PICTORIAL ESSAY Cardiovascular Imaging

Role of MDCT in Transcatheter Mitral Interventions

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ABSTRACT

In recent years there has been a rapid development in transcatheter mitral valve procedures. Detailed clinical and imaging evaluation is essential before such type of procedure. In this case, echocardiography and CT can aid in the diagnosis and determination of the severity of mitral valve regurgitation and identification of patients suitable for this type of procedure. This review analyses the role of MDCT in these procedures and describes all the information that MDCT can provide to the Heart team to ensure a successful procedure

KEY WORDS
Mitral valve, Computed Tomography, Transcatheter Interventions

Introduction

Mitral valve disease is the most common valvular heart disorder affecting almost 10% of the people older than 75 years old [1]. Mitral regurgitation (MR) is the most common disease of the mitral valve. MR typically is classified into primary (degenerative or structural) when an abnormality of more than one component of the mitral valve apparatus is noted and secondary (functional) when MR occurs with functional impairment secondary to ventricular remodelling while mitral valve remains intact.

Surgical mitral valve repair or replacement are standard therapies however many elderly patients with clinically significant MR are considered too high risk for surgical intervention due to co-morbidities and associated risk and are often precluded from surgical treatment [2]. Transcatheter mitral interventions are emerging as an alternative therapy for these patients and are increas-

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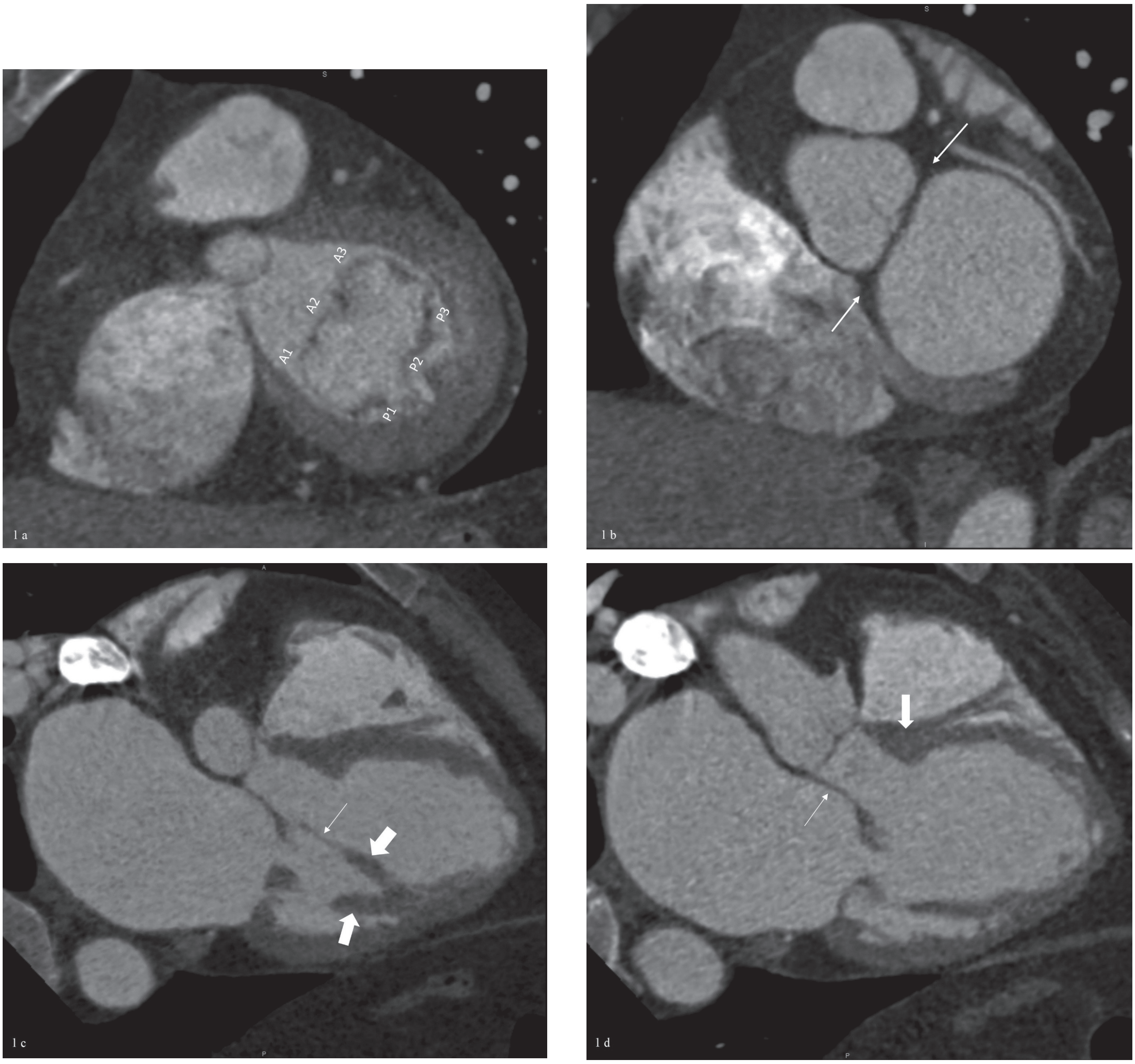


Fig. 1. *CT-based anatomy of the mitral valve. (a) anterior and posterior leaflets of the mitral valve with corresponding scallops (A1, A2, A3 and P1, P2, P3). (b). Medial and lateral trigone (c). posterolateral papillary muscles and chordae tendineae (d) aorto-mitral continuity and intraventricular septum.*

ingly adopted in clinical practice.

