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Assessment of calibration methods on impedance pneumography accuracy

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Abstract: The aim was to assess accuracy of tidal volumes (TV) calculated by impedance pneumography (IP), reproducibility of calibration coefficients (CC) between IP and pneumotachometry (PNT), and their relationship with body posture, breathing rate and depth. Fourteen students performed three sessions of 18 series: normal and deep breathing at 6, 10, 15 breaths/min rates, while supine, sitting and standing; 18 CC were calculated for every session. Session 2 was performed 2 months after session 1, session 3 1–3 days after session 2. TV were calculated using full or limited set of CC from current session, in case of sessions 2 and 3 also using CC from session 1 and 2, respectively. When using full set of CC from current session, IP underestimated TV by -3.2%. Using CC from session 2 for session 3 measurements caused decrease of relative difference: -3.9%, from session 1 for session 2: -5.3%; for limited set of CC: -5.0%. The body posture had significant effect on CC. The highest accuracy was obtained when all factors influencing CC were considered. The application of CC related only to body posture may result in shortening of calibration and moderate accuracy loss. Using CC from previous session compromises accuracy moderately.

Keywords: calibration; impedance pneumography; lung volume measurements; pulmonary ventilation; spirometry.

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Introduction

Pneumotachometry (PNT) is a gold standard in measurements of airflow and tidal volume. It is mainly performed in stationary, laboratory conditions and requires a facemask and/or a mouth assembly and a nose clip [4, 17], what makes it impractical or even impossible to be conducted outside a clinical environment.

It was found that the impedance pneumography (IP) method, which measures transthoracic electrical impedance changes, could replace PNT [2, 4, 5, 8–10, 22]. IP may be considered as a method for measuring ventilation in absolute units, which enables identifying hypo-, normo- or hyperventilation. Long-term and fairly unobtrusive measurement with IP may be a valuable option in chronic conditions. Chronic hypoventilation occurs in obese subjects [14], persons with neuromuscular diseases [24], as a side effect of pharmacotherapy [3] and in elderly [6]. Of special significance would be nighttime monitoring, as the respiratory dysfunctions exacerbate during sleep.

However, several factors affect the correspondence between PNT and IP. The most important ones are electrode configuration, subject's height and weight, and body posture [2, 4, 5, 8, 18, 22, 26]. Houtveen et al. suggested that subject- and posture-specific calibration should be performed before calculating any respiratory parameters from impedance signals [4]. It was also observed that a linear relationship could be obtained by placing the electrodes on the axillary lines [5, 8, 18, 19, 21, 22].

The primary aim of this study was to assess the accuracy of tidal volumes (TV) determined by IP using a prototype constructed in earlier research [11] and to check the reproducibility of the calibration.

In the authors' preliminary research, the percentage impacts of subject (inter-individually), body posture, breathing rate and depth on overall variance of calibration coefficients (CC) were estimated [12, 13]. The results showed that subject- and posture-specific impacts are predominant. On this basis, we presumed that the breathing rate and depth could be skipped during the calibration [12, 13]. Therefore, the secondary aim was to assess the loss of accuracy caused by simplification of the calibration.

This simplification would rely on limiting the number of CC used, which would effectively shorten the calibration.

Methods

Subjects and measurements

The study participants were 14 healthy students: 10 males, aged 20–25 (M: 22.6; SD: 1.7) and four females, aged 21–26 (M: 23.0; SD: 2.4); body mass indexes were 19.3–34.2, without any reported respiratory diseases. We have complied with the World Medical Association Declaration of Helsinki regarding ethical conduct of research involving human subjects. All subjects were informed about the aim of the study. Informed consent was obtained from all individual participants and the Ethical Committee of Warsaw Medical University approved the study.

We measured transthoracic impedance using our own impedance pneumograph prototype – the Pneumonitor (with single-frequency 100 kHz sinusoidal excitation current with 250 μA amplitude) [11]. As a reference, we used the Flow Measurement System with a Spirometer Unit M909 and a Fleisch-type Heatable Flow Transducer 5530, with a Conical Mouthpiece M9114 connected to the PNT sensor, without any flow resistance, all made by Medikro Oy (Kuopio, Finland). IP measurements were performed using the tetrapolar method with the electrode placement configuration as proposed by Seppa et al. [19, 21]. The receiving electrodes were positioned on the midaxillary line at about 5th-rib level. The application electrodes were placed on the proximal side of the arm on the level of receiving ones. Standard spot ECG electrodes (EK-S 61 PSG, 55×53 mm, made by Sorimex, Torun, Poland) were used.

