Computed Tomography for Structural Heart Disease and Interventions

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Abstract

Transcatheter cardiac interventions are a fast evolving field. The past decade has seen the development of transcatheter aortic valve replacement, transcatheter mitral valve repair and replacement, septal defect closure devices and left atrial appendage closure devices for thromboprophylaxis. More than ever, medical imaging is taking a central role in the care of patients with structural heart disease. In this review article we outline the use of MSCT as a tool for diagnosis of structural heart interventions, as well as patient selection, pre-procedural planning, device sizing and post-procedural assessment. We focus on procedures targeting the aortic valve, the mitral valve, the inter-atrial septum and the left atrial appendage.

Keywords

Computed tomography, interventional imaging, structural heart interventions, aortic stenosis, mitral regurgitation, atrial septal defect, thromboembolism prophylaxis, transcatheter aortic valve replacement, transcatheter mitral valve replacement, transcatheter mitral valve repair, left atrial appendage occlusion

Disclosure: P Thériault-Lauzier is co-founder of FluoroCT Software; Marco Spaziano is a consultant for FluoroCT Software; G Martucci is a proctor for Medtronic and a consultant FluoroCT Software; N Piazza is a proctor and consultant for Medtronic and co-founder of FluoroCT Software; B Vaquerizo and J Buithieu have no conflicts of interest to declare.

Received: 1 July 2015 **Accepted:** 24 August 2015 **Citation:** *Interventional Cardiology Review*, 2015; **10**(3):149–54

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Valvular Disease

Aortic valve

Severe symptomatic aortic stenosis (AS) bears a dismal prognosis. The mean survival is 2.0 to 4.7 years after the onset of angina, 0.8 to 3.8 years after the onset of syncope and 0.5 to 2.8 years after the onset of congestive heart failure.¹ Surgical aortic valve replacement (SAVR) is the mainstay of treatment for these patients.² In the last decade transcatheter aortic valve replacement (TAVR) has become an accepted alternative in patients for whom surgery would impart a high or prohibitive risk of mortality or morbidity. TAVR does not require open-heart surgery. Instead, bovine or porcine pericardial prosthetic leaflets are mounted on a metal frame, which is delivered using a catheter via an endovascular or transapical route. The CoreValve US Pivotal Trial showed absolute mortality benefit of TAVR over SAVR of 4.9 % in high-risk patients ($P < 0.001$ for non-inferiority, $P = 0.04$ for superiority) at one year follow up.³ In the Placement of Aortic Transcatheter Valves 1 trial (PARTNER 1 trial), the absolute mortality benefit in TAVR versus SAVR was of 5.4 % at five years ($P = 0.76$).⁴

The dimensions of the aortic valve complex are critical for sizing of device (see *Table 1* and *Figure 1*). The aortic annulus, sinuses of Valsalva, ascending aorta, coronary arteries ostia and any bypass grafts should be assessed in all patients considered for TAVR.⁵ While 2D echocardiography provides valuable haemodynamic information and is readily available, a MSCT-based analysis of the aortic root and vascular access sites has become a *sine qua non* step in the pre-operative evaluation of patients for TAVR.⁶ Device sizing using multi-slice computer tomography (MSCT) has been shown to offer more precise

measurements of the aortic root than echocardiography and thus reduces rates of paravalvular leak (PVL),^{7–10} an independent predictor of post-operative mortality from 30 days to 2 years.^{11–20}

MSCT provides a precise method of evaluating aortic valve calcification (see *Figure 2*). Calcification is particularly important because it correlates with rates of post-intervention PVL.^{9,21–24} It was recently demonstrated that rates of at least moderate PVL increase with left ventricular outflow tract (LVOT) calcification (OR 2.8, [95 % CI 1.2–7.0], $P = 0.022$), and a leaflet calcium volume greater than 235 mm³ for a threshold of 850 HU (OR 2.8 [95 % CI 1.2–6.7], $P = 0.023$).²⁴

One of the most common complications of TAVR is a new left bundle branch (LBBB) or complete atrioventricular (AV) block requiring the implantation of a permanent pacemaker. The pathophysiology of these iatrogenic conduction abnormalities is the mechanical compression of the left bundle branch in the uppermost aspect of the muscular inter-ventricular septum by the TAVR implant (see *Figure 3*). An increased depth of implantation is the most frequently identified predictor of LBBB with both balloon- and self-expandable prostheses.^{25–30} In order to obtain an optimal implantation depth, the operator must minimise parallax inherent to 2D fluoroscopy used during the implantation.³¹ MSCT can be used to plan optimal C-arm angulations,^{32–41} i.e. angulations that present the axis of the aortic root parallel to the fluoroscopic detector (see *Figure 4*). In a recent study,⁴¹ such optimised angulations were associated with a significant decrease in implantation time ($P = 0.0001$), radiation exposure ($P = 0.02$), amount of contrast ($P = 0.001$), and risk of acute kidney injury ($P = 0.03$).

