Original Research Article

Hemodynamic and functional assessment of mechanical aortic valves using combined echocardiography and multidetector computed tomography

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KEYWORDS:
Aortic valve; Echocardiography; Heart valve disease; Heart valve prosthesis; Spiral computed tomography

BACKGROUND: Limitations are found in the ability of transthoracic echocardiography to evaluate mechanical aortic valve replacements (AVR). We evaluated the ability of combined echocardiography and computed tomography (CT) to enhance the hemodynamic and functional evaluation of AVR.

METHODS: We performed a retrospective evaluation of 41 consecutive patients with AVR (27 bi-leaflet, 14 single disc) and both transthoracic echocardiography and 64-detector electrocardiographic-gated CT. Each study was interpreted by 2 independent, blinded readers. The effective orifice area was compared with the corrected energy-loss coefficient area and the geometric orifice area. Patients with an elevated mean pressure gradient (>15 mm Hg) were assessed for potential abnormal findings, including patient–prosthesis mismatch, elevated cardiac index, valve dysfunction, significant regurgitation, or pressure recovery effect.

RESULTS: Significant differences ($P < 0.05$) and moderate-to-high correlations ($r = 0.55–0.98$) were observed between the effective orifice area ($2.2 \pm 0.8 \text{ cm}^2$), corrected energy-loss coefficient area ($3.0 \pm 1.5 \text{ cm}^2$), and geometric orifice area ($3.6 \pm 0.9 \text{ cm}^2$). At least one abnormality was observed in 7 of 25 patients with normal gradients and in 14 of 16 patients with elevated gradients ($P < 0.001$). In 16 patients with elevated mean pressure gradient, a potential cause could be determined in 4 with echocardiography alone and in 14 patients with combined echocardiography and CT ($P = 0.001$).

CONCLUSION: CT aids in the interrogation of prosthetic valve function, enhancing evaluation for patient prosthesis mismatch, and correction for pressure recovery by the corrected energy-loss coefficient. CT is additive to the assessment of mechanical AVR with transthoracic echocardiography, and the combination permits a more complete assessment of both AVR function and hemodynamics.

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Introduction

The assessment of mechanical aortic valve replacements (AVR) can present diagnostic challenges. Transthoracic echocardiography (TTE) can evaluate valve hemodynamics by measuring the transvalvular Doppler gradient and aortic regurgitation. However, evaluation of disc excursion often is not possible with TTE or transesophageal echocardiography because of shadowing and artifact. Elevated transvalvular gradients can be caused by a high-flow state because of a number of factors, including elevated cardiac index or significant aortic regurgitation, patient–prosthesis mismatch, pressure-recovery effect, or valvular dysfunction typically a result of partial disc obstruction as a result of thrombus, pannus, or vegetation. An accurate determination of the cause of elevated transvalvular gradients is vital, because treatment can range from thrombolytic therapy to repeat AVR surgery, each associated with inherent risk. With the use of TTE alone, it can be difficult to determine the cause of elevated transvalvular gradients. Reports of incorrect echocardiographic diagnoses in patients undergoing repeat AVR surgery highlight the potential clinical utility of additional imaging modalities.

Cinefluoroscopy can assess disc excursion (opening and closure); however, this can be time consuming, requires the presence of an experienced operator during acquisition, and may not be readily available during off hours or at sites without a cardiac catheterization laboratory. Electrocardiogram (ECG)–gated multidetector computed tomography (CT) was recently reported to accurately measure disc excursion when well visualized, and it may be able to identify AVR complications that include pannus formation, vegetations, and thrombus. In addition, because ECG-gated multidetector CT can directly visualize the cross-sectional area of the aortic sinotubular junction, it may permit improved correction for pressure recovery. We hypothesized that the combination of CT and TTE could provide a more thorough evaluation of the hemodynamics and function of AVR than TTE alone and could help distinguish the cause of elevated transvalvular gradients. The purpose of this study was to compare TTE and CT evaluation of AVR in regard to (1) comparison of the geometric orifice area (GOA) determined by CT, the effective orifice area (EOA) determined by continuity equation with TTE, and the energy loss coefficient (ELCo) area and (2) determine the ability of combined CT and TTE to assess the cause of elevated transaortic gradients.

