Impedance pneumography – is it possible?

Marcel Młyńczak [a], Gerard Cybulski [a,b]

[a] Institute of Precision and Biomedical Engineering, Faculty of Mechatronics, Warsaw University of Technology, ul. św. Andrzeja Boboli 8, 02-525 Warsaw, POLAND
[b] Department of Applied Physiology, Mossakowski Medical Research Centre, Polish Academy of Sciences

E-mail: G.Cybulski@mchtr.pw.edu.pl

ABSTRACT

The main purpose of this study was to describe the technique of impedance pneumography, the noninvasive method of quantitative, long lasting examination of respiratory system. In this paper there were presented physical foundations of the method, the measurement equipment and the different approaches to the measurement procedures. Also, various types and configurations of the electrodes were shown. The validation studies of impedance pneumography using clinically accepted reference the method were described, too. Finally, there were presented some proposals for future development of the technique.

Keywords: impedance pneumography, long-term monitoring, respiratory system

1. INTRODUCTION

Spirometry, the method for measuring changes in lung function by specifying the volume and rate of breathing, is the gold standard for clinical monitoring of the respiratory system. However, it requires large, stationary equipment (face mask and mouthpiece-nose clip assembly) and have bad psycho-physiological effect on the process of measuring. Also, this method could be intrusive, because it alters breathing space and may obstruct normal breathing pattern which could be gauged without a mask and a mouthpiece. Spirometry apparatus may also disturb the ventilation measurement in sleeping patient, because it forces a fixed position of the patient, which may not be a natural one. It could be difficult to measure ventilation parameters in infants or neonates, because of their small body. On the other hand hardware and implements can be expensive.

There are many clinical and physiological reasons for requiring a reliable, long-lasting quantitative measure of respiration parameters. It suffice to mention only the respiratory system diseases monitoring, sleep apnea diagnosis, psycho-physiological or sport medicine applications. Several methods have been used to measure respiration, but in stationary, clinical conditions. There were some attempts to make this vital sign measurement more portable. However, as it was noticed by *Houtveen et al.* [1], speech, posture and physical activity present a much larger problem to the measurement of respiration than they do to cardiovascular recordings.

Therefore, there is a need to implement another method which could provide the volume measurement of respiration process during long lasting monitoring outside the clinical environment. It seems that there are two suitable techniques satisfying mentioned requirements: plethysmography and impedance pneumography. In this paper we tried to review only the second method which, in our opinion, has a higher chance to be applied for long term respiratory monitoring. Impedance pneumography seems to be cost effective and rela-

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tively easy to use without active cooperation of the patient. Also it might be used to asses the function selected region of the lung.

2. METHOD AND MEASUREMENTS

2.1. Impedance pneumography

Impedance pneumography (IPG) is the method which measures changes in transthoracic electrical impedance with electrodes fastened on patient's thorax. Respiratory-related changes are a signal which may provide a valuable index of respiration and are considered to be measured in the same way as in impedance cardiography (ICG). These changes are mainly a result of the following effects [2]:

1. gas volume increase in relation to the fluid volume displacement during inspiration which causes decrease in conductance,
2. as a result of expansion during inspiration there is an increase of the length of the conductance paths.

These effects when combined increase the electrical impedance. It was found that there is good correlation between changes in impedance and the volume of ventilated air. This relationship is approximately linear which gives a rational assumptions to use this method (after the calibration procedure) instead of spirometry or pneumotachometry [1-4].

Some authors treat IPG signal as a noise in impedance cardiography (ICG) [3], but there are several possibilities to extract IPG signal from ICG signal. One of the method is to change the electrical parameters of the rheocardiograph to emphasize breathing signal or try to extract part of the signal using advanced signal analysis.

2.2. Measured variables

Thanks to impedance pneumography we could quantitatively evaluate ventilation in two ways:

- respiratory rate (RR) – by measuring only peaks of impedance signal which related to respiration and provide a number of breaths in the period of time,
- static parameters of spirometry from the shape of the signal after a calibration.

The respiration rate is easy to obtain using other, more direct methods (even from ECG signal). However accurate measurement of the respiration volume parameters seems to be a challenge. The most important parameters characterizing ventilation are: Tidal Volume (TV), which defines changes of the volume of chest during natural breathing and Vital Capacity (VC) – amount of air, which the lungs can contain during strenuous inspiration after maximal expiration. Other important parameters are shown in Fig.1. presenting example-shape of respiratory signal.

