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Driving Pressure and Lung Compliance Obtained by Electrical Bioimpedance: The Case of Smokers

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Abstract. Survival in patients with mechanical ventilation depends on careful regulation of some critical parameters as the tidal volumes (VT), positive end expiratory pressure (PEEP), lower end inspiratory pressure (Plateau), the driving Pressure (DP=Plateau - PEEP), and respiratory system compliance (Crs= VT/DP) related with the functional lung size. These parameters are obtained from the flux signal in Pneumotachometer (PNT) technique. The present work studies the possibility of using the Electrical Bioimpedance (EBI) technique to obtain flux parameters as driving pressure and lung compliance in smokers, before and after tobacco consumption. Ventilatory pattern is obtained by initial comparison of EBI signal with a simultaneous measurement of integrated PNT signal. By differentiating in time EBI signal EBI flux pattern and then its corresponding flux parameters are obtained. Thirty-four young and healthy volunteers (17 men and 17 women) were evaluated. EBI flux parameters were compared with those obtained directly from PNT. By obtaining an initial personalized proportionality constant between the PNT signal and the electrical bioimpedance, it can be observed a good agreement between both techniques in the volumes estimation, in other stages of the experiment, flows and parameters derived from these such as driving pressure and compliance. An initial and personalized correlation between the PNT and bioelectrical impedance signals can be used to predict subsequent volumes, flows, driving pressure and lung compliance.

Keywords: Driving pressure, compliance, bioelectrical impedance, pulmonary ventilation.

1 Introduction

There are some standard methods to detect lung pathologies and respiratory system performance. The most common is spirometry [1], using a pneumotachometer (PNT), that measures flux parameters and by integration assesses volume capacities (Fig. 1). Normal respiration volume is known as tidal volume.

The PNT records the flux, and there are some parameters that come from the flux pattern (Fig. 2).

Survival in patients with mechanical ventilation depends on careful regulation of some critical parameters as the tidal volumes (VT), positive end expiratory pressure (PEEP), lower end inspiratory pressure (Plateau), the driving Pressure (DP=Plateau - PEEP), and respiratory system compliance (Crs= VT/DP) related with the functional lung size [2]. These parameters are obtained from the flux signal in PNT technique. Even when DP and Crs are parameters associated to mechanical ventilation, they can be estimated in a normal respiration. It is known that smoking effects directly the respiratory system [3], therefore it is important to search if DP and Crs parameters change in the case of damages due to tobacco consumption.

Electrical Bioimpedance (EBI) has been investigated for many years to be used in respiratory monitoring [4]. EBI considers the opposite of the flux of alternating electrical current

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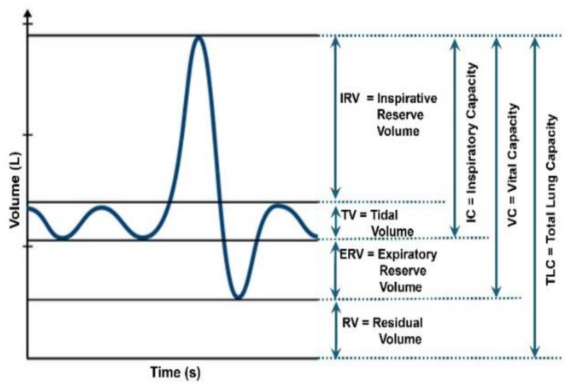

Fig. 1. Volumes obtained by spirometry

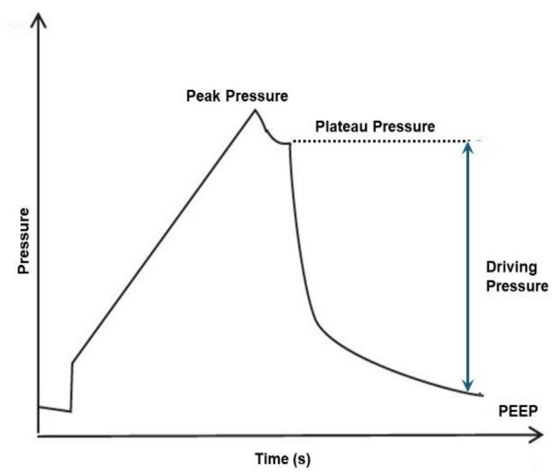

Fig. 2. Flux and flux parameters

coming from the resistivity and capacity properties of the tissues, giving a resistance (R) and a capacitive reactance (Xc) respectively that combined build the impedance of the material. The impedance is analyzed as a complex parameter because the phase shift (ϕ) that appears in any reactive element, and it depends on the frequency through the reactance (Xc= 1/ωC):

