Diagnosis of aortic valvular stenosis by multislice cardiac computed tomography

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KEYWORDS
Aortic stenosis; Diagnosis; Cardiac computed tomography

Introduction
Aortic stenosis (AS) is the most frequent valvular disease in Western countries, and the incidence of degenerative AS, the main cause of AS, should still increase because of the ever-increasing life expectancy. The timing for surgical treatment is the main concern in medical management of AS and requires accurate measurement of the aortic valvular area (AVA),1

Catheterism has been the standard method of evaluation for several decades but is declining in use because of concerns regarding the risk of catheter-related damage such as stroke2 and technical limitations. Today, Doppler echocardiography is the current reference technique1,3 providing insights into both aortic valve as well as left ventricular (LV) function. The Doppler-derived continuity equation has been largely validated, but entails technical limitations such as suboptimal apical acoustic windows, important angulation of the ascending aorta with the LV outflow tract, difficult measurement of the LV outflow tract diameter, and associated subaortic stenosis or aortic regurgitation. These limitations result in relatively high inter- and intra-observer variability.4,5 In addition, the haemodynamic model underlying the Doppler measurement fails in cases of low cardiac output.6

Meanwhile, recent technical improvements in multislice electrocardiography (ECG)-gated computerized tomography (MSCT) allows for visualization of the aortic valve throughout the cardiac cycle. In addition, cardiac MSCT gives information about the left ventricle and coronary artery anatomy. Thus, cardiac MSCT could be an alternative and integrated imaging technique in the management of valvular disease. However, MSCT has not been evaluated for AS.

Our aim was to compare 16-slice MSCT with Doppler echocardiography for quantifying AVA and diagnosing AS.

Methods
Population
From September 2003 to February 2005, we prospectively enrolled 131 consecutive patients referred for cardiac CT (LightSpeed Pro16 by GE Healthcare, Waukesha, WI, USA). Patients were referred for coronary artery imaging because of chest pain, abnormal ascending aorta, mediastinal/pericardial abnormalities in a peri-operative setting, or congenital heart disease. Exclusion criteria were renal failure (serum creatinine $>$150 mmol/L), severe allergy to iodine contrast, atrial fibrillation with fast ventricular rhythm, or sinus tachycardia $>$100/min. The study complied with the declaration of Helsinki and the local Ethics Committee approved the research protocol.

MSCT method
CT was acquired in a breath-hold, eased by oxygen supply, and ECG-gated, after verification of proper R-waves. A reference slide

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acquired at the level of the ascending aorta, regularly updated, allowed for detecting the contrast bolus and triggering the acquisition, to avoid the use of test contrast bolus, to shorten the examination time, and to optimize the synchronization between injection and acquisition.

Standard cardiac acquisition parameters were 16 slices, SFOV 250 mm, slice thickness 0.625 mm, reconstruction interval 0.625, 120 kV, 600 mA, 220–250 mA s, and scan rotation 0.4 s. No ECG mA-modulation was used. Rotation speed and pitch were automatically adjusted to the acquisition protocols and the heart rate. Acquisition time varied between 18 and 25 s, depending on anatomical coverage and pitch. The temporal resolution depended on rotation time and reconstruction mode and ranged from 200 to 80 ms. Contrast media (320–350 mg I/ml) was infused in triple bolus through a 18-gauge catheter in an antecubital vein with use of a dual-barrel injector (90 cc of contrast media at 5 cc/s, 30 cc of contrast medium diluted with 30 cc of isotonic solution at 3.5 cc/s, washed out by 40 cc of isotonic solution at 3.5 cc/s). The reconstruction algorithm depended on heart rate: segment mode under 65 b.p.m. (half rotation), burst mode (90° sector on two consecutive beats) between 65 and 85 b.p.m., and burst plus mode (45° sector on four consecutive beats) over 85 b.p.m. Phases from 0 to 90% every 10% were systematically reconstructed to allow for imaging both coronary arteries, valvular apparatus, and cardiac chambers.

