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Computer assessment of indirect insight during an airflow interrupter maneuver of breathing

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ABSTRACT

The paper answers the questions if it is possible to conclude in objective way on more (than one – R_{int} – in a classical IT) number of parameters from the time domain post-interrupter signals during the occlusional measurement of respiratory mechanics and also verifies what accuracy can be achieved in such attempt. To obtain reported results, the time-domain enhanced interrupter technique (TD-EIT) was developed in this paper using computer simulations. Three-stage scheme of work was assumed in the project. First, the quality of the model identification was assessed for various combinations of pressure and flow signals recorded during the interruption. Then, the correlation between the working characteristics of the interrupter valve and the precision of the parameter estimation were assessed for the TD-EIT algorithm. Finally, a verification experiment by forward-inverse modeling was organized, in which the mechanical characteristics of a complex model were mapped with reduced analogs and with the use of neural networks for three typical modes: 'Normal state', 'Airway constriction' and 'Cheeks supported'. Obtained results show that to became effective in time-domain post-interrupter data exploration, both pressure and flow signals should be used in assessment of respiratory mechanics, taken in a range of at least 100 ms and when both slopes (valve closing and opening) of quasi-step excitation are included. What is more, the faster the valve the smaller error of parameter estimation in proposed TD-EIT was observed, and this uncertainty importantly falls down for the length of time window exceeding the limit of 100 ms. The pioneering use of neural network for mapping the mechanical properties of lungs with the use of interrupter experiment methodology proves that it is possible to conclude about more (than one) number of parameters characterizing the complex system and that this insight is biased with the error not exceeding of 10%; only peripheral properties are estimated worse. Such observation has a potential to change the experimental protocol, which was used in interrupter measurements up to date and to make this technique more attractive in comparison to other method, i.e. forced oscillation technique or impulse oscillometry. As regards the practical meaning of reported results for engineers and end-users (physicians and patients), proposed solution can be applied in simple portable devices with a feature of easy operation (important for e-monitoring).

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1. Introduction

The rate of sickness, complex course and consequences of respiratory diseases reduce the physical conditions of patients and the financial resources of communities around the world. Diagnostics of respiratory mechanics is a popular way to deduce the actual state of the system and to support possible treatment. A gold standard for spirometric measurements was proposed as a reliable tool for early detection of pathology, but this method possesses practical disadvantages connected with a need to perform a forced expiratory maneuver during the measurement [1,2]. This feature discredits spirometry as an effective method for the diagnosis of newborns or patients with respiratory muscle impairment. There are also other techniques that have been developed for respiratory mechanics measurements, e.g., the forced oscillation technique (FOT) [3,4], impulse oscillometry [1,5] or whole-body plethysmography [1]. However, none of them is well suited for portable applications in a home-based environment.

The airflow interrupter technique (IT), consisting of pressure (P_{ao}) and flow (Q_{ao}) measurements during a short-term airflow occlusion at the mouth, was suggested as a simple and noninvasive method for respiration monitoring [6,7]. In the classical version of IT, the airway resistance (R_{aw}) is assessed on the basis of measured interrupter resistance $R_{int} = \Delta P_{ao}/Q_{ao}$ (see Fig. 1), but this estimator is biased and has poor repeatability [8,9], which makes this attempt diagnostically unimportant. Some improvement is expected because the postocclusional transients are used when making conclusions about the system [10–12].

Most of the reports presented in the area of the interrupter technique are of an experimental nature, and they quantify the observations in relation to the other methods or describe each tendency in a range by itself [13–15]. This paper offers a new mode for occlusional measurements, here called the time-domain enhanced interrupter technique (TD-EIT). It uses time-domain pressure (P_{ao}) and flow (Q_{ao}) signals to make indirect conclusions about the system by model identification. Thus, TD-EIT, in contrast to classical IT, explores the information contained in the postocclusional transients. Furthermore, the optimization of this new attempt is conducted in a formal way in the paper with the use of forward-inverse modeling methodology [16]. Objectively, quantitative indications are calculated in a two-stage computer experiment. First, the quality of model identification during airflow interruption is tested. Then, the projections between a complex forward and two simple inverse analogs are assessed with neural networks.

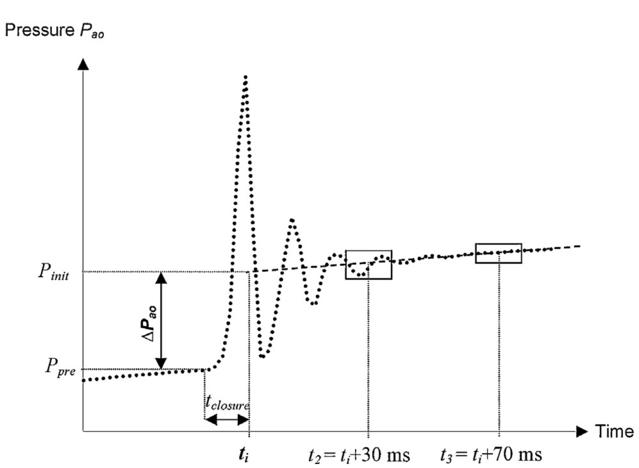

Fig. 1 – Calculation of the initial pressure step (ΔP_{ao}) in the classical version of the interrupter technique.

2. Methods

2.1. *Forward-inverse modeling of the respiratory system during airflow interruption*

The structural and physical variety of the respiratory system has been a topic of many investigations and is often associated with a specific measurement attempt [17–20]. However, there is a lack of detailed models in studies that involve an interrupter technique. Theoretical assumptions in the simplicity of the method have not found experimental confirmation in typical one- or two-element analogs [8,13,21,22], and an abundance of properties and processes accompanied by rapid occlusion should be represented with a more sophisticated description (such a need was explicitly indicated by Frey et al. [10,23]). First, the regions of an airway duct (with its acoustic interrelations created by gas filling the airways and the mechanical properties of their walls) and lung tissue should be separated in the model, which would enable more precise quantification of the response of each of the segments. Moreover, it is very important to address the reconstruction of the high-speed damped oscillatory behavior manifested at the mouth. Such assumptions have been exploited in presented investigations, where the modified DuBois' model is explored for the evaluation of the quality of identification during an interrupter experiment (Fig. 2). A detailed modeling study will be a subject of other considerations for the sake of methodological correctness in designing the inverse measurement procedure as well.

In relation to the basic version, the analog depicted in Fig. 2 includes some modifications, which are appropriate for the airflow interrupter technique. The mouth compliance C_m and a resistance R_d, which represents a flow transducer resistance, were considered. The necessity of model enhancement with the additional compliance element comes from the results of Jaeger [24] and Bates et al. [22]. The mouth compliance (mainly of the cheeks) was assumed to be 9×10^{-3} L/kPa, and the values of the other parameters were fixed according to the data calculated by Lutchen and Jackson (after conversion to SI units) [25].

An important part of the measurement path in the IT method is the valve-transducer unit. It consists of a constant resistance R_d, which is proportional to the limitation of gas movement through the short measurement head with a tube-like internal geometry, and the time-varying resistance R_v of the occlusional valve (Sw), often shutter-type in practice [11,12,26]. Thus, the resulting resistance of this segment can be depicted as $R_{v\text{-}tr} = R_d + R_v$ and its conductance as $G_{v\text{-}tr} = 1/R_{v\text{-}tr}$. Jaeger's construction of the measurement head was mimicked in a designed computer experiment [10,15,27]. For this case, $R_d = 0.098$ kPa/(L/s) was calculated with Poiseuille's equation, which defines the flow resistance through the cylindrical tube