Accuracy of Prospective Two-Dimensional/Doppler Echocardiography In the Assessment of Reparative Surgery

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Between January 1987 and January 1989, all 129 patients (aged 11 days to 25 years, median 39 months) undergoing both an echocardiographic examination and cardiac catheterization after reparative surgery were prospectively included in a study to assess the accuracy of combined two-dimensional and Doppler color flow imaging. The patient diagnoses were transposition of the great arteries (n = 20), tetralogy of Fallot (n = 38), coarctation of the aorta (n = 24), complete atrioventricular (AV) canal (n = 15), atrial septal defect (n = 8), ventricular septal defects (n = 3), pulmonary stenosis (n = 4), aortic stenosis (n = 8) and subaortic stenosis (n = 9).

In arterial tract stenosis, there was high correlation between Doppler estimates and catheterization-derived measurements of residual right ventricular outflow tract obstruction in patients after the arterial switch operation for transposition of the great arteries (r = 0.95) as well as in patients after corrective repair of tetralogy of Fallot (r = 0.84).

In semilunar/AV valve regurgitation, graded as none, mild, moderate or severe, echocardiographic estimates correlated exactly with angiographic grading in 84% and differed by one angiographic grade in the other 16%.

In residual left to right shunting, no hemodynamically significant shunt was missed by echocardiography. For residual shunts at the ventricular level (n = 32), addition of Doppler color flow imaging improved the sensitivity (from 63% to 94%) and the negative predictive value (from 88% to 98%).

In elevated right ventricular pressure, Doppler-derived right ventricular–right atrial pressure estimates in 24 patients correlated well with catheterization measurements (r = 0.93).

Combined two-dimensional and Doppler color flow echocardiography was highly accurate in the prospective evaluation of these four types of postoperative residua.

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Progressive improvements in two-dimensional echocardiographic technique (1–3) have led to its adoption in some institutions as the sole diagnostic procedure for certain malformations before palliative or reparative surgery is performed (4–9), especially when morphologic information is more important than precise physiologic measurements of pressure differences or shunt magnitude.

By contrast, the management of the survivor of reparative surgery is more dependent on the validity of noninvasive physiologic assessments. By causing acoustic shadowing and blooming artifacts, the synthetic patch materials utilized for ventricular outflow tract or aortic arch reconstruction and septal defect closure make ultrasound imaging more difficult than in the preoperative setting. Furthermore, the presence of various degrees of valvular regurgitation coexisting with residual stenoses may make the noninvasively estimated maximal instantaneous pressure gradient across an arterial valve less reliable as an indicator of stenosis severity.

The purpose of this study was to quantify the strengths and limitations of combined two-dimensional and Doppler color flow imaging in the assessment of four important postoperative residua: 1) arterial tract stenosis, 2) valvular regurgitation, 3) left to right shunts, and 4) elevated right ventricular pressure.

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Methods

Study patients. Patients were included in the study if they had 1) "two ventricular" corrective surgery (that is, procedures that leave the pulmonary and systemic circulations each supported by a ventricle); 2) cardiac catheterization after surgery; and 3) complete echocardiographic study (including Doppler color flow imaging) <65 days before their cardiac catheterization. Balloon dilations were deemed reparative surgery. Patients with transposition of the great arteries routinely underwent cardiac catheterization after reparative surgery; however, patients with other diagnoses usually underwent catheterization only if clinical or echocardiographic examination suggested postoperative residua. Patients with more than one diagnosis (for example, tetralogy of Fallot with common atrioventricular [AV] canal) were included under the separate diagnoses and therefore counted as two patients (there were eight such patients and one patient with three diagnoses). Patients with a ventricle to pulmonary artery external conduit were excluded because image quality often precluded any determination of the integrity of the distal anastomosis, branch pulmonary artery origins or pulmonary artery segments adjacent to previous (noncentral) shunt sites. Patients with a Mustard-type intraatrial baffle were not included in the study.

We reviewed the cardiac catheterization and echocardiographic data from all 129 patients who fulfilled the inclusion criteria from January 1987 through January 1989. Age at echocardiographic examination ranged from 11 days to 25 years (mean 65 ± 72 months, median 39). The interval between echocardiography and cardiac catheterization ranged from 1 to 65 days (mean 20 ± 22, median 10). The age at surgery for the entire study group ranged from 1 day to 17.7 years (mean 35 ± 51 months, median 12).

The patients were grouped into five large diagnostic categories (Table 1): 1) transposition of the great arteries after the arterial switch operation (pericardial patches being used to close defects in the native aortic sinuses of Valsalva) (n = 20); 2) tetralogy of Fallot after ventricular septal defect closure and augmentation of the right ventricular outflow tract with a Dacron or Gore-Tex transannular patch (n = 38); 3) coarctation of the aorta after subclavian flap or homograft patch repair (n = 24); 4) AV canal defect after single or double patch repair (n = 15); and 5) others (n = 32) including atrial septal defect (n = 8); ventricular septal defect (n = 3); valvular pulmonary stenosis (n = 4); valvular aortic stenosis (n = 8); and discrete subaortic stenosis (n = 9).