CT data were analysed by the use of Advantage Workstation (GE Healthcare, Version 4.2). CT readers (E.B. and J.L.S.) were blinded to the echographic results. Multiplanar reformat was applied to systolic phases of the cardiac cycle (from 0 to 40% of the cardiac cycle). Imaging planes for planimetry were chosen from the sagittal and coronal views to include the orifice of the ascending aorta, mainly in the case of limited apical acoustic window, required transesophageal echocardiography to allow direct planimetry of the AVA. Transesophageal echocardiography was performed with the use of a multiplane probe. The planimetry was usually performed in a 30–50° plane, when the aortic valve annulus appeared circular and all cusps were seen at the same time. Subtle movements of the probe allowed for precise identification of the smallest AVA at the time of maximal systolic opening. Three measures were averaged. Stenosis was graded according to the American College of Cardiology (ACC)/American Heart Association (AHA) classification: mild (150–200 mm²), moderate (>100–150 mm²), severe (>75–100 mm²), and critical (<75 mm²). LV ejection fraction was measured by the use of the Simpson biplane method.

Statistical analysis

Given the uncertainty regarding the expected agreement between the two techniques (echography and MSCT) and the exploratory nature of such a pilot study, 30 patients with significant AS were empirically included. Continuous variables are reported as mean and standard deviation or median and range, and compared using t-test or Mann–Whitney U test. Categorical variables are reported as count and percentages and compared using χ² tests. The agreement between CT and echography was displayed using the Bland and Altman plots. Among CT examinations, 30 cases were randomly and independently analysed by two trained operators who repeated the whole analysis of CT from the same acquired data in order to evaluate inter- and intra-observer variability regarding the planimetry of the AVA; the intraclass correlation coefficient was used for this analysis. Confidence intervals were by bootstrap resampling. All tests were two-sided with P < 0.05 indicating statistical significance. Tests were not corrected for multiple testing.

Results

Among 131 patients initially assessed for inclusion, five refused to give their consent, eight were excluded because of renal failure or allergy, seven because of heart rate >100 b.p.m., and four had no reliable Doppler measurement and refused TEE. Finally, CT analysis of the aortic area was not feasible in four patients because of a bad signal/noise ratio or arrhythmia-related artefacts. Table 1 describes the characteristics of the 103 included patients. Echocardiographic LV ejection fraction was 61 ± 14%. Echocardiographic AS was diagnosed in 30 patients (mean AVA = 80 ± 27 mm²) and was graded as follows: 15 critical, 11 severe, four moderate or mild.

Echocardiography

Echocardiographic examination was systematically performed by a trained operator (C.S. or T.T.) blinded to the CT results. The mean delay between CT and echocardiographic examination was 2 (1–13) days. The AVA was measured by Doppler-based continuity equation and/or 2D quantification from transesophageal echocardiography if necessary. Patients with a normal M-mode aortic valve (valvular opening >15 mm) and normal transvalvular velocity (peak systolic Doppler velocity <1.5 m/s) were classified as non-stenotic. Otherwise, the valvular area was calculated with the continuity equation, \( AVA = \frac{\pi \times D^2}{2} \times \frac{VTI_{DVOT}}{VTI_{AVO}} \), where \( D \) is the LVOT diameter and \( VTI_D \) the Doppler-based velocity-time integrals through the aortic valve (VTI_{AVO} or LVOT (VTI_{LVOT}). We averaged \( VTI_{AVO} \) on the three highest velocities and \( VTI_{LVOT} \) on three consecutive heartbeats when a Doppler click of aortic valve closure was identified. Improper imaging of the aortic valve and ascending aorta, mainly in the case of limited apical acoustic window, required transesophageal echocardiography to allow direct planimetry of the AVA. Transesophageal echocardiography was performed with the use of a multiplane probe. The planimetry was usually performed in a 30–50° plane, when the aortic valve annulus appeared circular and all cusps were seen at the same time. Subtle movements of the probe allowed for precise identification of the smallest AVA at the time of maximal systolic opening. Three measures were averaged. Stenosis was graded according to the American College of Cardiology (ACC)/American Heart Association (AHA) classification: mild (150–200 mm²), moderate (>100–150 mm²), severe (>75–100 mm²), and critical (<75 mm²). LV ejection fraction was measured by the use of the Simpson biplane method.

