ORIGINAL ARTICLES

Monitoring of Breathing Pattern at Rest by Electrical Impedance Tomography

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OBJECTIVE: Electrical impedance tomography (EIT) involves the application of a small alternating current to produce a series of chest images that can be used to monitor breathing pattern. The relation between chest images and tidal volume has not been sufficiently validated. The aim of the present study was to analyze the correlation between EIT images and the volume–time signal measured with a pneumotachometer in 13 healthy volunteers.

MATERIAL AND METHODS: The following measurement devices were used: *a)* MedGraphics preVent™ Pneumotach, with special software for recording the volume–time signal (reference test), and *b)* EIT-4, a fourth-generation prototype unit designed by the Department of Electronic Engineering at the Universidad Politécnica de Cataluña, Spain that records the volume–time signal and produces a graphic depiction of a cross section of the thorax at the sixth intercostal space.

RESULTS: The mean (SD) tidal volume measured by the pneumotachometer and the EIT-4 was 0.523 (0.102) L and 0.527 (0.106) L, respectively (*P* value not significant). The linear correlation coefficient between the 2 measurements was 0.923 (*P*=.001), and the mean of the differences between the 2 procedures was –0.003 L (95% confidence interval, –0.045 to 0.038). The greatest differences were associated with female gender, body mass index, and chest circumference. In view of these differences, a different equation based on these variables was needed for calibration of the EIT-4.

CONCLUSIONS: The EIT-4 provides an alternative means of monitoring breathing pattern, although a number of issues related to the circumference of the rib cage need to be resolved.

Key words: *Electrical Impedance Tomography. Breathing pattern. Pneumotachometer.*

Seguimiento del patrón ventilatorio en reposo mediante tomografía por impedancia eléctrica

OBJETIVO: La tomografía por impedancia eléctrica (TIE) permite realizar un seguimiento del patrón ventilatorio a partir de una secuencia de imágenes torácicas obtenidas por la captación de una corriente alterna de baja intensidad. La relación entre las imágenes torácicas y el volumen circulante no está suficientemente validada. El propósito del presente estudio ha sido comparar, en un grupo de 13 voluntarios sanos, la correspondencia entre las imágenes de la TIE y la señal volumen/tiempo obtenida mediante un neumotacómetro.

MATERIAL Y MÉTODOS: Los equipos que se utilizaron para las mediciones fueron: *a)* MedGraphics prevent TM™ Pneumotach, implementando el *software* adecuado para registrar las señales volumen/tiempo (prueba de referencia), y *b)* TIE-4, cuarta versión de un equipo diseñado por el Departamento de Ingeniería Electrónica de la Universidad Politécnica de Cataluña, que permite tanto el registro de la señal volumen/tiempo como una representación gráfica de la sección transversal situada en el sexto espacio intercostal.

RESULTADOS: La media ± desviación estándar de volumen circulante obtenida mediante el neumotacómetro fue de 0,523 ± 0,102 l, y con la TIE-4, de 0,527 ± 0,106 l (p no significativa). El coeficiente de correlación lineal entre ambas determinaciones fue de 0,923 (p = 0,001). La media de las diferencias entre ambos procedimientos fue de –0,003 l (intervalo de confianza del 95%, –0,045 a 0,038). Las mayores diferencias estaban relacionadas con el sexo femenino, el índice de masa corporal y el contorno torácico, lo que obligó a una ecuación diferente para calibrar la TIE-4 en función de estas variables.

CONCLUSIONES: La TIE-4 se presenta como un método alternativo para realizar el seguimiento del patrón ventilatorio, aunque deben resolverse aspectos relacionados con la conformación de la caja torácica.

