NON-INVASIVE QUANTITATIVE EVALUATION OF AORTIC REGURGITATION USING AN ULTRASONIC PULSED DOPPLER FLOWMETERS

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The severity of aortic regurgitation (AR) is usually evaluated using cine-aortography, but this procedure cannot be carried out easily because of its invasive nature. For estimating the severity of AR non-invasively as well as quantitatively, we measured the blood flow in the aortic arch using an ultrasonic pulsed Doppler flowmeter (UPDF) from a suprasternal notch. The regurgitant ratio was calculated from the waves of relative flow volume and compared with the severity determined cine-aortographically.

The following results were obtained: 1) Reproducible waves of the aortic arch flow were recorded in all normal subjects and also in 19 out of 23 patients with AR. 2) Distinctive waves of the regurgitant flow, which could not be seen in normal subjects, were recorded in AR except for some mild cases. 3) The regurgitant ratio obtained from the UPDF corresponded well with the severity based on the cine-aortogram. It may be concluded that the UPDF is clinically useful and reliable for quantifying AR non-invasively.

CONVENTIONALLY, the severity of aortic regurgitation (AR) is evaluated invasively using cine-aortography. Using an ultrasonic pulsed Doppler flowmeter (UPDF), we devised a method to measure the blood flow waveform in the aortic arch non-invasively, and the severity of AR was evaluated quantitatively.

SUBJECTS AND METHODS

Subjects

The present study included 23 patients with AR, diagnosed cine-aortographically. Severity of regurgitation was expressed according to Sellers' classification. The subjects were 11 males and 12

females. There were 12 cases with AR alone, 10 combined with other valvular diseases and one combined with ventricular septal defect. Among the patients with AR alone, one case had aortitis syndrome and 3 had annulo-aortic ectasia, one of which was Marfan syndrome. Nineteen normal subjects were examined as the controls.

Equipments

The UPDF used here was manufactured by the Hitachi Co., based on the design of Furuhashi.¹ A block diagram of this UPDF is shown in Fig. 1. The ultrasonic oscillator frequency is 2 MHz, and the pulse repetition frequency is selectable at either 5 KHz or 10 KHz. The gate width can be varied up to 30 mm at a step of 6 mm, and the gate position is adjustable at a step of 3 mm. With a pulse repetition frequency of 5 KHz, the maximum measurable depth is 15 cm and the

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Fig.1. The block diagram of the pulsed Doppler flowmeter.

Fig.2. The block diagram of the calculation circuit.

Fig.3. Two-dimensional echogram of aortic arch.

a = the depth of anterior aortic wall, b = the depth of posterior aortic wall,
PA = pulmonary artery

maximum measurable flow velocity is about 200 cm/sec for an incident beam angle of 60° , while with a pulse repetition frequency of 10 KHz they are 7.5 cm and about 400 cm/sec, respectively.

The probe is of semi-disked opposing type (barium titanate) with a diameter of 20 mm, and has an acryl concave lens at the frontal surface. The beam width is about 10 mm. The detected blood flow signal is processed by a calculation circuit based on the following theoretical formulae, and the average velocity ($\bar{V}$) and the relative flow volume (Q) are presented through the real

time analogue display:

$$\bar{V} = \frac{\int_{-\infty}^{\infty} f \cdot P(f) df}{h \int_{-\infty}^{\infty} P(f) df}$$

$$Q = k \int_{-\infty}^{\infty} f \cdot P(f) df$$

where f = Doppler frequency, $P(f)$ = instantaneous frequency spectrum of Doppler signal, $h = 2f_c \cos \theta / c$, c = sound velocity, f_c =

Fig.4. Toward flow in a normal subject.

Fig.5. Reverse flow in a normal subject.

Fig.6. Aortic blood flow detected at aortic arch in a patient with moderate AR.

carrier frequency, θ = incident angle, $k = 1/LQsh$, L = beam width, Qs = scattered power per unit area.