$$Z = R + jXc, \tag{1}$$

$$\phi = arctan(R/Xc), \tag{2}$$

Thoracic EBI changes (ΔZt) has been demonstrated to have linear correlation with lung ventilation changes measured by PNT (ΔVp = C + Ai * ΔZt) in each subject with a negligible intercept (C $\approx$ 0) [5]:

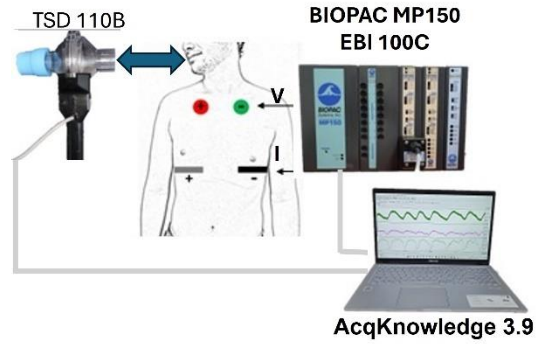

Fig. 3. Schematic explanation of data acquisition procedure

$$\Delta Vp = Ai \times \Delta Zt. \tag{3}$$

There had been attempts to correlate the proportionality constant value “Ai” to the anthropometric parameters of each subject [6,7]. Nevertheless, there are important errors in estimating volumes using these correlations mainly in women. Also, PNT records flux and evaluate volume by integration, whereas EBI senses volume changes and should be differentiated to obtain flux pattern. The present work studies the possibility of using the EBI technique to obtain flux parameters as driving pressure and lung compliance, and search if they change after tobacco use.

2 Methodology

Ventilatory pattern is obtained by initial comparison of EBI signal with a simultaneous measurement of integrated PNT signal. By differentiating in time EBI signal EBI flux pattern and then its corresponding flux parameters are obtained.

2.1 Subjects

Thirty-four young and healthy volunteers (17 men and 17 women) were evaluated. The volunteers had an average age of 21 years (21±4 years), with a range of body composition (men: BMI=28.1± 8.6, women: BMI=26.9 ±7.1). All the volunteers declare

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not to have any respiratory pathological symptoms or diagnosed pathology (cough, phlegm, sore or swollen throat, runny nose, fever or low-grade fever, general discomfort). EBI flux parameters were compared with those obtained directly from PNT. All the volunteers were occasional smokers and were evaluated before and after voluntary tobacco use.

The protocol was approved by the ethical committee of the University og Guanajuato (Registration number: CONBIOÉTICA-11-CEI-001-20230127). All volunteers signed an informed consent.

2.2 Materials and Equipment

A Biopac MP 150 with the modules EBI100C for impedance recordings, and TSD110B for respiratory flux recordings. Impedance module injects 0.4 mA current at 50 KHz in a tetrapolar configuration electrodes (Ag/AgCl). Simultaneously, the PNT uses a disposable sterile mouthpiece and a nose clip to record the respiration flux. Both signals are registered simultaneously through the AcqKnowledge 3.9 Biopac software (Fig. 3).

2.3 Procedure

The protocol is divided in three steps as below.

The first step consists of an interview to explain the experiment to the volunteers and sign the informed consent. Also, the volunteers are questioned about their general health condition during the last two weeks including diagnosed chronic pathologies. Some anthropometric parameters were evaluated as weight, height and some skin folds (bicipital, tricipital, subscapularis and suprailiac) and finally the chest and non-dominant arm circumferences.

The second step: after at least 24 hours of refrain of tobacco consume, four electrodes were placed in the thoracic region (two of them in the second intercostal symmetrically placed and the other two on the sides at the level of the sixth intercostal), also the nose clip and the disposable m5outhpiece were placed. Standing on feet but in a calm state, with a normal breath, 60 seconds of signals were recorded.