IP and PNT outputs were fed to a WinAcq-F 2000-01 ADC converter (manufactured by Absolute Aliens Oy, Turku, Finland), which sampled the signals at 200 Hz and wrote to data files. Next, the oversampled signals were smoothed using a 2nd order Savitzky-Golay filter with window length 25 [16].

Protocol and analysis

For every subject, three measurement sessions were performed: sessions 1, 2 and 3. Session 2 was performed 2 months after session 1, session 3 1–3 days after session 2. In all three sessions, each subject was asked to perform a series of 8 breaths, which varied in breathing depth (normal and deep), breathing rate (6, 10 and 15 breaths/min, with LED indicator coordination) and which were carried out in three body postures (supine, sitting and standing). Between every series there were short breaks lasting at least 10 s. Thus, 18 series of measurements were obtained for every subject. The changes of impedance measured by the IP relate to the volume changes and the PNT signal provides flow changes. Therefore in order to compare volume-related signals the PNT one was integrated using the Simpson quadrature, and confronted with IP. The baseline of the IP and integrated PNT was removed from signals using detrending methods. For all corresponding pre-processed values of PNT and IP signals, the linear regression was calculated.

For each of the 18 series, one calibration coefficient (CC, slope value of the linear regression model without the constant term, a_v) was determined. Next, TV were estimated for each breath using integrated PNT and IP after calibration with help of the corresponding CC. The TV values obtained during one series were averaged. In order to assess the correspondence between IP and PNT, we calculated relative differences

$$RD=\frac{TV_{IP}-TV_{PNT}}{TV_{PNT}} \quad (1)$$

for each series and for each subject. For each session there were 90 RD, hereafter called the initial set. The calculation scheme for one subject is presented in Figure 1.

In order to elucidate the influence of body posture, breathing rate, breathing depth, session number, sex and body mass index (BMI) on CC, repeated ANOVA were performed.

As we found (considering the previous results of the analysis) that the breathing rate and breathing depth did not have statistically significant impact on the CC, we wanted to find out whether using a reduced number of CC would substantially decrease the accuracy of IP measurements. We neglected the influence of breathing rate and depth and for each body posture we used only a single CC (always that for normal breathing at 10 breaths/min). This choice of CC was arbitrary. Using this reduced set of CC, TV were calculated again for the 18 series of sessions 1, 2 and 3. For every session we obtained new set of 90 RD, hereafter called the first simplification set.

We compared the initial set and first simplification set of RD in order to assess the effect of simplified calibration. The hypothesis that usage of reduced set of CC would increase the RD between TV derived from IP and PNT was checked with a one-sided paired t-test.

Taking this one step further, we tested the effect of further simplification of calibration, using only one CC, for normal breathing at 10 breaths/min in a sitting position, in the same manner as described above. Again, for every session, we obtained new set of 90 RD, hereafter called the second simplification set. The scheme of calibration simplifications is presented in Figure 2.

We also wanted to know whether it is possible to use the CC estimated in session 1 to calibrate the measurements from session 2. We thought that this would likely worsen the correspondence between PNT and IP. To test this hypothesis, we compared the RD for session 2, calculated with help of the CC set from this session (current CC set) and that from session 1 (previous CC set). The absolute values of RD of TV calculated with current and previous CC sets we compared using a one-sided paired t-test. We performed that analysis for the initial set of 18 CC, for the first simplification set of 3 CC and for the second simplification set of 1. The scheme is presented in Figure 3.

Finally, in the same manner as described above, we assessed the effect of using the CC obtained in session 2 for calculation of the respiratory parameters measured in session 3.

Signal processing and calculations were performed using the MATLAB software. All statistical analyses were carried out with the R software with corresponding packages [15].

Results

The tidal volume during normal breathing was 1172±414 ml (mean±SD), and during deep breathing it was 2456±857 ml.

Posture	Supine						Sitting						Standing					
Depth	Normal			Deep			Normal			Deep			Normal			Deep		
Rate	6	10	15	6	10	15	6	10	15	6	10	15	6	10	15	6	10	15
Series No.	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.	13.	14.	15.	16.	17.	18.