Table 1: Transcatheter Aortic Valve Replacement Manufacturer Recommendations for Pre-procedural Anatomic Evaluation

	Aortic Annulus Diameter, mm	Ascending Aorta Diameter, mm	Sinus of Valsalva Width, mm	Sinus of Valsalva Height, mm	Distance Aortic Annulus to Left Main Ostium, mm	Minimal Iliofemoral Diameter, mm
Medtronic CoreValve						
Evolut 23 mm	18—20†	≤34	≥25	≥15	—	≥6.0
26 mm	20—23†	≤40	≥27	≥15	—	≥6.0
29 mm	23—27†	≤43	≥29	≥15	—	≥6.0
31 mm	26—29†	≤43	≥29	≥15	—	≥6.0
Edwards SAPIEN XT						
23 mm	20—23*	—	—	—	≥10	≥6.0
26 mm	23—26*	—	—	—	≥10	≥6.5
29 mm	26—29*	—	—	—	≥10	≥7.0
Edwards SAPIEN 3						
23 mm	20.7—23.4*	—	—	—	≥10	≥5.5
26 mm	23.4—26.4*	—	—	—	≥10	≥5.5
29 mm	26.2—29.5*	—	—	—	≥10	≥6.0

†: CT perimeter-derived diameter (perimeter/n) *: CT area-derived diameter ($2\sqrt{(\text{Area}/n)}$)^{62,86}

Figure 1: Pre-Transcatheter Aortic Valve Replacement Analysis for the Aortic Root

A: A CT image of the aortic root showing the location of the aortic annulus formed by joining the basal attachment of the aortic leaflets (green), the crown-like leaflet attachment line (red), the outline sinus of Valsalva (yellow), the sinutubular junction (blue) and the outline of the ascending aorta at 40 mm above the aortic valve annulus. B: A volume rendering generated from the CT scan. C: A double oblique multiplanar reconstruction showing the aortic valve annulus en face. D: The distance from the aortic annulus to the ostium of a coronary vessel (magenta). E: A multiplanar reconstruction showing the outline of the sinuses of Valsalva with corresponding width measurements. Note that the height of the sinus of Valsalva is measured between the aortic annulus (green) and the sinutubular junction (blue). The images were generated using the FluoroCT imaging software.

MSCT also plays a role in determining the suitability of access vessels in patients evaluated for TAVR. The majority of TAVR performed today is via the retrograde trans-femoral approach. This technique is the least invasive when compared with trans-apical, trans-aortic, trans-subclavian or trans-carotid TAVR.^{42–44} While less invasive, trans-femoral TAVR can result in vessel dissection, stenosis, perforation, rupture, arterio-venous fistula, pseudoaneurysm, haematoma or nerve injury.⁴⁵ The main risk factors of vascular injury secondary to the insertion of the catheter sheath include the vessel diameter, calcification, and tortuosity,^{46,47} (see Figure 5). Contrast-enhanced MSCT provides information about these three aspects within the same imaging study. The sheath-to-vessel diameter ≥ 1.05 – 1.12 is

Figure 2: Calcifications of the Aortic Leaflets

A: A double oblique multiplanar reconstruction of the aortic root demonstrating the calcification burden. B: A volume rendered view of aortic valve calcifications. C: A maximum intensity projection of the aortic root showing in red the image voxels that are above a threshold attenuation. The images were generated using the FluoroCT imaging software.

Figure 3: Relationship of the Left Bundle Branch with the Aortic Root

The left bundle branch (LBB) is in the uppermost aspect of the muscular inter-ventricular septum (MusS) at its junction with the membranous septum (MemS). Ao: aorta; LV: left ventricle; NCS: non-coronary sinus of Valsalva; LCS: left coronary sinus of Valsalva; RA: right atrium; RV: right ventricle.

Figure 4: Optimal Fluoroscopic Angulations of the Aortic Root

(A) and (C) each are simulated fluoroscopic view generated from a MSCT scan where the aortic annulus is drawn in yellow. (B) is a plot of fluoroscopic angulations demonstrating in yellow the optimal fluoroscopic angulation, i.e. the combinations of craniocaudal (CRA/CAU) and right-/left- anterior oblique (RAO/LAO) angles that show the aortic annulus in profile. This configuration minimises parallax errors and maximises accuracy of depth perception during the delivery of the TAVR device. The images were generated using the FluoroCT imaging software.

