Verification of the Respiratory Parameters Derived from Impedance Pneumography during Normal and Deep Breathing in Three Body Postures

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Abstract— **We designed a small, battery-powered impedance pneumograph intended for holter monitoring of respiratory activity. Volume-related signal from impedance pneumo-graphy (IP) and airflow signal from reference method, pneumotachometry (PNT), were registered. First derivate of IP with PNT and IP with integral of PNT signals were compared in order to calculate slope values of linear regression. The effect of respiratory rate, depths of breathing, body posture, sex and body mass index (BMI) on slope values and coefficients of determination (R^2) was determined. The measurements were conducted on a group of young volunteers without any respiratory diseases. An electrode configuration known for its good linearity between impedance and volume signals was chosen. Average R^2 between IP signal and integral of PNT signal was 98.05%, and between first derivative of IP signal and PNT signal – 95.75%. It was demonstrated that the slope values were individually different and affected mostly by body posture.**

Keywords— **Impedance pneumography, Pneumotachometry, Spirometry, Holter examination.**

I. INTRODUCTION

There are a lot of situations when monitoring respiratory system activity is necessary or even indispensable, but the use of direct measurement of airflow and tidal volume could be significantly limited. Pneumotachometry (spirometry), the gold standard [1,2], could be avoided in long-term applications [3], diagnosis and prevention of asthma [4], research on breathing mechanics in children [5], or even as a gate signal for MRI tomography [6].

Impedance pneumography was proposed as an alternative method [1,3,7,8,9], which could be used in the listed applications, which are difficult from the standpoint of direct measurements. Apart from the relationship between thoracic impedance changes and respiratory function, impedance pneumography could be combined with the determination of intrathoracic fluid accumulations [10].

Trials were conducted to establish the transfer function between direct flow- and volume- related signals and thoracic impedance [1,3,7,8,9,11,12]. It was noted that many factors affect the compatibility between these two signals.

Electrode configuration seems to be the most important factor. Logic at al. observed that a linear relationship can be obtained by placing the electrodes on the axillary lines [7]. Khalafalla et al. tested different electrode positions [8]. Seppa et al. studied various configurations, seeking linear compliance and a minimum signal degradation due to the mechanics of breathing [3,12]. Recently, they proposed a new set, for which there is high linearity of the $\Delta Z/\Delta V$ relation presented on the Lissajoux plots [11,13]. However, they carried out the research only on subjects in the standing position.

Khalafalla et al. observed dependence between physique and calibration coefficients [8]. Seppa et al. connected the measurements with body mass index (BMI) and found a similar effect [3].

Other factors, pointed by Houtveen et al., were body posture and respiratory rate [1]. They suggested subject-specific and posture-specific calibration procedure before referencing any respiratory parameters derived from the change in the impedance curves. They also analyzed the impact of sex and age and concluded that it is statistically insignificant [1]. However, it seems that the electrode configuration used deviated from the optimum [14]. Koivumaki et al. obtained high correlation coefficients for various respiratory rates and depths of breathing, but lower for women [6].

During the calibration process, it is also important to determine the time shifting, whose occurrence has been noticed [6,9,11] and whose appearance seems to be obvious because of the different source of signals.

The primary goal of the work was to specify a quantitative impact of respiratory rate, depths of breathing, body posture, sex and body mass index on the slope values of linear regression and coefficients of determinations (R^2) for flow and volume waveforms for one electrode configuration – presented by Seppa et al. [13]. Secondly, we wanted to determine whether scalar calibration coefficients (from a linear model), which do not change the shape of the signal, are enough, after phase alignment, for determination of volume- and flow-related respiratory parameters.

II. METHOD

We used our own prototype impedance pneumograph and Artificial Patient module [15] to perform the validation

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process (assessment of the stability of the amplitude and frequency of the 250μA, 100kHz digitally synthesized sinusoidal excitation current, and definition of the amplification of the receiver part and output-voltage-to-impedance transition function). The amplitude of the excitation current was chosen as a compromise between power supply and signal-to-noise ratio.

As a reference, we used pneumotachometer M909 with Fleisch's type Heatable Flow Transducer 5530, by Medikro Oy, headquartered in Kuopio, Finland. The flow measurement was calibrated using a three-liter calibration syringe (assumed to be a constant flow - the flow is determined by dividing the volume of the syringe and duration time of blowing). The voltage-to-flow-transition function was provided using a linear regression model [16].

The participants of the study were 15 healthy students: 11 males aged 20-25 (M: 22.1; SD: 1.8) and 4 females aged 21-26 (M: 23.0; SD: 2.4); body mass indexes were 19.3-34.2, without any reported respiratory diseases. All were informed about run of events and gave written informed consent.

The procedure for each subject is as follows: 10 normal breaths and 10 deep breaths in supine, sitting and standing postures (static conditions) at a rate of 6, 10 and 15 breaths per minute. Between individual sessions there were short breaks.

