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REVIEW

Role of Multidetector Computed Tomography in Transcatheter Aortic Valve Implantation – from Pre-procedural Planning to Detection of Post-procedural Complications

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ABSTRACT

Transcatheter aortic valve implantation (TAVI) is an effective treatment option for patients suffering from symptomatic, severe aortic valve stenosis. Previously, only patients with prohibitive or high surgical risk were TAVI candidates; however, current guidelines already recommend TAVI as a treatment alternative for patients with intermediate surgical risk. Multidetector computed tomography (MDCT) has gained great importance in the periprocedural assessment of patients who undergo TAVI. Due to the three-dimensional image visualization, MDCT allows the evaluation of anatomical structures in a more comprehensive manner compared to echocardiography, the traditional tool used in TAVI patient work-up. By providing accurate measurements of the aortic root, MDCT helps to avoid potential patient-prosthesis mismatch throughout transcatheter valve sizing. Moreover, MDCT is also a feasible tool for access route evaluation and to determine the optimal projection angles for the TAVI procedure. Although the routine MDCT follow-up of patients is currently not recommended in clinical practice, if performed, it could provide invaluable information about valve integrity and asymptomatic leaflet thrombosis. Post-procedural MDCT can provide details about the position of the prosthesis and complications such as leaflet-thrombosis, aortic regurgitation, coronary occlusion, and other vascular complications that can represent major cardiac emergencies. The aim of the current review is to overview the role of MDCT in the pre- and post-procedural assessment of TAVI patients. In the first part, the article presents the role of pre-TAVI imaging in the complex anatomical assessment of the aortic valve and the selection of the most appropriate device. The second part of the review describes the role of MDCT in patients who underwent TAVI to assess potential complications, some of them leading to a major cardiovascular emergency.

Keywords: transcatheter aortic valve implantation, multidetector computed tomography, pre- and post-procedural assessment, major cardiac emergencies

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INTRODUCTION

Aortic stenosis (AS) is the most frequent valvular disease in Western countries, affecting approximately 5% of individuals above 75 years of age.[1] Due to its poor prognosis and high prevalence, AS represents an important public health problem. AS promotes left ventricular hypertrophy and conveys significant risk for adverse events including mortality, ischemia, and heart failure.

Since its first application in 2002, transcatheter aortic valve implantation (TAVI) has proved to be an effective alternative to surgical valve replacement for patients with AS who are at high risk or considered inoperable.[2] However, cumulating data suggest that TAVI might be a noninferior therapeutic method for a broader spectrum of patients, including those with intermediate risk.[3]

An extensive assessment of patients is required before the planned procedure. Imaging methods that contribute to the periprocedural patient work-up are 2D and 3D echocardiography, invasive angiography, and, with an increasingly recognized importance, multidetector computed tomography (MDCT).

MDCT plays an increasing role in the periprocedural assessment of the patients. As part of the pre-TAVI imaging assessment, MDCT provides detailed anatomic information about the aortic root and annulus, and helps to identify the most suitable interventional approach and the appropriate projection angles for prosthesis deployment. Post-procedural MDCT can provide details about the position of the prosthesis and complications such as leaflet-thrombosis, aortic regurgitation, coronary occlusion, and other vascular complications.

PRE-TAVI IMAGING

CT has a well-established role in pre-TAVI assessment. According to current recommendations, in case of no contraindications, all patients should undergo CT imaging during the evaluation process that takes place before TAVI.[4] A multidisciplinary revision of the CT images, with the interventionist present, could improve procedure planning and lead to better post-procedural outcome.

Current protocols agree that a scanner with at least 64 detectors is required for pre-TAVI image acquisition.[5] The examinations should be performed with the use of iodinated contrast medium in order to achieve better visualization of vascular and cardiac structures. Special attention should be paid to minimize the amount of injected contrast medium, as the majority of the examined population comprises predominantly elderly patients with a considerable number of comorbidities such as impaired renal function. As low as 30 mL of iodinated contrast medium can already be sufficient to properly visualize the aortic root and the iliofemoral vasculature.[6] A flow of 3 mL/s (in contrast with the 5–6 mL/s usually used for coronary imaging) is, in most cases, feasible for the pre-TAVI imaging.

