Functional Anatomy of Aortic Regurgitation

Accuracy, Prediction of Surgical Repairability, and Outcome Implications of Transesophageal Echocardiography

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Background—For patients with aortic regurgitation (AR), aortic valve sparing or repair surgery is an attractive alternative to valve replacement. In this setting, accurate preoperative delineation of aortic valve pathology and potential repairability is of paramount importance. The aim of the present study was to assess the diagnostic value of preoperative transesophageal echocardiography (TEE) in defining the mechanisms of AR, as identified by surgical inspection, and in predicting repairability, by using the final surgical approach as reference.

Methods and Results—One hundred and sixty-three consecutive patients (117 males, mean age: 58±14 years) undergoing AR surgery were included. Mechanisms of AR were categorized by TEE and surgical inspection as follows: type 1, aortic dilatation; type 2, cusp prolapse; and type 3, restrictive cusp motion or endocarditis. At surgery, mechanisms of AR were type 1 in 41 patients, type 2 in 62, and type 3 in 60. Agreement between TEE and surgical inspection was 93% (κ=0.90). Valve sparing or repair was performed in 125 patients and valve replacement in 38 patients. TEE correctly predicted the final surgical approach in 108/125 (86%) patients undergoing repair and in 35/38 (93%) patients undergoing replacement. The gross anatomic classification of AR lesions by TEE was determinant of valve repairability and postoperative outcome (4-year freedom from > grade 2 AR, reoperation, or death, P=0.04).

Conclusions—TEE provides a highly accurate anatomic assessment of all types of AR lesions. In addition, the functional anatomy of AR defined by TEE is strongly and independently predictive of valve repairability and postoperative outcome. (Circulation. 2007;116[suppl I]:I-264–I-269.)

Key Words: echocardiography ■ surgery ■ valves ■ aortic regurgitation ■ aortic valve repair

Aortic valve replacement has been the standard surgical procedure for the treatment of aortic regurgitation (AR) since reliable prosthetic valves became available. Accordingly, in most centers, aortic valve repair has been reserved for patients with AR attributable to aortic disease or associated ventricular septal defects. In recent years, however, repair techniques for diseased aortic valves have received increasing attention.1–10 Innovations in operative techniques, an improved understanding of the functional anatomy of the aortic valve and root, as well as an increased awareness of the mechanisms leading to AR have undoubtedly contributed to this renewed interest.11,12

Recently, we have described a functional classification of AR that addresses most of the pathological aspects of leaking aortic valves.12 Like Carpentier’s classification of mitral valve diseases, this AR functional classification primarily focuses on the mechanisms of valve dysfunction and provides the surgeon with a functional description of the aortic lesions that helps him in choosing the most appropriate surgical technique to restore normal valve physiology. Currently, this functional assessment is performed in the operating theater by the surgeon himself. It would nonetheless be desirable to perform this analysis preoperatively to identify earlier on the best candidates for conservative surgery.

Because it provides excellent real-time visualization of the anatomy of the heart, especially the aortic valve, transesophageal echocardiography (TEE) is probably the best currently available technique to identify AR lesions that are suitable for aortic repair. Yet, its accuracy in diagnosing anatomic lesions and its predictive value for valve repairability and postoperative outcome are not well defined. Accordingly, in the present study, we sought to determine the accuracy and implications of AR lesions assessed by TEE. For this purpose, we examined, in our consecutive experience in routine clinical practice, the accuracy of TEE compared with surgical assessment and the implications of TEE findings for valve repairability and postoperative outcome.
TABLE 1. Surgical and TEE Classification of Aortic Regurgitant Lesions

<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type 1</td>
<td>Enlargement of the aortic root with normal cusps.</td>
</tr>
<tr>
<td>Type 2</td>
<td>Cusp prolapse or fenestration.</td>
</tr>
<tr>
<td>Type 3</td>
<td>Poor cusp tissue quality or quantity.</td>
</tr>
</tbody>
</table>

Methods

Study Population

The study population consisted of all consecutive patients who underwent surgical correction of AR at our institution between June 1998 and January 2006 and met the following inclusion criteria: (1) > grade 2 AR; (2) absence of concomitant aortic stenosis (peak aortic transvalvular velocity <3 m/s or aortic valve area >1.2 cm²); (3) detailed surgical description of the valve lesions by the surgeon, and (4) preoperative TEE images available for review. No patients were excluded on the basis of age, LV function, associated mitral valve disease, aortic enlargement, or coronary abnormalities.