Echocardiographic examination. All patients underwent a complete two-dimensional echocardiographic study performed with use of the Hewlett-Packard model 77020 (Sonos 500) phased array scanner with Doppler color flow imaging capability. In infants, 5 MHz short and medium focus transducers were used for assessment of morphology, a 3.5 MHz medium focus transducer was utilized for Doppler color flow study and a 1.9 MHz independent probe was used for nonimage-directed continuous wave Doppler interrogation. In older children, 3.5 and 2.5 MHz transducers were used for evaluation of morphology and Doppler color display; a 2.5/1.9 MHz dual function transducer (fixed continuous wave cursor) and the 1.9 MHz independent probe were used for continuous wave Doppler interrogation. Steerable continuous wave Doppler cursor capability was not available during the study interval.

Table 1. Summary of Findings in 20 Patients After Repair of Transposition of the Great Arteries

Patient No.	Age at Surgery (wk)	Age at Echocardiography (mo.)	Age at Catheterization (mo.)	Echo-Cath Interval (days)
1	2	4	4	8
2	26	7	7	6
3	1	8	9	30
4	1	14	16	47
5	2	12	12	1
6	1	12	12	17
7	1	5	5	1
8	1	1	1	13
9	1	1	1	12
10	1	18	19	54
11	2	11	11	1
12	1	20	21	25
13	2	13	14	33
14	1	13	13	1
15	1	4	5	23
16	17	18	18	1
17	2	11	13	60
18	2	16	16	1
19	1	12	12	31
20	1	7	7	1
Mean ± SD	3.4 ± 6.4	10.4 ± 5.6	10.8 ± 5.8	18.3 ± 19.0
Median	1	12	12	12

Echo-Cath Interval = interval between echocardiography and cardiac catheterization.

Patients <3 years but >3 weeks of age were sedated with 60 to 125 mg/kg body weight chloral hydrate (oral or rectal) before the echocardiographic examination.

Anatomic information. In infants and young children, this information was gathered mainly from the subcostal (frontal, long-axis oblique and sagittal sweeps) (10) and a right oblique–equivalent view (11,12) and parasternal and suprasternal windows.

Pulsed Doppler data. These were obtained from all four windows (subcostal, apical, parasternal and suprasternal). Arterial tracts were interrogated by placing the sample volume sequentially along sites in the outflow tract and then above the valve.

Continuous wave Doppler study (Doppler color flow and image directed). This technique was used to estimate the maximal instantaneous pressure gradients when residual valvular, supravalvular or subvalvular stenoses were discovered. The 1.9 MHz continuous wave transducer was used from multiple views (apical, suprasternal and parasternal). The maximal instantaneous pressure gradient (ΔP) from the maximal Doppler velocity was calculated by the modified Bernoulli equation: $\Delta P = 4 \times V^2$ (ΔP was in torr and velocity [V] distal to the obstruction was in m/s). In patients with coarctation, the velocity proximal to the coarctation was not neglected (13); we thus used $\Delta P = 4(V_2^2 - V_1^2)$, where V_2 was the velocity distal and V_1 was the velocity proximal to the area of coarctation. The maximal right ventricular to right atrial pressure difference was estimated by measuring the tricuspid regurgitation jet velocity and using the Bernoulli equation. We directly compared this transvalvular pressure gradient derived from Doppler echocardiography with the right ventricular to right atrial pressure difference measured during cardiac catheterization.

Doppler color flow examination. This was performed from multiple views in all patients to look for a residual septal defect as well as valvular regurgitation. The severity of valvular regurgitation was graded as none, mild, moderate or severe. In arterial valve regurgitation, the ratio of the height (that is, width) of the regurgitant jet to the height (width) of the respective ventricular outflow tract was assessed as suggested by Perry et al. (14). We utilized a slightly different grading system from that of Perry et al. and deemed regurgitation mild if this ratio was <0.4 in all views. Regurgitation was considered moderate if this ratio was >0.4 but <0.6 in any view; a ratio >0.6 was taken to indicate severe regurgitation. Echocardiographic estimation of the severity of AV valve regurgitation was made by qualitatively assessing the width of the regurgitant jet and semiquantitatively assessing the ratio of the maximal jet area to atrial area (15). If the latter ratio was <0.2 in all views, regurgitation was considered mild. A ratio >0.4 in any view was considered severe. To optimize the color signal for the regurgitant jet, nonstandard imaging planes were occasionally used. Finally, the gain was adjusted by starting at low settings and increasing upward until background white noise was visualized; the gain was then adjusted downward until white noise disappeared. A velocity map without variance display was used in all cases and, in most examinations, a velocity variance map was also utilized.

Cardiac catheterization. All patients underwent cardiac catheterization within 10 weeks after their complete echocardiographic study. Sedation consisted of either oral administration of 4 mg/kg pentobarbital and 3 mg/kg meperidine or intramuscular injection of 0.15 mg/kg morphine sulfate and 4 mg/kg pentobarbital.