Figure 6: Mitral Valve Annulus

(A–C) show three views of the D-shaped mitral annulus, which cuts across from the right to the left fibrous trigones thus neglecting the portion of the anterior mitral leaflet which is part of the aorto-mitral curtain. (D–F) show three views of the saddle-shaped mitral annulus. The asterisk (*) indicates the aortomitral curtain.

a predictor of vascular injury when measured with CT.^{47,48} The use MSCT correlates with a decrease in vascular complications.⁴⁶ MSCT also yields a greater predictive value for vascular complications than plain angiography.⁴⁸

Mitral valve

Motivated by the success of TAVR, transcatheter mitral valve procedures are seen as the next frontier of structural cardiac interventions for patients at high surgical risk. These procedures consist in the implantation of a device that repairs or replaces the native mitral valve leaflets with the goal of reducing mitral valve regurgitation. The therapies fall into four categories⁴⁹; edge-to-edge repair (MitraClip), annuloplasty rings (Carillon, Mitralign, Accucinch, Cardioband), chordal implants (NeoChord, V-Chordal) and transcatheter mitral valve replacement (CardiaQ mitral valve, Fortis mitral valve, TIARA mitral valve, Tendyne mitral valve, HighLife mitral valve). These therapies are at various stages of development, from pre-clinical research to commercial availability.

Figure 5: Evaluation of the Iliofemoral Arteries for Transfemoral Transcatheter Aortic Valve Replacement

A: A curved multiplanar reconstruction of the right iliofemoral artery showing the centreline of the vessel in yellow. B: A multiplanar reconstruction of the vessel in cross-section to enable analysis of the width. C: Coronal multiplanar reconstruction of the CT scan. D: A volume rendering demonstrating the relationship of the iliofemoral arteries with the pelvis.

Figure 7: Optimal Fluoroscopic Angulations of the Mitral Valve Annulus

(A) and (C) each are simulated fluoroscopic view generated from a MSCT scan where the saddle-shaped mitral annulus is drawn in yellow. A: A three-chamber view which distinguished the anterior from the posterior mitral leaflets. C: A two-chamber view where the anterior and posterior leaflets are overlapping but segments can be distinguished. B: A plot of fluoroscopic angulations demonstrating in yellow the optimal fluoroscopic angulation, as previously described in Figure 4. The images were generated using the FluoroCT imaging software. CRA: cranial; CAU: caudal; RAO: right-anterior oblique; LAO: left-anterior oblique.

MSCT will likely play a crucial role in the assessment of the mitral valvular complex with these new therapies. MSCT has been investigated to assess the function and anatomy of the mitral valve. In the context of mitral regurgitation, MSCT can be used to determine the disease etiology,^{50,51} to quantify the severity,^{52,53} to describe changes in the geometry of the valvular complex^{54,55} and to diagnose mitral valve prolapse.^{56–58}

In the context of transcatheter mitral valve replacement (TMVR), MSCT has been proposed to quantify the mitral valve annulus. The mitral valve annulus is often described as either saddle-shaped or as D-shaped (see Figure 6). It has been argued that for some of the devices, in particular those that are not axially symmetrical, the D-shaped annulus may be more appropriate for sizing purposes.^{59,60} This question remains to be studied, but in the interim we suggest that both techniques be employed.

MSCT also plays a role in the optimisation of fluoroscopic viewing angles for mitral valve therapies.^{31,61} In particular, MSCT allows one to determine the optimal projection curve of the mitral valve annulus (see Figure 7). One may also preselect a fluoroscopic viewing angle corresponding to *two-chamber view*, which distinguishes mitral valve segments A₁P₁ from A₂P₂ and from A₃P₃ but overlaps the anterior and posterior leaflets such that A₁ overlaps P₁, A₂ overlaps P₂, and A₃ overlaps P₃. Conversely, one may preselect a fluoroscopic viewing angle corresponding to a *three-chamber view* that distinguishes the anterior from the posterior leaflets but overlaps segments A_{1,2,3} and separately P_{1,2,3}.

Figure 8: Mitral Valve Leaflets

CD represents the coaptation depth, also called tenting height. CL is the coaptation length. In edge-to-edge repair, CD should be <11 mm and CL $\geq$ 2 mm. ALL: anterior leaflet length; PLL: posterior leaflet length.

Figure 9: Left Atrial Appendage

A: A double oblique multiplanar reconstruction showing the left atrial appendage ostium en face. B: An endovascular volume rendering showing the left atrial appendage from the left atrium. C: A double oblique multiplanar reconstruction showing a profile of the left atrial appendage. D: A vascular volume rendering showing a cast of the lumen of the left atrial appendage. (C) and (D) show the anchoring planes of the left atrial appendage occluder (blue and red) and the waist length of the ostium (yellow). The images were generated using the FluoroCT imaging software.

