Doppler Hemodynamic Profiles of 82 Clinically and Echocardiographically Normal Tricuspid Valve Prostheses

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Background. Normal Doppler hemodynamics for tricuspid prostheses have not been well characterized in a large group of patients. Therefore, we analyzed comprehensive Doppler echocardiographic examinations of 82 patients with tricuspid prostheses that were normal by clinical and two-dimensional echocardiographic examinations to establish the normal hemodynamics of various types and sizes of tricuspid prostheses.

Methods and Results. The earliest complete postoperative echocardiographic study from each patient was chosen for analysis. Doppler examinations were analyzed on an off-line station from tapes or Doppler strip charts. Early velocity, atrial velocity, end-diastolic velocity, pressure half-time, and mean gradient were obtained by digitizing tricuspid velocity curves. The incidence of “physiological” tricuspid prosthetic regurgitation was noted. Ten Doppler cycles were measured for each patient, and maximal, minimal, and average measurements were recorded. The mean values ± SD of early velocity, atrial velocity, end-diastolic velocity, mean gradient, and pressure half-time and incidence of mild prosthetic regurgitation were reported for each type of prosthesis, as were highest Doppler measurements for each valve type. Average pressure half-time was significantly lower for St Jude than for heterograft prostheses (P = .04). There were no significant differences between the valve types for mean gradient, early velocity, or incidence of prosthetic regurgitation. Increasing prosthesis size was associated with lower average pressure half-time for heterograft prostheses (P = .024). Average differences (respiratory- and cycle-length-dependent) between maximal and minimal values for 10 cardiac cycles were established for each prosthesis.

Conclusions. This study establishes normal ranges for Doppler hemodynamics of various tricuspid prostheses and emphasizes the importance of measuring multiple cycles for each tricuspid prosthesis, regardless of cardiac rhythm. (Circulation. 1993;88:2722-2727.)

Key Words • echocardiography • prosthesis

Doppler echocardiography has become the method of choice for assessing prosthetic valve hemodynamics. Valvular prostheses are inherently stenotic compared with native valves. The use of Doppler echocardiography as a tool to screen for pathological obstruction of prosthetic valves necessitates establishment of normal ranges for various prosthesis types and sizes.

Doppler hemodynamics have been validated by comparison with invasive hemodynamics in several different studies that have included a small number of tricuspid prostheses. Doppler mean gradients and effective orifice areas have also been determined for normal aortic and mitral prostheses. However, similar data are available for only a small number of tricuspid valve prostheses.

To establish normal Doppler values for different valve types and to compare different types and sizes of tricuspid prostheses, we reviewed comprehensive Doppler examinations of 82 patients with tricuspid prostheses that were normal by clinical and echocardiography examinations. We established normal ranges for velocity, mean gradient, and pressure half-time.

Methods

Patient Selection

Through the surgical and echocardiography laboratory databases, 82 patients with tricuspid prostheses were identified who met the inclusion criteria, which were (1) clinically normal tricuspid prosthesis (history, physical examination, and echocardiography), (2) adequate Doppler examination, and (3) mild tricuspid regurgitation or less.

Patient Data

There were 57 female and 25 male patients, ranging in age from 3 to 80 years (mean, 45.6 ± 22.2 years). The indications for tricuspid valve replacement were rheumatic heart disease (n = 33), Ebstein’s anomaly (n = 25), other congenital abnormalities (n = 9), idiopathic tricuspid regurgitation (n = 7), and carcinoid heart disease (n = 8).
Doppler study able normal mitral had (linear Braunwald-Cutter); z

Types of tricuspid valve prostheses included 41 heterografts (32 Carpentier-Edwards, 6 Hancock, and 3 Ionescu-Shiley); 33 ball-cage (31 Starr-Edwards and 2 Braunwald-Cutter); 7 St Jude; and 1 Björk-Shiley. Valve size ranged from 25 to 35 mm (Fig 1), and the duration from implantation to the Doppler assessment ranged from 4 days to 22.7 years (mean, 3.1 years) (Fig 2).