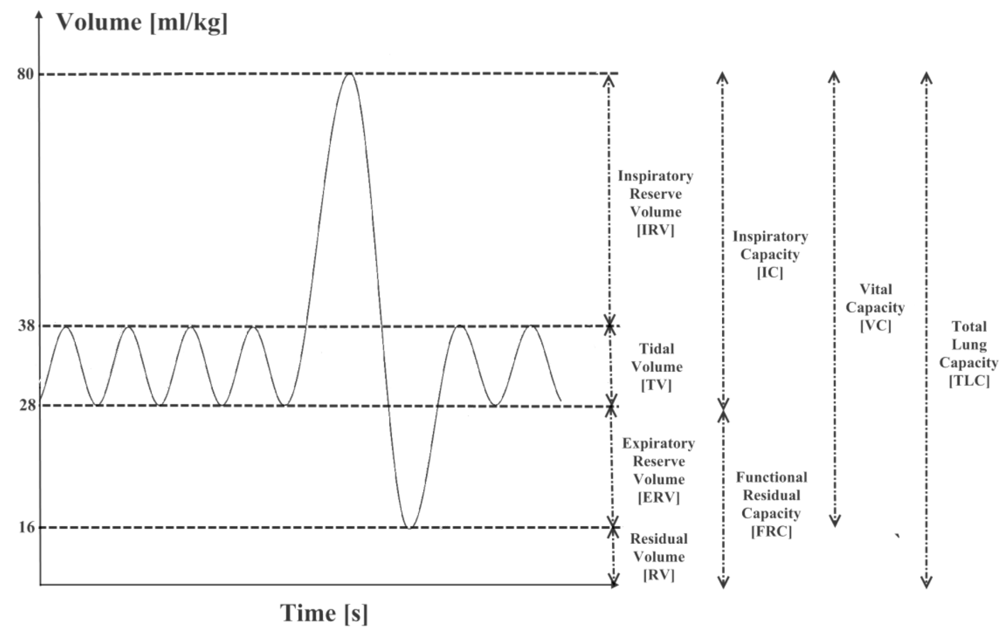

Figure 1. Static spirometry parameters

Quantitative measurement by IPG may be modified by subject's for amount of adipose tissue [5], his/her posture and breathing mechanics [4]. These uncertainties could be reduced by usage of a subject-specific, posture-specific and measurement place-specific calibration [1,4]. It must be remembered that calibration coefficients are merely scalar. Therefore they do not change the shape of gained signal waveform [4]. Since error seems to be deterministic (at the same phase of the each cycle) it is difficult to overcome it with a calibration scalar (if this error is stochastic the averaging could cancel it) [4]. Certainly, some more advanced calibration techniques will have to be utilized in order to increase agreement between IPG and reference - Pneumotachometry (PNT) or Spirometry in long-term measurement.

2.3. Physical foundations

In Impedance Pneumography the measurement is carried out with the electrodes, which play a role of driving excitation current and sensing voltage. Depending on tasks which these electrodes are used for there are four basic methods for signal generation:

- bipolar
- bipolar guarded
- tetrapolar
- tetrapolar guarded.

The scheme of the impedance measurements are presented on Figure 2.

