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INTRODUCTION TO RESPIRATORY MECHANICS MEASUREMENT BY ENHANCED INTERRUPTER METHOD

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Abstract: In the paper, there are postulated the basic requirements for the effective modification of a standard scheme of the interrupter technique (IT). The new method dedicated to respiration mechanics measurements, which meets such assumptions, is called enhanced interrupter technique (EIT). Using the idea of indirect measurements, it was showed by computer simulations the possibility to estimate the more number of parameters in EIT (Tab. 1, Tab. 2) than in IT (only airway resistance R_{aw}) for the proposed, modified Dubois' model. EIT gives the higher accuracy and the reduced dispersion of the measurement results, at the same time. As it follows from the computer simulations, analysing the measurement data in the time domain and the use of as quick as possible occlusion valve - Fig. 8 - (occlusion needs to include both the sudden, post-occlusional transient states and the slow rise of the pressure at the mouth P_{ao}) is essential to optimize EIT from the metrological point of view. The worked out problems are a base to construct a portable device, dedicated to measurement of the mechanical properties of the respiratory system.

Keywords: indirect measurement, enhanced interrupter technique, system identification.

1. INTRODUCTION

The respiratory system is one of the basic systems which determines life and its quality, hence, so important question is a knowledge of the rules governing its work, which leads to the ability to diagnose the pathologies and establishing the procedures of their elimination. A wide group of illness finds its expression in a change of the mechanical status of the lungs. The need to its following and the ability to its interpretation are a source of impulse to the research work in the area of measurement protocol.

There have been proposed a number of algorithms to the evaluation of respiration mechanics [1-4]. They base on the varied methods of the system stimulation and assume data analysis both in the time and the frequency domain [5, 6]. Among the postulated propositions, the interrupter technique (IT) draws authors' attention mainly for the sake of its distinctive, utilitarian virtues: small invasiveness, short time of measurement, not large hardware requirements, minimal requirements regarding patient co-operation. In the original version [7], the method assumes determining only the value of the interrupter resistance $R_{int} = \Delta P_{ao} / Q_{ao}$ (ΔP_{ao} – change of pressure measured at the mouth during occlusion, Q_{ao} – flow at the mouth just before interruption). Its ambiguous interpretation as well as important measurement dispersion placed IT historically in the order of the small effective algorithms. To a large extent, the source of important inaccuracy and dispersion of R_{aw} measurement is a way of evaluation of P_{ao} pressure change during occlusion. The applied back-extrapolation procedures (linear and non-linear) [8-11] are based on elimination of the transient states observed during interrupter manoeuvre (e.g. Fig. 1) and on a false assumption that at the moment of occlusion $\Delta P_{ao} \approx \Delta P_A$ (P_A – alveolar pressure).

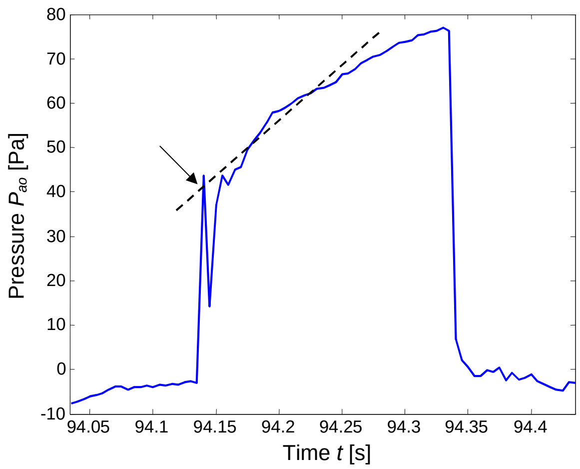

Fig. 1. Example of applying of the back-extrapolation procedure in evaluation of the P_{ao} change at the airway opening during occlusion; arrow – point where interruption pressure was measured.

