Hemodynamic predictors of outcome in patients undergoing valve replacement

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ABSTRACT The afterload-corrected end-systolic volume index (ratio of end-systolic stress to end-systolic volume index [ESS/ESVI]) was previously useful in predicting outcome in patients with mitral regurgitation undergoing valve replacement. Therefore we tested ESS/ESVI together with standard hemodynamic variables as possible predictors of outcome in 39 patients with various valvular lesions who underwent valve replacement. Thirteen patients had preoperative mitral regurgitation, 16 had aortic stenosis, nine had aortic regurgitation, and one had mitral stenosis. Twenty-seven patients (group S) had a satisfactory outcome as defined by a return to NYHA class I or II together with a normal postoperative ejection fraction. Twelve patients who died, remained in class III or IV, or had a subnormal postoperative ejection fraction were deemed to have an unsatisfactory result (group U). Mean right atrial pressure, pulmonary arterial pressure, pulmonary capillary wedge pressure, end-diastolic volume index, end-systolic volume index (ESVI), and end-systolic wall stress were all greater in group U, whereas ESS/ESVI and ejection fraction were lower in group U. When these and other factors were submitted to stepwise discriminant multivariate analysis, ESS/ESVI and ESVI were the only independent predictors of outcome. However, when patients with mitral regurgitation (who might have biased the study) were excluded, discriminant analysis showed ESVI as the only independent predictive variable. We conclude that end-systolic indicators of ventricular function are superior to other standard hemodynamic variables in predicting outcome of valve replacement.

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PREOPERATIVE left ventricular function is generally accepted as an important determinant of the outcome of valve replacement surgery.1 Thus accurate assessment of left ventricular function is important in preoperative patient evaluation. Unfortunately, standard ejection phase indexes of left ventricular function such as ejection fraction are altered by the abnormalities in preload and afterload that usually accompany valvular heart disease. It is not surprising, therefore, that ejection phase indexes have been shown to overestimate or underestimate ventricular function in patients with valvular heart disease according to the loading abnormalities present.1-5 Thus a measure of left ventricular function that is independent of or accounts for loading conditions should be superior to ejection phase indexes in predicting surgical outcome. End-systolic volume is independent of preload and varies directly and linearly with afterload.6-10 Correcting end-systolic volume for afterload and body size could yield an index of ventricular function that would be less influenced by loading than would ejection phase indexes. We postulated that such an index would be useful in the preoperative evaluation of patients with valvular heart disease. In a previous study of patients with mitral regurgitation, end-systolic volume index corrected for wall stress (i.e., the ratio of end-systolic wall stress to end-systolic volume index [ESS/ESVI]) was superior to other preoperative hemodynamic and angiographic measurements in predicting surgical outcome.3 We wished to assess the usefulness of this index in predicting surgical outcome of valve replacement in patients with valvular heart disease whether the lesion was stenotic or regurgitant or involved the mitral or aortic valve. Therefore this study was conducted to test the ESS/ESVI as a predictor of outcome in patients with valvular heart disease.

Methods

Patients and experimental design. Angiograms and pressure tracings from all 74 patients who underwent single, first
valve replacement from June 1, 1980, to September 1, 1985, at Temple University were evaluated for study. Patients were excluded from the study if (1) there was obstructive coronary disease reducing vessel luminal diameter by 50% or more (15 patients), (2) angiographic images did not permit adequate edge detection for the determination of ventricular volumes and/or thickness (12 patients), or (3) there were not two consecutive sinus beats or, if the patient had atrial fibrillation, there were not two consecutive nonectopic beats during angiography. Premature beats and premature beats were excluded from evaluation (eight patients).

The remaining 39 patients composed the study group. Of these, 13 had mitral regurgitation, 16 had aortic stenosis, one had mitral stenosis, and nine had aortic regurgitation. After identification, the previously obtained preoperative catheterization and angiographic data were analyzed by two independent observers who were blinded to the results of any follow-up data. Preoperative clinical classification was determined from the attending cardiologist’s evaluation that had been recorded at the time of admission for preoperative catheterization. After the retrospective determination of preoperative status, a prospective follow-up was performed consisting of interview, physical examination, and radionuclide ventriculography. The investigators were blinded to all postoperative data when preoperative clinical and hemodynamic status was evaluated. Patient follow-up was available in all 39 patients. Six patients died in the postoperative period with congestive heart failure. The remaining 33 patients underwent follow-up study.