In addition to the tricuspid prosthesis, 18 patients had a mitral prosthesis, 21 had mitral and aortic prostheses, 1 had mitral, aortic, and pulmonary prostheses, and 1 had a homograft extracardiac pulmonary conduit. All but 3 nontricuspid prostheses were normal. One patient had an abnormal but unobstructed mitral prostheses (linear thrombus material noted on transthoracic and transesophageal echocardiography). A second patient had a stenotic and insufficient mitral prosthesis and a normal mitral prostheses at the time of the index study. The third patient had abnormal aortic and mitral heterograft at the time of the index study.

The rhythm was sinus in 34 patients (41.5%), atrial fibrillation in 33 (40.2%), paced in 12 (14.6%), nodal in 1, first-degree atrioventricular block in 1, and accelerated junctional in 1. The heart rate ranged from 48 to 119 beats per minute (mean, 80 beats per minute). The blood pressure during Doppler examination was available for 81 patients; the mean was 122/68 mm Hg.

Doppler Measurements

The earliest postoperative two-dimensional and Doppler study for each patient was chosen for analysis.

Continuous-wave Doppler recordings of the tricuspid inflow pattern were made with a 2-MHz nonimaging transducer. Doppler examinations were reviewed on an off-line station (Dextra D-200 Spectral Doppler quantification program) from tapes or Doppler strip charts.

Doppler spectral displays were used for direct measurements of tricuspid early (E) and atrial (A) velocities. The outer edge of the velocity profile was traced, and the mean gradient was automatically calculated by computer from the simplified Bernoulli equation.14,15 By identifying the E velocity and the deceleration slope, the pressure half-time was measured as the time for the E velocity to fall to a level of E velocity divided by 1.4.16

Ten Doppler cycles were measured for each patient, and the maximal, minimal, and average of the 10 values were determined. The difference between maximal and minimal values (Δ) for each of the Doppler measurements was also recorded. The percentage of prosthetic valves with trivial or mild regurgitation was assessed by color flow imaging and continuous-wave Doppler.

Left ventricular ejection fraction (EF) was calculated by a modification of the method of Quinones et al.17 When these measurements were inadequate for EF calculation, a visual estimate of the EF was made.18 The presence and severity of pulmonary regurgitation were noted.

Statistical Analysis

The following patient and valve measurements were compared between valve types and assessed for associations: heart rate, systolic and diastolic blood pressure, cardiac rhythm, EF, pulmonary regurgitation, patient age, body surface area, sex, valve age, symptoms of congestive heart failure, reason for tricuspid valve replacement, and presence of prosthetic regurgitation.

Because the primary interest was assessing the different performance measurements between the valve types, pairwise comparisons were made between the major types with two-sample t tests for continuous measurements and 2 tests for nominal variables. The Björk-Shiley valve was excluded. Assessments of associations between other valve or patient characteristics were based on the Pearson correlation for continuous measurements, Spearman rank correlation for highly skewed or ordinal measurements, and χ² analysis for nominal measurements. ANOVA was used to compare continuous Doppler measurements across nominal patient characteristics (eg, rhythm, cause of valve replacement, or child versus adult). All tests were two-tailed; values of P<.05 were considered statistically significant, and values between .05 and .10 were considered suggestive.

Results

The mean left ventricular EF (n=81) was 54.4±11.6% (range, 23% to 79%). Pulmonary regurgitation was present in 18 patients: trivial in 2, mild in 10, moderate in 2, and severe in 4.

Doppler data for the various prostheses are displayed in the Table and Figs 3 through 5. In 18 patients, there was E-A fusion; for these patients, the combined E and A velocity was included as "E" velocity in our analysis. The average E velocity for heterograft and ball-cage prostheses (1.3±0.2 m/s) was similar to that for the only Björk-Shiley prosthesis (1.3 m/s) and the St Jude prostheses (1.2±0.3 m/s). For the 19 patients in sinus rhythm
Doppler Echocardiographic Data for Various Tricuspid Valve Prostheses

