Measuring Breathing Pattern in Patients With Chronic Obstructive Pulmonary Disease by Electrical Impedance Tomography

Marco Balleza, a, b * Núria Calaf, a Teresa Feixas, a Mercedes González, a Daniel Antón, b Pere J. Riu b and Pere Casan a

a Unitat de Funció Pulmonar, Departament de Pneumologia, Hospital de la Santa Creu i de Sant Pau, Facultat de Medicina, Universitat Autònoma de Barcelona, Barcelona, Spain
b Departament d’Enginyeria Electrònica, Universitat Politècnica de Catalunya, Barcelona, Spain

ABSTRACT

Background and Objective: The measurement of breathing pattern in patients with chronic obstructive pulmonary disease (COPD) by electrical impedance tomography (EIT) requires the use of a mathematical calibration model incorporating not only anthropometric characteristics (previously evaluated in healthy individuals) but probably functional alterations associated with COPD as well. The aim of this study was to analyze the association between EIT measurements and spirometry parameters, static lung volumes, and carbon monoxide diffusing capacity (DLCO) in a group of male patients to develop a calibration equation for converting EIT signals into volume signals.

Materials and Methods: We measured forced vital capacity (FVC), forced expiratory volume in 1 second (FEV1), FEV1/FVC, residual volume, total lung capacity, DLCO, carbon monoxide transfer coefficient (KCO) and standard anthropometric parameters in 28 patients with a FEV1/FVC ratio <70%. We then compared tidal volume measurements from a previously validated EIT unit and a standard pneumotachometer.

Results: The mean (SD) lung function results were FVC, 72 (16%); FEV1, 43% (14%); FEV1/FVC, 42% (9%); residual volume, 161% (44%); total lung capacity, 112% (17%); DLCO, 58% (17%); and KCO, 75% (25%). Mean (SD) tidal volumes measured by the pneumotachometer and the EIT unit were 0.697 (0.181) L and 0.515 (0.223) L, respectively (P<0.001). Significant associations were found between EIT measurements and CO transfer parameters. The mathematical model developed to adjust for the differences between the 2 measurements (R²=0.568; P<0.001) was compensation factor=1.81 – 0.82 × height (m) – 0.004×KCO (%).

Conclusions: The measurement of breathing pattern by EIT in patients with COPD requires the use of a previously calculated calibration equation that incorporates not only individual anthropometric characteristics but gas exchange parameters as well.

© 2008 SEPAR. Published by Elsevier España, S.L. All rights reserved.

Medición del patrón ventilatorio mediante tomografía por impedancia eléctrica en pacientes con EPOC

RESUMEN

Introducción: La medición del patrón ventilatorio (PV) en pacientes con enfermedad pulmonar obstructiva crónica (EPOC) mediante tomografía por impedancia eléctrica (TIE) requiere disponer de un modelo matemático de calibración que tenga en cuenta no sólo las características antropométricas (ya evaluadas en la persona sana), sino probablemente también las alteraciones funcionales propias de la enfermedad. El objetivo del presente estudio ha sido relacionar, en un grupo de pacientes (varones) con EPOC, las variables de la función pulmonar —espirometría, volúmenes estáticos, transferencia de monóxido de carbono (CO)— con las determinaciones de TIE y obtener una ecuación de calibración que permita convertir la señal eléctrica de la TIE en una señal de volumen.

*Corresponding author:
E-mail addresses: jballeza@santpau.cat; mabaor@hotmail.com (M. Balleza).

© 2008 SEPAR. Published by Elsevier España, S.L. All rights reserved.
Material y métodos: Se estudió a 28 pacientes —volumen espiratorio forzado en el primer segundo (FEV1) < 70%— con un equipo TIE-4 previamente validado y se compararon los resultados con los de un neumotacómetro estándar. Previo se determinaron los siguientes parámetros: FVC, FEV1, FEV1/FVC, volumen residual, capacidad pulmonar total, capacidad de difusión de CO y coeficiente de transferencia de CO (KCO), además de las variables antropométricas habituales.

Resultados: Los valores medios ± desviación estándar de las diferentes pruebas funcionales fueron: FVC del 72 ± 16%; FEV1 del 43 ± 14%; FEV1/FVC del 42 ± 9%; volumen residual del 161 ± 44%; capacidad pulmonar total del 112 ± 17%; capacidad de difusión de CO del 58 ± 17%, y KCO del 76 ± 25%. Los valores medios de volumen circulante de las determinaciones obtenidos con el neumotacómetro y la TIE fueron de 0,697 ± 0,181 y 0,515 ± 0,223 l, respectivamente (p < 0,001). Se encontraron relaciones significativas entre las medidas de la TIE y la transferencia de CO. El modelo matemático para ajustar las diferencias entre ambas determinaciones (R² = 0,568; p < 0,001) fue: factor de compensación = 1,81 – 0,82 × talla (m) – 0,004 × KCO (%).