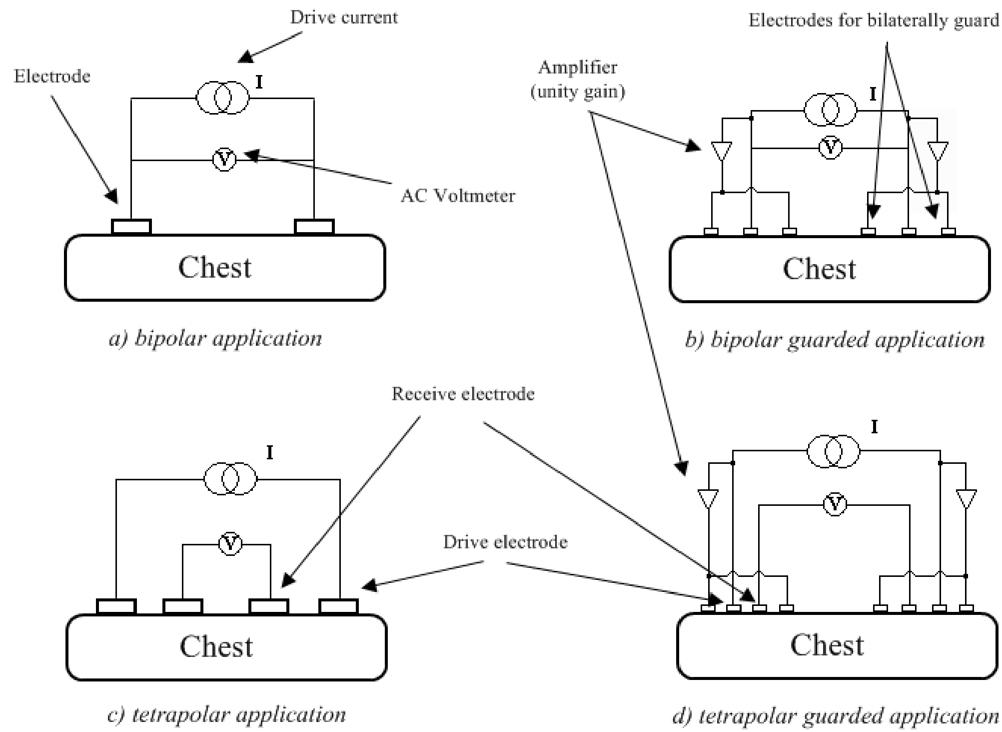

Figure 2. The scheme of the impedance measurement

The bipolar arrangement was the most popular method used in commercially available systems for rheocardiography during the 1980s. Nowadays this method is replaced by tetrapolar application. In bipolar method the current-injection electrodes are also used to sense the voltage, which describes changes in transthoracic impedance by U/I ratio [6]. Advantage of this method is simplicity and little requirement for number of electrodes, but it must be noticed that the impedances of the electrodes and underlying skin are inseparable from the desired ones [6]. According to [6], for each maneuver (obstructed inhalation, arm motion or running in place) the bipolar arrangement showed the worst motion-induced volume artifact coefficients, because of inclusion too many undesired impedance components.

The more advanced solution is the bipolar method with guarded electrode. There is an establishment of isopotential between the electrode used for driving and sensing and the surrounding tissues [6]. This solution gives better distribution of injected current and decrease the sensitivity to the electrode motion. In Fig.2b. there is an arrangement with bilaterally electrodes, however we could use only one electrode to guard and then we have the unilateral guarded bipolar setting, but despite this two kinds of guarded improvement, this technique is used not very often. It is because the increased complexity of the design while the most important disadvantage of the bipolar application (using the same electrodes as driving and sensing) remains. The solution of this problem is tetrapolar electrode design in which the two divergent function of the electrodes are split into the pair of electrodes, which have different tasks. First pair is utilized for driving excitation, the second for sensing the voltage. Changes in the gauged voltage reflect the changes of impedances on the measured tissue region. The impedance value Z we can obtained by Equation 1. [4,7]:

$$Z = \int_{v} \frac{1}{\rho} J_{LE} J_{LI} dv \tag{1}$$

where ρ is conductivity distribution within the volume conductor v, J_{LE} is the lead current density field of voltage measurement, J_{LI} is the current density field raised by current injection. In this situation there is strongly better distribution of current density and the sensed voltage does not change the impedance of each electrode and underlying skin or tissues [6]. The pairs of electrodes are physically separated hence tetrapolar measurement is favoured over the bipolar one due to the opportunity to focus the sensitivity into the area of interest and ignore the impedance between electrode and skin [4].

It is possible to combine the last two ideas to yield the tetrapolar guarded application. It has small benefit to the tetrapolar one, but it requires the greatest number of elements (as many as five electrodes in the unilaterally case, which we could also utilize as a way of guarding) [6]. Additionally, if guarded element is itself driven to ground by the circuitry, this element may be connected to ground at once and then there is no necessity to use any extra guard [6].

Thus, the measurements are usually executed by a current method with current drive and voltage sense into a number of electrodes, which depends on a design and an application of the electrodes. Impedance gauged on chest is presented as constant value (baseline impedance) Z and variable element (respiration induced impedance) ΔZ and is marked as voltage/current ratio. Typically baseline impedance is at the level of 500Ω and ΔZ in range of 0.1Ω to 1Ω [2]. Instruments to measure IPG may be the same as reograph with modification of frequency band and amplification. First, because frequencies of ventilation are smaller than cardiac ones. The time constant of the amplifier system must be changed in order to gain defined band in range of 0.1Hz to 0.5Hz. Because baseline impedance in IPG is much larger than in ICG and we must reduce an amplification in order not to bring to saturation. However the current excitation with 100µA-1mA at 10kHz-100kHz, remains the same as in cardiac applications [2]. A high frequency AC signal is injected into the body and as a result of the breathing action this signal is amplitude-modulated. Therefore it must be demodulated in order to extract breathing signal for the receiver.