Transthoracic and Transesophageal Echocardiography

Echocardiographic examinations were performed using a Sonos 2500, 5500, or 7500 ultrasound system equipped with a 1- to 3-MHz wide angle phased array S3 transducer and a 2- to 7-MHz Omniplane II or III transducer (Philips Medical System). Preoperative grayscale and color TEE images from the transesophageal long- and short-axis views were acquired at the level of the aortic valve and root in all patients. Postoperative transthoracic echocardiographic (TTE) examinations were performed in every patient before hospital discharge as well as at follow-up. All images were stored digitally and transferred onto a dedicated image server for subsequent review.

Pre- and postoperatively as well as at follow-up, AR severity was evaluated semi-quantitatively and graded in 4 grades. The archived echocardiographic examinations were reviewed off-line by 2 experienced observers who had no knowledge of the operative findings.

Aortic Regurgitation Lesions

Aortic cusp and root lesions were categorized according to previously established surgical criteria. The description of the mechanisms of AR by the surgeon used a uniform transcription, unaltered from the reports dictated by the surgeon in an online data entry system.

The functional AR classification scheme used in this study was described elsewhere and is summarized in Table 1. Briefly, the surgeon identified 3 main mechanisms of AR: dilatation of the aortic root (type 1), excess cusp motion, including cusp prolapses and free edge fenestrations, with good cusp tissue quality (type 2), and poor cusp tissue quality, including cusp retraction, extensive cusp calcifications (>grade 3) and/or endocarditis (type 3). Cusp prolapses were further categorized in 3 groups: cusp flail (erosion of the cusp into the left ventricular outflow tract), partial or distal cusp prolapse, and whole cusp prolapse.

Evaluation of the mechanisms of AR by TEE followed the same principles. Type I dysfunction was identified when the dimensions of any components of the aortic root, including the aortic annulus, the sinuses of Valsalva, and the sinotubular junction exceeded the upper limits of published normal values and no other cause of AR was identified. Isolated dilatation of the ascending aorta not involving the aortic root was not considered as a plausible mechanism of AR. Type 2 dysfunction was considered in the presence of an eccentric AR jet and either a cusp prolapse or a cusp fenestration. Cusp prolapse was considered whenever the free edge of 1 or more of the aortic cusps overrode the plane of the aortic annulus. Similar to surgery, 3 subtypes of cusp prolapses were identified on TEE: cusp flail, whole cusp prolapses, and partial cusp prolapses. Cusp flail was defined as the complete erosion of a cusp into the LV outflow tract in long-axis views (Figure 1A). Partial cusp prolapse was considered whenever the distal part of a cusp was prolapsing into the LV outflow tract. This was usually associated with clear bending of the cusp body, on long-axis views (Figure 1B), and with the presence of a small circular or oval structure near the cusp free edge, on short-axis views. Whole cusp prolapse was considered each time the free edge of a cusp clearly overrode the plane of the aortic annulus and the entire body of the same cusp was billowing into the LV outflow tract (Figure 1C). Billowing of the cusp body was best seen on short-axis views of the LV outflow tract, immediately beneath the valve, where it appears as a large circular or oval structure. Fenestration of a cusp free edge was considered in the presence of an eccentric AR jet, but no definite evidence of cusp prolapse. Careful inspection of long-axis gray-scale and color Doppler images usually allowed identifying small defects near the free edge of the affected cusp (Figure 1D).

Echocardiographic Prediction of “Repairability”

Unless severely calcified, most type 1 and 2 AR lesions were considered as “repairable”, ie, amenable to some form of conserva
tive surgery, including valve sparing surgery, cusp repair, or a combination thereof. In moderately calcified valves (<grade 3), the localization of the calcifications was taken into account. Whenever these calcifications were confined to the free margins, aortic repair was considered to be feasible. By contrast, when the calcifications involved the body of the cusp, the valve was considered as nonrepairable. Finally, type 3 lesions were a priori considered as nonrepairable.