The latest report of Frey, Schibler and Kraemer [12] stirred research interest in interrupter technique up anew but this effort still concentrates mainly on the standardization of the operational procedures [13-15]. Meanwhile, the authors perceive the chance to solve the IT algorithm inconveniences in applying of the indirect measurement methodology. Nevertheless, the task requires the solution of many problems, and the most important among them are the following:

- no simulation models (linear or nonlinear) available for the interrupter technique providing much accuracy in mechanical character of the respiratory system and the processes undergoing while measurement,

- no mathematical models available for estimation of respiratory system parameters based on signals measured during the transient state,
- concentration exclusively on the measurement of airways resistance which given the complexity of the system leads to significant systematic errors,
- difficulties with variation of the upper-airway compliance, which with the lack of including it in the model causes the increase of accidental errors,
- not including of transient state information observed after occlusion during measurements,
- lack of analysis of parameters influence of the measuring device (e.g. kind and speed of valve) on the parameters estimation accuracy.

The inclusion of the above-mentioned factors into the measurement procedure establishes a new canon for the air-flow interrupter technique and the enriched algorithm is further called the enhanced interrupter technique (EIT).

2. PURPOSE

The subjects of the presented work are the simulational-estimational considerations on the mentioned, elementary basics of EIT. They lead to the improvement of the classical IT method, which manifests in increasing of the informativity and the precision of estimations through application of the suggested modification. Structural investigations in the area of the model creation are not a matter of the paper.

3. METHODS

In our research we concentrated on the quality of identification criterions and their dependency on the equipment properties (here: mainly the occlusion valve). To analyze the problems we adopted the modified DuBois' model [16] (Fig. 2), which in our computer experiment of the indirect measurement plays a role of both the forward and the inverse structure.

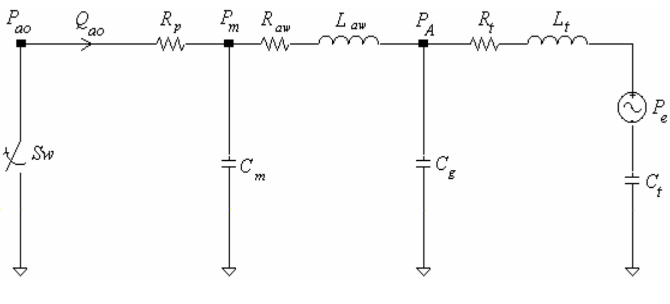

Fig. 2. Electrical replacement model of the respiratory system during airflow interruption: *Sw* – switch which represents shutter with R_{sr} resistance [Pa·s/dm³], R_p – pressure transducer resistance [Pa·s/dm³], C_m – upper airways compliance [dm³/Pa], R_{aw} and L_{aw} – resistance [Pa·s/dm³] and inertance [Pa·s²/dm³] of airways, C_g – alveolar gas compliance [dm³/Pa], R_t, L_t and C_t – resistance [Pa·s/dm³], inertance [Pa·s²/dm³] and compliance [dm³/Pa] of lung tissue and chest wall, , P_e – source adequate to respiratory muscle activity [Pa], P_A – alveolar pressure [Pa], P_m – mouth pressure [Pa].

The measured signals of pressure P_{ao} and flow Q_{ao} trends were taken in the proper ranges and totted up with Gaussian noise; there was proposed a new combination of the data. For the physiological parameters [17-19] the output data analysis was conducted in the time and the frequency domain.

3.1. Quality of identification

Identification of the proposed model of the respiratory system during airflow interruption, both in the time and the frequency domain, needs applying of the iterative algorithms for the signals: pressure P_{ao} and flow Q_{ao} – time domain and respiratory impedance Z_{rs} – frequency domain, respectively. The result of their application is a vector of the parameter estimators $\hat{\boldsymbol{\theta}}$ and the estimator of their variance $\boldsymbol{\Sigma}$:

$$\boldsymbol{\Sigma}(\hat{\boldsymbol{\theta}}) = \left[\boldsymbol{\eta}^{\mathrm{T}}(\hat{\boldsymbol{\theta}})\mathbf{R}^{-1}\boldsymbol{\eta}(\hat{\boldsymbol{\theta}})\right]^{-1}, \qquad (1)$$

where $\boldsymbol{\eta}$ is a sensitivity matrix of the output $\mathbf{y}$ of the model in relation to the parameters:

$$\boldsymbol{\eta} = \frac{\partial \mathbf{y}}{\partial \boldsymbol{\theta}} \qquad (2)$$

(in case of nonlinear models it depends on values of parameters), and $\mathbf{R}$ is a covariance matrix adequate to disturbances of pressure and flow signal.