Conclusiones: La mediación del PV mediante un equipo de TIE en pacientes con EPOC requiere una calibración previa que tenga en cuenta no sólo las características físicas de cada individuo, sino además la situación funcional del área de intercambio gaseoso.

© 2008 SEPAR. Publicado por Elsevier España, S.L. Todos los derechos reservados.
The pneumotachometer was calibrated using a 3-L gas syringe in accordance with standard laboratory protocols (acceptable deviation, <1%).

The EIT-4 was calibrated using a previously validated equation for healthy individuals.6,7 Finally, image capture speed (16–18 images per second) was tested at the moment of measurement.

Before each measurement, we recorded anthropometric data (age, weight, height, and body mass index) and measured skinfolds (front, side, back, and subscapula) using electronic skinfold calipers. We then performed the corresponding lung function tests (spirometry, static lung volumes, and carbon monoxide transfer), and finally, following a 15-minute rest period, proceeded to measure breathing pattern. For each patient, once the 16 electrodes had been positioned and the units calibrated and connected, 3 different readings were recorded and stored in txt- and asc-extension files for subsequent processing. Tidal volume measurements over periods of 30 seconds (between 5 and 8 respiratory cycles) were recorded both graphically and numerically, with a 3-minute interval between measurements. A total of 20 to 25 cycles were recorded for each patient.

**Statistical Analysis**

Data were expressed as means (SD), and pneumotachometer and EIT-4 measurements were compared using the test for nonparametric variables. Relationships between variables were analyzed using the Spearman correlation coefficient and differences in tidal volume measurements were evaluated using Bland-Altman analysis. Statistical significance was set at a value of $P < .05$ in all cases. Finally, all the variables were studied using multivariate regression analysis to obtain an equation model that could be used to calibrate the EIT-4 for patients with COPD.

**Results**

The mean (SD) anthropometric parameters for the series (which included men only) were an age of 69 (9) years, a height of 1.65 (0.07) m, a weight of 76 (12) kg, and a body mass index of 28 (4.2) kg/m$^2$. The skinfold measurements were 23 (6) mm (front), 25 (8) mm (side), 24 (8) mm (back), and 26 (9) mm (subscapula).

PVC and FEV$\_1$ values were 72% (16%) and 43% (14%) of predicted, respectively, and the FEV$\_1$/FVC ratio was 42% (9%). For the 22 patients in whom we were able to measure static lung volumes, we found a mean residual volume of 161% (44%) of predicted and a total lung capacity of 112% (17%) of predicted. Based on CO transfer measurements performed in 19 patients, we found a mean carbon monoxide diffusing capacity (DLCO) of 58% (17%) of predicted and a CO transfer coefficient (KCO) of 76% (25%) of predicted (Table 1).

Mean tidal volume measured by the pneumotachometer and the EIT-4, respectively, was 0.697 (0.181) L and 0.515 (0.223) L ($P < .001$). The mean of the differences between the measurements obtained using both units was 0.182 (0.125) L, with a Spearman correlation coefficient of $r = 0.825$ ($P < .01$).

The correlation between the lung function parameters studied and the impedance index, together with the differences in tidal volume measurements from both units, are shown in Table 2. Statistically significant correlations were found between the impedance index and FEV$\_1$/FVC, DLCO, and KCO on the one hand and the differences in tidal volume measurements from the 2 systems and DLCO and KCO, on the other.

The Figure shows the differences in tidal volume measurements from both units with respect to values obtained using the pneumotachometer. The mean of the differences was 0.432 L, with limits of agreement ranging from $0.422$ to $-0.068$ L. All the measurements fell within this interval. Nonetheless, this mean difference can be corrected using the following expression: $(R^2=0.568, P<.01)$.

**Differences** = $1.81 - 0.82 \times \text{height (cm)} - 0.004 \times \text{KCO (})$

The estimation for COPD patients would therefore be as follows:

$\Delta V_{\text{COPD}} = \Delta V_{\text{male}} + \text{Differences}$

**Discussion**

The findings of the present study indicate not only that tidal volume measured by EIT in patients with COPD should be adjusted for external factors (basically height) but also that lung alterations,
expressed in terms of reduced gas exchange area, change the value of the EIT signal recorded.