Postoperative Outcome

Follow-up information was obtained by review of the medical records of the patients followed at our institution and by questionnaires and telephone interviews of the other patients, their families, and their physicians. Follow-up was complete up to 2006 or death for 156/163 patients (96%). The outcome events analyzed were long-term survival, need for reoperation, and recurrence of >grade 2 AR.

Statistical Analysis

All analyses were conducted using SPSS software (version 12.0, SPSS Corp). Continuous variables were expressed as mean± standard deviation (SD), categorical variables as counts and percent-
ages, and follow-up times as median and range. Differences between groups were analyzed with a 1-way analysis of variance. A probability value of <0.05 was considered indicative of a statistically significant difference. The sensitivity, specificity, and accuracy of TEE for the diagnosis of the mechanisms of AR and for the prediction of repairability were calculated according to standard formulae. Kappa statistics was used to determine intertechnique diagnostic concordance. Survival curves were computed with the Kaplan-Meier method and compared using the log-rank χ² test. A multivariate logistic regression analysis was performed to identify independent predictors of outcome.

Responsibility

The authors had full access to and take full responsibility for the integrity of the data. All authors have read and agree to the manuscript as written.

Results

Baseline Characteristics

Among the 311 patients who were operated on during the study period, 163 (117 males, mean age 58±14 years, range 25 to 85 years) fulfilled the inclusion criteria. The remaining
148 patients were excluded either because of missing TEE data \((n=138)\) or concomitant aortic stenosis \((n=10)\). At surgery, the cause of AR was type 1 dysfunction in 41 patients \((24\%)\), type 2 dysfunction in 62 \((38\%)\), and type 3 dysfunction in 60 \((37\%)\). The aortic valve was tricuspid in 104 patients \((64\%)\), bicuspid in 58 patients \((36\%)\), and quadricuspid in the single remaining patient. Five patients \((3\%)\) had Marfan disease.

On the basis of the surgical findings, 38 patients underwent aortic valve replacement, 13 an isolated valve sparing operation, 67 an isolated aortic cusp repair, and 45 a combined valve sparing operation and aortic cusp repair. The techniques used to spare or repair the aortic valve have been described elsewhere.\(^2\)\(^,\)\(^3\)\(^,\)\(^16\) In addition to aortic surgery, 63 patients needed an additional procedure, including mitral valve repair in 29, tricuspid valve annuloplasty in 4, coronary artery bypass graft surgery in 24, closure of an atrial septal defect in 5, and closure of a ventricular septal defect in 1.

### Diagnostic Accuracy of TEE

The concordance between surgical and TEE findings is shown in Table 3. The gross anatomic classification by TEE compared with surgery was accurate in 152/163 patients \((93\%\) of cases, \(\kappa=0.90\)), with 3 false-positives for type 1 dysfunction \((3\) type 2 dysfunction), 5 for type 2 dysfunction \((3\) type 1 and 2 type 3 dysfunction), and 3 for type 3 dysfunction \((2\) type 1 and one type 2). We also examined the ability of TEE to identify type 2 subtypes as their treatment involves specific surgical approaches. As shown in Table 4, the concordance between surgical and TEE findings for the identification of the different subtypes of type 2 dysfunction was good.

### TEE Prediction of Valve Repairability

As shown in Table 5, TEE correctly predicted the final surgical approach in 108/125 \((86\%)\) patients in whom the surgeon opted for a valve sparing operation, a cusp repair, or a combination thereof. Similarly, TEE correctly predicted the final surgical approach in 35/38 \((93\%)\) patients undergoing

### TABLE 2. Grading of Aortic Valve Calcification

<table>
<thead>
<tr>
<th>Grade</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>No calcification</td>
</tr>
<tr>
<td>2</td>
<td>Isolated small calcification spots</td>
</tr>
<tr>
<td>3</td>
<td>Bigger calcification spots interfering with cusp motion</td>
</tr>
<tr>
<td>4</td>
<td>Extensive calcifications of all cusps with restricted cusp motion</td>
</tr>
</tbody>
</table>

