Assessment of the orifice diameter by a multigated pulsed Doppler system in children with congenital semilunar valve stenosis

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SUMMARY This study investigated whether the jet diameter measured by a multigated pulsed Doppler system could be used to assess the severity of valve disease in children with pulmonary (n = 11) or aortic (n = 4) valve stenosis. The results obtained were compared with those obtained at cineangiography and at operation. Multigated pulsed Doppler examination of a stenosed valve showed a region of relatively high velocities in the velocity profile (jet flow). There was good agreement between the diameter of the disturbed region on the Doppler echocardiogram and the diameter of the jet on the lateral angiocardiogram. In severe valve stenosis the agreement between the valve diameters measured by multigated pulsed Doppler and at operation was also good. In less severe valve stenosis Doppler measurements systematically underestimated the valve diameter at operation. It is likely that the functional opening of a semilunar valve is a more relevant estimate of the degree of stenosis than the anatomical measurement of the orifice.

The findings of this study indicate that multigated pulsed Doppler systems are useful in the non-invasive diagnosis of stenotic valve disease.

The severity of valve stenosis is usually assessed by the pressure gradient across the valve^{1,2} or from the orifice area (calculated by the Gorlin formula³). The orifice area can also be derived from the width of a jet of contrast.⁴ This angiocardiographic orifice area accorded with the haemodynamically calculated orifice area, when the area of the stenosis was assumed to be circular.⁴ In eight out of nine patients the valve orifice calculated from the angiocardiographic jet diameter was smaller than the diameter measured during operation.⁵

The introduction of echocardiography, especially cross sectional and Doppler techniques, has improved the potential for the non-invasive prediction of the severity of valve stenosis.⁶ Pulsed and continuous wave Doppler systems allow the gradient across a stenotic valve to be calculated from the Bernoulli equation.⁷⁻⁹ But this approach is restricted

by the dependence of the pressure gradient on cardiac output. Also single gated pulsed Doppler systems cannot accurately detect high blood flow velocities. So single gated pulsed Doppler is reliable only in mild pulmonary valve stenosis.¹⁰

Johnson *et al* used a single gated pulsed Doppler device to detect the jet in aortic valve stenosis.¹¹ They measured the diameter of the jet by assessing the width of a region of flow disturbance distal to the stenosis. But this technique was accurate only when stenosis was severe. Recently, Veyrat *et al* introduced a single gated pulsed Doppler mapping technique to assess the severity of aortic valve stenosis in adults.¹² The method reliably diagnosed less severe aortic valve stenosis, but it was time consuming.

Multigated pulsed Doppler systems allow the on-line recording of series of velocity profiles at discrete time intervals during a cardiac cycle.¹³⁻¹⁵ Under normal circumstances the systolic velocity profiles in the pulmonary artery and ascending aorta are likely to be nearly flat, but valve stenosis produces a region of relative high flow velocities (a jet).

We have assessed the accuracy of a multigated pulsed Doppler system used to measure orifice size

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non-invasively. The multigated method is less dependent on cardiac output than the single gated method.

Patients and methods

PATIENTS

For 28 months all children with pulmonary valve or aortic valve stenosis undergoing catheterisation and subsequent cardiac surgery were admitted to the study if satisfactory cross sectional and Doppler echocardiograms were obtained with a 5 MHz system and it was possible to perform a multigated pulsed Doppler investigation. The investigation was part of the routine examination before heart catheterisation and operation.

Eleven children had isolated pulmonary valve stenosis. The age at catheterisation ranged from 14 days to 3 years 8 months except for one patient with Noonan's syndrome,¹⁶ who was 11 years 8 months. The second group consisted of four children with aortic valve stenosis, aged from 13 days to 1 year 2 months at catheterisation.

In those with pulmonary stenosis the delay between catheterisation and operation was about two months (range 13 days to 4 months 3 weeks). In two children (cases 1 and 5, table 1) the delay was 23 and 20 months. In all those with pulmonary stenosis all multigated pulsed Doppler examinations were per-

formed a few days before operation, under sedation if necessary.

The mean interval between the multigated pulsed Doppler examination and catheterisation or operation was 10 days (range 1-30 days) in those with aortic valve stenosis.

CATHETERISATION STUDIES

All children were investigated by catheterisation except for one patient with pulmonary valve stenosis. She had an operation on the basis of echocardiographic and Doppler investigations alone.

Catheterisation was performed under general anaesthesia with artificial ventilation. Pressures were measured under steady state conditions; when it was possible to pass the stenosis we measured the gradient across the stenosed valve.