**Analysis of catheterization data.** Right atrial pressure, pulmonary arterial pressure, pulmonary capillary wedge pressure, aortic pressure, and left ventricular end-diastolic pressure were obtained through properly damped fluid-filled catheters in each patient. Cardiac outputs were calculated with computer-assisted analysis of dye dilution curves.

Cardiac volumes were obtained from single-plane cineangiograms filmed in the right anterior oblique position at 60 frames/sec. Volumes were calculated by the area-length method and were corrected by the regression equation derived by Wynne et al. End-systole was defined angiographically as the smallest ventriculographic volume in the cycle and hemodynamically as the point of the aortic dicrotic notch. We recognize that neither of these points may represent end-systole as defined by peak elastance (especially in mitral regurgitation). They were chosen because they are easily and accurately defined and applied. Seven patients were in atrial fibrillation and 32 were in sinus rhythm. In patients in atrial fibrillation, 3 beats were averaged to obtain the end-diastolic and end-systolic volumes. Volumes were indexed for body surface area in all patients.

Ejection fraction was calculated in the standard manner. Mean velocity of circumferential fiber shortening (VcF) was calculated as:

\[
VcF = \frac{EDD - ESD}{EDD \times ET}
\]

where \( EDD \) = end-diastolic minor-axis dimension, \( ESD \) = end-systolic minor-axis dimension, and \( ET \) = ejection time. Minor dimension was calculated as \( D = 4A/\pi L \) where \( A \) = area and \( L \) = length. Ejection time was measured from the beginning of the upstroke of the aortic pressure tracing to the nadir of the dicrotic notch. End-systolic wall stress was calculated by Mirsky’s formula:

\[
Stress = \frac{P \cdot b}{h} \cdot \left[ 1 - \frac{h}{2b} - \frac{b^2}{2a^2} \right] \times 1332 \text{ dyne/cm}^2
\]

where \( P = \) end-systolic pressure, \( h = \) end-systolic wall thickness, \( b = \) end-systolic semimajor axis (ESD + ESh)/2, and \( a = \) end-systolic semimajor axis (ESL + ESh)/2. End-systolic pressure was taken at the dicrotic notch of the aortic pressure tracing immediately before ventriculography. End-systolic wall thickness was calculated from end-diastolic wall thickness using the amount of shortening and the assumption that left ventricular wall mass is constant throughout systole. Echocardiograms were available in 20 of the 39 patients for corroboration of measured end-diastolic wall thickness. Angiographically determined anterior wall thickness and echocardiographically determined posterior wall thickness were remarkably concordant and did not vary by more than 1 mm in the 16 patients in whom echocardiographic wall thickness was discernible. Ejection fraction, VcF, and stress data allowed for construction of the stress-shortening relationship.

Pressures were recorded nonsimultaneously just before ventriculography. In patients in atrial fibrillation, RR intervals preceding the beats used for volume determination were matched to similar RR intervals from the pressure tracings. End-systolic pressures and volumes were thus obtained from beats matched by their RR intervals. RR intervals varied from 0.66 to 0.92 sec.

All ventriculograms were measured twice by two independent observers blinded to each other’s results as well as to the follow-up data. Interobserver variability averaged 17 ± 7 cc for end-diastolic volume and 5 ± 2 cc for end-systolic volume. Volumes were recorded as the average of the observations of both observers.