There were 2 signals and 1 calibration coefficient, for each series

Signals	IP	Integrated **PNT**
Calibration coefficient	Slope a_V	

TV relative differences were calculated with these calibration coefficients, for each series

Signals	IP (with a_V)	Integrated PNT
Parameters for each breath	8 x **TV**	8 x **TV**
Averaging	Mean **TV**	Mean **TV**
Final calculation	**TV** relative difference	

Figure 1: The calculation scheme presenting the way of determining calibration coefficient and tidal volume (TV) for a specific session, subject and series; abbreviations are explained in the text.

Posture	Supine						Sitting						Standing					
Depth	Normal			Deep			Normal			Deep			Normal			Deep		
Rate	6	10	15	6	10	15	6	10	15	6	10	15	6	10	15	6	10	15
Initial	a_1	a_2	a_3	a_4	a_5	a_6	a_7	a_8	a_9	a_{10}	a_{11}	a_{12}	a_{13}	a_{14}	a_{15}	a_{16}	a_{17}	a_{18}
First simplification	a_2						a_8						a_{14}					
Second simplification	a_8																	

Figure 2: The scheme for simplifications of calibration, presenting which coefficients were used. In the first simplification, for every six CC related to given posture, only one was taken, that for normal breathing at 10 breaths/min. In the second simplification of the calibration, only one calibration coefficient was used, that for sitting posture, normal breathing at 10 breaths/min.

The correspondence between PNT and IP was determined using the initial set of CC, thus taking into account all considered factors (body posture, breathing rate and breathing depth). It was observed that certain results (<2%, 113 from 6015; due to the artefacts some breaths were removed – the protocol assumed 6048 breaths) were strongly inaccurate (more than 30% of error) and that they were not bound to particular person, but rather occurred randomly. Therefore, the statistics of the relative differences between TV derived from PNT and IP are calculating after removing the outliers and presented as the mean±SD in Table 1.

The ANOVA analyses showed that the subject's sex, the session's order and body posture had statistically significant impact (with α=0.05 significance level) on CC. The Tukey HSD and "Holm" pairwise T tests demonstrated that CC for different postures differ significantly.

We applied first and second simplifications and calculated RD of TV measured by PNT and IP. We used the current CC in all three sessions. The RD obtained in this way are collected in Table 2. (in the "Current" reproducibility section). Using first-simplification CC enhanced the underestimation of TV values measured with the IP method; using the second simplification increased the underestimation even more. RD were statistically significant.

We performed the same analysis for the session 2 measurements, using the CC from session 1. In this way,

Posture	Supine						Sitting						Standing					
Depth	Normal			Deep			Normal			Deep			Normal			Deep		
Rate	6	10	15	6	10	15	6	10	15	6	10	15	6	10	15	6	10	15
Current initial set	a_1^2	a_2^2	a_3^2	a_4^2	a_5^2	a_6^2	a_7^2	a_8^2	a_9^2	a_{10}^2	a_{11}^2	a_{12}^2	a_{13}^2	a_{14}^2	a_{15}^2	a_{16}^2	a_{17}^2	a_{18}^2
Previous initial set	a_1^1	a_2^1	a_3^1	a_4^1	a_5^1	a_6^1	a_7^1	a_8^1	a_9^1	a_{10}^1	a_{11}^1	a_{12}^1	a_{13}^1	a_{14}^1	a_{15}^1	a_{16}^1	a_{17}^1	a_{18}^1
Current first simplification set	a_2^2						a_8^2						a_{14}^2					
Previous first simplification set	a_2^1						a_8^1						a_{14}^1					
Current second simplification set	a_8^2																	
Previous second simplification set	a_8^1																	

Figure 3: As a first step of the long-term reproducibility assessment, the respiratory parameters were calculated using current (initial, first simplification, second simplification) and previous (initial, first simplification, second simplification) CC sets. The number of the session from which the CC were taken is denoted in the superscripts.

Table 1: The relative differences (RD) between PNT and IP (mean±SD).

	RD of TV
Session 1 (%)	-3.2±1.2
Session 2 (%)	-3.3±1.2
Session 3 (%)	-3.2±0.9

Table 2: The relative differences (RD) of TV measured with PNT and IP; IP measurements were calculated using the current (initial, first simplification, second simplification) and previous (initial, first simplification, second simplification) CC – CC from session 1 for session 2 (long-term reproducibility) and CC from session 2 for session 3 (short-term reproducibility).