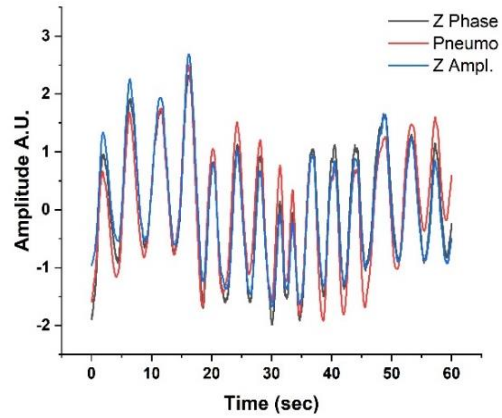
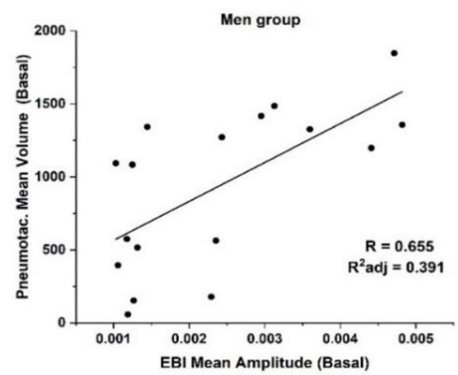
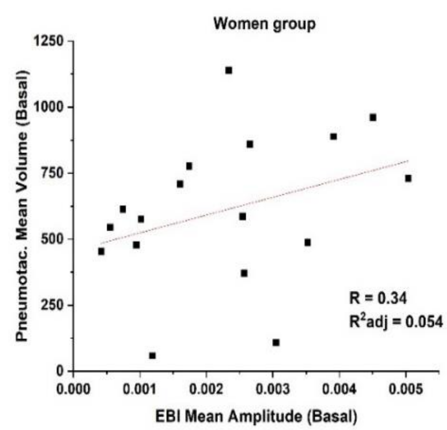


Fig. 4. Example of a correlation between EBI signal and tidal volume measured by PNT. This coincidence is achieved through an appropriate and individual proportionality constant



(a)



(b)

Fig. 5. Example of a correlation between EBI signal and tidal volume measured by PNT in men (a) and women (b)

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Third step: After the second step procedure, and after the voluntary tobacco consumption, another recording of 60 seconds breath signals (EBI and PNT) was performed.

2.4 Signal Processing

EBI signals were filtered by a Butterworth order 3 low pass filter (cutoff frequency = 50 Hz). This cutoff frequency allows for effective removal of electronic noise and artifacts without distorting the overall wave shape. PNT signal (flux signal) was integrated in time and detrended to obtain the tidal volume changes. This is a routine procedure performed by the BIOPAC software to get the volume changes signal. Similarly, the EBI signal was differentiated in time to obtain the flux signal. This procedure required an extra smoothing of the signal (using second order polynomials and periods of 0.5 seconds) to avoid extreme fluctuation due to the remanent noise. From both flux signals (EBI and PNT) driving pressure and compliance were calculated. The individual proportionality constant used during the entire experiment was the one calculated from initial (before tobacco use) between PNT volume and EBI impedance. Correlations between the parameters obtained by both techniques using the initial proportionality constant were obtained and changes due to tobacco use were analyzed.

3 Results

The parameters that show normal distribution were analyzed by parametric analysis (T test or ANOVA) and those parameters that do not show normal distribution were analyzed by non-parametric methods (Wilcoxon, Kruskal- Wallis).

By simple observation, It can be seen that the EBI changes signal (ΔZt magnitude and phase) highly correlates with the tidal volume changes measured by PNT (ΔVp) with the appropriate proportionality constant (Ai) as is shown in figure 4. Nevertheless, this proportionality constant is not the same for each volunteer, so the direct correlation between these two parameters (ΔZt and ΔVp) including all the subjects is low (Fig. 5a).

