Respiratory system impedance in patients with acute left ventricular failure: pathophysiology and clinical interest

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ABSTRACT To investigate the relationship between alterations in lung mechanics and acute pulmonary vascular congestion, repeated measurements of the respiratory system impedance (Zrs) were performed in 11 patients with and in seven without acute left ventricular failure. Indexes of Zrs were obtained by calculating the average and slope of the resistance and reactance in low (10 to 20 Hz) and high (20 to 50 Hz) frequency intervals. Zrs indexes in patients with ventricular failure differ significantly from those in patients without failure. Pulmonary vascular congestion is regularly associated with an abnormal frequency dependence of resistance at low frequencies and with an increased resonant frequency. Discriminant analysis of Zrs indexes allows 92% correct classification of pulmonary capillary wedge pressures lower than and those equal to or higher than 18 mm Hg. Zrs differences between patients with and without left ventricular failure are consistent with the presence of a small airways obstruction even in patients with mild left ventricular failure. Furthermore, use of Zrs indexes permits moderate and severe pulmonary vascular congestion to be distinguished from one another and this is probably due to a significant narrowing of the large airways during severe left ventricular failure. Circulation 73, No. 3, 386–395, 1986.

ALTERATIONS in lung function have been shown to be related to hemodynamic impairment.1,2 Pulmonary vascular distension due to increased pulmonary blood volume appears as one of the early processes involved in the perturbations of lung mechanics.3,4 A specific increase in the small airways resistance, which may be due to “competition for space between the vessel and airway in the bronchovascular sheath,” has been observed in the dog with an increase in left atrial pressure from 0 to 15 mm Hg.4 Similarly, a reversible decrease in lung compliance with increasing left atrial pressure in the phase of rapid rise of pulmonary blood volume has been described in the isolated rabbit lung.5 In man, the rapid increase in left end-diastolic pressure observed during anginal syndrome has been shown to be accompanied by a significant fall in lung compliance and in specific conductance.2

The existence of small airways dysfunction in pulmonary vascular congestion is suggested by an increased closing volume6–8 and the development of an abnormal frequency dependence of the total pulmonary resistance (Rt).1,3 Indeed, the frequency dependence of Rt has been shown to be closely related to that of lung compliance,9–11 which is considered as one of the most sensitive indicators of small airways obstruction.12

Using forced sinusoidal oscillations, Dubois et al.13 first described the frequency dependence of the Rt at frequencies above the spontaneous one. With the same technique, Interiano et al.1 observed a frequency dependence of Rt in the 3 to 9 Hz range in patients with acute myocardial infarction that was reversible within the following 2 to 3 weeks. Rt at 3 Hz was significantly correlated with the pulmonary capillary wedge pressure (Pcwe). In a further study, Gray et al.1 did not find such a close relationship between Rt and pulmonary vascular pressures. They did show, however, that the frequency dependence of Rt was probably related to a decrease in functional residual capacity (FRC), which was significantly correlated with pulmonary vascular pressures.

Quantification and interpretation of the frequency-dependent mechanical response of the lung underwent
considerable development with the advent of the forced random excitation technique. The measurement of the respiratory system impedance ($Z_{rs}$) by the forced random noise technique was introduced by Michaelson et al. Different lung models have since been studied and several algorithms have been developed to partition $R_T$ into central and peripheral components.

Little information is available on the resistance and reactance frequency dependence above 10 Hz in cardiac patients. Moreover, the two studies of the oscillatory resistance in patients with acute myocardial infarction included patients with only mild pulmonary vascular congestion. New results are reported in this article, which describes the influence on $Z_{rs}$ of pulmonary vascular congestion induced by acute left ventricular failure. $Z_{rs}$ indexes are compared with $P_{RCW}$ and their relationship is discussed.

**Patients and methods**

**Patients.** Eighteen patients were investigated during hospitalization in the coronary care unit of the Centre Hospitalier Universitaire Vaudois in Lausanne. The group without ventricular failure (group 1) includes seven patients with acute uncomplicated myocardial infarction. The absence of left ventricular failure was assessed by the following criteria: absence of an $S_T$ or summation gallop, absence of adventitious pulmonary sounds, absence of cardiomegaly (cardiothoracic index less than 0.5), and chest x-ray labeled class 0 according to McHugh's classification. The ventricular failure group (group 2) includes 11 patients with acute ventricular failure, induced by acute myocardial infarction (nine patients), a hypertensive crisis (one), or severe arrhythmia (one). In spite of treatment, moderate-to-severe clinical signs of pulmonary vascular congestion were present in all patients with ventricular failure. Hemodynamic measurements were therefore made in all patients in this group. Clinical data and initial hemodynamic values for patients in group 2 are listed in table 1.

