ALTHOUGH tricuspid valve regurgitation can be due to organic disease of the tricuspid valve, it is generally a functional disorder, and frequently occurs after valvular disease of the left heart or in association with congenital heart disease.2 Although tricuspid regurgitation is functional, it can adversely affect the hemodynamic state of the patient.2 3 Thus, methods for assessing the severity of tricuspid regurgitation are needed, but there are none available.4 8 Attempts have been made to assess the degree of regurgitation by contrast echocardiography,9 10 but this method requires the injection of contrast material.

The ultrasonic pulsed Doppler technique has proved useful for detecting blood flow disturbances in the right heart.12 16 This technique is reported to be sensitive in detecting tricuspid regurgitation.17 20 In the present study, we analyzed tricuspid regurgitation in detail using ultrasonic pulsed Doppler and two-dimensional echocardiography;21 we specifically evaluated the severity of tricuspid regurgitation.

Materials and Methods

Sixty-six consecutive patients in whom tricuspid regurgitation was suspected from routine clinical evaluation underwent ultrasonic pulsed Doppler examination and right ventriculography between February 1980 and May 1981. The Doppler study was inadequate in one patient because sound penetrated poorly through the chest wall; right ventriculography was inadequate in three patients because premature ventricular complexes occurred. These four cases were excluded. The remaining 62 patients, ages 21–65 years (average 46 years), were the subjects of the present study. Eight patients were in sinus rhythm and 54 patients were in atrial fibrillation. The underlying disorders were rheumatic mitral valve disease in 51 patients, mitral valve prolapse with ruptured chordae tendineae in two, patent ductus arteriosus in three, idiopathic pulmonary artery dilatation in two, lung embolism in two, and left atrial myxoma and traumatic tricuspid regurgitation in one patient each. Ten healthy subjects, ages 22–36 years (average 28 years), served as controls.

Equipment

We used a system that combined a directional ultrasonic pulsed Doppler flowmeter (Hitachi Medico EUD-4Z) and an ECG-gated, compound, two-dimensional echocardiograph (Aloka SSD-120). The master oscillation of the pulsed Doppler flowmeter was 2.5 MHz and the pulse repetition rate was 4500 or 6300 bursts/sec. The sample volume was 6 × 6 mm wide and 5 mm deep. In 13 recent cases, we used an ultrasonic pulsed Doppler flowmeter (Toshiba SDS 10A) incorporated in a real-time, phase-array, two-dimensional echocardiograph (Toshiba SSH 11A). The sample volume was 4 × 4 mm wide and 3 mm deep.*

The beam direction for Doppler use and the position of the sample volume were displayed on the two-dimensional image, which was superimposed on the cross section of the intracardiac structures. The Doppler signal was passed through a high-pass filter (400 Hz) to eliminate the influences of movements of the

*The site of sample volume on the screen of the Braun's tube indicated the proximal end of the sample volume with both systems. The distance reached by the abnormal signal from the tricuspid orifice was the same with both systems. Therefore, during the last part of study, the Toshiba equipment was used because it was easy to operate.
intracardiac structures; frequency analysis of the Doppler signals was carried out in real time by fast Fourier transform. The flow pattern was simultaneously displayed with the ECG, phonocardiogram, and the M-mode echocardiogram, which was recorded by the same beam used for the Doppler study, on a strip-chart recorder. The Doppler signal components that indicated movement away from and toward the transducer were displayed, respectively, below and above the baseline on the recording paper (fig. 1).

Searching Techniques

The Doppler examination was performed within 5 days before or after cardiac catheterization. The patient rested for about 15 minutes in a supine position. The Doppler examination was done while the patient was breathing in a relaxed manner to keep the respiration effect as weak as possible. First, the ultrasonic beam was transmitted from the third or fourth intercostal space of the left sternal border into the right atrium. Then, abnormal Doppler signals were sought over the right atrium from the tricuspid valve to the posterior wall. The M-mode echocardiogram was used to monitor the site sample volume. If abnormal Doppler signals indicating possible tricuspid regurgitant flow were obtained, the beam was directed to obtain the abnormal Doppler signals as deep as possible from the tricuspid orifice toward the posterior wall of the right atrium. A two-dimensional parasternal four-chamber view was recorded and the beam angle was changed in several directions on this cross section. The region in which the abnormal signals were obtained was determined by shifting the sample volume in each direction, and was delineated in the two-dimensional image by light spots (fig. 1). The Doppler signals that were most distinct through one respiratory period in each sample volume were analyzed. The grading of the tricuspid regurgitant Doppler signal was done by two observers without knowledge of the right ventriculographic findings.

