QUANTITATIVE EVALUATION OF PULMONARY REGURGITATION AFTER REPAIR OF TETRALOGY OF FALLOT USING REAL-TIME FLOW IMAGING SYSTEM

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Real-time flow imaging of pulmonary regurgitation (PR) by two-dimensional pulsed Doppler echocardiography was performed in 34 patients after repair of tetralogy of Fallot. The right ventricle and pulmonary artery were demonstrated in the parasternal short axis view and PR flow was visualized. The image was frozen when the velocity of regurgitant flow was maximum at the level of the pulmonary valve. Pulmonary regurgitant area index (PRAI) was calculated from planimetric measurement of the area where PR flow was expressed. Grading of PR (1 to 3) was independently attempted according to the extension of PR flow detected in pulmonary artery by a range-gated pulsed Doppler echocardiography. PRAI (cm^2/m^2) was 0.36 ± 0.29 (mean $\pm$ standard deviation) in grade 1, 1.48 ± 0.46 in grade 2, and 2.80 ± 0.94 in grade 3. Severity of PR (grade 1 to 3) was also rated on the basis of the pulmonary arteriography and compared with PRAI. PRAI was 0.64 ± 0.60 in grade 1, 1.07 ± 0.63 in grade 2, and 2.21 ± 1.67 in grade 3, respectively. PRAI showed strong correlation with pulmonary regurgitant fraction measured by videodensitometric study of right ventriculography ($r = 0.84$). Quantitative evaluation of PR using real-time flow imaging system is a reliable and useful method.

PULMONARY regurgitation (PR) is one of the serious sequelae after correction of tetralogy of Fallot (TF) because it may lead to right ventricular failure.¹⁻⁴ Pulmonary arteriography is the usual procedure for evaluating PR, but it is invasive and not quantitative. Videodensitometry by right ventriculography is another existing method for assessing PR.⁵ However, these invasive methods are difficult to perform repeatedly to follow the progression of PR.

Range-gated Doppler echocardiography is a new technique that allows the assessment of

valvular regurgitation,⁶⁻¹² but quantitative assessment is difficult in patients with TF after corrective surgery because residual pulmonary stenosis remains and the direction of regurgitant flow is various. In the present study we have examined the reliability and usefulness of the real-time two-dimensional Doppler flow imaging system to assess the PR after correction of TF.¹³⁻¹⁵

METHODS

Patients: 34 patients (24 males and 10 females) were randomly selected after corrective surgery of TF and studied. The age at surgery ranged from 1 year 3 months to 27 years (mean 5.0 ± 4.8 years) ($\pm$ standard deviation). At the

Key words:

Tetralogy of Fallot
Pulmonary regurgitation
Pulsed Doppler
Real-time flow imaging

(Received November 29, 1988; accepted February 21, 1989)

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Fig.1. Imaging of pulmonary regurgitant flow.

The pulmonary artery and right ventricle were demonstrated in the parasternal short axis view, and the PR flow was demonstrated. Pulmonary regurgitant area index (PRAI) was calculated from planimetric measurements of the area (S) where PR flow was visualized maximally and then standardized for the body surface area. Ao: aorta, B.S.A.: body surface area, PA: pulmonary artery, PR: pulmonary regurgitation, PRAI: pulmonary regurgitant area index, RV: right ventricle, S: area of PR flow.

Fig.2. Pulmonary flow by pulsed Doppler echocardiography.

Timing of freezing the image was decided by measuring the time delay (T) from the peak of the R wave on electrocardiogram to the maximal velocity of pulmonary regurgitant flow at the pulmonary valve.

time of postoperative study the age range was 1 year 4 months to 28 years (mean 10.2 ± 6.0 years). The interval from operation to the study was 1 month to 16 years (mean 5.2 ± 4.4 years).

Study method: PR was assessed using real time color flow imaging system. The results were compared with the conventional grading

of PR by range-gated pulsed Doppler echocardiography, pulmonary arteriography and videodensitometric study of PR by right ventriculography. The influence of PR on right ventricular size was also examined.