Methods

Study population

The study group comprised patients with mechanical AVR and both TTE and ECG-gated 64-detector cardiac- or aorta-protocol CT performed between January 2005 and February 2008. Inclusion criteria included adult patients (age ≥ 18 years; range, 19–83 years), with a maximum of 3 months between CT and TTE examinations (mean time difference, 7 ± 19 days). Patients were excluded if there was an interval change in clinical status between CT and TTE, such as new cardiac symptoms or cardiac surgery. This retrospective study was approved by the Institutional Review Board with a waiver of informed consent, and is compliant with the Health Insurance Privacy and Portability Act.

A total of 41 consecutive patients with AVR (27 bileaflet, 14 single disc) were studied. The valve manufacturer was known for 13 of 14 single-disc valves (Medtronic Hall valve; Medtronic, Inc, Minneapolis, MN) and 24 of 27 bileaflet valves (St Jude Medical, Inc, St Paul, MN).

Image analysis

Two fellowship-trained cardiothoracic radiologists blindly and independently evaluated the CT examinations, and 2 experienced cardiologists blindly and independently reviewed TTE studies. All readers were blinded to clinical data and the results of the other readers. Echocardiographic measurements included cardiac index, mean pressure gradient, EOA, aortic regurgitation, sinotubular aorta diameter, and the left ventricular ejection fraction. Cardiac CT measurements included opening angles, GOA, aorta sinotubular cross-sectional area, and an assessment for complete closure.

Elevated gradients

An elevated AVR gradient was defined as a mean pressure gradient >15 mm Hg. Patients with elevated gradient were assessed for possible causes, including valve dysfunction, patient–prosthesis mismatch, high cardiac index, significant aortic regurgitation, and pressure recovery effect. Valve dysfunction was defined by evidence of abnormal disk motion, with either an opening angle >20 degrees below normal specifications or with incomplete valve closure. Complete valve closure was defined as disc coaptation during diastole for bileaflet valves or closure to the plane of the annulus for single-disc valves. Prosthesis–patient mismatch was defined as an effective orifice area index (effective orifice area divided by calculated body surface area) <0.85 cm²/m² in a nonobstructed valve. High cardiac index was defined as >4.0 L/min/m². The presence and severity of aortic regurgitation were established on TTE and was considered abnormal in the presence of more than mild regurgitation (because small regurgitant jets are normal in the design of many mechanical valves). ELCo area was calculated to correct the EOA for pressure-recovery: ELCo area = (sinotubular aorta area × EOA)/(sinotubular aorta area − EOA). Elevated gradient because of pressure recovery was defined as an elevated mean gradient with significantly reduced EOA by the continuity equation,
but no more than mildly reduced valve area as calculated with the use of the energy loss coefficient (EOA < 1.5 cm\(^2\) and ELCo area ≥ 1.5 cm\(^2\)).

**CT technique and evaluation**

All CT studies were ECG-gated, using a protocol for the thoracic or thoracoabdominal aorta. No patients with cardiac CT met the inclusion and exclusion criteria. No pharmacologic agents were used for heart rate control. A timing bolus of 15 mL was used to determine the optimal scan start time. Nonionic iodinated intravenous contrast material, either 135 mL iopromide (370 mg/mL; Berlex/Bayer Health Care, Montville, NJ) or 95 mL ioxaglate (320 mg/mL; General Electric Health Care, Princeton, NJ) was administered at a rate of 4 mL/s. CT examinations were performed with a 64-detector CT scanner (VCT; General Electric Health Care, Milwaukie, WI) with the use of retrospective ECG-gating. Scanner settings included detector collimation width of 0.625 mm, coverage of 40 mm, re-constructed slice thickness of 1.25 mm, and slice interval of 1.25 mm. Gantry rotation time was 0.35 seconds, and scan pitch ranged between 0.16 and 0.20 (adjusted for heart rate). Maximum tube current ranged from 450 to 700 mA, depending on patient size, with a fixed tube voltage of 120 kVp. Dose modulation was applied for CT examinations of patients without tachyarrhythmia with maximum tube current during ventricular diastole (between 60% and 80% of R-R interval) and 20% of the maximum tube current for the remainder of the cardiac cycle.