The ratio of right (RV) to left ventricular systolic pressure (LV) was used to estimate the severity of the stenosis in patients with pulmonary valve stenosis (modification after Emmanouilides and Baylen¹). To avoid the effects of infundibular stenosis we measured the pressure in the right ventricular out-flow tract and not in the cavity. Severe pulmonary valve stenosis was defined as a RV/LV ratio ≥ 1.00 and a moderate stenosis as a RV/LV ratio between 0.5 and 1.00.

When the left ventricle could not be reached at catheterisation we measured the systolic brachial

Table 1 Orifice diameters in pulmonary valve and aortic valve stenosis measured by multigated pulsed Doppler (MPD), cineangiography, and at operation. The reference standards for age and height are derived from Schulz and Giordano.¹⁹

Pulmonary valve stenosis						
Patient number	RV/LV systolic pressure ratio	Before operation			At operation	
		MPD diameter (mm)	Angio jet diameter (mm)	Reference diameter (mm)	Operation diameter (mm)	Reference diameter (mm)
1	0.53	4.9	4.9	13.7	12	14.7
2	0.57	6.3	5.2	10.4	11	10.6
3	0.64	4.4	3.7	14.3	11	14.3
4	0.69	7.3	6.5	15.7	12	16.3
5	0.70	—	7.0	13.2	9	14.1
6	0.70	3.1	3.5	10.1	6	10.2
7	1.00	5.8	5.1	12.6	6	12.7
8	1.14	5.5	5.2	14.1	5	14.2
9	1.17	4.2	No jet	7.2	4	8.6
10	1.60	4.1	3.0	7.3	3	9.2
11	—	7.3	—	11.0	6	11.0
Aortic valve stenosis						
Patient number	LV-AO gradient in mm Hg	Before operation			At operation	
		MPD diameter (mm)	Angio jet diameter (mm)	Reference diameter (mm)	Operation diameter (mm)	Reference diameter (mm)
12	50	3.8	3.8	6.8	4	6.8
13	75	3.9	3.7	8.7	3	8.7
14	45	3.8	3.8	7.3	3	8.3
15	95	3.6	3.4	8.3	3	8.3

RV, right ventricle; LV, left ventricle; AO, aorta.

Fig 1 Lateral cineangiographic view of the jet in pulmonary valve stenosis after contrast injection into the right ventricle. The diameter of the jet is measured just downstream from the stenotic valve. The site of measurement is indicated with two arrows. RV, right ventricle; PA, pulmonary artery.

artery pressure by an appropriate cuff, using a Dynamap blood pressure measuring system. This systemic arterial pressure was then used to assess the RV/LV ratio.

In infants aortic valve stenosis was regarded as severe when the peak systolic gradient across the valve was ≥ 50 mm Hg. In critical aortic valve stenosis, however, the pressure in the left ventricle and the gradient across the valve may be lower because left ventricular function is impaired; this will lead to an underestimation of the severity of the disease.

CINEANGIOCARDIOGRAPHY

Cineangiocardiology was performed during catheterisation to visualise the jet stream. A lateral view was used in those with pulmonary valve stenosis and a left anterior oblique view in those with aortic valve stenosis. The contrast medium was Angiografin 65% (meglumine-amidotrizoate) in a dose of 0.5–2 mg/kg body weight. The contrast medium was injected into the cavity of the ventricle with a catheter

dependent flow rate (NIH 5–7 F). The cine frame rate was 75/s (fig 1).

From each film we selected a frame showing a well defined opacified jet and we measured the diameter of the jet stream. This procedure was performed three times with an interval of at least one day between the measurements. The site of measurement was just downstream of the stenotic valve. In most cases the jet flow was detected in early systole of the first or second heart beat after contrast injection. We used the diameter of the image of the catheter in the right ventricular outflow tract as a reference to calculate the real jet diameters. We took the mean of a series of three measurements as the diagnostic value.

MULTIGATED PULSED DOPPLER MEASUREMENTS

We used a 5 MHz multigated pulsed Doppler system with 64 adjacent sample volumes over a distance of 38.4 mm (one sample volume = 0.6 mm in length). To visualise the site of investigation, we connected the multigated pulsed Doppler system to an ATL mark V real time echo-scanner. The site of sampling across the vessel was selected by moving the M line direction and adapting the delay indicating the depth of the sample range along the M line just as in the single gated pulsed Doppler system.

Measurements were made with child lying on its left side. To visualise the pulmonary artery or the ascending aorta in a long axis view, we placed the transducer in the first or second left intercostal space in patients with pulmonary valve stenosis and in the third or fourth intercostal space in patients with aortic stenosis. If necessary the patients were sedated with an intramuscular injection of promethazine (0.5 mg/kg), chlorpromazine (0.5 mg/kg), and pethidine (1 mg/kg).