High quality preprocedural non-invasive imaging is essential providing information about the suitability of such approach, the likelihood of success and the risk of complications. The need is even greater given the fact that mitral valve shows complex anatomy and function compared to aortic valve.

Building on the lessons from TAVI the integration of MDCT has been rapid and essential component of transcatheter mitral valve interventions. This review is to provide all the necessary information regarding the role of MDCT in these interventions.

Anatomy of the Mitral Valve

Mitral valve apparatus is much more complex anatomic structure compared to the aortic annulus. The mitral valve apparatus includes a fibrous annulus, 2 leaflets (anterior and posterior), 2 papillary muscles (posteromedial and anterolateral) and multiple chordae tendineae that connects the papillary muscles to the leaflets and the annulus [3] (**Fig. 1**).

Mitral annulus has a non-planar saddle shaped configuration consisting of 2 elevated horns (anterior and posterior) that attach to the medial and lateral trigone. The anterior horn proceeds upward to the aortic root where

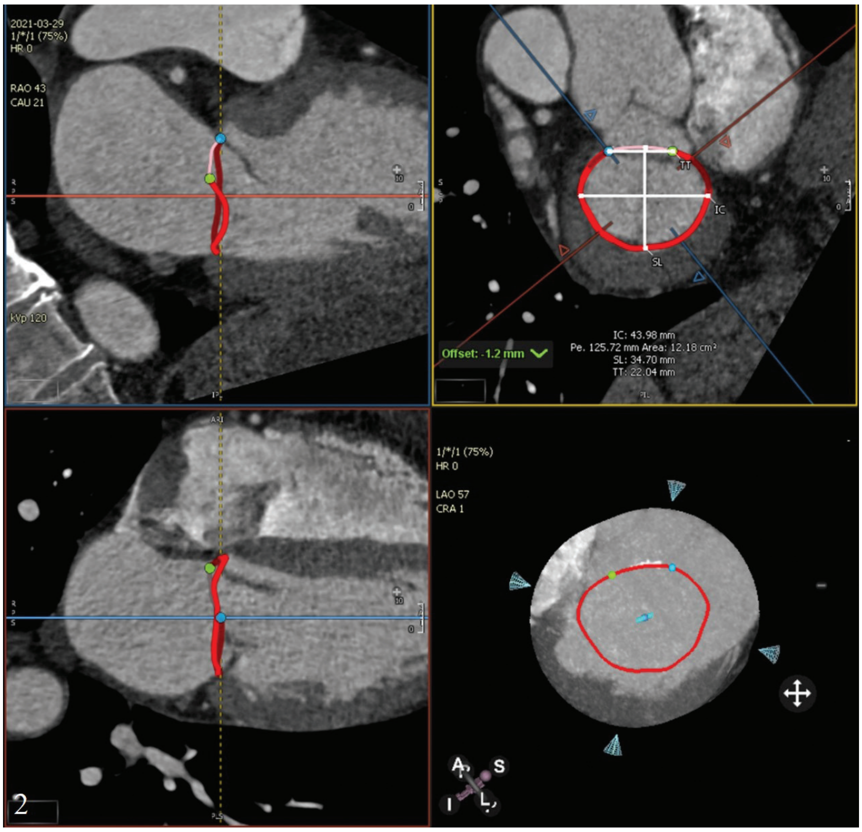


Fig. 2. *Segmentation of the mitral annulus using dedicated software annulus measurements.*

it is in fibrous continuity with the non-coronary and left coronary leaflet of the aortic valve which is known as the aortic mitral curtain. The fibrous nature of the anterior mitral annulus makes it less prone to pathological remodelling. Contrary the posterior horn of the annulus which is located between atrial and ventricular myocardium is predominantly muscular and thus prone to remodelling. The trigones (medial and lateral) are fibrous thickenings that represent the anatomic junction between the anterior and the posterior annulus.

The mitral valve has two leaflets: the anterior mitral leaflet (AML) and the posterior mitral leaflet (PML). The leaflets are asymmetrical in shape with the AML being rounded and occupying one third of the annular circumference whereas the radially narrower PML occupies the other two thirds. Each leaflet has three scallops A1, A2 A3 anteriorly and P1, P2 P3 posteriorly. The coaptation line represents a semilunar arc where the leaflets converge at the anterolateral and posteromedial commissures [4].

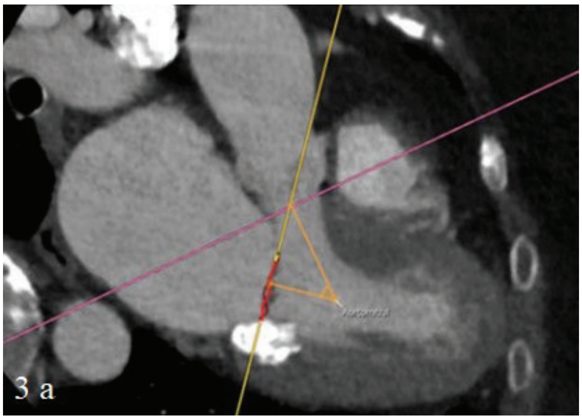
The papillary muscles located along the middle to apical segments of the left ventricle are usually called anterolateral and posteromedial muscles. The papillary muscles are labelled this way based on their respective relationships to the mitral valve commissures.