Quantification of postoperative left ventricular performance was made by radionuclide ventriculography as follows: The patients’ red blood cells were labeled in vivo with 20 mCi (740 MBq) of Tc-99m pertechnetate 20 min after intravenous administration of stannous pyrophosphate. Four to five minutes after injection with the pertechnetate, 40 to 45 degree left anterior oblique gated equilibrium images were acquired in byte mode in a 64 x 64 matrix until 300,000 counts were collected in at least one of 16 frames of the cardiac cycle. The scintillation camera was peaked for Tc-99m with a 25% window and fitted with a low-energy parallel-hole collimator. Data were acquired with a commercial nuclear medicine computer system. Left ventricular ejection fraction was obtained from the left anterior oblique gated blood-pool images with a semiautomated computer program (MUGE, Medical Data Systems) that generates a region of interest around the left ventricle based on a combination second-derivative and count-threshold algorithm. These left ventricular counts were then corrected for background with a region of interest adjacent to the left ventricle. If necessary, operator intervention could be used to reposition the background region to avoid vascular structures. The ejection fraction was then calculated as (end-diastolic counts - end-systolic counts)/end-diastolic counts.

**Analysis of outcome.** Preoperative clinical, hemodynamic, and angiographic variables were analyzed as to their prognostic importance. Outcome was assessed as satisfactory (group S) if patients returned to NYHA class I or II and had a radionuclide ejection fraction of 0.45 or higher, the lowest limit of normal in our laboratory. Since load is returned toward normal by ablation of the valvular lesion, ejection fraction is a reasonable indicator of postoperative ventricular function.7 No patient had clinical evidence of a paravalvular leak, although Doppler confirmation was not available to prove the complete absence of valvular regurgitation. Results were classified as unsatisfactory (group U) if patients died of cardiac causes, remained in class III or IV, or had a radionuclide ejection fraction of less than 0.45. Only one patient had a discrepancy between clinical and radionuclide angiographic outcome by these criteria. This patient was in class II but had a postoperative ejection fraction of 0.24 and was
included in group U. Analysis of the data was performed in
three separate groupings. First, all 39 patients were analyzed to
determine which preoperative factors had prognostic signifi-
cance. However, because we demonstrated in a previous study3
the usefulness of ESS/ESVI in patients with mitral regur-

gitation, the presence of 13 patients with mitral regurgitation in
this study could have biased our results in favor of finding
ESS/ESVI a significant variable. Therefore we also analyzed
the whole group of 39 patients, end-systolic volume
index (ESVI) and ESS/ESVI had independent prognostic
significance. With these factors, the equation 1.79 ESS/ESVI − 0.042
ESVI + 2.28 predicted a good outcome when the resultant value was a positive
number. This equation predicted outcome correctly
(overall accuracy) in 33 of the 39 (85%) patients, with
five false bad-outcome predictions and one false good-

**Surgical technique.** Thirty of the 39 valve replacements
were performed by the same cardiac surgeon, providing reason-
able consistency of technique. All patients received intraop-
erative cold hyperkalemic cardiopleic solution. Cross-clamp time
for group S was 69 ± 7 min and that for group U was 64 ± 3
min (p = NS). No patient had electrocardiographic or enzymat-
e evidence of intraoperative myocardial infarction. Mitral
valve replacement was performed after resection of the native
valve including the chordae tendineae.

**Normal stress-shortening relationship.** The normal stress-
ejection fraction and stress-VcF relationships were derived from
20 patients who were catheterized for chest pain atypical of
myocardial ischemia and who subsequently were found to have
normal coronary arteriograms. All had normal ejection fraction,
VcF, and left ventricular end-diastolic pressure. None had a left
ventricular wall thickness of greater than 1.0 cm or mitral valve
prolapse.

**Statistics.** Univariate analysis between groups S and U was
performed with the unpaired t test as well as with the more
stringent Bonferroni test. Attributes were compared with
Fischer’s exact test. When ejection fraction was compared pre-
operatively and postoperatively, a paired t test was used. To
find which variables had independent prognostic significance,
linear multivariate stepwise discriminant analysis was per-
fomed. Linear regression by least squares was performed to
obtain the relationship of end-systolic stress to ejection fraction
and to VcF. Ninety-five percent prediction bands were then
obtained. For all results, dispersion from the mean is reported as
± SEM. Variables were considered to be different at the p ≤ .05
level.

