Pulmonary Regurgitation Studied with the Ultrasonic Pulsed Doppler Technique

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SUMMARY Sixty patients with pulmonary regurgitation were studied by the pulsed Doppler technique combined with two-dimensional and M-mode echocardiography. Patients with pulmonary regurgitation had abnormal Doppler signals just below the pulmonic valve in the right ventricular outflow tract in diastole on the two-dimensional image. These signals were considered to indicate the regurgitant flow.

There are two patterns of pulmonary regurgitant Doppler signals. In pulmonary hypertension, the maximal component of instantaneous flow velocity is sustained at about the same signal strength throughout diastole, but when the pulmonary arterial pressure is normal, the velocity slows down gradually from early diastole to end-diastole.

Pulmonary regurgitation was detected by phonocardiography in about half the patients. In the remaining half, pulmonary regurgitant murmur could not be differentiated from aortic regurgitant murmur or was masked by coexistent aortic regurgitation or patent ductus arteriosus, whereas the Doppler technique indicated pulmonary regurgitation.

THE ULTRASONIC pulsed Doppler technique is useful in the noninvasive assessment of intracardiac blood flow.1-4 Blood flow from the right heart can be measured from the precordial approach because the right heart is located near the anterior chest wall and the flow direction is nearly parallel to the direction of the ultrasound beam for the Doppler technique. We investigated pulmonary regurgitation using a range-gated, pulsed Doppler technique combined with two-dimensional echocardiography and compared its sensitivity for diagnosis of pulmonary regurgitation with phonocardiography.

Methods

We examined 1200 patients by the pulsed Doppler method from January 1979 to August 1980. In 60 of these patients, abnormal diastolic Doppler signals were detected in the subpulmonic area and the right ventricular outflow tract. These 60 patients were the
subjects of this retrospective study. The subjects were 16–75 years old and had various cardiac diseases (table I). Forty-one patients underwent cardiac catheterization; 36 had pulmonary hypertension (mean pulmonary artery pressure greater than 25 mm Hg).

Three equipment systems were used. The first consisted of an ultrasonic directional pulsed Doppler flowmeter (Hitachi Medico EUD-4Z), combined with an M-mode echocardiograph for monitoring the site of sample volume. The Doppler flowmeter used ultrasound of 2.5 MHz and had a pulse repetition rate of 6.3 kHz; the sample volume had a teardrop shape and was 5 or 10 mm deep and 6 mm wide. The second system combined the Doppler flowmeter and a twodimensional echocardiograph (Aloka SSD-120), and the third a pulsed Doppler flowmeter and an electronic sector, two-dimensional echocardiograph (Toshiba SSH 11A). The third system operated at 2.4 MHz with a pulse repetition rate of 6 kHz. The sample volume had a teardrop shape 2 mm deep and 4 mm wide. This system was designed so that the Doppler recording could be performed in any direction within the sector angle.

The Doppler signals underwent frequency analysis in real-time and were displayed simultaneously with the M-mode echocardiogram, ECG and phonocardiogram.

Recording Technique

When only the M-mode echocardiogram was monitored, ultrasound was transmitted from the third to fifth intercostal space along the left sternal border toward the pulmonic area. After the pulmonic valve was detected, abnormal Doppler signals were sought in the pulmonary artery and the right ventricular outflow tract. When the two-dimensional echocardiograms were monitored, the pulmonic valve was detected and the cursor directed along the line from the right ventricle to the pulmonary artery; then, abnormal Doppler signals were sought on the pulmonary artery and right ventricular outflow tract sides of the valve. The same search was also made for the aortic valve and other valves. The findings from auscultation and phonocardiography were compared with the Doppler findings. Aortic regurgitation and patent ductus arteriosus were diagnosed by the pulsed Doppler technique and routine examinations, with or without aortography.

Results

Doppler Flow Signals in the Right Ventricular Outflow Tract in Healthy Subjects

Doppler flow signals obtained in the right ventricular outflow tract just below the pulmonic valve in healthy subjects provide a basis for comparing the findings in patients with pulmonary regurgitation (fig. 1). In systole, Doppler flow signals of ejection flow exhibit a monophasic pattern of a narrow-band spectrum of unidirectional velocity component, indicating laminar flow. The direction of this velocity component was assumed to be the same as the direction of the flow. In diastole, a slow-velocity flow continued in the same direction as the systolic flow, exhibiting slight acceleration in early diastole and end-diastole. This diastolic flow was considered to be related to the diastolic inflow through the tricuspid valve.

