Respiration monitoring by Electrical Bioimpedance (EBI) Technique in a group of healthy males. Calibration equations.

M Balleza[1], M Vargas[1], S Kashina[2], M R Huerta[3], I Delgadillo[1] and G Moreno[4]

[1] Physics Engineering Department, Division of Science and Engineering, Campus León, University of Guanajuato, León, Mexico.
[2] Department of Chemistry, Division of Natural Sciences, Campus Guanajuato, University of Guanajuato, León, Mexico.
[3] Applied Sciences to Work Department, Division of Health Sciences, Campus León, University of Guanajuato, León, Mexico.
[4] Engineering Department, Universidad Iberoamericana, Campus León.

E-mail: marco.balleza@fisica.ugto.mx

Abstract. Several research groups have proposed the electrical impedance tomography (EIT) in order to analyse lung ventilation. With the use of 16 electrodes, the EIT is capable to obtain a set of transversal section images of thorax. In previous works, we have obtained an alternating signal in terms of impedance corresponding to respiration from EIT images. Then, in order to transform those impedance changes into a measurable volume signal a set of calibration equations has been obtained. However, EIT technique is still expensive to attend outpatients in basics hospitals. For that reason, we propose the use of electrical bioimpedance (EBI) technique to monitor respiration behaviour. The aim of this study was to obtain a set of calibration equations to transform EBI impedance changes determined at 4 different frequencies into a measurable volume signal. In this study a group of 8 healthy males was assessed. From obtained results, a high mathematical adjustment in the group calibrations equations was evidenced. Then, the volume determinations obtained by EBI were compared with those obtained by our gold standard. Therefore, despite EBI does not provide a complete information about impedance vectors of lung compared with EIT, it is possible to monitor the respiration.

1. Introduction

Several research groups have proposed different methods and techniques to monitor and measure the lung tidal volume in a non-invasive way. Nowadays, the gold standard to perform these tasks is the pneumotachometer. However, it is not well tolerated by patients due to the use of a mouth piece and clip nose. This fact cause overestimation of the volume determinations between a 15% and 30% [1-3]. There are other devices such as the respiratory inductive plethysmography (RIP) that allow to perform a qualitative analysis of lung ventilation [4].

One of the most used non-invasive technique for this propose is electrical impedance tomography (EIT). This technique is aimed to image a cross section of thorax and obtain a set of dynamic frames through 16 electrodes placed around the thoracic box. With EIT it is possible to obtain an alternating signal by quantifing all pixels of each EIT image. Therefore, a signal in terms of impedance corresponding to respiration is obtained. In previous studies, our research group has obtained a calibrations equation in order to transform the impedances changes into a measurable volume signal in a group of males, females and chronic obstructive pulmonary disease (COPD) patients. From the obtained results, it was evidenced that the adjustment of calibration equations obtained in males was

better than in females [5]. In the case of COPD patients, the calibration equations were corrected by adjusting factor with promising good results [6]. Subsequently, from the main 16-electrodes arrangement, we have chosen the most significant 4 electrodes in order to monitor tidal respiration in a group of healthy males. The most significant results revealed that the mathematical adjustment was as good as that obtained in previous study [7]. Due to previous, our research group proposes the use of 4-electrodes impedance device to monitor and quantify the tidal volume in a group of healthy males. Therefore, the main objective of this research is to obtain a set of calibration equations determined by 4 different frequencies of current injection.

2. Material and methods

2.1 Pneumotachometer
The pneumotachometer was a BIOPAC TSD107B highly linear. It is a wide-range airflow transducer and it interfaces with the BIOPAC DAC100C (general-propose transducer amplifier). The TSD107B is factory calibrated to nominally satisfy the scaling factor: 1 mVolt output = 11.1 liters/sec flow rate. When it is connected to the DA100C with Gain =1,000, the calibration factor is: 1 Volt = 11.1 liters/sec.