### TABLE 3. Agreement Between Surgery and Transesophageal Echocardiography for Identification of AR Mechanisms

<table>
<thead>
<tr>
<th>Surgery</th>
<th>Type 1</th>
<th>Type 2</th>
<th>Type 3</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>TEE</td>
<td>36</td>
<td>3</td>
<td>0</td>
<td>39</td>
</tr>
<tr>
<td>Type 2</td>
<td>3</td>
<td>58</td>
<td>2</td>
<td>63</td>
</tr>
<tr>
<td>Type 3</td>
<td>2</td>
<td>1</td>
<td>58</td>
<td>61</td>
</tr>
<tr>
<td>Total</td>
<td>41</td>
<td>62</td>
<td>60</td>
<td>163</td>
</tr>
</tbody>
</table>

\(\kappa=0.90\).
aortic valve replacement. Although in patients with bicuspid valves, valve sparing or repair was attempted less frequently than in patients with tricuspid valves (67±6% versus 82±3%, respectively, χ²=0.03), the ability of TEE to predict valve reparability was similar in both valve types.

Among the 3 patients whose aortic lesions were deemed repairable by TEE but the aortic valve was finally replaced, 2 had type 3 dysfunction at surgery (attributable to rheumatic valve disease or infective endocarditis with an abscess extending into the interventricular septum), and 1 had multiple fenestrations that were treated by a Ross operation.

Among the 17 patients whose aortic lesions were considered as nonrepairable by TEE but were nonetheless repaired by the surgeon, 8 experienced recurrent >grade 2 AR at follow-up, of whom 6 needed a reoperation.

Figure 2 (left panel) shows how often conservative surgery was performed in the different TEE subtypes of valve dysfunction. Attempts to preserve the native aortic valve were significantly more frequent in TEE type 1 and 2 than in type 3 dysfunctions.

Follow-Up Data
The median clinical and echocardiographic follow-up in patients undergoing valve sparing or repair was 29 months (range 0 to 75 months). Figure 3 shows the 4-year event-free survival of patients undergoing valve sparing or repair surgery. Over this 4-year period, 2 patients died (1 at day 26 from multiorgan failure and 1 after 31 months from aortic dissection), 12 patients experienced recurrent >grade 2 AR, of whom 6 needed a reoperation.

Outcome of Valve Sparing Surgery According to Anatomic Classification
Figure 2 (right panel) shows the outcome of patients undergoing valve sparing or repair surgery according to the anatomic classification by TEE. As shown, patients who underwent conservative surgery and presented with type 1 or 2 dysfunction by TEE experienced significantly less events than patients presenting with type 3 dysfunction. Figure 4 shows that, for all end points (4-year survival, 4-year freedom from >grade 2 AR, 4-year freedom from reoperation), the gross anatomic classification was significantly associated with outcome. Univariate and multivariate logistic regression analyses identified type 3 dysfunction as the only factor significantly associated with event-free survival (OR=6.2, IC95% [1.2 to 31.9], P=0.03). Similar results were obtained after adjustment for gender, bicuspid valve, Marfan disease, and eccentric AR jets.

Discussion
The present study of a large number of patients undergoing AR surgery shows that the accuracy of TEE for the assessment of the functional anatomy of AR is excellent both for the gross anatomic classification and the detailed anatomic evaluation of AR lesions. In addition, our data show that the |

TABLE 4. Agreement Between Surgery and Transesophageal Echocardiography for Identification of Type 2 AR Lesions

<table>
<thead>
<tr>
<th>Surgery</th>
<th>Cusp Flail</th>
<th>Whole Cusp Prolapse</th>
<th>Distal Cusp Prolapse</th>
<th>Free Edge</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>TEE</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cusp flail</td>
<td>3</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>4</td>
</tr>
<tr>
<td>Whole cusp prolapse</td>
<td>0</td>
<td>25</td>
<td>0</td>
<td>1</td>
<td>26</td>
</tr>
<tr>
<td>Partial cusp prolapse</td>
<td>0</td>
<td>2</td>
<td>11</td>
<td>1</td>
<td>14</td>
</tr>
<tr>
<td>Fenestrations</td>
<td>0</td>
<td>2</td>
<td>1</td>
<td>11</td>
<td>14</td>
</tr>
<tr>
<td>Type 1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Type 3</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Total</td>
<td>3</td>
<td>30</td>
<td>12</td>
<td>17</td>
<td>62</td>
</tr>
</tbody>
</table>

κ: 0.90.