During the initial study, four to nine $Z_{rs}$ measurements were made in each patient within a period of 1 to 5 days. The first $Z_{rs}$ measurement was taken within 24 hr after the onset of myocardial infarction in all but one group 1 patient (53 hr). In group 2, the first $Z_{rs}$ measurement was taken within 4 hr after insertion of the Swan-Ganz catheter in all but two patients (23 and 60 hr). Sixty-four $Z_{rs}$ measurements were obtained simultaneously with hemodynamic measurements in the patients in group 2.

The follow-up study (3 to 13 weeks after the first investigation) included standard lung function tests, obtained in all group 1 and in nine group 2 patients, and $Z_{rs}$ measurements in six patients of each group. The results of the lung function tests are given in table 2. No patient had clinical signs of pulmonary vascular congestion. Three patients in group 2 had chronic obstructive pulmonary disease (COPD), based on a typical history of chronic bronchitis, residual volume/total lung capacity greater than 0.4, and forced expiratory volume in 1 sec/forced vital capacity lower than 0.6.

**Hemodynamic measurements.** Right heart catheterization was performed by the flow-directed balloon-tipped catheter technique. The pressures were measured with a Statham P-23 Db transducer, positioned 5 cm below the sternal angle. Cardiac output was determined by the thermodilution technique with a KMA 3500 computer.

**Follow-up lung function tests.** Lung volume and airways resistance were measured with a pressure-corrected body plethysmograph Pulmorex SAB (Fenyes & Gut) and respiratory flow was determined with a Fleisch No. 3 pneumotachograph. Results of lung function tests were compared with the predicted values published by Bates et al.

**$Z_{rs}$ measurements.** $Z_{rs}$ measurements were obtained at the bedside with the forced excitation technique. The corresponding apparatus was developed at the Ecole Polytechnique Federale de Lausanne. We shall first give a general description of the principle of the forced oscillations technique (figure 1). Small amplitude acoustical pressure oscillations (a forcing noise) in the frequency band 1 to 50 Hz are generated at the patient's mouth by a loudspeaker. The induced flow oscillations superim-

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**TABLE 1**

<table>
<thead>
<tr>
<th>Subject</th>
<th>Diagnosis</th>
<th>Radiologic class</th>
<th>Treatment</th>
<th>$B_F$ (mm Hg)</th>
<th>$P_{rx}$ (mm Hg)</th>
<th>$P_{sp}$ (mm Hg)</th>
<th>$P_{rcw}$ (mm Hg)</th>
<th>CI (l/min/m²)</th>
<th>SI (ml/beat/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. H.</td>
<td>ILMI</td>
<td>III IA</td>
<td></td>
<td>78</td>
<td>6</td>
<td>35</td>
<td>25</td>
<td>2.5</td>
<td>35</td>
</tr>
<tr>
<td>B. A.</td>
<td>IMI</td>
<td>III D</td>
<td></td>
<td>93</td>
<td>10</td>
<td>34</td>
<td>21</td>
<td>1.0</td>
<td>29</td>
</tr>
<tr>
<td>B. Y.</td>
<td>IMI</td>
<td>II V</td>
<td></td>
<td>77</td>
<td>16</td>
<td>20</td>
<td>12</td>
<td>3.6</td>
<td>40</td>
</tr>
<tr>
<td>B. E.</td>
<td>AA</td>
<td>II —</td>
<td></td>
<td>92</td>
<td>2</td>
<td>17</td>
<td>9</td>
<td>3.3</td>
<td>41</td>
</tr>
<tr>
<td>B. G.</td>
<td>IMI</td>
<td>II D + IA</td>
<td></td>
<td>73</td>
<td>6</td>
<td>17</td>
<td>11</td>
<td>2.6</td>
<td>39</td>
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<tr>
<td>E. L.</td>
<td>ASMI</td>
<td>II D + V</td>
<td></td>
<td>103</td>
<td>5</td>
<td>20</td>
<td>9</td>
<td>2.7</td>
<td>35</td>
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<tr>
<td>G. P.</td>
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<td>III IA</td>
<td></td>
<td>88</td>
<td>10</td>
<td>30</td>
<td>19</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>G. G.</td>
<td>IMI</td>
<td>II D + IA</td>
<td></td>
<td>93</td>
<td>5</td>
<td>25</td>
<td>15</td>
<td>2.1</td>
<td>19</td>
</tr>
<tr>
<td>K. A.</td>
<td>HTC</td>
<td>III —</td>
<td></td>
<td>140</td>
<td>13</td>
<td>42</td>
<td>31</td>
<td>4.4</td>
<td>46</td>
</tr>
<tr>
<td>K. E.</td>
<td>IMI</td>
<td>III D + V</td>
<td></td>
<td>82</td>
<td>10</td>
<td>23</td>
<td>14</td>
<td>4.0</td>
<td>42</td>
</tr>
<tr>
<td>V. S.</td>
<td>IMI</td>
<td>II IA + V</td>
<td></td>
<td>92</td>
<td>7</td>
<td>22</td>
<td>14</td>
<td>4.2</td>
<td>40</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td></td>
<td></td>
<td>91.9</td>
<td>8.2</td>
<td>25.9</td>
<td>16.4</td>
<td>3.2</td>
<td>36.6</td>
</tr>
<tr>
<td>± SD</td>
<td></td>
<td></td>
<td></td>
<td>18.2</td>
<td>4.0</td>
<td>8.2</td>
<td>7.0</td>
<td>0.8</td>
<td>7.7</td>
</tr>
</tbody>
</table>

