

EVALUATION OF NORMAL  
PROSTHETIC VALVE FUNCTION BY  
DOPPLER ECHOCARDIOGRAPHY

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## Evaluation of normal prosthetic valve function by Doppler echocardiography

Previous investigations have suggested that Doppler echocardiography is useful in detecting dysfunction in aortic (AVR) and mitral prostheses (MVR). However, to diagnose abnormalities, the spectrum of normal velocities through these valves must be established. Therefore, we used Doppler echocardiography to study 100 patients with 105 prosthetic valves that had no clinical evidence of valve dysfunction 9 ± 8 days postoperatively. There were 66 Carpentier-Edwards (C-E), 23 St. Jude (S-J), and 16 Ionescu-Shiley (I-S) valves. In 70 AVR, the peak instantaneous gradient was 26.4 ± 8.2 Hg, mean systolic gradient was 15.6 ± 5 mm Hg, and gradients varied inversely with valve size, although differences were significant only when comparing the smallest vs the largest valve sizes ( $p \leq 0.03$ ). Peak instantaneous gradients >36 mm Hg occurred only in AVR size 23 or smaller. There were no significant differences in gradients among C-E, S-J, and I-S AVR. In 35 MVR, mean gradient was 6.9 ± 2.3 mm Hg and valve area was 2.7 ± 0.8 cm<sup>2</sup>; neither varied significantly with valve size. However, S-J MVR group had smaller mean gradients and larger effective valve area than C-E bioprosthetic MVR ( $p = 0.01$  and  $p = 0.05$ , respectively). Regurgitation was more common in AVR (26%) than in MVR (9%),  $p = 0.04$ , although all instances were mild and clinically silent. We conclude that normal AVR and MVR of a given size and type have a predictable range of Doppler echocardiographic parameters. Doppler evidence of mild regurgitation is a frequent finding in normal AVR and MVR. The inverse relationship between valve size and gradient should be taken into account when interpreting Doppler echocardiographic measurements in AVR. (AM HEART J 1987;114:576.)

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The recognition of prosthetic valvular dysfunction is a difficult clinical problem. Cardiac catheterization has been the "gold standard" to identify prosthetic valve malfunction, but the difficulties and risks of an invasive procedure may be increased when studying prosthetic valves. A reliable noninvasive technique to evaluate prosthetic valve function would be useful. Clinical deterioration in patients with prosthetic valves can be detected by finding changes in auscultatory findings. In addition, noninvasive techniques such as fluoroscopy, phonocardiography, M-mode and two-dimensional echocardiography can be helpful in analyzing motion and timing of prosthetic valves, but are insensitive to prosthetic valve dysfunction.<sup>1,2</sup> Doppler echocardiography allows the assessment of intracardiac blood flow,<sup>3,4</sup> and preliminary studies have shown that Doppler is useful in evaluating prosthetic valves.<sup>5,6</sup> However, before

abnormalities can be diagnosed, the range of normal must be defined. The purpose of this study was to assess the normal flow characteristics, transvalvular gradients, valve area, and presence of regurgitation, with the use of Doppler echocardiography in a series of patients with normal prosthetic valves. The range of normal for these parameters will be useful as a reference in identifying prosthetic malfunction in future patients examined with similar methods.

