Recent Progress in Ultrasonic Diagnosis of the Heart: Doppler Flow Imaging

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It is appreciated that, linked with B-mode echocardiography, the real-time two-dimensional Doppler flow imaging technique provides information on the heart, which has never been available with conventional methods, greatly improving the capabilities of cardiac ultrasound. In general, the concept of major heart disease consists of anatomical abnormalities and those in intracardiac flow condition. The present method provides information on these two aspects simultaneously; consequently, it is regarded as a closer approach to heart diseases, compared with conventional examinations and techniques. The equipment is also convenient to operate. The combination of real-time two-dimensional Doppler flow imaging and B-mode echocardiography is expected to become a standard tool of the ultrasound examination of the heart.

Two-dimensional echocardiography made an epoch in the anatomical diagnosis of heart diseases. However, one of its limitations is that the method offers no direct information on the intracardiac flow conditions, data on which are essential for major heart diseases. Since about ten years ago, the ultrasonic pulsed Doppler technique has been combined with two-dimensional echocardiography, making it possible to analyze intracardiac hemodynamic conditions noninvasively from the transcutaneous approach. However, the procedure was troublesome and inconvenient for clinical application.

Subsequent developments in medical electronics, however, have recently led to a technique for visualizing flow information in the M-mode or B-mode echo images of the heart structure in real-time. The real-time two-dimensional Doppler flow imaging technique makes it feasible to observe blood flow topography in the cardiac cavity in the cine-mode.1–5 In the present study, attempt was made to assess the capabilities of this technique in clinical application.

MATERIALS

About 2000 patients were examined using a real-time two-dimensional Doppler flow imaging system from June, 1983 to March, 1984. Cardiac catheterization was performed on 190 of them, comprising 120 cases with valvular heart disease, 40 with congenital heart disease, 20 with ischemic heart disease and 10 with other heart diseases. Their age ranged from 18 to 72 years. Findings in the 190 patients were studied in detail on the basis of general trends observed in the 2000 patients.

METHODS

1) Equipment

The equipment used was a real-time two-
dimensional Doppler flow imaging system recently developed by Namekawa and Kasai, an ALOKA XA-54, with an ultrasound frequency of 2.5 MHz and a pulse repetition rate of 4 kHz.

The sending part of this equipment was about the same as that of the conventional wide-angle phased array system. The reflected pulses were partly used for conventional B-mode imaging of the heart structure. From the remainder, components of small amplitude were separated through a comb filter (Fig. 1). Such components must include those scattered by the blood flow with Doppler frequency shift. They were processed with the high-speed autocorrelation technique to calculate flow direction, mean velocity and frequency variance at each point in the B-mode image. The frequency variance was considered related to flow turbulence. The flow informations obtained were displayed in the color-coded mode at the corresponding point in the cardiac chamber on the B-mode image in real-time. Flow toward the transducer was expressed in reddish color, that away from the transducer in bluish color. The magnitude of flow velocity was indicated in brightness of color on 8-step scale from 0 to the upper limit of the measurable range, 2 kHz. The lowest step was provided with no brightness. When flow velocity exceeded the upper limit, color reversal occurred, corresponding to “aliasing” in conventional spectrography based on the fast-Fourier transformation analysis. When flow velocity was so fast as to cause multiple times of aliasing, the hue showed a mosaic pattern consisted of reddish and bluish colors. The variance was expressed by adding green to each color according to its degree, reddish changing to yellowish and bluish to cyan.

The sector scan for the B-mode echo image was done with the angle of 50° at the frame rate of 10 times a second. Real-time cine-mode images of intracardiac blood flow were recorded on videotape. ECG-gated still images were recorded on Polaroid film.

Color-coded M-mode display was also available by change-over of switch. Frequency spectrograms could be also obtained, based on the fast-Fourier transformation analysis on the blood flow at an arbitrary point in the B-mode image. The beam direction and site of sample volume for the spectrogram were indicated by a cursor line and a mark thereon in the B-mode image, respectively.

2) Examination Techniques

The procedure for real-time two-dimensional Doppler flow imaging was about the same as that for conventional two-dimensional echocardiography. In general, the parasternal long-axis view, parasternal short-axis view and apical long-axis view were used for the observation. A variety of other approaches was also needed in some patients to detect localized flows in the cardiac cavity.