Right Venticulography

For comparison, right ventriculography was performed. The following procedures were used to minimize possible artifactual tricuspid regurgitation: (1) A hook-like, preshaped pigtail catheter was used to prevent the catheter from pushing aside the tricuspid valve (fig. 2); (2) the contrast material (Urographin 76) was restricted to a small dose and injected slowly, i.e., 24 ml over 3 seconds; (3) the lung field was covered with a copper plate to obtain a contrast picture. A biplane cineangiograph and a highly sensitive image intensifier were used. The right ventriculograms were evaluated independently on a four-point scale similar to the Sellers classification of mitral regurgitation,22 by a radiologist who had no knowledge of the Doppler findings (fig. 2).

The grade of regurgitation based on right ventriculography and that based on the Doppler method were compared.

Results

Healthy Control Subjects

Blood flowed toward the tricuspid valve in systole and in diastole in the right atrium (fig. 3). Doppler signals were sometimes recorded near the tricuspid valve in early systole, after the closure signal of the valve. This signal was directed away from the transducer and did not exceed the first third of systole.

Patients with Heart Disease

Signal of Tricuspid Regurgitation

In 58 of 62 patients, abnormal signals were detected adjacent to the tricuspid valve in the right atrium dur-

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![Diagram](image_url)
ing systole. In four patients, no abnormal signal was detected. The abnormal signals lasted from valve closure to the subsequent opening and consisted mainly of components moving away from the tricuspid valve. The wide-band velocity spectrum of these signals suggested that the blood flow was turbulent. The signals were detected within a spindle-shaped region parallel to the interatrial septum, extending from the tricuspid valve to the right atrium (fig. 3). These signals were considered to be due to tricuspid regurgitant flow for the following reasons: (1) all patients in whom they were detected were found to have tricuspid regurgitation at right ventriculography; (2) the time of appearance of the signals was pansystolic; (3) the blood flow was directed away from the tricuspid valve; and (4) the area in which the signals were present was contiguous to the tricuspid valve in the right atrium.

Among patients in whom regurgitation was shown to be slight by right ventriculography, the duration of the abnormal signals was short and not pansystolic (fig. 4). The duration of abnormal signals was also brief in the area surrounding the regurgitation, even in patients with moderate or severe regurgitation. The abnormal signals whose duration exceeded one-half of systole were interpreted to indicate tricuspid regurgitant flow. In the four patients who had extremely severe regurgitation by right ventriculography, the Doppler signals showed that the velocity component had a narrow-band spectrum, which indicates that the central part of regurgitant flow in severe regurgitation is probably laminar (fig. 5).

Severity of Regurgitation Based on the Distance Reached by the Regurgitant Flow Signal

The maximal distance from the tricuspid orifice reached by the regurgitant signals was measured from echocardiograms in the parasternal four-chamber view. Based on this distance, the severity of tricuspid regurgitation was classified on a four-point scale: 1+ = less than 1.5 cm; 2+ = 1.5 cm or more and less than 3.0 cm; 3+ = 3.0 cm or more and less than 4.5 cm; 4+ = 4.5 cm or more (fig. 6).

The severity of regurgitation was classified as 0 in four patients, 1+ in nine (fig. 4), 2+ in 23, 3+ in 16, 4+ in 10 (fig. 5). The grade based on right ventriculography was 0 in two patients, 1+ in 14, 2+ in 21, 3+ in 16, and 4+ in nine. In 34 patients, the two scores matched exactly; in 25 patients, the scores differed by one level and in three by two levels (fig. 7). The two methods correlated well ($r = 0.75$, $p < 0.001$ using Pearson's method). One of the three patients in whom there was a discrepancy of two levels had tricuspid valve prolapse. In this patient, the region in which the regurgitant flow signals were detected was not parallel to the interatrial septum, but was directed to the opposite side from the prolapsed leaflet (fig. 8).

