Continuous Wave Doppler Echocardiographic Measurement of Prosthetic Valve Gradients
A Simultaneous Doppler-Catheter Correlative Study
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Studies correlating prosthetic valve gradients determined by continuous wave Doppler echocardiography with gradients obtained by cardiac catheterization have, to date, been limited to patients with mitral and tricuspid prostheses or have compared nonsimultaneous measurements. Simultaneous Doppler and catheter pressure gradients in 36 patients (mean age, 63±13 years) with 42 prosthetic valves (20 aortic, 20 mitral, one tricuspid, and one pulmonary) were studied. Catheter gradients were obtained using a dual-catheter technique. The simultaneous pressure tracings and Doppler flow velocity profiles were digitized at 10-msec intervals to derive the corresponding maximal and mean gradients. The correlation between the maximal Doppler gradient and the simultaneously measured maximal catheter gradient was 0.94 (SEE=6), and that between the Doppler gradient and the simultaneously measured mean catheter gradient was 0.96 (SEE=3). There were no significant differences in correlation between gradients for the 32 mechanical valves (maximal gradients: r=0.95, SEE=6; mean gradients: r=0.96, SEE=3) and the 10 bioprosthetic valves (maximal gradients: r=0.89, SEE=6; mean gradients: r=0.93, SEE=3). In patients with mitral prostheses, Doppler gradients correlated well with the corresponding catheter gradients obtained with direct measurement of left atrial pressure (maximal gradients: r=0.96, SEE=2; mean gradients: r=0.97, SEE=1.2). A close correlation between corresponding Doppler and catheter gradients also was found in patients with aortic prostheses (maximal gradients: r=0.94, SEE=6; mean gradients: r=0.94, SEE=3). Thus, continuous wave Doppler echocardiography can accurately predict the pressure gradient across prosthetic valves. (Circulation 1989;80:504–514)

Diagnosis of prosthetic valve dysfunction remains a clinical challenge. Earlier noninvasive techniques were of limited success because of their relatively low specificity and their inability to provide quantitative hemodynamic information. However, the introduction of continuous wave Doppler echocardiography has provided a noninvasive method for determining transvalvular pressure gradients. The recording of transvalvular flow velocity (v) with continuous wave Doppler allows pressure gradient (P) to be determined with the modified Bernoulli equation: 

\[ P = 4v^2 \]

The clinical accuracy of this technique has been validated in native valve stenosis, right and left ventricular outflow obstruction, and left-sided regurgitant lesions. However, because of the unique geometry and flow characteristics of prosthetic valves, the Doppler technique cannot be assumed to remain equally accurate for calculating prosthetic valve gradients. To date, validation studies in patients with prosthetic valves have been confined to a small number of patients with mitral and tricuspid prostheses. Moreover, limited and conflicting data are available regarding the accuracy of the Doppler measurements of transvalvular gradients in patients with aortic prostheses.

Thus, the usefulness of continuous wave Doppler echocardiography for determining a wide range of prosthetic valve gradients has not been validated by

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See p 707
simultaneous measurement of transvalvular gradients at cardiac catheterization. Therefore, we prospectively studied 36 patients at the time of cardiac catheterization to assess the accuracy of the continuous wave Doppler technique.

**Methods**

**Patients**

The study group consisted of 36 patients (15 men, 21 women) ranging in age from 44 to 80 years (mean, 63±13 years) who were scheduled for clinically indicated cardiac catheterization. In 23 patients, prosthetic valve dysfunction was suspected clinically. The remaining 13 patients underwent cardiac catheterization for evaluation of coronary artery disease or if of a valve other than the prosthetic valve; in these patients, a complete hemodynamic assessment of the prosthetic valve was thought to be warranted. Six of these patients had two prosthetic valves. Thus, a total of 42 prosthetic valves were studied: 20 aortic prostheses, 20 mitral prostheses, one tricuspid prosthesis, and one pulmonary prosthesis. Of the 42 prostheses studied, 32 were mechanical (15 Starr-Edward, seven Björk-Shiley, four Braunwald-Cutter, two Hall-Medtronic, two St. Jude, one Sorin, and one Smeloff-Cutter), and 10 were bioprosthetic (five Hancock, two Ionescu-Shiley, two Carpentier-Edward, and one Dura Mater). Sixteen patients were in atrial fibrillation, 13 in sinus rhythm, six in paced rhythm, and one in second-degree atrioventricular block. Comprehensive two-dimensional and Doppler echocardiography had been performed on all patients before cardiac catheterization.

