Ambulatory impedance pneumography device for quantitative monitoring of volumetric parameters in respiratory and cardiac applications

Marcel C Młyńczak[1], Wiktor Niewiadomski[2], Marek Żyliński[1], Gerard P Cybulski[1,2]

[1] Institute of Precision and Biomedical Engineering, Faculty of Mechatronics, Warsaw University of Technology, Poland
[2] Mossakowski Medical Research Centre, Polish Academy of Sciences, Warsaw, Poland

Abstract

Aims: *The estimation of respiratory flow and volume parameters is difficult to perform and uncomfortable for the patient during long-term monitoring outside the clinical environment. It is also hard to perform during sleep due to the usage of a facemask. The impedance pneumography (IP) device allows monitoring of breathing activity, estimates the respiratory rate and provides the quantitative measurements of the static and dynamic respiratory parameters, e.g. tidal volume (TV) or peak expiratory flow (PEF). A miniaturized, Holter-type impedance pneumography device, Pneumonitor, with analog output and intrinsic digital memory, was designed and constructed. The system allows long-term assessment of ventilation by measuring changes in thoracic impedance using the tetrapolar method.*

Methods: *The Artificial Patient module was used to check the stability of the amplitude and frequency of the application current (sinusoidal, 100kHz, 250μA) and to calibrate the measurements obtained by the IP device by finding the transfer function between voltage and impedance. Impedance values obtained by the IP device from patients were compared those from another bioimpedance measuring device in different electrode placement configurations in patients (for cardiac and respiratory applications). The volume-related impedance signal was also compared with the volume signal calculated from pneumotachometry (PNT). These measurements were conducted in a group of 12 young, healthy volunteers (8 male).*

Results: *The comparison of impedance values from the IP device with those from another one bioimpedance measuring showed high agreement in all tested electrode configurations. High values of determination coefficients (R^2), describing the fit of the linear regression model relating corresponding IP and PNT signals, varied in the range of 0.934 to 0.997 (average: 0.985). However, the differences between average tidal volume parameters (calculated for each subject) derived from IP and PNT are statistically significant, although negligible (average relative error is 3.2%; 1.9% min., 7% max.).*

Conclusion: *Preliminary results show that our portable IP device provides impedance values related to respiratory activity according to a formula obtained individually for each subject. An impedance pneumography signal describing volumetric parameters could be used in analysis of respiratory and cardiac activities, e.g. might be helpful in asthma monitoring or autonomous nervous system testing.*

1. Introduction

Economic development favors the proliferation of diseases of affluence, such as allergy (asthma), type 2 diabetes, coronary heart disease, cerebrovascular disease, peripheral vascular disease, obesity, sleep apnoeas, hypertension or cancer [1]. Many of them are the result of sedentary lifestyle and have a direct impact on the cardiovascular and respiratory system.

It seems important to monitor (estimate) breathing mechanics (respiratory flow and volume parameters) in ambulatory conditions to prevent asthma episodes, diagnose and detect apnoeas or analyze subjects' physical activity. The gold standard in spirometry, pneumotachometry (PNT), relies mostly on measuring the change in pressure across a Fleisch-type pneumatic impedance mesh and calculating the airflow values. It requires a facemask and/or mouth assembly and nose clip to be worn [2]. This makes it impractical to perform PNT measurements outside a clinical environment or during sleep [3].

It was found that the impedance pneumography (IP) method, which measures thoracic electrical impedance, allows monitoring of breathing activity, estimating respiratory rate and providing quantitative measurements of the static and dynamic respiratory parameters, e.g. tidal volume (TV) or peak expiratory flow (PEF). In the literature, there were attempts to test the agreement between impedance and airflow signals only in static conditions or during controlled, sport-imitating tasks, but not outside laboratory (without active assistance) [4-7].

Therefore, a miniaturized, Holter-type impedance pneumography device, Pneumonitor, with analog output (to quickly test the device's proper operation) and intrinsic digital memory (allowing performance of holter-type measurements), was designed and constructed. The system allows on-board signal processing, according to the current need/application.

2. Methods

The impedance pneumography device - Pneumonitor (Figure 1.) - consists of four parts: application, receiver supply-steering and control. The block diagram is presented in Figure 2.