CT data sets with images throughout the cardiac cycle at 5%–10% increments of the R-R interval were reviewed on an advanced processing workstation (General Electric Advantage Windows Workstation, version 4.3_05, CardIQ software; GE Healthcare, Milwaukee, WI). Valve evaluation was performed with the use of multiplanar reformatted images with a cine mode. Each AVR was viewed in an oblique long-axis view and a double-oblique short-axis view. The long-axis view was rotated around the plane of the valve annulus to visualize an optimal on-edge view of the opening and closing of the disc or discs. An electronic protractor measured the opening angles, using the plane of the valve annulus as the baseline. The short-axis view of the valve was used to measure the GOA by planimetry when available. When accurate planimetry was not possible (n = 3), the GOA was calculated from the internal diameter of the annulus (Fig. 1 and Fig. 2).

The radiation dose was available in 36 of the 41 patients and included the cumulative dose for the thoracic and abdominal aorta in all patients, with the pelvic aorta included in 14 cases. The timing bolus was incorporated in the radiation dose estimate. The effective dose was determined by multiplying the dose-length product by 0.015 for the tissue-weighting factor. At our institution, the typical radiation dose is 25 mSv for the thoracic aorta alone.

**TTE technique and evaluation**

TTE studies were performed with standard echocardiography equipment (Sequoia 256 or 572; Siemens Medical, Mountain View, CA; or Phillips 5500; Bothell, WA). Images were acquired digitally and reviewed off-line using Prosolv Cardiovascular Analyzer version 3.0.48 (Prosolv Cardiovascular Solutions; FujiFilm USA, Indianapolis, IN). Each reader measured the transvalvular mean pressure gradient by electronically integrating the area under the continuous-wave Doppler spectral envelope of the highest velocity signal available. Both left ventricular ejection fraction and regurgitation grade were determined with the use of standard clinical criteria. The ability of TTE to evaluate disc function was also assessed. The EOA was calculated by the continuity equation: EOA = (π × (left ventricular outflow tract diameter/2)\(^2\) × (velocity time integral of the left ventricular outflow tract)/velocity time integral of the aortic valve). The sinotubular aorta area was calculated with the formula π × (sinotubular aorta diameter/2)\(^2\). The area at the sinotubular junction could not be measured in one case with CT, and ELCo therefore was not available; patient height was not known in one case, with calculation of body surface area (and assessment of patient–prosthesis mismatch and cardiac index) not possible. All other variables could be determined in all cases.

**Statistical analysis**

Statistical analysis was performed with SPSS version 12.0 for Windows (SPSS Inc, Chicago, IL). Comparison between groups was performed with Pearson correlations, paired t tests, unpaired t tests, and Fisher’s exact tests. A P value of <0.05 was considered significant.

**Results**

Mean age was 48.8 ± 13.9 years, and 34 of the patients were men. The mean ejection fraction was 62.8% ± 6.3% and ejection fraction was <50% in one patient. No study patients had examinations limited to the thoracic aorta or the heart. For studies of the thoracic and abdominal aorta, the mean effective radiation dose was 41.9 ± 9.2 mSv, whereas for studies of the thoracic, abdominal, and pelvic aorta it was 47.5 ± 6.6 mSv.