A block diagram of the calculation circuit is shown in Fig. 2. The blood flow waveform was recorded together with the ECG using a pen recorder (San-ei Sokki, Rectigraph Model 8S) at a speed of 25 mm/sec.

Measurement of Blood Flow

The aortic blood flow was measured by monitoring the Doppler sounds and the A mode signal at the suprasternal notch of the subjects in the supine position. In order to obtain the aortic blood flow and the sampling positions properly, the shortest distance from the suprasternal notch to the anterior wall (a) and to the posterior wall

Fig.7. Aortic blood flow detected at aortic arch in a patient with severe AR.

Fig.8. Difference of aortic blood flow pattern between the pulse repetition frequency of 5KHz and 10KHz in a patient with AR.

(b) of the aorta were determined by a two-dimensional echogram of the aortic arch, taken from the suprasternal notch as shown in Fig. 3. Then, setting the sample gate position of the flowmeter between (a) and (b), the beam direction was changed along the aorta to find the positions giving the strongest signal for the blood flow approaching the beam ("toward flow") and that going away from the beam ("reverse flow"). During these procedures the beam direction was fixed. The sampling positions could be properly set within the aortic arch by gate positioning and by beam fixing as mentioned above. Moreover, the gate position was moved by 3 mm steps so as to record the waveforms of the toward and the reverse flows at the various positions within the vessels.

Fig.9. Relationship between the sampling position in the aorta and the regurgitant ratio.

Calculation of Regurgitant Ratio

The difference in the patterns of the aortic waveforms of the relative flow volume, thus obtained was examined between the patients with AR and normal subjects. In all patients with AR, the regurgitant ratio was calculated from the ratio between the areas of the systolic flow waveform and that diastolic regurgitant flow waveform, and this ratio was compared with the severity of the regurgitation according to Sellers' classification² based on a cine-aortogram.

RESULTS

Aortic Blood Flow Waveform in Normal Subjects

In 19 normal subjects, the waveforms of both the toward and the reverse flows or either of them could be recorded satisfactorily. As judged from the cine-aortogram and the two-dimensional echogram, the toward flow seemed to correspond to the blood flow in the upper segment of the ascending aorta and the reverse flow to the blood flow in the upper segment of the descending aorta. Figure 4 shows the toward flow obtained from one normal subject. The blood flow waveform rose steeply in the systolic phase immediately after R-wave of ECG, formed a peak at a time corresponding approximately to the ascending portion of the T-wave, and returned to

the zero-flow level in the diastolic phase. Figure 5 shows the reverse flow obtained from another normal subject. The reverse flow was nearly symmetrical to the toward flow with respect to the base line. In some subjects, very slight regurgitation was observed in the early diastolic phase on both the toward and the reverse flows.

Aortic Blood Flow Waveforms in Patients with AR

In 19 out of 23 patients with AR both the toward and the reverse flows or either of them could be recorded. Four patients, whose waveforms could not be recorded, were complicated with other valvular diseases. In many cases with a +3 severity or higher in Sellers' classification, it was difficult to detect the toward flow.

The diastolic regurgitant flow waveforms could be recorded, except for mild AR. In patients with moderate AR, the regurgitant flow was limited to the earlier diastolic phase as shown in Fig. 6, while it tended to cover the whole diastole in patients with severe AR, as shown in Fig. 7.

In patients with aortic stenosis and regurgitation (ASR) and some patients with AR alone, the systolic blood flow waveform recorded with a pulse repetition frequency of 5 KHz had two peaks, as shown in Fig. 8. In these cases, record-

Fig.10. Two-dimensional echogram of aortic arch and the sampling position of the UPDF.

Fig.11. Comparison of the regurgitant ratio obtained by the UPDF with cineangiographic severity of AR. T = toward flow, R = reverse flow

ing with a pulse repetition frequency of 10 KHz so as to increase the measurable flow velocity resulted in single peaked waveform.