**Continuous Wave Doppler Technique**

All Doppler examinations were performed during cardiac catheterization, and continuous wave Doppler flow velocities and transvalvular pressure gradients were recorded simultaneously. The study was approved by the Mayo Institutional Review Board, and informed consent was obtained from each patient before inclusion in the study. Doppler flow velocities were recorded with an Irex Model 3B (Upper Saddle River, New Jersey) or Hewlett-Packard Model 77020 echocardiographic instrument (Palo Alto, California) using a nonimaging 2.0-MHz transducer. Immediately before cardiac catheterization, a screening Doppler examination was performed to identify the acoustic window from which the maximal flow velocity could be obtained. For aortic prostheses, recording of flow velocities was attempted from suprasternal, right parasternal, and apical windows. For mitral and tricuspid prostheses, the apical and left parasternal windows were used. For the pulmonary prosthesis, the left parasternal and suprasternal windows were used.

**Cardiac Catheterization Technique**

Diazepam (2.5–15 mg i.v.) was used for sedation during catheterization. Fluid-filled catheters (7F or 8F) connected to strain-gauge pressure transducers (Gould P231D, Cleveland, Ohio) were used for pressure measurement. All pressure measurements were recorded, with a direct-current coupler, simultaneously with the Doppler spectral signal on a calibrated strip-chart recorder at paper speeds of 50 and 100 mm/sec. The presence or absence of prosthetic valve regurgitation was evaluated by contrast angiography after hemodynamic recordings were completed.

**Aortic prostheses.** In all 20 patients with aortic prostheses, the transvalvular pressure gradient was measured by dual-catheter technique with simultaneous recording of left ventricular and ascending aortic pressures. Of these 20 patients, 15 had the left ventricular pressure recorded by transseptal technique, and five underwent transthoracic left ventricular puncture because of the presence of a mitral prosthesis.

**Mitral prostheses.** In all 20 patients with a mitral prosthesis, transvalvular pressure gradient was measured by dual-catheter technique. In 12 of these patients, left atrial pressure was measured directly by transseptal technique; in the remaining eight patients, pulmonary capillary wedge pressure was measured. In each case, wedge pressure measurements were confirmed by lower phasic and mean pressures compared with the pulmonary artery and by oxygen saturation of 95% or more. Left ventricular pressure was obtained simultaneously by retrograde crossing of the aortic valve in 14 patients and by transthoracic left ventricular puncture in five patients because of the additional presence of an aortic prosthesis. In the remaining patient, who also had an aortic prosthesis, the mitral bioprosthesis was crossed antegrade by the transseptal technique with a double-lumen, dual-port catheter in which the proximal port measured left atrial pressure while the distal port simultaneously measured left ventricular pressure.

**Tricuspid and pulmonary prostheses.** The patient with the tricuspid prosthesis underwent right atrial catheterization through the femoral vein and a simultaneous transthoracic right ventricular puncture. In the patient with the pulmonary prosthesis, the transvalvular gradient was measured by inserting two catheters into the femoral vein: one placed antegrade across the prosthesis and one in the right ventricular outflow tract.