DIAGNOSIS OF AORTIC STENOSIS AND VALVE MORPHOLOGY ASSESSMENT

Although in current clinical practice, echocardiography is the gold standard in the evaluation of valve morphology and AS severity, MDCT seems to be a reliable alternative. Calcium scoring of the aortic valve has gained importance in the preoperative assessment of AS severity, in particular among patients with low-flow, low-gradient AS with preserved ejection fraction.[7] Moreover, MDCT images could be used to derive the aortic valve area needed for the detection of AS, with similar accuracy to transesophageal echocardiography (TEE). Currently, however, these measurements are not primer indications of MDCT prior to TAVI.

MEASUREMENT OF AORTIC ANNULUS, AORTIC ROOT, ASCENDING AORTA

TAVI valve size selection is a complex decision, and various factors must be taken into account. Examining the exact

FIGURE 1. Contrast-enhanced MDCT images of annular calcification (white arrow) and severe AS with moderate calcification of all three cusps. A cross-sectional image of the aortic valve is seen in the bottom right corner, demonstrating thickened cusps.

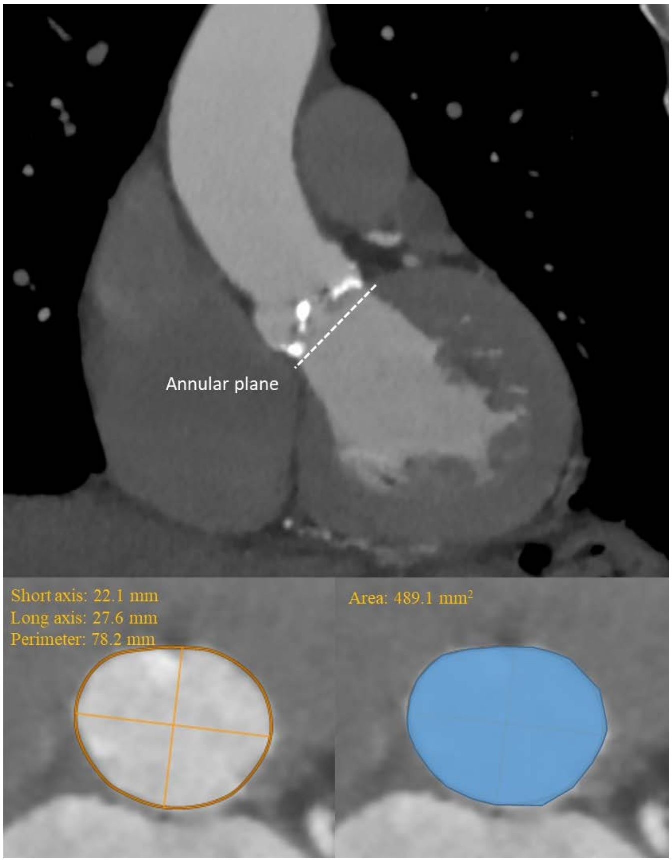

FIGURE 2. Annular measurements on contrast-enhanced MDCT. Short axis, long axis, perimeter, and area values are calculated on a plane containing the 3 lowest insertion points of the cusps.

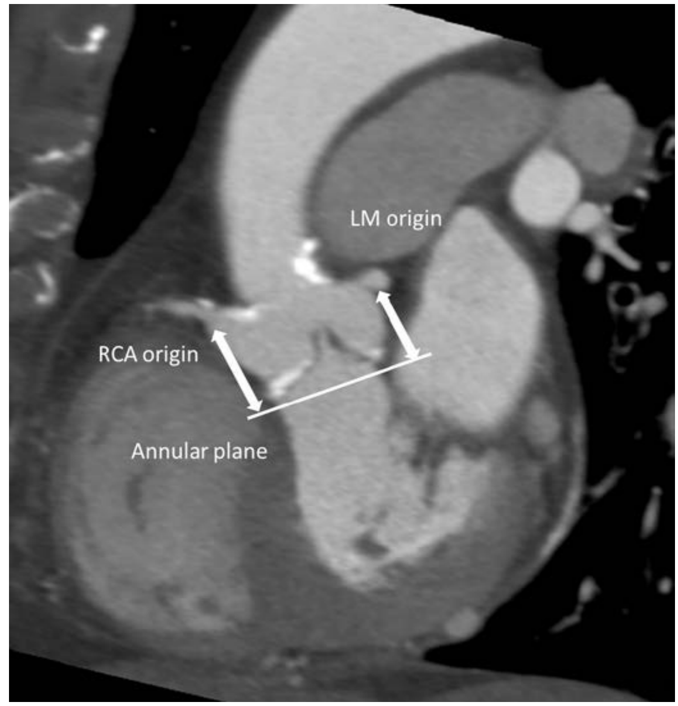

FIGURE 3. Calculation of the distance of the coronary ostia from the aortic annulus plane.