Real-time flow imaging of PR: We used a commercially available Aloka SSD-880 two-

dimensional echocardiographic system with UGR-100 color Doppler unit (Aloka, Tokyo, Japan). The apparatus consisted of a 3.5 MHz transducer having a diameter of 1.2 cm and a two-dimensional 90-degree wide-angle electrical sector scan of 9 or 12 cm depth. The pulsed Doppler repetitive frequency was set on 3 KHz. Real-time color imaging of the blood flow was demonstrated on two videomonitors by utilizing auto-correlation techniques. The blood flow

toward the probe was presented in red, while the flow away was in blue. The velocity of flow was shown in 8 degrees of brightness. The lowest velocity detected with this instrument was 5 cm/sec. The frame formation rate was 7.5/sec. Ordinary range-gated pulsed Doppler echocardiography was also available and able to show real-time Doppler frequency with a fast Fourier transforming device. Other detailed characteristics of this apparatus have been reported previously.¹³⁻¹⁵

The pulmonary artery and right ventricle were demonstrated in the parasternal short axis view at the third intercostal space, and the image of PR flow was visualized in color and frozen when the velocity of regurgitant flow was maximum at the level of the pulmonary valve (Fig. 1). The timing of freezing the image was set beforehand by measuring the time delay from the peak of the R wave on electrocardiogram to the maximum velocity of regurgitant flow at the pulmonary valve annulus level using range-gated pulsed Doppler echocardiography (Fig. 2). The images were recorded with a Victor video recorder model 6060 and a Fuji instant camera.

The pulmonary regurgitant area index (PRAI) was calculated from planimetric measurement of

Fig.3. Grade of pulmonary regurgitation by pulsed Doppler echocardiography. Severity of pulmonary regurgitation was estimated on the basis of detection of regurgitant flow in the pulmonary artery. (grade 1, 2, 3)

Fig.4. Measurement of right ventricular size.

The right ventricle was demonstrated in the apical four chamber view and the image was frozen at the peak of the R wave on the electrocardiogram. The right ventricular end-diastolic area index (RVEDAI) was calculated by planimetric measurement of the dotted area. LA: left atrium, LV: left ventricle, RA: right atrium, RA: right ventricle.

TABLE 1 PULMONARY FLOW PATTERN BY PULSED DOPPLER

Systolic Flow			
Laminar	27		
Peak Flow Velocity < 2.0 m/sec		24	
≥ 2.0 m/sec		3	
Turbulent	7		
Peak Flow Velocity < 2.0 m/sec		0	
≥ 2.0 m/sec		7	
Diastolic Flow			
Absent	4		
Present	30		
Turbulent	24		
		Unidirectional	22
		Bidirectional	2
Laminar	6		

the area where the PR flow was visualized maximally and then standardized for the body surface area (Fig. 1).

Grading of PR using conventional range-gated pulsed Doppler echocardiography: Examination by range-gated pulsed Doppler echocardiography was performed independently in all cases within 24 hours after the real-time flow imaging. Aloka model SSD-720 and pulsed Doppler unit model UGR-23 with a 3 MHz mechanical transducer were used. The pulmonary artery and its main branches were visualized in the parasternal short axis view from the standard chest position. The sample volume was positioned at the site of the pulmonary valve. Then sample volume was positioned progressively distal to the right or left pulmonary artery. The flow signal at each site was expressed by the fast Fourier transfer method and recorded on a strip chart. The presence of PR flow was diagnosed when the Doppler flow velocity was more than 0.26 m/sec and its duration was longer than 50% of the diastolic phase. The PR degree was arbitrarily decided as follows. (1) Grade 0: PR flow was absent at the level of the pulmonary valve. (2) Grade 1: PR flow was detected below the middle point of the pulmonary valve and bifurcation. (3) Grade 2: PR flow extended beyond the middle point but below the bifurcation. (4) Grade 3: PR flow was detected beyond the bifurcation into the right or left pulmonary artery (Fig. 3).

