Echocardiographic Evaluation of Pulmonary Artery Distensibility*

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The aim of this study was to verify the hypothesis that pulmonary artery (PA) distensibility may modify the pattern of right ventricular ejection. Pulmonary artery distensibility was evaluated with M-mode measurements of right pulmonary artery diameter from suprasternal notch simultaneous with pulmonary pressure measurements. Pulmonary artery pressure was measured in 19 subjects, 29 to 75 years old (mean age, 49 years). Pulmonary artery systolic pressure was 22 to 108 mm Hg (mean, 52 mm Hg). Pulmonary artery pressure strain modulus (Ep) was calculated as follows: PADD × (PASP-PADP)/PADD-PADS (PADS-PA diameter in systole, PADD-PADS (PAS-M diameter in diastole, PAS-PADP systolic pressure, PAD-M diastolic pressure) was 6 ± 5 × 10^6 dynes/cm². Right ventricular outflow tract velocity was recorded with pulsed Doppler echocardiography and acceleration times (AT) and ejection times (ET) were measured. Log Ep was correlated with pulmonary artery systolic and mean pressure (r = 0.90 and r = 0.87, p < 0.0001) but not with age (r = 0.30, p = NS). Acceleration time and AT/ET ratio were correlated with log Ep (r = 0.73 and r = 0.76, p < 0.001) and with pulmonary artery mean pressure (r = 0.91 and r = 0.89, p < 0.001). When pulmonary artery pressure was included in multiple analyses, the relationships between Doppler indices and elastic modulus did not prove to be significant. These findings emphasize the independence of Doppler right ventricular outflow tract velocity indexes used for noninvasive evaluation of pulmonary hypertension from pulmonary artery distensibility in a clinical setting.

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P Pulmonary artery acceleration time has been widely used for the noninvasive evaluation of pulmonary hypertension. Despite a good correlation between mean pulmonary artery pressure and pulmonary artery acceleration time (AT), a significant error in noninvasive estimation of pulmonary artery pressure using Doppler echocardiography has persisted.1-4 Decreased pulmonary artery distensibility abbreviates the duration of right ventricular-pulmonary artery systolic ejection gradient.5 We hypothesized that decreased pulmonary artery distensibility would abbreviate right ventricular ejection AT contributing to the error of estimating pulmonary artery pressures from right ventricular ejection indexes.

Echocardiographic Methods

All echocardiographic studies were performed with a commercially available echocardiographic unit (Hewlett Packard 77020A). M-mode studies were performed with 5.0- and 3.5-MHz frequency probes. The Doppler studies were performed with 3.5-MHz and 2.5-MHz frequency probes.

Right Pulmonary Artery Pressure Strain Elastic Modulus

The study was performed at rest in the supine position with slightly extended neck. The right pulmonary artery was visualized from suprasternal view by two-dimensional echocardiography (Fig I). An M-mode cursor was oriented along the right pulmonary artery diameter. All tracings were recorded on hard copy at 100 mm/s speed and subsequently digitized and analyzed. Diastolic (at the beginning of QRS) and systolic (maximal) right pulmonary artery diameter were measured. Leading edge to leading edge method was used for measurements. Three to five end-expiratory cardiac cycles were used for analysis. Right pulmonary artery pressure strain (PAS) was defined as follows: (PADS-PADD/PADD where PAS is right pulmonary artery diameter in systole and PADD is right pulmonary artery diameter in diastole. Right pulmonary artery pressure elastic modulus (Ep) 10^6 dynes/cm² was calculated as follows: pulmonary artery pulse pressure/PAS.

Right Ventricular Outflow Tract Doppler Velocity

The study was performed either in a left-sided position using the short axis parasternal view or in a supine position using the short axis subcostal view. The pulsed-wave Doppler sample volume was placed just below the level of the pulmonary valve in the middle of the right ventricular outflow tract. The position of the sample was confirmed both by the two-dimensional image and by the typical presentation of the Doppler tracing characterized by the absence of the pulmonary valve opening signal and presence of the closure signal. All tracings were recorded on hard copy at a speed of 100 mm/s and subsequently analyzed. The analysis consisted of measurement of AT as the interval from the onset to the maximal velocity of forward flow and ejection time (ET) as the interval between

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onset and termination of flow in the right ventricular outflow tract. The average of five cycles was used for analysis.

Pulmonary Artery Pressure Measurement

Right heart catheterization was performed via the right internal jugular or subclavian vein either simultaneously or within 30 min of the echocardiographic study. A Swan-Ganz fluid-filled catheter was used for measurements. The position of the catheter tip in the pulmonary artery was verified by fluoroscopy or chest radiography. Pressure measurements were made with the use of a transducer and recorder (Electronics for Medicine). Measurements were referred to zero level at 5 cm below the sternal angle. Systolic and diastolic pulmonary artery pressure was averaged from five end-expiratory cardiac cycles. Pulmonary artery mean pressure (PAMP) was calculated as pulmonary artery diastolic pressure + 1/3 (pulmonary artery systolic pressure [PASP]-pulmonary artery diastolic pressure).