anatomy of the aortic root is an important step in choosing the appropriate valve size and minimizing paravalvular leakage (PVL) and other complications (Figure 1). A virtual basal ring is used for prosthesis sizing.[8] The basal ring is a crown-like structure, where the prosthetic valve anchors. It is the ring that crosses the insertion points of each cusp.[9] Good contact must be achieved here in order to prevent PVL. Therefore, the three-dimensional examination of the basal ring is of high importance (Figure 2). Due to its spatial resolution and high reproducibility, MDCT is a useful tool for this purpose. Ciobotaru *et al.* came to the conclusion that the decision concerning prosthesis size would have been changed in 32% of the cases if three-dimensional annulus sizing were applied.[10] However, we have to keep in mind that the basal ring is only a virtual approximation of the anatomic aortic annulus (AA), with limitations. During the cardiac cycle, more than half of the aortic circumference moves – e.g., during diastole, the aortic annulus is more ovoid-shaped.[10] These changes can lead to a weaker contact between the annulus and the prosthesis. Thus, basal ring MDCT measurements underestimate the real aortic annulus area, and the three-dimensional oversizing index ([transcatheter heart valve area / 3D-AA area – 1] × 100) proved to be the most predictive independent factor for PVL.[10]

The pre-procedural assessment of patients is not limited to the evaluation of the aortic annulus; complete anatomic characterization of the aortic root and the ascending aorta is required. These measurements should provide information about the dimensions of the leaflets, the aortic sinus, the sinotubular junction, and the ascending aorta as well. Additionally, it is essential to describe the distance of the coronary ostia to the aortic valve plane in order to prevent potentially fatal complications such as post-procedural coronary occlusion (Figure 3).

Imaging of the aorta and peripheral vessels should extend from the aortic arch (and potentially the subclavian artery) to below the groin, including the aorta, and the iliac and femoral arteries.

ECG-synchronization is required for imaging of the aortic root: the use of either retrospective or prospective gating depends on patient characteristics and scanner capabilities. Most institutions, however, prefer retrospective gating, considering the higher incidence of arrhythmias. Another important aspect in favor of retrospective gating is that the largest dimensions of the annulus are observed in systole, which should be covered entirely during data acquisition. The inherently higher radiation dose can be acceptable considering the higher age of the patient population.

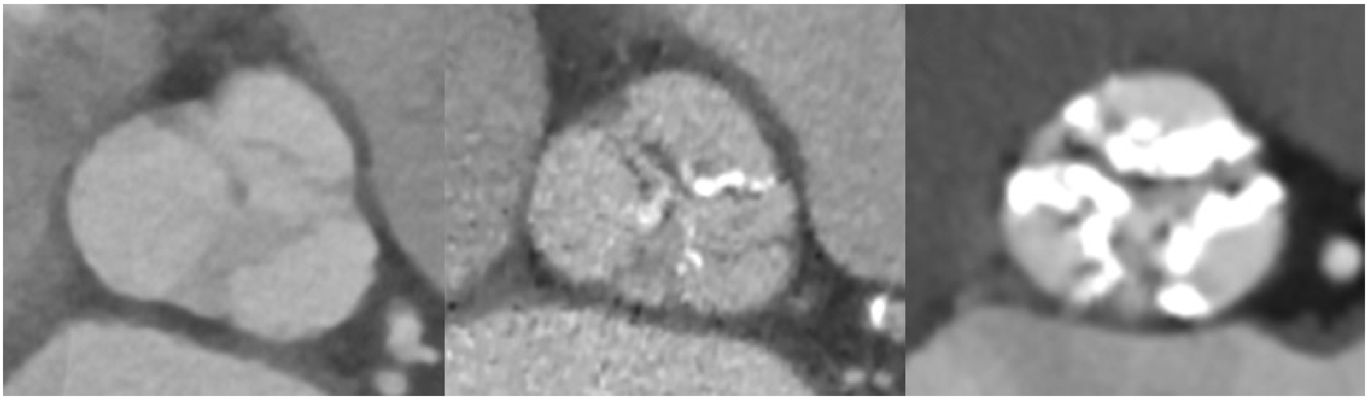

FIGURE 4. Representative images of non-calcified aortic valves (**A**) and examples of mild (**B**) and severe (**C**) calcification.

