An Insight Into Transcatheter Aortic Valve Implantation—A Perspective From Multidetector-Computed Tomography

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Transcatheter aortic valve implantation (TAVI) has now become an acceptable alternative to surgical aortic valve replacement for patients with severe aortic stenosis at high risk. The early enthusiasm for this technology has not diminished but rather has developed at an unprecedented rate over the last decade. Alongside the developments in implantation technique, transcatheter design, and postprocedural care, cardiac imaging modalities have also had to concurrently evolve to meet the perpetual demand for lower peri- and postprocedural complication rates. Although transthoracic and transesophageal echocardiography remain vital in patient’s selection and peri-procedural guidance, there is now emerging evidence that indicates that multidetector-computed tomography (MDCT) may also have an equally important role to play. The aim of the current review is to examine the modern role of MDCT in assessing patients with aortic stenosis being considered for TAVI.

Key words: aortic valve; aortic stenosis; computed tomography; transcatheter aortic valve implantation

MULTIDETECTOR-COMPUTED TOMOGRAPHY AND AORTIC STENOSIS—AORTIC VALVE CALCIFICATION

Although transthoracic echocardiography remains the mainstay for the evaluation of patients with aortic stenosis (AS), multidetector-computed tomography (MDCT) has received much recent interest. One of the primary reasons for this is the recognition that valvular calcification is a hallmark of AS and that extensive aortic valve calcification (AVC) is predictive of a poor clinical outcome [1]. Electron beam-computed tomography, and the later MDCT, has the distinct ability to not only accurately detect (Fig. 1), but also quantify AVC using Agatston units [2,3]. The degree of valvular calcification in turn has been shown to relate to the peak transvalvular gradient [4,5], the effective valve orifice area [2], and also the mean transvalvular gradient [4] measured echocardiographically. Although thresholds for AVC to predict the presence of severe AS have been proposed, these are variable, and accordingly no general consensus exists. In clinical practice, the presence of aortic calcification on MDCT should alert the clinician as to the possibility of AS and with increasing levels of calcification prompting referral to echocardiography.

AORTIC VALVE STENOSIS—MEASUREMENT OF SEVERITY BY VALVE AREA

With the rapid advancements in MDCT scanner technology over the last decade, it is now possible to

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image the aortic valve and aortic root at sub 0.6 mm resolution with three-dimensional (3D) isotropic imaging, at any stage of the cardiac cycle. This strength of MDCT permits the measurement of the aortic valve area (AVA) by direct planimetry. Studies comparing the AVA measured on MDCT show good correlation, but systematic overestimation, when compared with the EOA measured echocardiographically. In a recent meta-analysis by Shah et al. of nine studies involving a total of 437 patients, the mean AVA measured by MDCT was $1.0 \pm 0.1 \text{ cm}^2$ compared with a mean EOA of $0.9 \pm 0.1 \text{ cm}^2$ measured by transthoracic echocardiography ($r = 0.89$, 95% confidence interval [CI] $= 0.84–0.93$) [6]. The overall mean-weighted difference was reported to be $0.03 \pm 0.05 \text{ cm}^2$. Another meta-analysis of 14 studies and involving 470 patients by Abdulla et al. [7] showed similar findings with MDCT significantly overestimating the AVA with a bias of $0.08$ (95% CI $= 0.04–0.13$, $P < 0.001$) when compared to echocardiography. Although this suggests that MDCT may be inaccurate for estimating the EOA, this difference is likely explained by the differences in techniques by which the valve area is estimated. Although echocardiography derives the EOA by the continuity equation that relies on Doppler flow information at the left ventricular outflow tract, the cross-sectional area of the outflow tract and flow across the stenosed aortic valve, MDCT relies on the direct visualization and planimetry of the valve opening area. In the continuity equation, it is assumed that the left ventricular outflow tract is circular; however, the studies with MDCT have shown that the LVOT is more ellipsoidal in shape [8,9]. Consequently, the AVA measured by the continuity equation is smaller than that measured by direct anatomic measurement. Halpern et al. [10] studied 41 patients, all of who underwent MDCT and echocardiography. The authors found that the anatomically measured LVOT area was on average $0.6 \text{ cm}^2$ greater than the LVOT area derived by echocardiography. When the authors substituted the MDCT LVOT area into the continuity equation, the correlation between the planimetered AVA and the corrected continuity AVA improved from $r = 0.65$ to 0.88, and the difference between the planimetered AVA and the continuity AVA decreased from 0.6 to 0.16 $\text{ cm}^2$ ($P = 0.36$). Recently, it has been proposed that the integration of MDCT 3D imaging data into the assessment of AS, by means of a corrected continuity equation, may lead to important disease severity reclassification and an improvement in concordance between echocardiographic markers of AS severity [9].