**Data Analysis**

The simultaneous catheter and Doppler flow velocity recordings were digitized manually on a computer system, as previously described.13 The instantaneous pressure and Doppler flow velocities were analyzed at 10-msec intervals (Figure 1). With the modified Bernoulli equation (pressure gradient=4v²,
in which \(v\) = velocity in meters per second), the instantaneous Doppler velocities were then converted to instantaneous pressure gradients. With these data, maximal and mean gradients derived by both continuous wave Doppler and catheterization were obtained for each patient. For aortic prostheses, the widely used peak-to-peak gradient was also obtained by subtracting peak aortic systolic pressure from peak left ventricular systolic pressure obtained at cardiac catheterization. In patients with mitral prostheses in whom pulmonary capillary wedge pressure was measured, the catheter gradients were also calculated before and after correction for phase delay in the wedge pressure tracing. To correct for phase delay, the pulmonary capillary wedge tracing was shifted leftward until the peak of the V wave was bisected by the rapid downstroke of the left ventricular pressure decline as suggested by Carabello and Grossman.\(^{14}\) Mean values for catheter and Doppler gradients were obtained by averaging five representative cardiac cycles.

**Statistical Analysis**

Data are expressed as mean ± SD. The correlation between Doppler and catheterization gradients was assessed by linear regression analysis with a least squares method. The variation between Doppler and catheter gradients was evaluated by calculating the signed (+ or −) differences between the Doppler and the corresponding catheter gradients. The effect of valve subtype (mechanical compared with tissue) and catheterization technique (pulmonary capillary wedge compared with transseptal) on the variation between Doppler and catheter gradients was assessed by comparing the signed differences for each subgroup with a paired Student’s \(t\) test. A \(p\) value less than 0.05 was considered statistically significant. Finally, the beat-to-beat correlation between Doppler and catheter gradients within individual patients was also assessed. This was done by calculating, in each patient, the signed differences between each of the five single gradient measurements and the mean value of that measurement (obtained by averaging the five gradient measurements). The signed differences from the mean (termed “residuals”) were obtained for each Doppler and each corresponding catheter gradient selected for analysis. Thus, the residuals represent the direction and magnitude of beat-to-beat variation in the gradient measurements from the mean value in an indi-
Mean gradients.

**A**: Plot of maximal (Max) gradients. Regression equation is Doppler gradient = 1.09 × catheter gradient − 3.3. Panel B: Mean gradients. Regression equation is Doppler gradient = 1.03 × catheter gradient − 1.2. Dotted line, regression line; solid line, line of identity.

individual patient. The correlation between the Doppler gradient residuals and the catheter gradient residuals was assessed with linear regression analysis.

**Results**

**Continuous Wave Doppler Recordings**

The maximal systolic velocities recorded across the aortic and pulmonary prostheses ranged from 1.9 to 4.3 m/sec (mean, 3.1 ± 0.6 m/sec). The acoustic window from which the maximal velocity was obtained was apical in 18 patients, suprasternal in two patients, and left parasternal in the patient with the pulmonary prosthesis. For mitral and tricuspid prostheses, the maximal diastolic velocities recorded ranged from 1.4 to 2.9 m/sec (mean, 2.0 ± 0.4 m/sec). The maximal velocity was obtained from the apical window in all cases.

**Correlation of Simultaneous Doppler and Catheter Pressure Gradients**

The maximal Doppler gradients ranged from 8 to 74 mm Hg (mean, 29 ± 17 mm Hg), and the simultaneous maximal gradients measured by catheter ranged from 8 to 70 mm Hg (mean, 29 ± 15 mm Hg). The correlation between maximal Doppler gradient and the simultaneously obtained maximal catheter gradient was highly significant (r = 0.94, SEE = 6) (Figure 2A). The mean Doppler gradients ranged from 2.6 to 42 mm Hg (mean, 14 ± 10 mm Hg), and the mean pressure gradients measured by catheter ranged from 3.6 to 40 mm Hg (mean, 15 ± 10 mm Hg). These gradients also showed close correlation (r = 0.96, SEE = 3) (Figure 2B). A low cardiac index or the presence of significant prosthetic valve regurgitation did not affect the correlation between catheter- and Doppler-derived maximal or mean gradients (Tables 1 and 2).