CALCIFICATION

The calcification of all regions of the aortic valve complex can predict post-procedural PVL. Bulky calcifications of the commissures might prevent complete apposition between the prosthesis and the AA leading to gaps and regurgitant jets.[11] Valve calcium volume and left ventricular outflow tract calcium are independent predictors of PVL.[12]

Furthermore, recent studies suggest a potential association between aortic valve calcification and prosthesis dislodgement, and severe calcification could result in obstruction of the coronary ostia during TAVI.[13,14] Therefore, description of the extent and severity of aortic calcification is recommended. In Figure 4 we can see various degrees of aortic valve calcification.

IMAGING OF ACCESS ROUTES

MDCT imaging is also the method of choice for the evaluation of access routes, as the extent of calcification, and the tortuosity and minimal diameters of the arteries can be both visualized in detail. Imaging of the abdominal aorta and peripheral vessels does not need to be ECG-gated. The use of three-dimensional volume-rendered images, curved multiplanar reformats, and maximum intensity projections are recommended for the measurements and for further assessment by the heart team. The most frequently used access route is transfemoral, but valves can alternatively be implanted via the subclavian artery, a transapical route, or even through the aorta. The probability of vascular complications rises significantly with the number of risk factors present. Such risk factors include moderate or severe calcification, with an emphasis on circumferential and horseshoe calcification, peripheral vascular disease, substantial vessel tortuosity, and small artery diameters compared to external sheath diameters.[15] The presence of these risk factors can be depicted by MDCT, thus allowing for the selection of the most appropriate access route (Figure 5). It is also essential to report the minimal artery diameter along the iliofemoral vascu-

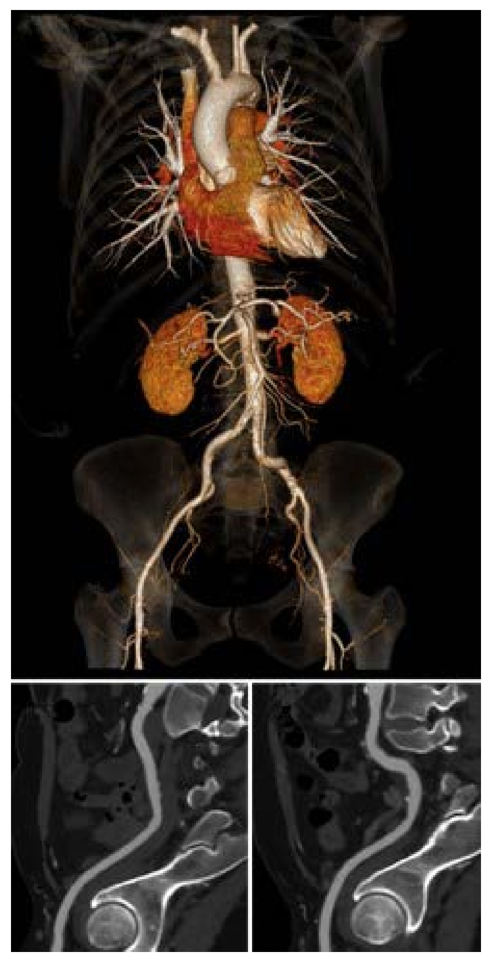

FIGURE 5. 3D-volume rendered MDCT images of the vasculature extending from the aorta to the iliofemoral system (**A**). Detailed analysis of the vascular system (including the definition of minimal arterial diameter) is feasible on curved multiplanar reconstruction images. The right and left iliofemoral vasculatures are depicted on images **B** (left femoral artery) and **C** (right femoral artery), respectively.

