Ability to Determine Dynamic Respiratory Parameters Evaluated during Forced Vital Capacity Maneuver Using Impedance Pneumography

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Abstract— **Flow-volume loops are used to calculate dynamic respiratory parameters. We examined whether our newly developed impedance pneumograph is able to measure properly respiratory parameters during Forced Vital Capacity (FVC) maneuver. Impedance measurements were performed using an electrode configuration known for providing good linearity between impedance pneumography (IP) and pneumotachometry (PNT) signals. The tests were performed on a group of 14 young volunteers (11 male and 3 female) without symptoms of respiratory dysfunctions. The volume-related signal from impedance pneumography and airflow signal from the reference method, pneumotachometry, were recorded. The IP signal was converted into volume units using a transfer function determined during calibration, and flow-volume loops for IP and PNT were obtained. Their shapes were compared using modified Mahalanobis distance metrics. Additionally, we compared the ratio of time of peak expiratory flow (PEF) to total expiratory time (T_{TPEF}/T_E) and that of volume at PEF to maximal volume (V_{TPEF}/V_E). The differences between these parameters, obtained for pneumotachometry and impedance pneumography, were statistically insignificant.**

Keywords— **Impedance pneumography, Pneumotachometry, Spirometry, Forced Vital Capacity maneuver.**

I. INTRODUCTION

Spirometry is treated as a gold standard for determining respiratory function [1]. Recently, research based on direct flow measurements using pneumotachometry (PNT) or volume spirometers has attempted to anticipate asthma episodes and support therapy [2,3,4,5,6,7]. However, such prediction seems to be possible only using long-term, ambulatory monitoring which allows the recording of signals before and during asthma episodes [4]. It is not possible to use classic spirometry during everyday patient activity. Therefore, it is necessary to use the indirect method, which allows holter-type recordings.

Impedance pneumography (IP) is the method of measuring electrical impedance of the thorax. The most commonly used method is tetrapolar current one, wherein the two electrodes inject an application current at an amplitude in range of 250μA-5A and frequency 20kHz-100kHz, while the remaining two receiving ones measure voltage. The ratio of the voltage amplitude to the amplitude of the current determines the impedance. Thoracic impedance consists of constant component (e.g. body fluid accumulation and residual volume of air in lungs – 50-200 Ω) and variable component (e.g. from changes of volume of air – 1-10 Ω) [8]. IP measurements seem to be in agreement with pneumotachometric ones allowing ambulatory applications [9-12].

Dynamic respiratory parameters are derived from a flow-volume loop which is obtained during the Forced Vital Capacity (FVC) maneuver. The volume of exhaled air is marked on the horizontal axis and the associated airflow is on the vertical axis. Positive values of flow are assigned to exhalation and negative to inhalation [13,14].

Dynamic respiratory parameters consist of, inter alia, Forced Volume Capacity (FVC [l]]; Forced Expiratory Volume in one second (FEV1 [l]) [15]; Peak Expiratory Flow (PEF); FEV1/FVC ratio [%]; Maximal Expiratory Flow determined for 75%, 50%, and 25% of FVC (denoted MEF75, MEF50 and MEF25, respectively [l/s]); and Maximal Inspiratory Flow for 50% of FVC (MIF50 [l/s]).

Other parameters connected to the flow-volume loop are time to achieve PEF to total expiratory time (T_{TPEF}/T_E) and volume at PEF to maximal volume (V_{TPEF}/V_E) [16]. These parameters, collected using e.g. bodyplethosmography with piezoelectric sensor, are regarded as good indicators for predicting wheezy respiratory illness in the new-born [17] and allow discrimination between asthmatic and non-asthmatic children of pre-school age [3,6].

The aim of the work was to validate the ability to determine dynamic respiratory parameters during Forced Vital Capacity maneuver using Impedance Pneumography. We also wanted to check linear and nonlinear regression for best agreement of the flow-volume loops derived from impedance pneumography and pneumotachometry. Finally, we wanted to compare two dynamic respiratory parameters (T_{TPEF}/T_E, V_{TPEF}/V_E) derived from flow-volume loops.

The significance of research on impedance pneumography method is to improve lung function diagnosis, especially for patient groups that are unable to perform spirometry or bodyplethysmography.

II. METHOD

We used an impedance pneumograph (with a sinusoidal 250μA, 100kHz application current) we built, which was

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tested using the specially constructed Artificial Patient module [18].

The Medikro Flow Measurement System (Spirometer Unit M909 device with Fleisch's type Heatable Flow Transducer 5530) was utilized as a pneumotachometry reference. A three-liter calibration syringe was used to provide the voltage-to-flow transition function (using a linear regression model) [19].

