



Expert Consensus

Cardiac computed tomography for prosthetic heart valve assessment. An expert consensus document of the Society of Cardiovascular Computed Tomography (SCCT), the American College of Cardiology (ACC), the European Society of Cardiovascular Radiology (ESCR), the North American Society of Cardiovascular Imaging (NASCI), the Radiological Society of North America (RSNA), the Society for Cardiovascular Angiography & Interventions (SCAI) and Society of Thoracic Surgeons (STS)^{☆,☆☆}



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Abbreviations: 18F-FDG, 18F-fluorodeoxyglucose; AVR, Aortic Valve Replacement; BVD, Bioprosthetic Valve Degeneration; CT, Computed Tomography; ECG, Electrocardiography; HALT, Hypoattenuated Leaflet Thickening; MVR, Mitral Valve Replacement; PET, Positron Emission Tomography; PHV, Prosthetic Heart Valve; PPM, Patient-Prosthesis Mismatch; PVE, Prosthetic Valve Endocarditis; PVL, Paravalvular Leakage; SAVR, Surgical Aortic Valve Replacement; SMVR, Surgical Mitral Valve Replacement; SVD, Structural Valve Dysfunction; TAVI, Transcatheter Aortic Valve Implantation; TAVR, Transcatheter Aortic Valve Replacement; THV, Transcatheter Heart Valve; TMVR, Transcatheter Mitral Valve Replacement; TPV, Transcatheter Pulmonary Valve; TTE, Transthoracic Echocardiography; ViV, Valve-in-valve.

* In accordance with SCCT policy, writing group members and reviewers must disclose their relationships with industry (RWI). Please refer to Appendix 1 for the RWI disclosures of writing group members and Appendix 2 for the RWI disclosures of reviewers.

☆☆ This article was published in Journal of Cardiovascular Computed Tomography, Budde RPJ et al., Cardiac computed tomography for prosthetic heart valve assessment: An expert consensus document of the Society of Cardiovascular Computed Tomography (SCCT), the American College of Cardiology (ACC), the European Society of Cardiovascular Radiology (ESCR), the North American Society of Cardiovascular Imaging (NASCI), the Radiological Society of North America (RSNA), the Society for Cardiovascular Angiography & Interventions (SCAI), and the Society of Thoracic Surgeons (STS). The articles are identical except for minor stylistic and spelling differences in keeping with each journal's style. Either citation may be used when referencing this document.

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<https://doi.org/10.1016/j.jcct.2025.04.007>

Received 5 July 2024; Received in revised form 11 April 2025; Accepted 14 April 2025

Available online 17 June 2025

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ARTICLE INFO

Keywords:
Computed tomography
Valve
Cardiac
Imaging
Dysfunction
Prosthetic

ABSTRACT

Prosthetic heart valve (PHV) dysfunction is increasingly seen due to the increase in the number of PHV that are being implanted worldwide. Cardiac CT imaging has emerged as a valuable tool to assess PHVs and determine the cause of dysfunction. This consensus document first summarizes the available techniques for PHV assessment. Then the use of CT in PHV (dys)function assessment is discussed in detail including consensus statements for correct indications and patient selection for CT assessment of PHVs, image acquisition, reconstruction and measurement protocols and how to interpret and report the CT findings for specific types of PHV dysfunction.

1. Introduction

The number of prosthetic heart valve (PHV) implantation procedures continues to increase worldwide.¹ Traditionally, surgeons replaced valves surgically, but in the last 15 years transcatheter implantation techniques have become firmly established in routine clinical care.^{1–3} PHV dysfunction includes obstruction, (para)valvular leakage, structural valve deterioration and endocarditis.⁴ Echocardiography remains an excellent first-line imaging tool for PHV assessment, providing both anatomical and functional information.⁴ However, cardiac computed tomography (CT) may provide complementary information to assess PHV functioning and, in case of dysfunction, helps determine its cause and plan a potential re-operation or intervention.^{4,5}

This multi-society consensus document is written by a team of experts and provides a brief overview of heart valve replacement techniques, and available imaging techniques for PHV assessment. It then discusses in depth the role of cardiac CT, including scan acquisition, image post-processing, imaging findings, interpretation, and reporting in light of the various types of PHV dysfunction. Given the relatively limited amount of available data and literature on the application of CT to evaluate PHV function, the writing group has included consensus statements. These are based on the available published literature complemented by expert consensus but do not represent a formal

guideline with levels of evidence. In addition, we provide an overview table summarizing the different techniques for PHV assessment (Table 1).