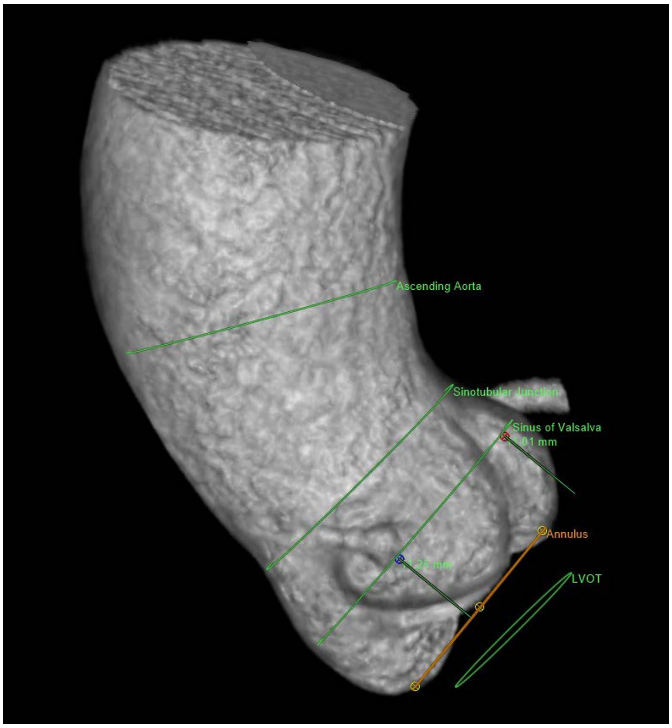

FIGURE 6. The most frequently used projection angle for the implantation of aortic valve in fluoroscopy. The right coronary cusp is positioned in the center, while the left and noncoronary cusps lie symmetrically to the left and right. The annular plane is a virtual ring (orange line) that lies beneath the hinge point of the aortic valve cusps.

lature. MDCT is also capable of identifying other high-risk features, such as dissections or complex atheromas, as the most commonly documented factors contributing to morbidity and mortality following TAVI are vascular complications.[14] MDCT is able to provide invaluable information of these risk factors, facilitating the process of patient and sheath selection.

PROJECTION ANGLES

MDCT allows the determination of the optimal fluoroscopic projection angles, providing orthogonal views onto the valve (Figure 6). This can be achieved by accurately determining the orientation of the aortic root in relation to the body axis. The majority of centers use a projection on which the right coronary cusp is positioned centrally, while the left and noncoronary cusps can be seen on either side of the right coronary cusp. MDCT allows for the determination of C-arm angulations that permit such projection.

These measurements enable significant intraprocedural dose and contrast reduction and facilitate the appropriate implantation of the prosthesis.[16]

OTHER FINDINGS

The assessment of the atria and ventricles is also necessary in order to exclude the presence of a thrombus, as it could potentially be a source of embolic complications. Furthermore, the assessment of other concomitant cardiac diseases is also feasible with MDCT. It is particularly important for pre-procedural planning to describe the severity of left ventricular hypertrophy, the angle between the aorta and the left ventricle, or a subclinical obstruction which can hinder femoral and subclavian access.

Moreover, other findings such as tumors or anomalies can also be seen on MDCT images, which can potentially have therapeutic consequences.

POST-TAVI IMAGING

While the literature regarding the post-procedural MDCT assessment of patients provides a rapidly growing amount of information about the utility of MDCT in the post-TAVI follow-up, currently, MDCT has no well-defined role in the routine follow-up of patients. However, in the detection of post-procedural complications, such as leaflet thrombosis, aortic regurgitation, conduction abnormalities, coronary occlusion, and other vascular complications, MDCT could be of great use.

LEAFLET THROMBOSIS, REDUCED LEAFLET MOTION, HYPOATTENUATED LEAFLET THICKENING, HYPOATTENUATION AFFECTING MOTION

TAVI prosthetic valves, like all foreign bodies in the cardiovascular system, are thrombogenic. Hypo-attenuated leaflet thickening (HALT) is an MDCT diagnosis, and it is considered to be the hallmark of leaflet thrombosis.[17,18] The prevalence of HALT is approximately 10%.[18] On contrast-enhanced MDCT images, HALT can be seen both in systole and diastole as a semilunar or wedge-shaped low-density structure involving the base of the TAVI leaflet and extending towards the center of the frame (Figure 7.)