For various reasons, it is more comfortable to assess the variance of the estimators before creation of the identification algorithm. Proposed in the paper approach of the forward–inverse model possess the advantage, that we know both the structure of the model and the chosen vector of the parameters $\boldsymbol{\theta}_0$ of the forward model, which represents the real system. Since $\hat{\boldsymbol{\theta}} \approx \boldsymbol{\theta}_0$ is an effect of work of the identification procedure, thus we can assess the variance of the obtained estimators as $\boldsymbol{\Sigma}(\boldsymbol{\theta}_0)$. Then, we can calculate the vector of the relative uncertainties of estimation $\mathbf{d}$, defined as standard deviations to the real values of the parameters ratio, as follows:

$$\begin{aligned}\mathbf{d} &= \boldsymbol{\theta}_0{}^{-1}\mathrm{diag}(\boldsymbol{\Sigma}(\boldsymbol{\theta}_0))^{1/2}, \\ \boldsymbol{\theta}_0 &= \mathrm{diag}(\boldsymbol{\theta}_0).\end{aligned} \qquad (3)$$

3.2. Valve influence on identification

In this section, the model of the valve-transducer unit was included in our analog from Fig. 2 in place of *Sw*. It was assumed the popular in practice valve construction of the shutter type (Fig.3).

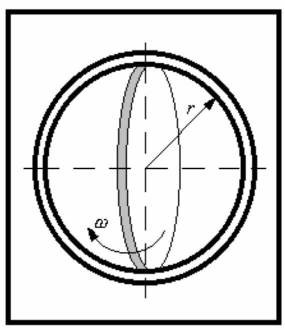

Fig. 3. Valve construction (frontal view).

The conductance of the unit $G = 1/R$, where R is the total its resistance:

$$R = R_p + R_{sr} \,. \tag{4}$$

The resistance of pressure transducer R_p is constant and determined by hardware construction, and the valve resistance R_{sr} equals to:

$$R_{sr} = \frac{k(l)}{\pi^2 r^4 \left[1 - \sin\left(\frac{2\pi}{T} \cdot t\right)\right]} \,, \tag{5}$$

where: $k(l)$ – coefficient which depends on length l, r – valve radius, T – period of valve turning, t – time.

Using the procedure of evaluation of the identification quality from the point 3.1, there were calculated the estimation uncertainties $\mathbf{d}_i$ for the various values of t_c (time of valve closure; in simulations 1, 5 10, 15, 20 ms) and t_o (time of occlusion: 50, 75, 100, 150 ms) – Fig. 4.

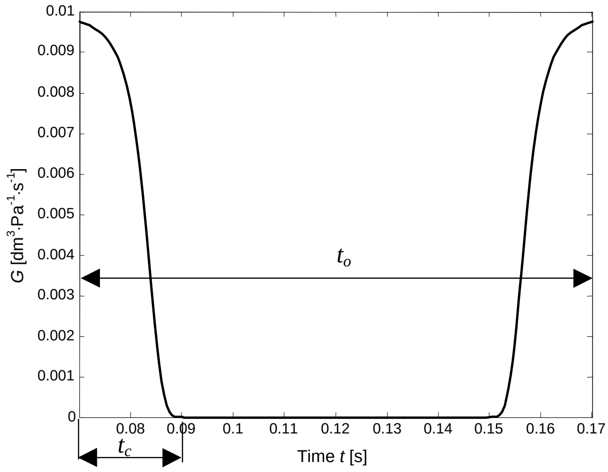

Fig. 4. Simulation of the interrupter valve characteristic.