2.2 Impedance Device
The impedance device used in this study was a BIOPAC EBI100C. The EBI100C measures both impedance magnitude and phase simultaneously. Impedance can be recorded at four different measurement frequencies (12.5 kHz, 25 kHz, 50 kHz and 100 kHz). This device injects a small current of 400 µA. This device interface with the MP150 data acquisition and analysis platform and Acq*Knowledge* software.

2.3 Volunteers
In this study, a group of 8 healthy males was analysed. We have chosen this sample because this study is the pilot one. So, in this group we have assessed new anthropometric parameters that describe fat mass, muscle mass and other different perimeters of body. All subjects were non-smokers. All test were performed between 9:00 am and noon in the Laboratory of Bioimpedance of the Department of Physics Engineering of the University of Guanajuato, Campus León. All volunteers consented to participate in the study singing an informed consent document.

2.4 Procedure
The pneumotachometer (TSD107B) and the impedance device (EBI100C) were connected simultaneously to each volunteer. The impedance and volume signal were recordered at the same time by the BIOPAC software (Acq*Knowledge*s) for the frequencies of 12.5 kHz, 25 kHz, 50 kHz and 100 kHz. Single respiratory manoeuvre for each frequency was performed. In the group of volunteers, we used a general equation that allows to adjust impedance changes into a measurable volume signal. The equation is expressed as following:

$$\Delta Z = A \times \Delta V \tag{1}$$

where ΔZ is the impedance changes obtained with BIOPAC impedance amplifier, ΔV is the volume changes obtained with the pneumotachometer and A is the proportionality coefficient or calibration coefficient. This latter parameter is defined by different anthropometric parameters (A=[age, weight, height, BMI, etc.]).

   The respiration of each volunteer was recorded at standing position during periods of 40 seconds, with 3 minutes rest between measures. Each respiratory test was registered numerically and graphically. Prior to measure of the respiration pattern, we have recorded anthropometric parameters: age, weight, height and body mass index. Also, different skinfold measures (lateral chest, subscapular, triceps, biceps, suprailiac, pectoral, abdominal, the skinfold of both thigh and calves) have been recorded. We have measured the diameters corresponding to both humerus and femurs. Also, we have registered some other body perimeters as wrist, arm, chest, waist, abdomen, hip, both thighs and calves.

2.5 Statistical analysis

All data were expressed in terms of mean ± standard deviation. The test of Kolmogorov-Smirnov was used for assessing the normal distribution of data (p > 0.05). The calibration equations were obtained by multivariate linear regression of anthropometric parameters and by the proportionality coefficients (A). This parameter is estimated by the quotient of impedance mean value and tidal volume mean value, see equation 1. So, for each frequency of current injection, a calibration mathematical model was obtained. The comparison of the volume determinations obtained by both devices was performed by a Statistical test for paired data. All volume differences were assessed by a set of graphics of Bland & Altman [8].

3. Results

All data series have shown a normal distribution (K-S test p > 0.05). Therefore, all the statistical tests are parametric. The main values of anthropometric parameters corresponding to the male sample were: an age of 25 ± 6 years, a height $1,72 \pm 0.06$ m, a weight of 73.8 ± 6.8 kg and a body mass index (BMI) of 24.9 ± 1.6 kg/m^2. The main values of body skinfolds were: for the lateral chest 18.8 ± 7.4 mm, for the subscapular 19.3 ± 3.2, for triceps 15.0 ± 2.3 mm, for biceps 7.0 ± 1.2 mm, for suprailiac 19 ± 4.2 mm, for the pectoral 18.5 ± 4.9 mm and for the abdominal 22.3 ± 4.0 mm. The mean values of skinfold for the left and right thigh were of 17.1 ± 3.4 and 17.7 ± 2.7 mm, respectively. The mean values of skinfolds for the left and right calf were of 13.3 ± 3.3 and 12.4 ± 3.7 mm, respectively.

The mean values of the diameters of the left and right humerus were of 6.4 ± 0.4 cm, respectively. The mean values of the diameters of the left and right femur were of 9.3 ± 0.3 cm, respectively.