For the conclusive visualization of HALT, we have to use ideally 100 mL, but at least 50 mL of contrast agent, full retrospective gating with submillimeter slice thickness, and 120–140 kV tube voltage without dose modulation. Heart rate should be kept below 70 beats per minute.[19] HALT has to be scanned in the diastolic phase together with leaflet coaptation. For the measurement of HALT, we can use either the maximal thickness of the leaflet, the maximal area of HALT, or the volume of HALT.[19] Since

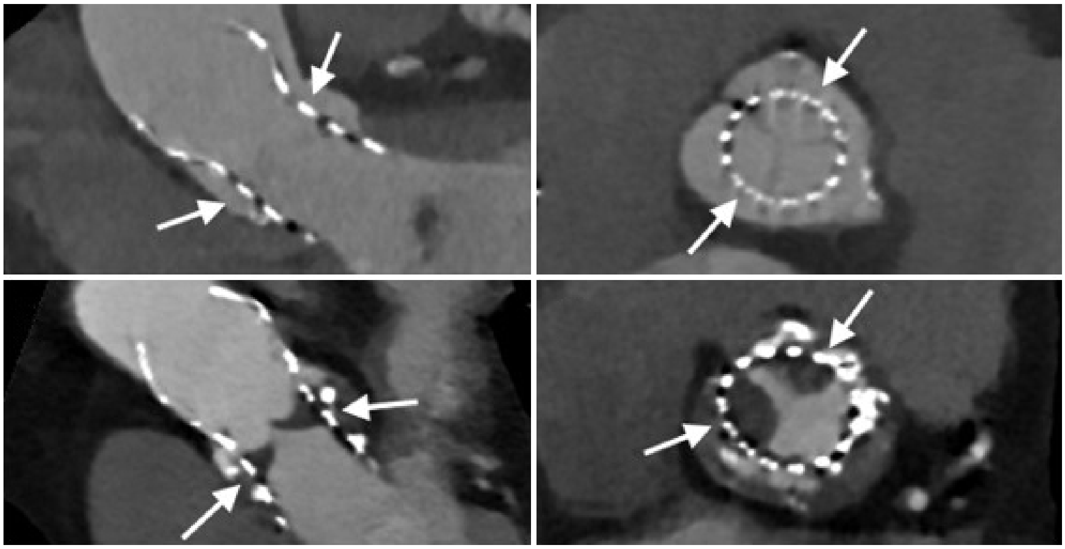

FIGURE 7. Longitudinal and cross-sectional MDCT images of normal TAVI prosthesis (**A** and **B**) and HALT (**C** and **D**).

HALT first involves the frame, the maximal thickness can be measured on the base of the prosthesis (Figure 8). The maximal HALT area can be measured on axial cross-section MDCT images.

HALT poses not only the risk of a possible thromboembolic event, but it can cause valve dysfunction as well.[20] Makkar *et al.* have observed reduced aortic valve leaflet motion (RELM) in 13% of patients after TAVI procedure with four-dimensional, volume-rendered MDCT images both in systole and diastole (Figure 1).[17] RELM can be detected on MDCT and TEE but not on transthoracic echocardiography (TTE).[17] The dysfunction might be the consequence of several factors such as thrombosis, PV degeneration, vegetation causing endocarditis, or fibrotic pannus ingrowth.[21] RELM can be determined on en face projections of three-dimensional, volume-rendered MDCT images with maximal valve opening in the systolic phase. For the quantification of RELM, we have to use at least 10 phases. The percentage of RELM (%RELM) is equal to leaflet width (the distance between the frame and the maximally open leaflet tip of the most affected leaflet) divided by half of the diameter of the frame (1/2D), multiplied by 100.

$$\%\text{RELM} = \frac{\text{W (base-to-tip width)}}{\text{1/2D (half of the diameter of the frame)}} \times 100$$

On the basis of this percentage, RELM can be divided into 5 groups (Table 1). This technique provided 100% correlation with TEE examinations in the early Portico trial.[17]