The mean GOA (3.6 ± 0.9 cm\(^2\)) was substantially higher than the EOA (2.2 ± 0.8 cm\(^2\)) with the mean ELCo area (3.0 ± 1.5 cm\(^2\)) falling between the GOA and EOA. Significant differences were observed between the GOA and EOA (P < 0.001), GOA and ELCo (P = 0.019), and GOA and ELCo (P < 0.001), with moderate correlation between the GOA and EOA (r = 0.61, P < 0.001) and the GOA and ELCo (r = 0.55, P < 0.001) (Fig. 3A and B). Because the ELCo area is derived from the EOA, high correlation was expected (r = 0.98,
The sinotubular aorta area was moderately correlated and larger with CT than with TTE ($r = 0.48$, $P = 0.002$; $9.3 \pm 3.1$ versus $8.3 \pm 2.1$ cm², $P = 0.035$), resulting in a strongly correlated and smaller ELCo area with the sinotubular area from CT than with that derived with TTE ($r = 0.98$, $P < 0.001$; $3.0 \pm 1.6$ versus $3.2 \pm 1.6$ cm², $P = 0.029$).

An elevated mean transvalvular gradient was observed in 16 patients (mean gradient, $19.6 \pm 3.6$ mm Hg; range, 15.1–28.3 mm Hg; peak velocity, $3.0 \pm 0.3$ m/sec; range, 2.6–3.6 m/s), with a gradient below the cutoff observed in 25 cases. Hemodynamic and functional differences existed between these groups (Table 1). At least one potential cause of elevated gradient was present in 7 of 25 patients with
normal gradients, and 14 of 16 patients with elevated gradients \((P < 0.001)\). Among 16 patients with elevated gradients, TTE alone could determine a cause in 4 cases, and CT combined with TTE could determine a cause in 14 cases \((P = 0.001)\). Among patients with elevated gradients, TTE observed a high cardiac index in 4 patients (with no evidence of other causes in these patients) and significant aortic regurgitation in no cases. With the use of both TTE and CT, 10 patients were identified with patient–prosthesis mismatch, and 4 patients (all with patient–prosthesis mismatch as well) were noted to have a significant pressure recovery effect. A cause of the elevated gradient was not determined in 2 cases. No cases of valve dysfunction were observed. Valve disc function could not be assessed in any patients with the use of TTE alone.

The GOA was inversely correlated to the mean transvalvular gradient \((r = -0.66, P < 0.001)\), but no significant correlation was observed between the opening angle and the transvalvular gradient for either single-disc \((P = 0.54)\) or bileaflet \((P = 0.06)\) AVR.

**Discussion**

Although cinefluoroscopy has traditionally been used to evaluate valve function by measuring the opening angle and assessing for disk closure, CT has potential use as an alternate test to evaluate both valve function and other parameters. When combined with echocardiography, it may permit a thorough evaluation of mechanical AVR with elevated gradients. Evaluation of disc excursion remains one of the most important variables when assessing elevated transvalvular gradients. Decreased disc opening or closure, whether because of thrombus, pannus, vegetations, or mechanical dysfunction, can be catastrophic and can lead to progressive or acute heart failure through obstruction of flow, significant valvular regurgitation, or both.

A common cause of elevated transvalvular gradients is patient–prosthesis mismatch (typically defined as the ratio of the EOA to body surface area \(< 0.85 \text{ cm}^2/\text{m}^2\)), in which the prosthesis size is not adequate for expected cardiac output despite normal valve function. Although TTE can determine the EOA, an additional test, such as cinefluoroscopy or CT, is usually required. In this study, prosthetic valve disc function could not be accurately assessed in any patients with TTE. Importantly, because the diagnosis of patient–prosthesis mismatch requires a low indexed valve orifice area in the presence of normal disc excursion, the addition of CT to TTE permitted the diagnosis in 10 cases, whereas either test alone could not establish the diagnosis. This suggests a useful potential role for combined CT and TTE. The significant difference between EOA and GOA
in this study establishes that GOA cannot be substituted for EOA and that CT alone cannot assess for patient–prosthesis mismatch.

The pressure-recovery effect is an established phenomenon in fluid hemodynamics that can lead to overestimation of gradients and underestimation of the EOA. As blood gains velocity through a valve, some of the pressure is converted to kinetic energy, which is converted back to pressure energy distal to the valve. Pressure recovery occurs to a greater degree when the cross-sectional area distal to the restrictive orifice is relatively similar to the valve orifice area as in the case of aortic valves, when the proximal ascending aorta is not dilated. In vitro, animal, and patient data suggest that Doppler interrogation results in an underestimation of the EOA compared with that measured by catheterization, and that after correction for pressure recovery (using the cross-sectional area of the aorta) there was no longer a significant difference between the EOA by Doppler scan and cardiac catheterization. When applied to clinical practice, this has provided improved concordance between TTE and cardiac catheterization–derived EOA.