Severity of Regurgitation Based on the Area Covered by the Regurgitant Flow Signal

The area of the region in which the regurgitant flow signals were detected was determined from the echocardiograms in the parasternal four-chamber view. The area analysis was graded on a four-point scale: 1+ = less than 2 cm$^2$; 2+ = 2 cm$^2$ or more and less than 4 cm$^2$; 3+ = 4 cm$^2$ or more and less than 10 cm$^2$; 4+ = 10 cm$^2$ or more (fig. 6). The severity of regurgitation based on area assessment was 0 in four patients, 1+ in 15, 2+ in 22, 3+ in 17, and 4+ in four. The grading based on the area covered by the regurgitant signals correlated well with that by right ventriculography ($r = 0.74$, $p < 0.001$) (fig. 7). The area method and the distance method showed similar correlation coefficients.
Discussion

There have been few reports on the analysis of tricuspid regurgitation by the ultrasonic pulsed Doppler technique. In these reports, M-mode echocardiography was used to monitor the Doppler sampling sites and it was difficult to define the spatial distribution of the abnormal signal in the right atrium. We used pulsed Doppler technique and two-dimensional echocardiography to analyze tricuspid regurgitation. This method allowed better definition of the abnormal signal, including its direction and distribution in the right atrium, so we could confirm that the abnormal signal was related to the tricuspid orifice. The regurgitant flow signal was generally pansystolic, but if the regurgitation was slight, the flux of regurgitant flow was so fine or narrow that the ultrasound beam might miss it because of cardiac movement. A short signal could be recorded near the tricuspid valve in early systole even in healthy subjects. Based on the time of appearance and the feature of this signal, we thought it originated from the closing movement of the tricuspid valve and the movement of the blood adjacent to the valve. Thus, we considered a signal with an abnormal duration exceeding one-half of systole as representing tricuspid regurgitation.

In the majority of cases, the regurgitant flow signals exhibited a wide-spectrum velocity component, so they were interpreted as originating from turbulent flow. However, in the four cases of severe tricuspid regurgitation, the regurgitant flow signals were unidirectional and exhibited a rather narrow-band spectrum.
in the central part of the flow, which indicated that the flow was laminar. In these severe cases, the flux of the regurgitant flow was so thick that the central part of the flow was not disturbed by eddies, but laminar.

The findings from the Doppler evaluation and right ventriculography were evaluated on a four-point scale. From the practical point of view global analysis may be convenient. Because the boundaries of each level were established as a matter of convenience for both the Doppler technique and right ventriculography, the grade determined by the Doppler technique and that by right ventriculography might not show an exact consistency to each other. The grades of regurgitation obtained by the two methods respectively correlated relatively well. However, several factors may account for the discrepancy between the two methods.

Figure 4. Mild tricuspid regurgitation in a 44-year-old woman with left atrial myxoma. (top) The region in which the abnormal signal was detected is shown in the cross-sectional image. It is small and the severity of regurgitation was graded as 1+. (bottom) The abnormal Doppler signals recorded in the right atrium were in systole. There are also some beats in which the abnormal signals were not pansystolic. Abbreviations are as in figure 1.

Figure 5. Severe tricuspid regurgitation in a 44-year-old woman with rheumatic aortic and mitral valve disease. (top) In cross section, the region covered by abnormal signals is spindle-shaped and large, reaching as far as the posterior wall of the right atrium. The severity of regurgitation was evaluated as 4+ by both the Doppler technique and right ventriculography. (below) The abnormal pansystolic Doppler signal in the right atrium was unidirectional and exhibited a narrow spectrum (the white arrow). Because the flow velocity was so high that it exceeded the measurable range, the excess part was displayed on the opposite side (the black arrows). The diastolic inflow showed rapid velocities during diastole, indicating tricuspid stenosis. Abbreviations are as in figure 1.
Establishment of the Ultrasonic Cross Section

In the majority of subjects, the regurgitant flow was directed toward the posterior wall of the right atrium. The parasternal four-chamber view is most suitable for detecting regurgitant flow in this direction. However, the regurgitant flow may not be entirely involved in this section. In patients with tricuspid valve prolapse, for example, the overall direction of the regurgitant flow was not directed toward the posterior wall of the right atrium parallel to the interatrial septum, but to the opposite side to the prolapsed leaflet. Therefore, a grading system based on the distance reached by the regurgitant flow signal may not be suitable. In these cases, the grade based on distance may be somewhat less than that observed by right ventriculography.

Marked Enlargement of the Left Atrium

In patients with a large left atrium, the interatrial septum bulges into the right atrium. In such cases, the overall direction of regurgitant flow may not strike the posterior wall of the atrium, but instead may impinge on the interatrial septum. Therefore, the severity of regurgitation could be evaluated as lower.

Right Ventriculography

There has been no reliable reference for evaluating the severity of tricuspid regurgitation. However, we compared findings obtained by the pulsed Doppler technique with those obtained by right ventriculography. During right ventriculography, artifactual tricuspid regurgitation frequently occurs. To prevent this type of regurgitation,23 various measures were taken in the present study, including use of a special catheter, reducing the dose of contrast material injected, and

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**Figure 6.** Grading the severity of tricuspid regurgitation on a four-point scale by the Doppler technique. (Left) Grading based on the maximal distance from the tricuspid orifice reached by the regurgitant flow. (Right) Grading based on the area of the region in which the regurgitant flow signals were detected.