Abnormal Doppler Signals in the Right Ventricular Outflow Tract in Patients with Pulmonary Regurgitation

Abnormal Doppler signals were detected in the right ventricular outflow tract in diastole. In 55 of 60 patients, these abnormal Doppler signals consisted of unidirectional velocity components with a wide-band velocity spectrum. The direction of these velocity components was opposite to that of the ejection flow. In five of 60 patients, the signals consisted of bidirectional velocity components.

Time of Appearance of the Abnormal Doppler Flow Signals

In 19 patients, the abnormal flow signals were pandiastolic, lasting from the pulmonic component of the second heart sound until the beginning of the next ejection. This finding was substantiated in patients with fixed wide or paradoxical splitting of the second heart sound by observing that the abnormal flow signal starts from the pulmonic component of the second heart sound. In the remaining 41 patients, the abnormal flow signal was not pandiastolic: In 39 patients, the abnormal flow signals started a little later than the second heart sound and continued until late diastole or the next ejection and in two occurred only in early diastole (fig. 2).

In some patients in which the abnormal flow signals were detected throughout diastole, the abnormal flow signals started a little later than the second heart sound just below the pulmonic valve, but were pandiastolic when the sample volume was placed in the lower right ventricular outflow tract. The reason for this phenomenon is considered to be the change in the site of the sample volume above and below the pulmonic valve with the heart movement. That is, the sampling site was positioned in the pulmonary artery above the pulmonic valve in early diastole but below the valve later in diastole because the valve moved slightly upward. This finding was clearly substantiated by two-dimensional echocardiography.

<table>
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<tr>
<th>Table 1. Cardiac Diseases in the Patient Population</th>
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<td>Cardiac Diseases</td>
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<tr>
<td>Aortic and mitral valve diseases</td>
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<tr>
<td>Atrial septal defect, ventricular septal defect, patent ductus arteriosus</td>
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<td>Idiopathic pulmonary artery dilatation, pulmonary valve lesion</td>
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<td>Pulmonary embolism, aortitis</td>
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<td>&lt; 25 mm Hg</td>
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PULMONARY REGURGITATION BY DOPPLER/Miyatake et al.

band spectrum of velocity component and sustained the same velocity throughout diastole (fig. 2). This pattern was seen in 50 cases. In type B flow, the velocity peaked in early diastole and then gradually

Figure 1. Doppler flow signals in the right ventricular outflow tract. (above) A healthy subject. The Doppler signals of the systolic ejection flow exhibit a dome-shaped pattern. There is also a slow flow in diastole, the direction of which is the same as the systolic flow. These flow signals show a narrow-band velocity spectrum, which suggests that the flow is laminar. (below) A patient with pulmonary regurgitation. Systolic ejection flow with a narrow-band velocity spectrum is revealed, followed by a reverse flow in diastole with a wide-band velocity spectrum, which suggests that the flow is turbulent. SV = sample volume; PCG = phonocardiogram.

Distribution of the Abnormal Doppler Flow Signals in the Right Ventricular Outflow Tract

Abnormal Doppler signals were seen only in the right ventricular outflow tract, not above the pulmonic valve. The spatial distribution of the abnormal Doppler signals in five patients was circumstantially examined on the two-dimensional image. In two patients, the spatial distribution of the abnormal Doppler signals was strictly limited to a small area just below the pulmonic valve, whereas it extended from the pulmonic valve to the main part of the right ventricle in three patients (fig. 3). These abnormal diastolic Doppler signals were interpreted to indicate pulmonary regurgitant flow on the basis of their detecting position, time of appearance and flow direction.

Patterns of Pulmonary Regurgitant Flow

The abnormal diastolic Doppler signals had two basic flow patterns. Type A flow exhibited a wide-
FIGURE 4. Relation between the regurgitant flow pattern and mean pulmonary artery (PA) pressure. Triangle indicates an intermediate type of flow pattern.

FiguRe 4. Relation between the regurgitant flow pattern and mean pulmonary artery (PA) pressure. Triangle indicates an intermediate type of flow pattern.

slowed in later diastole. This pattern was seen in 10 cases. The spectrum of velocity component tended to be narrower in type B than in type A flow.

The two types of flow patterns mentioned above and the mean pulmonary artery pressure were compared in 41 patients who underwent cardiac catheterization. In 36 patients with type A flow, the mean pulmonary artery pressure was 25 mm Hg or higher. However, the four patients with type B flow had a mean pulmonary artery pressure of 18 mm Hg or lower. The remaining patient had a flow pattern that was intermediate between types A and B and a mean pulmonary artery pressure of 12 mm Hg (fig. 4).