First one generates a sinusoidal application current (without a direct current component) with an amplitude of 250μA and a frequency of 100kHz, independent of load impedance. A DDS voltage generator establishes the shape and frequency of the signal. Amplitude could be regulated by changing the setting of a potentiometer in the voltage-to-current converter.

Filtration in the receiver part is selected to pass frequencies near to 100kHz before amplitude demodulation (high-pass filtering) and to fulfil the Nyquist criteria before analog-to-digital conversion (low-pass filtering). Amplification is set to fit the dynamics of the recording (in order to gain the highest possible signal-to-noise ratio and to avoid overdrive).

The supply-steering part is used to provide different supply voltage levels to different electronic elements, both analogue and digital. The last part is used to control the DDS voltage generator, ADC conversion with a sampling frequency of 200 Hz, storage to an SD memory card and operator commands. A simple block diagram of the steering program is presented in Figure 3.

The verification of Pneumonitor was performed into two steps: testing of the device (determination of the static characteristics) and comparison of the volumetric respiratory parameters measured using Pneumonitor and a reference PNT device.

Testing of the device (using Artificial Patient [8]) consists of:

- checking the stability of the amplitude and frequency of the application current,
- calibration of the measurements obtained by Pneumonitor by finding the transfer function between voltage and impedance,
- comparison analysis of impedance values provided by Pneumonitor and another bioimpedance measuring device in different electrode placement configurations (for cardiac and respiratory applications) [9].

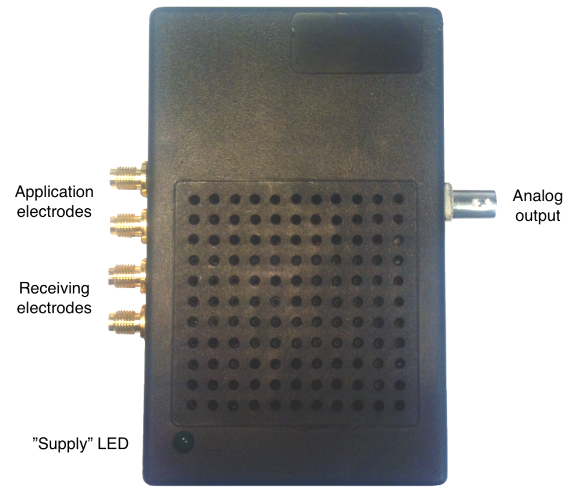

Figure 1. The photo of the Pneumonitor with description of the main elements

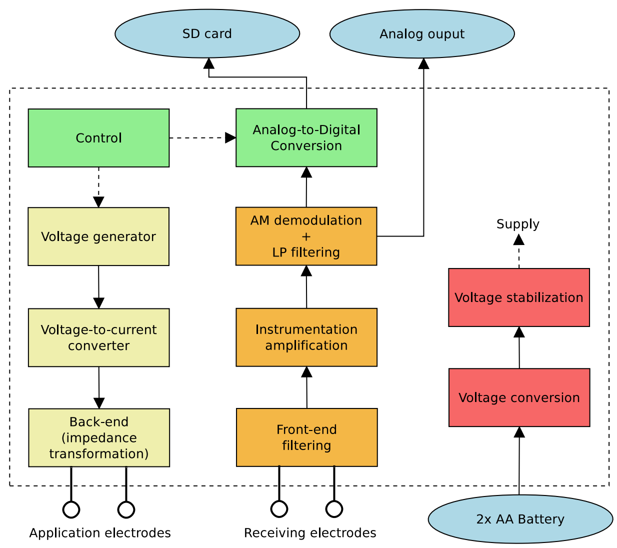

Figure 2. The block diagram of the Pneumonitor; yellow - application part, orange - receiver part, red - supply-steering part, green - control part and blue - interface

Application current amplitude is calculated indirectly, by measuring the amplitude of the input voltage, and dividing by the impedance set in the Artificial Patient module. Application current frequency is determined as the frequency of the input voltage amplitude. The transfer function between voltage and impedance is calculated as a linear regression model for impedance values (treated as an independent variable) and output voltage (as a dependent variable). The measuring set-up is presented in the Figure 4. The analyses of the impedance values obtained using Pneumonitor and ReoMonitor [10] were evaluated.