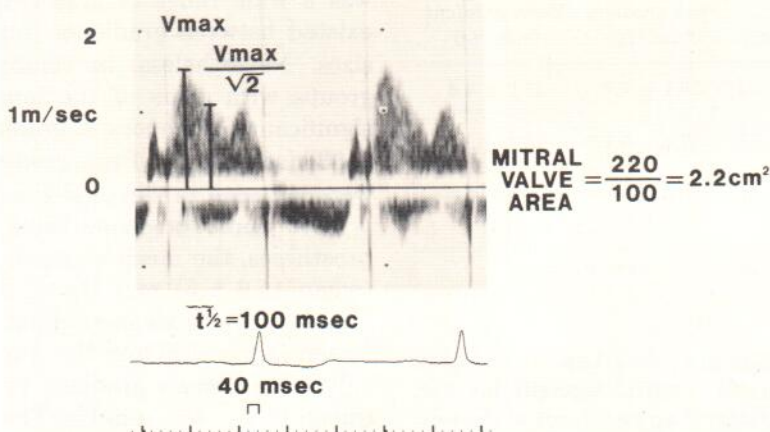
### METHODS

**Patient group.** Between October, 1985, and February, 1986, 100 patients who underwent aortic and/or mitral prosthetic valve implantation and who had no clinical evidence of valvular malfunction were prospectively studied with both pulsed and continuous wave Doppler echocardiography. The patients were clinically stable postoperatively and had no auscultatory findings of prosthetic valvular regurgitation. Doppler evaluation was performed at a mean interval of 9 ± 8 days after surgery. Fifty-five men and 45 women were studied. The mean age was 60 years, with a range of 20 to 87 years. Information regarding prosthetic valve type, size, and location was obtained from the operative reports, and was available prior to the Doppler examination.

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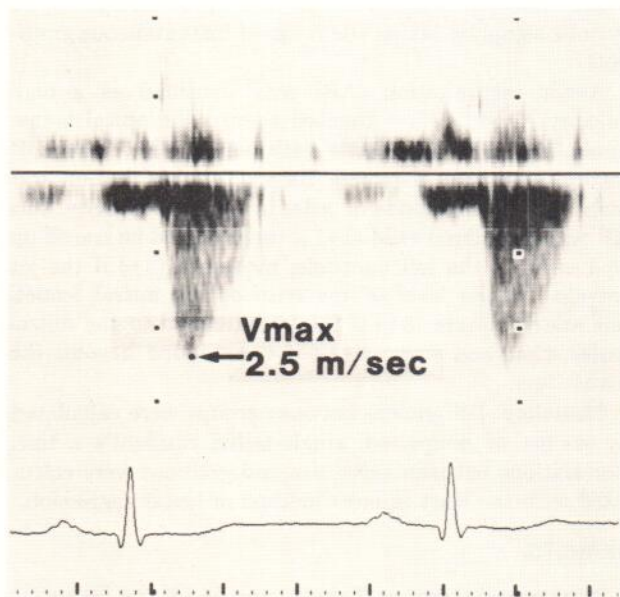
**Fig. 1.** Spectral display of mitral flow of a normal Carpentier-Edwards mitral bioprosthesis size 25 interrogated with continuous wave Doppler from the cardiac apex. The pressure half-time ( $t_{1/2}$ ) is measured from the time it takes for the maximum velocity ( $V_{max}$ ) to decline to  $V_{max}$  divided by the square root of 2. This time is used to calculate mitral valve area. msec = milliseconds; m/sec = meters per second.

A total of 70 patients with aortic valve prostheses were examined. There were 41 Carpentier-Edwards (C-E) and 16 Ionescu-Shiley (I-S) bioprostheses, and 13 St. Jude (S-J) prostheses. Thirty-five patients with mitral valve prostheses were examined, including 25 with C-E bioprostheses and 10 with S-J mechanical prostheses. Patients who underwent valve repair were excluded.

**Doppler study.** A Meridian Doppler echocardiographic system (Irex Ultrasound, Ramsey, N.J.) was used to perform the studies. Doppler transducers with a crystal frequency of 2.0 MHz were utilized, including dedicated Doppler (Pedof, Vingmed, Inc., Trondheim, Norway) and two-dimensional echo-directed transducers. Continuous wave and pulsed modes were used to interrogate flow across prosthetic valves. Velocity recordings utilizing spectral analysis were recorded on video tape and on paper at speeds of 50 to 75 mm/sec.

**Doppler evaluation of mitral prostheses.** Mitral diastolic flow was evaluated from the cardiac apex, searching for signals with the most clearly defined profile and the highest obtainable velocities. The transmitral velocity ( $V_{max}$ ), measured from the top of the velocity envelope, was used to calculate instantaneous gradients by means of the Bernoulli<sup>3</sup> equation ( $\text{gradient} = 4v^2$ ). The mean diastolic gradient was calculated by planimetry of the diastolic signal, taking the mean of instantaneous gradients. The mitral valve area was calculated by the pressure half-time method (Fig. 1), which has been previously described.<sup>3</sup> The Irex Meridian analysis software was used for the calculation of these measurements from the video tape.