The participants were 14 volunteers, students without any reported respiratory diseases: 11 males aged 20-25 (M: 22.1; SD 1.8), with BMI indices in the range of 19.3 – 34.2; and 3 females aged 21-26 (M: 23.7; SD: 2.5), BMI: 19.7 – 25.6. All subjects were informed about the purpose of the study and gave written informed consent.

The protocol consisted of three FVC maneuvers performed by each subject. Since the signals were incorrectly registered in two volunteers, the final analysis was performed for 12 subjects.

Each participant wore a Conical Mouthpiece M9114 connected to the PNT sensor. No flow resistance was applied. Impedance pneumography was performed using the tetrapolar method with the electrode placement configuration proposed by Seppa et al [20]. The application electrodes were positioned on the midaxillary line at about 5th rib level and the receiving electrodes were attached on the proximal side of the arm on the level of the current electrodes, between the biceps and triceps. Standard spot ECG electrodes were used.

All sensors were connected to the multichannel signal recorder WinCPRS, which digitized and stored the signals at 200Hz sampling frequency. Because of the high sensitivity of the sensors and the self-noise of the recording equipment, the signals were filtered (40Hz) smoothed using a 25th order Savitzky-Golay filter [21]. We resigned from carrying out signal decimation despite the small value of the filter cutoff frequency to sampling frequency ratio.

In order to produce flow-volume loops (tidal breathing flow-volume curves) we had to prepare flow signals (impedance pneumography signal was differentiated using second order finite difference, phase shift was corrected) and volume ones (pneumotachometry signal was integrated using Simpson quadrature, and phase shift was also corrected). Volume drift was corrected within the analysis program.

Comparing flow-volume loops derived from pneumotachometry and impedance pneumography requires defining transfer function for both volume and flow signals, separately. We checked various regression models (linear, squared, reciprocal, logarithmic, exponential and more complex ones) and applied the one with the largest value of the coefficient of determination (R^2). Calibration was performed using the data from the first FVC maneuver.

To determine how much better the fit of the flow-volume curves is using non-linear transformations, we used a modified Mahalanobis distance (MD) [22], which is a measure of the distance between two vectors. It differs from Euclidean distance, because it takes into account the correlations between the variables and is invariant to data scaling. Pneumotachometry measurements were used as baseline vectors. A modification is to take the two vectors – the flow and volume, according to the formula (1):

$$MD^* = \sqrt{\left[MD_{flow}(IP - PNT)\right]^2 + \left[MD_{volume}(IP - PNT)\right]^2} \quad (1)$$

As the Mahalanobis measure indicates shape compliance, the quantitative parameters, T_{TPEF}/T_E and V_{TPEF}/V_E, were also calculated. Signal processing and calculations were performed using MATLAB.

We compared quantitative parameters using the Wilcoxon signed-rank test (data did not come from a normal distribution) with the 5% significance interval. Statistical analysis was performed using STAT graphics software (Two Samples/Paired Analysis section).

III. RESULTS

Figures 1 and 2 present sample direct air flow and impedance waveforms and calculated flow-volume curves, respectively, for the first participant. The black line in Figure 2 corresponds to the pneumotachometry signal; the red one to the impedance pneumography signal.

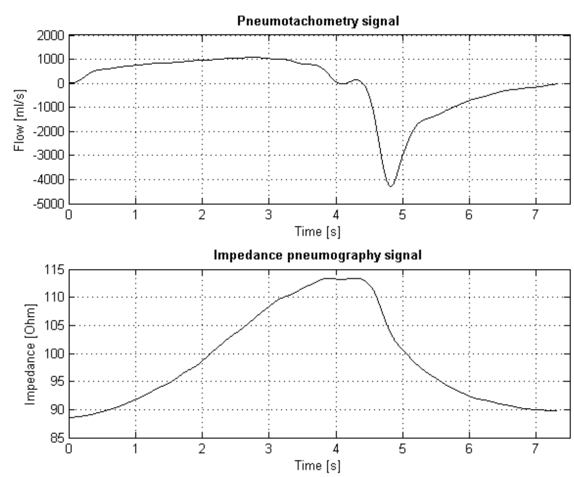

Fig. 1 Sample direct flow and impedance signals for FVC maneuver, first subject

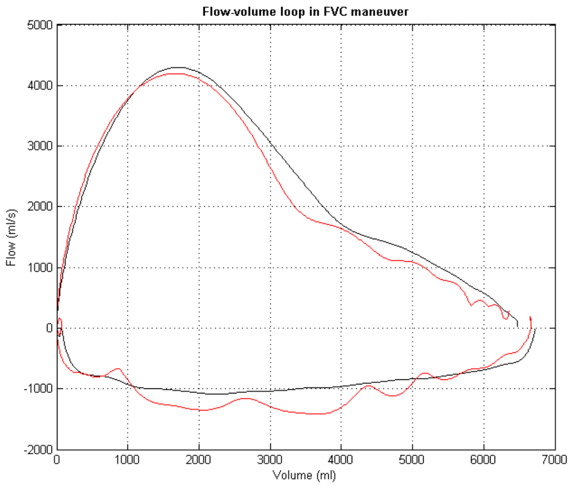

Fig. 2 Sample flow-volume loop for FVC maneuver, first subject (modified MD equals 14.2)

