Evaluation of Transthoracic Electrical Impedance in the Diagnosis of Pulmonary Edema

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SUMMARY To evaluate the clinical usefulness of measuring transthoracic electrical impedance in patients with pulmonary edema, we studied 27 normal subjects and 33 patients. In normal subjects, impedance increased when body position changed from supine to standing (p < 0.01) and when lung volume increased from residual volume to total lung capacity (p < 0.01). Impedance values varied (±2.7 Ω) when measured on 4 separate days but were relatively constant (± 0.7 Ω) when measured hourly without removing the electrodes. In only five of 11 patients with clinically severe pulmonary edema and five of eight with radiologically severe pulmonary edema were impedance values outside the normal range. Changes in impedance values correlated with changes in clinical and radiographic indexes of pulmonary edema. We conclude that (1) single measurements of impedance are useless in diagnosing pulmonary edema, and (2) impedance changes as predicted as pulmonary edema increases and decreases, and these changes are readily detected by simpler methods of evaluation.

DETECTION OF PULMONARY EDEMA before the clinically obvious stage of alveolar flooding has been a long-sought-after but elusive goal. The inadequacies of physical and radiologic examinations1 and of pulmonary function testing2,3 as means of diagnosing early pulmonary edema are well documented. Thus the availability of transthoracic electrical impedance monitoring, a new, simple, noninvasive method for detecting and quantifying pulmonary edema, is of interest because of its considerable potential clinical value. This technique has been used to evaluate pulmonary edema in a variety of clinical states4,5 and in animal models of both increased permeability6,7 and hydrostatic pulmonary edema.4,5 Despite these studies, no systematic attempt has been made to relate impedance measurements to clinical and roentgenographic indexes commonly used to assess pulmonary edema. The purpose of this study was twofold: first, to examine the determinants of transthoracic impedance values in normal subjects, and second, to compare the results of changes in impedance measurements in patients with and without pulmonary edema with changes in physical and radiologic examinations, blood gas determinations, serial body weight measurements and pulmonary capillary wedge pressures. From these observations, the role of transthoracic electrical impedance in the diagnosis and management of patients with known or suspected pulmonary edema can be defined realistically.

Methods

Normal Subjects

Twenty-seven nonsmoking, healthy clinical and laboratory personnel, ages 22-50 years, were studied using a commercially available tetrapolar impedance plethysmograph (Chest Fluid Monitor, Instrumentation for Medicine, Inc., Greenwich, Connecticut). This device applies a constant alternating current (4 mA, 100 kHz) through two electrodes (#1 and #4) to a tissue segment and measures the voltage drop across it with two other electrodes (#2 and #3). An increase in fluid within the segment being analyzed increases the conductivity of the medium and decreases the impedance. Details of the theory and applications of this method were reported by Kubicek et al.8

Aluminum-coated plastic electrodes (Cardiograph Tape, 3M Co., Minneapolis, Minnesota) were placed according to the instructions supplied by the impedance plethysmograph’s manufacturer. Electrode 1 was placed at the top of the neck, electrode 2 at the base of the neck, electrode 3 at the level of the xiphosternal junction, and electrode 4 at the caudal end of the rib cage. The electrodes are adhesive and no paste is required.

The effects of changes in body position and lung volume were determined by measuring impedance in each subject in three positions (supine, seated and standing) at three lung volumes (total lung capacity, functional residual capacity and residual volume). Linear regression analysis was used to examine the effect of changes in age, height, weight, position, lung volume, single breath-diffusing capacity for carbon monoxide (DLco) and dimensions of the chest on impedance. Day-to-day variability of impedance was determined by repeating the measurements in 11 normal subjects on 4 separate days, with the electrodes...
removed after each study. These results were compared with four measurements made hourly without removing the electrodes in 12 patients who had no evidence of pulmonary edema and who were clinically and radiologically stable. These measurements were all obtained at functional residual capacity with the subjects or patients in the supine position.

Patients

Thirty-three unselected patients being treated in the respiratory or coronary care units at San Francisco General Hospital Medical Center were studied after informed consent was obtained. All had transthoracic impedance monitored with the electrodes continuously in place during a 24-hour period. The results of changes in impedance values were compared with changes in simultaneously obtained measurements of alveolar-arterial oxygen tension difference after breathing 100% oxygen and with changes in serial assessments of body weight and clinical and radiologic status. Pulmonary capillary wedge pressures were obtained in 11 patients in whom pulmonary arterial catheterization was deemed clinically necessary. Anteroposterior chest roentgenograms were obtained while the patients were in bed according to a standardized method: a semi-erect posture (approximately 45°) and a 152-cm (60-inch) target distance. The radiologist interpreted the roentgenograms without knowledge of clinical or hemodynamic data and scored the films according to the following system: 0 = no edema, 1R = interstitial edema and 2R = alveolar edema. A clinical estimate of the stage of pulmonary edema was made by one of the investigators on the basis of the history and the physical examination: 0 = normal (asymptomatic normal physical examination), 1C = mild-to-moderate pulmonary edema (slight dyspnea, cough and localized rales) and 2C = severe pulmonary edema (marked dyspnea, diffuse rales, cyanosis and frothy sputum).