These conclusions are essentially based on the association observed between the overall impedance value and variables that reflect the size of the gas exchange area. Although we also observed a significant relationship between impedance and airflow obstruction, this parameter was not included in the final equation. No significant correlation was found between impedance and residual volume, indicating that air trapping, regardless of its extent, does not have a significant effect on the transmission of the electrical signal.

While tidal volume measurements obtained using both the pneumotachometer and the EIT-4 were, logically, significantly associated, the distribution of these measurements on a Bland-Altman plot (Figure) shows that almost all of the EIT measurements were lower than those obtained using the pneumotachometer. Furthermore, the difference between the measurements was statistically significant. Nonetheless, as shown in the multivariate equation, this difference can be compensated for with a mathematical process that corrects this practically systematic error.

The main problem associated with using EIT to measure tidal volume during breathing at rest lies in the difficulty of calibrating the electrical signal and obtaining a comparable and lasting volume signal. Anthropometric parameters, and particularly those that refer to the chest (skinfolds and weight) must be taken into account when adjusting EIT measurements in healthy individuals. In patients with COPD, however, lung parameters, such as airflow obstruction, air trapping, and reduced gas exchange area, must also be taken into account. Of these variables, the only one that had a significant effect on measurements in our case, and consequently should be incorporated into the adjustment equation for COPD, was KCO. Because we only studied men, skinfold thickness did not have a significant effect on our measurements. Indeed, as occurs in spirometry, height was the factor that had the greatest influence. The above observations are particularly relevant for studies involving female patients with COPD.

Numerous international research groups are involved in the study of how to calibrate EIT volume-time measurements using different mathematical equations that model individual characteristics. The main problem lies in finding a method capable of converting the electrical signal into a volume signal. The research group at the University of Biomedical Engineering of Tel-Aviv in Israel is based on a calibration method involving the characterization of the right and left lung using a theoretical reconstruction algorithm that measures the resistivity of each lung. They validated their model in 33 healthy individuals and obtained volume-time results that were not significantly associated with anthropometric parameters.

An alternative approach proposed by the research group at the University of Biomedical Engineering of Tel-Aviv in Israel is based on a calibration method involving the characterization of the right and left lung using a theoretical reconstruction algorithm that measures the resistivity of each lung. They validated their model in 33 healthy individuals and obtained volume-time results that were not significantly associated with anthropometric parameters.

Frerichs, in a magnificent review of the literature, evaluated the efforts made by different groups to resolve this calibration problem. Her analysis of 37 articles published between 1985 and 1999 highlighted the vast diversity of applications proposed, the small size of the groups (healthy individuals and patients) studied, the complexity of the methods described, and finally, the need to find a simple solution to adjust EIT measurements to changes in lung volume. The only efforts made in this respect in recent years have been by Nebuya et al and Zlociher et al. Our findings are both novel and practical as our method involves the use of simple variables (anthropometric data) and basic lung function parameters, readily available for patients with COPD. They do, however, need to be validated in a second group of patients with COPD and similar physical characteristics.

The behavior of an electric current flowing through body tissue is influenced by the characteristics of the current. A wide range of factors such as the distribution of body fat around the chest, lung volume, skin rigidity, height, and weight all influence current transmission, and consequently, changes in tissue impedance. Other factors that occur within the chest in different diseases, such as rigidity, obstruction, and air trapping, can also alter current flow. This complicates the matter of calibration even further as different diseases alter lung tissues in a different manner, meaning that separate calibration systems would be required for different types of disease.

Figure. Band-Altman Plot. Distribution of tidal volume measurements with respect to pneumotachometer values. EIT, electrical impedance tomography; SD, standard deviation.
One solution would be to use EIT to monitor breathing pattern only and not to measure volume. Given the lack of a simple, quick procedure that could be used to evaluate from the outset the main variables that might modify current flow through the chest, EIT should be used only to assess changes over time, regardless of true tidal volume. An alternative would be to perform measurements simultaneously with an EIT unit and a pneumotachometer, but this would not eliminate the need for consecutive measurements over a long period of time.

**Funding**

This study was funded by grants from the Breathe Network (Red Respira) of the Instituto de Salud Carlos III, the Spanish Society of Pulmonology and Thoracic Surgery (SEPAR), and La Marató de TV3.

**References**