2.4. Types of Electrodes

The electrodes used for IPG measurement may be the same as applied in reocardiography. There are two main groups of the electrodes with respect to their shape and size (area):

- band electrodes
- spot (ECG) electrodes.

It is assumed that the minimum surface is about $1\ \mathrm{cm}^2$. One of the first works which study the results obtained with band electrodes is [3]. They tried to record the changes in impedance for eight healthy adults during rest, paced breathing, abdominal breathing, thoracic breathing and a breathing during mental arithmetic task [3]. As an outcome, they found quiet highly coherence coefficients between IPG and Spirometry about 0.9. Moreover, they proved closely alignment in phase [3]. There was only minimal phase lag with the reference research. They also studied the gain and found that calibration with IPG is relatively simple because of the linear relationship between the impedance and spirometry signal [3]. But we must noticed that they prepared the calibration coefficients before each session and did not examine what would be the signal during the change of kind of breathing where would be the largest possibility to worsen the agreement of the measures. They also paid attention to the fact that the origin of lung volume changes is largely irrelevant [3]. Preliminary findings from their laboratory suggested the signal obtained from the spot electrodes have decidedly worse mean coherence than for band electrodes [3]. The contrary opinion was presented in [1]. They tried to validate the change in transthoracic impedance obtained from four spot electrodes. The authors noticed that *Ernst et al.* [3] had analysed coherence, which could demonstrate a (linear) relationship, but could not present the absolute difference between two methods [1]. They also pointed out the limitations of the study [3] because all breathing manipulations were conducted in sitting position. In their study they conducted the experiment in three different body positions (sitting, supine and standing) at four paced frequencies of breaths and utilized multilevel analysis to find between- and within-subject regression of the amplitudes of the impedance signal on the spirometric volume [1]. They carried out standard procedure of measurement and found deployment which is less sensitive to movement artefacts. The measuring electrodes were positioned vertically. Upper, at the jugular notch of the sternum between the collarbones. Lower, at the tip of the sternum. The current electrodes were placed on the back at least 3 cm above and below the upper and the lower measuring electrodes, respectively [1]. They also computed posture-combined and posture-specific gain and variability of gain. As a result they obtained 0.934 coherence for sitting, 0.823 coherence for supine and 0.817 coherence for standing position [1] and they found no influence of gender and age on signal [1].

The coherence coefficients gained by *Houtveen et al.* [1] are comparable but worse than acquired by *Ernst et al.* [3]. This was also confirmed by *Sahakian et al.* [6]. They showed that increasing of the area of electrode from 0,8 cm^2 (spot one) to 33 cm^2 (band one) reduces the mean compliant, arm-motion and body-motion artifacts, so the exactitude is strongly easier to get by band electrodes.

Vuorela et al. [8] noticed that in physiological impedance measurement there was an essential requirement to contact to the skin as close as possible. Electrodes should be stable and stay in place firmly, but it seems to be hard to achieve during physical exercises. In clinical adaptation there are two ways to fulfil these demands: using gel-paste or textile electrodes [8]. Problem with gel-paste electrodes is that the gel could dry after long session of measurement and then it would have to be an intervention of the specialist, which hamper the use of gel-paste electrodes in long-term home-settled measurements. The solution seems to be the textile electrodes, which have no problem with drying because of lack of any gel between the electrode and a skin. Furthermore, the contact area is larger for textile ones and they have no glue, which could have irritate effect on the skin [8]. However, it should be guaranteed proper skin contact, for example with an elastic band [8].

In some works there were used different kinds of electrodes:

- pre-gelled Ag/AgCl EKG electrodes [5]
- tetrapolar circumferential mylar-band electrodes secures at standard cervical and thoracic sites [3]
- standard disposable Ag/AgCl electrodes with adhesive and conductive gel (13.2 mm^2) [9]

- custom-made flexible chest band with 40 electrodes embroidered of silver yarn; the electrode matrix consists of two 20 electrode rows of square electrodes (225 mm^2) and 30 mm separation, with no electrode in the middle of the front side of the subject, because of the worst possibility to achieve good electrode-skin contact [4, 10].

2.5. Electrodes configurations

One way of positioning was described in previous part, but it was related to spot electrodes. The usage of band electrodes demands different approach. According to the study of *Seppä et al.* [9], there are three main conditions for achievement of good IPG measurement [11]:

- low artefacts caused by physical movement and in general the lowest possible number of artefacts caused by any kind of movement,
- availability of ECG signal for polyphysiographic low bioimpedance signal induced by cardiac action.