The volume-related impedance signal was also com-

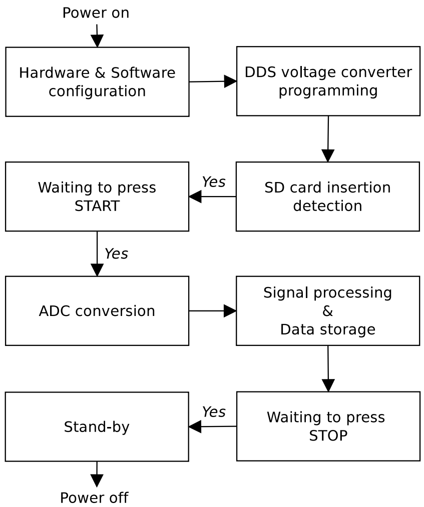

Figure 3. The block diagram of the control program of the Pneumonitor

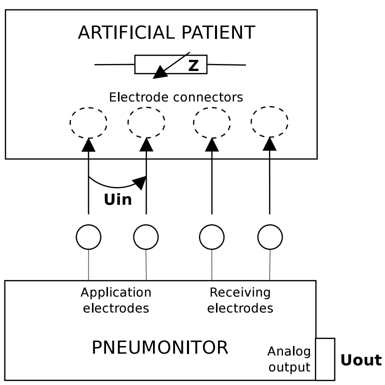

Figure 4. The scheme of the measuring set to check stability of amplitude and frequency of application current and determine transfer function between voltage measured by Pneumonitor and impedance set in Artificial Patient module; Vin - input voltage amplitude, Vout - Pneumonitor output voltage, Z - set impedance

pared with the volume signal calculated from pneumotachometry (the airflow signal was integrated using Simpson quadrature, as in Equation 1).

$$I_P\left(i\right) = \sum_{i=1}^{N} \frac{P\left(i-1\right) + 4 \cdot P\left(i\right) + P\left(i+1\right)}{3 \cdot h} \qquad (1)$$

where: P is pneumotachometry signal, I_P is an integral of the PNT signal, i - one signal sample, N - number of signal samples and h - interval of integration.

Comparative measurements were conducted in a group of 12 young, healthy volunteers (8 male) at the Department of Applied Physiology, Mossakowski Medical Research Centre, PAS, Warsaw. All subjects were asked to take 8 breaths for each of three breathing rates (6, 10 and 15 times per minute) and two qualitative breathing depths (normal and deep), in each of three different body postures (supine, sitting and standing). We checked various regression models (e.g. linear, quadratic, reciprocal, logarithmic, exponential) to find which one best fits the impedance and reference signals. For all 18 protocol elements (three breathing rates, two breathing depths and three body postures) for each subject, we calculated tidal volume and used the t-Student test to determine the statistical insignificance of the differences. All signal processing and data analysis were performed using the MATLAB environment. We used the R Studio environment to perform statistical analysis.

3. Results

The testing of the device provided the following results:

- Application current amplitude was 229μA (linear model, $p < 0.00001$, $R^2 \simeq 0.996$)
- Application current frequency equalled 100kHz and was stable.
- Amplification of the receiver part equalled 27.
- Transfer function between impedance and output voltage of the Pneumonitor could be determined using the linear regression model without a constant component and its statistical quality is great ($p < 0.00001$, $R^2 \simeq 0.995$).

The comparison between impedance values derived from Pneumonitor and ReoMonitor showed an agreement in cardiac (vertically, receiving electrodes located on the neck and under the bridge, application ones stuck on a forehead and about 5 cm below the lower receiving electrode) and respiratory (horizontally, one of the electrodes under the arm, application above the receiving) electrode configurations.

Linear regression models are sufficient to transform impedance into volume space. The high values of determination coefficients (R^2), describing the fits of linear regression models relating IP and PNT signals, varied within the range of 0.934 to 0.997 (average: 0.985). Sample volume signals are presented in Figure 5.

A comparison of tidal volume parameters was carried out in order to determine whether the good fit between impedance and direct airflow signal could provide information useful from a medical point of view. We calculated appropriate extremes for the signals and set amplitudes corresponding to various tidal volumes. Results (differences between parameters derived from Pneumonitor and the pneumotachometry reference device and the ratios between differences and reference tidal volume values) were collected in Table 1. All differences are statistically significant.