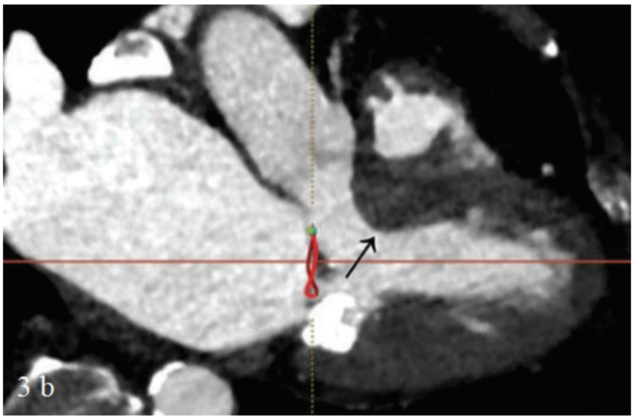
The chordae tendineae are papillary muscles extending toward and inserted into the MV leaflets. Depending on where they attach the chordae tendineae may be classified into three types: primary, secondary and marginal.

MDCT data acquisition

MDCT scanners with at least 64 slices are a prerequisite for detailed assessment of the mitral valve. Newer generations of MDCT scanners with a higher number of slices (128, 256, 320) are ideal for these cases.

A standard protocol for examination of the mitral valve should necessarily include imaging of the entire heart, similar to the examination of the coronary arteries. The goal of the protocol is to provide adequate contrast enhancement of the left atrium and left ventricle to depict the anatomical structures of the mitral valve complex. However, considering the dynamic changes that occur throughout the cardiac cycle in the anatomical structures of the mitral valve complex, the LVOT and the left ventricle, the scanning protocol should be performed with





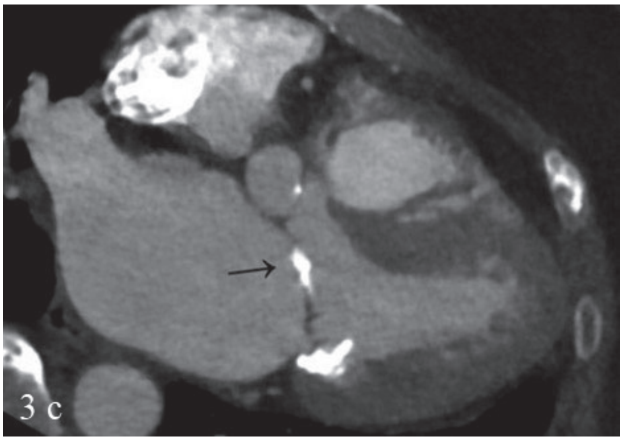


***Fig. 3.** Anatomic factors related to LVOT obstruction. (a) insufficient aorto-mitral angle (b) hypertrophy of the intraventricular septum (c) extensive calcifications of the anterior mitral leaflet.*

retrospective ECG gating and dose modulation turned off to obtain a detailed imaging of the mitral valve anatomy throughout the cardiac cycle [5]. In cases where the mitral valve is to be accessed transapically, it is necessary to scan the entire thoracic cage in order to determine the appropriate intercostal space for puncture. Finally, scanning before intravenous contrast is recommended in cases of paravalvular leakage closure in order to detect calcifications and pledgets.

The protocol of contrast agent injection in our department includes three phases: In the first phase, 60 ml of pure contrast agent is administered at an injection rate of 4 ml/sec, followed by 40 ml of a solution of contrast agent and saline in a 50%/50% ratio at an injection rate of 4 ml/sec, while in the third phase, 50 ml of normal saline is injected at an injection rate of 4 ml/sec (a total of 80 ml of contrast agent is administered). The protocol is adjusted considering the weight and height of the patient.

During post-processing of the mitral valve, image reconstructions are performed throughout the cardiac cycle at 5% or 10% intervals (e.g. 0% to 95% or 0% to 90%). In patients with irregular heart rhythm, as in patients with atrial fibrillation image quality may be compromised. Different methods have been proposed to maintain the image quality. First, ECG editing can be performed on the scanner to remove ectopic beats or those with very short R-R intervals. Secondly, absolute millisecond reconstructions can be used where a specific absolute delay (every 50ms) can be reconstructed after the R wave (e.g. 0-400ms). This is preferable for patients with irregular heart rhythms, as the duration of systole (the first few hundred milliseconds after the R wave) does not change significantly with different R-R intervals. It is recommended to avoid Best Systole/Diastole reconstruction with certain types of scanners (Siemens/Toshiba) as they are optimised for coronary artery imaging. The reconstructed slices should be very thin (< 0.75 - 1mm) using either filtered back projection or iterative reconstruction techniques with a soft reconstruction kernel.