Reproducibility	Initial	First Simplification	Second Simplification
Current (%)	-3.2±1.1	-5.0±7.4	-7.0±9.7
Long-term (%)	-5.3±11.0	-7.0±10.4	-10.9±10.8
Short-term (%)	-3.9±10.1	-4.1±13.9	-8.3±12.2

we checked “long-term” reproducibility. Similarly, the session 3 measurements were taken and the CC from session 2 were used in order to determine the “short-term” reproducibility. All results are collected in Table 2. in the appropriate sections.

In order to illustrate the accuracy of IP, the impact of the simplifications and the effect of taking the CC from previous measurement sessions, the boxplots of RD of TV are presented in Figure 4.

Discussion

Impedance pneumography is not intended to replace PNT in a laboratory setting; rather, the most important advantage of this method is that it might be applied in those circumstances in which the use of PNT would be either impossible or uncomfortable for the patient. We confirmed the good accuracy of IP in comparison to PNT. On average, the values of TV were slightly underestimated, which might be acceptable from the physicians’ point of view, more so given that IP may additionally provide estimation of intrathoracic fluid accumulation level or cardiac activity [1, 18].

To our knowledge, this is the first study to demonstrate that the most significant factors affecting the values of CC were subject and posture. Furthermore, the TV values did not change considerably when only body posture’s effect was taken into account, disregarding rate and depth of breathing. In that way, the calibration could be simplified. We also found, that using only one CC (a sitting-related one, because this posture was regarded as an intermediate state in terms of CC values [12]) worsens the accuracy further, but the degree of worsening may be acceptable when considering measurements in ambulatory conditions, because it obviates the need to detect body posture. On the other hand, this study proves that, for good accuracy, the detailed calibration should be performed, and appropriate CC should be applied backward once the breaths are classified according to duration and amplitude of breathing, as well as according to body posture.

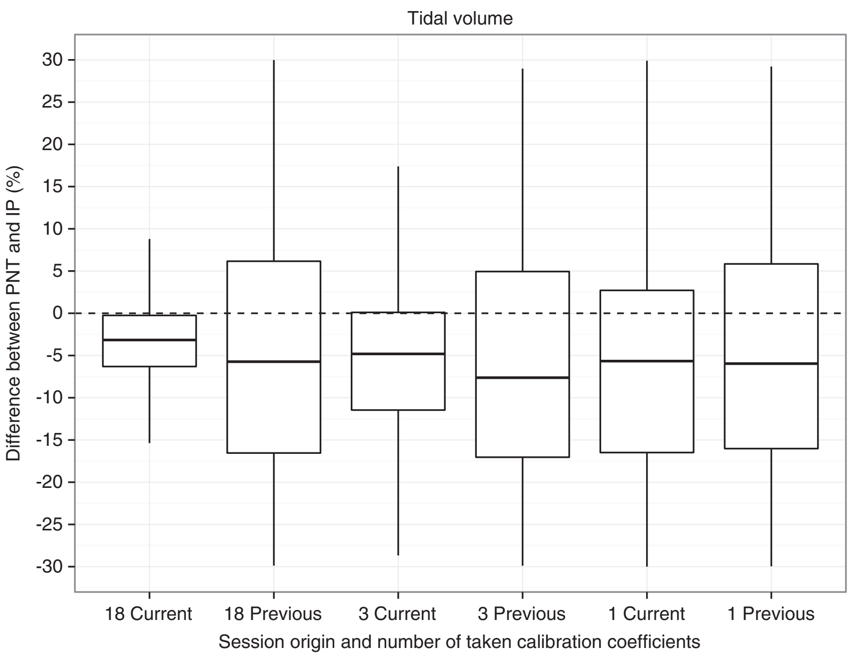

Figure 4: The relative differences (RD) between tidal volume measured with PNT and IP, according to the CC' origin (current, previous) and the CC set used (18 – initial, 3 – first simplification, 1 – second simplification).

Also this work is the first to determine the reproducibility of the IP calibration, the key question being whether a single calibration has to provide CC, which can be used for long-term monitoring. We found that use of CC for measurements performed 1–3 days later slightly increased the RD of TV between PNT and IP. Further loss of accuracy resulted from using the CC calculated 2 months before current measurements. The combination of applying a limited set of CC and using a set calculated previously for current measurements decreased accuracy only slightly. In our opinion, this proves that CC calculated at the beginning of long-term measurement would provide correct TV during the entire study. This observation may have implication for the use of IP for ambulatory monitoring of respiratory activity, as it predicts that measurements carried out over 24–48 h may be reliably evaluated using a single set of CC.