Mitral regurgitation was identified by continuous wave Doppler with the transducer at the apex, as a high velocity jet, which began with mitral valve closure and was directed toward the left atrium. After identification of the jet by continuous wave mode, the Doppler was switched to



**Fig. 2.** Spectral display of aortic flow of a normal Carpentier-Edwards aortic valve size 23 interrogated with continuous wave Doppler from the cardiac apex. The peak velocity ( $V_{max}$ ) is 2.5 m/sec, indicating a peak instantaneous gradient of 25 mm Hg.

pulsed mode to assess the extension of the regurgitant jet into the left atrium, using the apical four- and two-chamber views and the parasternal long-axis view. The extension of the jet up to 1 cm into the left atrium was considered to be mild regurgitation (1+). Moderate regurgitation (2+) was interpreted as a jet found up to one third of the way to the back of the left atrium. Moderately

**Table I.** Aortic valve prostheses (n = 70)

	$V_{max}$ (m/sec)	Peak gradient (mm Hg)	Mean gradient (mm Hg)
Carpentier-Edwards (n = 41)	2.5 ± 0.4	26.1 ± 7.7	15.2 ± 4.8
Ionescu-Shiley (n = 16)	2.6 ± 0.5	27.4 ± 9.1	16.4 ± 5.3
St. Jude (n = 13)	2.5 ± 0.5	26.5 ± 9.1	16.0 ± 5.6
	NS	NS	NS

$V_{max}$  = maximum velocity; NS = not statistically significant.

severe (3+) mitral regurgitation extended up to two thirds of the atrial length. Severe (4+) mitral regurgitation was defined as a jet mapped greater than two thirds of the way to the back of the left atrium.

**Doppler evaluation of aortic prostheses.** By means of the apical five-chamber, the upper right parasternal and the suprasternal windows, the maximal flow velocity ( $V_{max}$ ) across the aortic valve was recorded (Fig. 2). The peak instantaneous transaortic gradient<sup>7</sup> was calculated with the modified Bernoulli equation: gradient =  $4(V_{max})^2$ . Mean gradient was obtained after planimetry of the systolic signal by taking the mean of instantaneous gradients.

Aortic regurgitation (AR) was identified as a high velocity diastolic flow directed toward the apical transducer, starting immediately with aortic valve closure. If regurgitation was detected, its spatial distribution was mapped in pulsed mode in order to estimate severity. The AR was considered mild (1+) if the jet could be traced up to 1 cm into the left ventricle, moderate (2+) if the jet traveled to the level of the base of the mitral leaflet, moderately severe (3+) if the jet extended to the mitral leaflet tips, and severe (4+) if it extended beyond the leaflet tips.

**Statistics.** Differences between groups were calculated by means of nonpaired, single-tailed Student's *t* test. Correlations between valve size and gradient were calculated with the least squares method of linear regression.

## RESULTS

**Peak aortic gradient (Tables I and II).** Of the 70 aortic prostheses, the peak instantaneous gradient ranged from 15 to 42 (mean  $26.4 \pm 8.2$ ) mmHg. Among 41 C-E valves, the peak gradient ranged from 16 to 41 (mean  $26.1 \pm 7.7$ ) mm Hg. Of 16 I-S valves, the peak gradient ranged from 16 to 42 (mean  $27.4 \pm 9.1$ ) mm Hg. In the 13 S-J valves, the peak gradient ranged from 15 to 38 (mean  $26.5 \pm 9.1$ ) mm Hg. There were no significant differences between these groups (Table I). In addition, a comparison between different valve types of the same size revealed no significant differences (Table II).

There was a significant inverse relationship between valve size and peak aortic prosthetic gradi-

ent ( $p = 0.001$ ,  $r = -0.36$ ) (Fig. 3). However, there was a wide range of gradients, and great overlap existed between gradients from valves of different sizes. Nevertheless, in comparing the small size groups with some of the large valve size groups, significant differences in gradient were found ( $p \leq 0.03$ ) (see Fig. 3). Peak gradients over 36 mm Hg were not seen in valves above size 23.