The mean values of the of body perimeters were: for the wrist 16.4 ± 1 cm, for the arm 29.9 ± 1.9 cm, for the chest 93.8 ± 3.9 cm, for the waist 83.9 ± 3.5 cm, for the abdomen 88.2 ± 3.7 cm and for the hip 99.4 ± 3.9 cm. The perimeters of the left and right thigh were of 50.7 ± 2.0 cm and 51.1 ± 2.5 cm, respectively. The perimeters of the left and right calf were of 37.0 ± 1.1 cm and 37.0 ± 1.3 cm, respectively.

The mean value of volume determinations obtained by the pneumotachometer at the frequencies of 12.5 kHz, 25 kHz, 50 kHz and 100 kHz were 0.579 ± 0.176 ml, 0.579 ± 0.225 ml, 0.572 ± 0.192 ml and 0.556 ± 0.211 ml, respectively.

The calibration equations obtained to each frequency are expressed as following:

$$A_{12\text{kHz}} = 28.23 - 2.13 \times \text{DLHum} + 0.111 \times \text{SkSuprail} - 0.092 \times \text{PAbdom} - 0.134 \times \text{PLCalf} \qquad R^2 = 0.999 \ (p < 0.01) \tag{2}$$

$$A_{25\text{kHz}} = 7.94 - 0.02 \times \text{Age} + 0.014 \times \text{SkLChest} + 0.165 \times \text{SkRCalf} - 0.019 \times \text{DRHum} - 2.48 \times \text{DLHum} + 0.087 \times \text{DLFem} + 0.094 \times \text{PChest} \qquad R^2 = 0.999 \ (p < 0.01) \tag{3}$$

$$A_{50\text{kHz}} = 11.57 + 0.27 \times \text{SkRCalf} - 0.21 \times \text{SkLCalf} + 0.027 \times \text{SkRThigh} - 1.69 \times \text{DRHum} + 0.24 \times \text{DRFem} - 0.004 \times \text{PWaist} + \alpha_{14} \times \text{PAbdom} - 0.005 \times \text{PLCalf} \qquad R^2 = 0.999 \ (p < 0.01) \tag{4}$$

$$A_{100\text{kHz}} = 13.54 + 0.17 \times \text{SkRCalf} - 0.083 \times \text{SkLThigh} - 1.71 \times \text{DRHum}$$

$$R^2 = 0.974 \ (p < 0.01) \tag{5}$$

Where the A_i stands for the calibration factor at 12 kHz, 25 kHz, 50 kHz and 100 kHz, SkSuprail is the suprailiac skinfold, the SkRCalf and SkLCalf are the right and left calf skinfolds, the SkRThigh and

SkLThigh are the right and left thigh skinfold, DRHum and DLHum are the diameters of right and left humerus, DRFem and DLFen are the diameters of right and left femurs, PChest is the perimeter of chest, PWaist is the perimeter of waist, PAbdom is the perimeter of abdomen and PLCalf is the perimeter of the left calf.

The volume values obtained with pneumotachometer and impedance device, using the calibration equations, and its differences are show in table 1.

Table 1. Volume determinations obtained by pneumotachometer and impedance device using the calibration equations.

Frequency at 12 kHz (using equation 1)			Frequency at 25 kHz (using equation 2)		
V_Pneumotach[a] (liters)	V_Impedance[b] (liters)	Differences (liters)	V_Pneumotach[a] (liters)	V_Impedance[b] (liters)	Differences (liters)
0.604	0.603	0.002	0.574	0.579	-0.005
0.425	0.426	-0.001	0.427	0.431	-0.004
0.397	0.395	0.002	0.421	0.425	-0.004
0.380	0.379	0.002	0.276	0.278	-0.002
0.881	0.869	0.013	0.949	0.964	-0.015
0.669	0.667	0.002	0.824	0.835	-0.011
0.721	0.729	-0.008	0.674	0.685	-0.010
0.557	0.555	0.002	0.486	0.492	-0.006
0.579 ± 0.176	0.578 ± 0.174	0.002 ± 0.006	0.579 ± 0.225	0.586 ± 0.229	-0.007 ± 0.004
		Error: 0.96%			Error: 0.76%
Frequency at 50 kHz (using equation 3)			Frequency at 100 kHz (using equation 4)		
V_Pneumotach[a] (liters)	V_Impedance[b] (liters)	Differences (liters)	V_Pneumotach[a] (liters)	V_Impedance[b] (liters)	Differences (liters)
0.591	0.595	-0.004	0.600	0.614	-0.013
0.390	0.393	-0.003	0.393	0.397	-0.004
0.382	0.385	-0.003	0.371	0.346	0.025
0.376	0.379	-0.003	0.335	0.340	-0.004
0.830	0.842	-0.012	0.904	0.845	0.059
0.850	0.859	-0.009	0.793	0.812	-0.018
0.637	0.644	-0.007	0.623	0.638	-0.016
0.516	0.522	-0.006	0.426	0.451	-0.026
0.572 ± 0.192	0.577 ± 0.196	-0.006 ± 0.003	0.556 ± 0.211	0.555 ± 0.202	0.0003 ± 0.028
		Error: 0.58%			Error: 5%