Since the extent of the signal range for a certain flow on the television screen was dependent on the gain in the equipment, the gain was required to be appropriately adjusted. In the present study, the gain was set at the maximum level at which white noise did not yet appear on the screen. Although the gain was raised beyond that point, the range of flow signals did not become wider than that at this level, being disturbed by white noise.

*Japanese Circulation Journal Vol. 49, July 1985*
Fig.2. Mitral regurgitation.
Left upper panel: long axis view from the parasternal approach in systole. A blue and yellow mosaic signal was recorded from the mitral orifice into the left atrial cavity. It indicates a mitral regurgitant jet.
Right upper panel: short axis view. The mosaic signal was recorded from the center of mitral orifice.
Bottom panel: in the M-mode image, blue mosaic signals were observed in the left atrium through systole. The frequency spectrogram showed bi-directional wide-band signals through systole.

Fig.3. Aortic regurgitation.
Left panel: apical long-axis view. Aortic regurgitant flow was recorded as a reddish belt-like signals from the aortic orifice into the left ventricle in diastole.
Right panel: short-axis view. Aortic regurgitant flow was recorded as the round-like area in the left ventricular outflow tract.

Fig.4. Tricuspid regurgitation and pulmonary regurgitation.
Left panel: parasternal four-chamber view. Tricuspid regurgitant flow was recorded in systole as the blue area from the tricuspid orifice into the right atrium along the interatrial septum.
Right panel: sagittal view. Pulmonary regurgitant flow was recorded as the reddish belt-like signal from the pulmonic orifice into the right ventricular outflow tract in diastole.

Fig.5. Mitral stenosis.
Left panel: apical long-axis view. Mitral inflow flux was recorded as the narrow belt-like signals from the stenotic orifice into the left ventricle. These inflow signals were displayed as the blue signal in the central zone and yellow signal in the surrounding zone.
Right panel: In the frequency spectrogram, by the fast Fourier transform analysis, the Doppler signal of mitral inflow showed the aliasing due to the high velocity.

Fig.6. Atrial septal defect and ventricular septal defect.
Left panel: parasternal four-chamber view in a patient of atrial septal defect. The left to right shunt flow was recorded as the reddish signal from the left atrium into the right atrium through the defect.
Right panel: parasternal four-chamber view in a patient with ventricular septal defect. The left to right shunt flow was recorded as the mosaic signal spurtling from the defect into the right ventricle.

RESULTS

1) General description on intracardiac flow images

Mitral inflow and ejection flow in the left ventricle were clearly demonstrated via the parasternal long-axis and apical long-axis views. These flows were imaged well in patients whose cardiac structures were clearly imaged in the B-mode.

In early diastole, reddish signals, or the mitral inflow, spread through the maximally opened mitral valve over the left ventricle. This reddish signal area soon narrowed and bluish signals, or flow away from the apex, appeared on the left ventricular outflow tract. These signals were interpreted as follows: the inflow became a eddy current in the apical region and flowed up along the interventricular septum. In atrial systole, a reddish flux again reached near the apex from the mitral ostium.

In the ejection phase, bluish signals filled the left ventricle. The flow velocity appeared was low in the region from the left ventricular posterior wall to the apex and highest in the outflow tract along the interventricular septum. In systole, generally, no high velocity flow was observed near the mitral valve in the left atrium.

2) Regurgitant flow

(a) Mitral regurgitation

The two-dimensional features of mitral regurgitant flow were examined from the parasternal approach in cases with mitral regurgitation. Mitral regurgitation in these cases had been documented by angiography and Doppler echocardiography. It was revealed on the left ventricular long-axis view that blue or mosaic signals spread in an inverted-cone form from the mitral ostium into the left atrial cavity. The mosaic pattern of reddish and bluish signals usually observed at the central part of the regurgitant signal area was interpreted to show high velocity, reflecting the large retrograde transmitral pressure gradient in systole. In general, mitral regurgitant signals were localized in a certain area in the left atrial cavity, requiring thorough searching near the mitral ostium by gradually shifting and tilting the cross-sectional plane to detect the regurgitant. Long-axis and short-axis observations revealed the spatial orientation of the regurgitant flow (Fig. 2).

Mitral regurgitant signals were generally recorded throughout systole. In some patients, however, the signals were found only in early systole.