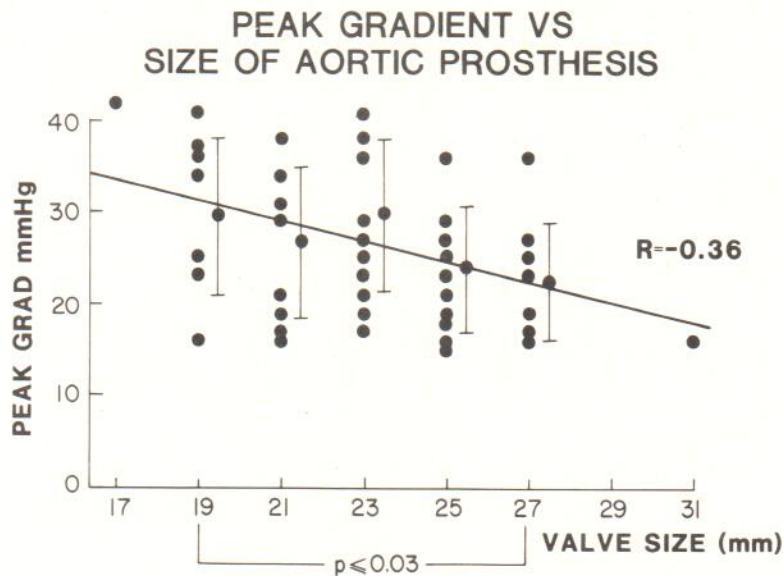
**Mean aortic gradient (Table I).** In all 70 aortic prostheses, the mean gradient ranged from 5 to 26 (mean  $15.6 \pm 5$ ) mm Hg. C-E bioprostheses were found to have a mean gradient ranging from 5 to 23 (mean  $15.2 \pm 4.8$ ) mm Hg. Among I-S bioprosthetic valves, the mean gradient ranged from 10 to 26 (mean  $16.4 \pm 5.3$ ) mm Hg. The S-J valves had mean gradients varying from 7 to 24 (mean  $16.0 \pm 5.6$ ) mm Hg. There were no significant differences between these groups. There was an inverse relation between mean aortic gradient and valve size ( $p = 0.003$ ,  $r = -0.34$ ) (Fig. 4). Differences between groups were significant only when comparing some of the small valve sizes with some of the large valve sizes ( $p \leq 0.02$ ).

**Aortic prosthetic regurgitation.** Among the 70 aortic prosthetic valves, Doppler evidence of aortic regurgitation was detected in 18 patients (26%), and was mild in all cases. None of the 18 patients had auscultatory evidence of aortic insufficiency. There was no significant difference in the percentage of regurgitation detected among the three types of valves (Fig. 5).

**Peak mitral diastolic gradient (Table III).** In 35 patients with a mitral prosthesis, the peak gradient ranged from 6 to 31 (mean  $15.8 \pm 5.6$ ) mm Hg. In 25 patients with C-E bioprostheses, the peak gradients ranged from 10 to 31 (mean  $17.3 \pm 5.3$ ) mm Hg. Among 10 patients with a S-J prosthesis, the peak gradients ranged from 6 to 21 (mean  $12 \pm 4.4$ ) mm Hg, which was significantly smaller than the C-E valve group ( $p = 0.01$ ).

**Mean mitral diastolic gradient (Table III).** Mean gradient in the entire group ranged from 2 to 12 (mean =  $6.9 \pm 2.3$ ) mm Hg. The mean gradient obtained in the C-E bioprosthesis subgroup ranged from 4 to 12 (mean  $7.5 \pm 2.2$ ) mm Hg. In patients with S-J prostheses, the mean gradient ranged from 2 to 9 (mean  $5.6 \pm 2.1$ ) mm Hg, which was significantly less than that of the C-E group ( $p = 0.01$ ).