[a] Volume determinations obtained by pneumotachometer.

[b] Volume determinations obtained by impedance device using calibration equations.

The analysis of volume differences was performed by a Bland and Altman graphics (see figure 1). From the t-test statistical analysis of the volume differences obtained by both monitoring devices at each frequency, statistically significant differences in the volume determinations obtained at 25 kHz ($p = 0.003$) and 50 kHz ($p = 0.002$) were evidenced. However, there was no significant differences for the frequencies 12.5 kHz ($p = 0.499$) and 100 kHz (0.981). The Pearson's correlation between volume determinations obtained by pneumotachometer and impedance device at four frequencies was over 0.99.
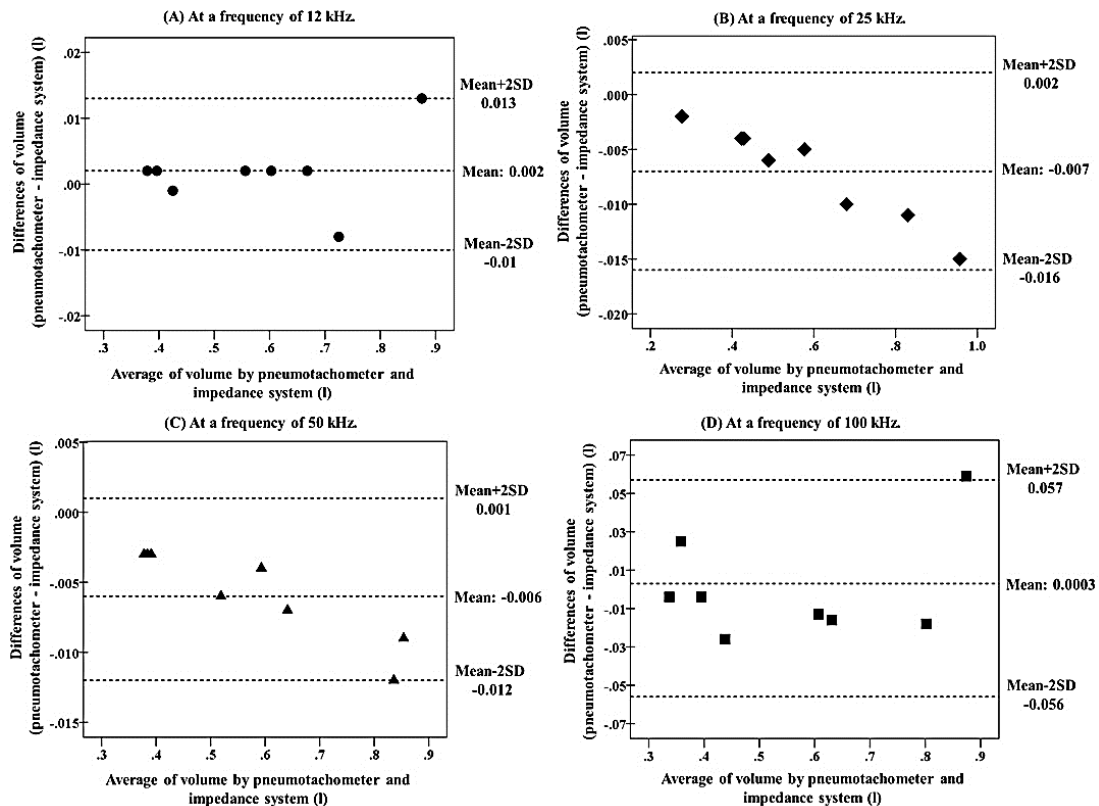
Figure 1. Analysis of volume differences by a Statistical analysis of Bland and Altman. Graphic (A) shows the differences of volume determinations at 12.5 kHz. Graphic (B) shows the differences of volume determinations at 25 kHz. Graphic (C) shows the differences of volume determinations at 50 kHz. Graphic (D) shows the differences of volume determinations at 100 kHz.