For comparison with maximal instantaneous gradients estimated by continuous wave Doppler ultrasound, peak to peak systolic gradients measured at catheterization were chosen only because clinical decision making has traditionally been most heavily based on this variable. If catheter pullbacks were done, the values obtained from them were used to calculate the peak to peak gradients. Otherwise, the temporally most closely related measurements were employed. Pressure measurements were usually made with a balloon wedge catheter (Arrow International) on the venous side and with a pigtail catheter (Universal Medical Instruments) on the arterial side. Pressure measurements were made with the Transpac II transducer from Abbott Critical Care.

Atrioventricular valve regurgitation was graded by the method described by Nagle et al. (16). For arterial valves,

Table 2. Summary of Findings in 38 Patients After Repair of Tetralogy of Fallot

Patient No.	Age at Surgery (mo.)	Age at Echocardiography (mo.)	Age at Catheterization (mo.)	Echo-Cath Interval (days)
21	1	1	1	1
22	1	1	1	12
23	2	4	4	1
24	110	111	113	60
25	50	54	54	1
26	56	133	135	61
27	41	41	41	4
28	45	57	59	62
29	49	49	49	1
30	3	15	15	1
31	12	22	23	39
32	56	134	134	1
33	13	20	20	10
34	7	19	21	60
35	12	59	59	1
36	65	76	78	62
37	149	182	183	41
38	28	78	78	1
39	62	137	137	1
40	110	262	264	61
41	10	31	33	60
42	30	150	150	1
43	212	228	228	1
44	37	43	43	1
45	5	18	18	1
46	34	54	54	1
47	68	90	92	65
48	1	23	23	1
49	55	140	140	1
50	89	102	104	65
51	97	198	198	1
52	71	75	77	42
53	8	8	8	1
54	9	21	21	1
55	57	67	69	65
56	182	236	237	32
57	208	209	209	43
58	209	209	209	7
Mean ± SD	59.3 ± 61.3	88.3 ± 75.5	89 ± 75.6	22.9 ± 26.9
Median	47	63	64	2

Abbreviations as in Table 1.

Table 3. Summary of Findings in 24 Patients After Repair of Coarctation of the Aorta

Patient No.	Age at Surgery (mo.)	Age at Echocardiography (mo.)	Age at Catheterization (mo.)	Echo-Cath Interval (days)
59	16	39	40	23
60	45	58	60	62
61	30	37	37	14
62	34	143	145	60
63	5	85	87	60
64	1	61	63	60
65	1	4	4	2
66	1	2	2	1
67	1	73	73	26
68	1	5	5	3
69	44	92	93	27
70	109	209	209	1
71	19	92	92	1
72	1	11	12	60
73	1	1	1	6
74	1	63	65	61
75	38	149	150	30
76	1	48	48	1
77	1	7	9	56
78	49	73	73	1
79	1	2	2	1
80	1	4	4	2
81	1	2	2	2
82	13	23	25	37
Mean ± SD	17.7 ± 26.1	53.5 ± 55.0	54.2 ± 55.2	24.9 ± 25.3
Median	1	43	44	19

Abbreviations as in Table 1.

Table 4. Summary of Findings in 15 Patients After Repair of Atrioventricular Canal Defect

Patient No.	Age at Surgery (mo.)	Age at Echocardiography (mo.)	Age at Catheterization (mo.)	Echo-Cath Interval (days)
57	208	209	209	43
58	209	209	209	7
83	13	23	25	37
84	4	4	4	14
85	5	7	7	2
86	10	50	50	25
87	10	11	11	1
88	5	5	7	42
89	2	3	3	8
90	20	54	54	1
91	12	57	57	12
92	6	6	6	2
93	5	6	6	10
94	12	47	48	43
95	29	30	30	13
Mean ± SD	36.7 ± 70.1	48.1 ± 68.3	48.4 ± 68.2	17.3 ± 16.2
Median	10	23	25	12

Abbreviations as in Table 1.

grading of regurgitation was similar to the method described by Hunt et al. (17) as follows: mild = minimal contrast medium seen to regurgitate into the ventricle and completely clearing during the subsequent systole; moderate = opacification of the ventricle with density of contrast medium in the ventricle less than the density of dye in the great artery; and severe = rapid opacification of the ventricle with density of contrast medium in the ventricle equal to or greater than the density of contrast in the great artery. Comparison between echocardiography and catheterization was done only if an angiographic injection was made to assess valve competency. Left ventricular angiography was performed with a retrograde arterial catheter.

A residual atrial septal defect was considered present if there was an oximetry step-up of >5% between the superior vena cava and the right atrium and if there was an interatrial left to right shunt by angiography. A residual ventricular septal defect was diagnosed by left ventriculography in the long-axis oblique projection (or hepatoclavicular projection in the case of common AV canal). The dose of contrast agent (Hypaque-70, Winthrop Pharmaceuticals) was 1 to 2 ml/kg and the injection rate was chosen so that the dye was usually delivered in <1 s.