<table>
<thead>
<tr>
<th>Prosthesis</th>
<th>n</th>
<th>Early Velocity, m/s</th>
<th>Mean Gradient, mm Hg</th>
<th>Pressure Half-time, ms* (n)</th>
<th>Regurgitation, %†</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heterograft</td>
<td>41</td>
<td>1.3±0.2</td>
<td>3.2±1.1</td>
<td>146±39 (29)</td>
<td>22.0</td>
</tr>
<tr>
<td>Ball-cage</td>
<td>33</td>
<td>1.3±0.2</td>
<td>3.1±0.8</td>
<td>144±46 (29)</td>
<td>9.1</td>
</tr>
<tr>
<td>St Jude</td>
<td>7</td>
<td>1.2±0.3</td>
<td>2.7±1.1</td>
<td>108±32 (6)</td>
<td>28.6</td>
</tr>
<tr>
<td>Björk-Shiley</td>
<td>1</td>
<td>1.3</td>
<td>2.2</td>
<td>144</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>82</td>
<td>1.3±0.2</td>
<td>3.1±1.0</td>
<td>142±42 (65)</td>
<td>17.1</td>
</tr>
</tbody>
</table>


*Pressure half-time not measured in patients with fusion of the early and atrial velocities.
†Percentage of tricuspid prostheses with mild regurgitation or less.

without E and A fusion (Fig 2), the average A velocities were 1.0±0.3 m/s for ball-cage, 1.0±0.2 m/s for heterograft, and 1.0±0.3 m/s for St Jude prostheses. There was no significant difference of A velocity among valve types. The average mean gradient was similar for heterograft and ball-cage prostheses (3.2±1.1 and 3.1±0.8 mm Hg, respectively) and was lower for both the St Jude and the Björk-Shiley prostheses (2.7±1.1 and 2.2 mm Hg, respectively); however, this difference did not reach statistical significance.

The mean pressure half-time in 65 patients (excluding patients with E and A fusion) was significantly lower for St Jude prostheses (108±32 milliseconds) than for heterografts (146±39 milliseconds) (P = .032) and tended toward being lower for ball-cage prostheses (144±46 milliseconds) (P = .082). The percentage of valves with trivial or mild regurgitation was highest for St Jude (28.6%) and lowest for ball-cage prostheses (9.1%). (The Björk-Shiley valve was not regurgitant.)

There were 10 patients between 3 and 15 years of age. There were no significant differences between the younger group and the adult group with regard to any of the Doppler measurements.

When the Doppler data were correlated with valve size (within each valve type), it was found that increasing heterograft size was associated with decreasing average pressure half-time (P = .024). There was also a trend between increasing size of St Jude and ball-cage prostheses and decreasing average mean gradient (P = .089 and .080, respectively).

The average differences between maximal and minimal values (Δ) for 10 consecutive measurements of each Doppler variable were established for each of the prostheses. Beat-to-beat differences were a result of both respiratory and cycle-length variation. There were no significant differences among the various prosthetic valve types for Δ E velocity, Δ mean gradient, or Δ pressure half-time. As a group, the Δ were as follows: Δ E velocity = 0.5±0.2 m/s, Δ mean gradient = 2.3±1.0 mm Hg, and Δ pressure half-time = 81.7±37.2 milliseconds.

Beat-to-beat variability can occasionally lead to individual cycle lengths with mean gradients or pressure half-times that are usually associated with significant obstruction. For instance, a 7-year-old girl with a heterograft tricuspid prosthesis had mean gradient as high as 8.4 mm Hg and E velocity as high as 2.1 m/s during inspiration. However, averaged over 10 cycles, the mean gradient was 5.0 mm Hg and the E velocity was 1.6 m/s. This underscores the importance of averaging multiple cardiac cycles when obtaining Doppler hemodynamics for all patients with tricuspid prostheses.

Several significant findings were noted when Doppler measurements were compared with patient and valve variables. Average pressure half-time was significantly

![Fig 3](image-url) Graph showing early velocity for each type of tricuspid valve prosthesis (H, heterograft; BC, ball-cage; SJ, St Jude; BS, Björk-Shiley). Solid horizontal line represents the mean for each valve type; hatched box represents 1 SD; vertical line represents the highest and lowest mean values. There are no statistically significant differences between the early velocities of various prosthesis types.