4. Discussion

The first objective of this research was to obtain a set of calibration equations to adjust a 4 electrodes impedance signal at four different frequencies (corresponding to ventilation) into a measurable volume signal. In order to accomplish this aim, we have performed a statistical multivariate analysis of anthropometric parameters and calibration factors (A). This factor is unique for each subject. From the resulted analysis we have obtained 4 calibration equations with a high determinations coefficients. All those equations involved parameters that describe the anthropometry of lower extremities. It seems that the physical activity and the possible development of lower extremities have a high relation.

In previous studies [5-7], we have measured those anthropometrical parameters that describe the anthropometry of thorax as thoracic skinfolds, diameters of chest at rest, maximal expiration and maximal inspiration. The obtained calibration equations evidenced a high coefficient of determination. However, the errors obtained in each obtaining group were between 5% and 7%. Comparing these results with the obtained in this study, we have improved the mathematical adjustment at a 20% just in the obtaining group. This fact will affect the estimation of volume in a different group of volunteers.

In the case of those results obtained from the statistical comparison, we evidenced that the volume differences at 25 kHz and 50 kHz showed statistical significant differences despite to obtain lower volume differences. This fact can be attributed to the small sample. Probably, the calibration equation does not adjust correctly the impedance determinations due to the anthropometrical parameters of one subject. In graphics A, C and D, it is possible to evidence one point around the upper and lower boundaries. Therefore, we need to increase the sample in order to obtain more reliable results. It is important to mention that this study is a first attempt to calibrate a set of tetrapolar impedance determination in order to obtain a volume signal.

5. Conclusion

All these obtained results are limited to a sample of healthy males. Therefore, the assessed calibration equation might not be suitable for patient. All volume determinations are restricted to a range of 300 ml to 900 ml. So, all conclusion are restricted to this range. The main conclusion of this study is that the impedance determinations can be adjusted by using the parameters that describe the anthropometry of lower extremities. This fact can be related with the physical activities and therefore, the lung conditioning.

Acknowledgments

References

[1] Askanazi J., Silverberg P A, Foster R J, Hyman A I 1980 *J Appl Physiol* **48** 577-80.
[2] Perez W and Tobin J 1985 *J Appl Physiol* **59** 1515-20.
[3] Paek D and McCool D (1992) J Appl Physiol 73 887-93.
[4] Whyte K F, Gugger M, Gould G A, Molloy J, Wraith P K, Douglas N J 1991 *J Appl Physiol* **71** 1866-71.
[5] Balleza M, Fornos J, Calaf N, Feixas T, Gonzalez M, Antón D, Riu P J, Casan P 2007 *Arch. Bronconeumol* **43** 300-3.
[6] Balleza M, Calaf N, Feixas T, Gonzalez M, Antón D, Riu P J, Casan P 2009 *Arch Bronconeumol* **45** 320-24.
[7] Balleza-Ordaz M, Alday-Perez E, Vargas-Luna M, Kashina S, Huerta-Franco M R, Torres-González L A, Riu-Costa P J 2016 *Biomed Signal Process Control* **27** 68-76.
[8] Bland J M, Altman D 1986 *The lancet* **327** 307-10.