IPG signal is highly sensitive on an electrode configuration, therefore we could distinguish at least four classes of typical signal morphologies [10]:

- completely clean signal, perfect agreement with the reference
- a signal with small cardiogenic distortions superimposing on the accurate IPG signal, which we could obtain applying averaging techniques or specific demodulation
- a signal with small insight of the breathing, but without the agreement with spirometry
- completely distorted signal.

The most comprehensive studies of the band electrode configurations were presented by *Seppä et al.* [4, 10]. The scheme of the best locations at the level of axilla provided and studied by them is presented at the Figure 3.:

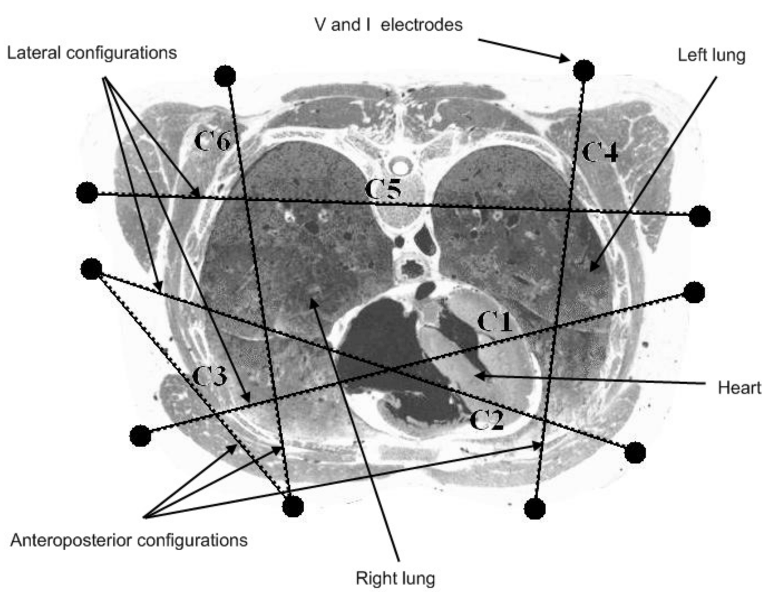

Figure 3. Electrode configuration proposed by Seppä et al. [10] (adapted).

In their measurements, the electrodes were used in vertically positioned pairs, each pair having a current lead in the upper, and sensing lead in the lower, close to each other. This resulted in high sensitivity of impedance changes to changes in the lung air content [4,10].

The studies [4,10] showed that:

- the median value of Pearson linear correlation coefficients between spirometry and all of six configurations had been in range of 0.957 to 0.997,
- there had been an uncertain negative correlation between subject body mass index (BMI) and per-subject correlation (authors had admitted that the population is too small to qualify that),
- an occurrence of the artefacts had not been able to be explained by sex or BMI,
- the lowest count of cardiogenic distortions had been for C2 configuration,
- the agreement between IPG and spirometry had been increasing with higher V_T,
- the signal agreement had been higher in the lateral configurations (C1,C2,C5) than in the anteroposterior ones (C3,C4,C6),
- we had been able to explain the lower agreement in supine postures and with low breathing by the higher ratio of the magnitude of cardiogenic oscillations in IPG signal,
- after the smoothing techniques the configuration C5 had been considered the best for measuring flow signals.

Although their studies [4, 10] were crucial in development of IPG we have to mention that the study [10] was conducted only in static conditions, and in paper [4] there were manual changes in calibration factors related to subject and posture. It seems that for the long-term measurement it is needed to validate those results under more dynamic and diverse conditions with adaptive algorithm of automatic changes of calibration coefficients. The most obvious solution would be an arrangement of accelerometers for detection the postures and their changes.

The fact, that lateral configurations give us better results is also very important for an idea of long-term measurement, because in these arrangements it is easier to keep good skin contact.

2.6. Signal simulation

It is very important to seek a configuration, which could provide the best reflection of the respiratory system activity with as little as possible artifacts fractions and cardiogenic (or other disturbing oscillations). It could be done also by simulation. *Väisänen et al.* [7] applied a finite difference model (FDM) based on the 3D male thorax dataset of the Visible Human Man (VHM). In dataset there were 2.6 million elements joint with 2.7 million nodes and implemented model contained over 20 different organs and tissues with resistivities corresponding to them. They pointed out the FDM allowed the execution of complex anatomical geometry and calculation of the resulting potentials and currents within the whole volume conductor model [7]. Impedance and its changes caused by changes in the volume conductor could be described by sensitivity distribution of bioimpedance. In the paper of *Väisänen et al.* [7] was studied the effect of ventilation to the measured impedance Z by applying lead field approach. The FDM allowed to calculate at all locations (configurations) with a single calculation. They found that the best configuration is located above diaphragm [7], which was verified in the subjects. However, their research was perform only for a static conditions.