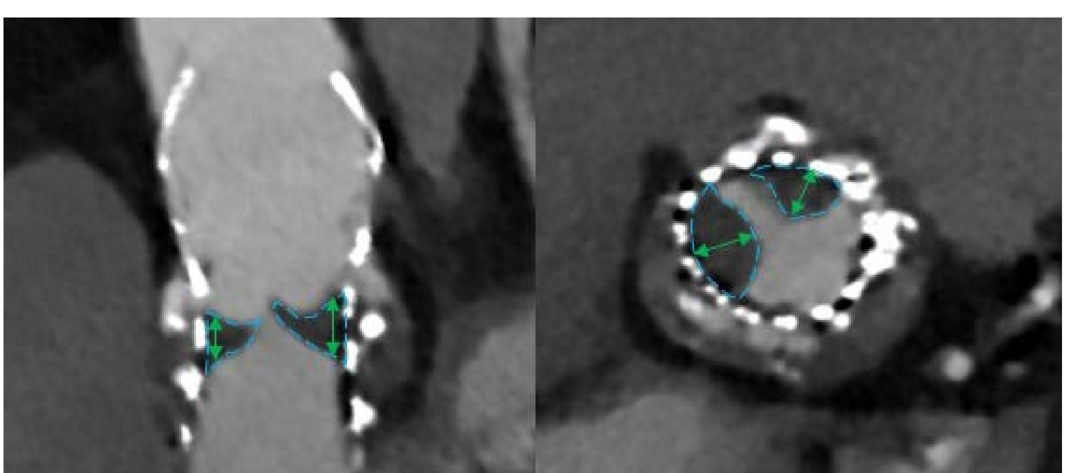

FIGURE 8. Cross-sectional (**A**) and longitudinal (**B**) pictures of HALT.

TABLE 1. Classification of RELM based on %RELM

Normal	Normal leaflet opening	
Mild	<50% RELM	
Moderate	50-70% RELM	Significant RELM
Severe	>70% RELM	
Immobile	100% RELM	

HALT, together with significant RELM (≥50%), have recently been described as hypoattenuation affecting motion (HAM), which can be used as definition for subclinical leaflet thrombosis.[19]

HALT and RELM were assessed more commonly in patients not receiving oral anticoagulant (OAC) therapy. Moreover, as a result of OAC therapy with warfarin, HALT was resolved and RELM was restored, suggesting that these findings might be in association with subclinical leaflet thrombosis.[17] However, the exact etiology, predictors, and clinical significance of HALT are still obscure. There are several recently posted randomized controlled trials that compare standard of care with OAC therapy in patients with HALT or RELM such as the 200-patient RETORIC trial (Rule Out Transcatheter Aortic Valve Thrombosis With Post Implantation Computed Tomography; NCT02826200) or the RESOLVE trial (NCT02318342), where 1,000 patients with early bioprosthetic valve thrombosis will be treated with OAC for 3 months and resolution will be assessed using MDCT. These prospective studies will introduce high-quality evidence regarding the incidence of subclinical thrombosis and the optimal antithrombotic therapy for the subsequent subacute period. The results of these studies may provide data supporting a possible change in current recommendations and practice patterns, and may lead to a larger end-point trial of major adverse cardiovascular events.

Since TAVI frame depth and stent canting can cause non-laminar flow, these factors can significantly contribute to leaflet thrombosis. Therefore, stent frame analysis is an important part of the post-TAVI follow-up. Prosthesis depth can be stratified based on the centerline-derived longitudinal distance between the base of the native aortic annulus and the prosthetic inflow (the most proximal portion of the frame): if this distance is below 4 mm, it is high, between 4 and 8 mm, it is nominal, and if the distance is above 8 mm, it represents a low implantation depth. Stent canting can be assessed with the deployed depth eccentricity index (the difference between the largest and the smallest depth).[19]

The first-line method for post-procedural valve assessment is TTE, which is affordable, repeatable, can easily access and assess the transaortic pressure gradient, but it cannot visualize the detailed structure of the prosthetic leaflets.[22] TEE could solve this issue; however, shadowing of the implanted valve's frame can cause difficulties sometimes, and due to its invasiveness, it cannot be a routine part of TAVI follow-up.[23] Guidelines recommend post-implantation imaging with echocardiography prior to discharge, at 6 and 12 months, then yearly.[24] However, subclinical valve thrombosis can develop within a few weeks after TAVI. In their study, Marwan *et al.* detected leaflet thrombosis in 23% of the enrolled patients with MDCT performed at a median of only 4 months after TAVI implantation.[25] As a consequence, the number of reported symptomatic TAVI thrombosis cases highly underestimates the exact incidence due to the suboptimal timing of follow-up imaging in TAVI patients.