$	ext{IMI} = $ inferior myocardial infarction; $\text{ILMI} = $ inferolateral myocardial infarction; $\text{ASMI} = $ anterosetal myocardial infarction; $\text{HTC} = $ hypertensive crisis; $\text{AA} = $ acute arrhythmia; $\text{IPMI} = $ inferoposterior myocardial infarction; $\text{D} = $ diuretics; $\text{V} = $ vasodilators; $\text{IA} = $ inotropic agents; $\text{BP} = $ mean blood pressure; $P_{ex} = $ mean right atrial pressure; $P_{sp} = $ mean pulmonary arterial pressure; $\text{CI} = $ cardiac index; $\text{SI} = $ systolic index.

$^a$Radiologic classification of McHugh.18
pose on spontaneous breathing, from which they can be distinguished because of their higher frequency content. With the use of appropriate computing techniques (spectral analysis), the pressure and flow signals are resolved into a large number of sinusoidal components with frequencies ranging from the lowest to the highest present in the forcing noise. At each frequency, the relationship between pressure and flow oscillations — $Z_{rs}$ — is characterized by two quantities: oscillatory resistance and reactance. Both have the physical dimension of pressure divided by flow. Resistance is related to the pressure/flow amplitude ratio. Reactance is related to the time lag between pressure and flow peaks; reactance can be positive or negative depending on whether pressure peaks lead or lag corresponding flow peaks. A more formal description of the apparatus used is given below. A computer-controlled loudspeaker generates a pseudorandom acoustical noise that is applied to the mouth of the patient. The pressure and flow signals, delivered by appropriate transducers, are bandpass filtered and transmitted to a

![Diagram of equipment](http://circ.ahajournals.org/)

**FIGURE 1.** Schematics of the equipment used to measure $Z_{rs}$. 1. Screen pneumotachograph; 2. bias flow to avoid CO$_2$ buildup in the system; 3. loudspeaker; 4 and 5. pressure transducers.
microcomputer. The frequency spectra of the analogic/digital-converted pressure and flow signals are computed through a standard fast-Fourier transform at each of the 128 frequency values in the range from 0 to 50 Hz. The Zrs is computed from 2 sec runs of pressure/flow data as the ratio of the autospectrum of the pressure (Gpp) to the cross-power spectrum (Glp) of the flow and pressure signals as follows:

\[ Z_{rs} = \frac{G_{pp}}{|G_{lp}|} \]

To obtain a reliable estimate of Zrs the average is taken over 16 runs. Confidence limits for the mean of modulus and phase of Zrs are derived from the calculated coherence function as follows:

\[ \gamma^2 = \frac{G_{lp}^2}{|G_{pp}G_{lp}|} \]

where Gpp is the autospectrum of flow. Only those measurements for which \( \gamma^2 \) was higher than 0.90 throughout the whole range from 10 to 50 Hz were retained.