The measure of the fitting quality of the inverse model to the real, respiratory system (here: the forward model), for the following t_c and t_o values, can be the relative mean square error of estimation:

$$d_{MSE} = \sqrt{\frac{1}{p}\left(d_1^2 + \ldots + d_N^2\right)} \,, \tag{6}$$

where p is the number of parameters.

4. RESULTS

4.1. Quality of identification

For the preliminary assumptions, it was obtained high accuracy of the parameter estimation of the modified DuBois' analog in the time domain during simulational investigations (Tab. 1).

Tab. 1. Parameter estimation accuracy of the model of the respiratory system in the time domain.

	C_m	R_{aw}	L_{aw}	C_g	R_t	L_t	C_t	P_0
d [%]	0.3	1.9	0.3	4.3	3.4	2.3	0.6	0.6

The estimation in the frequency domain showed interesting results in the structural sense (see Tab. 2) as well as the information contained in the measured data, examples of which are Fig. 5 – Fig 7.

Tab. 2. Parameter estimation accuracy of the model of the respiratory system in the frequency domain.

	C_m	R_{aw}	L_{aw}	C_g	R_t	L_t	C_t
d [%]	1.3	46	6.5	113	93	45	43
$\mathbf{d}_{Cg}$ [%]	1.2	5.7	3.7	—	12	34	38

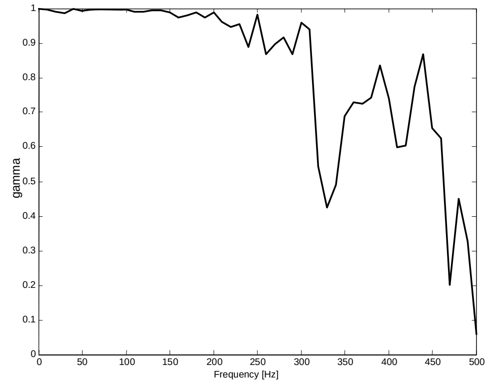

Fig. 5. Coherence function $\gamma(f)$ calculated for the estimated respiratory impedance.

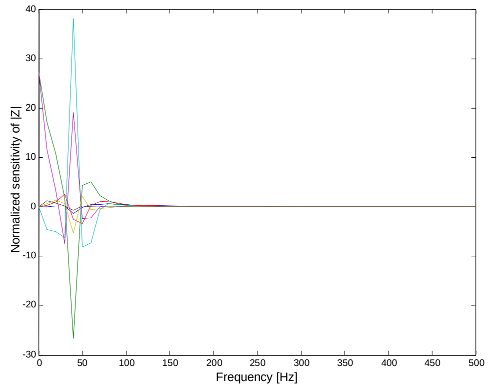

Fig. 6. Normalized sensitivity function of the impedance modulus for the proposed model.

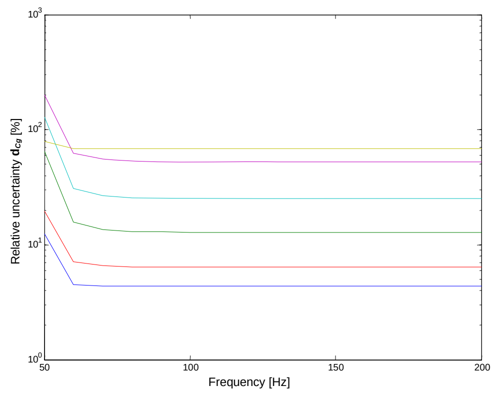

Fig. 7. Estimation accuracy $\mathbf{d}_{Cg}$ of the six parameters in relation to the frequency range of the measured data.

4.2. Valve influence on identification

Knowing the results presented in section 4.1, the valve influence on the estimation accuracy was checked only in the time domain. The obtained information is collected in Fig. 8.