**Figure 7.** Comparison of the grades of regurgitation based on the Doppler technique and those based on right ventriculography (RVG). (A) Comparison of the grades based on the distance attained by the Doppler signal and those based on RVG. (B) Comparison of the grades based on the area of the Doppler regurgitant signal and those based on RVG. △ = sinus rhythm, ○ = atrial fibrillation, ⋄ = tricuspid valve prolapse.
enhancing photographic quality to allow a smaller dose of contrast material. Consequently, we assumed that artifactual regurgitation was very small, but it is possible that it may be present nonetheless.

Although many problems remain in evaluating the severity of tricuspid regurgitation based on the Doppler technique and right ventriculography, the effects of these factors may counterbalance each other. The correlation between the results obtained by both methods was good, so grading of tricuspid regurgitation by the ultrasonic pulsed Doppler technique and two-dimensional echocardiography should be practicable.

The results based on the distance reached by the regurgitant flow signal were similar to those based on area. The grading based on distance is easy both to record and to evaluate, and takes only 10–20 minutes. For these reasons, this form of analysis may find wide clinical application.

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Assessment of Transesophageal Pulsed Doppler Echocardiography in the Detection of Mitral Regurgitation

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SUMMARY The value of transesophageal pulsed Doppler echocardiography (PDE) was studied in six patients with competent mitral valve and in 12 patients with angiographically proved mild to moderately severe mitral regurgitation. The results were compared with those from the standard transthoracic method of investigation. The advantages of the esophageal over the transthoracic approach in the detection of mitral regurgitation are (1) absence of anatomic obstacles between the ultrasound transducer and the heart; (2) nearly parallel alignment of the ultrasound beam with the blood flow direction; (3) the use of high pulse repetition frequencies; and (4) detection of localized regurgitant jets by left atrial scanning. This results in a superior recording quality and greater sensitivity. Based on a specific systolic flow pattern in the time-interval histogram, mitral regurgitation was detected in all patients by the transesophageal technique (100% sensitivity), but in only 58% by the precordial approach. Thus, transesophageal pulsed Doppler echocardiography can accurately detect the presence of mitral regurgitation, particularly in cases of mild or moderate severity.

STANDARD M-mode and two-dimensional echocardiography are useful in the noninvasive diagnosis of various cardiac malfunctions. In certain cases of mitral regurgitation, both techniques can be applied to establish the cause; yet they fail to yield specific results if the lesion is not accompanied by structural abnormalities. By its ability to record flow velocity patterns, though, the recently developed technique of range-gated pulsed Doppler echocardiography (PDE) is a direct, noninvasive means of detecting valvular incompetence as well as stenotic valves thereby establishing itself as a powerful adjunct to conventional echocardiography and cineangiography. Although the quantification of flow velocities and, consequently, of degrees of regurgitation is not possible, transcutaneous PDE has a high diagnostic potential.

We report our experience with a new Doppler technique using the transesophageal approach.

Methods

The basic concepts of range-gated PDE have been reported in detail elsewhere. They are briefly reviewed here to emphasize the advantages of an esophageal position of the ultrasound transducer.

Theoretically, the magnitude of the Doppler frequency shift depends on the blood flow velocity and on the angle between the ultrasound beam axis and the blood flow velocity vector. To get a high sensitivity for velocity measurements, the ultrasound beam should be aligned as parallel as possible to the blood flow direction.

PDE permits determination of the investigation site (i.e., sample volume) within the cardiac region of interest. This advantage over continuous Doppler systems, however, has a serious drawback: the fundamental limitation of a constant range-velocity product. Since each reflected pulse must reach the receiver before the next pulse is emitted (to avoid range ambiguities), the pulse repetition frequency (PRF) sets an upper limit to the maximum travel distance. Furthermore, due to the pulsed nature of the system, the Doppler signal cannot be obtained as a continuous wave form. It is constituted from samples at the rate of the PRF and thus obeys the laws of information theory; specifically, the sampling (Nyquist) theorem, which demands that the highest signal frequency be less than half the PRF. Therefore, not only does the PRF limit the maximum depth range to be investigated, but it also determines the highest measurable Doppler frequency shift, and thus the highest measurable blood flow velocity in that range. The higher the PRF is set,
Evaluation of tricuspid regurgitation by pulsed Doppler and two-dimensional echocardiography.

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