overestimation, reported in earlier studies [11, 28, 35], which have a direct correlation with the R_{int} estimation accuracy. Drawing a curve from the third phase of P_{ao} signal through the damped oscillation to the time of interruption, $R_{int}D = (P_{int}D - P_{pre})/Q_{ao}$ is obtained.

A verification of the multiple occlusion algorithms, so far reported e.g. in [23, 27], and the solutions standardizing the diagnosis [22, 36, 37] is also planned in the future, which finds its expression in acquisitive flexibility of the constructed stage, dedicated to the evaluation of the respiratory mechanics by the occlusion technique.

2.2. EIT method

Our modification of the interrupter technique, named the enhanced interrupter technique (EIT), is based on the measurement of the dynamic system properties by the identification of its model. Thus, apart from the analysis of the influence of the technical aspects of measurement and the efficiency of numerical procedures on our algorithm reliability, it is very important to assure a highly adequate representation of the physiological system. The details of the investigations on the mentioned issues can be found [12, 13, 14, 31]. The comparative simulation experiments showed that EIT methodology gives more accurate and more detailed information about the respiratory system than all the IT algorithms postulated until now [12]. At first, the new technique denies concentration exclusively on the measurement of the airways resistance, typical for the classical IT variants, which, given the complexity of the system, leads to significant systematic errors – the author's complex and metrological model for EIT was proposed [38, 39]. Additionally, the incorporation of transient state information obtained after the occlusion maneuver during measurement increases the accuracy of the assessment of the system state in the EIT experiment.

The model identification can be boiled down to the application of the iterative algorithm of parameter estimation in order to minimize the criterion function, depending on the output fitting from the metrological model ($\mathbf{Y}$) and measured in the real object ($\mathbf{Y_m}$)

$$\hat{\boldsymbol{\theta}} = \arg\min_{\boldsymbol{\theta}} (\mathbf{Y_m} - \mathbf{Y})^T \mathbf{R_Y} (\mathbf{Y_m} - \mathbf{Y}), \tag{2}$$

where $\boldsymbol{\theta}$ is the unknown parameters vector and $\mathbf{R_Y}$ represents the covariant matrix of the output signal disturbances.

There is a need to study the EIT algorithm and its application to the object of the respiratory system in a wide range of acquisitive configuration of the output signals. It concerns both the time and the frequency variant of the author's technique. Applying a new robust identification framework, that allows for combining parametric and nonparameric models and frequency and time-domain data [40, 41], can be a solution which introduces a new quality in the area of measurement by the occlusion methods. The prospective exploitation of the approach can find its connotation with the other methods dedicated to respiratory system investigations and the widely comprehended question of data fusion. Hence, the design assumptions for the stage for the evaluation of the respiratory mechanics by the occlusion techniques, by their acquisitive flexibility, refer to and realize the guidelines of all the above-mentioned structures of data analysis.

3. MODELS OF THE RESPIRATORY SYSTEM DURING AIRFLOW INTERRUPTION

Physical-mathematical modeling of the systems plays an important role in a cognition process, proper for the metrology area. Methodological conceptions found on the idea of forward and inverse modeling [42]. Usually, the forward analogs are the complex representations of the real objects, used to interpret the measurement observations. On the other hand, the main assignment of the inverse models, reduced in structure and parametrically, is the ability to imitate the selected basic features of a system in a way that would ensure their quantitative estimation in the structure.

The previous modeling process for the respiratory system during air-flow interruption has based on simple, one- or two-element analogs [3, 23, 33], which have been interpreted as a reflection of the airways resistance or resistance and compliance of the whole respiratory system. Meanwhile, the authors have proposed a methodological transformation from the real physiological system, through its linear complex model (forward model) [38], to the reduced metrological form (inverse model) [39]. A detailed description of the transition between the forward and the inverse structure was reported in [39].