Calculation of Regurgitant Ratio in AR Using the UPDF

The regurgitant ratio obtained from the UPDF tended to differ slightly depending upon the sampling position. In Fig. 9, the regurgitant ratios calculated from the reverse flow in one patient with AR are plotted against the depth of the sampling position. Black dots represent the regurgitant ratios for a single heart beat, and open dots the mean regurgitant ratios for 5 heart beats. In this case, the highest blood flow signal was obtained at the depth of 4.4 cm, where both the regurgitant ratios for a single heart beat and the mean for 5 heart beats coincided. These 2 ratios tended to differ as departing from the

highest signal position. Figure 10 shows a two-dimensional echogram of the same patient as in Fig. 9. It is evident that the sampling position of the UPDF giving the highest blood flow signal with the least variation in the regurgitant ratio fell into the midportion of the aorta (4.4 cm) and the points giving greater variation in the regurgitant ratio lied around the periphery of the aorta. Since the similar tendency was recognized in other patients, the mean regurgitant ratio for 5 heart beats at the point giving the highest blood flow signal was considered as a reasonable representative regurgitant ratio for that patient.

Comparison of the UPDF-based Regurgitant Ratio with Cineangiographic Findings

The regurgitant ratio obtained by the above-mentioned method was compared with the cineangiographic findings according to Sellers' clas-

sification (Fig. 11).

The higher the regurgitant severity according to Sellers' classification the greater the regurgitant ratio calculated from the UPDF data was demonstrating a fairly good correlation between these two. The regurgitant ratios in all patients with a Sellers' +4 regurgitation were 50% or larger, while those in patients with +1 regurgitation were 0%.

DISCUSSION

In general, cine-aortography has been used for the evaluation of the severity of AR.² For this purpose, however, several other methods have been employed: evaluation based on the aortic blood flow waveforms obtained using an electromagnetic flowmeter³⁻⁶ or a catheter-tip Doppler flowmeter⁷; quantitative determination of the regurgitation by a combination of Fick's method with biplane angiocardiology⁸ or with impedance cardiography.⁹ All these techniques are invasive and not easy to perform. Since 1974, the authors have developed an ultrasonic pulsed Doppler flowmeter combining an analogue operational circuit so as to display the average flow velocity and the relative flow volume in the analogue form, and attempted to apply it for the measurement of the blood flow in the deep portion of the body.^{1,10} The present study aimed at a quantitative non-invasive evaluation of the severity of AR using the UPDF.

Measurement of Blood Flow

In order to diagnose AR quantitatively, it is desirable to record the aortic blood flow waveforms at a position as close as possible to the heart. Initially, the blood flow in the ascending aorta immediately above the aortic valve was measured from the anterior thoracic wall. However, we failed to obtain a stable blood flow waveform, except in some special cases, probably due to the difficulty in obtaining a favorable angle (approximately 60°) between the ultrasonic beam and the blood flow. Moreover, the waveforms were easily affected in this position by interference signals from the vascular wall, the valves and the blood flow in the cardiac cavity. When the blood flow in the aortic arch is measured from the suprasternal notch, recordings of both the toward and the reverse flows or either of them could be reproduced in all normal subjects. In some cases, the blood flow waveform was interfered by the venal blood flow signals

from shallower position, but this interference could be easily discriminated from the aortic blood flow by the phase difference. The authors measured the aortic blood flow from the suprasternal notch. In 19 out of 23 patients with AR, either the toward or the reverse flow could be recorded. However, their recording was more difficult in patients with combined valvular disease such as AR with aortic stenosis than in patients with AR alone. This difficulty may be attributable to the presence of turbulence, an increased velocity and vibration of the aortic wall caused by these complications. In patients with severe AR, it was generally difficult to record the toward flow. This may be attributable to aortic wall pulsation caused by an increase in the aortic blood flow.