Hereafter, the EBI parameter used to be analyzed and compared with PNT results is the

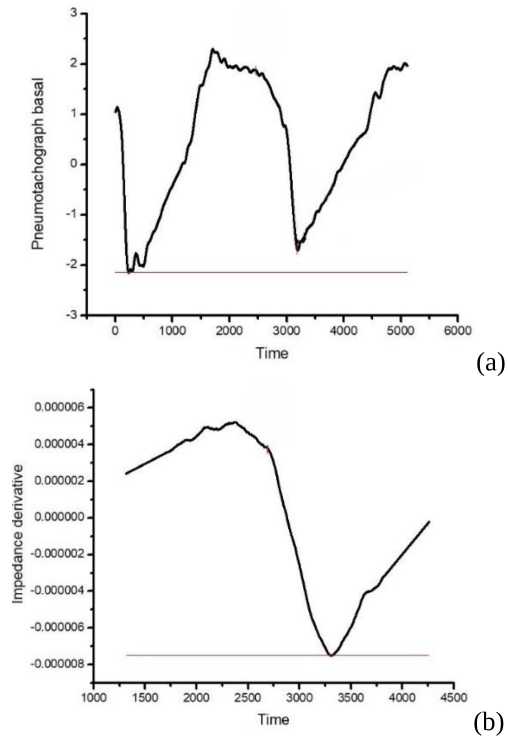


Fig. 6. Flux pattern obtained by PNT (a) and the EBI signal derived in time (b)

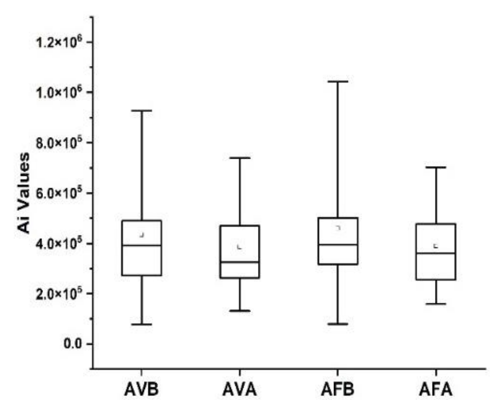
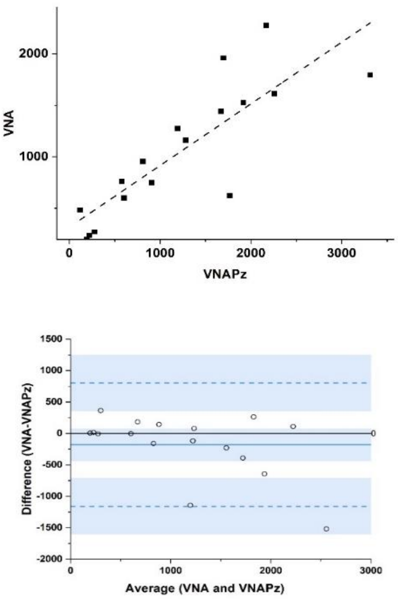


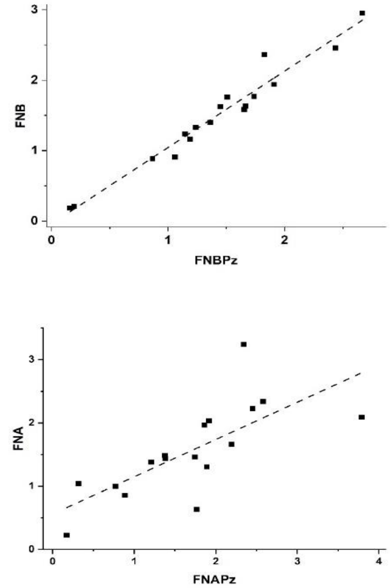
Fig. 7. Kruskal Wallis analysis and paired tests of the Ai's of volume constants (AVB, AVA) and flux constants (AFB, AFA). No statistically significant differences were found

magnitude of EBI. Also, here and in previous investigations the results for women show higher variability because the body composition of the thoracic region of women. Therefore, the following analysis results are restricted to men group.