The frequency response of the pressure transducers (Valdyne MP45) with their metal tubing (5 cm long) and amplifier was flat in the 0 to 50 Hz range. This was established by comparison with a carrier-system microphone (Bruel Kjaer system 2631). The phase error was kept below 5 degrees. The in-phase rejection of the differential pressure transducer was verified to be higher than 40 dB over the 0 to 50 Hz range. Particular attention was given to the characteristics of the screen pneumotachograph. Nonlinearities as well as the frequency dependence of the resistance were measured on a test bench equipped with a piston pump and specially engineered to deliver any flow between 0 and 5 liter sec\(^{-1}\) in the whole 0 to 50 Hz frequency range. The pneumotachograph was calibrated at each frequency and the computed impedance was corrected accordingly.

The frequency dependence of Zrs can be described by two curves, i.e., that of resistance and that of reactance, being defined, respectively, as the in-phase and the out-of-phase components of pressure divided by flow.\(^{14}\)

**Indexes derived from Zrs.** To characterize the frequency dependence of Zrs, we have partitioned both resistance and reactance into a low- (10 to 20 Hz) and a high- (20 to 50 Hz) frequency interval. The average values and slopes of resistance and reactance have been computed for each frequency interval separately, thus producing eight Zrs indexes. The resonant frequency (fREs), which is the frequency at which the reactance is equal to zero, has also been computed. A detailed list of the Zrs indexes is given in table 3, with an indication of their respective intraindividual variabilities.

**Experimental procedure.** All initial and follow-up Zrs measurements were performed under the following clinical conditions. The patient was semirecumbent in bed, with the head of the bed elevated 45\(^\circ\) from horizontal. The Zrs measurement was obtained 2 min after three vital capacity maneuvers. The patient breathed normally through a mouthpiece for 1 min. His nose was closed with a clip and his cheeks were supported to minimize the parallel impedance of the mouth. Each considered Zrs measurement resulted from the averaging of three to four Zrs measurements, repeated within a period of 10 min. The whole procedure was achieved within a maximum of 15 min. The Zrs measurement was easily obtained in most of patients, even in those with severe acute pulmonary edema. Patient No. 12 whose coherence functions were too low, was excluded from the study.

**Statistical procedures.** The Wilcoxon rank-sum test for two independent samples (Mann-Whitney) and Wilcoxon signed-ranks test for matched pairs were employed whenever appropriate. Discriminant analysis was performed by maximizing the Mahalanobis distance between samples and by the stepping procedure described in the SPSS User’s Guide.\(^{22}\)

### TABLE 3

<table>
<thead>
<tr>
<th>Zrs indexes</th>
<th>Range</th>
<th>SE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average resistance at low frequencies (10–20 Hz)</td>
<td>1.855–4.301</td>
<td>0.093</td>
</tr>
<tr>
<td>Slope of resistance at low frequencies</td>
<td>-0.082–0.000</td>
<td>0.014</td>
</tr>
<tr>
<td>Average resistance at high frequencies (20–50 Hz)</td>
<td>2.516–4.566</td>
<td>0.082</td>
</tr>
<tr>
<td>Slope of resistance at high frequencies</td>
<td>0.030–0.076</td>
<td>0.003</td>
</tr>
<tr>
<td>Average reactance at low frequencies</td>
<td>-2.579–0.000</td>
<td>0.132</td>
</tr>
<tr>
<td>Slope of reactance at low frequencies</td>
<td>0.055–0.236</td>
<td>0.015</td>
</tr>
<tr>
<td>Average reactance at high frequencies</td>
<td>-0.360–1.009</td>
<td>0.060</td>
</tr>
<tr>
<td>Slope of reactance at high frequencies</td>
<td>0.025–0.068</td>
<td>0.005</td>
</tr>
<tr>
<td>fRES</td>
<td>20–41</td>
<td>0.948</td>
</tr>
</tbody>
</table>

Values are the result of the averaging of three to four measurements (see text). The range and SE (SE = SD/\( \sqrt{n} \)) were computed from the individual values of each Zrs index obtained at the initial measurement in group 2.

**Results**

**Influence of left ventricular dysfunction on Zrs measurements.** The initial Zrs measurements in group 1 and 2 patients are shown in figure 2. In group 1, resistance increased with frequency over the whole frequency range in all but one patient and the fRES was lower than 14 Hz. In group 2, resistance clearly decreased from 10 to 20 Hz in all patients. This abnormal frequency dependence of resistance in the low-frequency range (10 to 20 Hz) was associated with a low reactance and a high fRES ranging from 22 to 38.5 Hz.

