Multislice Computed Tomography for Prediction of Optimal Angiographic Deployment Projections During Transcatheter Aortic Valve Implantation

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Objectives This study assessed whether multislice computed tomography (MSCT) could predict optimal angiographic projections for visualizing the plane of the native valve and facilitate accurate positioning during transcatheter aortic valve implantation (TAVI).

Background Accurate device positioning during TAVI depends on valve deployment in angiographic projections perpendicular to the native valve plane, but these may be difficult to determine.

Methods Twenty patients underwent MSCT before TAVI. Using a novel technique, multiple angiographic projections accurately representing the native valve plane in multiple axes were determined. The accuracy of all predicted projections was determined post-procedure using angiography according to new criteria, based on valve perpendicularity and the degree of strut overlap (defined as excellent, satisfactory, or poor). The accuracy of valve deployment using MSCT was compared with the results of 20 consecutive patients undergoing TAVI without such MSCT angle prediction.

Results Correct final deployment projections were more frequent in the MSCT-guided compared with non–MSCT-guided group: excellent or satisfactory projections (90% vs. 65%, p = 0.06). The MSCT angle prediction was accurate but dependent on optimal images (optimal images: 93% of predicted angles were excellent or satisfactory, suboptimal images: 73% of predicted angles were poor). A “line of perpendicularity” could be generated with optimal projections across the right-to-left anterior oblique plane by adding the correct cranial or caudal angulation.

Conclusions Pre-procedural MSCT can predict optimal angiographic deployment projections for implantation of transcatheter valves. An ideal deployment angle curve or “line of perpendicularity” can be generated. Understanding and applying these principles improves the accuracy of valve deployment and may improve outcomes. (J Am Coll Cardiol Intv 2010;3:1157–65) © 2010 by the American College of Cardiology Foundation
valve plane in a given patient. As the native aortic valve is typically directed cranially, to the left, and slightly anteriorly, the right anterior oblique (RAO) views tend to require caudal angulation and the left anterior oblique (LAO) views require some cranial angulation. However, patients’ anatomy varies, necessitating individualized assessment and understanding.

Operators may use their own preferred projections during TAVI. However, to more accurately determine the valve plane, multiple orthogonal aortic root angiograms can be performed until an angiographic projection angle is found in which the base of all aortic valve cusps/sinuses of Valsalva are on a straight line (Fig. 1). The valve plane is thus perpendicular to the image intensifier. However, this may be difficult to determine and incorrect projections may result in suboptimal valve positioning.

Multislice computed tomography (MSCT) has shown utility in TAVI (6–9). It has been suggested that MSCT may be helpful in predicting angiographic projection angles (10). We describe a novel method of predicting optimal angiographic deployment projections for TAVI and assess whether such predictions may result in improved valve positioning and outcomes.

**Methods**

**Patient selection.** Twenty patients undergoing TAVI underwent MSCT as part of their pre-procedural work up. Exclusion criteria included a glomerular filtration rate < 35 ml/min or known severe peripheral vascular disease (not planned for an MSCT to assess femoral access). Patients with bicuspid aortic valves were excluded as such valves typically show significant cusp asymmetry (11,12). All patients were deemed, by a team of senior cardiologists and cardiothoracic surgeons, at prohibitive or excessive surgical risk and were not candidates for open-heart surgery. All patients gave written informed consent to the procedure and MSCT evaluations.

MSCT was used to recommend angiographic projection angles to facilitate correct representation of the aortic valve plane. These angles were available to the implanting physician at the time of the procedure. The decision whether to use 1 of the predicted angles was at the operator’s discretion. Following valve implantation, the actual implant angle and all other predicted angles were evaluated by fluoroscopic examination to determine their accuracy.