Palabras clave: *Tomografía por impedancia eléctrica. Patrón ventilatorio. Neumotacómetro.*

Introduction

The breathing pattern is determined by a complex system of receptors, pathways, integration sites, and effector organs, all of which together make up the respiratory system. It has traditionally been expressed by the equation: ventilation = tidal volume × respiratory rate, or alternatively:

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ventilation = tidal volume/inspiratory time $\times$ inspiratory time/total respiratory time. The parameters of the second equation are better indicators of respiratory drive and rhythm.[1] The breathing pattern is normally measured using a pneumotachometer, but this apparatus alters respiration because it requires the patient to use a mouthpiece. Respiratory inductive plethysmography is an alternative measurement system that does not interfere with breathing dynamics.[2]

Electrical impedance tomography (EIT) is a noninvasive imaging technique that can be used to produce chest images during spontaneous breathing. Its effectiveness in determining single lung function[3] and other aspects of the respiratory system[4] has been demonstrated and the procedure has been sufficiently standardized for use in respiratory medicine.[5]

A simple, cheap, noninvasive unit for measuring breathing pattern, however, is still needed in respiratory medicine. Moreover, an EIT unit capable of storing a large number of signals and of monitoring breathing pattern for long periods would also be a welcome development. The main aim of this study was to test how well a fourth-generation EIT prototype unit (EIT-4) could monitor resting breathing pattern. We were also interested in comparing the data obtained from the EIT-4 with reference data obtained from a pneumotachometer in a group of healthy volunteers, and in describing the main advantages and disadvantages of using EIT for monitoring breathing pattern.

Materials and Methods

Pneumotachometer

We used the MedGraphics preVent™ Pneumotach (Medical Graphics Corporation, St. Paul, Minnesota, USA) controlled by software supplied by the manufacturer to record continuous inline measurements of flow and time signals. The results were recorded both graphically and numerically. The pneumotachometer was calibrated using a 3-L syringe in accordance with standard laboratory protocols (acceptable difference <1%).

EIT-4

The EIT-4 is a fourth-generation prototype unit designed by the Department of Electronic Engineering at the Universidad Politécnica de Cataluña, Spain. It can be used to produce a volume–time signal (tidal volume) from a graphic depiction of a cross section of the chest at the sixth intercostal space. The unit was calibrated using a 64×64-pixel reference image. For each volunteer, we input 2 parameters, A and B, to calculate the final impedance signal. These parameters varied according to the physical characteristics of each volunteer and were calculated on completion of the initial test (see Discussion section). The impedance signals were measured via 16 electrodes (Red Dot 2560; 3M, London, Ontario, Canada) placed around the individual's chest (Figure 1). The EIT-4 generated a 48-kHz current, which was then distributed by a pair of multiplexers to one of the electrode pairs on the volunteer for current injection. The other electrodes sequentially measured the voltages on the surface of the patient's chest via a detector system. Once all the readings had been recorded for the first electrode pair, the injection point was changed to the next electrode pair and a new cycle began. The procedure was repeated until all the electrodes had been used as injectors and detectors. The EIT-4, once tested, was then used for further measurements.[3,5]

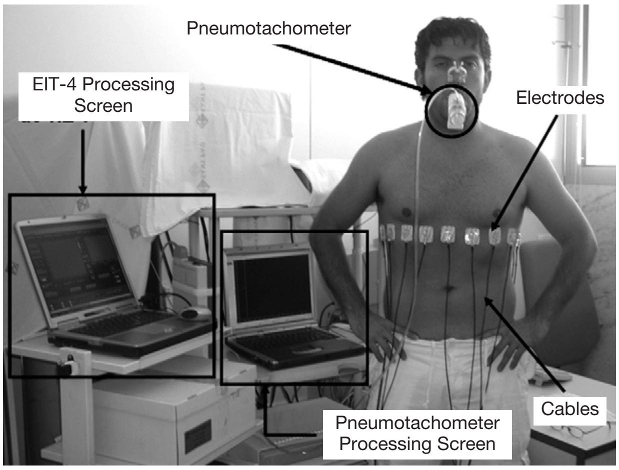

Figure 1. Arrangement of 2 units. On the right, the electrodes around the chest. The pneumotachometer is connected to the volunteer's mouth. On the left, the computer equipment used for the study. Both tests were controlled with a laptop computer. EIT indicates electrical impedance tomography.