POST-PROCEDURAL AORTIC REGURGITATION: PARAVALVULAR LEAKAGE AND TRANSVALVULAR REGURGITATION

Aortic regurgitation (AR) is the most frequent complication after TAVI, with an unfavorable overall 1-year mortality.[26] The overall incidence of AR after TAVI is 50 to 85%, higher than after surgical aortic valve replacement.[27,28] PVL results mainly from incomplete apposition between the prosthetic valve and the AA. Although techniques have been developed to seal the space between the native aortic annulus and the TAVI frame, PVL still remains a critical problem due to the sutureless method and the calcified annulus.[29]

Short-axis view is the most useful for the echocardiographic assessment and quantification of PVL. The Valve Academic Research Consortium-2 guideline recommends several quantitative and semi-quantitative Doppler-echocardiographic parameters for the hemodynamic assessment of PVL; however, these results are still limited.[30] Cardiac MDCT may allow more accurate measurements, less sizing errors, more comprehensive aortic root complex assessment, and, since it is independent from the examiner, it is more standardized. Moreover, it is also more accurate in the case of heavily calcified valves.

Transvalvular AR is less frequent than PVL and is mainly the consequence of leaflet damage, e.g. after aggressive ballooning, or due to an oversized prosthetic valve.

ATRIOVENTRICULAR CONDUCTION ABNORMALITIES

After TAVI, patients present an increased risk for atrioventricular (AV) conduction abnormalities, leading to permanent pacemaker (PM) dependency.[31] Permanent PM implantation is required in 9.6% of patients after TAVI.[32] These patients have increased left ventricular dyssynchrony, impaired recovery of left ventricular ejection fraction, and increased mortality.[33] The main cause might be mechanical compression and inflammation of the proximal His-Purkinje system and AV node due to their close proximity to the aortic root complex.[11] Male gender, first-degree AV block, left anterior fascicular block, right bundle branch block, and intra-procedural AV block are predictors of post-TAVI permanent PM requirement.[31] A recent study has demonstrated that the prosthetic valve size to sinus of Valsalva (SOV) diameter index, determined by cardiac MDCT, is a novel predictor of permanent PM implantation after TAVI.[32] Patients with a higher index are most likely to require permanent PM, suggesting that larger prosthetic valves relative to the SOV diameter compress the conduction system more. Thus, the selection of a smaller prosthetic valve size might decrease the risk of conduction abnormalities, but it increases the risk of PVL.

CORONARY ARTERY OCCLUSION

Coronary artery occlusion after TAVI has an incidence of less than 1%, and it is more common in women and in patients with balloon-expandable valves.[34] The left coronary artery is the most frequently involved (88%).[35] The distance between the AA and the coronary artery ostia is an important factor, a distance of more than 10 mm being considered safe. For the assessment of coronary artery occlusion, MDCT is a feasible method. Percutaneous coronary intervention is a safe and successful treatment in the majority of cases, without increased risk of adverse outcomes.[35]

CONCLUSION

TAVI bears an increasingly pronounced role in the therapy of AS, as rapidly growing evidence supports its use. Traditionally, echocardiography is the most commonly used method in the periprocedural assessment of patients; however, MDCT has emerged as an extremely useful tool before and after TAVI, on account of its significant incremental value. The accurate, 3D visualization of anatomic structures allows for a robust assessment of the aortic annulus and the aortic root and could substantially modify patient and prosthesis selection. The detailed evaluation of the iliofemoral vasculature provides invaluable information for determining the adequate access route, while predicting the optimal angle of angiographic prediction is also feasible with the use of MDCT. Although the routine follow-up of patients after TAVI is not yet recommended, several complications potentially occurring after the implantation can accurately be assessed by MDCT. It can be expected that continuous advancements in devices and rapidly growing data about the procedure may eventually lead to the broadening of the indication of TAVI in the treatment of severe AS, and MDCT will most definitely keep its integral role in any TAVI program.

CONFLICT OF INTEREST

Nothing to declare.

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