Data analysis. Patients' original diagnoses, nature of surgery and all data obtained from cardiac catheterization and echocardiography (anatomy, residual stenosis of outflow tracts if any, residual regurgitation of valves if any and residual left to right shunts if any) were collected. The age of patients at surgery, echocardiography and cardiac catheterization was determined and tabulated; the exact interval (in days) between the echocardiographic and catheterization studies was also determined (Tables 1 to 5).

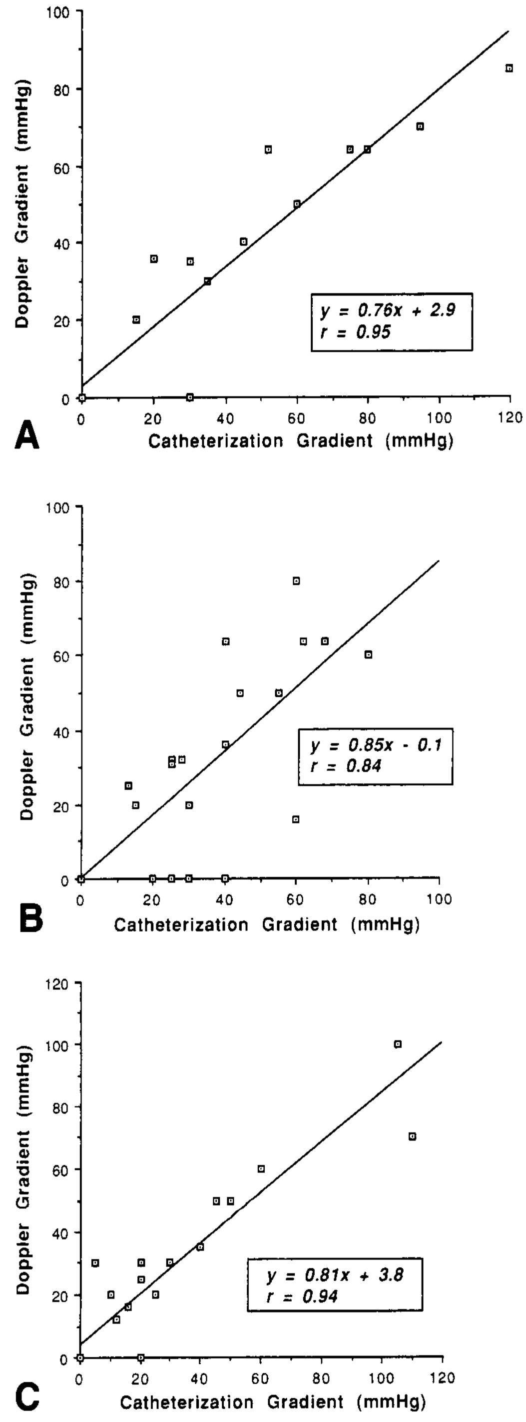
Pearson's correlation coefficient was used to analyze the data for catheterization-derived versus echocardiography-estimated pressure gradients to measure the degree of association. Linear regression was then used to compare Doppler peak instantaneous gradients with catheterization peak to peak gradients for arterial tract stenosis. Linear regression was also used to compare right ventricular to right atrial pressure differences by echocardiography and catheterization. The chi-square method was used to compare combined two-dimensional and Doppler color flow echocardiographic data with angiographic data for residual left to right shunts. Sensitivity is defined as true positives/(false negatives + true positives). Negative predictive value is defined as true negatives/(false negatives + true negatives). Sensitivity was chosen because it reflects the impact of false negatives, and negative predictive value was chosen because it defines the probability that a test (echocardiography) that is interpreted as negative (compared with a reference standard) is correct.

Table 5. Summary of Findings in 32 Patients After Repair of Other Congenital Lesions

Patient No.	Age at Surgery (mo.)	Age at Echocardiography (mo.)	Age at Catheterization (mo.)	Echo-Cath Interval (days)
ASD				
59	16	39	40	23
96	107	109	109	1
97	107	108	108	21
98	60	214	214	1
99	132	299	299	8
100	82	102	102	3
101	17	116	116	1
102	93	237	237	1
VSD				
103	23	73	73	7
104	3	13	13	1
105	11	13	13	12
Pulmonary stenosis				
106	1	7	8	26
107	3	15	15	1
108	4	17	18	65
109	30	69	69	1
Aortic stenosis				
78	49	73	73	1
110	108	120	121	28
111	1	13	13	1
112	1	144	145	29
113	166	262	264	52
114	1	1	1	6
115	1	95	95	1
116	9	157	158	27
Subaortic stenosis				
59	16	39	40	23
61	30	37	37	14
76	1	48	48	1
83	13	23	25	37
87	10	11	11	1
89	2	3	3	8
117	55	85	85	16
118	72	222	222	10
119	41	97	97	23

ASD = atrial septal defect; VSD = ventricular septal defect; other abbreviations as in Table 1.

Figure 1. Linear regression plots comparing catheterization-measured peak to peak gradients (mm Hg) with Doppler-derived peak instantaneous gradients (mm Hg). **A,** Right ventricular outflow tract obstruction after an arterial switch operation for transposition of the great arteries (20 patients). **B,** Right ventricular outflow tract obstruction after repair of tetralogy of Fallot (38 patients). Note that 1 patient had a catheterization-determined gradient of 60 mm Hg, whereas Doppler ultrasound predicted a gradient of only 16 mm Hg. **C,** Residual or recurrent gradient after repair of coarctation of the aorta (24 patients).