2.7. Suppression of cardiogenic oscillations

Although the main source of the distortion in biological signals are stochastic in IPG there are also the oscillations with regular, deterministic origin. In IPG the cardiogenic oscillations are additional source of disturbance. Therefore, there are some filtering operations for suppressing the cardiac component. However *Seppä et al.* [4] found there is a strong relation between posture and the magnitude of cardiogenic oscillations. In erect postures there is threefold increase in reference to supine ones. It might be explained by an alteration of gravitational pressure exerted on the internal organs and fluids, particularly on heart.

In [10] they utilized in signal track a Butterworth type low-pass. Apart from the main function, this filter fulfil the role of minimization the start-up and ending transients in the signals.

Another solution was implemented in [4]. After standard operations on raw impedance signal (linear low pass and linear high pass filters) there is a non-linear part. It is necessary because frequency spectrum of ECG and IPG overlap. They applied a Savitzky-Golay (S-G) smoothing filter with frame size equals 1000 ms and second-order fitting [12]. The optimal frame size was found by experimental way. The effect was satisfying, because with preservation the high-frequency IPG content, they obtained effective attenuation of cardiogenic oscillations. In order to obtain flow signals, they implemented two S-G filters:

- differentiation filter (250 ms frame rate, second-order fitting)
- smoothing filter (2000 ms frame rate, second-order fitting).

The last third approach was presented in [13]. *Seppä et al.* assessed Schuessler adaptive filter [14] for attenuating cardiogenic oscillations on an esophageal pressure signal and tried to modify it to produce a long-volume-dependent parameters. Later that technique was compared with raw signal, and the signal after linear filters or S-G filter mentioned earlier.

A modified version of Schuessler-Bates method is divided into two phases. In the first one there is a finding of cardiogenic oscillations waveforms, in the second – removal the unnecessary component from the original signal. In the first part all operations is performed to obtain an estimation of cardiac impedance constituent. The output signal is high-pass filtered with a cut-off frequency of $0.6 \cdot HR$. Then there is a segmentation to get cardiogenic oscillations ensembles using the ECG signal (R-wave) as a trigger. After that the algorithm distribute the ensembles into four bins. In the second part after finding the ensemble averages of each bin, waveform of the cardiogenic oscillations is interpolated from the representatives and added in inversion to the original signal at the time of each R-wave signal in ECG in order to get the estimation of respiratory impedance. The modification from the initial version relies on the lack of implementation the recursive adaptive features, so that it is possible to divide the processing into two phases [13]. Results showed that this approach had the closest representation to the reference (integrated PNT flow signal by the trapezoid method), the best distortive effect, the most consistent behaviour in the frequency spectrum of analysis, particularly for HR. The signal after filtering had preserved harmonic components of the respiration waveform without an adjustment any low-pass filter [13].

2.8. Validation problems

Thanks to Impedance Pneumography it is possible to measure ventilation qualitatively and quantitatively. The signal could be detected in the similar way as in Impedance Cardiography, but with some differences. Firstly, the use band-pass filtration in order to proceed the signal in lower then ICG frequencies. Secondly, the tetrapolar configuration should be used with band electrodes fixed on the thorax [4]. Those electrodes provide the best respiratory signal when their configuration is lateral, not anteroposterior one like in Impedance Pneumography. Generally, the S/N ratio may vary for different configuration of electrodes.

There are a lot of potential sources of distortions. The electrical contact could be weak because of changes in the surface pressure of the electrodes, slight motions, strong hair [4], drying of the substance between skin and electrodes which requires using an adhesive gel or when the subject perspires (this changes the skin resistance which might influence to the transthoracic impedance). These artefacts are one of the strongest problem in IPG. If the errors are deterministic, it is difficult to overcome, but if they are stochastic we could attenuate using for example ensemble of averaging techniques over the signal [4]. These distortions usually have different origin, therefore they differ with amplitude, phase, period of existence and positive or negative influence on the main signal.