In individual patients, there was good beat-to-beat correlation between Doppler and catheter pressure gradients, including those with irregular rhythm. In the 16 patients with atrial fibrillation, the Doppler gradient residuals correlated well with the catheter gradient residuals for both maximal (r = 0.91) and mean (r = 0.87) gradients, an indication of close tracking of the catheter gradient by the Doppler gradient despite varying RR intervals.

**Aortic prosthetic valve gradients.** The maximal Doppler gradients ranged from 15 to 74 mm Hg (mean, 40 ± 17 mm Hg), and the simultaneous maximal gradients measured by catheter ranged from 13 to 70 mm Hg (mean, 39 ± 14 mm Hg) (Table 1, Figure 3). The correlation coefficient for maximal Doppler and catheter gradients was 0.94 (SEE = 6) (Figure 4A). The mean Doppler gradients ranged from 9 to 42 mm Hg (mean, 22 ± 10 mm Hg), and the mean pressure gradient measured by catheter ranged from 6 to 40 mm Hg (mean, 22 ± 9 mm Hg). For the mean aortic gradients, the correlation coefficient was 0.94 (SEE = 3) (Figure 4B). The Doppler gradients reliably estimated the corresponding catheter gradients; the mean difference between the maximal gradients was 1 ± 6 mm Hg (range, −10 to +13 mm Hg), and that between the mean gradients was −0.1 ± 3 mm Hg (range, −6 to +6 mm Hg) (Table 3).

Peak-to-peak gradient measured by catheterization ranged from 1 to 39 mm Hg (mean, 14 ± 10 mm Hg) and was consistently lower than maximal Doppler and maximal catheter gradients (Table 3). The correlation between peak-to-peak catheter gradient and maximal Doppler gradient was 0.72 (SEE = 11) (Figure 5A). Overall, the correlation between peak-to-peak gradient and mean Doppler gradient was 0.74 (SEE = 6) (Figure 5B).

**Mitral prosthetic valve gradients.** The catheter-derived transmitral gradients were obtained from
both direct (transseptal technique) and indirect (pulmonary capillary wedge pressure) measurements of left atrial pressure. Thus, results were analyzed separately according to the catheterization technique (Table 2).

For the subgroup of 12 patients in whom left atrial pressure was measured directly with transseptal technique, the maximal Doppler gradients ranged from 13 to 33 mm Hg (mean, 19±7 mm Hg), and the simultaneous maximal gradients measured with catheter ranged from 13 to 28 mm Hg (mean, 18±5 mm Hg). The correlation coefficient for maximal Doppler and catheter gradients was 0.96 (SEE=2) (Figure 6A). Mean gradients derived by Doppler technique ranged from 4.0 to 19.0 mm Hg (mean, 7.8±4.5 mm Hg), whereas the mean gradients measured simultaneously with catheter ranged from 4.2 to 16 mm Hg (mean, 7.8±4.0 mm Hg). For mean gradients, the correlation coefficient was 0.97 (SEE=1.2) (Figure 6B). Again, the Doppler gradients showed little variation from the corresponding catheter gradients; the mean difference between the maximal gradients was 1±2 mm Hg (range, −3 to +5 mm Hg), and that between the mean gradients was 0.1±1 mm Hg (range, −2 to 3 mm Hg) (Table 3).

For the subgroup of eight patients in whom left atrial pressure was measured indirectly by pulmonary capillary wedge pressure, the maximal Doppler gradients ranged from 9 to 31 mm Hg (mean, 16±7 mm Hg), and the simultaneous maximal gradients measured with catheter ranged from 17 to 33 mm Hg (mean, 24±7 mm Hg). The correlation coefficient for maximal gradient was 0.67 (SEE=5.2), which was lower than the correlation obtained with the transseptal technique (Figure 6A and 7). The Doppler mean gradients ranged from 2.6 to 10.0 mm Hg (mean, 5.4±2.3 mm Hg), and the simultaneous mean gradients measured by catheter ranged from 3.6 to 13.0 mm Hg (mean, 8.6±2.9 mm Hg). For mean gradient, the correlation coefficient was 0.44 (SEE=2.2), which, as with the maximal gradient, was lower than that obtained with the transseptal technique (Figures 6B and 7).