Results

Arterial Tract Stenosis

In residual right ventricular outflow tract stenosis, correlation between catheterization- and Doppler-derived gradients was high in both transposition of the great arteries after an arterial switch operation (r = 0.95, SE 9.9 mm Hg) (Fig. 1A) and tetralogy of Fallot after transannular patch repair (r = 0.84, SE 13.4 mm Hg) (Fig. 1B).

Table 6. Comparison of Sensitivity and Negative Predictive Value of Doppler Echocardiography After the Arterial Switch Operation for Transposition of the Great Arteries (TGA) and After Repair of Tetralogy of Fallot (ToF)

	TGA (n = 20)	ToF (n= 38)
Sensitivity		
Gradient ≥20 mm Hg	10/11 (91%)	11/16 (69%)
Gradient ≥50 mm Hg	6/6 (100%)	5/6 (83%)
Negative predictive value		
Gradient ≥20 mm Hg	8/9 (89%)	19/22 (86%)
Gradient ≥50 mm Hg	14/14 (100%)	31/32 (97%)

Transposition of the great arteries after arterial switch operation. In these 20 patients, the correlation between the Doppler- and catheterization-derived residual right ventricular outflow tract gradient was excellent (r = 0.95). The Doppler-derived peak instantaneous gradient underestimated the peak to peak pressure gradient obtained from catheterization with the equation for linear regression calculated to be Doppler gradient = 0.76 × Catheterization gradient + 2.9.

In the 11 patients with a peak to peak gradient ≥20 mm Hg at catheterization, Doppler peak instantaneous gradient was ≥20 mm Hg in all but one patient (sensitivity 91%); in this patient, although echocardiography did not identify narrowing along the right ventricular outflow tract or branch pulmonary origin, cardiac catheterization revealed a right pulmonary artery branch stenosis with a 30 mm Hg peak to peak gradient. For catheterization-proved moderate or severe stenoses (that is, peak to peak gradient ≥50 mm Hg) (six patients), combined Doppler color and continuous wave imaging always predicted a peak instantaneous gradient to be >50 mm Hg (sensitivity 100%, negative predictive value 100%) (Table 6).

The most common site of stenosis was the supravalvular area. In the 11 patients who had a residual gradient ≥20 mm Hg, 8 had narrowing at this site. The other three patients who had a gradient >20 mm Hg had right pulmonary artery branch stenosis (n = 2) and combined subvalvular and valvular pulmonary stenosis (n = 1).

Tetralogy of Fallot after repair. In the 38 patients who had transannular patch repair for tetralogy of Fallot, correlation between catheterization-derived peak to peak and Doppler-derived peak instantaneous gradient was very good (r = 0.84, SE 13.4 mm Hg). The equation for linear regression was Doppler gradient = 0.85 × Catheterization gradient − 0.1. As in patients who had an arterial switch procedure for transposition of the great arteries, the Doppler-derived peak instantaneous gradient underestimated the peak to peak pressure gradient obtained from catheterization (slope 0.85).

Among all 16 patients with a residual peak to peak gradient ≥20 mm Hg, Doppler echocardiography was able to detect a peak instantaneous gradient ≥20 mm Hg in only 11 (sensitivity 69%, negative predictive value 86%). In the patients with a catheterization-derived residual peak to peak gradient ≥50 mm Hg (6 of 38 patients), Doppler recording detected the peak instantaneous gradient to be ≥50 mm Hg in all but 1 patient (sensitivity 83%, negative predictive value 97%) (Table 2). The latter patient had a Doppler peak instantaneous estimate of 16 mm Hg across the right ventricular outflow tract compared with a much higher residual gradient of 64 mm Hg during catheterization. In this patient, however, the Doppler transtricuspid right ventricular to right atrial pressure difference was 50 mm Hg, thus predicting a higher right ventricular pressure than would have been expected had the outflow gradient truly been only 16 mm Hg.

The most common site of right ventricular outflow tract obstruction after corrective surgery in tetralogy of Fallot was subvalvular (11 of 16 patients who had a residual peak to peak gradient ≥20 mm Hg had narrowing at this site). Other sites of stenosis were valvular (n = 2), right pulmonary artery branch (n = 1) and left pulmonary artery branch (n = 2).

Left-sided outflow tract obstruction. *In 24 patients with coarctation of the aorta after surgical repair*, correlation was excellent between catheterization-derived peak to peak gradient and Doppler-derived peak instantaneous gradient (r = 0.94, SE 9.7 mm Hg) (Fig. 1C). The regression equation was Doppler gradient = 0.81 × Catheterization gradient + 3.8. In the four patients with a residual peak to peak gradient ≥50 mm Hg detected by catheterization, Doppler echocardiography estimated a maximal instantaneous gradient >50 mm Hg in all of these patients.