Statistical Analysis

To analyze the relationship between the data, linear regression analysis was performed. Pearson correlation coefficients were also calculated. Multiple regression analysis was performed to evaluate the relationship between pulmonary artery Doppler ejection indices and pulmonary artery distensibility and pressure. All data are given as mean ± 1 SD.

Table 1—Results of Hemodynamic and Echocardiographic Measurements

<table>
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<tr>
<th></th>
<th>Mean</th>
<th>SD</th>
<th>Range</th>
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</thead>
<tbody>
<tr>
<td>Heart rate, beats per minute</td>
<td>85.2</td>
<td>14.6</td>
<td>60-111</td>
</tr>
<tr>
<td>Pulmonary artery systolic pressure, mm Hg</td>
<td>52</td>
<td>27</td>
<td>22-106</td>
</tr>
<tr>
<td>Pulmonary artery diastolic pressure, mm Hg</td>
<td>27</td>
<td>11</td>
<td>15-120</td>
</tr>
<tr>
<td>Pulmonary artery mean pressure, mm Hg</td>
<td>35</td>
<td>16</td>
<td>15-66</td>
</tr>
<tr>
<td>Right pulmonary artery diameter systole, mm</td>
<td>25</td>
<td>6</td>
<td>15-38</td>
</tr>
<tr>
<td>Right pulmonary artery diameter diastole, mm</td>
<td>23</td>
<td>6</td>
<td>14-37</td>
</tr>
<tr>
<td>Pulmonary artery pressure strain modulus, 10⁶ dynes/cm²</td>
<td>6</td>
<td>8</td>
<td>1.1-31.6</td>
</tr>
<tr>
<td>Pulmonary artery strain, %</td>
<td>10.4</td>
<td>6.3</td>
<td>3-25</td>
</tr>
<tr>
<td>Acceleration time, ms</td>
<td>90</td>
<td>29</td>
<td>37-134</td>
</tr>
<tr>
<td>Ejection time, ms</td>
<td>280</td>
<td>35</td>
<td>196-333</td>
</tr>
</tbody>
</table>

RESULTS

The results of hemodynamic and echocardiographic measurements are presented in Table 1. Intraobserver variability standard error of estimate (SEE) of pulmonary artery diameter measurement in systole was 0.6 mm and in diastole it was 1.1 mm. Interobserver variability SEE of pulmonary artery diameter measurement in systole was 0.9 mm and in diastole it was 1.3 mm. Pulmonary artery pressure strain elastic modulus (Ep) values ranged from 1.1 to 31.6 × 10⁶ dynes/cm² (mean, 6 × 10⁶ dynes/cm²). Log Ep was correlated with PASP (r = 0.90, p < 0.0001) (Fig 2), diastolic pressure (r = 0.77, p < 0.001), and mean pressure (r = 0.87, p < 0.0001), but not with age (r = 0.30, p = NS). The AT and AT/ET ratio were correlated with log Ep (r = 0.73 and r = 0.76, p < 0.001) (Fig 3). There was a strong correlation between both AT and AT/ET ratio and PAMP (r = 0.91 and r = 0.89, p < 0.0001, SEE = 7.0 mm Hg) (Fig 4). Pulmonary artery strain
was inversely correlated with PAMP \( r = -0.53, p<0.05 \).

No gradient across the site of pulmonary anastomosis was found in heart transplant patients. No difference in elastic modulus or AT was found between heart transplant patients and the other patients.

Multiple regression analysis revealed that when pulmonary artery pressure was included as one of the analyzed variables, no independent relationship between Doppler indices and \( E_p \) was found. Pulmonary artery strain was used together with pulmonary artery AT for prediction of pulmonary hypertension. An independent relationship between PAS and PASP was found. A multiple regression equation using PAS and pulmonary artery AT as independent variables and PAMP as a dependent variable was developed:

\[
PAMP = 83 - 0.61 \text{PAS} - 0.47 \text{AT}
\]

Age and gender did not contribute to this equation. Although this multivariate analysis improved estimation of pulmonary artery pressure \( r = 0.93, \text{SEE} = 6.2 \text{mm Hg} \) in comparison to univariate regression, the measurement of PAS is too cumbersome to justify its routine use for the evaluation of pulmonary artery pressure.

**DISCUSSION**

**Pulmonary Artery Distensibility**

Distensibility of the major arteries is determined by the elastic properties of elastic and collagen fibers which are the major constituents of the arterial wall. \(^7\) When the distending pressure is low, elastic properties are determined by distensible elastic fibers. When the vessel wall is stretched by higher pressures, the less distensible collagen fibers cause increased steepness in the elastic modulus-pressure curve. \(^8\) These well-known observations have been confirmed in the current study, as a strong linear relationship between log elastic modulus and PAMP was found. It cannot be determined, however, whether the increase in elastic modulus observed in pulmonary hypertension is caused by higher distending pressure alone.