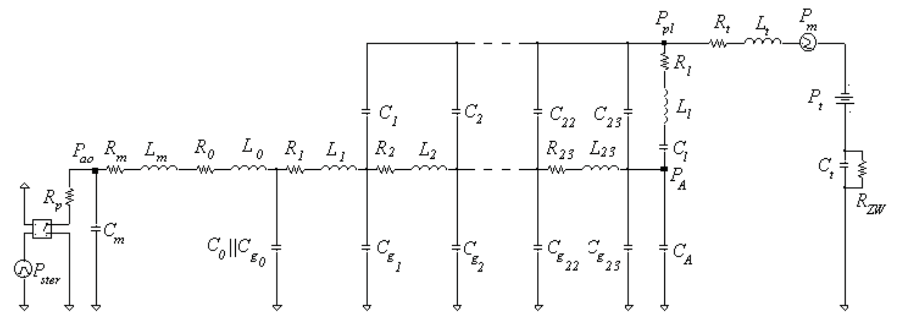

Fig. 3. Linear electrical replacement model of the respiratory system during airflow interruption [38].

Created in the Chair of Electronic and Photonic Metrology, the complex model of the respiratory system for the airflow interruption conditions is an appropriate configuration of the analogs of six main subsystems (Fig. 3): occlusion valve, upper airways, bronchial tree (symmetrical geometry by Weibel with 24 generations), lung tissue, chest wall and respiratory muscle. To incorporate the mechanical properties of the lungs and to make in an easy way the computer implementation of the model, the electrical replacement model of the system was exploited. That circuit is the physical model which uses the electrical analogs of the mechanical quantities related to breathing. They include: potential difference – pressure difference, current – flow, electric charge – volume, electrical resistance – mechanical resistance, capacitance – compliance, inductance – inertance. Various data related to the anatomy and the physiology of the respiratory system has been included in demonstrated, complex representation of the system. Simulation research, conducted in the PSpice and Matlab environment, exhibited an important consistence of the forward model behavior in relation to the real structure, both during spontaneous breathing and flow interruption, reliably reconstructing the characteristics in the time and the frequency domain [38].

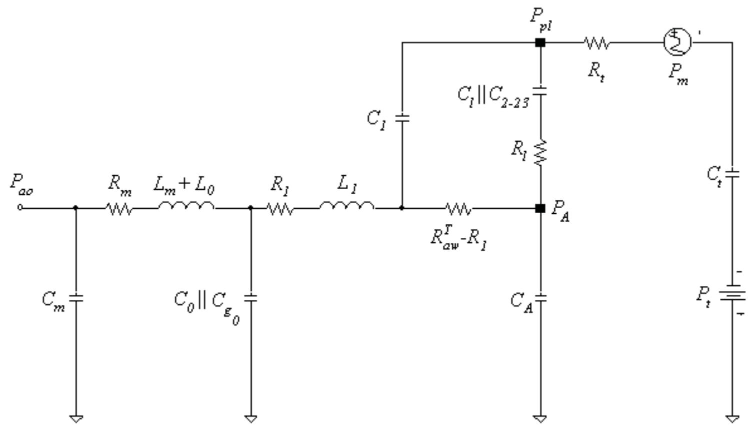

Fig. 4. Metrological model of the respiratory system during airflow interruption [39].

Using an assumption of a sensitivity theory, the complex (about 180 parameters) structure was reduced to the identifiable metrological form (inverse model, Fig. 4). As was shown in [39], it follows the basic properties of the physiological system in conditions of normal breathing as well as in occlusion, during observations in the time and the frequency regime.

The proposed structures (forward and inverse) need experimental verification and the flexible acquisition system of occlusion data prepared in KMEIF is a tool intended to do it.

4. SYSTEM OF ACQUISITION OF THE OCCLUSIONAL RESPIRATORY SIGNALS

The measuring module (Fig. 5) dedicated to a development of the occlusional techniques of inference on the respiratory system is a complementary part of the designed, multi-task “pulmonary combine”, constructed in a prototypical form to conduct evolutionary-laboratory investigations. Its main hardware parts are:

- pressure and flow medical sensors with a shutter valve (Jaeger, Germany),
- acquisition card Keithley DAQ KPCI – 3108 (National Instruments, USA),
- supply unit.

Fig. 5. The station for interrupter data acquisition for the evaluation of respiratory mechanics.

The stage is also equipped with a PC computer together with installed environment of LabVIEW 6.1 (National Instruments).

Only the power supply of the module has been planned at this stage of work.