There was also greater variation between the Doppler and catheter gradients obtained using wedge pressure recordings when compared with the results obtained using the transseptal technique (Table 3). For the former, the Doppler gradients were consistently lower than the corresponding catheter gradient; the mean difference between maximal gradients was −7±6 mm Hg (range, −15 to +1 mm Hg), and that between mean gradients was −3±3 mm Hg (range, −9 to −1 mm Hg). With correction for phase delay in the pulmonary capillary wedge pressure, the correlation coefficient for maximal gradients improved to 0.87 (SEE=3.3), and the correlation coefficient for mean gradients improved to 0.83 (SEE=1.4). However, the variation between gradients remained significantly greater than that obtained with the transseptal technique (Table 3).
TABLE 2. Doppler and Catheterization Data From 21 Patients With Mitral and Tricuspid Prostheses

<table>
<thead>
<tr>
<th>Patient</th>
<th>Age (yr)/sex</th>
<th>Prosthesis type</th>
<th>Size (mm)</th>
<th>Catheter technique</th>
<th>Gradient (mm Hg)</th>
<th>CI (l/min/m²)</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>TS</td>
<td>Wedge</td>
<td>Maximal Cath</td>
<td>Dopp</td>
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<tr>
<td>22</td>
<td>69/F</td>
<td>Starr-Edwards 3M</td>
<td>30</td>
<td>+</td>
<td>13 14</td>
<td>4.2 4.0</td>
</tr>
<tr>
<td>23</td>
<td>44/F</td>
<td>Starr-Edwards 3M</td>
<td>30</td>
<td>+</td>
<td>18 18</td>
<td>5.2 4.8</td>
</tr>
<tr>
<td>24</td>
<td>71/M</td>
<td>Starr-Edwards 3M</td>
<td>30</td>
<td>+</td>
<td>28 32</td>
<td>14.8 13.0</td>
</tr>
<tr>
<td>25</td>
<td>64/F</td>
<td>Björk-Shiley</td>
<td>25</td>
<td>+</td>
<td>12 13</td>
<td>5.8 4.8</td>
</tr>
<tr>
<td>26</td>
<td>77/M</td>
<td>Björk-Shiley</td>
<td>31</td>
<td>+</td>
<td>15 17</td>
<td>6.2 6.4</td>
</tr>
<tr>
<td>27</td>
<td>72/F</td>
<td>Björk-Shiley</td>
<td>29</td>
<td>+</td>
<td>13 12</td>
<td>4.2 4.0</td>
</tr>
<tr>
<td>28</td>
<td>67/F</td>
<td>Hancock</td>
<td>29</td>
<td>+</td>
<td>28 33</td>
<td>16.0 19.0</td>
</tr>
<tr>
<td>29</td>
<td>68/F</td>
<td>Hancock</td>
<td>29</td>
<td>+</td>
<td>20 22</td>
<td>10.8 11.0</td>
</tr>
<tr>
<td>30</td>
<td>54/M</td>
<td>Hall-Medtronic</td>
<td>27</td>
<td>+</td>
<td>19 15</td>
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<td>31</td>
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<td>Smeloff-Cutter</td>
<td>31</td>
<td>+</td>
<td>18 19</td>
<td>5.2 5.4</td>
</tr>
<tr>
<td>32</td>
<td>54/F</td>
<td>Ionescu-Shiley</td>
<td>27</td>
<td>+</td>
<td>15 17</td>
<td>8.4 8.4</td>
</tr>
<tr>
<td>33</td>
<td>67/F</td>
<td>Braunwald-Cutter</td>
<td>31</td>
<td>+</td>
<td>16 16</td>
<td>6.2 7.2</td>
</tr>
<tr>
<td>34</td>
<td>54/M</td>
<td>Starr-Edwards 3M</td>
<td>30</td>
<td>+</td>
<td>22 16</td>
<td>6.4 5.6</td>
</tr>
<tr>
<td>35</td>
<td>61/F</td>
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<td>30</td>
<td>+</td>
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<td>7.8 6.2</td>
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<td>36</td>
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<td>7.8 3.0</td>
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<tr>
<td>37</td>
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<td>34</td>
<td>+</td>
<td>24 17</td>
<td>8.4 5.4</td>
</tr>
<tr>
<td>38</td>
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<td>+</td>
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</tr>
<tr>
<td>39</td>
<td>66/M</td>
<td>Björk-Shiley</td>
<td>31</td>
<td>+</td>
<td>12 12</td>
<td>3.6 2.6</td>
</tr>
<tr>
<td>40</td>
<td>56/F</td>
<td>Carpentier-Edwards</td>
<td>27</td>
<td>+</td>
<td>30 18</td>
<td>10.8 5.8</td>
</tr>
<tr>
<td>41</td>
<td>67/F</td>
<td>Braunwald-Cutter</td>
<td>31</td>
<td>+</td>
<td>33 31</td>
<td>10.8 10.0</td>
</tr>
<tr>
<td>42</td>
<td>73/F</td>
<td>Braunwald-Cutter (TVR)</td>
<td>32</td>
<td>–</td>
<td>8 8</td>
<td>4.2 4.0</td>
</tr>
</tbody>
</table>