**MSCT image acquisition.** The MSCT examinations were performed on 2 64-slice scanners (GE Healthcare, Milwaukee, Wisconsin). From 80 to 120 ml of ioxudol 320 (GE Healthcare, Princeton, New Jersey) was injected at 5 ml/s followed by 30 ml of normal saline. The MSCT scanner detector collimation width was 0.625 mm, detector coverage was 40 mm, reconstructed slice thickness was 1.25 mm, and the slice interval was 1.25 mm. Gantry rotation time was 0.35 s and the scan pitch ranged between 0.16 and 0.20 (adjusted per heart rate). Electrocardiogram-gated dose modulation was used for all cases.

**MSCT image reconstruction and analysis.** A 3-dimensional volume-rendered transparent reconstruction of the thoracic aorta was performed using a transparent display to help mitigate the negative effects of significant valve calcification (Fig. 2). Reconstructions were developed from double oblique transverse images with points deposited at the most inferior aspects of the valve cusps. From these points, a triangular trace was created that connected the 3 points corresponding to the most inferior aspects of the valve cusps. From these points, a triangular trace was created that connected the 3 points corresponding to the most inferior aspect of the aortic cusps.

Two physicians with extensive cardiac MSCT experience reviewed all cases. By convention, 3 angles were determined by a consensus between operators by manually rotating the 3-dimensional aortic reconstructions to discern the appropriate angles for implant (Fig. 3). Angles were generated on the following 3 axes: 1) cranial-caudal with no RAO or LAO angulation; 2) straight RAO to LAO as needed with no cranial or caudal angulation; and 3) LAO 30° with cranial or caudal angulation as needed. The angle was deemed appropriate when the triangle was not evident and was replaced by a line, suggesting that the 3 deposited points were in line (Fig. 3, Online Video 1). Given the early nature of the work and significant aortic root/valve calcification, these angles were recorded with a
confidence and image quality consensus Likert score of 1 to 3, defined as:

1. Suboptimal—Evaluation is limited by motion, calcification, poor contrast opacification, and/or gating. Image quality limits confident angle prediction (Online Video 2).
2. Adequate—The images show minimal valve plane degradation due to calcification, motion, or contrast issues. Angle of implant prediction can be performed with reasonable confidence.
3. Excellent—The aortic valve plane is very well visualized without limitations in discerning the valve cusps. Motion and calcification do not degrade image quality. Angle prediction is performed with a high degree of confidence.

For patients with differing scores, the operator endeavored to use a prediction angle with the highest Likert score for the actual valve implantation.

Post-valve implantation angiographic evaluation. Detailed angiographic evaluation of the implanted valves was performed in all cases. Alignment of the stent in the implanted and other predicted angles was assessed by analyzing the implanted valve stent frame and determining the degree of overlap of the superior cell struts (Fig. 4). The angiographic projection was defined as excellent, satisfactory, or poor, depending on the degree of overlap as outlined here (Fig. 4):

- Excellent—Gap between superior valve struts is within half a cell height.
- Satisfactory—Gap between superior valve struts is between half to a whole cell height.
- Poor—Gap between superior valve struts is greater than the height of a full cell.

To assess the accuracy of MSCT angle prediction, angiographic evaluation was performed in each projection angle predicted by MSCT, allowing for post-implant assessment of each of the 3 predicted angles in all 20 patients (60 angles evaluated).

To determine the accuracy of the actual final deployment angle, the deployment angle in the MSCT-guided group was compared with the proceeding 20 consecutive patients who underwent TAVI without angle prediction.
using MSCT (non–MSCT-guided group). In the latter cases, only orthogonal aortic root angiography was used to assess the aortic valve plane before implantation. **Determining an ideal deployment angle curve using CT: the “line of perpendicularity.”** To determine the average cranial or caudal angulations required across the RAO-to-LAO axis to result in correct perpendicular valve implant projections, a retrospective analysis of patients who had undergone MSCT or DynaCT imaging after TAVI at our institution was performed. In cases using DynaCT (Siemens AG, Erlangen, Germany), the angiographic C-arm using a monoplane flat-panel 30 cm × 40 cm detector angiographic suite was used. Image reconstruction was performed on a commercially available dedicated workstation (Syngo X Workplace, Siemens Healthcare, Erlangen, Germany).