We have to consider the matters of skin irritation, discomfort, and drift of the characteristics of electrodes [5]. Now it is not as major problem, since *Poon et al.* [5] published their work, but this question should be considered particularly in long-term measurement.

In IPG there is a necessity to calibrate the signal with the reference, which in nowadays is Spirometry or Pneumotachometry. Several studies [1,3-5] have shown that the relation between IPG and Spirometry had been almost linear, but we had had different subject-specific and posture-specific calibration coefficients. Therefore in the long-term investigations it is essential to develop the automatic system of recognition of postures and their changes to set the optimal calibration factor.

Pneumographic signal is intrinsic to the impedance signal, therefore ventilation can be measured without the need for using additional sensors, recording channels or storage capacity [3]. *Bland and Altman* in their statistical study [15] criticized the use of correlation coefficients in order to compare two method of medical measurement which have the same output dimensions. They argued that correlation is not the same as agreement. They offered the mean and standard deviation to estimate how far are the measurement by two different methods. Comparison between IPG and reference we may assess by the agreement coefficient (ρ) using standard error of measurement (SEM) [4]:

$$\rho = 1 - SEM \qquad (2)$$

It was noticed in research, that the waveform agreement between flows obtained by IPG and PNT is better for the higher breaths (higher V_T) [4].

Ernst et al. [3] suggested that in their Minnesota impedance device there had been an inductive coupling between the ΔZ signal and the output of the device. Therefore it could come out low-frequency filtering and distortion. They implied that we could derive the measure of ΔZ by integrating the dZ/dt signal, because mentioned coupling was implemented after the utilization dZ/dt signal by derivation ΔZ signal and in this connection we might bypass the worse way of getting the best form of the interesting signal. After transfer function analysis they reported that the ΔZ signal derived by integration provided the best estimate of the reference signal for all examined parameters (coherence, phase and gain).

3. APPLICATIONS

3.1. Measurements during sports activities

Spirometry seems to be useless and impractical during sport physical activity. One of the major problem is the large equipment which could burden the respiratory system. *Seppä et al.* [9] and *Lahtinen et al.* [11] tried to implement IPG during physical exercise. They wanted to yield the best signal (with the maximum signal-to-artefact ratio) according to configuration by IPG in order to eliminate the disturbing influence of the movements of the body during exercise on a treadmill.

The application of IPG during the physical exercise requires the solution of three main problems. The first is what electrode setup would be the best and how to attach them to skin. Secondly, which places of attachment may give us the best signal, and finally, in what situations there are more artefacts and how to correct the signal even when we do not have the possibility to extract the thoracic impedance signal from the complex one corrupted by stochastic artefacts. In the foregoing studies authors [9, 11] used standard disposable Ag/AgCl electrodes with adhesive gel. The authors [9] found that C5 (Fig. 3) is the best configuration. *Lahtinen et al.* [11] gained average signal to artefact ratio (SAR) while sitting on the level 2.49, and 2.11 while running. We must notice that in the configuration like C1 at Fig. 3. they obtained better average SAR in running measurement, however the median one was worse than the same for the first mentioned configuration. Unfortunately, the tests proved differences related to individuals. The measurements were also not taken in the same way. Tested subject did not breathe similarly or with the same depth during the whole test, so that the comparison with reference was not so reliable [11].

3.2. Implementation of respiratory biofeedback based on pneumography

It was found that Impedance Pneumography could be applied in respiratory biofeedback (BFB) practice. One of the areas of interest is treatment of asthma, which is characterized by sudden attacks of impaired breathing, and the anticipation of these attacks may generate an anxiety in patients, which could also cause the advantageous situation for the attack [16].

Grishin et al. [16] reported that there had been a development of an asthma attack in children as a response to a situations that are similar to a previous attack. This could stimulate the occurrence of Hyperventilation Syndrome (HVS) and other functional respiratory disorders (FRD) in a lot of people with asthma. When patient would learn to control his/her breathing pattern with his emotional state, he/she could reduce the number of attacks and improve the quality of life.

The respiratory BFB include capnography, mechanography of breathing and the signal of respiratory sinus arrhythmia (RSA), but there are some disadvantages of using these techniques. *Grishin et al.* [16] tried to create a hardware devise and software resource for the implementation of BFB based on IPG, because of the high correlation between pneumogram and the pattern of breathing. The following parameters were measured: breathing frequency, inhalation and exhalation time and the duration of a pause [16]. Patients could try to react on the changes of these parameters in the realistic time and to get into the habit of stopping the attack. The results obtained in [16] were not extensively described. But with their report, showing that a patient has the opportunity to reproduce various breathing patterns, suggest the possible development of this method in the future.