**Results**

Six patients, two with preoperative mitral regur-
gitation, three with preoperative aortic stenosis, and one
with preoperative aortic regurgitation, died in congest-
ive heart failure in the perioperative period. Follow-
up for the remaining 33 patients averaged 18 ± 6
months (table 1). Twenty-seven patients (69%) had a
satisfactory outcome (group S) and 12 (31%) had an
unsatisfactory outcome (group U). Seven of 13 (54%)
patients with mitral regurgitation, seven of nine pa-
tients with aortic regurgitation (78%), and 13 of 16
patients (81%) with aortic stenosis were in group S.

Variables and attributes examined for differences
between groups S and U for the entire group are shown
in table 2. Tables 3 and 4 display these same variables
for 13 patients with mitral regurgitation (table 3) and
for the group of 26 patients who had lesions other than
mitral regurgitation (table 4). When these factors were
subtracted from stepwise discriminant variant analysis for

### TABLE 1

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<tr>
<th>Patient</th>
<th>Age (yr)</th>
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<th>Postop. NYHA class</th>
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AR = aortic regurgitation; AS = aortic stenosis; MR = mitral
regurgitation; MS = mitral stenosis; D = cardiac death; EF = ejection
fraction.
outcome prediction. Thus a positive test (equation predicts a bad outcome) detected 11 of 12 patients with a bad outcome (91% sensitivity). A negative test (equation predicts a good outcome) predicted a good outcome in 22 of 27 patients (81% specificity) with a good outcome. Figure 1 displays ESS/ESVI and ESVI for the 39 patients. Discriminant analysis for the 26 patients without mitral regurgitation found ESVI to be the only independent variable predictive of outcome. The equation 19.10 – 0.179 ESVI predicted outcome correctly in 23 of 26 patients (88% accuracy), with one false good-outcome prediction and two false bad-outcome predictions (sensitivity 83%, specificity 90%). For the 13 patients with mitral regurgitation, ESS/ESVI was the only independent predictor of outcome, and the equation 85.11 ESS/ESVI – 224 accurately separated group S from group U for all 13 patients. As shown in figure 1, patients with mitral regurgitation and ESS/ESVI of less than 2.6 had a poor surgical outcome. Recent studies emphasize that large end-systolic volume (and thus low ESS/ESVI) could simply represent adaptive eccentric hypertrophy instead of failure of the ventricle to shorten normally.\textsuperscript{18} Correction of end-systolic volume by multiplying by end-diastolic volume has been recommended.\textsuperscript{18} However, when ESS/ESVI was corrected for end-diastolic volume, discriminant analysis did not find it to be an independent predictor of outcome.

Preoperative and postoperative ejection fraction is shown in figure 2 for patients with mitral regurgitation, aortic stenosis, and aortic regurgitation. Ejection fraction for patients with mitral regurgitation fell from 0.55 ± 0.05 preoperatively to 0.45 ± 0.06 postoperatively (p < .05). Ejection fraction in patients with

### TABLE 2

Univariate analysis of predictors of outcome: all patients

<table>
<thead>
<tr>
<th>predictor</th>
<th>Group S (n = 27)</th>
<th>Group U (n = 12)</th>
<th>P</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>NYHA class</td>
<td>2.9 ± 0.11</td>
<td>3.3 ± 0.014</td>
<td>&lt;.05</td>
<td>NS</td>
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<tr>
<td>Age (yr)</td>
<td>59.4 ± 2.5</td>
<td>59.8</td>
<td>NS</td>
<td>NS</td>
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<tr>
<td>Cardiac index (l/min/m(^2))</td>
<td>2.5 ± 0.1</td>
<td>2.2 ± 0.15</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>Mean VcF (circ./sec)</td>
<td>0.88 ± 0.08</td>
<td>0.63 ± 0.10</td>
<td>NS</td>
<td>NS</td>
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<td>Mean right atrial pressure (mm Hg)</td>
<td>8 ± 0.7</td>
<td>12.3 ± 1.8</td>
<td>&lt;.01</td>
<td>NS</td>
</tr>
<tr>
<td>Mean pulmonary arterial pressure (mm Hg)</td>
<td>29 ± 2.2</td>
<td>38.1 ± 2.5</td>
<td>&lt;.05</td>
<td>NS</td>
</tr>
<tr>
<td>Mean pulmonary wedge pressure (mm Hg)</td>
<td>20.7 ± 1.6</td>
<td>27.8 ± 1.8</td>
<td>&lt;.05</td>
<td>NS</td>
</tr>
<tr>
<td>EDVI (cc/m(^2))</td>
<td>123 ± 9</td>
<td>208 ± 29</td>
<td>&lt;.001</td>
<td>&lt;.01</td>
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<tr>
<td>ESVI (cc/m(^2))</td>
<td>56 ± 6</td>
<td>131 ± 20</td>
<td>&lt;.001</td>
<td>&lt;.01</td>
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<tr>
<td>EF</td>
<td>0.56 ± 0.03</td>
<td>0.36 ± 0.04</td>
<td>&lt;.01</td>
<td>&lt;.05</td>
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<tr>
<td>ESS (kdyn/cm(^2))</td>
<td>145 ± 11</td>
<td>200 ± 15</td>
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<td>NS</td>
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<tr>
<td>ESS/ESVI [kdyn/cm(^2)/cc/m(^2)]</td>
<td>3.06 ± 0.2</td>
<td>1.66 ± 0.14</td>
<td>&lt;.001</td>
<td>&lt;.01</td>
</tr>
</tbody>
</table>