Wilcoxon rank-sum tests were performed comparing the initial Zrs measurements in the group 1 and 2 patients. Average values and standard deviations are listed in table 4 for the slope of resistance at low frequencies, the average reactance at low and high frequencies, and fRES. The values were significantly different in the two groups. The slope of resistance at low frequencies was slightly positive in group 1, but was very negative in group 2, reflecting the initial decrease in resistance at low frequencies (figure 2, B). The average reactance at low and high frequencies were much lower in group 2 than in group 1. The slope of resistance at low frequencies was significantly correlated with the average reactance at low and high frequencies (\( r = .62 \) and \( r = .54 \), respectively, \( p < .001 \)). These results do not depend on the inclusion of data from the three patients with COPD in the group 2 data (table 4).

Results of individual follow-up are given in figure 3, which illustrates the initial and follow-up Zrs measurements obtained in six of 11 group 2 patients. The morphologic alterations in the Zrs frequency depend-
ence observed in group 2 during the acute phase (figure 2, B) completely disappeared in two of six patients, partially disappeared in three of six, and remained unchanged in a patient with COPD. Values for follow-up $Z_{rs}$ indexes are given in table 5 for groups 1 and 2. In group 1, the follow-up $Z_{rs}$ measurements did not differ from the initial measurements (table 5). In group 2, follow-up slope of resistance at low frequencies was less negative than that in the acute phase, the average reactance increased over the whole frequency range, and $f_{res}$ decreased in all but the patient with COPD. When the data from the latter patient were excluded, follow-up average reactance at low and high frequencies and $f_{res}$ significantly differed from those at the time of the first $Z_{rs}$ measurements ($p < .05$). No significant difference was found between the follow-up $Z_{rs}$ measurements in groups 1 and 2.

$Z_{rs}$ modifications induced by changes in $P_{PCW}$. A typical example of modifications in the $Z_{rs}$ frequency dependence observed with changes in $P_{PCW}$ is illustrated in figure 4. When $P_{PCW}$ rose from 11 to 23 mm Hg, resistance increased over the whole frequency range, most significantly at high frequencies. Simultaneously, reactance decreased over the whole frequency range, the decrease being most pronounced at low frequencies. The follow-up $Z_{rs}$ measurements show a decrease in resistance with persistent abnormal frequency dependence at low frequencies and an increase in reactance with a decrease in $f_{res}$. Similar $Z_{rs}$ modifications have been observed in all patients experiencing changes in $P_{PCW}$.

**Relationship between the $Z_{rs}$ indexes and $P_{PCW}$**. To demonstrate quantitative changes in $Z_{rs}$ indexes induced by changes in $P_{PCW}$, all initial $Z_{rs}$ measurements from

![Figure 2](image)

**Figure 2.** A, Resistance and reactance curves of the first $Z_{rs}$ measurements in the group 1 patients. B, The first $Z_{rs}$ measurements in the group 2 patients. The solid curves represent the patients without COPD; the broken lines represent those with COPD.

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**TABLE 4**

<table>
<thead>
<tr>
<th>$Z_{rs}$ index values in groups 1 and 2 (initial $Z_{rs}$ measurements) (average values ± SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Group 1</strong></td>
</tr>
<tr>
<td>SRL</td>
</tr>
<tr>
<td>SRL without COPD</td>
</tr>
<tr>
<td>AXL</td>
</tr>
<tr>
<td>AXL without COPD</td>
</tr>
<tr>
<td>AXH</td>
</tr>
<tr>
<td>AXH without COPD</td>
</tr>
<tr>
<td>$f_{res}$</td>
</tr>
<tr>
<td>$f_{res}$ without COPD</td>
</tr>
</tbody>
</table>

SRL = slope of resistance at low frequencies (10–20 Hz); AXL = average reactance at low frequencies; AXH = average reactance at high frequencies (20–50 Hz).

*p < .01 (Wilcoxon rank-sum test for two independent samples for group 1 vs group 2).
group 2 patients (n = 64) have been divided into two
groups, one corresponding to \( P_{pcw} \) lower than 18 mm
Hg (mean \( P_{pcw} = 12.8 \pm 3.3 \) mm Hg) and the other
corresponding to \( P_{pcw} \) equal to or higher than 18 mm
Hg (mean \( P_{pcw} = 22.6 \pm 3.7 \) mm Hg). Discriminant
analysis of the \( Z_n \) indexes yielded 77% correct classifi-
cation (p < .001).

