ORIGINAL ARTICLES

Assessment of Differential Lung Function by Electrical Impedance Tomography

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OBJECTIVE: To compare differential lung function estimated by 2 methods: electrical impedance tomography (EIT) and ventilation-perfusion lung scintigraphy.

PATIENTS AND METHODS: This prospective clinical study was carried out in the pulmonary function laboratory of a general hospital. Twenty patients diagnosed with lung cancer (17 men and 3 women, ranging in age from 25 to 77 years) who were candidates for lung resection underwent ventilation-perfusion lung scanning breathing radioactive gas.

Differential lung function was estimated based on images taken at 2 intercostal spaces in which ventilation and perfusion were represented by changes in bioelectrical impedance. Each lung's contribution to overall respiratory function was also calculated based on scintigraphy.

RESULTS: The right lung contributed a mean (SD) of 54% (9%) of ventilation (range, 32%-71%) according to EIT. Scintigraphy similarly estimated the right lung's contribution to be 52% (10%) of total ventilation (range, 31%-80%) and 50% (9%) of perfusion (range, 37%-71%). The difference between the 2 estimates was not significant (t test), and the correlation coefficients between them were *r* = 0.90 for ventilation and *r*=0.72 for perfusion (*P*<.05 in both cases). The analysis of agreement showed that the mean difference between the methods was 1.9% (95% confidence interval [CI], 10.5% to –6.8%) for ventilation and 3.4% (95% CI, 17.1% to –10.3%) for perfusion.

CONCLUSIONS: EIT is able to estimate differential lung function as accurately as ventilation-perfusion scintigraphy.

Key words: *Differential lung function. Electrical impedance tomography. Lung cancer.*

Evaluación de la función pulmonar unilateral mediante tomografía por impedancia eléctrica

OBJETIVO: Comparar la función pulmonar unilateral (FPU) estimada mediante tomografía por impedancia eléctrica (TIE) con la misma determinación obtenida a partir de la gammagrafía de ventilación y perfusión pulmonar

PACIENTES Y MÉTODOS: Se trata de un estudio clínico prospectivo, realizado en un laboratorio de función pulmonar de un hospital general. Se incluyó a 20 pacientes diagnosticados de cáncer de pulmón (17 varones y 3 mujeres, con edades comprendidas entre los 25 y los 77 años), candidatos a cirugía resectiva pulmonar, a quienes se realizó un estudio de ventilación/perfusión pulmonar con radioisótopos.

La FPU se calculó a partir de imágenes en 2 espacios intercostales en las que se representaban la ventilación y la perfusión relacionadas con los cambios en la bioimpedancia eléctrica. Se determinó asimismo la participación de cada pulmón en la función global a partir de estudios isotópicos.

RESULTADOS: El valor promedio ± desviación estándar de ventilación en el pulmón derecho obtenido mediante TIE fue del 54 ± 9% (rango: 32-71%). El mismo valor mediante radioisótopos fue del 52 ± 10% (rango: 31-80%) para la ventilación y del 50 ± 9% (rango: 37-71%) para la perfusión (prueba de la t de Student, p no significativa). El coeficiente de correlación entre ambas determinaciones fue de r = 0,90 (p < 0,05) para la ventilación y de r = 0,72 (p < 0,05) para la perfusión. El análisis de concordancia mostró una media de las diferencias del 1,9% (intervalo de confianza del 95%, del 10,5 al –6,8%) para la ventilación y del 3,4% (intervalo de confianza del 95%, entre el 17,1 y el –10,3%) para la perfusión.

CONCLUSIONES: La TIE es capaz de cuantificar la FPU con una precisión similar a la gammagrafía de ventilación o perfusión con radioisótopos.