The flow velocity profiles of the orifice were recorded with the M line positioned just downstream from the stenotic valve.^{17,18} The angle of the M line to the axis of the pulmonary artery was measured on the sector scan. To calculate the jet diameter we assumed that the flow direction corresponded with the axis of the pulmonary artery. To obtain a cross sectional profile we chose an angle of about 80°; at 90° the Doppler signal becomes impaired. Narrowing of the valve orifice caused a region of high velocities in the profile. The diameter of this region in systole was assumed to represent the flow diameter of the orifice. Aliasing was seen if the jet flow exceeded the velocity limits of the pulsed mode. When this happened we increased the angle of interrogation. An observation close to 90° with the jet will affect the accuracy with which the jet diameter can be established since the velocities, corrected for the estimated angle, are compared with a threshold. With a pulse repetition frequency of 7.8 KHz, velocities of up to 60 cm/s can

Fig 2 Example of a pulmonary valve stenosis investigated with multigated pulsed Doppler. The site of measurement (M line) is indicated. There are three measurable orifice flow profiles in the pulmonary artery (PA). In systole in the first flow profile the diameter of the ostium flow is indicated ("JET"). It runs from the beginning of the first fast deflection till the end of this deflection. The jet diameter is related to the total length of the 64 sample gates (38.4 mm) and corrected for the angle between the flow direction and M line. There are vague aortic (Ao) flow patterns below the pulmonary artery flow profiles. The electrocardiogram is shown as a time scale.

be estimated at 0° , up to 3.5 m/s at 80° , and up to 7.0 m/s at 85° . Deviations from the real jet direction (for instance 90°) and assumed jet direction (for instance 70°) are not critical because a deviation of 20° gives rise to a maximum error of 12%. The number of contributing gates (0.6 mm each) gave the diameter of the jet flow, which was corrected for the estimated angle of interrogation (fig 2). A series of frames of velocity profiles was stored and only the largest and most typical jet flow patterns were chosen because the smaller disturbances will have been measured obliquely. Measurements were repeated three times and the mean of these measurements was used for further analysis.

MEASUREMENTS DURING OPERATION

During operation the diameter of the pulmonary valve orifice was measured with a circular probe before valvotomy or valvectomy. The probe that just fitted the valve without stretching it was regarded as the size. To avoid accidental rupture of stenosed aortic valves we measured the length of the slit of the collapsed valve, which we assumed to be half the internal circumference of the orifice. This approach was necessary because the clinical consequences of aortic valve regurgitation are severe. These calculated measurements were rounded down to probe values. In one patient (case 12) the diameter was measured at necropsy.

We used the age and height dependent internal circumference reference values¹⁹ to calculate the valve orifice.

S de K measured the width of the jet by the multigated pulsed Doppler system and by angiocardiology. The surgeon was not informed of the outcome of the non-invasive measurements.

STATISTICAL ANALYSIS

The mean (2 SD) of paired differences was calculated to compare the results of multigated pulsed Doppler and cineangiocardiology. To compare the results of multigated pulsed Doppler and operation we calculated the mean (2 SD) for only the severe stenoses. All the results are presented (figs 3 and 4) with limits of agreement according to Bland and Altman²⁰ and Gardner and Altman.²¹

Results

The 1 SD of the mean of each series of three measurements ranged from 0.05 to 0.44 mm at angiocardiology and from 0.15 to 0.83 mm in the multigated pulsed Doppler measurements (one sample gate measures 0.6 mm).

Table 1 lists the results. In patient 5 the multigated pulsed Doppler investigation was impossible because the child would not stay still. Patients 4 and 9 had

Noonan's syndrome and in one of them no jet was detected. One patient (case 11) had cardiac operation without catheterisation; the reference diameter at operation suggested severe pulmonary stenosis (orifice area < 30% of normal (table 1). The valves were tricuspid (shape unknown in patient 6) in those with pulmonary stenosis and bicuspid in those with aortic stenosis.

Table 2 shows the mean (1 SD) of the paired differences of the different methods of investigation. There was strong agreement between the jet diameters assessed by the multigated pulsed Doppler system and angiocardiology. Figure 3 shows the combined results for the groups with pulmonary and aortic valve stenosis. The paired difference between the diameters measured by multigated pulsed Doppler and angiocardiology were compared with the mean diameter calculated from multigated pulsed Doppler and angiographic findings.

Figure 4 shows a comparison of the paired differences between the diameters assessed by multigated pulsed Doppler and at operation and the mean diameter derived from the findings at multigated pulsed Doppler and operation. The mean and 2 SD are calculated only for the severe pulmonary and aortic valve stenoses. The values of moderate pulmonary valve stenosis were outside these limits of agreement (2 SD), but agreement between the methods was good in patients with severe stenosis. The multigated pulsed Doppler method underestimated the diameter of moderately stenosed valves measured at operation, but only to the same extent as cineangiocardiology did.