Since some of the \( Z_n \) measurements have been taken
for extremely unstable \( P_{pcw} \), discriminant analysis has
been further carried out on the subset of \( Z_n \) measure-
ments corresponding to relatively stable \( P_{pcw} \) (\( P_{pcw} \)
remaining either lower or higher than 18 mm Hg for at
least 1 hr [n = 47]). This resulted in a new partition,
with 27 \( Z_n \) measurements corresponding to \( P_{pcw} \) lower
than 18 mm Hg (mean \( P_{pcw} = 12.7 \pm 3.5 \) mm Hg) and
20 \( Z_n \) measurements corresponding to \( P_{pcw} \) equal
or higher than 18 mm Hg (mean \( P_{pcw} = 23.1 \pm 4.0 \)
mm Hg). No patient was excluded from this new
analysis, which yielded 92% correct classification (table
6). Two \( Z_n \) measurements corresponding to \( P_{pcw} \) equal
to 7 and 13 mm Hg were misclassified in the group
with \( P_{pcw} \) higher than 18 mm Hg (false positives) and

![Figure 3](http://circ.ahajournals.org/content/73/3/423/figure4)

**Figure 3.** The initial (solid curves) and the follow-up (dotted curves) resistances and reactances for each group 2 patient in which follow-up \( Z_n \) measurements were obtained. All but the patient with COPD (A) show a clear trend toward normalization of
the \( Z_n \) frequency dependence.

### Table 5

<table>
<thead>
<tr>
<th>( Z_n ) index values in groups 1 and 2 (follow-up ( Z_n ) measurements) (average values ± SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Group 1</td>
</tr>
<tr>
<td>SRL</td>
</tr>
<tr>
<td>SRL without COPD</td>
</tr>
<tr>
<td>AXL</td>
</tr>
<tr>
<td>AXL without COPD</td>
</tr>
<tr>
<td>AXH</td>
</tr>
<tr>
<td>AXH without COPD</td>
</tr>
<tr>
<td>( f_{RES} )</td>
</tr>
<tr>
<td>( f_{RES} ) without COPD</td>
</tr>
</tbody>
</table>

Abbreviations as in table 4. No significant difference exists between the groups.

*Ap < .05 for initial vs follow-up \( Z_n \) measurements in the same patient (Wilcoxon signed-ranks test for matched pairs).
two $Z_{rs}$ measurements corresponding to $P_{PCW}$ equal to 18 and 24 mm Hg were misclassified in the group with $P_{PCW}$ lower than 18 mm Hg (false negatives). The slope of resistance at high frequencies was the only index significantly correlated with $P_{PCW}$ ($r = .53$, $p < .001$).

**Discussion**

Indexes describing the $Z_{rs}$ frequency dependence. Fundamental information on mechanical properties of the lung is contained in the frequency-dependent behavior of $Z_{rs}$, which therefore has to be depicted by relevant indexes. Bronchial obstruction has been shown to be associated with an increased frequency dependence of the resistance in the low-frequency range (3 to 9 Hz). The slope of the resistance and the ratio of low- (5 to 9 Hz) to high- (15 to 19 Hz) frequency resistance are simple indexes that have been used to quantify the frequency dependence of resistance. Furthermore, the resonant frequency has been shown to be increased in bronchial obstruction, reflecting an abnormally low reactance. In other studies, $Z_{rs}$ indexes have been proposed that are based on a simple series resistance, compliance, and inertance lung model. However, in a nonhomogeneous lung, more complicated models with parallel compartments must be used, although their application is still hazardous.

Michaelson, Landser, Nagels, Pimmel, and Hayes and their colleagues have published measurements obtained in patients with obstructive disease over a large frequency range. Their results suggest that, in those patients, the modifications of $Z_{rs}$ at frequencies lower than 20 Hz should be distinguished from those above 20 Hz since they likely originate from different pathophysiologic mechanisms. Most of the modifications in the resistance observed in patients with COPD take place in the 0 to 20 Hz range. Above 20 Hz very little experimental data on the effect of bronchial obstruction are available. Model studies suggest that high-frequency $Z_{rs}$ values should be influenced by large airways mechanical alterations, in particular the diameter and compliance of the large airways. These considerations support the partition of the frequency range used in this study.