Table 1  Echocardiography/Doppler scan and CT variables in patients with normal versus elevated AVR gradients

<table>
<thead>
<tr>
<th>Variable</th>
<th>Normal gradient (n = 25)</th>
<th>High gradient (n = 16)</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>High cardiac index, n (%)</td>
<td>3 (12)</td>
<td>4 (25)</td>
<td>NS</td>
</tr>
<tr>
<td>Aortic regurgitation (&gt; mild), n (%)</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Low EOA (&lt;1.5 cm²), n (%)</td>
<td>3 (12)</td>
<td>6 (38)</td>
<td>0.12</td>
</tr>
<tr>
<td>Low ELCo Area (&lt;1.5 cm²), n (%)</td>
<td>0</td>
<td>2 (13)</td>
<td>0.15</td>
</tr>
<tr>
<td>Indexed EOA, mean ± SD</td>
<td>3.5 ± 1.7 cm²</td>
<td>2.2 ± 0.8 cm²</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Patient–prosthesis mismatch, n (%)</td>
<td>4 (16)</td>
<td>10 (63)</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Valve dysfunction, n (%)</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

AVR, aortic valve replacement; EOA, effective orifice area; ELCo, energy loss coefficient; SD, standard deviation.

Figure 3  Correlation between the GOA and ELCo area (A), GOA and EOA (B), and EOA and ELCo area (C). GOA indicates geometric orifice area; ELCo, energy loss coefficient; EOA, effective orifice area.
Although correction for the sinotubular aorta by TTE has resulted in improved agreement with cardiac catheterization, there is a potential for error because the cross-sectional area is calculated from the diameter measured with TTE. Direct measurement of the cross-sectional area is possible with CT and would be expected to have improved accuracy.

The ELCo area for the study population was closer to the GOA than the EOA. The large and significant difference between the EOA and ELCo area in this cohort of patients with mechanical AVR suggests that routine correction for pressure-recovery should be considered in AVR patients, whether with TTE or with CT. The finding that the ELCo and EOA are smaller than the GOA is expected, because the minimal cross-sectional area of blood flow often occurs distal to the valve orifice, in a manner dependent on the inflow shape of the valve. This is one reason that planimetry of the aortic valve area (by TEE or by CT) may overestimate valve area compared with the EOA by Doppler scanning with the use of the continuity equation. For the purpose of this analysis, significant pressure-recovery effect was defined as a moderately to severely decreased EOA (<1.5 cm²) that was reduced to a mildly decreased ELCo (≥ 1.5 cm²). The pressure-recovery effect obviously represents a continuum. The use of a single cutoff is simplistic, and in clinical practice the effect should be assessed on an individual basis.

An elevated cardiac index or significant aortic regurgitation represents additional causes of elevated transvalvular gradients, and typically are evaluated well with TTE. However, some patients can have more than one cause of an elevated gradient, and a thorough evaluation of each potential cause may be needed.

Study limitations

Limitations include the retrospective nature of the study and the use of a single center. Although others have previously reported the ability of CT to identify patients with valve dysfunction, cases of significant valvular dysfunction or pathologic regurgitation were not present in this study cohort. As such, the applicability of these findings to patients with abnormal AVR function cannot be established. Because patients with mechanical AVR dysfunction are uncommon and can be critically ill and because CT has not been routinely used to evaluate suspected valve dysfunction, larger prospective studies may be required to further assess the utility of combined CT and TTE in these patients.

Conclusions

CT may permit determination of valve function, which in turn allows evaluation for possible patient–prosthesis mismatch and enhances correction for pressure recovery by ELCo. In patients with mechanical AVR and an elevated transvalvular gradient, CT is additive to the TTE assessment, and the combination of tests permits a more complete assessment of both AVR function and hemodynamics.

References