Palabras clave: *Función pulmonar unilateral. Tomografía por impedancia eléctrica. Cáncer de pulmón*

Introduction

Lung function tests provide information about how the respiratory system is performing as a whole. However, in certain circumstances, such as when a patient is being

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evaluated for lobectomy or pneumonectomy, decisions must be based on knowing the contribution of each lung.[1] Several procedures have been developed to estimate what is referred to as "unilateral" or differential lung function, among them temporary unilateral occlusion of the pulmonary artery,[2] bronchospirometry,[3] testing in decubitus position on alternate sides,[4] ventilation-perfusion scintigraphic lung scans,[5,6] computed tomography,[7] and, more recently, lung sound vibration response analyzed by imaging or collection of raw numerical data.[8] Among these, perfusion scanning to detect technetium-labeled microaggregated (^{99m}Tc) albumin is currently considered the gold standard.[9] However, as that technique uses ionizing radiation and is available only in large hospitals given the special conditions and equipment required, less costly procedures that would be within the reach of lung function laboratories in any hospital are of great interest.

Electrical impedance tomography (EIT), a means for obtaining quantifiable images based on the passage of electrical current through anatomic structures, has been applied in respiratory medicine.[10] Among the main advantages of EIT are the absence of radiation, portability, easy handling, and low cost. Technological advances in this type of equipment have made possible diverse clinical applications in respiratory medicine, examples of which are the characterization of ventilatory pattern and pleural effusions[11] and the quantification of perfusion in each lung.[12]

We aimed to compare the estimation of differential lung function by EIT to the findings of ventilation-perfusion lung scanning with the patient breathing radioactive gas in a group of patients diagnosed with lung cancer who were being evaluated as candidates for resection.

Patients and Methods

Patients

Twenty patients diagnosed with lung cancer (17 men and 3 women), ranging in age from 25 to 77 years (mean [SD], 65 [18] years) were enrolled consecutively for evaluation prior to lung resection surgery. All were undergoing ventilation-perfusion scintigraphy to assess surgical risk.

Study Design

Studies were carried out in the lung function laboratory of the nuclear medicine department of our hospital. Respiratory function tests, carried out in accordance with the recommendations of the Spanish Society of Pulmonology and Thoracic Surgery (SEPAR), were as follows: spirometry, static lung volumes, carbon monoxide diffusing capacity, and arterial blood gases. Patients were assigned randomly to begin evaluation of differential lung function with either the scintigraphic scan or EIT. The 2 tests were done on consecutive days. The hospital ethics committee approved the study and written informed consent was obtained from each patient.

EIT Procedure

The tests were carried out with a 16-electrode device (TIEsys-4) built by engineers belonging to the research group (E. S. and P. J. R). The TIEsys-4 had been previously validated in the laboratory for use in this and other procedures.[12] The TIEsys-4 met the quality and safety specifications of the International Electrotechnical Commission (IEC 60601-1, 1992) for medical electrical equipment. Signals were received at a rate of 10 images/s. An average of 300 images were obtained in duplicate.

Readings were taken at the fourth and sixth intercostal spaces by high quality electrodes (Red Dot 2560, 3M, London, Ontario, Canada) placed on clean skin. The patient was seated comfortably with arms folded and supported,[11] and the electrodes were then placed at the previously located points. Electrode number 0 was placed on the sternum, number 4 on the left midaxillary line, number 8 on the right midaxillary line, and number 12 on the spinal column. The 12 remaining electrodes were distributed at regular intervals between those 4 points. The leads were then connected and the patient's chest covered with elastic mesh to hold the electrodes in place.

Bioimpedance signals were reconstructed by assigning a circular form to the transaxial slice of the chest and filtering to separate the cardiac signals from the respiratory ones. Each lung's contribution to total ventilation was calculated as a percentage based on the number of pixels in the images within each circle.

Ventilation-Perfusion Scanning Procedure

To obtain ventilation scans, the patient was seated comfortably, breathing 74 MBq of ^{99m}Tc-labeled graphite particles (2 mCi) delivered evenly to both lungs through a mouthpiece connected to a closed circuit. Images corresponding to radioisotope distribution were then acquired using a gamma camera (Symbia, Siemens, Erlanguin, Germany) equipped with a low-energy, high-resolution collimator. The results were expressed as the percentage contribution of each lung.