![Fig 4](image-url) Graph showing mean gradient for each type of tricuspid valve prosthesis (H, heterograft; BC, ball-cage; SJ, St Jude; BS, Björk-Shiley). Solid horizontal line represents the mean for each valve type; hatched box represents 1 SD; vertical line represents the highest and lowest mean values. There were no statistically significant differences between the mean gradients of the prosthesis types.
longer with increasing valve age ($P = .03$), increasing diastolic blood pressure ($P = .05$), and decreasing heart rate ($P < .001$). The Δ pressure half-time was greater with increasing left ventricular EF ($P = .041$) and with decreasing heart rate ($P = .013$). Mean pressure half-time was significantly ($P = .007$) different for sinus rhythm (118 ± 47 milliseconds) compared with either atrial fibrillation (149 ± 37 milliseconds) or paced rhythm (156 ± 26 milliseconds). There was also a tendency toward differences in average $E$ velocity ($P = .053$), sinus rhythm (1.24 ± 0.20 m/s) tending to be lower than either atrial fibrillation (1.35 ± 0.20 m/s) or paced rhythm (1.41 ± 0.16 m/s).

Four of the patients with carcinoid heart disease had severe pulmonary regurgitation at the time of the index study. This had no significant effect on mean gradient, pressure half-time, or maximum $E$ velocity compared with patients without significant pulmonary regurgitation. No patient with significant pulmonary stenosis was included in this study.

**Discussion**

Doppler echo is a valuable tool in the evaluation of prosthetic heart valves. Complete assessment requires integration of data from two-dimensional, M-mode, spectral Doppler, and flow imaging. All prostheses are intrinsically obstructive. Continuous-wave Doppler evaluation of prosthetic valve gradients has been validated with simultaneous Doppler-catheter studies by Wilkins et al., Burstow et al., and Kapur et al. For mitral and aortic prostheses, excellent correlation was demonstrated between mean gradient obtained by manometry and those obtained by continuous-wave Doppler. Close correlation was also demonstrated for the small number of tricuspid prostheses in the first two studies.

Establishment of normal Doppler hemodynamic values requires study of a large number of prostheses because the hemodynamics vary with valve position, type, and size. Normal Doppler velocities and gradients for mitral and aortic prostheses have been reported previously, but very few normative data have been available for tricuspid prostheses. Our study has supplied Doppler data for a larger group of patients with normal tricuspid prostheses. By including patients with trivial or mild degrees of regurgitation, we have allowed for normal closure or leakage volumes or both. However, we excluded prostheses with greater degrees, because significant regurgitation per se can influence forward-flow hemodynamics.

In contrast to previous reports of mitral prostheses, we found no significant correlations between the type of tricuspid valve prosthesis and mean gradient or $E$ velocity. The trend for mean gradient was similar to that previously reported for mitral prostheses; ie, the average mean gradient for ball-cage prostheses was higher than for St Jude prostheses. Although this difference was not statistically significant, the sample size available may not have been large enough to detect important differences between these groups. The pressure half-time of heterograft prostheses was significantly higher than that of St Jude prostheses, corresponding with findings for mitral prostheses.

When prosthesis size was analyzed, a significant correlation was found in each valve type. Overall, increasing prosthesis size was associated with lower Doppler measurements. Increasing heterograft size was significantly associated with decreasing average pressure half-time ($P = .024$). Increasing ball-cage size tended to be associated with a decreased average $E$ velocity ($P = .080$), and increasing St Jude size tended toward a decreased average mean gradient ($P = .089$). However, because numbers of prostheses in each size grouping were small and the hemodynamic trends, according to valve size, were also small, we chose to combine all sizes when displaying the normal ranges for each type of tricuspid prosthesis (Figs 3 through 5).