TABLE 5. Agreement Between TEE Prediction of Repairability and the Final Surgical Procedure

<table>
<thead>
<tr>
<th>Surgery</th>
<th>Repair</th>
<th>Replace</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>TEE prediction</td>
<td>108</td>
<td>3</td>
<td>111</td>
</tr>
<tr>
<td>Repair</td>
<td>17</td>
<td>35</td>
<td>52</td>
</tr>
<tr>
<td>Replace</td>
<td>125</td>
<td>38</td>
<td>163</td>
</tr>
</tbody>
</table>

κ: 0.70.

Figure 2. Incidence of valve sparing or repair surgery in the whole population (left) and event rate in patients undergoing sparing or repair surgery (right), according to anatomic classification by TEE. Closed bars, type 1; Half-tone bars, type 2; Open bars, type 3. ***χ²<0.001 type 3 vs type 1 and 2.
anatomic classification provided by TEE is a strong predictor of repairability and long-term outcome. This indicates that the functional anatomy of AR as defined by TEE is of major importance for clinical decision making, particularly for the choice of surgery.

Functional Anatomy of AR

With the advent of conservative aortic valve surgery, including valve sparing operations and aortic cusp repair, the management of severe AR has changed significantly. These operations indeed have a low operative mortality and a good long-term durability. Unfortunately, although valve sparing or repair operations have become more feasible because of new surgical techniques, they cannot be performed in all patients. Valve lesions are thus critical data that a surgeon needs to determine the likelihood of valve sparing or repair surgery. This underscores the importance of the preoperative assessment of the functional anatomy of AR. Until now, the accuracy of the anatomic assessment of AR lesions by TEE compared with direct examination has only been analyzed in series limited by their small size.17,18 Furthermore, the influence of the TEE diagnosis on outcome was mainly attributable to its ability to predict valve repairability. Indeed, multivariate analysis demonstrated significant relationships between the anatomic classification by TEE and the likelihood of valve sparing or repair surgery, the recurrence of AR, and the long-term survival. The outcome of patients whose AR lesions were deemed non repairable by TEE is a good illustration of the diagnostic power of this technique. Indeed, among the 125 patients undergoing valve sparing or repair surgery, TEE had predicted the valve to be poorly suitable for such a procedure in 17. Eight of these patients (47%) experienced recurrent >grade 2 AR during follow-up, of whom 6 (35%) needed a reoperation. This is in contrast with the outcome of the 108 patients in whom TEE had predicted the valve to be repairable. Among these patients indeed, only 14 (13%) experienced recurrent >grade 2 AR, and 4 (3.7%) needed a reoperation.

Study Limitations

This study has several limitations that should be acknowledged. First, the surgeons were not blinded to the results of the preoperative TEE. Therefore, we cannot exclude the possibility that this might have somehow influenced their judgment. However, at the time most of the interventions...
were performed, the current classification of AR dysfunction by TEE had not yet been defined. Accordingly, it is likely that the decision to repair or to replace the aortic valve was based more on the results of the direct intraoperative inspection of the valve tissue rather than on the intraop TEE assessment. The fact that the surgeons decided to repair several valves that we eventually judged to be nonrepairable when reviewing the TEE images supports this hypothesis. The prediction of repairability is an end point highly dependent on the surgeon’s skill and cannot be generalized to each and every surgeon performing aortic surgery. Accordingly, repairability should always be determined at each institution based on the local surgical team experience and skills. Also, the present results apply only to patients with clinically significant AR and should not be extrapolated to other populations with milder degree of AR.

Conclusions
Our data demonstrate that TEE provides a highly accurate anatomic assessment of all types of AR lesions. The functional anatomy of AR defined by TEE is strongly and independently predictive of repairability and postoperative outcome. Therefore, the AR lesions assessed by TEE represent essential information for clinical decision making.

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Disclosures
None.

References
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