Volunteers

The study enrolled 13 healthy volunteers (6 males and 7 females) aged between 20 years and 55 years. They were all nonsmokers with spirometry values within the normal range. The tests were performed in a quiet room at sea level with an ambient temperature of 25ºC and a relative humidity of 60%. Testing lasted for 4 weeks and always took place between 9 AM and noon.

Procedure

The 2 measurement units (the pneumotachometer and the EIT-4) were mounted in parallel and operated independently of each other with no mutual interference. The breathing patterns of the volunteers at rest were recorded numerically and graphically for periods of 30 seconds with a 3-minute rest period between measurements. Between 5 and 8 respiratory cycles were captured for each measurement and a total of 20 to 25 cycles were analyzed for each individual. Data are presented as means (SD). Before measuring the breathing pattern of each volunteer, we recorded anthropometric data (height, weight, body mass index), gender, and age, and measured the chest circumference at rest and during maximum inspiration and expiration. We also measured skinfold thickness (at the front, side, and back of the chest) using electronic skinfold calipers.

TABLE 1
Sex, Age, Anthropometric Characteristics—Height, Weight, and Body Mass Index—, and Chest Circumference and Skinfold Measurements of the Volunteers*

Volunteer	Sex	Age, y	Height, m	Weight, kg	BMI kg/m²	Chest Circumference, cm			Skinfold, mm		
						Insp	Exp	At rest	Front	Back	Side
1	M	23	1.84	73	21.6	92	84	87	12	15	9
2	M	29	1.81	87	26.6	104	98	100	23	29	22
3	M	19	1.82	74	22.2	86	81	84	12	15	11
4	M	23	1.83	79	23.6	93	86	87	12	12	12
5	M	30	1.66	60	21.8	92	82	88	12	12	12
6	M	51	1.68	75	26.6	103	97	100	16	28	17
7	F	51	1.62	77	29.3	87	84	85	14	21	16
8	F	54	1.61	61	23.5	81	77	79	16	19	19
9	F	46	1.58	66	26.4	80	77	77	17	17	10
10	F	50	1.53	55	23.5	80	76	77	19	19	20
11	F	25	1.65	63	23.1	78	74	76	15	17	11
12	F	27	1.70	70	24.2	79	75	76	15	18	16
13	F	49	1.58	54	21.6	79 7	5	76	18	18	18
Mean		36.7	1.68	68.8	24.2	87.2	82	84	15.5	18.5	14.8
SD		13.4	0.11	9.9	2.4	9.0	7.9	8.5	3.3	5.2	4.2

*BMI indicates body mass index; Insp, inspiration; Exp, expiration; M; male; F; female.

We began recording respiratory cycles once both units had been calibrated, the 16 electrodes had been attached to the patient, and the pneumotachometer (Figure 1) had been connected. Three separate readings for each individual were stored in txt- and asc-extension files for subsequent processing.

Statistical Comparison

The resulting data were compared using a 1-tailed Student *t* test for paired data, the Spearman correlation coefficient for nonparametric data, and Bland-Altman analysis. A multivariate approach was used to calculate the parameters A and B for the EIT-4 from the volunteers'

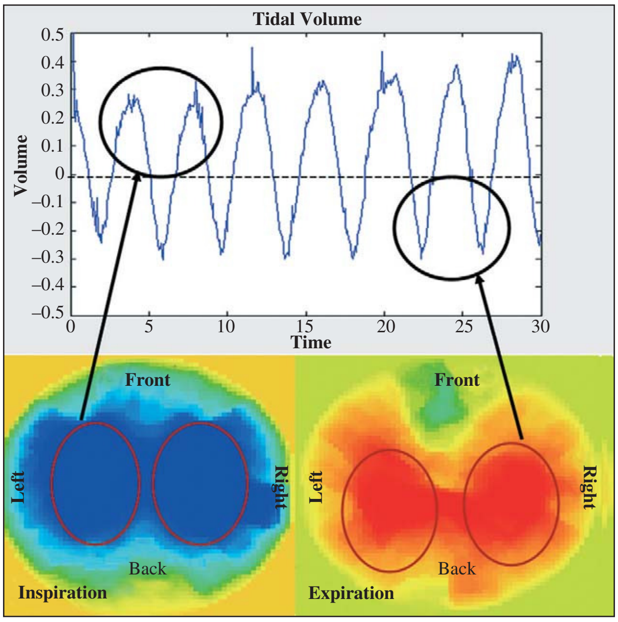

Figure 2. The lower panel shows electrical impedance tomography image obtained during maximum inspiration and expiration for calculating tidal volume, shown in the top panel.