The control of the appropriate elements of the system, in accordance with the idea of the interrupter technique and the requirements imposed on the occlusional methods of the respiratory mechanics measurements [22, 23], was realized by an original application written in LabVIEW. It guaranteed the possibility to collect post-interrupter data of pressure and flow at the mouth in a regime of the classical IT algorithms [28, 33, 34, 35] and the original EIT proposition [12, 13]. This alternativity, aimed at testing the various variants of acquisition signals and related to the future evolutionary works of the authors, can be summarized as follows:

- acquisition of the signals P_{ao} and Q_{ao} and the signal of occlusion valve control,
- defining the sample time for the signals: 0.5 ms and from 1 ms to 10 ms, with resolution 1 ms,
- occlusion execution during inspiration or expiration,
- occlusion execution for a maximal expiratory flow,
- occlusion execution at a chosen value of flow (inspiratory or expiratory),
- occlusion execution in a defined moment since the beginning of inspiratory/expiratory phase,
- occlusion execution with a defined duration time (t_d): $t_d = 50 \div 180$ ms for a one-time valve closure, $t_d = 50 \div 100$ ms for a multiple occlusion,
- defining the number of occlusions ($1 \div 6$),

- defining the time between successive interruptions (multiple occlusion case): 50 ÷ 200 ms,
- defining the number of the respiratory cycle during which shutter closure is demanded (counting from the start of measurement).

Proper software realization of the system of post-interrupter data acquisition enables to arrange and realize numerous measuring-acquisitive, informative and archival tasks, providing a wide configurational optionality of the factors which determine occlusional diagnostics (service of the individual functions is held at the level of the main panel, presented in Fig. 6).

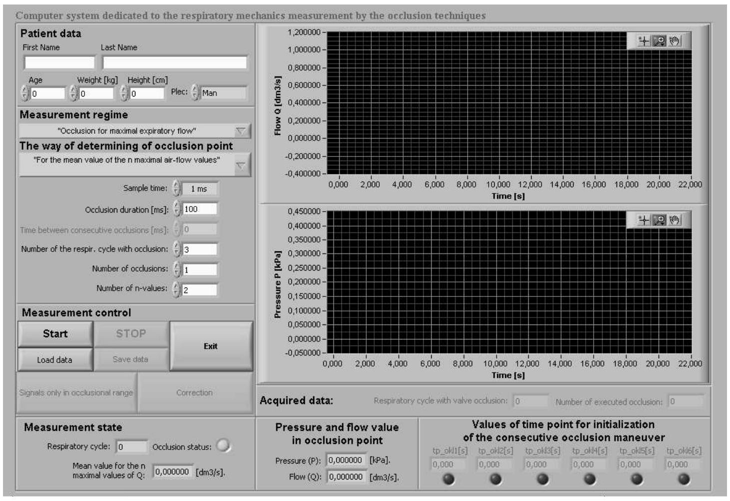

Fig. 6. The main panel of the program for the occlusional data acquisition.

5. SUMMARY

Apart from the pure cognitive virtues, the important motivation to conduct developmental work in the area of respiratory system diagnosis by the occlusional algorithms is the need to provide the medical environment with a "handy" and reliable device for respiratory mechanics evaluation. In the previous papers [12, 13], using computer simulation methodology it was shown that realization of the theoretical guidelines of the interrupter test in an indirect measurement procedure gives an opportunity to level the inference complementarity on the system with the other techniques and to reduce considerably the hardware demands. The experimental verification of the former achievements of the authors needs working out a flexible construction allowing also a prospective developmental activity in the discussed domain. The stage presented in the publication is the hardware-software configuration, by its optionality reflecting an extent of the analysis available in the future.

The occlusional measuring system is also the base of knowledge coupled with the pioneering, original studies of the physical-mathematical models of the respiratory system during airflow interruption. So, it is expected that measurements conducted at the stage allow their verification, completion and extension of the diagnostic, interpretative abilities. Hardware factors are also the issues that need optimization, especially the occlusion valve, characteristics of which seem to determine the quality of inference about the physiological system [29, 30], both in the time and the frequency domains. A possibility of more careful post-interrupter signal exploration is also perceived in the "fusion-type" structures of data analysis [40, 41]. In the author's opinion, elimination of the indeterminacy of the upper airways contribution to the entire output of the object is an important issue which needs a practical solution. The stage elaborated in the Chair of Electronic and Photonic Metrology, by its construction meets the above-mentioned (the most fundamental point of view at the actual level of knowledge) questions, enabling far-reaching evolutionary work on the classical IT method as well as author's enhanced interrupter technique (EIT). The utilitarian virtue of the occlusional procedures is also located in their predisposition to application for diagnostically very difficult subjects – infants and children, unique among the other techniques.

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