3.3. Portable versatile devices for long-term measurement

Vuorela et al. [17] presented two types of prototype devices devoted for measuring ECG and bioimpedance signals. The first is conceived as wireless type with real-time sending to a computer PC by an ANT^{TM} radio link. The second one could save data on the memory card and then after a measurement session transfer them to a PC through Universal Serial Bus (USB). They reported some benefits and disadvantages of these solutions. The first one has good signal-to-noise ratio SNR and no 50Hz interference because of battery powering.

In their radio transmission solution the data transfer of only 20kbit/s was used to minimise the power consumption, which resulted in 125Hz sampling rate for both channels [17]. In the second solution radio link was replaced by storing data to the memory card and transferring data after session.

In the paper [17] they referred an idea of encapsulation the third type of device with layers of epoxy and silicone to achieve fully waterproof device, which could be very suitable in sport measuring.

This idea was extended by *Vuorela et al.* [8]. They designed the device for measuring ECG, bioimpedance and user's activity with 3-axis sensor of acceleration. Although the system generally measured bioimpedance, but with specific electrodes position the main application would be monitoring subject's respiration. One the important problems was the high power consumption. They reduced the power consumption to 3mW. Another areas of interest were accuracy, biocompatibility, communication channel and security. They also managed twofold principle of the device, with measuring and analysing in real-time or only recording data in order to send them later to the further analysis. The system was tested with two kind of electrodes: commercial Ag/AgCl gel-paste electrodes and custom-made textile electrodes [10]. Results revealed that there had been movements artefacts, which could be attenuated by averaging techniques, but better in vertical than horizontal position. The depth of the breathing was also detected in good quality from the original signal [8]. However, the signal were distorted by cardiac activity. Secondly, the calibration signal from pneumotachograph was valid only for the fixed position of the subject [8]. Therefore, in long-term measuring it is needed to utilize accelerometers to detect the changes of a position and conditions and set suitable calibration coefficients in a right time. It supposedly requires advanced algorithm with e.g. neural network to teach the system, what changes in the signal from accelerometer are related to what changes in calibration factor.

4. FINAL CONCLUSIONS AND FUTURE DIRECTIONS

4.1. Prospects for Impedance Pneumography

It seems that Impedance Pneumography would be good alternative or improvement for spirometry. Below are presented some possible fields of IPG application: connection IPG with pulse oximetry in order to check the relation between blood saturation and the pattern of breathing or its deterioration

- connection IPG with a medical ventilator; IPG signal as an indicator of respiratory rate could monitor respiration and eventually control a medical ventilator in Intensive Care Unit; however the influence of possible artefact should be considered,

- automatic detection of subject behaviour with accelerometers and settlement of non-linear calibration coefficients (perhaps vector or matrix ones), which could give us the opportunity to establish the 24-h measurement sessions without any technical control
- achievement reographic and pneumographic signal from the lateral tetrapolar configuration, which reduce artefact rate; if we subtract from original signal the waveform after operations which suppress cardiogenic oscillations (IPG signal), it is possible to obtain ECG signal, that get two measurements in the same time from only four electrodes arrange in the best configuration for Pneumography
- exploitation of belt wrapped up the thorax with larger number of electrode in use and fast sequential switching of active electrodes in order to obtain the signal from several configuration and assess the occurrence or non-occurrence of the artefacts.

4.2. Clinical importance of Impedance Pneumography

The very important aspect is that in all presented studies research was implemented for the group of women and men in the young and middle age, not on the people for whom Impedance Pneumography could be dedicated. We think credibility and usefulness of the method have to be checked in a larger spectrum of people and in a larger range of medical diseases.

Impedance pneumography seems to be prospective technique particularly during detection and diagnosing respirator system illnesses or in the purpose of prophylaxis for sportsperson and the others. IPG could be utilized in such diseases as: obstructive sleep apnea syndrome (OSAS), asthma, pleural effusion or inhalation/exhalation disorders, but we could imagine that, as ECG, role of Impedance Pneumography is mainly prevention, so that if there is a connection of the conclusions of the papers reviewed here, Holter-like respiratory 24h measuring will see the light of day.

SUMMARY

The main purpose of this study was to describe the technique of impedance pneumography, the noninvasive method of quantitative, long lasting examination of respiratory system. In this paper there were presented physical foundations of the method, the measurement equipment and the different approaches to the measurement procedures. Also, various types and configurations of the electrodes were shown.

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