VNA = 316.3 + 0.6 x VNAPz (R^2adj = 0.682) p=2.7 10^{-5}

Fig. 8. Correlation between PNT volume (VNA) and the same volume predicted by EBI signal (VNAPz) after tobacco use, and the corresponding Bland Altman graph



FNB = -0.04 + 1.085 x FNBPz (R^2adj = 0.954) p < 10^{-5}

Fig. 10. Correlation between PNT flux (FNB) and the flux predicted by derivative of EBI signal (FNBPz) before tobacco use, and the corresponding Bland Altman graph

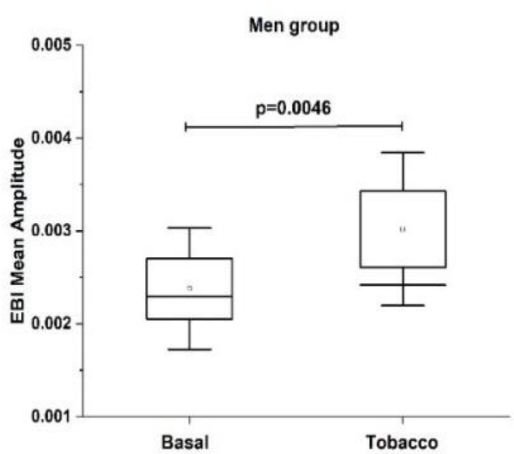
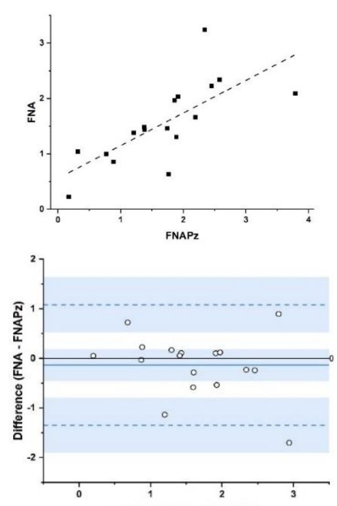


Fig. 9. Magnitude of the thoracic impedance changes after the tobacco use



FNA = 0.56 + 0.59 x FNAPz (R^2adj = 0.493), p=0.001

Fig. 11. Correlation between PNT flux (FNA) and the flux predicted by derivative of EBI signal (FNAPz) after tobacco use, and the corresponding Bland Altman graph

Table 2. Comparison of the means (or medians) of volumes and fluxes before and after tobacco use for men

Technique	Signal	p	Test
PNT	Volume	0.18	T
	Flux	0.66	T
EBI	Amplitude (Volume)	**0.0046**	Wilcoxon
	Derivative (Flux)	0.21	Wilcoxon

Table 3. Comparison of medians od DP and Crs before and after tobacco use either with PNT or EBI technique

Comparison	p	Text
DPNB vs DPNA	0.52	Wilcoxon
DPNBPz vs DPNAPz	0.30	Wilcoxon
CNB vs CNA	0.74	Wilcoxon
CNBPz vs CNAPz	0.85	Wlcoxon

By mathematically differentiating the EBI signal, the general pattern emulates that obtained by the PNT flux (figure 6).

A proportionality constant (A = first letter) is searched for each subject to correlates **V**olumes and EBI signals or **F**luxes and EBI derivative (V or F = second letter), **B**efore or **A**fter tobacco use (B or A = third letter).

A Kruskal-Wallis ANOVA did not show any difference between the constants (p=0.45), but also any paired test (parametric or not, according to the normality of the data sets considered) AVB vs AVA (p=0.18) and (AFB vs AFA (p=0.32)) (Fig. 7.).

With these results an initial and individual proportionality constant can be determined at the beginning of the experiment and be used all along the experiment either to estimate further volumes, fluxes and parameters derived from these patterns.

After derivation of EBI, the flux-pressure conversion is based in Bernoulli expression:

$$P = \frac{\rho}{2}\frac{F^2}{A^2}, \qquad (4)$$

where P = driving pressure, ρ = air density (room temperature) = 0.96, F = EBI flux estimation, A = average tracheal area = 2.54 cm^2.