P = results of t test; B = results of t test followed by Bonferroni inequality test; EDVI = end-diastolic volume index; EF = ejection fraction; ESS = end-systolic stress.

### TABLE 3

Univariate analysis of predictors of outcome: patients with mitral regurgitation

<table>
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<tr>
<th>predictor</th>
<th>Group S (n = 7)</th>
<th>Group U (n = 6)</th>
<th>P</th>
<th>B</th>
</tr>
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<tr>
<td>NYHA class</td>
<td>2.7 ± 0.18</td>
<td>3.3 ± 0.2</td>
<td>&lt;.05</td>
<td>NS</td>
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<tr>
<td>Age (yr)</td>
<td>59.4 ± 4.1</td>
<td>59.6 ± 4.3</td>
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<td>Cardiac index (l/min/m(^2))</td>
<td>2.4 ± 0.1</td>
<td>2.1 ± 0.2</td>
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<td>NS</td>
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<tr>
<td>Mean VcF (circ./sec)</td>
<td>0.77 ± 0.1</td>
<td>0.63 ± 0.1</td>
<td>NS</td>
<td>NS</td>
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<tr>
<td>Mean right atrial pressure (mm Hg)</td>
<td>7.3 ± 2</td>
<td>14 ± 3.5</td>
<td>NS</td>
<td>NS</td>
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<tr>
<td>Mean pulmonary arterial pressure (mm Hg)</td>
<td>29.7 ± 4.0</td>
<td>38.8 ± 2.1</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>Mean pulmonary wedge pressure (mm Hg)</td>
<td>21.7 ± 3.5</td>
<td>26.8 ± 2.0</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>EDVI (cc/m(^2))</td>
<td>124 ± 11</td>
<td>184 ± 22</td>
<td>&lt;.05</td>
<td>NS</td>
</tr>
<tr>
<td>ESVI (cc/m(^2))</td>
<td>44 ± 8</td>
<td>109 ± 13</td>
<td>&lt;.01</td>
<td>NS</td>
</tr>
<tr>
<td>EF</td>
<td>64 ± 0.06</td>
<td>0.40 ± 0.03</td>
<td>&lt;.01</td>
<td>&lt;.05</td>
</tr>
<tr>
<td>ESS (kdyn/cm(^2))</td>
<td>143 ± 24</td>
<td>210 ± 27</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>ESS/ESVI [kdyn/cm(^2)/cc/m(^2)]</td>
<td>3.3 ± 0.2</td>
<td>1.93 ± 0.15</td>
<td>&lt;.001</td>
<td>&lt;.05</td>
</tr>
</tbody>
</table>

Abbreviations as in table 2.
aortic regurgitation rose from 0.50 ± 0.03 to 0.59 ± 0.06 (p < .05). For those with aortic stenosis, ejection fraction rose from a preoperative value of 0.53 ± 0.06 to a postoperative value of 0.69 ± 0.03 (p < .01).