Angiographic assessment of PR: Pulmonary arteriography was performed and PR was graded

Fig. 5. PRAI and the degree of PR by pulsed Doppler echocardiography.

PRAI: pulmonary regurgitant area index, PR: pulmonary regurgitation.

in 17 patients by the radiologist. The severity of PR was rated as follows. (1) Grade 1 (mild): Contrast medium was observed in the right ventricular outflow at diastole and disappeared at the following systole. (2) Grade 2 (moderate): Contrast medium entered the sinus portion during each diastole and was not completely cleared with each systolic ejection. (3) Grade 3 (severe): Contrast medium filled almost the whole right ventricular chamber with the same opacity as the pulmonary artery.

Videodensitometric assessment of pulmonary regurgitation: In 17 cases the degree of PR was quantified by the videodensitometric method reported by Bürsch et al.⁵ The total amount of contrast medium was measured by videodensity of the electronic sampling window covering the entire silhouette of the right ventricle in the lateral view. The ratio of the regurgitant volume over the total stroke volume was defined as the PR fraction (PRF). The systolic decrease in the contrast medium was equivalent to the stroke volume, and the following diastolic increase was equivalent to the regurgitant volume.

Evaluation of right ventricular size: Two-dimensional echocardiographic evaluation of the right ventricular size was simultaneously performed after real-time flow mapping. The transducer was positioned at the point of cardiac pulse and angled toward the right clavicle until the image of the 4 cardiac chambers and 2 atrio-ventricular valves was demonstrated. Then the transducer was angled to obtain the maximum

Fig. 6. PRAI and the degree of PR by pulmonary arteriography.
PRAI: pulmonary regurgitant area index,
PR: pulmonary regurgitation.

Fig. 7. Relationship between PRAI and PRF by videodensitometry.
PRAI: pulmonary regurgitant area index,
PRF: pulmonary regurgitant fraction.

Fig. 8. Relationship between PRAI and RVEDAI.
PRAI: pulmonary regurgitant area index, RVEDAI: right ventricular end-diastolic area index.

right ventricular size, and the image was frozen at the peak of the R wave on electrocardiogram as the end-diastolic phase. This image on the videomonitor was photographed with a polaroid camera. In 31 patients, the end-diastolic area of the right ventricle was able to be measured with a digitizer and defined as the right ventricular end-diastolic area index (RVEDAI) (Fig. 4).

Statistic Analysis: All values of the variables were expressed as mean $\pm$ standard deviation. Comparisons between groups were made by a Newman-Keuls test and the p value of <0.05 was considered significant.

RESULTS

Pulsed Doppler echocardiographic result: The pulmonary systolic flow was laminar in 27 patients and turbulent in 7 patients. In 27 patients whose systolic flow was laminar, the peak systolic flow was less than 2.0 m/sec in 24 patients, and more than 2.0 m/sec in only 3 patients. In all 7 patients whose systolic flow was turbulent, the peak systolic flow was over 2.0 m/sec. The PR flow was turbulent in 24 patients and laminar in only 6 patients. The PR flow almost exclusively unidirectional, with 2

exceptions (Table I).

Comparison of PRAI and the degree of PR with range-gated pulsed Doppler: PRAI was 0 in all 4 patients with PR grade 0. In those patients, right ventricular outflow reconstruction was performed by pulmonary valvotomy without outflow patch. PRAI ranged from 0.10 to 1.06 cm^2/m^2 (mean $0.36 \pm 0.29 \text{ cm}^2/\text{m}^2$) in grade 1. Nine out of 10 patients with grade 1 had a PRAI of less than 1.0 cm^2/m^2 . PRAI ranged from 0.70 to 2.30 cm^2/m^2 (mean $1.48 \pm 0.46 \text{ cm}^2/\text{m}^2$) in patients with PR grade 2, and from 2.00 to 4.59 cm^2/m^2 (mean $2.80 \pm 0.94 \text{ cm}^2/\text{m}^2$) in patients with PR grade 3. The differences in PRAI between these 3 groups were significant ($p < 0.001$) (Fig. 5).