Following image reconstructions using MSCT or DynaCT, 3-dimensional rotations were performed so the implanted valve lined up perpendicular to the valve plane in each projection (Fig. 5). Starting at RAO 45°, the appropriate caudal/cranial angle was added until the valve lined up perpendicularly, followed by similar reconstructions at 5° intervals until LAO 45°. The mean cranial or caudal
projection needed at each point along the RAO to LAO spectrum was then determined and plotted.

**Statistical analysis.** Continuous variables are described as mean ± SD when normally distributed or as medians with interquartile ranges (IQR) when not. Normality was tested using the Shapiro-Wilk goodness-of-fit test. Categorical variables are described by frequencies and percentages. Comparison of categorical variables was performed using a chi-square analysis. Comparisons of continuous variables were performed using Student t tests. Analyses were performed using SPSS version 17.0 (SPSS Inc., Chicago, Illinois).

**Results**

**Baseline characteristics.** There were no significant differences between the 2 groups (Table 1). The mean age (MSCT-guided: 83.2 ± 5.2 years vs. non–MSCT-guided: 84.6 ± 5.8 years, p = 0.68), the mean Society of Thoracic Surgery risk score (MSCT-guided: 8.6 ± 3.4% vs. non–MSCT-guided: 8.4 ± 3.6%, p = 0.45), and proportion of transfemoral procedures (MSCT-guided 80% vs. non–MSCT-guided: 70%, p = 0.47) were all similar.

**Clinical outcomes.** Forty patients underwent TAVI. Overall procedural success was 100% (Table 2). There was no in-hospital mortality. There were no cases of valve embolization or coronary obstruction. There were similar rates of post-procedural aortic incompetence, all of which were trivial or mild. There were no cases of worsening mitral regurgitation or mitral valve impingement. No patients suffered renal failure due to the contrast load from the MSCT scan.

**Predicting valve plane orientation using MSCT.** In the cranial-caudal axis, the median predicted angle was caudal 20° (IQR: 7° to 40°). In the straight RAO-LAO (no cranial or caudal) axis, the median predicted angle was LAO 14° (IQR: 9° to 24°). In the LAO 30° cranial/caudal axis, all but 4 patients required the addition of cranial angulation. Three patients had a predicted cranial-caudal axis projection of caudal >45°, and 1 patient had a predicted straight RAO-LAO projection LAO >45°. The latter patient had severe spinal kyphoscoliosis and an unfolded aorta with predicted cranial-caudal axis angle of caudal 43° and LAO 30° cranial/caudal axis angle of LAO 30°/caudal 14°.

**Table 1. Baseline Characteristics**

<table>
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<th>No MSCT Angle Prediction (n = 20)</th>
<th>With MSCT Angle Prediction (n = 20)</th>
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<td>8.4 ± 3.6</td>
<td>8.6 ± 3.4</td>
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</table>

Values are mean ± SD or %.

GFR = glomerular filtration rate; MSCT = multislice computed tomography; NYHA = New York Heart Association; STS = Society of Thoracic Surgeons.
Use of MSCT-predicted angles during TAVI. An angiographic projection angle as predicted by MSCT was used as the final implant angle by the TAVI operator in 16 cases (80%). Of 4 cases where predicted angles were not used, in 3 the valve was deployed in a satisfactory or excellent projection, and in 1 case the projection was poor. The Likert scores in these 4 cases were generally low (only 2 of 12 predicted angles with Likert 3), indicating poor MSCT image quality. Of the 12 predicted angles in these 4 patients, 58.3% were subsequently assessed as poor. In the case where deployment was in a poor projection, MSCT predicted 2 excellent angles and 1 poor.

Impact of MSCT angle prediction on valve deployment. The 20 patients who underwent TAVI with pre-procedural MSCT angle prediction were compared with the proceeding consecutive cohort of 20 patients that had TAVI without MSCT angle prediction. When MSCT was used, an excellent or satisfactory final valve implant projection angle was achieved in 18 cases (90%) versus 13 cases (65%) when MSCT was not used (p = 0.06) (Fig. 6). The reduction in poor projection angles was from 35% to 10% (p = 0.06).