TABLE 2
Calibration Parameters A and B for Fitting EIT signal (See text) and Tidal Volume Measured by Pneumotachometer and EIT-4

Volunteer	A	B	Tidal Volume, L	
			Pneumotachometer	EIT-4
1	1477	–542	0.538 (0.057)	0.521 (0.053)
2	826	170	0.513 (0.063)	0.506 (0.065)
3	1431	143	0.499 (0.072)	0.501 (0.078)
4	1293	44	0.606 (0.081)	0.654 (0.110)
5	2054	458	0.680 (0.107)	0.679 (0.103)
6	1091	–45	0.711 (0.089)	0.712 (0.069)
7	1610	–143	0.390 (0.036)	0.378 (0.033)
8	847	–44	0.491 (0.049)	0.526 (0.050)
9	1407	–249	0.535 (0.058)	0.500 (0.058)
10	989	–357	0.382 (0.051)	0.389 (0.057)
11	1498	–556	0.427 (0.049)	0.431 (0.046)
12	1623	–348	0.582 (0.069)	0.596 (0.073)
13	1036	–29	0.451 (0.053)	0.454 (0.045)

*Values are given as means (SD). EIT indicates electrical impedance tomography.

anthropometric and physical characteristics. Statistical significance was set at *P* less than .05.

Results

The volunteers had a mean (SD) age of 37 (13) years, height of 1.68 (0.11) m, weight of 69 (10) kg, and body mass index of 24.2 (2.4) kg/m². The mean (SD) chest circumference at rest and during maximum inspiration and expiration was 84 (8.5) cm, 87.2 (9) cm, and 82 (7.9) cm, respectively. The mean (SD) skinfold measurements at the front, back, and side of the chest were 15.5 (3.3) mm, 18.5 (5.2) mm, and 14.8 (4.2) mm, respectively. The data corresponding to each of the 13 volunteers are shown in Table 1.

The mean (SD) tidal volume measured by the pneumotachometer and the EIT-4 was 0.523 (0.102) L and 0.527 (0.106) L, respectively (*P* value not significant)

(Table 2). The respiratory rate readings were identical for both units, which is to be expected as they were connected simultaneously and in parallel. Comparison of these rates, however, was not an aim of this study.

The linear correlation coefficient between the 2 tidal volume measurements was 0.923 (P=.001). The distribution of differences of means between the readings (concordance analysis) is shown in Figure 2. The mean of the differences was –0.003 L (95% confidence interval, –0.045 to 0.038).

The values of the parameters A and B used to adjust the EIT-4 to each individual are shown in Table 2.

Discussion

Respiratory medicine specialists have still not achieved their goal of being able to measure resting breathing pattern using a simple, noninvasive procedure that does not interfere with the dynamics of breathing. The conclusive results obtained from a group of healthy volunteers represent a promising step in the right direction. Our statistical comparison of tidal volume measurements taken by the EIT unit with reference measurements from a pneumotachometer indicates that EIT and pneumotachometry could well be interchangeable.

One of the first conclusions to emerge from our findings is that disruption to the breathing pattern caused by the pneumotachometer can be kept to a minimum provided the apparatus is used carefully, the individual is at rest, the measurements are preceded by a period of adaptation, and the reading is averaged over a large number of cycles. This is supported by findings from other studies[6] and the fact that we found only very slight differences between the 2 procedures analyzed in our study.