In the context of percutaneous edge-to-edge repair such as the MitraClip procedure, MSCT has been proposed for patient selection. Anatomical criteria essential for this procedure include:^{62,63} (1) central regurgitant jet located in the A2 and P2 mitral leaflets; (2) in functional mitral regurgitation, a coaptation length $\geq$ 2 mm and coaptation depth <11 mm (see Figure 8) and (3) in degenerative mitral regurgitation, a flail gap <10 mm and flail width <15 mm.

As new mitral valve devices undergo clinical trials, MSCT will likely play a critical role in determining patient eligibility. Further research is necessary to determine if MSCT has an impact on procedural success and clinical outcomes of these interventions.

Atrial Septal Defect and Patent Foramen Ovale

The prevalence of a patent foramen ovale (PFO) reaches 25 to 30 % of the general population. In patients having suffered a cryptogenic stroke, the incidence reaches 45.9 %, ⁶⁴ which suggests that PFO may play a significant role in the pathogenesis of cryptogenic stroke.⁶⁵ Atrial septal defects (ASD) are the most common congenital heart defect found in adult patients.

The indications for defect closure include right ventricular volume overload with a pulmonary-to-systemic flow ratio >2:1, paradoxical embolisation and platypnea-orthodeoxia syndrome. The transcatheter treatment of PFOs and ASDs was first performed in 1975.⁶⁶ Subsequent studies demonstrated that percutaneous closure has a similar rate of success when compared to surgical closure but offered reduced rates of complications and duration of hospital stay.⁶⁷⁻⁶⁹

Contrast-enhanced MSCT using a saline-chaser can be used to detect and differentiate inter-atrial shunts,^{70,71} and can also be used to assess disease severity.⁷² Ostium secundum ASDs, which represent 70 % of cases, are the only type amenable to percutaneous closure. In this context, MSCT can be useful to establish the diagnosis of sinus-venosus type ASD with partial anomalous pulmonary venous return, a condition better treated surgically.^{73,74}

MSCT is also comparable to but less invasive than trans-esophageal echocardiography in the assessment of ASD prior to percutaneous septal occluder implantation.⁷⁵

Thromboembolic Prophylaxis by Left Atrial Appendage Closure

Atrial fibrillation (AF) is the most common arrhythmia in the general population⁷⁶ and is an important factor in the pathophysiology of atrial thrombus formation. Chronic anticoagulation is generally indicated in patients with AF and deemed at risk for stroke. A significant number of patients for whom thromboprophylaxis would be indicated are not eligible due to a high bleeding risk. Interestingly, studies suggest that 90 % of thrombus causing strokes in patients with AF originate from the left atrial appendage (LAA).⁷⁷ This is thought to result from the presence of pectinate muscles within the LAA thus creating an appropriate milieu for blood stasis and thrombus formation. This prompted the development of surgical LAA ligation and eventually, of minimally invasive procedures.

Percutaneous transcatheter LAA closure was first described in 2002 and has since been studied in clinical trials. The Watchman Left Atrial Appendage System for Embolic Protection in Patients With Atrial Fibrillation trial (PROTECT AF trial) demonstrated that the procedure is non-inferior to warfarin therapy but resulted in higher rates of complications such as pericardial effusion.⁷⁸ Four devices are currently available or under investigation: the WATCHMAN device, the Amplatzer Cardiac Plug, the WaveCrest device and the Lariat epicardial suture-snare delivery device.

MSCT allows the anatomy of the LAA to be evaluated, which is valuable for device selection,⁷⁹ assessment of procedural success and longer-term outcomes.⁸⁰ It has been suggested that the perimeter-

derived diameter of the LAA ostium is the most appropriate for device sizing.⁷⁹ Other important parameters include the minimum and maximum diameters, as well as the waist length of the LAA ostium⁸¹ (see *Figure 9*). MSCT can also be used to determine optimal fluoroscopic angulation for the deployment of the LAA closure device.³¹

The information provided by MSCT regarding outcomes is complementary to that obtained from transoesophageal echocardiography (TEE). MSCT has a higher rate of detection than TEE for device leaks, which are defined as flow of blood within the LAA past the device.⁸² The localisation of leaks is also easier with MSCT

than with TEE.⁸² Contrast-enhanced MSCT also enables the evaluation of device thrombus,⁸³ embolisation and pericardial effusion.^{84,85} Further studies are necessary to provide evidence regarding the impact of MSCT imaging on outcomes of LAA closure.

Conclusions

Herein, we described the utility of MSCT in the context of structural heart interventions. With the fast development of these therapies, MSCT will likely play a role in the development of future sizing algorithms. In the future, interventional cardiologists will likely need to become imaging experts to offer their patients the most optimal outcomes from structural heart interventions. ■

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