Statistical comparisons were carried out using one-way analysis of variance and unpaired t tests. Intraindividual variability was assessed using repeated measures analysis as described by Winer. All data are reported as mean ± SEM.

Results

Studies in Normal Subjects

Changes in body position and in lung volume significantly affected impedance (fig. 1). Impedance increased when body position was changed from supine to standing (p < 0.01) and when lung volume was increased from residual volume to functional residual capacity (p < 0.01). Linear regression analysis for all the measured variables showed that transthoracic impedance correlated best with weight and chest circumference (table 1). Using multiple linear regression, impedance (I), in the supine position at functional residual capacity, could best be predicted by the combination of sternal length and chest circumference, I (Ω) = 35 + 0.58 sternal length (cm) - 0.3 chest circumference (cm) (r = 0.73). Intraindividual variability was greater when measurements were performed on different days with the electrodes replaced each time (mean change ± 2.7 Ω) than when measurements were repeated hourly on the same day without removing the electrodes (mean change ± 0.7 Ω).

Value of Impedance as a Measure of Pulmonary Edema

When initial impedance was recorded as a single isolated measurement and plotted against initial

![Figure 1. The influence of change in position and lung volume on impedance measurements in 27 normal subjects. Values are mean ± SEM.](image)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Correlation coefficient</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chest circumference</td>
<td>0.67</td>
<td>&lt;0.05</td>
</tr>
<tr>
<td>Weight</td>
<td>-0.61</td>
<td>&lt;0.05</td>
</tr>
<tr>
<td>Height</td>
<td>-0.39</td>
<td>NS</td>
</tr>
<tr>
<td>Alveolar volume</td>
<td>0.24</td>
<td>NS</td>
</tr>
<tr>
<td>Sternal length</td>
<td>0.22</td>
<td>NS</td>
</tr>
<tr>
<td>DLCO</td>
<td>-0.13</td>
<td>NS</td>
</tr>
<tr>
<td>Age</td>
<td>0.05</td>
<td>NS</td>
</tr>
</tbody>
</table>

Abbreviation: DLCO = single breath-diffusing capacity for carbon monoxide.
clinical (fig. 2) and radiologic staging (fig. 3), there was considerable overlap among all grades of pulmonary edema. Only five of 11 patients with clinically severe (stage 2C) and five of eight patients with radiologically severe (stage 2R) pulmonary edema had impedance values outside the normal range (mean ± 2 SD, 27 normal subjects). No patient with mild-to-moderate (stage 1C or 1R) pulmonary edema could be distinguished from normal subjects using the impedance method.

Serial Impedance Measurements

To assess the value of changes in serial impedance measurements, patients were assigned to one of four groups depending on their chest roentgenographic findings at the beginning and end of the 24-hour monitoring period (table 2). Patients in group 1, who had no radiologic evidence of pulmonary edema at any time, showed a 4% variation in impedance during the period of study. Similarly, those who already had pulmonary edema and who failed to improve radiologically (group 2) had only a 1% alteration in impedance. Only four of 20 patients in these two groups of stable patients, one group without and one group with pulmonary edema, had more than a 6% change in impedance from initial values while being monitored. In contrast, those deteriorating (group 3) had a 35% decrease (p < 0.01) in impedance and those improving (group 4) had a 16% increase (p < 0.01).

**Figure 2.** Initial impedance values in patients with different clinical stages of pulmonary edema: 0 = none, 1 = mild or moderate, 2 = severe. Shaded area represents the range of normal values.

**Figure 3.** Initial impedance values in patients with different roentgenographic stages of pulmonary edema: 0 = none, 1 = mild or moderate, 2 = severe. Shaded area represents the range of normal values.
All but one patient in these groups had a change from the initial value greater than 10%. Patients whose impedance changed significantly (groups 3 and 4) also had alterations in measurements of alveolar-arterial oxygen tension difference, weight and pulmonary capillary wedge pressure. In contrast, patients whose impedance changed less than 5% during the monitoring period showed smaller or no changes in these measurements (table 2).