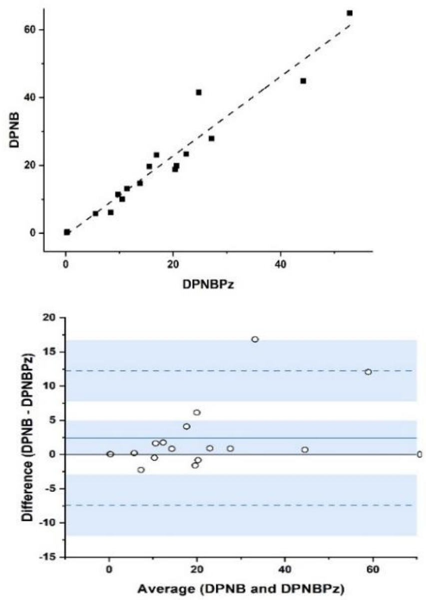
That is: $P = 7.44 \times F^2$

where F = FPB or FPA, FZB or FZA.

So, the statistical comparison of driving pressures is equivalent to the statistical comparison of the square of flux.

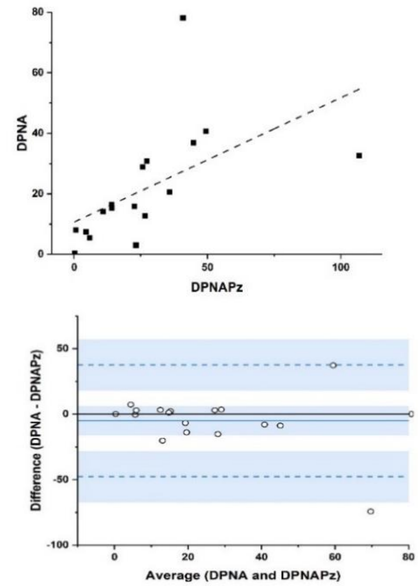
In the case of the compliance the use of the relation DP = Vt/Crs is based in the fact thar the curve static pressure-volume is rater lineal in the range of the tidal volume (around 600 ml), this means that in that range the lung has a linear elasticity. In general, the volumes that appear in a normal respiration are of the order of 1-2 liters and the pressures are around 100-200 Pascals, in this region the respiration is considered mechanically a linear phenomenon.

Both parameters, the driving pressure and the compliance are used mostly in mechanical ventilation. The driving pressure reflects the degree of stretching of the lung during respiration. Higher DP implies higher stretch of the lung parenchyma and therefore could have consequently higher inflammatory response at the alveolar level. Therefore, in the case of smokers, he comparison of the volumes, flux, and their corresponding parameters are based in the hypothesis that if an alveolar or in general a parenchyma inflammation appears it could be detected by a change in the DP or Crs in a normal respiration.



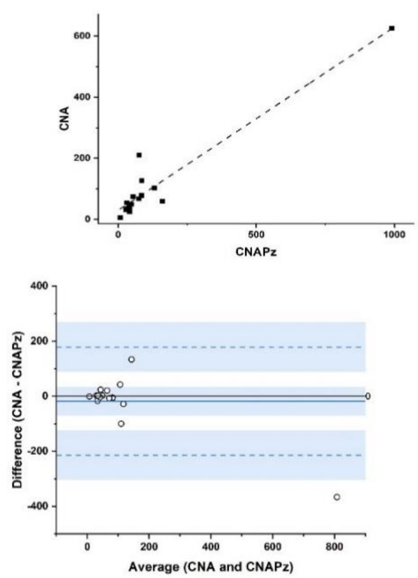
DPNB = -0.65+1.17xDPNBPz (R^2adj = 0.93)
p < 0.001

Fig. 12. Correlation of DP parameters predicted by EBI and measured by PNT, before tobacco use, and its corresponding Bland Altman graph



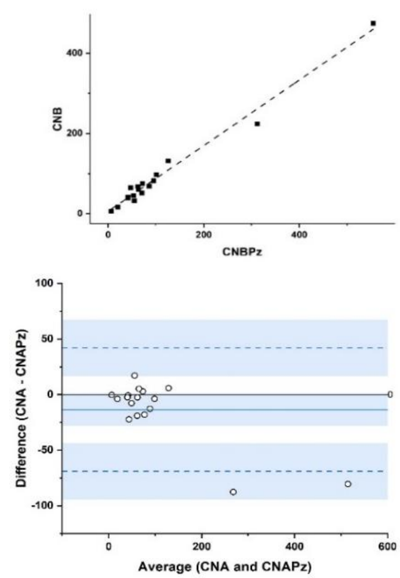
DPNA = 10.64+0.41xDPNAPz (R^2adj = 0.26)
p=0.021