**Mitral valve area (Tables III and IV).** The calculated valve area in all prosthetic mitral valves ranged 1.6 to 4.2 (mean  $2.7 \pm 0.8$ ) cm<sup>2</sup>. The valve area in C-E bioprostheses ranged from 1.7 to 4.2 (mean  $2.6 \pm 0.7$ ) cm<sup>2</sup>. In S-J prostheses, the area ranged from 1.6 to 4.1 (mean  $3.1 \pm 0.8$ ) cm<sup>2</sup>, which was somewhat



**Fig. 3.** Relationship between peak gradient and valve size in the 70 aortic prostheses studied. An inverse correlation is present, but with great overlap ( $p = 0.001$ ,  $r = -0.36$ ) among different sizes. A significant difference was noted between sizes 19 and 27 ( $p = 0.03$ ), 19 and 25 ( $p = 0.03$ ), 23 and 27 ( $p = 0.01$ ), 23 and 25 ( $p = 0.01$ ). All other comparisons between groups were not significant.

**Table II.** Peak gradient (mm Hg) of aortic prosthesis (n = 70)

Valve type	Valve size						
	#17	#19	#21	#23	#25	#27	#31
I-S (n = 16)	42.0 n = 1	27.7 ± 8.8 n = 6	26.6 ± 9 n = 8		18.0 n = 1		
S-J (n = 13)		36.5 ± 0.7 n = 2	27.3 ± 7.6 n = 3	33.7 ± 7.5 n = 3	19.0 ± 3.5 n = 3	16.0 n = 1	16.0 n = 1
C-E (n = 41)		N.S.	N.S.	29.1 ± 8.7 n = 15	24.9 ± 7 n = 17	23.2 ± 6.3 n = 9	

I-S = Ionescu-Shiley; S-J = St. Jude Medical; C-E = Carpentier-Edwards.

higher than the C-E valves ( $p = 0.05$ ). In addition, the valve area of size 31 S-J prostheses was found to be significantly larger ( $p = 0.01$ ) than C-E valves of the same size (Table IV). Other comparisons of different sizes could not be made.

**Mitral prosthetic regurgitation.** Among the 35 patients with mitral valve prostheses, three showed Doppler evidence of mitral regurgitation (two S-J and one C-E), all of which were mild in severity. This frequency of 9% (3 of 35) was significantly less than the 26% (18 of 70) of aortic prostheses showing aortic regurgitation ( $p = 0.04$ ) (Fig. 6).

**DISCUSSION**

Although significantly improved from first generation prostheses, the hemodynamic performance, durability, and complication rate of currently uti-

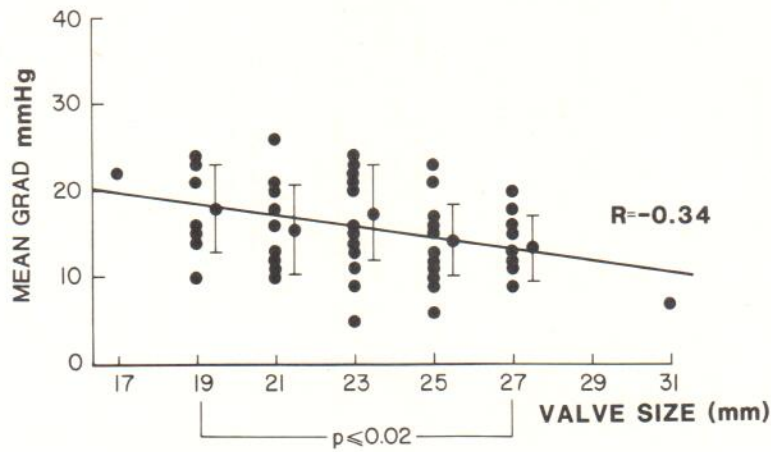
**Table III.** Mitral valve prosthesis (n = 35)

	Peak diastolic gradient (mm Hg)	Mean diastolic gradient (mm Hg)	MVA (cm <sup>2</sup> )
Carpentier-Edwards (n = 25)	17.3 ± 5.3	7.5 ± 2.2	2.6 ± 0.7
St. Jude (n = 10)	12.0 ± 4.4	5.6 ± 2.1	3.1 ± 0.8
	$p = 0.01$	$p = 0.01$	$p = 0.05$