The correlation between catheterization- and Doppler-derived data for residual aortic stenosis (n = 8) was excellent, with a correlation coefficient of r = 0.95, (SE 9.8 mm Hg). The calculated regression equation was Doppler gradient = 1.04 × Catheterization gradient + 3.4. The Doppler maximal instantaneous gradient was >50 mm Hg in all four patients who had a catheterization-measured peak to peak gradient >50 mm Hg.

In nine patients with subaortic stenosis after resection, correlation between catheterization- and Doppler-derived data was also good (r = 0.89, SE 19.2 mm Hg). The regression equation was Doppler gradient = 0.85 × Catheterization gradient + 1.8. The Doppler peak instantaneous gradient was ≥50 mm Hg in all three patients with a peak to peak catheterization gradient >50 mm Hg.

In the four patients who had cardiac catheterization after surgical valvotomy or balloon dilation of the pulmonary valve, correlation was excellent (r = 0.99, SE 5.9 mm Hg).

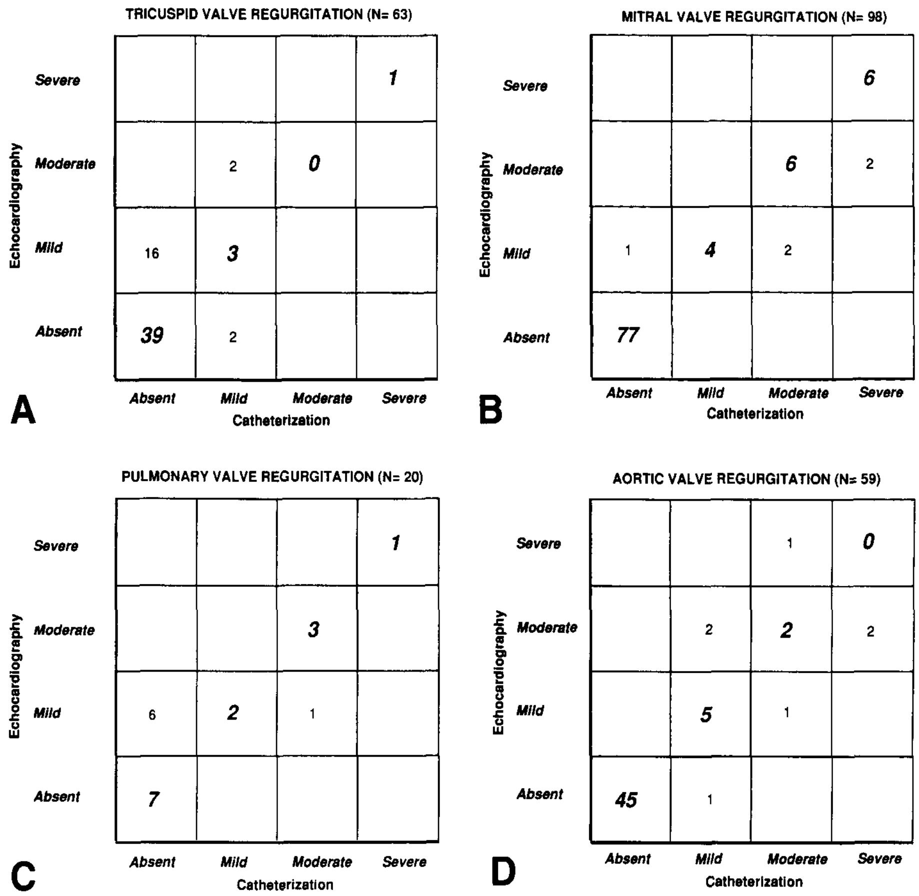


Figure 2. Assessment of valvular regurgitation comparing echocardiography with catheterization for all four valves. Numbers of patients in ***bold italics*** represent those who had exact agreement between echocardiographic and catheterization grades of valvular regurgitation.

Valvular Regurgitation

Echocardiographic assessment of valvular regurgitation, graded as absent, mild, moderate or severe, correlated exactly with catheterization-derived grades in 201 (84%) of 240 valves. Of the remaining 39 valves, echocardiographic grade was always within one catheterization grade.

Tricuspid valve (Fig. 2A). Of all 129 patients, 63 had a right ventricular injection during their cardiac catheterization. Direct comparison of Doppler- and catheterization-derived estimation of valvular regurgitation showed that 43 patients (68%) had an exact correlation and 20 patients (32%) had a valvular regurgitation grade that was within one grade. Sixteen of these 20 patients were estimated to have mild regurgitation by echocardiography and were considered to have no regurgitation by right ventricular angiography.

Mitral valve (Fig. 2B). A total of 98 of the 129 patients had a left ventricular injection during cardiac catheterization. Again, echocardiographic estimation of valvular regurgitation was always within one grade of catheterization estimates. Of these 98 patients, 93 (95%) had exact correlation of grades of valvular regurgitation.

Pulmonary valve (Fig. 2C). Only 20 of the 129 patients had a pulmonary artery injection during their cardiac catheterization to allow for direct comparison between echocardiography and cardiac catheterization. Of these 20 patients, 13 (65%) had exact correlation and 6 had mild regurgitation on echocardiography but no regurgitation at catheterization.