We chose to report the pressure half-time for each of these tricuspid valve prostheses without converting them to effective orifice areas for two reasons. First, the constant that Hatle et al. introduced for mitral stenosis (constant = 220) has never been validated for the tricuspid valve. Second, the validity of using this constant for mitral prostheses has been questioned by Dumesnil et al. on the basis of their comparison of mitral prosthesis effective orifice area determined by in vivo continuity and pressure half-time methods versus effective orifice area determined for similar prostheses in vitro. In our laboratory, we currently report the pressure half-time for tricuspid prostheses as a separate measurement because, in general, it will be inversely related to the degree of obstruction. We calculate the effective orifice areas for tricuspid prostheses from the continuity equation. However, during the time span of this study, we were not routinely measuring the left ventricular outflow tract diameter and time velocity integral for patients with tricuspid prostheses. Therefore, we cannot retrospectively calculate the prosthetic effective orifice area by the continuity equation for this group of patients.

Beat-to-beat changes in flow and gradient across tricuspid prostheses result not only from changing cycle length but also from respiration (Figs 6 and 7). This creates a potential pitfall. If a single cycle, occurring at peak inspiration, is measured and reported as representative, then the clinician may be given a false impression that the prosthesis is abnormally obstructed. In addition, an isolated cycle obtained during respiration or with held respiration does not represent the physiolog-
Fig 6. Continuous-wave Doppler velocity spectrum from a patient with a 4M Starr-Edwards tricuspid valve prosthesis. The respiratory variation for the mean gradient (MG) and pressure half-time (PH) are demonstrated during six consecutive beats in normal sinus rhythm.

Fig 7. Continuous-wave Doppler velocity spectrum from a patient in atrial fibrillation with a 4M Starr-Edwards valve prosthesis. Respiratory variation in the mean gradient (MG) is demonstrated. Lower line is recorded from a heat-sensitive nasal respirometer and verifies that the maximal mean gradient occurs with inspiration (insp) and decreases with expiration (exp).

ical situation presented to the right atrium. The mean gradient that the right atrium works against to fill the right ventricle is the average gradient throughout the respiratory cycle (Fig 7). On the basis of our data, we recommend that at least 10 cycles be measured for tricuspid valve prostheses, even for patients in sinus rhythm. For these 10 cycles, average values for E velocity, mean gradient, and pressure half-time should be reported.

The hemodynamic data that we have obtained for clinically normal tricuspid prostheses are most useful with patients who have not undergone a baseline Doppler study after tricuspid valve replacement. It is still the best strategy to obtain a baseline study within 6 weeks of prosthesis implantation. This study will serve as a “fingerprint” for future comparison and is particularly useful if problems develop, such as right-sided heart failure, that may or may not be related to the prosthesis.

Study Limitations
Ideally, normal hemodynamics of tricuspid prostheses should be determined prospectively during the first month after implantation. This is particularly true for tissue prostheses, because degeneration will eventually occur, with an increasing likelihood of dysfunction with increasing prosthesis age. However, it is notable that hemodynamics for the oldest prostheses in our series were not significantly different from those studied in the
early postoperative period. This supports the contention that we have selected normal prostheses for analysis. Another limitation of this study is that transesophageal echocardiography was not used to assess the degree of prosthetic regurgitation. However, patients included in this study not only had no evidence of significant tricuspid regurgitation by surface echo but also had no clinical findings for tricuspid regurgitation. Therefore, it is highly unlikely that any patients with significant tricuspid regurgitation were included.

Finally, the interpretation of the hemodynamics observed for the Björk-Shiley and St Jude prostheses is limited by the small numbers. This underscores the importance of continuing to acquire normal prosthetic valve Doppler echocardiography data prospectively.

Conclusions

Figs 3 through 5 illustrate that for each type of tricuspid prosthesis, there were patients who were clinically normal but had hemodynamics that were more than 1 SD from the mean. There were 10-cycle average values as high as 5.3 mm Hg for mean gradient and 238 milliseconds for pressure half-time. We suspect that this simply represents patient-prosthesis mismatch. For patients with mean gradients and pressure half-times significantly greater than 5.3 mm Hg and 238 milliseconds, respectively, or for patients with increasing obstruction on serial studies, pathological stenosis of the tricuspid prosthesis must be seriously considered.

Our study establishes normal ranges for Doppler hemodynamics of various tricuspid valve prostheses. It also underscores the importance of measuring multiple cycles for each tricuspid prosthesis, regardless of cardiac rhythm.

References

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