For the perfusion scan, the patient was placed in supine decubitus position and a peripheral vein was catheterized for injection of 296 MBq (8 mCi) of ^{99m}Tc-labeled albumin macroaggregates while the patient breathed deeply during 3 vital capacity maneuvers. The distribution of the radioisotope was captured and quantified by the aforementioned gamma camera.

Statistical Analysis

Results are presented as mean (SD) and compared by *t* test for paired values. Pearson linear correlation coefficients were also calculated. Bland-Altman plots were used to analyze agreement between the methods. A value of P less than .05 was considered significant in all cases.

Results

The right lung contributed a mean (SD) 54% (9%) of total ventilation (range, 32%-71%) according to EIT. Estimated by scintigraphy, the right lung's contribution was a mean 52% (10%) of ventilation in this group (range, 31%-80%). Mean right lung perfusion by scintigraphy was 50% (9%) (range, 37%-71%). The *t* test for paired samples demonstrated that none of the differences were significant. The Pearson linear correlation coefficients between values obtained by EIT and scintigraphy were r=0.90 (P<.05) for ventilation and r=0.72 (P<.05) for perfusion.

The mean difference between ventilation estimated by EIT and scintigraphy was 1.85% (95% confidence interval [CI], 10.5 to –6.8%). A single patient (number 5) had estimated values lying outside the 95% CI. The mean

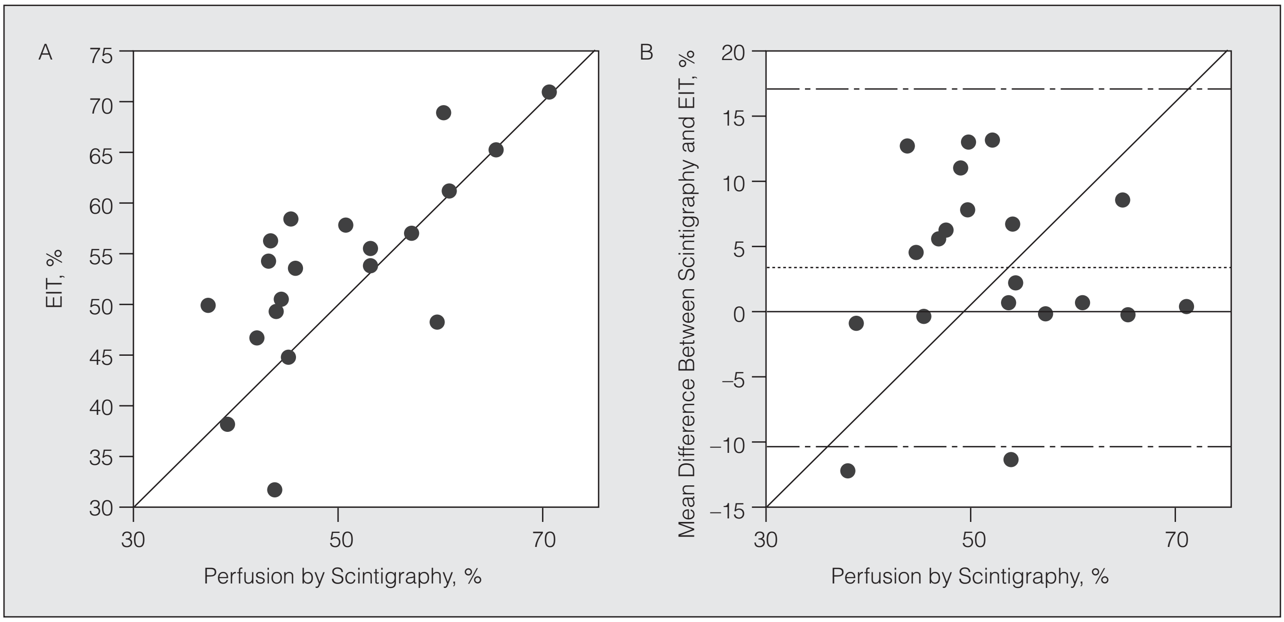

Figure 1. A: The Pearson linear correlation between right lung perfusion estimated by electrical impedance tomography (EIT) and scintigraphic scanning. B: Bland-Altman plot depicting agreement between the 2 methods.