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Figure 1 Representative CT of severe aortic stenosis. CT imaging shows fibrous cusps with few calcifications; AVA is 64 mm².
Transesophageal imaging was required in 17 patients (only three with AS). During the CT examination, the mean heart rate was 71 ± 16 b.p.m. and the optimal phase for aortic valvular measurement was 10% of the R–R cycle in 9 patients, 20% in 67 patients, 30% in 30 patients and 40% in one patient. The mean CT-based AVA was 244 ± 133 mm² (range 27–555 mm²). CT imaging identified 30 instances of AS, graded as 12 critical, 12 severe, four moderate, and two mild. The intra- and inter-observer agreements were very good with intraclass correlation coefficient of 0.99 for both (95% CI 0.99–1.00). Heavily calcified valves were easier to delineate with the MIP technique. Purely fibrous stenoses were analysed with the MinIP technique. Mixed stenoses required concordant analysis of both rendering techniques. Bicuspid was diagnosed in six patients from both CT and echocardiographic analysis. The acquisition time of CT data ranged between 18 and 25 s, the examination time between 7 and 11 min, and the post-processing time for AVA planimetry ranged between 10 and 18 min.

Among the 30 patients with echocardiographic AS and AVA ≤ 200 mm², the CT-based AVA was 87 ± 33 mm². The Bland and Altman analysis showed good agreement between echography and MSCT (Figure 3) with a mean difference of −7 mm² (95% CI: −40–25 mm²).

According to the ACC/AHA classification, CT and echocardiographic grading matched in 21 patients and differed by one class in nine patients: seven were overestimated and two were underestimated by CT imaging (Table 2).

**Table 1** Main characteristics of patients

<table>
<thead>
<tr>
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<th>Whole population (n = 103)</th>
<th>Aortic stenosis (n = 30)</th>
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<tbody>
<tr>
<td>Age (years)</td>
<td>62.1 ± 13.2</td>
<td>69.9 ± 12.4</td>
</tr>
<tr>
<td>Male, n (%)</td>
<td>63 (61)</td>
<td>18 (59)</td>
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<tr>
<td>LVEF</td>
<td>0.61 ± 0.14</td>
<td>0.73 ± 0.11</td>
</tr>
<tr>
<td>Coronary artery disease, n (%)</td>
<td>33 (32)</td>
<td>5 (17)</td>
</tr>
<tr>
<td>Hypertrophic or dilated cardiomyopathy, n (%)</td>
<td>42 (41)</td>
<td>25 (83)</td>
</tr>
<tr>
<td>Aortic aneurysm, n (%)</td>
<td>15 (15)</td>
<td>2 (7)</td>
</tr>
<tr>
<td>Bicuspid valve, n (%)</td>
<td>6 (6)</td>
<td>5 (17)</td>
</tr>
<tr>
<td>Other valvulopathy, n (%)</td>
<td>9 (9)</td>
<td>2 (7)</td>
</tr>
<tr>
<td>Pericardial disease, n (%)</td>
<td>10 (10)</td>
<td>0</td>
</tr>
<tr>
<td>Congenital disease, n (%)</td>
<td>9 (9)</td>
<td>0</td>
</tr>
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</table>

**Discussion**

This study shows that CT imaging of AS is feasible and reliable when compared with echocardiography. We demonstrate the relevance of 16-slice MSCT for diagnosing and grading AS.

Cardiac CT is a fast, non-invasive, well-tolerated, and reproducible imaging method with reliable diagnostic accuracy when compared with echocardiography. CT-based and
echocardiographic measurements of the AVA are closely related and the ACC/AHA classification is similar for the two techniques, which should lead to similar therapeutic management.