Fig. 13. Correlation of DP parameters predicted by EBI and measured by PNT, after tobacco use, and its corresponding Bland Altman graph



CNA = 29.75 + 0.6 x CNAPz (R^2adj = 0.91) p < 0.001

Fig. 15. Correlation of Crs parameters predicted by EBI and measured by PNT, after tobacco use, and its corresponding Bland Altman graph



CNB = 5.86 + 0.818 x CNBPz (R^2adj = 0.98)
p < 0.001

Fig. 14. Correlation of Crs parameters predicted by EBI and measured by PNT, before tobacco use, and its corresponding Bland Altman graph

Direct comparison of the volumes and fluxes before and after tobacco use is shown in table 2. Only the magnitude of the thoracic impedance changes (increases) after the tobacco use (p=0.0046 Wilcoxon test) (Fig. 9).

The increase can be understood due to the need of higher breath inspiration after tobacco use.

If the volume obtained from PNT after the tobacco intervention (VNA) is compared with the same value but predicted By EBI signal (VNAPz) the correlation is reasonably good (R2 = 0.68) with a high statistical significance ($p < 0.001$) (Fig. 8).

In the same way, the flux predicted by the derivative of EBI signal (and the Ai proportionality constant obtained from the relation between EBI magnitude – PNT volume), has good correlation with the flux obtained by PNT before and after tobacco use (Fig. 10-11).

As mentioned before, Driving Pressure (DP) is proportional to the square flux. Following the same procedure and using the same initial proportionality constant the flux from PNT and that predicted by EBI highly correlate before tobacco use but poorly correlates after the intervention (Fig. 12-13).

Similar results are obtained with the compliance parameters (Fig. 14-15).

The analysis to compare medians of DP or Crs before and after tobacco use did not show any statistical difference (Table 3).

4 Discussion

From the graphical similarities between the EBI signals (amplitude and phase) and the volume obtained from the PNT, it is observed that EBI gives analogous information on pulmonary ventilation.

Just as the PNT gives us the flow and we must integrate to obtain the volume information, the EBI signal, which is directly proportional to the volume, must be differentiated to give us flow information. The flow obtained in this way with the bioelectrical impedance signal has a similar shape to that obtained with the PNT, as expected.

The average volumes and flow obtained by both techniques are the first parameters that were compared before and after tobacco consumption, observing that the EBI is more sensitive to changes derived from the consequence of consuming tobacco (p=0.0046), the corresponding value of “p” for the case of the volume obtained with the PNT, although low, did not reach statistical significance (p=0.18), this in the case the men group.

Although the agreement of the signal shapes is very good, the correlation between the average signals for all the subjects indicates that this proportionality is individual. Obtaining this individual proportionality constants for volumes and flow, before and after the experimental intervention, and their subsequent comparison through an ANOVA analysis indicates that these proportionality constants although individual, are statistically equal. That is why obtaining the proportionality constant between the PNT values and the EBI can be done only at the beginning of the experiment and use that constant to obtain subsequent parameters.

With this procedure of using only an initial individual proportionality constant (volume before consuming tobacco), it was observed that there is a good correlation between values predicted by bioelectrical impedance and values obtained with the PNT: Volumes after consuming tobacco and flows before and after smoking.

Likewise, using this proportionality constant, a good prediction of distension pressures and compliance is obtained both before and after consuming tobacco.

Although the volume obtained with impedance was sensitive to tobacco consumption, the flow, that is the derivative of the volume signal, the distension pressure that is associated with the flow and compliance that is associated with the distension pressure and volume, no statistically differences were found.

5 Conclusions

The proportionality constant between EBI thoracic signal and Pneumotachometer volume signal is an individual parameter that does not change significantly in further steps of the experimental protocol. Using this appropriate initial and individual proportionality constant, obtained in basal state at rest, between the volume obtained with the PNT and that obtained with EBI, parameters, that have not been studied before with EBI signals, such as flow, driving pressure and compliance can be reasonably predicted with EBI measurements.

The volume obtained with EBI was statistically different before and after tobacco consumption, however, other parameters derived from this volume such as flow, distension pressure and compliance, did not achieve statistical significance to observe changes due to tobacco consumption.

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