Role of MDCT for Mitral valve assessment

Imaging assessment of the mitral valve is essential for

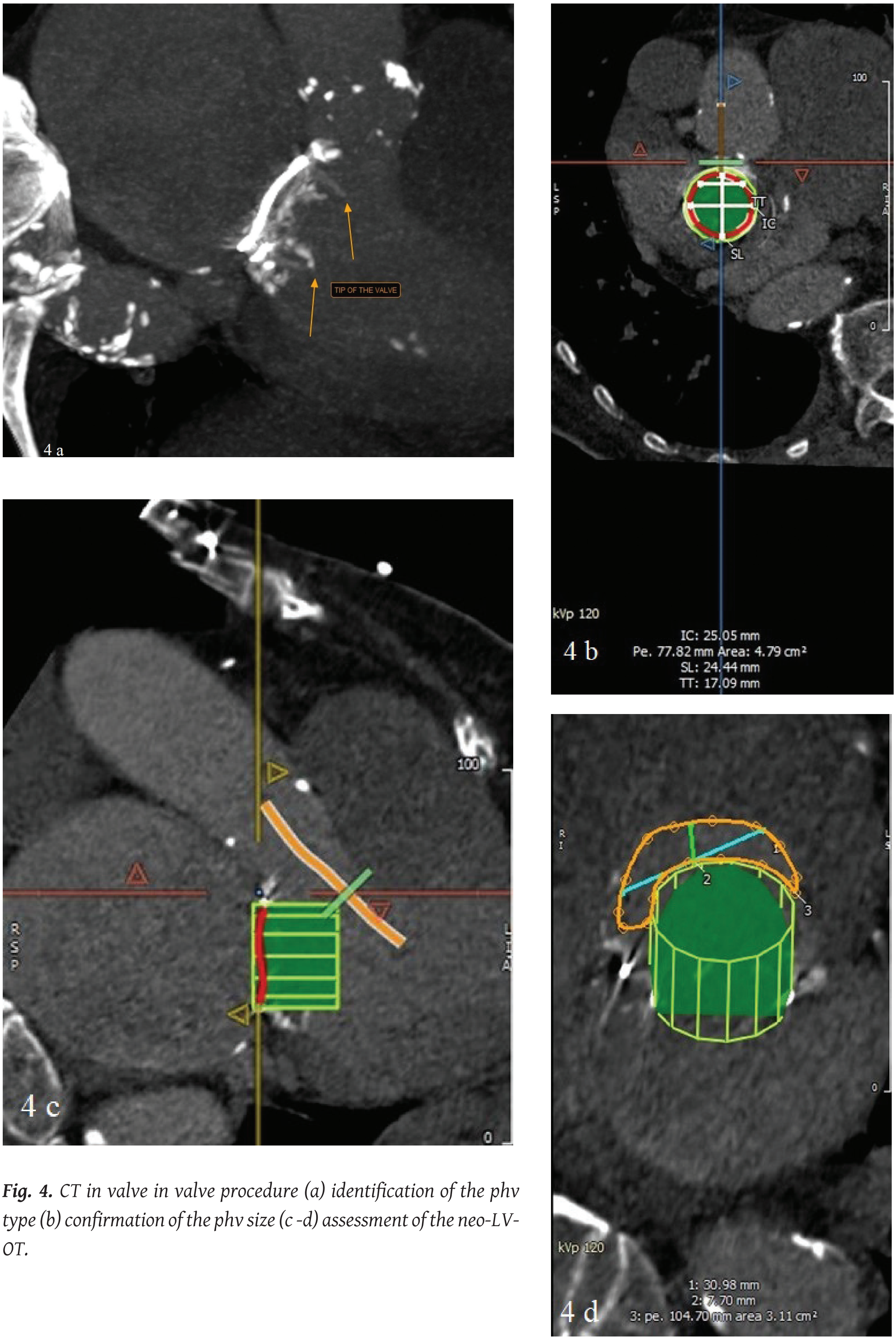


Fig. 4. *CT in valve in valve procedure (a) identification of the phv type (b) confirmation of the phv size (c -d) assessment of the neo-LV-OT.*