EIT provides an alternative means of measuring breathing pattern. It is a simple procedure and offers many advantages that make it worthy of consideration: the electrodes are easy to place around the patient's chest, and the unit emits no radiation, does not interfere with the dynamics of breathing, and can store a large number of signals. We did, however, encounter a number of problems, described below, and believe that further improvements need to be made to both the unit and the procedure.

The electrodes used to transmit and capture the electrical signal were of high quality. They were applied to a previously shaved chest and the conductance was high. They were also connected to the data processing unit via a 2-m, 50-ohm coaxial cable to limit interference. Despite these precautions, however, one of the greatest problems we encountered when recording signals was the noise (alternating current) caused by electrode movement or poor cable contact. This problem could not always be avoided and was responsible for errors of over 10% in some cases. The presence of noise obliged us to repeat measurements in 3 of the 13 volunteers and prevented us from computing respiratory drive and rhythm. Future prototypes need to be improved in order to filter out these signals in real time and improve the quality of the readings.

A second problem was the need for the simultaneous use of the pneumotachometer and the EIT-4 for the initial measurement. The fact that each individual has different physical characteristics meant that in order to calibrate the EIT-4 correctly for each individual, we had to calculate the parameters, A and B, using a polynomial equation[7] that included maximum chest circumference and the skinfold measurement. This information had to be fitted to a known tidal volume from the initial reading. To assign values to A and B, we averaged the minimum and maximum peaks for the signals produced by the pneumotachometer and the EIT-4. For the EIT-4, we plotted the number of counts on the y axis and the time along the x axis. The averages obtained were then entered into the following equations:

$$A = \frac{\text{Average of maximum counts} - \text{average of minimum counts}}{\text{Average maximum volume} - \text{Average minimum volume}}$$

$$B = \text{Average of maximum counts} - (\text{average maximum volume} \times A)$$

Once we had calculated A and B, we entered these into the EIT-4 via the main control panel and processed the asc-extension files with the data for the individual being tested. We then compared the tidal volume measurements produced by both units. The parameters A and B were unique for each volunteer. This is a drawback that can only be overcome in future versions of the prototype with the creation of alternative algorithms capable of interpreting the electrical signal according to the different physical characteristics of each individual.

In conclusion, despite the need to calibrate the EIT-4 according to the shape of each chest (with greater difficulties in reading data in individuals with obesity or chest deformities), the presence of unpredictable noise, and the need to use the pneumotachometer, at least during the first series of measurements, the EIT-4 could, in the not-so-distant future, provide respiratory medicine specialists with a cheap, reliable, simple, reproducible, and noninvasive means of monitoring breathing pattern. However, renewed efforts to improve the existing prototype and increase its signal-storage capacity are needed before the EIT can become a routine tool for monitoring respiratory function and controlling certain diseases.

REFERENCES

1. Cotes JE. Lung function. Assessment and application in medicine. 5th ed. Oxford: Blackwell Scientific Publications; 1993.
2. Konno K, Mead J. Measurement of the separate volume changes of rib cage and abdomen during breathing. J Appl Physiol. 1967;22: 407-22.
3. Serrano E, de Lema B, Casas O, Feixas T, Calaf N, Camacho V, et al. Use of electrical impedance tomography (EIT) for the assessment of unilateral pulmonary function. Physiol Meas. 2002; 23:211-20.
4. Harris ND, Sugget AJ, Barber DC. Applications of applied potential tomography (APT) in respiratory medicine. Clin Phys Physiol Meas. 1987;8:155-65.
5. de Lema B, Casan P, Riu PJ. Tomografía por impedancia eléctrica. Estandarización del procedimiento para su aplicación en neumología. Arch Bronconeumol. 2006;42:299-301.
6. Calverley PMA. Control of breathing. Lung function testing. In: Gosselink R, Stam H, editors. European respiratory monograph. 2005;10;44-56.
7. Coulombe N, Gagnon H, Marquis F, Skrobik Y, Guardo R. A parametric model of the relationship between EIT and total lung volume. Physiol Meas. 2005;26:401-11.