Relationships between Abnormal Doppler Signals and Pulmonary Regurgitant Murmurs

The relationships between the abnormal Doppler flow signals and the presence of pulmonary regurgitant murmurs in phonocardiography were examined retrospectively. In 31 of the 60 patients who exhibited the abnormal Doppler signals, diastolic murmurs interpreted to be due to pulmonary regurgitation were recorded on the phonocardiograms. Twenty-four of these patients had type A flow on the Doppler recordings and Graham-Steel murmurs on the phonocardiogram. These patients had mitral stenosis, patent ductus arteriosus and atrial septal defect with pulmonary hypertension (fig. 5). The remaining seven cases had type B flow on the Doppler recordings and decrescendo murmurs only in early diastole starting from the pulmonic component of the second heart sound on the
phonocardiogram (fig. 6). These patients had idio-pathic pulmonary artery dilatation or an organic pulmonary valve lesion.

In six patients, it was impossible to determine by phonocardiography whether the recorded diastolic murmurs were caused by pulmonary or aortic regurgitation or were misinterpreted due to aortic regurgitation. The Doppler method clearly revealed pulmonary regurgitation, but no aortic regurgitation, and was thus more specific than phonocardiography.

In 15 patients who had aortic regurgitation or patent ductus arteriosus combined with pulmonary regurgitation, phonocardiography showed only the diastolic murmur caused by aortic regurgitation or patent ductus arteriosus. However, the Doppler method showed regurgitant flow signals in the right ventricular outflow tract, as well as abnormal signals in the left ventricular outflow tract or in the pulmonary trunk (fig. 7).

In eight of the 60 cases, abnormal diastolic Doppler signals were recorded in the right ventricular outflow tract, but no diastolic murmur could be recorded by phonocardiography.

There were two false-negative studies among the 1200 cases examined; i.e., a pulmonary regurgitant murmur was recorded by phonocardiography, but
pulmonary regurgitant Doppler signals were not detected.

Discussion

Noninvasive detection of pulmonary regurgitation has been restricted to detecting the diastolic murmur clinically or by phonocardiography. The ultrasonic pulsed Doppler technique7 has augmented the ability to recognize regurgitant flow. Abnormal diastolic Doppler signals considered indicative of pulmonary regurgitation have been detected frequently in the right ventricular outflow tract by the Doppler technique. The abnormal Doppler signals, the hemodynamic conditions and other factors were analyzed in detail in the 60 cases in which such abnormal diastolic Doppler signals were detected. Comparisons were also made with heart murmurs.

The abnormal Doppler signals detected in the right ventricular outflow tract were regarded as indicating the regurgitant flow of pulmonary regurgitation because they were detected in the right ventricular outflow tract proximal to the pulmonic valve, generally from the pulmonic component of the second heart sound to the beginning of the next ejection, and because the velocity component was mainly directed opposite to the direction of systolic ejection flow.

The abnormal Doppler signals of the pulmonary regurgitant flow had mostly a unidirectional and wide-band velocity spectrum, indicating turbulent flow. However, in cases of aortic or mitral regurgitation, the pattern of regurgitant flows is usually bidirectional. This is considered to show that the flow is turbulent. The flow signals obtained by the pulsed Doppler flowmeter show the blood flow direction only within the small range of the sample volume, but do not necessarily indicate the overall direction of blood flow. Abnormal Doppler signals of pulmonary regurgitation in this study were mostly unidirectional and the signal direction was generally the same as the overall direction of regurgitant flow. Why the signals of pulmonary regurgitation and those of aortic or mitral regurgitation are different is not completely clear, but may be because the ultrasound beam is almost parallel to the overall direction of pulmonary regurgitant flow. Even when turbulence is present, the flow direction of the Doppler signals in the sample volume appears to reflect the overall flow direction.

The difference in the two flow patterns of pulmonary regurgitation is considered to be related to pulmonary artery pressure. For example, patients with the type B flow have a lower pulmonary artery pressure than those with the type A flow. The regurgitant flow velocity decreases gradually in type B flow because the pressure gradient between the pulmonary artery and the right ventricle becomes smaller in late diastole. Waggoner et al. reported that the pulmonary hypertension could be grossly recognized by the duration of regurgitant Doppler signal. In the present study, the flow patterns were qualitatively divided into two types, with and without pulmonary hypertension. The real-time spectroanalyzer was advantageous for recognizing the flow pattern clearly. However, it is difficult to assess the degree of pulmonary hypertension by the regurgitant flow pattern.

The spatial distribution of regurgitant signals in the right ventricular outflow tract varied, perhaps because of the degree of regurgitation. A reliable standard is necessary to evaluate the significance of the spatial distribution of regurgitant Doppler signals, but such a standard does not exist.