Discussion

We found that, whatever the degree of stenosis, the jet diameter measured on the angiogram corresponds well with the diameter measured by multigated pulsed Doppler. The diameter assessed from the width of the jets correlated well with the diameter measured at operation when pulmonary or aortic valve stenosis was severe. When the stenosis was less

Table 2 Comparison of diameters

(a) Diameters in all pulmonary and aortic valve stenoses			
Variable	No	Mean (mm)	1 SD
Multigated minus angio	12	0.40	0.46
Multigated minus operation	15	-1.44	2.96
Angio minus operation	13	-2.25	3.08
(b) Diameters in severe pulmonary and aortic valve stenoses			
Variable	No	Mean (mm)	1 SD
Multigated minus angio	7	0.38	0.39
Multigated minus operation	9	0.57	0.53
Angio minus operation	7	0.13	0.57

Fig 3 Patients with pulmonary or aortic valve stenosis. Differences between the diameters assessed with the multigated pulsed Doppler system and at cineangiocardiology are shown as a function of the mean diameters calculated from the findings with both methods. The mean (solid line) and ± 2 SD (dotted lines) are indicated.

severe, however, the diameter from the jet systematically underestimated the diameter measured at operation.

Multigated pulsed Doppler and angiography both measure functional diameter. With multigated pulsed Doppler systems a local disturbance in the flow profile can be visualised, and on the angiogram a region of fast filling contrast is seen. With multigated pulsed Doppler systems the frontal-dorsal diameter is assessed. The lateral projection at cineangiocardiology also estimates the frontal-dorsal diameter. In aortic valve stenosis a left oblique view is used, with nearly the same diameter in cross section as in multigated pulsed Doppler. The jet is directed towards the anterior wall of the main pulmonary artery (fig 1). The multigated pulsed Doppler measurements are performed at an angle of interrogation close to 90°. Underestimation of the orifice diameter by the multigated technique when the stenosis is less severe accords with previous observations.^{5,22} Compression of the jet by areas of recirculation²³ is not likely to be responsible for the

Fig 4 Patients with pulmonary or aortic valve stenosis. Differences between the diameters assessed with the multigated pulsed Doppler system and at operation are shown as a function of the mean diameters calculated from the findings with both methods. The mean (solid line) and ± 2 SD (dotted lines) of the severe pulmonary and aortic valve stenosis are indicated.

underestimation of the diameter.²⁴ The most likely explanation for the discrepancy is the difference between functional opening and the anatomical orifice assessed at operation. Under normal circumstances and in slight to moderate valve diseases maximum valve opening is not needed for adequate outflow at rest. The probe method probably measures the largest possible circular aperture. In severe stenosis although the orifice reaches its largest possible diameter blood flow is obstructed. In this situation the diameter measured at operation is likely to be similar to the functional diameter because the orifice can only be passed by a probe with a diameter about equal to the maximum diameter of the valve orifice.

The idea that the valve diameter calculated from the width of the jet represents the functional diameter is supported by the fact that the jet diameter assessed by cineangiography and the jet diameter calculated by the Gorlin equation are usually similar.⁴⁵ Berman *et al* only reported on cineangiograms obtained in a lateral view.⁴ The

assumption that the orifice is circular seems to be valid in more severe congenital pulmonary valve stenosis.²⁵⁻²⁸ When valve malformation is severe this assumption is not valid. These cases, however, can easily be diagnosed by cross sectional echocardiography. In one angiographic study the valve area was smaller than that calculated by the Gorlin equation.²² In this study, however, oxygen consumption (used to calculate cardiac output) was assumed rather than measured and this may introduce errors in the calculated haemodynamic area.

Nevertheless, in patients with moderate to severe aortic stenosis the diameter of the orifice measured by single gated pulsed Doppler flow mapping techniques resembled the diameter assessed haemodynamically.¹¹ Although Veyrat *et al* warned that the orifice of the aortic valve may not be circular,¹² 56% of the orifices were circular and only 6% were slits. These findings support the idea that functional assessment of the degree of stenosis is better than anatomical measurements.

With the new techniques of colour coded Doppler the jet is directly visible. Diameter measurements, however, depend on the adjustment of the colour imager. The combination of detection of jet direction by colour Doppler and measurement of the diameter by multigated pulsed Doppler seems promising.

In conclusion, a jet diameter that corresponds to that measured on the angiogram can be measured non-invasively by multigated pulsed Doppler systems. This diameter probably represents the functional opening of the valve.

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