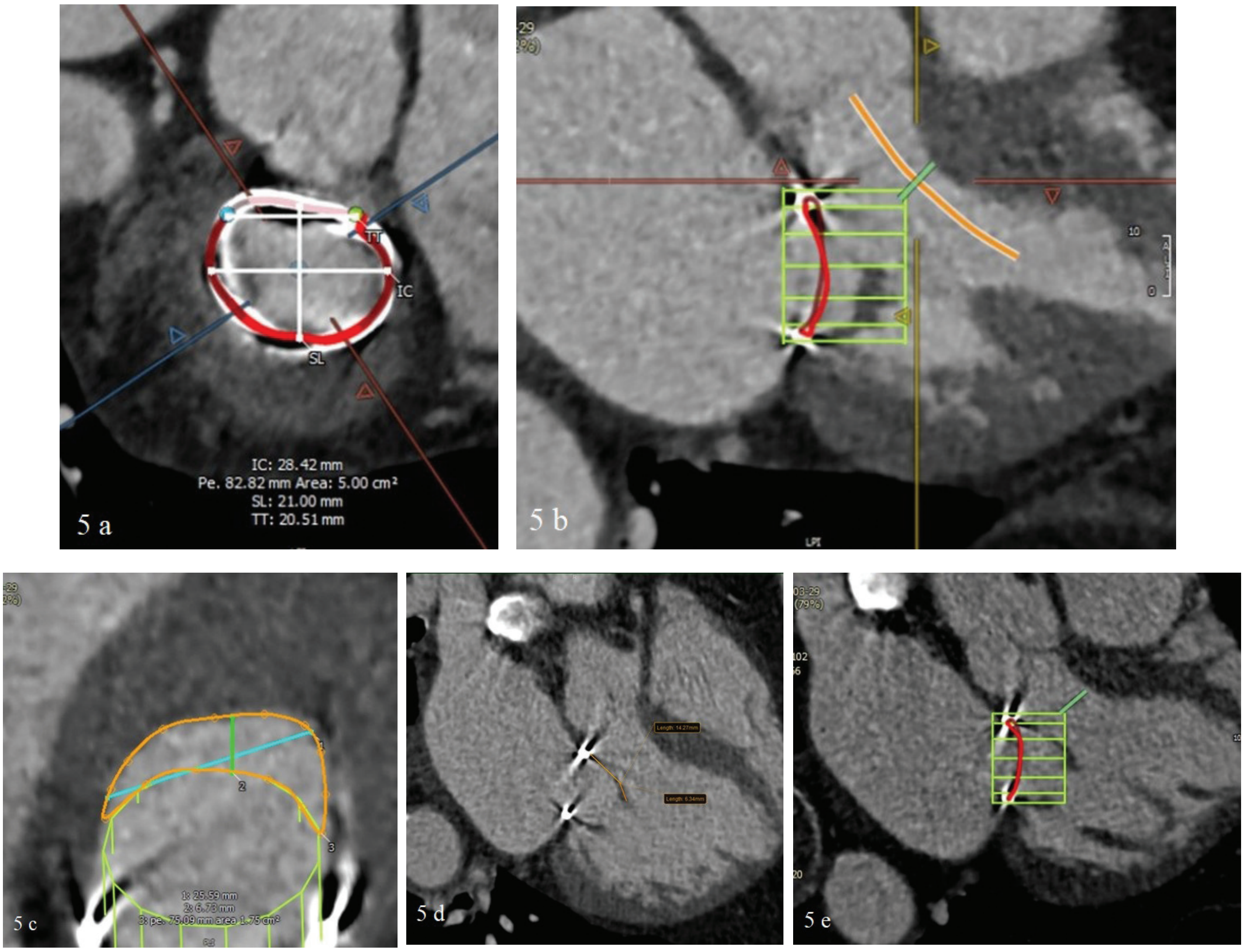


Fig. 5. *CT in valve in ring procedure. (a). confirmation of the size of the ring. (b – c) simulation and assessment of LVOT risk obstruction (d-e) elongated anterior mitral leaflet which may result in LVOT obstruction.*

the evaluation of mitral regurgitation. Assessment includes identification of regurgitation, severity of regurgitation, characterization of its aetiology, assessment of its suitability for structural intervention and planning of the intervention [6]. Echocardiography (TTE and TEE) is the first choice of imaging for this purpose. However, CT and MRI also play an important role in this work up. MDCT provides a comprehensive 3D anatomical dataset for the assessment of the mitral valve complex and morphological abnormalities due to its superior spatial resolution. In addition, MDCT provides important anatomical information regarding the entire heart (e.g. aortic root, LVOT coronary arteries).

MDCT in the context of TMVI procedures

Current clinical practice for the treatment of mitral regurgitation is repair or replacement of the mitral valve, with repair being the preferred treatment option [7]. There are 3 different repair techniques for reducing mitral regurgitation: mitral clip, Pascal system and annuloplasty. Although these techniques have high technical success rates, they are not able to completely eliminate mitral regurgitation, showing significant residual mitral regurgitation on follow-up [8,9]. The success of these procedures also depends on the integrity of the native valve components.

TMVI is a newer technique that has undergone significant development in the last 5 years. The goal of these devices is to completely eliminate mitral regurgitation by percutaneously replacing the abnormal valve. Potentially, TMVI devices may treat a wider range of mitral pathologies, including mitral stenosis, compared to percutaneous annuloplasty and valve techniques.