It became clear that the present technique allowed one to obtain information difficult to procure by the conventional methods. For example, the site of regurgitation in the valve could be mostly localized by shifting the sectional plane carefully: regurgitant flow was jetted out from the medial or lateral portions of the ostium in some and from the entire coaptation line in others. The close relationship between the dynamic features of regurgitant flow and the anatomical condition of the valve was disclosed: regurgitant signals were distributed from the ostium posteriorly in anterior mitral valve prolapse and anteriorly in posterior mitral valve prolapse, indicating the main direction of each regurgitation. Regurgitant jets showed complex features, often especially after valve surgery, including regurgitant jet spurring across the ostium, two jets spurring from the same site each into its different direction, and so forth. In severe cases, the direction of regurgitant jet was continuously change with heart beat, resulting from a change in orientation of the mitral valve. For these findings, we were exclusively indebted to the capabilities of the new technique.

Regurgitation signals were detected with the present technique in 83 of 98 cases, in which mitral regurgitation had been documented with left ventriculography, with the sensitivity of 85% and specificity of 100%. Mitral regurgitations were only very slight in the false negative cases. The degree of regurgitation as evaluated with left ventriculography was generally coincident with the size of the area of regurgitant signals as shown by the Doppler technique, suggesting the possibility of thus grading the regurgitation with the present technique.

(c) Aortic regurgitation

The parasternal two-chamber view or the apical two-chamber view was suitable for the study of aortic regurgitation with the new real-time two-dimensional Doppler flow imaging technique. Aortic regurgitant signals were observed in a belt-shaped area extending from the aortic valve into the left ventricular outflow tract (Fig. 3). Color reversal and mosaic pattern were frequently observed. As to the direction of aortic regurgitant flow, the flow ran along the interventricular septum in some cases, through the central zone of the outflow tract in some others and along the anterior mitral leaflet in remainders.

*Japanese Circulation Journal Vol. 49, July 1985*
The sensitivity and specificity of the present technique were 87% and 100% on the basis of those of aortography in 98 patients. The aortic regurgitant flow image was localized on the left ventricular outflow tract in some cases and reached the apical region in other cases. The extent of the image coincided with the severity as assessed by aortography. Therefore, it was thought that the severity of aortic regurgitation could be noninvasively graded using the present technique.

(c) Tricuspid regurgitation and pulmonary regurgitation

The parasternal four-chamber view was thought to be advantageous to detect tricuspid regurgitation. Tricuspid regurgitant jets were also observed, flowing mostly in parallel with the interatrial septum. In the above-mentioned view, tricuspid regurgitant signals were usually bluish and did not show color reversal or mosaic pattern as mitral regurgitant signals (Fig. 4). This was thought to be because the retrograde pressure gradient of the tricuspid valve was not so large as that of the mitral valve.

The sagittal section, including the right ventricular outflow tract to the pulmonary trunk, was best for observing the pulmonary regurgitant jet (Fig. 4).

3) Flow through the stenotic valve

The apical approach was advantageous for observing inflow through the stenotic mitral valve in mitral stenosis. While the normal mitral inflow spread over the left ventricle, that in mitral stenosis flowed like a narrow band from the stenotic valve into the left ventricular cavity (Fig. 5). The central zone of the flow usually showed color reversal. It was considered to be resulted from the flow acceleration owing to the elevation of left atrial pressure and narrowness of the stenotic pathway. The inflow jet flowed toward the apex in general, deviating posteriorly in some patients and anteriorly in some others.

The flow sinking into the ostium was sometimes imaged near the ostium in the left atrial cavity (Fig. 5). This flow signal was colored in red, indicating that the flow ran toward the ostium. It was frequently observed that this signal area expanded in a fan-like manner into the atrial cavity, i.e., into the opposite direction to the flow, in early diastole. The reason why this apparently paradoxical phenomenon occurred, will be mentioned in the chapter of discussion.