TS, transseptal; Cath, catheter-derived; Dopp, Doppler-derived; Regurg, regurgitation; TVR, tricuspid valve replacement; CI, cardiac index derived by cardiac catheterization (indocyanine green dye dilution technique); NA, not available.

Mechanical compared with tissue prostheses. When tissue valves (n=10) and mechanical valves (n=32) were analyzed separately, the correlation between Doppler and catheter gradients was similar for both prosthetic valve subtypes. For maximal gradients, the correlation coefficient was 0.89 (SEE=6) for tissue valves and 0.95 (SEE=6) for mechanical valves. For mean gradients, the correlation coefficient was 0.93 (SEE=3) for tissue valves and 0.96 (SEE=3) for mechanical valves. In addition, the mean difference between the Doppler and catheter gradients was similar in both subgroups for maximal and mean gradients (Table 3).

Clinical Outcome

Of the 42 prosthetic valves, 26 were categorized as functioning normally on the basis of the Doppler and cardiac catheterization evaluation. Nine of these valves were inspected by the surgeon at operation, which was being performed for other reasons (replacement of other valves in seven patients, coronary bypass grafting in one patient, repair of atrial septal defect in one patient); all nine valves were regarded as normal by the surgeon. Seventeen valves were in patients who were thought clinically to have normal-functioning valves and who did not undergo operation.

Seven prosthetic valves were diagnosed as having hemodynamically significant obstruction by both Doppler and cardiac catheterization. Five of these valves were replaced at reoperation (three, tissue valve leaflet calcification; two, mechanical valve thrombosis). Two valves were in patients who were asymptomatic and thought to have a moderate degree of obstruction, for which medical observation was elected.

In nine patients, the prosthetic valves were shown to have hemodynamically significant regurgitation. This condition was diagnosed by contrast angiography in eight instances. The comprehensive two-dimensional and Doppler examination performed before the study had identified seven patients who had valves with significant regurgitation, one of whom underwent reoperation without contrast angiography. Eight of these nine patients underwent reoperation for regurgitation (tissue valve leaflet tear in four and valve dehiscence in four). One patient with moderate regurgitation was treated medically.