However, this is a more complicated technique with

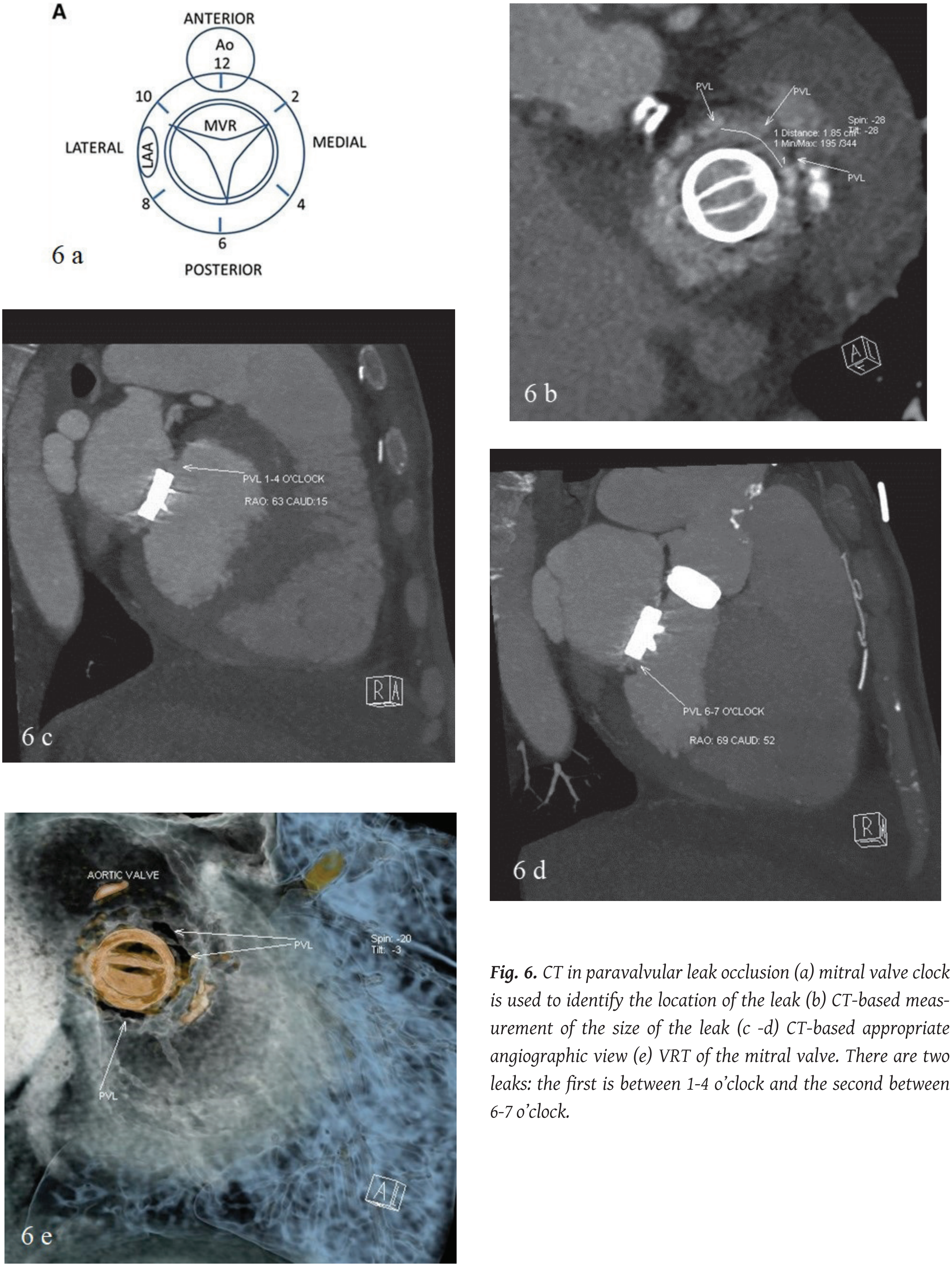


Fig. 6. *CT in paravalvular leak occlusion (a) mitral valve clock is used to identify the location of the leak (b) CT-based measurement of the size of the leak (c -d) CT-based appropriate angiographic view (e) VRT of the mitral valve. There are two leaks: the first is between 1-4 o'clock and the second between 6-7 o'clock.*

significant challenges to overcome. The complex geometry with significant variability between patients and the larger size of the devices make implantation into the mitral annulus more challenging than implanting the device into the aortic valve. There are currently 8 different types of TMVI devices in clinical trials and only one of them (Tendyne valve) has CE mark.

The role of MDCT in the context of TMVI is sizing the mitral valve annulus, characterising the landing zone, assessing the risk of LVOT obstruction and predicting fluoroscopic angulation

Annulus sizing

CT based sizing of the mitral annulus is very important for TMVI, similar to the assessment of the aortic annulus for TAVI. This assessment allows appropriate patient selection and determination of patient suitability for the procedure. Assessment of the mitral annulus is challenging because of its complex geometry. Unlike the aortic annulus, the mitral annulus is a non-shaped 3D saddle shaped structure. The projected area of the saddle-shaped annulus extends into the left ventricular outflow tract, which may lead to LVOT obstruction if the size of the implanted valve matches the projected area. To avoid this, a D-shaped concept for the mitral annulus was adopted. According to this concept, the anterior horn of the annulus at the level of the fibrous trigone is excluded from the measurements. The assessment of the D-shaped annulus can be achieved using dedicated software that systematically places seeding points at regular intervals along the mitral annulus [11]. In this way, a 3D model of the annulus is created, which can be used to perform 2D measurements of the annulus area, circumference, septal to lateral, intercommissural, and trigone-to-trigone distance (**Fig. 2**). The advantages of this technique are low interobserver variability and less risk of the implanted device protruding into the LVOT. The relevance of each of these measurements varies among devices with different methods of annulus sizing incorporated into the guidelines of different manufacturers.

Assessment of Mitral Annular Landing zone.

The anatomy of the landing zone (defined as the area where the TMVR device is deployed) is important for TMVR planning because different devices have different anchorage mechanisms for capture and stability. Therefore, it is important to identify certain characteristics that may exclude patients from TMVR procedures. It is important to remember that there are significant differences in the landing zone between FMR and primary (degenerative) MR [12].

In FMR, regional wall motion abnormalities and/or dilatation of the left ventricle lead to outward displacement of the papillary muscles. As a result, there is marked tethering of the mitral leaflets, annular dilatation, and basal myocardial remodelling with formation of a so-called myocardial shelf. This unique anatomical feature can be identified on both echocardiography and MDCT. Identification of the myocardial shelf in systole and diastole is important as many TMR devices rely on this shelf in order ensure proper capture and positioning [13].