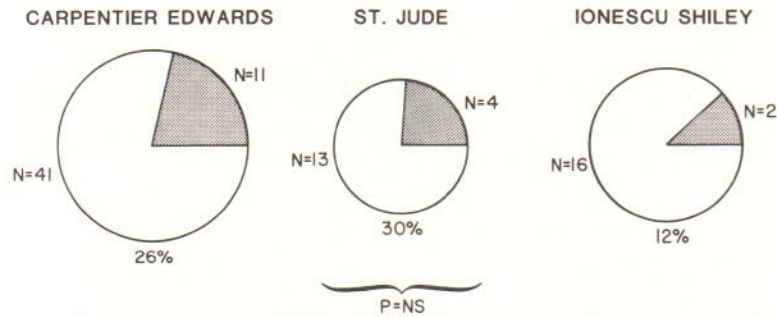
MVA = mitral valve area.

lized prosthetic valves are still less than ideal.<sup>8</sup> The identification of prosthetic valve malfunction involves an intimate understanding of normal prosthetic valve function, a thorough bedside clinical assessment, and an objective assessment with noninvasive and/or invasive techniques.

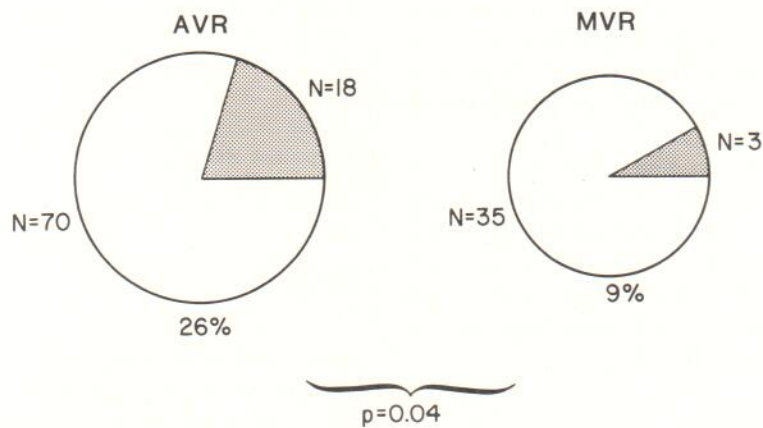
### MEAN GRADIENT VS SIZE OF AORTIC PROSTHESIS



**Fig. 4.** Mean gradient plotted as a function of valve size in the 70 aortic prostheses. A significant inverse relation was found, but with a considerable amount of scatter ( $p = 0.003$ ,  $r = -0.34$ ). A significant difference was noted between sizes 19 and 27 ( $p = 0.02$ ), 19 and 25 ( $p = 0.02$ ), 23 and 27 ( $p = 0.02$ ), 23 and 25 ( $p = 0.02$ ). All other comparisons between groups were not significant.



**Fig. 5.** Percentage of patients with normally functioning aortic prostheses in which regurgitation was detected. No significant difference was noted between the three types of valves.



**Fig. 6.** The finding of valvular regurgitation was seen more often in normally functioning aortic prostheses (26%) than in mitral prostheses (9%) ( $p = 0.04$ ). All were mild in severity and clinically silent.

**Table IV.** Valve area (cm<sup>2</sup>) of mitral prosthesis (n = 35)

Valve type	Valve size					
	#21	#25	#27	#29	#31	#33
C-E n = 25			2.4 ± 0.6 n = 7	2.9 ± 0.9 n = 5	2.5 ± 0.7 n = 9	3.0 ± 0.9 n = 4
S-J n = 10	3.8 n = 1	3.0 ± 0.6 n = 5	1.6 n = 1		3.8 ± 0.4 n = 3	
					p = 0.01	

Abbreviations as in Table II.

**Transvalvular gradients.** Significant gradients across normal prosthetic valves have been well demonstrated, both in vitro and in vivo.<sup>9,10</sup> Mean aortic gradients measured postoperatively by cardiac catheterization can be as high as 36 mm Hg in smaller-sized normally functioning prosthetic valves.<sup>10</sup> Therefore, normally functioning prosthetic valves can be considered mildly "stenotic" compared to normal native valves.