Discussion

Previous studies have shown the accuracy of continuous wave Doppler echocardiography for the determination of transvalvular pressure gradients in patients with native valve disease. However, the clinical accuracy of the Doppler technique for determining prosthetic valve gradients has remained controversial. The modified Bernoulli equation (P=4v²) excludes the effects of viscous friction, which is considered negligible in native valves. For the complex and multiple orifices of various prosthetic
valves, this assumption may not be valid. In addition, no comprehensive clinical study has correlated Doppler-derived pressure gradients with simultaneous catheter-derived gradients in a large number of patients with prosthetic valves.

Initial in vitro studies with multiple irregular obstructions\textsuperscript{16} and later prosthetic valves\textsuperscript{17,18} showed good correlation between Doppler-derived and manometric pressure gradients, although the correlation seemed to vary with the type and size of prosthesis in the report of Yoganathan et al.\textsuperscript{17} Thus far, clinical validation studies have been confined to a small number of patients with mitral and tricuspid prostheses. Wilkins et al\textsuperscript{8} reported a close correlation between Doppler- and catheter-derived mean gradients in 13 patients with mitral or tricuspid prostheses. However, studies in patients with aortic prostheses\textsuperscript{10,12} have compared Doppler-derived gradients with nonsimultaneous catheter-derived gradients, and the results have been conflicting. Thus, because of the limited data available and the reported variation in correlation between Doppler- and catheter-derived gradients, we studied a large group of patients with prostheses of various types (mechanical and tissue) and in various intracardiac positions. To show a beat-to-beat and instantaneous relation, we used a dual-catheter technique and a direct-current coupler, which permitted superimposition of calibrated catheter pressures and simultaneously recorded Doppler signals.

The present study documents that continuous wave Doppler echocardiography accurately measures transvalvular pressure gradients across prosthetic valves, irrespective of valve type and position. Both maximal and mean gradients determined by the Doppler technique correlated closely with

**FIGURE 3.** Simultaneous Doppler-catheter pressure recordings from three patients with three different aortic valve types (Panel A: Starr-Edwards; Panel B: Hancock, and Panel C: Björk-Shiley) in whom left ventricular and ascending aortic pressure measurements were obtained with dual-catheter technique. Note close correlation between Doppler- and catheter-derived maximal (max) and mean gradients throughout a broad range of measured gradients. The peak-to-peak (p-p) gradients are lower than both the maximal and the mean gradients.
FIGURE 4.  Correlation between Doppler gradients and simultaneous catheter (cath) gradients for 20 aortic prostheses.  Panel A: Plot of maximal (max) gradients.  Regression equation is Doppler gradient = 1.12 × catheter gradient - 3.9.  Panel B: Plot of mean gradients.  Regression equation is Doppler gradient = 1.01 × catheter gradient - 0.34.  Dotted line, regression line; solid line, line of identity.

The corresponding simultaneous catheter-derived gradients.  As expected, the peak-to-peak gradient calculated for aortic prostheses correlated less well with the maximal and the mean Doppler gradients.  Doppler-derived velocities represent an instantaneous pressure relation and therefore would not be expected to correlate with peak-to-peak gradient, which is obtained by arbitrarily subtracting two nonsimultaneous peak pressures.

This study also showed a significant difference in the correlation between Doppler- and catheter-derived transmitral gradients obtained with pulmonary capillary wedge pressure measurement and between Doppler- and catheter-derived transmitral gradients obtained with direct left atrial pressure measurement.  A previous study by Schoenfeld et al19 showed that use of pulmonary capillary wedge pressure can result in overestimation of the transmitral gradients in patients with mitral prostheses.  They proposed that these findings might be caused by the phase delay of the pulmonary wedge V wave relative to the transseptal V wave, resulting in a higher mean diastolic pressure and higher gradient.  In addition, the pulmonary capillary wedge pressure tracing also lacks the fidelity for rapid acceleration and deceleration, being a reflected pressure.  This might also have contributed to the lack of correlation.  With correction for phase delay, the correlation of mean gradients improved, but the variation between the Doppler and catheter gradients remained significantly greater than that obtained with the transseptal technique.  Our findings further indicate the inaccuracy of using pulmonary capillary wedge pressure to calculate transvalvular gradients in patients with mitral prostheses.