### Discussion

Our results indicate that changes in transthoracic impedance provide limited but occasionally useful information about the clinical state of patients either at risk of developing or with pulmonary edema. Patients who had more than a 5% decrease from initial values while being continuously monitored had not only roentgenographic evidence of pulmonary edema but also appreciable changes in arterial $\text{PO}_2$, pulmonary capillary wedge pressure and body weight. The impedance technique is safe, noninvasive and reproducible, provided electrode placement is not changed.

Despite certain advantages, several problems limit clinical application of transthoracic electrical impedance. Because of wide variability of normal values, isolated measurements of impedance are of no help in detecting patients with mild or moderate pulmonary edema. Even when severe pulmonary edema was present, only half of the patients could be identified by single measurements of impedance. Furthermore, the value of serial intermittent measurements is limited by the effects of variations in electrode placement on impedance. Even though we tried to reposition the electrodes in the same location during four separate daily studies, wide variation ($\pm 2.7 \Omega$) from the mean values occurred. These results agree with those of Pomerantz et al., who reported changes in impedance of 5 $\Omega$ when the electrodes were moved 6 cm.

Because of the influence of changes in lung volume, impedance measurements cannot distinguish between reduced lung volume and increased lung water. When healthy volunteers changed position from upright to supine, impedance decreased, reflecting both the increase in intrathoracic blood volume and the decrease in functional residual capacity that accompany this posture. Thus, decreased impedance in patients may reflect either an increase in lung water or a decrease in lung volume; both of these abnormalities are characteristically present in pulmonary edema. Monitoring impedance cannot distinguish intravascular from extravascular and pulmonary from nonpulmonary fluid. Instillation of saline into the pleural and pericardial spaces of the dog is associated with a decrease in impedance. Decreased impedance has been noted in patients after development of both pleural and pericardial effusions, with a subsequent increase in impedance after resolution. It is unknown whether this method can differentiate localized pulmonary edema, as occurs in patients with lobar pneumonia, from the more generalized forms of pulmonary edema.

The availability of a continuous monitoring of impedance raises the possibility of detecting pulmonary edema before it becomes clinically evident. In patients who remained radiologically and clinically stable (group 1) but who were monitored because of their high risk of developing pulmonary edema, eight of 12 patients had small increases in impedance but no significant changes in blood gases, wedge pressures or weight. A possible explanation for these findings is that the patients may have had slight pulmonary edema when...
the studies were begun that could not be detected by standard physical or radiologic examinations. The increase in impedance in this group might have reflected an improvement in subclinical hemodynamic disturbances. These findings are consistent with the work of Pomerantz et al., who noted that impedance decreased before changes in compliance, arterial oxygen pressure and central venous pressure in alloxa-induced pulmonary edema in dogs. In exercising patients with ischemic heart disease and in patients undergoing hemodialysis, impedance changed without any alteration in symptoms. These studies suggest that small increases in impedance may reflect resolving subclinical pulmonary edema and, conversely, that small decreases may detect the formation of small amounts of excess fluid. This emphasizes the problems of comparing the respective sensitivities of one method with another. If transthoracic impedance is in fact more sensitive than chest roentgenography or clinical examination, it could not be established by using these indirect comparisons.

It would be desirable to compare the results of impedance measurements with the results of a more precise method of quantifying the amount of extravascular water in the lungs. We have used the multiple indicator dilution method and are assessing the value of the soluble gas method. Unfortunately, our results agree with those of others in demonstrating inconsistent reproducibility, poor sensitivity and limitation by abnormalities in the distributions of blood flow and ventilation. Thus, at least for the present, clinical and roentgenographic indexes are the only practicable way of testing a method designed to detect pulmonary edema in human beings.

In summary, we foresee an adjunctive rather than a primary role for impedance monitoring in the hospital setting. Specific etiologic diagnosis still requires other physical, radiographic and laboratory techniques. However, there are a few situations in which impedance monitoring in certain patients may prove useful: 1) those at risk of developing pulmonary edema in environments where continuous emergency roentgenographic and blood gas facilities are not available, and 2) those who require a noninvasive alternative to the measurement of pulmonary capillary wedge pressure when the latter is unavailable, medically contraindicated (as in severe hemorrhagic disorders) or technically impossible. Additional studies should be carried out using other methods to determine if patients who appeared to be stable but whose impedance changed, indicating clearing of fluid, actually had excess extravascular lung water when measurements were first obtained.

References
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_Circulation_. 1979;60:1156-1160
doi: 10.1161/01.CIR.60.5.1156
_Circulation_ is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
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Print ISSN: 0009-7322. Online ISSN: 1524-4539

The online version of this article, along with updated information and services, is located on the World Wide Web at:
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