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Lung ventilation monitoring by electrical bioimpedance technique using three different 4-electrode thoracic configurations: Variability of calibration equations

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ABSTRACT

Our research group proposes the use of electrical bioimpedance (BE) technique to monitor the ventilatory pattern. The objective of this study was to obtain a set of calibration equations in a group of males (M:23) and females (F:22) and analyze the variability of their mathematical adjustments (R^2). All equations are aimed to adjust the impedance changes (IC) due to ventilation and transform them into a measurable volume signal. The IC were obtained by three 4-electrode configurations, where, the current injection electrodes were placed in different points around the sixth intercostal space and the voltage detection electrodes were placed in different points around the second intercostal space. All impedance determinations were validated by a pneumotachometer (gold-standard). The calibration equations were obtained from a multivariate analysis of the proportionality coefficients of volume and impedance signals; and the anthropometric parameters of each group of volunteers. The obtained results evidenced that just two sets of equations determined by one configuration had a high mathematical adjustment of 66% and 70% in the group of males and females, respectively. From the validation of these equations, errors of 22%±3% and 15%±3% in the group of males and females, respectively, were evidenced. The variability of errors was significant, however, the analysis of differences between them was not. We conclude that the variability of calibration equations depends on the variability of anthropometric parameters and the amplitudes of impedance changes which are determined by the anatomic spots where the electrodes were placed.

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1. Introduction

In the pneumology area and in the intensive care units (ICU), the lung ventilation pattern (LVP) is a key parameter to monitor lung respiration and evidence the neuromuscular disorders suffered by patients [1,2]. The devices used to measure LVP are invasive or present problems with calibration and most of them are expensive and can be only used in hospitals by qualified personal. The gold standard to monitor the respiratory pattern is the pneumotachometer. However, it overestimates the volume determinations in a range from 15% to 35% [3–6] due to the essential use of a mouth piece and a clip nose. The pneumotachometer is usually used to monitor a ventilatory pattern during effort respiratory trials [7]. Another device used to monitor LVP is the respiratory inductance plethysmograph (RIP). RIP obtains a volume signal by detecting thorax and abdomen movements by two inductive bands. The main RIP drawback is the continuous calibration of the system due to displacement of the bands, which causes measurement errors [8–10]. This device is used to follow qualitatively the respiration in patients with different lung pathologies. A new noninvasive technique proposed by different research groups that can be used for continuous monitoring is the electrical bioimpedance (EB) technique. The EB consists in the application of a small electrical current (AC) and the detection of biopotentials (or vice versa). The benefits of EB has been assessed in different clinical areas with promising results [11–16]. In pneumology area, many efforts have been performed to compare the thoracic bioimpedance determinations and different parameters from the established respiratory trials. For example, Charach et al. assessed the suitability of EB technique to detect pleural effusion through the ventilatory pattern monitoring it in a group of patients [17]. The results obtained in this study proved that thoracic impedance changes produced during respiration could be modified by the presence of internal injury of lung tissue. Other

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study compared changes of thoracic impedance in patients with different thoracic injuries caused by rib trauma. The inflammation of thorax muscles impairs respiratory pattern which cause decries in thorax impedance, this fact changes the respiration pattern and it can be detected by EB [18].

Voscopoulos et al. in 2015 proposed the use of EB to monitor the ventilatory pattern during general anesthesia (GA). In this study, the correlation between the volume-minute (VM), tidal volume (TV) and respiratory rate (RR) obtained by impedance technique during respiration and the same parameters obtained by a mechanical ventilator were evaluated. The results evidenced a high correlation (0.9, $p < 0.05$) between measurements obtained by both techniques (impedance and mechanical ventilator) [19]. So, it is possible to use EB to drive post-operative and post-extubation protocols at real-time.

Results obtained in previously mentioned studies were acceptable and statistically significant. However, none of them proposed a calibration method or adjustment equation to transform thoracic impedance determinations into a physiological parameter of interest (for example lung volume) to establish an impedance technique as an independent clinical diagnosis method.