The ejection fraction–end-systolic stress and VcF-end-systolic stress relationships have been proposed as indexes of contractile function.14-16 We therefore examined these relationships in our patients as compared to the same relationships and 95% predictive limits for normal subjects. Although many patients in both groups fell outside the predictive limits of normal, this method failed to separate group S from group U as shown in figure 3.

Discussion

It is generally believed that preoperative ventricular dysfunction is a key determinant of surgical outcome in patients with valvular heart disease. However, the load alteration in valvular heart disease affects ejection phase indexes such as ejection fraction and VcF, yielding inaccurate measurements of ventricular function. Therefore end-systolic indexes of contractile function that are independent of or account for loading conditions have been advocated in situations where load is altered.19 Thus Borow et al.20 found end-systolic volume index alone to be a better predictor of outcome in valvular regurgitation than ejection fraction. The ratio of end-systolic stress to end-systolic volume is independent of preload and, although partially afterload dependent and inferior to peak elastance (Emax),21 is a potentially useful indicator of contractile function.3 In previous studies, ESS/ESVI was concordant with Emax, a more widely accepted measure of contractile function.22,23 In another study, ESS/ESVI separated patients with mitral regurgitation who had a good surgical outcome from those with a poor outcome.3 Recently these results were corroborated by Jue et al.,24 who found that preoperative ESS/ESVI correlated well with cardiac performance after mitral valve replacement. Thus it seemed appropriate to test ESS/ESVI in a study of other types of valvular heart disease.

An important finding in this study was that ESS/ESVI was confirmed in a blinded fashion as a useful predictor of outcome in patients with mitral
regurgitation. An ESS/ESVI of less than 2.6 indicated a poor prognosis. A high ESS/ESVI was a good prognostic sign, suggesting good contractile function and left ventricular shortening to a small volume for a given load. However, when patients with lesions other than mitral regurgitation were examined, ESVI alone was the best indicator of outcome. Seven patients without mitral regurgitation whose ESS/ESVI was low (<2.5) ultimately had a satisfactory outcome. This may have occurred because end-systolic stress was less reflective of peak and mean systolic stress in aortic stenosis and aortic regurgitation, in which left ventricular systolic peak pressure is higher than normal. If this were the case, end-systolic stress could underestimate total afterload, causing the ratio of stress to volume to be low and suggesting poorer contractile function than was actually present.

Another cause for the mistaken predictions is the possibility that changes in contractile function occurred after surgery. Implicit in our study and others like it is the assumption that preoperative left ventricular contractile dysfunction persists postoperatively and is a major cause of poor outcome. However, if contractile function improves after surgery, indexes dependent on preoperative contractile dysfunction would erroneously predict a poor outcome. Most of our mistaken predictions were of a falsely predicted poor outcome. Of the five patients falsely predicted to do poorly, two had aortic stenosis and three had aortic regurgitation. Since several studies have shown improvement in ventricular function after surgery for these lesions, it is possible that such improvement occurred in our patients.25–28 Another possibility is that these indexes simply do not always reflect preoperative inotropic state. The simple ratio of ESS/ESVI is an empiric device used to correct end-systolic volume

FIGURE 2. Preoperative and postoperative ejection fraction for patients with mitral regurgitation (MR), aortic regurgitation (AR), and aortic stenosis (AS).

FIGURE 3. Stress shortening relationships and 95% prediction bands plotted from 20 normal subjects. Ejection fraction (EF) is plotted against end-systolic stress (ESS) in the left panel, and mean VcF is plotted against ESS in the right panel. Open circles represent group S patients; closed triangles represent group U patients. Although values for several patients from both groups fall down to the left of the normal range, indicating reduced shortening for any given afterload, this technique did not separate group S from group U.
(previously shown to be predictive of outcome\textsuperscript{20}) for the afterload present at end-systole and for body size. The ratio, which does not take $V_e$ into account, is not a substitute for $E_{\text{max}}$.\textsuperscript{19} Since no clinical “gold standard” of inotropic state is currently available, we could not assess this possibility independently.