The methods used in this study have several potential limitations.  Doppler examination was performed using a nonimaging transducer without angle correction.  Failure to obtain a small or zero angle between the Doppler beam and transvalvular flow will underestimate the valve gradient.  However, the good correlation between Doppler and catheter gradients obtained in this study shows that a meticulous examination using multiple transducer posi-

<table>
<thead>
<tr>
<th>TABLE 3. Mean Differences Between Doppler and Catheter Gradients for Total Group and Various Subgroups</th>
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<tr>
<td><strong>Mean differences (mm Hg)</strong></td>
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<tr>
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<tr>
<td><strong>Total group (n=42)</strong></td>
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<tr>
<td>Max Dop—max cath gradient</td>
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<tr>
<td>Mean Dop—mean cath gradient</td>
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<td>Max Dop—P-P cath gradient</td>
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<td>Mean Dop—P-P cath gradient</td>
</tr>
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</table>

TS, catheter gradients measured with transseptal technique; PCW (corrected), catheter gradients measured with pulmonary capillary wedge pressure corrected for phase delay; PCW, catheter gradients measured with pulmonary capillary wedge pressure; max, maximal; Dop, Doppler; Cath, catheter; P-P, peak-to-peak.

*p<0.01 compared with mitral (TS) group.
Figure 5. Correlation between Doppler gradients and simultaneous catheter (cath) gradients in 20 aortic valve prostheses. Panel A: Plot of correlation between peak-to-peak catheter gradient and maximal (max) Doppler gradient. Regression equation is Doppler gradient = 1.22 × catheter gradient + 2.2. Panel B: Plot of correlation between peak-to-peak catheter gradient and mean Doppler gradient. Regression equation is Doppler gradient = 0.75 × catheter gradient + 11. Dotted line, regression line; solid line, line of identity.

Figure 6. Correlation between Doppler gradients and simultaneous catheter (cath) gradients in 20 mitral prostheses. PCW, catheter gradients obtained with pulmonary capillary wedge pressure technique; TS, catheter gradients obtained with transseptal technique. Panel A: Plot of maximal (max) gradients. Regression equation (TS) is Doppler gradient = 1.22 × catheter gradient − 3.1. Regression equation (PCW) is Doppler gradient = 0.62 × catheter gradient + 1.5. Panel B: Plot of mean gradients. Regression equation (TS) is Doppler gradient = 1.1 × catheter gradient − 0.7. Regression equation (PCW) is Doppler gradient = 0.34 × catheter gradient + 2.4. Dotted line, regression line; solid line, line of identity.
eters of the same size and length were used to ensure equal phase delay in each pressure tracing.

As in native valve disease, the pressure gradient alone may be insufficient to diagnose prosthetic valve dysfunction in certain clinical situations, such as in patients with left ventricular dysfunction and depressed cardiac output. Recent studies\(^20,21\) have shown that the continuity equation using Doppler flow velocity data can accurately determine aortic valve area in patients with aortic stenosis. However, this method has not been used routinely at our institution for calculating aortic prosthetic orifice area because of, in part, uncertainty regarding the accuracy of the Doppler flow velocity in aortic prostheses. The present study has clearly shown that the Doppler measurement of flow velocity is accurate in both aortic and mitral prostheses and that further study of the Doppler determination of prosthetic orifice area in a large patient population appears indicated.

The present study shows that the calculation of prosthetic valve gradients by continuous wave Dopp-
iner echocardiography provides quantitative hemodynamic information that is comparable in accuracy to that obtained with cardiac catheterization and thus can be substituted safely for cardiac catheterization for the measurement of prosthetic valve gradients. In conjunction with clinical and two-dimensional echocardiographic assessment, this technique should further assist in the noninvasive assessment of prosthetic valve function.

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