Blood Flow Waveform

The aortic blood flow waveforms obtained in the present study using the UPDF closely resembled those obtained using an electromagnetic flowmeter³⁻⁶ and a catheter-tip Doppler flowmeter^{7,11} in both normal subjects and patients with AR. In some patients with AR, recording with a pulse repetition frequency of 5 KHz showed a deep-biphasic systolic waveform, while that with 10 KHz the waveform became monophasic. Recently, it has become possible to measure the velocity of blood flow in the ascending aorta using a hot film anemometer. Stein et al.¹² have reported its velocity to be over 230 cm/sec in cases with AR alone and 450 cm/sec in cases with AR and aortic stenosis. The maximum measurable velocity using our UPDF with a beam incident angle of 60° was about 200 cm/sec with a pulse repetition frequency of 5 KHz and about 400 cm/sec with 10 KHz. The distortion of waveform observed in the case of 5 KHz may be attributable to the fact that the velocity of the aortic blood flow was increased so much that it exceeded the maximum measurable limit.

Calculation of the Regurgitant Ratio Based on the UPDF

The regurgitant ratio is considered to be different at various segments of the aorta since the aorta bends at the aortic arch, and the regurgitation occurs at different portions of the aortic valve.

Moreover, the sampling position may shift within the aorta by its own pulsation, giving values which differ from the actual regurgitant

ratio. In order to obtain a more generalized regurgitant ratio, it seems necessary to make the sample volume so large that it fully covers the inner diameter of the aorta, thus eliminating interference caused by the aortic wall movement.

The authors set the range gate to 12 mm and used a sample volume of $10 \times 10 \times 12$ mm for the measurement of the blood flow. Even when the sample volume was sufficiently large, the regurgitant ratio varied to some extent depending upon the depth. When the beam direction was fixed as stated above, and when the sample position was moved along the aorta in order to locate the position giving the strongest blood flow signal, stable waveforms could be recorded and nearly constant regurgitant ratio was obtained. As compared with the two-dimensional echogram taken from the suprasternal notch, it was confirmed that the sampling position giving the strongest blood flow signal lies approximately at the midportion of the aorta.

On the basis of these facts, it was considered that reliable data can be obtained by averaging the regurgitant ratios of 5 heart beats calculated from the relative blood flow waveforms recorded at the position giving the strongest blood flow signal.

Quantitative Evaluation of Severity of AR Using the UPDF

A positive correlation was found between the regurgitant ratios obtained by our method and Sellers' classification. In all cases with a Sellers' +1 regurgitation, the regurgitant ratio was 0%. Since the aortic arch is situated at a distance away from the aortic valve, it seems that the hemodynamics in the aortic arch are not affected in mild AR. Although, the regurgitant flow in the aorta could not be detected in the mild cases, the present method proved to be effective for evaluating quantitatively the severity of AR with significant hemodynamic changes. The diagnosis of AR using the UPDF has already been reported.¹³⁻¹⁵ Ward et al.¹⁶ have stated that AR can be successfully diagnosed by recording the diastolic regurgitation waveforms at the left ventricular outflow tract from the anterior thoracic wall. It should be noted, however, that at the left ventricular outflow tract the direction of the blood flow from the left ventricle to the aorta in systole may differ from that of the regurgitant flow from the aorta to the left ventricle in diastole in some patients. Moreover, since the regurgitant flow waveforms in diastole may be

distinctly different due to a change of the sampling position, according to the relative position of the regurgitant jet in the left ventricle, our method seems not always to be useful for quantitative evaluation, even though it is convenient for a qualitative diagnosis. Veyrat et al.¹⁷ have recorded the blood flow waveforms in the aortic arch from the suprasternal notch using a UPDF, being the same as the authors', with a $2 \times 2 \times 4$ mm sample volume and reported its clinical usefulness for the diagnosis of AR. However, they failed to evaluate the severity of AR quantitatively. This failure may be attributable to the fact that the size of sample volume, the maximum measurable velocity and the selection of sampling position were different from ours. Although some problems such as the capability of measuring the high flow velocity must be solved in the future, the UPDF may be regarded as a very useful method for non-invasive quantitative evaluation of AR.

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