Accuracy of MSCT angle prediction. Angiographic images were obtained in all the different MSCT-predicted angles for each patient after valve implantation. The accuracy was similarly determined by the perpendicularity of the valve in each of the predicted angle projections. Overall, MSCT predicted an excellent or satisfactory angle in 75% of cases.

Impact of optimal MSCT images. The accuracy of MSCT angle prediction was analyzed according to the Likert confidence scale. Likert confidence scores were 1 for 15 predictions, 2 for 14, and 3 for 31. In those with Likert score of 1, 73% of predicted angles were poor. In those with Likert score 2, 57% were excellent, 29% were satisfactory, and 14% were poor. In those with Likert score 3, 74% were excellent, 20% were satisfactory, and 6% were poor (Fig. 7).

The Likert score was generally similar for all 3 predicted angles in any given patient. In 95% of cases, all Likert scores were either the same or within 1 score for all projections.

**Figure 6. Accuracy of Valve Deployment Without Versus With MSCT Angle Prediction**

When multislice computed tomography (MSCT) was used, an excellent or satisfactory final valve implant projection angle was achieved in 90% of cases versus 65% of cases when MSCT was not used (p = 0.06).

**Figure 7. Accuracy of Prediction Angle According to the Likert Confidence Score**

If multislice computed tomography is of high quality, the predictive accuracy is high. If the quality is low, the predictive accuracy is low.
Determination of the line of perpendicularity: the spectrum of angiographic projections resulting in valve implantation perpendicular to the valve plane. Twenty-seven patients underwent CT evaluation following TAVI (15 had MSCT and 12 had DynaCT). The resulting mean caudal or cranial angulation required at each angle across the RAO-to-LAO spectrum follows a curve crossing the cranial-caudal axis at caudal 10° ± 14°, and the RAO-to-LAO axis at LAO 10° ± 14° (Fig. 8).

In the RAO projection, caudal angulation is usually required to obtain the correct perpendicular projection. In the LAO projection, cranial angulation is usually needed. The amount of caudal angulation needed at RAO 45° is greater than the amount of cranial angulation needed at LAO 45° (RAO 45°/caudal 40° vs. LAO 45°/cranial 27°).

Discussion

The present study demonstrates that MSCT can correctly predict angiographic projection angles perpendicular to the aortic valve plane and help guide TAVI procedures. Prediction is best when MSCT image quality is optimal, resulting in greater accuracy of valve deployment, with a reduction in implantation at nonperpendicular angles. The MSCT and angiographic 3-dimensional reconstructions (DynaCT) performed after implantation also demonstrate the average “line of perpendicularity,” showing that valves may be deployed in a wide range of RAO or LAO projections as long as the appropriate caudal or cranial angulation is added—with RAO projections generally needing caudal angulations and LAO projections needing cranial angulations.

Importance of determining the correct valve plane. As the aortic valve and root are 3-dimensional structures viewed on a 2-dimensional screen during TAVI, correct evaluation of the aortic valve plane is necessary for a successful procedure. Operators need to choose an implant projection in which the implanted valve is perpendicular or orthogonal to the native valve plane. If 1 or more of the aortic leaflets is “off-axis,” accurate positioning is difficult to achieve, increasing the risk of malposition, embolization, and procedural complications.

Evaluation of the native aortic valve plane is generally performed by angiographic root angiograms in different projections until the valve cusps line up such that the native valve plane is perpendicular to the image intensifier. In some patients, this may be difficult to achieve, as the presence of heavily calcified leaflets may obscure the remaining cusps. Additional contrast is often required to find an acceptable projection. An advantage of MSCT lies in the ability to acquire images before the procedure and then analyze off-line to help plan the procedure. Peripheral vasculature/femoral access, annular dimensions, extent and distribution of leaflet calcification, and coronary artery position and relationship to bulky calcified leaflets can be assessed concurrently (6–9).