4) Congenital heart disease
   (a) Atrial septal defect

In the parasternal four-chamber view, reddish signals were widely observed from the left atrial cavity, through the interruption of the interatrial septum echo, into the right atrial cavity up to the tricuspid valve (Fig. 6). The central zone of the reddish area showed color reversal in some cases. Raddish signals were sometimes observed in both atrial cavities along the interatrial septum, even in healthy subjects, indicating flows from the great veins toward the atrioventricular valves. Since the interatrial septum echo was generally weak, care should be taken to differentiate them from those of the shunt through the defect on the interatrial septum.
   (b) Ventricular septal defect

A jets of mosaic pattern were observed to spurt from a certain point on the interventricular septum into the right ventricular outflow tract in systole on the parasternal four-chamber view and the cross-section including the right ventricular outflow tract and the pulmonary trunk. An yellowish jet was found in the same region in diastole in more than half the cases showing the mosaic jet in systole (Fig. 6). These signals were interpreted as indicating a left-to-right shunt. It should be emphasized that the defect location could be determined to be as the location of the jet by the Doppler, even if the echo interruption due to the defect is not detected on the echo image. It was necessary for this estimation to search for the source of the jet carefully. The simplicity of the equipment was helpful to the search.

DISCUSSION

1) Comments on the characteristic features of the flow image

Stevenson et al. first attempted to image heart structure and intracardiac blood flow at the same time. Doppler signals of blood flow were imaged in the color-coded mode on the M-mode image of the heart. After their report, Bommer et al. presented a trial of real-time two-dimensional display of the intracardiac flow Doppler signals in the color-coded mode, although it was a brief communication. The real-time two-dimensional Doppler flow imaging technique in the present study was developed by Namekawa and Kasai independently of those reports. It should be emphasized that the flow images of these methods are not echo images of
blood flow but reconstructed images based on flow velocity, thus being different from the image of cardiac structure. Strictly speaking, the flow image in the present technique is not visualization of flow, but of flow velocity. In mitral stenosis, the atrial portion of the mitral inflow signal area spread in the direction opposite that of the flow direction in early diastole. This finding appeared apparently to be paradoxical. However, it is practically possible because the present flow image is not the echo image of low, but a visualization of flow velocity.

Since the present flow image is a visualization of velocity, the hue of the flow image changes as the ultrasound beam is transmitted from different directions. However, no confusion owing to this change was noted in the present study. However, it must be kept in mind again that what is imaged is not the entire velocity but the velocity component in the beam direction. Theoretically, the noncolored portion in the cardiac chamber may indicate slow flow or speedy flow perpendicular to the beam. In practice, however, it was not particularly difficult to differentiate between these flows on the basis of observations from a variety of directions and anatomical or physiological considerations.

2) Advantages of Doppler flow imaging

The newly developed Doppler flow imaging technique includes various advantages for clinical application. First, the progress from the frequency spectrogram based on the fast Fourier transform analysis to the two-dimensional Doppler image is similar to that from the M-mode echorgram to the B-mode echorgram. The real-time two-dimensional observation facilitates to understand the spatial direction and distribution of a flow of interest and the positional relationship between this flow and other flows, which have been difficult to demonstrate clearly by the one-dimensional display.

Second, it is possible to understand intracardiac flow conditions in reference to anatomical conditions of the heart. For example, it was disclosed that the spatial orientation of mitral regurgitant flow closely depended on underlying conditions in the valve.

Third, it became feasible to demonstrate the change in intracardiac blood flow in real-time by the cine-mode display. For example, the direction of the mitral regurgitant jet changed even within one heart beat. This successive change, expected on the basis of contrast echocardiography findings, was demonstrated for the first time by the present technique. Hereafter, the new technique will become useful for acute intervention study.

Fourth, resolution in the present technique is fairly high. The site of regurgitation in the mitral valve could be determined, as could the site of shunt in the interventricular septum in ventricular septal defect. The small size of the transducer is convenient to operate, being advantageous to search regions of interest for such localized events.

Fifth, the new technique links anatomical information based on the B-mode echo image with physiological information on the intracardiac flow, greatly enhancing the diagnostic capability of cardiac ultrasound. Further, in some patients with interventricular septal defect, even when the defect was not clearly imaged by the B-mode echo, it could be diagnosed on the basis of the site of the shunt observed via the Doppler. Therefore, the Doppler and the echo are thought to have complementary roles in cardiac diagnosis.

Sixth, the M-mode display and the spectrogram based on the fast Fourier transformation analysis are thought to be advantageous to a quantitative study of flow dynamics in the heart. However, for such a study the beam direction and the site of interest should be determined on the basis of two-dimensional flow image guides.

Finally, markedly shortened examination time and greatly reduced discomfort to examine are also advantages of the new technique in clinical use. The new technique will serve for screening examination as well as for detailed examination in cardiology.

REFERENCES


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