Mitral annular calcifications

MDCT is superior to both echocardiography and MRI in the assessment of calcifications. Mitral annular calcifications (MAC) are commonly seen in the elderly population and are present in about 6% of the general population. More commonly, the posterior portion of the annulus is affected.

Although MAC is typically confined to the mitral annulus and the base of the leaflets in some cases they may extend further into the leaflets, chordae tendineae, papillary muscles and left ventricular myocardium. MDCT can precisely identify the location and extent of the calcifications.

Extensive MAC is a contraindication for TMVR, as these devices have their own anchoring mechanisms that are not dependent on the presence of MAC. Feasibility studies have tended to exclude patients with severe MAC as it is possible that severe and bulky MAC may hinder the deployment of TMVR devices [14]. Therefore, MDCT plays an important role in screening patients with asymmetric and particularly bulky and protruding calcifications that may interfere with device placement.

LVOT obstruction assessment

Obstruction of the LVOT is a rare but well-known complication following surgical implantation of a prosthetic mitral valve in which the anterior mitral leaflet is preserved. However, in transcatheter mitral valve procedures (native valve, valve-in-valve, valve-in-ring), it is a feared and potentially fatal complication that has been reported in 7-9% of all transcatheter procedures. The causes of obstruction are varied and not fully understood. It may be anatomical factors related such as hypertrophy of the interventricular septum, inadequate aorto-mitral angle (< 115o) or bulky calcifications in the anterior mitral leaflet or small size left ventricle (Fig. 3). It may be factors related to the procedure, such as tilt and displacement of the device towards the LVOT or failure of proper deployment. Finally, it may be a dynamic in cases of elongated anterior leaflet due to anterior systolic movement of the anterior leaflet of the mitral valve [16].

Considering that the increased likelihood of LVOT obstruction may be an exclusion criterion in 50% of patients eligible for such procedures, the role of CT in assessing the potential risk of LVOT obstruction is critical to the success of such a procedure.

After implantation of the prosthetic valve, the TMVR device displaces the native anterior mitral leaflet towards the interventricular septum. This results in remodelling of the LVOT with elongation of the LVOT. To describe the changes in the LVOT, the term neo-LVOT is introduced. The neo-LVOT is defined as the remaining space of the LVOT between the interventricular septum, the displaced anterior leaflet and the TMVR device. Implantation of the device at the mitral valve has the effect of reducing the area available for blood flow to the native LVOT.

The evaluation of the neo-LVOT begins with the design of a centreline that passes through the midline of the neo-LVOT. Then, dedicated software is used to embed a virtual prosthetic valve (stereolithographic image) that protrudes into the neo-LVOT as expected. The minimum area that is still available after embedding the virtual prosthetic valve is then determined. The assessment is done in an orthogonal projection in a similar way to the assessment of the vessel lumen. Although not much data is available for this case, based on hypertrophic cardiomyopathy data, it is estimated that an area > 2 cm^2 is sufficient to prevent LVOT obstruction. It should be noted that the assessment in these cases is performed in the systolic phase of the cardiac cycle, so multiple cardiac cycle reconstructions must be available (ideally every 5% of the cardiac cycle in the systolic phase).

Prediction of fluoroscopic angulations

Like TAVI, MDCT can suggest angiographic projections to facilitate proper placement of the endoprosthesis. The S-L view and the compromise view (between S-L view and I-C view) seem to be the most effective projections during the procedure [17].

MDCT in Valve-in-Valve and Valve-in-Ring procedures

The valve-in-valve procedure refers to the placement of a TAVI prosthetic valve on a pre- existing surgically placed prosthetic valve and the valve-in-ring procedure refers to the placement of a TAVI prosthetic valve on a pre- existing surgically placed ring.

In these cases, the role of CT is particularly important in identifying patients at increased risk of complications and in planning transcatheter treatment.

MDCT in valve-in-valve procedures

In patients where a prosthetic valve has been surgically implanted, it is common for the prosthetic valve to degenerate over time. In these cases, it is possible to insert a TAVI valve prosthesis into the already degenerated prosthetic valve.

In contrast to the CT evaluation of the native mitral valve, where all phases of the cardiac cycle are evaluated because the dimensions of the annulus may vary in the systolic and diastolic phases, in cases of valve-in-valve, the dimensions of the degenerated prosthetic valve are not expected to change during the cardiac cycle. For this reason, the best systolic phase is chosen, which allows on the one hand to determine the dimensions of the degenerated prosthetic valve and on the other hand to assess the possible risk of obstruction of the left ventricular outflow after implantation of the new prosthetic valve.

The role of CT in these cases is to confirm the type and size of the degenerated prosthetic valve, to assess the risk of left ventricular outflow obstruction and to provide other anatomical information that may influence the correct placement of the prosthetic valve.

In most cases the type and dimensions of the prosthetic valve are known from the surgical history, but in some cases this information is unclear. The radiologist evaluating the CT examination should be familiar with the appearance of prosthetic valves on CT to confirm the type of degenerated prosthetic valve.

Regarding the confirmation of prosthetic valve dimensions, it is important to remember that the accuracy of measurements is often affected by image quality, the opacity of the prosthetic materials, the presence of calcifications and factors related to the scan itself, such as the presence of arrhythmia or breathing artefacts. There are often blooming artifacts that make it difficult to determine the boundaries of the prosthetic ring and the accuracy of the measurements.