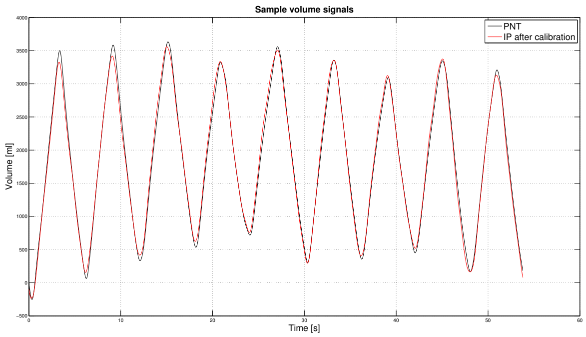

Figure 5. Sample volume signals derived from PNT (integral of airflow) and IP (after calibration) for third person, for deep breaths at 10x/min rate and for standing body posture

Table 1. Average differences between tidal volume parameters derived from pneumotachometry device and Pneumonitor and the ratios between differences and average tidal volume from PNT; * means female subject

Subject	Difference [ml]	Relative difference [%]
1	168.0	3.56
2	108.1	2.66
3	138.8	2.92
4	73.7	2.14
5	170.3	3.53
6	254.1	7.04
7	57.7	2.22
8	215.9	3.92
9*	63.9	2.35
10*	97.4	3.88
11*	48.7	2.17
12*	47.0	1.90
Mean	120.3	3.20

4. Conclusion

Preliminary results showed that our portable IP device, Pneumonitor, measures the electrical impedance of tissues. The impedance values could relate to respiratory or cardiac activity when using appropriate electrode configuration. For respiratory applications, the formula transforming impedance values into volumetric ones could be obtained individually for each subject.

The quality of the linear regression model is very good, although the largest differences are near the signals' extremes, therefore amplitude parameters, e.g. tidal volume, differ significantly from reference ones.

We think that Pneumonitor produces a signal which could describe changes in volumetric parameters and allow analysis of respiratory and cardiac activities, e.g. it might be helpful in asthma monitoring or autonomic nervous system testing.

Acknowledgements

This study was supported by the research programs of institutions the authors are affiliated with.

References

[1] Ezzati M, Vander Hoorn S, Lawes CMM, Leach R, James WPT, Lopez AD, Rodgers A, Murray CJL. Rethinking the ”diseases of affluence” paradigm: global patterns of nutritional risks in relation to economic development. PLoS Med 2005; 2/5:404-12

[2] Schermer TR, Jacobs J, Chavannes NH, Hartman J, Folgering HT, Bottema BJ, van Weel C. Validity of spirometric testing in a general practice population of patients with chronic obstructive pulmonary disease (COPD). THORAX 2003; 58/10:861-6

[3] Mlynczak M, Cybulski G. Impedance Pneumography - is it possible?, Proc of SPIE 2012; 8454: 1-14

[4] Ernst JM, Litvack DA, Lozano DL, Cacioppo JT, Berntson GG. Impedance pneumography: Noise as signal in impedance cardiography. Psychol 1999; 36:333-8

[5] Houtveen JH, Groot PFC, de Geus EJC. Validation of the thoracic impedance derived respiratory signal using multilevel analysis. Int J Psychol 2006; 59:97-106

[6] Seppa VP, Viik J, Hyttinen J. Assessment of Pulmonary Flow Using Impedance Pneumography. IEEE Trans Biom Eng 2010; 57/9:2277-85

[7] Lahtinen O, Seppa VP, Vaisanen J, Hyttinen J. Optimal Electrode Configurations for Impedance Pneumography during Sport Activities. IFBME Proc 2009; 22:1750-3

[8] Mlynczak M, Pariaszewska K, Niewiadomski W, Cybulski G. Design and construction of the Artificial Patient module for testing bioimpedance measuring devices. Proc of SPIE 2013; 8903:1-9

[9] Seppa VP, Hyttinen J, Uitto M, Chrapek W, Viik J. Novel electrode configuration for highly linear impedance pneumography. Biomed Tech 2013; 58/1:35-38

[10] Cybulski G, Kozluk E, Michalak E, Niewiadomski W, Piatkowska A. Holter-type impedance cardiography device. A system for continuous and non-invasive monitoring of cardiac haemodynamics. Kardiologia polska 2004; 61:138-46

Address for correspondence:

Gerard Cybulski
Warsaw University of Technology
Faculty of Mechatronics
Institute of Precision and Biomedical Engineering
Boboli 8 02-575 Warsaw
G.Cybulski@mchtr.pw.edu.pl