Despite the emerging evidence that the continuity equation may underestimate the AVA, echocardiographic techniques remain the gold standard for the assessment of AS. International guidelines for the treatment of patients with AS are based on evidence that has been derived from echocardiography [11,12]. MDCT is limited in that it provides predominantly anatomic information with only isolated studies suggesting a capability for physiological assessment [13]. Furthermore, MDCT involves ionizing radiation exposure, an intravenous contrast injection and is prone to interpretation difficulties in the presence of significant calcium (blooming artifact) and arrhythmias. Accordingly, MDCT should not be considered a first line investigation for the investigation of AS severity, but moreover a second line complementary investigation where discrepancies exist or echocardiographic image quality is significantly reduced owing to poor acoustic windows.

**MDCT AND TRANSCATHETER AORTIC VALVE IMPLANTATION**

One of the major noncoronary areas where MDCT has a particular strength is in the assessment of suitability of patients being considered for transcatheter aortic valve implantation. Although with conventional surgical aortic valve replacement surgeons have direct visualization of the aortic valve, the aortic root and their respective geometries, with transcatheter aortic valve implantation (TAVI) this is not available and the need for 3D anatomic information becomes more important. Implantation rates of transcatheter aortic valves are ever increasing [14] and operators continue to strive for low complication rates, reduced rates of paravalvular regurgitation, and increased patient longevity. Although initial guidelines for TAVI suitability including aortic annulus size, annulus-coronary ostia height, ascending aortic dimensions, and iliac and femoral artery diameters were developed with echocardiography and fluoroscopic imaging modalities in mind, there is emerging evidence that suggests that MDCT has a valuable contribution, if not vital contribution, to make.

Studies assessing aortic valve characteristics and aortic root geometry with MDCT have provided much insight into TAVI implantation. Stolzmann et al. [15] observed no significant difference in either the height of the left or the right coronary ostia from the aortic annulus in consecutive patients with AS compared to controls. However, as with prior reports they confirmed a lower height of the aortic annulus to the left coronary ostia and documented a high variability in this distance (7.7–28.5 mm) (Fig. 2). The authors also documented larger aortic annulus sizes for patients with severe AS.

One of the key factors determining transcatheter valve size selection is also the aortic annulus diameter. In this respect, MDCT has been shown to best correlate with direct surgical sizing. Yano et al studied 55
patients all of whom underwent surgical aortic valve replacement and compared the surgical aortic annulus sizing against MDCT, transthoracic echocardiography (TTE), and contrast angiography [16]. The authors showed that the surgical aortic annulus size (23.7 ± 3.99 mm) was best predicted by MDCT (23.9 ± 3.19

Fig. 1. Calcification at various levels of the aortic valve. (A) Heavy calcification at the aortic valve annulus, (B) calcification extending up to the mid-level of the aortic valve cusps, and (C) minimal calcification at the cuspal margins. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

Fig. 2. Annulus to coronary ostia measurements. (A) The measurement of the distance from the annulus to the left mainstem ostia and (B) the distance to the right coronary ostia.
mm) when compared with TTE (20.3 ± 2.5 mm) and contrast angiography (23.5 ± 3.55 mm). Similarly, Dashkevich et al. showed that intraoperative measurements of aortic annulus size correlated better with average annulus size measured by MDCT (r = 0.93, P < 0.001) than by transesophageal echocardiography (r = 0.52, P = 0.002) [17]. Furthermore, annulus measurements from TTE assume the aortic annulus to be circular. Recent studies with MDCT have, however, shown that aortic annulus is commonly ellipsoid in shape [15,18–20]. Tops et al. [18] showed, in 159 patients, of whom 11% had moderate or severe AS, that up to 50% of patients had an ellipsoid-shaped annulus with the coronal annulus dimension being on average 2.9 ± 1.8 mm greater than in the sagittal plane (corresponding echocardiographic plane). It is estimated that owing to annulus sizing differences, a strategy utilizing MDCT annulus measurements potentially changes TAVI implantation and sizing in up to 40% of patients [21,22]. Whether this translates to an improved outcome or reduced complication rates is an on-going area of research.