Relationships between diastolic regurgitant murmurs obtained by auscultation and phonocardiography and the regurgitant signals obtained by the Doppler method were examined. In most of the patients who had pulmonary regurgitation without aortic regurgitation and patent ductus arteriosus, the pulmonary regurgitant murmur was easy to diagnose from the phonocardiograms. In some patients with pulmonary regurgitation, the regurgitant murmurs were not clearly detected as pulmonary or aortic. Even in such cases, the Doppler method clearly showed pulmonary regurgitation. When regurgitant murmurs of pulmonary insufficiency were present together with regurgitant murmurs of aortic regurgitation or continuous murmurs of patent ductus arteriosus, diagnosis of the
regurgitant murmurs of pulmonary regurgitation was often difficult, but the Doppler method clearly differentiated between them.

No diastolic murmurs could be detected in 13% of the patients in the present study, although the abnormal diastolic Doppler signals were detected in the right ventricular outflow tract. In these cases, the distribution of the regurgitant Doppler signals was limited to a comparatively small area. One possible reason why a diastolic murmur could not be detected is that the diastolic murmur caused by a small degree of regurgitation could not be detected from the body surface. Another possibility is that transmission of the murmur to the surface of the chest wall might have been hindered. Waggoner et al.18 reported the relationship between the diastolic murmur and regurgitant Doppler signal. We examined the efficacy of phonocardiographic diagnosis for the pulmonary regurgitation in detail. In the half of patients with Doppler signals of pulmonary regurgitation, phonocardiography could not detect pulmonary regurgitation. The detection of pulmonary regurgitation was more sensitive and reliable by the Doppler method than by phonocardiography. The Doppler method is especially useful for differentiating the origin of murmurs when multiple valve lesions are present.

False-negative studies are possible with the Doppler method. This should be a point of caution and does not obviate the need to perform phonocardiographic and clinical examinations to detect pulmonary incompetence. However, the incidence of false-negative results by the pulsed Doppler technique was very low.

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Preoperative Secundum Atrial Septal Defect with Coexisting Sinus Node and Atrioventricular Node Dysfunction

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SUMMARY Sinus node dysfunction in patients after repair of the secundum atrial septal defect has been ascribed to surgical damage. We studied 15 consecutive patients with secundum atrial septal defect before operative intervention. Noninvasive testing included 24-hour electrocardiographic monitoring and a standard 13-lead ECG. Intracardiac electrophysiologic techniques included corrected sinus node recovery time, sinoatrial conduction time, His bundle recording to measure AH and HV intervals, the atrial pacing rate at which atrioventricular node Wenckebach occurred, and atrioventricular nodal refractory period. The ECG revealed an ectopic atrial rhythm in two patients. Intracardiac electrophysiology showed an abnormal corrected sinus node recovery time (range -40 to 800 msec) in 10 patients. Five patients had evidence of atrioventricular nodal dysfunction with prolonged AH interval or abnormal atrial pacing rate at which atrioventricular Wenckebach occurred. These data indicate that sinus node dysfunction or atrioventricular node dysfunction were present before surgical intervention.

SINUS NODE DYSFUNCTION is a frequently recognized abnormality after surgical repair of secundum atrial septal defects (ASDs). Since the early days of intracardiac repair, the postoperative abnormalities of sinus node function have been ascribed to surgical damage to the node or its artery. However, in a previous study, we recognized abnormalities of sinus node function in preoperative ECGs. Therefore, we undertook this study in 15 patients with physical findings consistent with left-to-right shunt at the atrial level to identify the incidence of electrophysiologic abnormalities.

Materials and Methods

The study group included nine girls and six boys, ages 10 months to 18 years, who were seen consecutively from June 1979 to December 1980 (table 1). Patient 2 complained of occasional lightheadedness and syncope and patient 10 had a history of dizziness; the others were asymptomatic. All patients had a standard 13-lead ECG and 11 had 24-hour ambulatory electrocardiographic recordings. These studies were evaluated for evidence of sinus node dysfunction, including sinus bradycardia for age; sinus arrest with atrial, junctional or ventricular escape beats or rhythm; any type of sinoatrial exit block; and/or brady-tachy arrhythmias. In addition, careful attention was paid to identify evidence of atrioventricular (AV) node dysfunction, including first-, second- or

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Received February 26, 1980; revision accepted July 24, 1981.

Pulmonary regurgitation studied with the ultrasonic pulsed Doppler technique.
K Miyatake, M Okamoto, N Kinoshita, M Matsuhisa, S Nagata, S Beppu, Y Park, H Sakakibara and Y Nimura

Circulation. 1982;65:969-976
doi: 10.1161/01.CIR.65.5.969

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

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the World Wide Web at:
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