Comparison of PRAI and the degree of PR by pulmonary arteriography: The PRAI of 4 patients with angiographical PR grade 1 was $0.64 \pm 0.60 \text{ cm}^2/\text{m}^2$, while it was $1.07 \pm 0.63 \text{ cm}^2/\text{m}^2$ in 8 patients with PR grade 2, and $2.21 \pm 1.67 \text{ cm}^2/\text{m}^2$ in 4 patients with PR grade 3. There were no significant differences between these 3 groups (Fig. 6).

Comparison of PRAI and PRF by videodensitometry: A significant positive linear correlation was observed between PRF and PRAI ($r = 0.84$, $p < 0.001$) (Fig. 7).

Relationship between RPAI and RVEDAI: RVEDAI also showed a linear correlation with PRAI ($r = 0.80$, $p < 0.001$) (Fig. 8).

DISCUSSION

Limitations of pulsed Doppler echocardiography: Pulsed Doppler echocardiography has become one of the most important non-invasive techniques for diagnosis of valvular regurgitation.⁶⁻¹¹ Its sensitivity and specificity have already been proven to be sufficient for clinical use. The degree of valvular regurgitation has been estimated according to the extension of the regurgitant flow in ventricles, atriums, or great arteries. However, this method has limitations for the assessment of PR after repair of tetralogy of Fallot because the regurgitant flow is sometimes directed in an unexpected way, especially when repaired with outflow patch. Also, residual pulmonary stenosis at the level of infundibulum may augment the extension of PR flow in the right ventricle compared with in patients without pulmonary stenosis. Secondly, the sample volume of range-gated pulsed Doppler echocardiography changes its position from systolic phase to dia-

stolic phase. The real-time position of the sample volume cannot be ascertained. Thirdly, the regurgitant flow from the pulmonary artery and the inflow from the right atrium are difficult to differentiate in patients with mild or severe PR.

Real-time flow imaging can visualize the PR flow in the right ventricle and pulmonary artery with two-dimensional echocardiography. Since the PR flow is visible in real time, it can be differentiated from the inflow through the tricuspid valve. The optimal gain setting is easy, and a false positive diagnosis of PR can be avoided. In this system, pulsed Doppler echocardiography is also available, and ghost signals can be differentiated from the true PR flow.

Quantitative evaluation of PR: Recently the PR fraction was calculated from the total blood volume of systolic forward flow and the diastolic regurgitant flow through the pulmonary valve by pulsed Doppler echocardiography.¹² However, the regurgitant flow was turbulent in 80% of the patients of this study and in those patients the total volume of the diastolic regurgitant flow could not be calculated. PRAI can be clearly differentiated by pulsed Doppler echocardiographic grading of PR regardless of residual pulmonary stenosis. There were no differences between PRAI of the 3 groups which were angiographically evaluated for the severity of PR. This result may be due to the objectivity of pulmonary angiographic evaluation and the deformation of its pulmonary valve by passing a catheter through it. PRAI is not equivalent to the PR fraction, but it showed good correlation with PRF measured in the videodensitometric study. PRAI is thought to be a good index because it is non-invasive and easy to measure repeatedly.

Importance of evaluating PR after correction of TF: In the present study the right ventricular size was correlated with the severity of PR. The PR after correction of tetralogy of Fallot was reported to disturb the ventricular function and exercise tolerance,¹⁶⁻¹⁹ and accurate assessment of PR is one of the most important studies in the management of patients after surgery.

It has not yet been elucidated how severe PR impairs the right ventricular function and how PR develops in the postoperative period. Recently, prosthetic materials like pericardium have been used to repair pulmonary valves and prevent PR at the right ventricular out flow reconstruction.²⁰ However, the fate of these materials is still unclear. PRAI assessed using

real-time flow imaging is thought to be very useful for resolving these problems.

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