Pneumo-tachometry and impedance pneumography were measured simultaneously using a worn Conical Mouthpiece M9114 connected to the PNT sensor without any flow resistance. We used the tetrapolar method with the electrode placement configuration proposed by Seppa et al. [4]. The current electrodes were positioned on the midaxillary line at about 5th rib level. The voltage electrodes were placed on the proximal side of the arm on the level of current electrodes. Standard spot ECG electrodes were used.

All sensors were connected to a multichannel signal recorder, WinCPRS, which digitized and stored the signals at 200Hz sampling frequency. Due to the high sensitivity of the sensors, the signals are noisy, so they were smoothed using a 25th order Savitzky-Golay filter [17].

Volume waveforms were compared after integration of the pneumotachometry signal using Simpson quadrature, while flow waveforms were compared after differentiation of the impedance signal using second order finite differences. Volume drift was corrected within the analysis program using detrending method. Signal processing and calculations were performed using the MATLAB package.

As the distribution of the signal samples differs slightly from the normal one, Spearman correlation coefficients were calculated in order to specify time shift and stability of breathing rate. Determination coefficients (R^2) were used as a stranger measure to analyze the compatibility of the models. We executed the time adjustments according to maximal Spearman correlation shift index.

Analyses of the quantitative influence of the factors are performed in STAT graphics using hierarchical analysis of variance (variable components analysis) for nested factors in the following order: subject (sex, BMI) – breathing rate – breathing depth – body posture.

III. RESULTS

In order to express the agreement between impedance pneumography and the reference we performed simple linear regression model to establish scalar calibration coefficients, which make it possible to convert impedance measures into flow and volume parameters. Figures 1 and 2 present subject- and posture-specific slope values of volume and flow waveforms, respectively. * - female indicator.

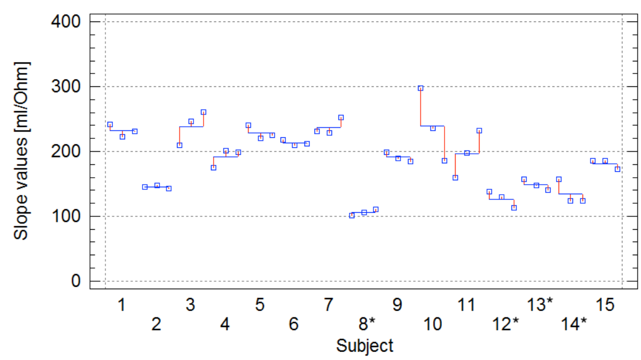

Fig. 1 Subject- and posture-specific slope values of the simple linear regression models for volume waveforms. The left points in set corresponds to the supine posture, the middle to sitting and the right to standing.

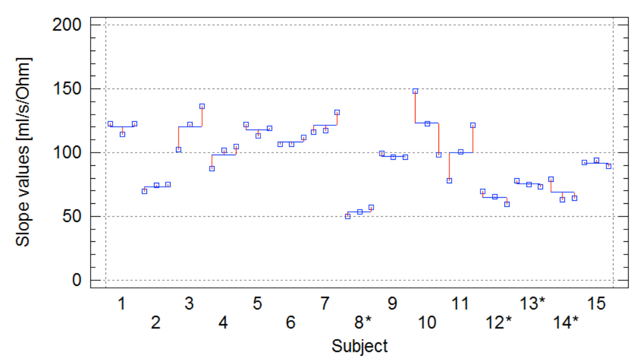

Fig 2 Subject- and posture-specific slope values of the simple linear regression models for flow waveforms

Tables 1 and 2 present the mean and standard deviation values of the coefficients of determination of calculated models for volume and flow waveforms for each condition. Outliers are measurements more than 1.5 standard deviations from the mean.

Table 1 Coefficients of determination for volume waveforms [%]

Rate	Depth	Posture	Mean	Std dev	Outliers
6x/min	normal	supine	98.2	3.0	1
		sitting	96.9	4.1	2
		standing	98.3	2.3	1
	deep	supine	97.3	2.9	2
		sitting	97.3	4.5	1
		standing	98.6	1.8	1
10x/min	normal	supine	98.3	1.5	1
		sitting	98.9	0.9	0
		standing	98.8	1.1	2
	deep	supine	98.5	1.0	2
		sitting	98.9	0.6	0
		standing	98.8	1.0	1
15x/min	normal	supine	98.2	1.3	1
		sitting	96.9	2.2	2
		standing	97.6	2.5	1
	deep	supine	98.2	1.1	1
		sitting	97.6	2.1	2
		standing	97.8	1.5	2

Table 2 Coefficients of determination for flow waveforms [%]