The pulmonary artery media are hypertrophied and the pulmonary artery is less distensible in patients in whom pulmonary hypertension has persisted since birth but is not altered when it is acquired in adult life. \(^9\) Jarmakani et al \(^10\) evaluated right pulmonary artery elastic modulus during right heart catheterization. The authors did not attempt to relate the pulmonary artery elastic modulus to pulmonary artery pressure as continuous variables. They found that the elastic modulus in patients with normal pulmonary artery pressure was much lower than the elastic modulus in patients with pulmonary hypertension. Gozna et al \(^11\) measured the elastic modulus in patients with normal pulmonary systolic pressure so the mean values obtained were in a lower range than the data from the present study. They also found a significant relationship between pulmonary artery pressure strain modulus and age. Increased age was associated with decreased in \( \text{vivo} \) pulmonary artery distensibility evaluated by Harris et al. \(^12\) This relationship did not prove to be significant in the present work perhaps due to the overwhelming influence of pulmonary artery pressure.

**Doppler Echocardiography**

Doppler echocardiographic evaluation of pulmonary artery acceleration time has been widely evaluated as a noninvasive, highly feasible index of pulmonary artery pressure. The SEE of the relationship between pulmonary artery AT and PAMP is, however, consistently higher than 7 mm Hg. \(^13\) This error of estimate is quite satisfactory for the diagnosis of severe pulmonary hypertension but does not allow for the precise diagnosis of mild pulmonary hypertension (PAMP, 30 to 40 mm Hg). \(^4\) Measurement of tricuspid regurgitation velocity by Doppler allows for precise evaluation of right ventricular pressure; however, the prevalence of tricuspid regurgitation is dependent on the severity of pulmonary hypertension, \(^15\) being less than 50 percent in patients whose PASP ranges from 30 to 40 mm Hg.

The SEE of the relationship between PAMP and pulmonary artery AT found in this work (7.0 mm Hg) was in the range of previously reported results. \(^14\) When pulmonary artery strain was incorporated into multiple regression, the SEE was slightly less (6.1 mm Hg). Although the increase in the accuracy is not impressive, this method may be considered when dealing with borderline abbreviation of the AT.

**Limitations of the Study**

To compare the elastic properties of the material that constitutes the vessel wall, pulmonary artery...
thickness should be measured and stress/strain modulus should be calculated. To date, the noninvasive methods for measuring pulmonary artery thickness have not been validated; therefore, comparisons are based on the pressure strain modulus introduced by Paterson et al.6

Although right pulmonary artery distensibility may theoretically not equal main pulmonary artery distensibility, we chose to measure it for several reasons. First, the suprasternal window has been used for evaluation of pulmonary artery size in pediatric cardiology.10 Second, the window takes advantage of the superior resolution of M-mode echo in comparison to two-dimensional echocardiography. Third, right pulmonary artery diameter measurements have been used in an angiographic study evaluating pulmonary artery distensibility.12 Fourth, because of similar arterial wall architecture, the elastic properties of the right and main pulmonary artery would not be expected to differ. Right pulmonary artery diameter measurements were also used in another invasive study that evaluated pulmonary artery distensibility.10 Because of similar arterial wall architecture, the elastic properties of the right and main pulmonary artery would not be expected to differ.

The change of the diameter of pulmonary artery during the cardiac cycle is usually in the range of 4 to 10 percent of its diastolic diameter.12 Although this is small, the error of M-mode measurements is at least an order higher than the observed changes.

In this study, we used pulsed Doppler recordings from the right ventricular outflow tract for estimation of pulmonary artery pressure. Other authors have used the same approach3,4 or recorded flow from the proximal part of the pulmonary artery4 or from both sites.1 The pattern of flow may differ between these two sites so a consistent approach is essential. In our experience, because of the closer proximity of the right ventricular outflow tract to the examining probe, this site is more feasible than pulmonary artery recordings.

CONCLUSIONS

Simultaneous invasive measurement of pulmonary artery pressure and M-mode echocardiographic right pulmonary artery diameter allows for estimation of pulmonary artery elastic modulus. Pulmonary artery pressure/strain modulus is strongly dependent on pulmonary artery pressure. Evaluation of right ventricular outflow tract velocity with pulsed Doppler allows for estimation of pulmonary artery pressure independently from alterations in pulmonary artery distensibility. Measurement of pulmonary artery strain and entering its value into multiple regression with pulmonary artery AP as another independent value improves the accuracy of the noninvasive determination of pulmonary artery pressure but may be too cumbersome to perform routinely.

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