difference between perfusion estimated by EIT and scintigraphy was 3.4% (95% CI, 17.1% to –10%). The perfusion estimates of 2 patients (numbers 8 and 9) lay outside the 95% CI. The 3 patients with outlying values had medical histories that included thoracic surgery prior to assessment of lung function. Results for all patients are summarized in the Table. Figures 1 and 2 show the analyses of agreement.

Discussion

EIT has recently been introduced into respiratory medicine and clinical applications are still being assessed. This study aimed to evaluate the utility of the technique for determining differential lung function. Our results demonstrate good agreement with estimates of ventilation and perfusion obtained by scintigraphy, confirming the findings of Kunst and coworkers[13] in a similar group of patients. Hinz and coworkers[14] also reported similar results in animals when they compared EIT estimates with assessments of differential lung function based on single-photon emission computed tomography.

We had previously validated EIT in a group of healthy volunteers.[11] In that study, the correlation between theoretical estimates for each individual and the contribution of each lung as a percentage of the total, as well as the analysis of agreement, allowed us to hypothesize the usefulness of EIT for clinical purposes. However, we observed that the results were less reliable for 3 patients who had previously undergone thoracic surgery. The shape of the thorax seems to play a role in generating differences that may be partly attributable to the method used to reconstruct images acquired by EIT or to the signal coming from the chest. The model used in calculations supposes the thorax forms a circle with a "homogeneous" or "common" distribution of internal structures,[15] differing from the shape of a thorax with external defects or internal modifications. These influences must be taken into consideration when attempting to use EIT if such anatomical anomalies are present.

Another issue to bear in mind is electrical noise in EIT

TABLE
Patient Characteristics and Right Lung Function Results

Patient	Sex	Age, y	FVC, %	FEV_1, %	V, %	P, %	EIT, %
1	M	77	104	71	53.8	44.4	50.4
2	M	59	84	75	60.5	60.3	68.9
3	F	72	121	122	53.1	53.3	55.5
4	M	52	103	84	38.4	39.2	38.3
5	M	25	60	59	80.1	70.6	70.9
6	M	58	99	61	63.6	65.4	65.2
7	M	67	61	68	48.6	45.4	58.5
8	M	49	86	32	31	43.8	31.9
9	M	60	86	79	53.4	59.6	48.3
10	F	76	87	80	49.3	37.4	50
11	M	47	87	67	50.9	45.8	53.7
12	M	50	104	71	47.8	43.4	54.3
13	M	56	75	49	52.1	53.2	53.9
14	F	58	76	78	54.9	50.9	57.7
15	M	67	62	44	44.2	43.9	49.5
16	M	71	69	45	52	43.5	56.3
17	M	69	71	58	44.3	45.2	45
18	M	65	69	43	55.8	60.8	61.3
19	M	66	65	75	56	57	57
20	M	57	95	90	47.2	42.2	46.8

Abbreviations: EIT, electrical impedance tomography; F, female; FEV_1, forced expiratory volume in 1 second; FVC, forced vital capacity; M, male; P, right lung perfusion estimated by scintigraphy; V, right lung ventilation estimated by scintigraphy.