Aortic valve (Fig. 2D). Of the 59 patients who had an aortic root injection during cardiac catheterization, 52 (88%) had the same grades of estimated valvular regurgitation.

Left to Right Shunts

Residual atrial septal defect. *In these nine patients*, (none with a ratio of pulmonary to systemic flow [Qp:Qs] >1.8:1), sensitivity of echocardiography in detection of these shunts was 100%. Negative predictive value of echocardiography in assessing a residual atrial septal defect was also 100%.

Residual ventricular septal defect (Fig. 3). In assessing a residual ventricular septal defect in 32 patients, Doppler color flow imaging improved the sensitivity from 63% (two-dimensional echocardiography alone) to 94%. Doppler color flow imaging missed only two residual ventricular septal defects detected by catheterization (neither left to right shunt was hemodynamically significant, with Qp:Qs of 1.2:1 and 1.1:1, respectively). The negative predictive value was increased from 88% (as observed with two-dimensional echocardiography without Doppler color flow imaging) to 98% with the addition of Doppler color flow imaging. In other words, if Doppler color flow imaging failed to detect a

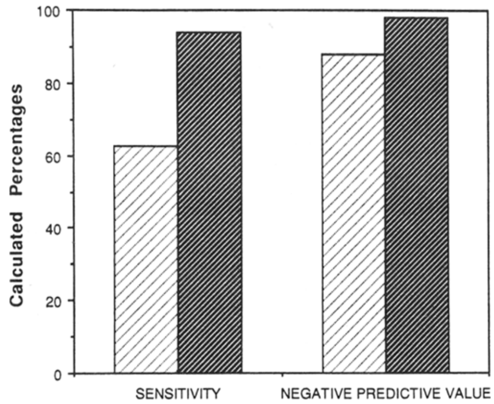


Figure 3. Improved sensitivity (from 63% to 94%) and negative predictive value (from 88% to 98%) seen with the addition of Doppler color flow imaging (**dark hatched bars**) to two-dimensional echocardiography alone (**light hatched bars**) in 32 patients with a residual ventricular septal defect.

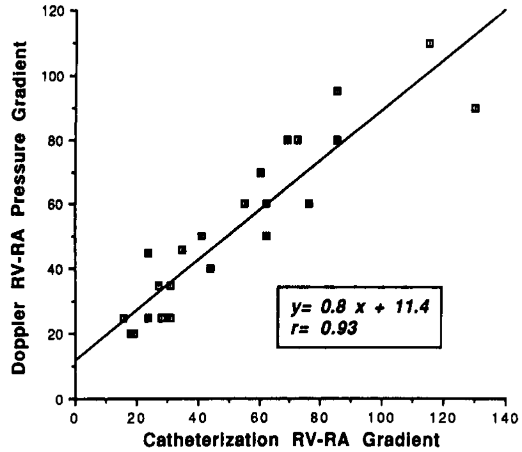


Figure 4. Comparison of right ventricular (RV) to right atrial (RA) pressure gradient (mm Hg) in 24 patients measured by catheterization and that estimated by echocardiography with use of tricuspid regurgitant jet velocity. Each Doppler-derived right ventricular to right atrial transvalvular pressure difference was directly compared with the catheterization-derived right ventricular to right atrial pressure difference.

residual ventricular septal defect in a postoperative patient in this group of study patients, this observation had a 98% chance of being true when catheterization was used for validation.

Only 4 of the 32 patients with a residual ventricular septal defect had a hemodynamically significant (Qp:Qs >2:1) shunt. Two-dimensional echocardiography with Doppler color flow imaging was able to detect the defect in all four patients. One patient with tetralogy of Fallot had a hemodynamically significant ventricular septal defect detected by Doppler color flow imaging but not by two-dimensional imaging alone.

Elevated Right Ventricular Pressure

Right ventricular to right atrial pressure differences were obtained in 24 patients from all five diagnostic categories. Correlation between Doppler- and catheterization-derived values for this transvalvular pressure difference was excellent (r = 0.93, SE 9.9 mm Hg) (Fig. 4). The equation for linear regression was Doppler gradient = 0.80 × Catheterization gradient + 11.4. All 14 patients with a catheterization-derived right ventricular to right atrial pressure difference ≥50 mm Hg were successfully identified by continuous wave Doppler ultrasound.

Discussion

Arterial tract stenosis. Although the closeness of correlation between Doppler echocardiography and cardiac catheterization might well have been improved by performing the two techniques simultaneously, the clinical utility of noninvasive evaluation is best tested by prospectively comparing nonsimultaneous invasive and noninvasive studies. The correlation between echocardiography-derived and catheterization-measured pressure gradients of the right ventricular outflow tract in patients after the arterial switch operation is excellent (r = 0.95). This degree of correlation is higher than that reported (18) before the addition of Doppler color flow imaging capability at our laboratory.