$Z_{rs}$ modifications induced by pulmonary vascular congestion. Our data show that in all patients with left ventricular failure pulmonary vascular congestion induces an increased frequency dependence of resistance at low frequencies and a decrease in reactance with an increase in $f_{RES}$, independent of $P_{PCW}$. Such modifications of the $Z_{rs}$ frequency dependence are not present in patients without ventricular failure in the same position. The difference observed between our group 1 and 2 patients is not due to a particular observation tilting the mean in small groups. In particular, there is no

![FIGURE 4. Modifications in resistance and reactance curves induced by a fluid challenge. The broken curves represent the $Z_{rs}$ measurement before ($P_{PCW} = 11$ mm Hg) and the solid curves the measurement after ($P_{PCW} = 23$ mm Hg) administration of 500 ml plasma over 5 hr. The follow-up $Z_{rs}$ measurements are represented by the dotted curves.]

<table>
<thead>
<tr>
<th>$P_{PCW}$</th>
<th>$Z_{rs}$ index</th>
<th>$P_{PCW}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$&lt; 18$ mm Hg</td>
<td>25</td>
<td>2</td>
</tr>
<tr>
<td>$\geq 18$ mm Hg</td>
<td>2</td>
<td>18</td>
</tr>
<tr>
<td>Total</td>
<td>27</td>
<td>20</td>
</tr>
</tbody>
</table>

Total percentage classified correctly was 92%, $p < .001$. $P_{PCW}$ less than 18 mm Hg or of 18 mm Hg or more for at least 1 hr.
overlapping in the range of reactances observed in the two groups (figure 2). The abnormal frequency dependence of resistance, although observed by us in a higher frequency range (10 to 20 Hz), is in agreement with the results reported by Interiano et al.3 (in the 3 to 9 Hz range during the first days after acute myocardial infarction). In their study, the frequency-dependence index [FDI = (R3 - RRES) ÷ (fRES - 3)] was increased in all patients compared with the values obtained in normal subjects. Furthermore, the lowered reactance and the consequently increased fRES observed in the group 2 patients in our study contrasts with the fRES reported by Interiano et al. (6 to 7 Hz), which was surprisingly close to normal in all patients for any frequency-dependence index.

The negative slope of resistance at low frequencies associated with a low reactance is not specific to pulmonary vascular congestion and has been described in obstructive lung diseases.14, 24, 29, 30 Mechanical inhomogeneities of the lung and upper airways have usually been invoked to interpret this characteristic Zns frequency dependence.11, 14, 30 According to the model described by Mead,33 an increase in slope of resistance vs frequency could be associated with an increase of resistance of the small airways. Numerous animal and human studies have shown that pulmonary vascular congestion could induce small airways dysfunction, as shown by an increase in closing volume and peripheral airways resistance and by a decrease in dynamic compliance. This has been related to mechanical compression of the small airways by adjacent distended vessels.4 Other mechanisms might also be involved, such as narrowing of the small airways by interstitial edema and/or vagally mediated active bronchoconstriction.34, 35

An abnormal frequency dependence of resistance at low frequencies, associated with a low reactance value, has also been observed in healthy subjects breathing at very low lung volumes.14, 30 Under these conditions, a large decrease in FRC, associated with closure of some lung areas, produces mechanical inhomogeneities of the lung. In man, a significant negative correlation has been described between FRC and the pulmonary vascular pressures.1 However, the decrease in FRC reported in patients with acute pulmonary vascular congestion1 was much smaller (less than 500 ml) than that inducing abnormal frequency dependence of resistance in healthy sitting subjects (greater than 1 liter).14, 30 It appears very unlikely, therefore, that a decrease of 0.5 liter in FRC could account for the frequency dependence observed in our group 2 patients.

Relationship between Zns indexes and PFW. Sensitivity of Zns to pulmonary capillary hypertension is shown by the high percentage of correct classification of Zns measurements obtained in the groups with 

\[ P_{FW} \]

lower than 18 mm Hg and equal or higher than 18 mm Hg for at least 1 hr (92%). This \[ P_{FW} \] value has been shown by McHugh et al.18 to be critical for the onset of radiologic signs of left ventricular failure. This same value has been used by Forrester et al.36 for defining hemodynamic subsets in acute myocardial infarction. The Zns indexes that discriminate between low and high \[ P_{FW} \] are different from those discriminating between groups of patients with and without left ventricular failure. This observation suggests that early pulmonary vascular congestion (\[ P_{FW} \] lower than 18 mm Hg) induces small airways obstruction, but once established, the phenomenon appears not to be directly related to the level of \[ P_{FW} \]. When severe, pulmonary capillary hypertension is associated with an increase in the slope of resistance at high frequencies, a situation that can be simulated on physical model studies by a decrease in the large airways diameter.32

In dogs, a narrowing of both central and peripheral airways has been described in acute pulmonary edema that is significantly correlated with a decrease in FRC.37, 38 Recent studies demonstrate the potential role of vagally mediated changes in bronchial and tracheal tone.38-40 It can therefore be inferred that the narrowing of the central airways could explain the increase in slope of the high frequency resistance that we observed at high \[ P_{FW} \].