**Figure 8. Line of Perpendicularity**

The graph represents the mean caudal or cranial angulation needed at the spectrum of right-to-left anterior oblique projections (5° intervals) to achieve valve perpendicularity to the X-ray beam. Abbreviations as in Figures 3 and 5.
Utility of MSCT angle prediction. Patients with MSCT-guided TAVI had more frequent implantation in excellent or satisfactory projections compared with non–MSCT-guided procedures (aortography alone). The comparison is one of MSCT prediction in conjunction with aortography versus aortography alone. Multislice CT is additive to aortography, especially in circumstances where the latter may be inadequate in confidently determining the valve plane. Eventually, real-time 4-dimensional coregistered CT may reduce the need for aortic root angiography.

We chose to predict 3 angles, but unlimited reformations and angle combinations can be achieved. Our choice of axes—cranial-caudal with no RAO or LAO, RAO-LAO with no cranial or caudal, and LAO 30° ± cranial/caudal—stems from prior experience and practical considerations in the catheterization laboratory. Future groups using this technology may choose different axes or angles with which they are more familiar, with any point along the line of perpendicularity of a given patient being potentially appropriate. Practical considerations with regard to radiation equipment and ergonomics are also important to consider. For example, if in the cranial-caudal axis, a very steep caudal angle (>40°) is predicted for a given patient, this may be difficult to achieve given the constraints of the patient’s body on the table. Adding LAO may result in less caudal angulation being required. Similarly, very steep LAO or RAO angles may be impractical for the operator given the physical position of the image intensifier or detector. Angle choice may differ for transfemoral versus transapical procedures for similar reasons, with transfemoral operators possibly preferring straight or LAO projections and transapical operators preferring RAO (+caudal) projections.

Recent studies have highlighted the potential role of MSCT in TAVI (6–9). Kurra et al. (10) compared imaging of the aortic root by X-ray angiographic planar imaging and 3-dimensional CT, suggesting the latter can aid in pre-procedural planning. Our study further extends the clinical utility of MSCT in the context of TAVI by demonstrating the ability to predict accurate deployment angles, resulting in improved valve deployment accuracy and reduction of incorrect angle choices, and providing operators with the average cranial or caudal angulations needed for a given RAO or LAO projection.

Our center has a large experience with TAVI. Despite this experience, MSCT was able to improve the frequency of correct angle choice. Multislice CT may have an even greater impact on the results of groups beginning their experience with TAVI.

Importance of optimal MSCT images. We found our predictions to be most accurate when the MSCT images were ideal (with a high Likert confidence grade). When the confidence grade was poor, 73% of the predicted angles would have resulted in suboptimal deployment angles. When the confidence grade was high, >90% of angles were excellent or satisfactory. This has important implications for the widespread use of such technology, especially during the learning curve of each center. TAVI operators should be aware that MSCT-generated predicted angles should be used with caution when the source MSCT images are suboptimal.

During reconstruction of the aortic root, particular attention must be paid to determining the most inferior margin of each aortic cusp from the orthogonal projection of the root. By linking these points in a triangular fashion, with each cusp represented by a point of the triangle, the correct valve plane can be determined even in patients with unfolded, horizontal, or vertical aortas. By rotating the image in 3 dimensions using the triangle for the valve plane, each angiographic projection in which the triangle “disappears” represents perpendicularity to the valve plane. However, if the inferior margin is chosen erroneously for 1 or more aortic cusps, the valve plane chosen may be incorrect.

Line of perpendicularity. Our post-implant CT analysis demonstrates that the average line of perpendicularity follows a curve across the RAO-LAO spectrum. A line of perpendicularity can be generated for each patient before the procedure, with essentially infinite angles along it that could achieve perpendicularity to the valve plane in a given patient. Given the typical plane of the native aortic valve, RAO views tend to require caudal angulation and LAO views some cranial angulation. Operators may choose any degree of RAO to LAO as long as the appropriate cranial or caudal angulation is added. For the average patient, the line of perpendicularity runs from a RAO-caudal projection, crosses the posterior-anterior projection at about 10° caudal and the straight LAO at about 10°, and then continues with increasing cranial requirements for steeper LAO projections. Consequently, if we are unable to perform MSCT secondary to significant renal dysfunction, we routinely do our initial screening aortogram at either straight caudal 10° or LAO 10° and make small adjustments accordingly. This can decrease both contrast and radiation exposure.