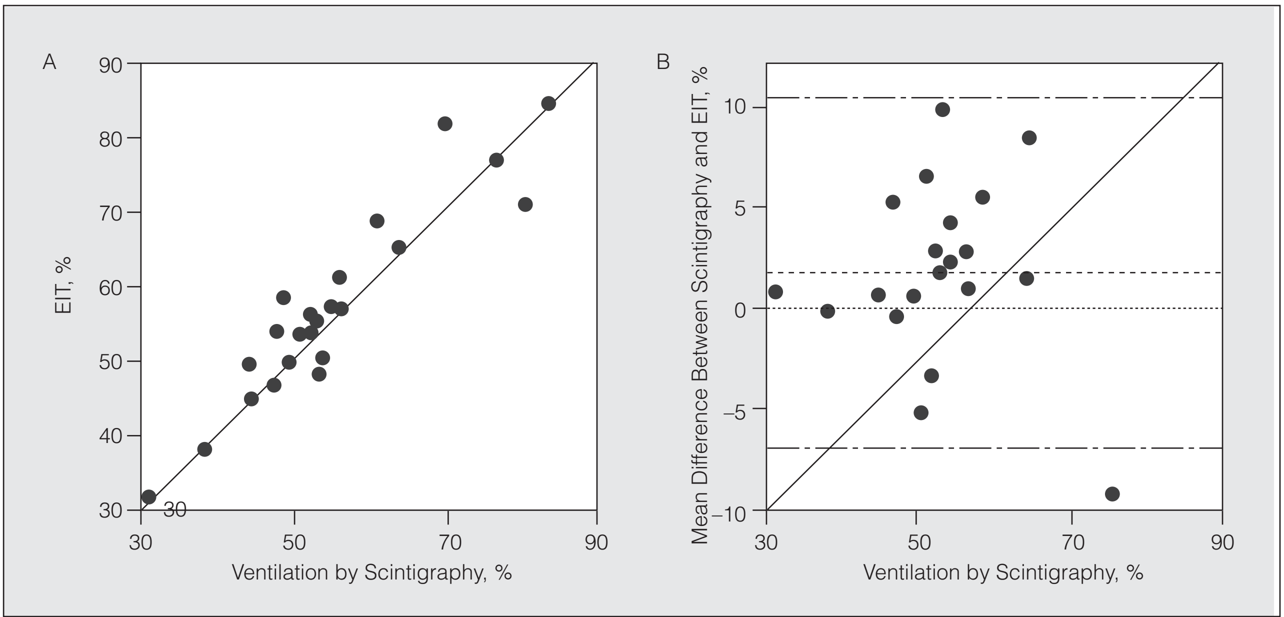

Figure 2. A: The Pearson linear correlation between right lung ventilation estimated by electrical impedance tomography (EIT) and scintigraphic scanning. B: Bland-Altman plot depicting agreement between the 2 methods.

signals, the result of the difficulty of electrical transmission across the thorax and of other artifacts. Electrode quality, the need for thorough cleansing of the skin at the points of contact, presence or absence of hair, and quality of leads are examples of conditions that may affect the reception and processing of signals. Some of these problems have been documented previously,[11] but they cannot always be resolved in actual practice.

Another aspect of interest is the reduction in the number of electrodes in order to simplify the procedure for acquiring signals. We attempted to reduce the number from 16 to 8, but the results were insufficiently conclusive to allow extrapolation to all measurements at this time.[16]

Given the small size of the sample studied and the difficulty of following these patients, we were able to undertake spirometry 6 months after resection in only 4 cases (patients 2, 7, 11, and 14 in the Table). The theoretical values of forced expiratory volume in 1 second (FEV_1) predicted by scintigraphy were 53%, 44%, 41% and 55%, respectively, for these patients. Their FEV_1 values predicted by EIT were 50%, 48%, 40% and 50%, respectively. The values actually measured were 56%, 50%, 43% and 57%, respectively. The small number of cases makes statistical comparison unnecessary, though the values appear to be highly similar.

In summary, EIT makes use of simple technology that is within the reach of hospitals that are not particularly specialized. Furthermore, it does not require the use of ionizing radiation and is inexpensive. EIT has certain advantages for use in determining differential lung function in patients who are candidates for resection. However, there remain disadvantages. There is still a need for simpler, better-designed equipment. The difficulty of interpreting EIT signals for patients with thoracic defects or a history of thoracic surgery also obliges caution when using this technique. Further studies in a variety of circumstances will be needed in order to evaluate when EIT should and should not be used.

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