Recent investigation suggests that end-systolic volume could increase as the number of sarcomeres in series increases during hypertrophy.\textsuperscript{18} In this case, increased end-systolic volume and thus reduced ESS/ESVI could occur without indicating decreased contractile force. Correction for ventricular size by multiplying by end-diastolic volume has been suggested as a means of dealing with this problem.\textsuperscript{18} However, when we corrected ESS/ESVI by multiplying by end-diastolic volume, discriminant analysis did not find corrected ESS/ESVI to be an independent predictor of outcome.

Finally, if differences in postoperative clinical outcome were not caused by differences in preoperative muscle function, then ESS/ESVI, even if it is an accurate indicator of preoperative contractile function, would not predict outcome. Although we cannot address this point directly, all postoperative negative clinical outcomes in our study were caused by heart failure. Since there was no evidence of intraoperative ventricular damage or of postoperative valve dysfunction, it seems likely that preoperative muscle dysfunction was the most likely cause of postoperative heart failure.

We and others have suggested that the ejection fraction–end-systolic stress or VcF–end-systolic stress relationship is useful in separating contractile function from loading conditions.\textsuperscript{14–16} Although most of our patients had lower afterload-corrected ejection fraction or VcF than normal subjects, these relationships did not separate group U patients from group S patients satisfactorily. If it was the degree of depression in contractile state that resulted in the poor results in group U, as seems likely, it may be that these methods, although able to perceive a reduction in contractile state, are unable to perceive the degree of contractile depression.

**Limitations.** Our study of a relatively small number of patients included all patients with valvular heart disease who met our study criteria; thus we had no control of the number of patients in each subgroup of valvular lesions. By chance, only one patient with mitral stenosis was evaluated during this study period. Obviously one cannot use the findings of our study to evaluate patients with mitral stenosis with any confidence, since only one such patient was included. Because ESS/ESVI has been shown useful in predicting outcome in patients with mitral regurgitation, the relatively large number of mitral regurgitation patients could have skewed our results in favor of ESS/ESVI being predictive.\textsuperscript{3, 24} Therefore we analyzed our results both inclusive and exclusive of patients with mitral regurgitation.

We compared preoperative ejection fraction obtained at cardiac catheterization with postoperative ejection fraction obtained by radionuclide techniques. Since ejection fraction by radionuclide methods tends to be slightly less than that by contrast ventriculography, it is possible that the postoperative fall in ejection fraction in patients with mitral regurgitation was partially a result of this discrepancy.\textsuperscript{20} Although we cannot rule this out, a postoperative fall in ejection fraction in patients with preoperative mitral regurgitation has been consistently reported in other studies in which preoperative and postoperative measurement of ejection fraction was made with similar methods.\textsuperscript{25, 30, 31}

Our pressures were recorded just before but not simultaneously with left ventriculography. Although it is unlikely that physiologic conditions changed in the minute or two between pressure recording and ventriculography, we cannot entirely exclude this possibility.

It should also be noted that 20 of 74 patients were excluded because of unsatisfactory ventriculographic results. Our findings are of limited use for patients who either do not undergo ventriculography or whose ventriculographic results are inadequate.

Finally there may be small errors in our stress measurements attributable to the use of a fluid-filled catheter. The delay in pressure recording when using a fluid-filled system matches a slightly higher than actual pressure with volume at end-systole and could cause overestimation of end-systolic stress. However, pressure and volume were carefully matched for RR intervals, and the delay in transmission of pressure through well-flushed fluid-filled catheters has been shown to be only about 10 msec, which is less than the time between cine frames. Previous studies in our laboratory demonstrate that no serious error is produced by these methods.\textsuperscript{32}

In summary, the afterload-corrected ESVI in patients with mitral regurgitation and in patients with valve lesions other than mitral regurgitation were independent predictors of outcome after valve replacement surgery for patients without coexisting coronary artery disease. It is likely that these indexes detect patients with preoperative left ventricular dysfunction that persists postoperatively and results in poor clinical out-
come. These indexes seem useful in assessing prognosis for patients with valvular heart disease undergoing valve replacement. However, no factor or combination of factors was a perfect predictor of outcome.

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