Rate	Depth	Posture	Mean	Std dev	Outliers
6x/min	normal	supine	93.5	4.1	1
		sitting	95.0	5.3	3
		standing	95.3	4.8	1
	deep	supine	94.3	2.5	1
		sitting	96.2	2.4	2
		standing	96.0	3.4	2
10x/min	normal	supine	94.9	3.4	1
		sitting	97.1	1.6	2
		standing	97.1	1.8	1
	deep	supine	95.3	1.9	2
		sitting	97.0	1.3	1
		standing	96.7	1.5	2
15x/min	normal	supine	95.1	2.0	2
		sitting	96.0	1.7	2
		standing	96.2	1.3	1
	deep	supine	95.8	1.6	2
		sitting	95.8	2.4	1
		standing	96.1	1.4	1

Sample Bland-Altman plots [18,19] for volume and flow measurements are presented in the Figures 3 and 4, respectively. Abbreviations: DIP – Differentiated IP signal, IPNT – Integrated PNT signal. Horizontal dashed lines indicate the values of ±1.96 times standard deviation of the differences.

Variance Components Analysis, in the order subject – breathing rate – breathing scheme – body posture - showed that the subject's contribution represents 45.6% of the total variation in volume slope values, body posture – 53.01%, respiratory rate – 1.39%, breathing scheme and error estimate – 0%. For flow parameters the contribution of the factors is as follows: subject – 48.56%, body posture – 48.47%, breathing rate – 2.97%, breathing scheme and error estimate – 0%.

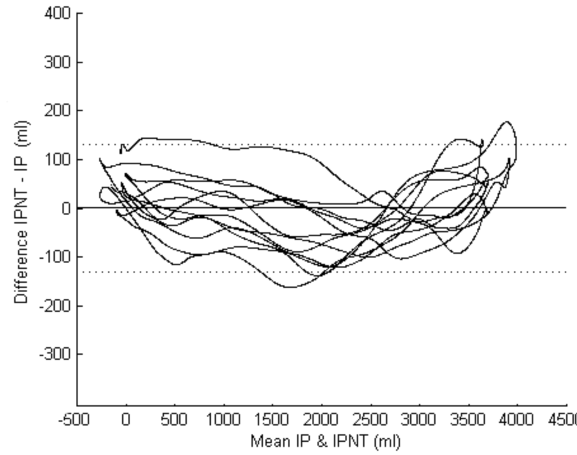

Fig. 3 Sample Bland-Altman plot for volume waveform of fourteenth subject (6x/min; deep breathing; standing) – 11770 points

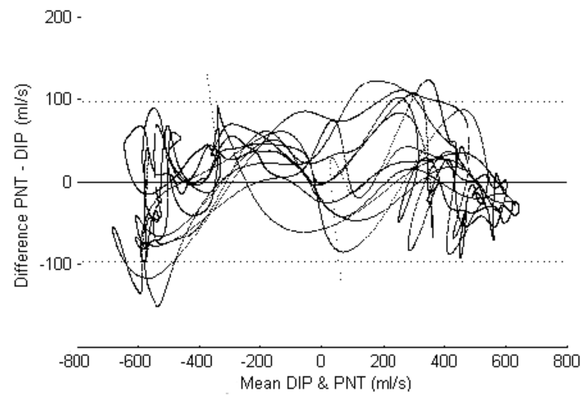

Fig. 4 Sample Bland-Altman plot for flow waveform of fourteenth subject 6x/min; deep breathing; standing) – 11770 points

Sex and BMI, as categorical values, have a linear effect on combination of subject-specific slope values for both (volume and flow) analyses. The higher the BMI, the higher the slope values are. Women have smaller slope values.

With regard to the signal processing operations, which introduced time shifts (especially numerical integration), in all cases the final signal time shifts were low, less than 50ms. None of the factors significantly affect the time shift. Appropriate corrections were applied.

IV. CONCLUSIONS

Linear regression model slope parameters (which allow one to convert impedance parameters into volume and flow parameters) appear sufficient for determination of respiratory parameters such as tidal volume or pulmonary flow.

Intercept values were not analyzed, because they are dependent on constant values of thoracic impedance. Impedance signals can be deprived of those constant values, because direct measurements of ventilation using a pneumotachometer provides no information about the absolute values of the volume of the lungs, only about the changes in volume (we lose all information about residual volume). Therefore, impedance information about residual volume and intrathoracic fluid accumulation is insignificant.

Subject variability and body posture have the greatest impact on the results. Breathing scheme and respiratory rate have no significant effect on the variability of the results, which could be expected. As the values of BMI and sex are associated with inter-individual variability, before long-term studies, calibration must be carried for each person individually and must take into account different body postures; other parameters seem to be irrelevant.

Repeatability and consistency of results suggest that the prototype impedance pneumograph functions well, but current studies were carried out only under static conditions. Similar analysis is required for dynamic conditions and for heterogeneously aged people before conclusions can be made about its ability to replace direct flow measurements in long-term measurement applications.

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CONFLICT OF INTEREST

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

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