Advantages and recent improvements in MSCT analysis

The spatial resolution of cardiac CT has improved since the advent of spiral 16-slice acquisitions: voxel size is now reduced to 0.625 mm in the Z-axis and 0.5 mm in the X and Y-axes, which compares favourably with echocardiography measurement. Temporal resolution has improved with increased rotating speed; our 16-slice CT achieves a complete revolution in 400 ms and, thus, allows for a temporal resolution of 80–200 ms. In the 60–100 b.p.m. range, aortic ejection accounts for about 30% of the cardiac cycle (i.e. 180–300 ms of the aortic valve opening, which can be slightly reduced in critical AS). Interestingly, the newer 64-slice CT will further improve the temporal resolution. In addition, cardiac CT results in a unique 3D image, which allows for analysis of the aortic valve in any plane and with various rendering techniques (multiplanar reformat, volume rendering, navigation) (Figure 4). Radiography is less sensitive to calcium artefacts than ultrasoundography and thus more reliable when calcifications are present. Importantly, intra- and inter-observer variabilities of CT measurements were very low in our study. In contrast to Doppler-based measurement, the pure anatomic approach of CT imaging is independent of inotropism as well as load, which may explain some differences between the two techniques.\textsuperscript{5–10} In our study, CT-based AVA is slightly larger than Doppler-based AVA, the latter representing the functional, effective valve opening which is smaller than the anatomic valve. Cardiac CT displays anatomic information comparable to transesophageal echocardiography\textsuperscript{11} (shape of the orifice, commissure, bicuspid valve, AVA, localization of coronary ostia, grading of calcification, enlargement of the aorta, atheroma, and calcification of the ascending aorta) but also offers imaging of the coronary tree and the LV function in the same examination. Finally, the need for preoperative coronary angiography could be reduced because MSCT is becoming a reliable tool for diagnosing coronary artery disease.\textsuperscript{12,13}

### Technical limits of MSCT

The heart rate variability remains the main limiting factor of CT analysis; atrial fibrillation, unstable sinus rhythm, and ventricular premature beats are responsible for band artefacts (two patients in our study). At the time of this study, we did not use beta-blockers, but now such medications are frequently prescribed and result in less heart rate-related artefacts. In addition, patients must be able to hold a breath during 25–30 s with 16-slice MSCT, but this duration is now reduced to 10–15 s with newer 64-slice MSCT. Heavily calcified cusps are a theoretical limitation for CT analysis because of the blooming artefact. In fact, such an effect is limited to adjacent voxels after proper adjustment of window/centre setting and is less worrying than with coronary imaging. In patients with low cardiac output, echography using dobutamine stress is advised because of the risk of AVA underestimation, and ultrasound analysis appears more suitable for such cases than MSCT. It should be reminded that MSCT use is limited in patients with renal failure and allergy and requires caution in patients with severe LV dysfunction. At last, CT-related radiation exposition is close to cardiac catheterism;\textsuperscript{14} the delivery dose from CT ranged between 10 and 17 mSv in our study.

### Comparison with magnetic resonance imaging

Several authors demonstrated that MRI could be used to analyse the AVA.\textsuperscript{15–18} However, when compared with MSCT, MRI is not feasible in patients with pacemakers, implantable defibrillators, vascular clips or claustrophobia, it does not allow for visualization of calcifications, signal voids are caused by turbulent flows, it offers poor imaging of the coronary tree, and it is time-consuming (40–60 min) and more expensive.

### Limitations of the study

The sample size of the study was relatively small. Patients with mild/moderate AS are under-represented because of recruitment bias, but the strong diagnostic accuracy and the relationship we showed in patients with severe AS suggest that MSCT should be reliable in all ranges of valve areas. In our study, we did not have the advantage of a gold standard such as haemodynamics or surgical findings. CT measurements were compared only with echocardiographic measurements. In fact, this study aimed to show...
how CT results are close to echocardiographic results and how CT examination could possibly substitute for the latter.

**Conclusion**

Cardiac CT is a promising new technique for comprehensive assessment of aortic valvular anatomy and for diagnosing AS. Although ultrasound examination is the current first-line imaging, MSCT can be of value when echocardiographic examination is technically difficult and/or does not match the clinical data. The combined use of echocardiography and CT imaging challenges the requirement for cardiac catheterism, especially in cases of pathological ascending aorta or low probability of coronary disease.

**Conflict of interest:** J.-L.S. has received fees for speaking a meetings funded by GE Healthcare. All other authors have no conflict to declare.

**References**