EB was also used to develop electrical impedance tomography (EIT). EIT is an imaging method whose frames represent the impedance distribution in a cross-sectional area of human body [20,21]. The EIT images are created by a reconstruction algorithm [22,23] from a set of tetrapolar impedance measurements (2 injection electrodes, 2 detection electrodes) [24,25] taken from the main arrangement of 16-electrodes placed around sixth thoracic intercostal space. Since air has a large resistivity, it cannot be measured directly by EIT, so lung volume changes caused by thoracic movement and fluctuations in inner conductivity of lung tissues are determined instead. Recently, different research works have assessed the feasibility of EIT to measure and monitor lung volume. Trepte et al assessed different levels of acute lung injury by EIT in pigs. From the obtained results, the authors evidenced a correlation between volume determinations obtained by EIT and pulse contour analysis (PC, gold standard) of 0.77, 0.88 and 0.48 for normal lung condition, acute lung injury induced by bronchoalveolar lavage and lung injury caused by oleic acid, respectively [26]. Other study was performed by Gloning et al in dogs submitted to anesthesia. A computed tomography scan (CT) was used to measure the mean value of lung radiodensity for the entire lung and for four regions of interest (ROI). The obtained results showed a significant correlation between the determinations obtained by EIT and those obtained by CT, using whole image and four ROI's [27].

Since studies performed in animals showed acceptable results and considering that EIT is noninvasive, different research groups conducted studies in humans. Previously, our research group compared EIT measurements (in terms of impedance) and lung volume (in liters) obtained by pneumotachometer (gold standard) [28–31]. Both signals evidenced high correlation, so a proportionality coefficient [32] can be established to obtain a set of mathematical models to transform impedance changes into a measurable volume signal. Since it is known that impedance changes largely depend on body composition [33], different anthropometric parameters were taken into account to determine this coefficient [28]. Using obtained calibration equations, impedance measurements were transformed into lung volume which was compared with the volume obtained by pneumotachometer and the corresponding errors were determined.

In a group of healthy males, a significant mathematical adjustment was evidenced (errors approximately 18%). However, we have obtained a poor mathematical adjustment in women, registering errors of 35%. In the case of chronic obstructive pulmonary disease (COPD) the male patients obtained error was roughly 24%.

Although EIT has shown an acceptable adjustment, EIT equipment requires a complex electronic system of current injection and voltage detection which allows adjacent acquisition of impedance measurements, and it also uses a sophisticated image reconstruction algorithm. This is not a standard algorithm and it varies largely among equipment manufacturers. All together, these features increase the cost of EIT equipment which makes it difficult for developing countries to purchase it.

On the other hand, EB equipment is cheaper due to the use of integrated circuits (for example, Circuit Integrated AFE4300 [34]) which are produced massively and are easy to program (for example, with ARDUINO). Besides, EB equipment requires a simple algorithm that allows to acquire an impedance signal throw a communication port.

The main problems with EB devices to be established for medical use in pneumology area are 1) to determine an optimal electrode placement in order to reach the larger lung area possible; and 2) to establish calibration equations to transform impedance measurements into lung volume.

For this reason, the main objective of this research was to obtain a set of calibration equations determined by three different 4-electrode configurations placed on thorax and analyze the mathematical adjustment variability of equations determined by each configuration. Likewise, the error variability, resulted from the validation of each calibration equation group, was assessed.

2. Material and methods

2.1. Impedance device

The impedance device used in this study was an EBI100C BIOPAC® amplifier [35]. The EBI100C® injects a small electrical current (AC) of 400 μA at different frequencies and obtains, simultaneously, the changes of impedances and phases. The sensitivity of impedance magnitude and phase at 10 Hz bandwidth is 1.5 milli-Ohms and 2.5 milli-degrees, respectively. The EBI100C operates with four gains (100, 20, 5 and 1 Ω/volt) that allows to amplify the signal of interest. In this study, the impedances determinations were obtained at a frequency of 50 kHz [11] using a gain of 100 Ω/volt. The schematic of experimental setup of impedance system is shown in Fig. 1. The device was calibrated by a resistance of 20 ohms, setting the phase to 0 degrees. The impedance determinations obtained by EBI100C® were recorded by the BIOPAC software: *AcqKnowledge®* [36].

2.2. Pneumotachometer

The pneumotachometer used in this study was a TSD107B BIOPAC® [37]. This device is highly linear and consists of a high-performance pneumotach coupled with an internal precision differential pressure transducer that converts the differential pressure generated across the pneumotach into a proportional voltage signal. The TSD107B interfaces with the a general-purpose transducer amplifier DA100C. The TSD107B requires the essential use of a mouth piece and a clip nose. The calibration is performed by a syringe of 3 liters. Subsequently, the TSD107B is calibrated to nominally satisfy the scaling factor: 1 mVolt output = 11.1 liters/sec flow rate. When the sensor is connected to the DA100C with Gain = 1,000, the calibration factor is: 1 V = 11.1 liters/sec. The volume determinations were also recorded by the BIOPAC software: Acq*Knowledge®* [36].

2.3. Volunteers

Two groups of volunteers were analyzed in this study: 23 healthy males and 22 healthy women. All volunteers were non-

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