The frequency of paravalvular regurgitation following TAVI is significant [23,24] and more than mild paravalvular regurgitation has been shown to be a significant independent predictor of outcomes between 30 days and 1 year [25]. It has been suggested that annulus geometry and correct valve sizing may be important in limiting significant regurgitation. In a study of 53 patients undergoing TAVI, Delgado et al. [26] evaluated aortic annulus size using MDCT and re-evaluated TAVI deployment at 1 month. The authors found that the incidence of moderate paravalvular regurgitation was related to the degree of AVC of the native aortic valve, a larger annulus size and also noncircular deployment of the prosthesis that was well visualized on MDCT. Willson et al. studied 109 consecutive patients who underwent MDCT pre-TAVI and found that moderate or severe paravalvular regurgitation was

![Fig. 3. Aortic annulus measurements. Measurements of the aortic annulus are taken at the level of the basal annulus ring which is defined as the level where the nadir of all three cusps can be seen in one imaging plane (A). At this level, the major and minor aortic annulus dimensions can be measured and the mean annulus measurement derived (B). These measurements can also be used to derive an eccentricity index (C). Tracing around the aortic annulus gives the annulus perimeter and annulus area from which annulus diameter measurements can be made (D). [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]](image-url)
associated with TAVI undersizing in respect to the mean annulus diameter and the area-derived annulus diameter measured by MDCT [27]. The authors proposed that modest oversizing of the transcatheter aortic valve might reduce the rates of moderate or severe paravalvular aortic regurgitation, while maintaining a circular deployment and complete expansion of the TAVI. In another study comparing 2D TEE annulus sizing against MDCT to guide TAVI, Jilaihawi et al. found that not only MDCT measures were of annulus size superior in predicting greater than or equal to mild regurgitation but also that an MDCT strategy would have resulted in a reassignment of TAVI size in up to 50% of cases [28]. In a comparison of rates of paravalvular regurgitation between a TEE (96 patients) and MDCT (40 patients) guided strategy, the authors found that a MDCT resulted in a reduction in the rate of mild-moderate regurgitation from 7.5 to 2.5%, moderate regurgitation from 10.8 to 2.5%, and moderate–severe regurgitation from 2.2 to 0%. Other areas where MDCT may be of benefit in planning TAVI implantation and reducing significant aortic regurgitation is by defining the angle of the LVOT to the aorta and the final depth of the prosthesis below the aortic annulus at the NCC [29]. A study has also suggested that MDCT may be used to predict optimal angiographic projections for valve deployment [30]. Correct valve sizing may also be important in also reducing postprocedural heart block. Bleiziffer et al. showed in their study of 159 patients of patients undergoing TAVI that procedural heart block was more likely in those patients in whom a large valve was implanted in a small annulus [31].

MDCT FOR TAVI ASSESSMENT

Owing to its high spatial resolution and isotropic voxels, MDCT has the capability to reconstruct the annulus in its true plane by double oblique imaging. At the basal annular ring, which can be defined as the point where the nadir of all three coronary cusps can be visualized, a number of different annulus measurements can be obtained. These include the maximal and minimal annulus diameters, the major and minor diameters along with the mean diameter, the eccentricity index \((1 - \frac{\text{minor/major diameter}}{100})\), the diameter derived from the annulus perimeter \((\text{perimeter}/\pi)\), the annulus area and the diameter derived from the annulus area \((2 \times \sqrt{\frac{\text{area}/\pi}{p}})\) (Fig. 3). Although this is an evolving area of research and no generally accepted guidelines exist as which measure to use, the most reproducible measures appear to be the mean diameter, the annulus area, and the diameter of the annulus derived from the perimeter [27,28]. Additional standard TAVI protocol measurements include the diameter at various levels of the aorta along with the distribution of any aortic wall calcium (Fig. 4). A further analysis is also performed of the iliac and femoral arteries for vessel calibre size, calcification, and vessel tortuosity, which is an important consideration in planning access for the TAVI procedure.

CONCLUSIONS

Recent studies with MDCT have improved our understanding of aortic root geometry and annulus configuration. These findings are now helping to guide TAVI operators to further to optimize valve sizing and...
deployment in an attempt to minimize periprocedural complications and postprocedural paravalvular regurgitation. Although further studies are required to determine how best to use the host of information available from MDCT, there is a growing body of evidence, suggesting that its routine use where possible should be considered.

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