Although we noticed that CC depend primarily the on subject's actual body posture, this does not exclude the possibility that aspects such as lying on the side, back or abdomen may also differentiate CC.

It is also important to mention, that not all respiratory parameters require calibration of IP, like Tptef:Te. While the linear model connecting the IP and PNT works well for the specific electrode configuration, proportional parameters do not depend on the calibration [20].

We encountered some issues and problems during analysis. We found that the absolute values of RD of IP are >30% for <2% of the results. It has to be said, that this occurred only when we used simplified or previously determined sets of CC. Perhaps this was caused by the different mechanics of breathing in different series. However, this implies that the mechanics of breathing might be another possible determinant, which would require a more sophisticated approach to the measurement process.

We are unable to explain why the measurement session's sequence number was a statistically significant factor identified by ANOVA.

Detaching the electrodes after session 2 and mounting them again before session 3 might decrease the short-term reproducibility. Therefore, it should be checked whether lack of electrodes displacement, as is in case during holter-type monitoring, would improve the accuracy of IP when using CC calculated at the beginning of measurement.

Although the accuracy of measurements, evaluated with previously gained CC, was satisfactory on average (RD ca. 3% for TV), individual differences happened to be much greater, as evidenced by large variance of the tidal volume values. This might be an essential issue requiring deeper scrutiny.

Seppa et al. [19] proved that, in a standing position, the configuration used in this study provided the highest linearity between PNT and IP among several configuration tested by these authors. We found that this configuration retains that linearity also in the sitting and supine positions, although the CC were modified by the change of posture.

The basic applications of IP are ambulatory measurements. However, we found no attempts to assess the agreement between PNT and IP signals outside the laboratory. They were performed only in static conditions or during controlled, sport-imitating tasks [2, 4, 7, 18]. In our opinion, the configuration proposed by Seppa et al. [19] seems to be appropriate mainly for static conditions. We noticed that this configuration produced more movement artefacts than the one, where the application electrodes, instead of being mounted on the arms, were placed on the ribcage. Seppa et al. [19] found that the latter configuration departs from linearity. However, this divergence might be of lesser importance than motion artefacts in ambulatory conditions. A similar line of reasoning was presented by Wang et al. [25].

We think that the main direction of research should be to test the IP method in a configuration suitable for ambulatory conditions, in subjects which represent the most likely target of this measurement, like children, elderly people, and in situations encountered during such measurements, like sleep, daily activities, and exertion.

Combining ventilator signal derived from PNT with that from pulse oximetry may help to recognize the likely site of respiratory system disturbances. As the case in point may serve obese subjects who in spite of being usually eucapnic, which proves normo-ventilation, develop hypoxia due to impaired oxygen transport caused likely by ventilation perfusion mismatch [23]. Also diminished respiratory response to hypoxia may be observed in aged persons in cases of heart failure, infection or aggravated airway obstruction, caused by decreased sensitivity of respiratory centres to hypoxia or hypercapnia [6].

Conclusions

The following conclusions may be raised:

1. The IP method allows measurement of respiratory activity with good accuracy (calculated as RD between tidal volume values calculated by IP and PNT).
2. IP could be linearly related to PNT in supine, sitting and standing positions. The CC were mainly affected by body posture and to a lesser degree by depth and rate of breathing.
3. When taking into account the effects of the mechanics of breathing and body posture, the RD was 3.2% for TV. Simplifying the calibration by omitting the impact of breathing, mechanics increased RD slightly (to 5% for TV). Further modification by using a single CC, disregarding body posture, increased RD to 7% for TV.
4. As the main application of IP should be ambulatory monitoring typically lasting 24–48 h, using a single calibration at the beginning of the measuring process would be practical. Therefore, CC estimated before commencing this monitoring (1–3 days before, either full or limited set) will cause a clinically acceptable error of about 4–8%.
5. It is necessary to change the electrode configuration to one appropriate for ambulatory conditions, and that, which would additionally minimize motion artefacts, even at the cost of divergence from strict linearity between PNT and IP signals.
6. We assume that the method of assessment of the effect of calibration modifications on IP accuracy presented in this paper would be applicable to IP measurements with electrode configurations better suited to holter-type measurements, as this scheme allowed evaluation of the impact of various factors and calibration modifications on IP accuracy.

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