Although the degree of correlation between Doppler and catheterization gradients of right ventricular outflow tract obstruction was lower for patients after corrective surgery for tetralogy of Fallot (r = 0.84) than for patients after the arterial switch operation (r = 0.95), this difference in correlation coefficients was not statistically significant. Remembering to cross-check the right ventricular outflow tract gradient by interrogating the tricuspid regurgitant jet when estimating right ventricular peak pressure should minimize false negative diagnoses of stenosis.

Although some patients after the arterial switch operation and the vast majority of patients after repair of tetralogy of Fallot had mild pulmonary regurgitation, this did not markedly impair the use of the modified Bernoulli equation in quantitating stenosis severity. The linear regression slopes of our Doppler peak instantaneous gradient versus peak to peak catheterization gradient plots were consistently <1, similar to those reported by other laboratories (19–21).

There are several explanations for potential error in estimating arterial tract stenosis. 1) The Doppler color flow imaging equipment utilized in this study did not have a steerable continuous wave Doppler cursor, theoretically hampering alignment of the ultrasound beam parallel to the stenotic jet, resulting in an underestimation of the outflow tract obstruction. 2) The presence of a nondiscrete stenosis at the subvalvular level may invalidate the simple Bernoulli equation. The two patients who had the largest discrepancy between catheterization and Doppler gradients after the arterial switch operation had at least two levels of stenosis. 3) The use of prosthetic materials, which are very efficient specular reflectors, in some patients with tetralogy of Fallot may result in signal attenuation in structures beyond the material.

The correlation between Doppler-derived peak instantaneous and catheterization-derived peak to peak gradients in patients after coarctation repair was high, as seen in other institutions (22). Accuracy of pressure gradient estimations before surgical or balloon catheter intervention has been reported previously in aortic stenosis (23) as well as pulmonary stenosis. Our findings in this postoperative group of patients are similar in degree of accuracy. No patient with a significant residual stenosis (peak to peak gradient ≥50 mm Hg) was missed by Doppler echocardiography.

Valvular regurgitation. Severity of both semilunar and AV valve regurgitation estimated by echocardiography correlated well with that determined by catheterization, although relatively few of our patients had a moderate or severe degree of regurgitation by angiography. Atrioventricular valve regurgitation in particular may prove more difficult to quantitate when a larger number of patients with higher grades of regurgitation are examined. It is as yet undetermined whether the criteria of Helmcke et al. (15) can be applied in pediatric patients. In comparing echocardiographic and catheterization assessment of valvular regurgitation in our study patients, the mitral and aortic valves more frequently correlated exactly (88% and 98%, respectively) than tricuspid and pulmonary valves (65% and 68%, respectively).

Left to right shunts. In assessing residual left to right shunts, Andrade et al. (24) previously assessed patients with a surgically closed ventricular septal defect by echocardiography in 120 patients. They found that in 15 patients with angiographic proof of a residual shunt, the echocardiogram was correct in 13 (86%); the two shunts missed were <1.5:1. With the addition of Doppler color flow imaging, both the sensitivity and the negative predictive value approached 100% in our study (94% and 98%, respectively) and no hemodynamically significant left to right shunt was missed.

In our study, estimation of the right ventricular to right atrial pressure difference by use of the tricuspid regurgitant jet was highly accurate compared with nonsimultaneous catheterization-derived measurements ($r = 0.93$). Because the trajectory of the jet through a residual ventricular septal defect is highly variable (depending on whether the defect is peripatch or in the muscular septum), we typically have interrogated the tricuspid regurgitant jet as well as the transventricular septal defect jet in our evaluation of patients who have undergone ventricular septal defect closure.

Limitations. There are certain limitations when data obtained from catheterization are compared with data derived from echocardiography: 1) Some of the patients who were selected for cardiac catheterization had evidence for significant postoperative residua detected by echocardiography. This approach introduces a bias toward increasing the sensitivity of echocardiography in the assessment of postoperative residua. 2) Because the echocardiographic and catheterization data are obtained at different times, the level of sedation and therefore the cardiac output of the patient may vary and thus affect the correlation of data, especially those of pressure gradients and valvular regurgitation. 3) Regurgitation of semilunar and AV valves was not evaluated by catheterization unless an injection was made in the appropriate great artery or chamber. Because catheterization in many patients involves a limited number of injections and often does not include injections to detect regurgitation in all four valves, a direct one to one comparison of regurgitation for every valve in every patient was not always possible. 4) Doppler-derived peak instantaneous gradients should not be expected to correlate as closely with catheterization peak to peak gradients as they would with catheterization peak instantaneous gradients.

Furthermore, some general constraints apply in the assessment of the postoperative patient, including the potential for the echocardiographic window to be inadequate in older patients and occasionally even in young patients during the immediate postoperative period. In older patients better results may be obtained with nuclear magnetic resonance imaging.

The accuracy of echocardiography during the immediate postoperative period needs to be investigated in more detail. In addition, imaging techniques for other patient groups excluded from our study group (patients with Fontan repair, shunts, conduits, prosthetic valves, for example) also need to be developed. In particular, transesophageal echocardiography may be advantageous in some of these patient groups.

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