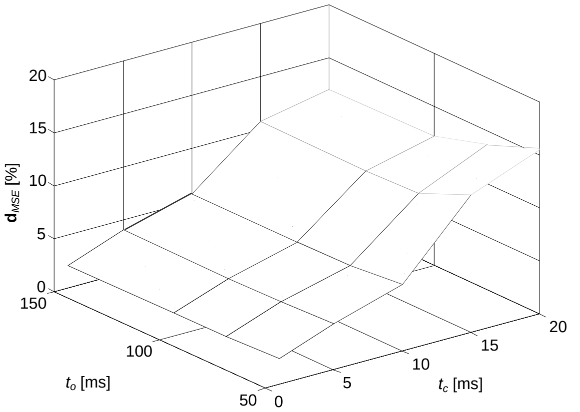

Fig. 8. Influence of the time of interruption on precision of parameter estimation of the respiratory system model.

5. DISCUSSION

The information attained by applying the typical interrupter algorithm (IT) boiling down to the estimation (with the error ~10-20 %) of the airways resistance, R_{aw}, on the basis of the only indicator (so, originally of the one-element model) – R_{int} – the interrupter resistance. Both the precision of the system description as well as the dispersion of the defined measure R_{aw} can't perceive the IT algorithm as competitive and satisfying diagnostically test. The main problem raised in scientific environment was the inability to separate tissue and airways properties, which, in the authors' comprehension, followed from the several reasons quoted in the introduction. They became the ground-work for the research and the proposition of the modification of the classical interrupter method, and the investigations reported in the article allow to set tentatively the standards for the new, enhanced interrupter technique (EIT). It is based on the indirect measurement of quantities, which define mechanical status of the lungs, in the model, which portray the structure and the phenomena observed in the real system adequately. In accordance with the results obtained in the presented forward-inverse simulation experiment (standard data were generated in the forward model and the estimation was performed in the inverse model), there are evidences to claim that EIT gives more precise description of the actual respiration mechanics. The informativity increasing of EIT in relation to the classical IT algorithm finds expression in possibility to determine the more number of the parameters (than only R_{aw}), which characterize the system, with the satisfying diagnostically accuracy (see Tab. 1 and Tab. 2).

The obtained results suggest, that the parameter estimators which are a result of the identification in the time domain are more reliable than the values obtained by fitting the model impedance to the respiratory impedance (compare Tab. 1 and Tab. 2). During analysis of the identification in the frequency domain, it was stated an important collinearity of the influence of compliance C_g and resistance R_t and R_{aw} on the respiratory impedance, which worsen the numerical condition of the estimation and can be a source of additional errors. Quality of estimation can be improved by C_g elimination from the procedure (see the results in Tab. 2), value of which can be calculated on the basis of air volume contained in the lungs, measured by the other method. It is worth to note, that sufficient is conducting the calculation up to ~120 Hz (and even 70 Hz), Fig. 5-7, which at he same time assures high value of the coherence function (Fig. 5).

The issue of complementarity of the phenomena investigated during identification process is included in the several factors highlighted in 'INTRODUCTION', and the results of the tests clearly show that such dependence applies also to the kinematic characteristics of the shutter (Fig. 7). It turned out that making as quick as possible occlusion, which includes in its duration time both the transient states and the linear rise of the pressure at the mouth (P_{ao}), is conductive to the accuracy increasing of the parameter estimation of the investigated system. It is consistent with intuition which suggests, that the oscillatory part of P_{ao} signal first of all represents the reactant (compliances, inertances) properties of the system, whereas the region with slow rise of P_{ao} describe notably its resistive character.

6. CONCLUSIONS

The paper discusses the basics of the enhanced interrupter method. The modified (in relation to the classical IT algorithm) proposal is a guarantee of informativity and estimation accuracy improvement during measurement of the mechanical properties of the respiratory system. Suggested, the indirect research protocol introduces the changes to the issue of modeling as well as post-interrupter data analysis and the presented, simulational results explain the basic conditions which determine getting the assumed goal. In this way, EIT can become the competitive measurement algorithm, conceivable to the realization in the structure of a simple, cheap and small invasive portable device.

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