Time course. The lower rate of correct classification between low and high \[ P_{FW} \] that was obtained when patients with unstable \[ P_{FW} \] were included suggests the presence of a time delay between hemodynamic changes and their consequences on Zns. Similar discrepancies between \[ P_{FW} \] and the degree of pulmonary vascular congestion derived from chest x-ray evaluation have been described by McHugh et al. under two conditions: “preclinical failure” and the “posttherapeutic phase lag.”18 The mechanical properties of the lung are not only influenced by the absolute level of \[ P_{FW} \] but also by the duration of the abnormality.41, 42

Follow-up. The follow-up Zns measurements (figure 3), obtained in six of 11 group 2 patients 3 to 13 weeks (mean 7.4 ± 4.2) after the first measurement show a clear trend toward normalization of both resistance and reactance in all but one patient with COPD (figure 3, A). In particular, the negative slope of resistance at low frequencies tended to disappear and fRES significantly decreased in all but the patient with COPD (table 5). Moreover, the follow-up values for the Zns indexes in
group 2 do not significantly differ from those in group 1 (table 5). The persistence of a slightly abnormal frequency dependence of resistance in the low frequency range in three of six patients with left ventricular failure (figure 3, A, C, and D) and the slightly increased \( f_{\text{RES}} \) in four of six (figure 3, A, C, D, and F) may be surprising. Two mechanisms could explain the lack of complete resolution of the \( Z_{ns} \) abnormalities: the effect on the lung of residual infraclinical left ventricular failure, and early chronic airways obstruction.

The probability of the presence of residual infraclinical left ventricular failure is supported by the results of Interiano et al.3 These authors performed early (2 to 3 weeks after myocardial infarction) and late (10 to 17 weeks) follow-up measurements of pulmonary resistance. Their data show that the frequency-dependence index normalized at late follow-up, while it was still slightly abnormal at early follow-up. It has been shown in the dog4 and in the isolated rabbit lung5 that small airways dysfunction appears early in pulmonary vascular congestion, even before accumulation of interstitial edema, and that it is related to the increased pulmonary blood volume. The persistence of moderately elevated pulmonary vascular pressures in some patients with left ventricular failure could therefore explain the lack of complete resolution of the \( Z_{ns} \) abnormalities even in absence of clinical signs of pulmonary vascular congestion. However, the residual \( Z_{ns} \) abnormalities observed in our group 2 patients could also be due to early airways obstruction, as suggested by low forced expiratory flow during the middle half of forced vital capacity and high residual volume and FRC values. In this case, the individual evolutions (figure 3) would show that the presence of an early pulmonary obstruction does not mask the effect of acute left ventricular failure.

In summary, comparison of resistance and reactance measurements over a wide frequency range in semirecumbent patients with and without acute left ventricular failure suggests the presence of small airways obstruction in patients with even mild pulmonary vascular congestion. Furthermore, \( Z_{ns} \) indexes are able to distinguish between moderate and severe pulmonary vascular congestion, probably because of significant narrowing of the large airways during severe and acute left ventricular failure. The specificity of \( Z_{ns} \) frequency dependence for lung mechanical alterations induced by vascular congestion vs those induced by COPD must be further investigated. Finally, it must be put forward that \( Z_{ns} \) measurements are easily obtained at the bedside in critically ill patients and, therefore, seem promising in monitoring the individual evolution of disease in patients with left ventricular failure.

We thank Prof. E. Mooser, Ph.D., Director of the Institut de Physique Appliquée, Ecole Polytechnique Fédérale de Lausanne, Switzerland, for his critical review of the manuscript and C. Anglada for invaluable technical assistance.

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Circulation. 1986;73:386-395
doi: 10.1161/01.CIR.73.3.386

Circulation is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
Copyright © 1986 American Heart Association, Inc. All rights reserved.
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:
http://circ.ahajournals.org/content/73/3/386

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