The type of applied fitting model, the value of the determination coefficient (R^2), the modified Mahalanobis distance (Dist) and the difference between nonlinear- and linear-based modified Mahalanobis distance (Diff) are presented in the Table 1.

T_{TPEF}/T_E and V_{TPEF}/V_E parameters after averaging the data from three FVC maneuvers, using the calibration coefficients calculated for only the first maneuver, are introduced in the Table 2.

We applied the Wilcoxon signed rank test. For T_{PTEF}/T_E parameters derived from pneumotachometry and impedance pneumography, we stated the null hypothesis as median equals 0.0 (alternative – not equals). The average rank of values below the hypothesized median was 6.222, and above the hypothesized median, 7.333. We calculated the large sample test statistic; after continuity correction, it was 1.294 and the p-value was 0.196. Given the 5% significance interval, we did not reject the null hypothesis.

For V_{PTEF}/V_E parameters, we stated the same hypothesis. The average rank of values below hypothesized median was 7.286, and above hypothesized median, 5.4. The large sample test statistic was 0.902 (after continuity correction) and p-value was 0.367. For the same significance interval, we also did not reject the null hypothesis.

Table 1 Coefficients of determination for volume signals

Subject	Flow		Volume		Dist	Diff
	Model	R^2	Model	R^2		
1	Linear	91.6	Linear	94.6	14.2	-
2	Linear	87.9	Squared	93.8	16.3	1.1
3	Linear	90.0	Linear	88.5	26.4	-
4	Linear	83.3	Squared	85.6	20.7	0.7
5	Linear	91.5	Linear	85.7	9.5	-
6	Linear	93.7	Linear	80.5	17.4	-
7	Linear	86.6	Squared	71.0	16.6	1.3
8	Linear	92.6	Linear	98.9	11.1	-
9	Linear	87.0	Squared	66.0	24.9	1.1
10	Linear	94.1	Squared	95.2	8.5	0.6
11	Linear	92.9	Linear	86.9	15.8	-
12	Linear	89.0	Linear	88.0	21.2	-

Table 2 Coefficients of determination for volume signals

Subject	T_{PTEF}/T_E [%]		V_{PTEF}/V_E [%]	
	PNT	IP	PNT	IP
1	14.1	14.5	24.9	24.3
2	15.2	17.4	24.7	29.5
3	17.6	28.9	24.1	31.4
4	14.0	15.0	20.1	25.6
5	35.6	30.0	33.2	38.7
6	31.7	33.0	43.8	40.1
7	27.0	33.3	39.5	45.8
8	31.6	25.9	37.8	35.9
9	20.0	17.9	49.0	40.0
10	23.7	31.9	25.9	31.9
11	16.1	21.4	38.5	38.8
12	68.0	68.9	68.1	63.1

IV. CONCLUSIONS

It seems that flow-volume loops determined with IP were similar to those obtained by PNT. The linear-regression-derived transfer function resulted in the best fit for most subjects. Although nonlinear models used for the transfer function provided better fitting than the linear one in few cases, the advantage was negligible. Therefore, using a linear model for the transfer function produces proper flow-volume curves for the FVC maneuver.

We speculate that the differences in the shape of the flow-volume curves (IP and PNT obtained) seem to derive from two sources: firstly, numerical errors and imperfect calibration, and secondly, the fact that thorax impedance does not depend solely on the volume of air in the lungs.

Additionally, we compared the ratio of time of peak expiratory flow (PEF) to total expiratory time The differences between parameters obtained for pneumotachometry and impedance pneumography (for T_{TPEF}/T_E as well as for V_{TPEF}/V_E) were statistically insignificant.

Replacing spirometry with impedance pneumography seems feasible in holter-type measurement, e.g. in asthma monitoring. Impedance pneumography has the potential to reliably estimate respiratory dynamics. It is worth considering whether it would be easier for children or diseased people to perform the FVC maneuver without a facemask.

This study is limited only to young, healthy people. It is necessary to perform the validation of IP method in patients of different age as well as with different types and severity of diseases. Further studies should perform verification in field conditions.

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CONFLICT OF INTEREST

No conflicts of interest, financial or otherwise, are declared by the authors.

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