Special considerations. Some patients will require steep and unusual projections to achieve perpendicularity to the valve plane. This is particularly so in patients with musculoskeletal abnormalities, kyposcoliosis, or horizontal or unfolded aortas, and here lies a particular advantage of MSCT angle prediction. In such patients, even if image quality is suboptimal, MSCT will allude to the need for an unusual angle and demand closer scrutiny. For example, in 1 patient with severe kyposcoliosis and an unfolded aorta, an unusually steep LAO caudal angle was needed. In this case, MSCT predicted an angle of LAO 30°/caudal 14° (Likert 1). The valve was deployed in this angle and resulted in poor projection (just over 1 cell width) according to our definitions. However, this was not far from an excellent perpendicular projection, which was determined at LAO 45°/caudal 14° after implant. When viewed in posterior-anterior projection with no caudal or cranial and no RAO or LAO, the valve was “down the barrel”; thus, had we used such a
projection, achieving correct positioning would have been highly unlikely. Hence, even though MSCT did not predict a perfect angle in this case, it highlighted an unusual angle need, and brought us within 15° of a perfect projection, and avoided possible malposition.

Other technologies to aid valve positioning. New systems using progress in image acquisition, angiographic 3-dimensional reconstructions, and software development have recently been applied to assist with valve positioning. Whereas DynaCT was used only for post-implant evaluation in the current study, this modality may also be used pre- or periprocedurally to evaluate deployment angles similar to pre-procedural scanning with MSCT. Aortic reconstructions and image interrogations are available rapidly during the procedure. The Shina Systems (Shina Systems Ltd., Caesarea, Israel) aortic valve assistance software can also be used to help integrate 3-dimensional CT data with angiograms and live fluoroscopy and help predict optimal valve plane orientation. Our center has also used the Paieon C-THV (Paieon Inc., Rosh Ha‘ayin, Israel), which is an image acquisition and processing system designed to facilitate TAVI. This stand-alone, real-time system is designed to assist with valve positioning, selection of valve size, and post-implant evaluation (13). Further evaluation is required to determine whether similar results can be achieved using these modalities.

Study limitations. Despite multiple predicted angles of deployment for each patient in the MSCT group, the final choice of angiographic projection or whether to use 1 of the predicted angles was left at the operator’s discretion. This was required given the early nature of the work, because incorrectly predicted MSCT angles may have resulted in dire clinical outcomes. In the 4 cases where the operator chose a different angle, this was largely due to suboptimal MSCT images. As the technique is improved over time, greater reliance and trust in the predicted angles will be possible. The MSCT scans were not performed at the same time as TAVI, thus unusual patient positioning during either procedure may have led to inaccurate angle assessment. To avoid this, we developed protocols to ensure all patients are kept supine during both their diagnostic tests and TAVI.

The similarity of clinical outcomes may be viewed as a limitation of this study. However, our center is highly experienced in TAVI with excellent clinical outcomes as a whole. Larger numbers are likely to be required to show clinical benefits in experienced hands, although centers commencing their TAVI experience may find use of this technology particularly beneficial earlier in the learning curve.

Conclusions

Pre-procedural MSCT predicts optimal angiographic deployment projections in which transcatheter valves should be implanted. Using such predictions improves the accuracy of valve deployment and may reduce malposition. An ideal deployment angle curve or line of perpendicularity that transitions from RAO to LAO and caudal to cranial can be generated.

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REFERENCES


Key Words: aortic stenosis • multislice computed tomography • transcatheter aortic valve implantation.

APPENDIX

For videos, please see the online version of this article.