It is important to mention the difference between the stent ID and True ID. Stent ID stands for the size of valve reported by the manufacturer and True ID represents the true internal diameter, which is defined by subtracting 1 - 2 mm from Stent ID, which corresponds to the thickness of the leaflets (for porcine valves is 2 mm and for bovine valves is 1 mm) [18]. For example, in the case of a Magna 25mm prosthetic valve, 25 corresponds to the stent ID, but the true ID is 24mm (25-1=24mm).

CT measurements (diameter and area) should be matched to reference tables (such as the Mitral valve in valve application) to confirm the size of the degenerated prosthetic valve.

To avoid blooming artefacts caused by the material of the prosthetic valve, measurements should preferably be taken in a wide window setting (e.g. the bone window). It is also recommended that the measurements of the dimensions of the prosthetic ring should be done by placing seed points on the middle line of the radiopaque prosthetic ring.

The presence of extensive and bulky calcifications in the prosthetic valve leaflets should be reported, as these may affect the accuracy of the measurements and the selection of the appropriate THV valve size (Fig. 4).

Finally, other anatomical information such as the orientation of the degenerative prosthetic valve should be reported as it may affect or even prevent the valve-in-valve procedure.

MDCT in Valve - in – Ring procedures

There are different types of surgically inserted rings. They are classified as rigid and semi-rigid, complete or incomplete rings and complete or incomplete bands. Not all types of rings are suitable for this procedure. In order to achieve fixation of the THV valve to the ring, the ring should ideally be rounded after insertion of the THV valve, so that it adapts to the shape of the prosthetic valve. Therefore, semi-rigid rings that allow partial deformation are ideal for the valve-in-ring procedure, as opposed to rigid and incomplete rings, where some degree of paravalvular leakage is observed after implantation of the THV valve.

Unfortunately, the dimensions of the prosthetic ring given by the manufacturer are not always reliable, as the shape of the prosthetic ring can change after surgical insertion. Therefore, the sizing of the prosthetic ring on CT is of particular importance, as the appropriate size of the THV valve can be selected based on these dimensions. The most common measurements given by CT are the area of the ring as well as the intercommissural (IC) and septal to lateral (SL) distance.

In assessing the risk of LVOT obstruction, all that has been mentioned previously applies. In addition, however, the length of the anterior leaflet of the mitral valve should be assessed. In contrast to the valve-in-valve procedure where the leaflet is covered by the stent frame, the anterior leaflet is free in the valve-in-ring procedure and therefore a long leaflet (> 26mm) may significantly limit LVOT during its movement after THV valve implantation [19]. This becomes even more important when there is significant hypertrophy of the interventricular septum (**Fig. 5**).

MDCT in paravalvular leakage

A paravalvular leak may occur when there is reverse flow around the prosthetic valve. It is associated with prosthetic valve regurgitation and is a common problem in patients with a bioprosthetic or mechanical valve. In these cases, the patient develops heart failure (at a rate of 85%) and haemolysis (up to 47%). With an incidence of up to 17%, this is a fairly common problem [20].

The causes of paravalvular leakage are not fully understood. Alignment between the prosthetic ring and the native valve may be incomplete due to extensive calcifications. The tissue around the prosthetic valve may be weakened by chronic inflammation.

The decision to re-operate has increased mortality rates (13% for the first operation, 15% for the second operation and 35% for the third operation). In these cases, an alternative option is transcatheter closure of the paravalvular leak.

It is important to select the appropriate patient for closure of the paravalvular leak. Therefore, it is important to exclude the possibility of active inflammation, the presence of thrombus and the possibility of instability of the prosthetic valve before planning such a procedure.

Diagnosis of these patients is initially performed with transoesophageal echocardiography (TEE) and complemented with CT scan. The key information that should be answered before such a procedure is the location, size, morphology, number of leaks and severity of the leaks.

Transoesophageal echocardiography (TEE) can identify the location, severity and number of paravalvular leaks. It can also estimate the size of the paravalvular leaks.

The role of CT in these cases is constantly evolving. It can confirm the location of the paravalvular leak and estimate its size. It can also contribute to the selection of the appropriate device to close the paravalvular leak by providing information about the morphology of the paravalvular leak. For example, in a large-sized defect, a ventricular septal occluder may be used [21].

However, it should be noted that factors such as cardiac arrhythmias and artefacts caused by the prosthetic valve material and/or calcifications around the annulus affect the diagnostic accuracy of the CT scan. The value of CT is also important in providing accurate information about the appropriate angle of angiographic projection to limit the duration of the procedure and the amount of contrast agent administered to the patient during the procedure.

Finally, CT can confirm normal valve prosthesis motion in cases of paravalvular leak in mechanical prosthetic valves using the retrospective ECG gating technique (Fig 6).

Conclusion

The rapid development of procedures has led to an increased demand for non-invasive imaging modalities to aid in patient selection and preoperative planning. However, these procedures are extremely complex and multimodality imaging is the key for the success of these procedures. Echocardiography is the imaging modality of choice for diagnosing mitral disease, assessing severity and selecting appropriate patients who can benefit from these procedures. MDCT is essential in preoperative planning as it provides information on the size of the annulus, assessment of the potential risk of LVOT obstruction, evaluation of the landing zone and prediction of fluoroscopic angle. **R**

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