In comparing this report with previously published data, it should be noted that transvalvular velocities measured by Doppler ultrasound reflect peak instantaneous gradients, which are higher than the peak-to-peak gradients measured during a pull-back catheterization.<sup>11</sup> Smith et al.<sup>12</sup> reported their results with experimental aortic stenosis in a canine preparation, demonstrating that the average difference between peak instantaneous and peak-to-peak gradients was 9 mm Hg in mild to moderate stenosis, with a smaller difference found in severe stenosis. The same investigators obtained similar results in patients with aortic stenosis,<sup>13</sup> when comparing the Doppler measurements with the invasive hemodynamic data.

In our study, we have found a relatively wide range of normal values among peak and mean gradients obtained in prosthetic valves of the same size, an observation similar to the data of Williams and Labovitz.<sup>6</sup> Transvalvular pressure drop is dependent on several factors in addition to the effective flow area: left ventricular function, heart rate, cardiac output, and flow period (systolic ejection period or diastolic filling period).<sup>14</sup> Wide variations in these parameters explain the wide variation in pressure gradients that can be expected when studying a diverse group of patients. In addition, these normal values for flow through prosthetic valves of clinically stable patients might be different than Doppler measurements obtained in patients with normal prostheses who have clinically significant hemodynamic compromise.

Among aortic prostheses, we found an inverse

correlation between valve size and both peak and mean gradients ( $r = -0.36$  and  $-0.34$ , respectively). Although there was a considerable amount of scatter, this inverse relation was significant when comparing smaller vs larger-sized valves ( $p \leq 0.03$  and  $p \leq 0.02$ , respectively). Similar results have been reported recently by Williams et al.<sup>6</sup> It should be noted that the parameters used to assess aortic prosthetic function were peak instantaneous and mean gradients. The calculation of aortic prosthetic valve area was not attempted. Valve area of stenotic native aortic valves can be determined by Doppler measurements,<sup>15,16</sup> but the methodology has not yet been validated for prosthetic aortic valves.

In this study, transmitral gradients and valve areas varied widely within each type, but were significantly better in S-J valves than in C-E valves. This observation has been reported with invasive data. In vitro, St. Jude valves have been found to be hydraulically more efficient than C-E porcine valves, a finding confirmed in hemodynamic studies in vivo.<sup>17</sup> Effective mitral orifice varies with flow, valve orientation, and the inertia of prosthetic leaflets.<sup>10,18,19</sup>

**Prosthetic valve regurgitation.** We found that mild valvular regurgitation can often be seen in normal aortic prostheses (18 of 70 or 26%), but is less frequently encountered in normal mitral prostheses (3 of 35 or 9%) ( $p = 0.04$ ). The frequent presence of mild regurgitation has also been documented by others who used Doppler<sup>6</sup> and angiography.<sup>5</sup> Among the three types of aortic prosthesis studied, the frequency of regurgitation was not significantly different.

Sagar et al.<sup>5</sup> evaluated patients with suspected prosthetic valve malfunction by simultaneous Doppler echocardiography and cardiac catheterization. An excellent correlation between the noninvasive and invasive data was shown, not only for transaortic and transmitral gradient ( $r = 0.93$ ), but also for the presence and severity of valvular regurgitation. Recently, Wilkins et al.<sup>20</sup> also demonstrated that the

Doppler estimations of mean transvalvular gradients are virtually identical ( $r = 0.96$ ) to those obtained invasively.

In summary, Doppler echocardiography can provide reliable hemodynamic information about the function of a prosthetic valve. The test may be particularly useful if used serially, when baseline values are known. Doppler echocardiography is a noninvasive test that can be repeated without risk to the patient. It is less expensive than cardiac catheterization, which also carries the risk of damaging a prosthetic valve. Cardiac catheterization should be reserved for cases in which strong evidence of valvular dysfunction is raised by the clinical and noninvasive examinations and additional data are needed. Doppler measurements of peak and mean gradient and valve area have an expected normal range that is specific for the prosthetic valve size, type, and anatomic position. This study showed significant differences in gradient between different valve sizes in aortic prostheses and significant differences between valve types in mitral prostheses. These features should be taken into account in evaluating prosthetic valves with Doppler echocardiography.

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