2. Heart valve replacement technique

PHVs include mechanical and biologic valves placed via surgical or transcatheter (biological valves only) techniques into an aortic, mitral, pulmonary, or tricuspid valve position. Common nomenclature includes surgical aortic valve replacement (SAVR), transcatheter aortic valve replacement (TAVR), transcatheter aortic valve implantation (TAVI), surgical mitral valve replacement (SMVR), transcatheter mitral valve replacement (TMVR), and transcatheter pulmonary valve (TPV).

Contemporary mechanical valves typically feature bileaflet designs (two semilunar shaped discs in a ring); however, patients may still present with complications of older type PHVs such as tilting disc or ball and cage valves.⁶ Biological valves include stented valves (bovine pericardium or porcine valve tissue), and less commonly, stentless bioprosthetic valves (i.e., Medtronic Freestyle™), homografts from human cadaveric tissue, or autografts with a patient’s pulmonary valve (i.e., Ross procedure).⁶ The stented valves are the most commonly used PHVs. Transcatheter valves consist of biological tissue mounted on an expandable frame. Fig. 1 provides examples of the various valve types.

Table 1
Overview of the different imaging modalities for prosthetic heart valve assessment.

	Echocardiography	CT	Cine fluoroscopy	Nuclear Imaging
Normal functioning PHV				
Leaflet motion	++	+++ (mechanical PHV) ++ (biological PHV)	+++ (mechanical PHV only)	n/a
Flow and pressure gradients	+++	n/a	n/a	n/a
Determination PHV type and size	+ (mechanical vs. biological)	+++	++	n/a
PHV dysfunction				
Pannus	+ (to detect ↑ pressure gradient)	+++	++ (indirect by detecting leaflet motion restriction in mechanical PHV)	n/a
Thrombus	++	+++	++ (indirect by detecting leaflet motion restriction in mechanical PHV)	n/a
Paravalvular leak	+++	+ (location and size)	+ (contrast needed)	n/a
Patient prosthesis mismatch	++	+	n/a	n/a
Endocarditis				
Endocarditis in general	+++	+++	–	++ (18F-FDG PET-CT)
Vegetations	+++	+	n/a	–
Valve dehiscence	+++	++	+++	n/a
Abscesses and mycotic aneurysms	+	+++	n/a	n/a
Biological PHV dysfunction				
HALT	++	+++	n/a	n/a
RELM	+	++	n/a	n/a
Structural valve deterioration/ BVD	++	+++	n/a	+++ (18F-Fluoride PET)*

Comparison of the information provided by different imaging modalities regarding PHV (dys)function. N/a = not applicable; HALT = hypoattenuated leaflet thickening; RELM = reduced leaflet motion; BVD = bioprosthetic valve dysfunction; 18F-FDG PET-CT = 18F-fluorodeoxyglucose positron emission tomography-computed tomography; 18F-fluoride PET = 18F-fluoride positron emission tomography; * mainly in research setting. Range: – to +++.

The choice of valve replacement type and technique depends on the patient's demographics, co-morbidities, clinical presentation, and the surgeon's and institutional practice pattern. Mechanical valves require lifetime anticoagulation to prevent valve thrombosis but can conversely demonstrate lifetime durability. Biologic valves can be managed with aspirin only but are limited in durability.

During surgical valve replacement the native valve is excised, valve sutures are placed around the annulus, and the PHV is seated and secured with sutures in the orthotopic position. Pledgets (small synthetic patches to reduce the risk of sutures tearing through tissue) may be placed in the supra- or sub-annular position, depending on the surgeon's preference. Sutures are secured with surgeon hand-knots or an automated suture fastening device (i.e., Cor-Knot®), which will appear as metal targets adjacent to the cuff of the prosthetic valve. In the last decade, stented sutureless aortic bioprostheses that are implanted have also been introduced clinically.⁷ After opening of the aorta and excising the leaflets the collapsed prosthetic valve is re-expanded under direct vision.

Transcatheter valves are mounted in a collapsed state on the delivery system, passed through the blood vessels, and then re-expanded in the orthotopic valve position. Importantly, the native valve remains in place, and the leaflets are left in the open position adjacent to the transcatheter valve. In patients with an existing valve prosthesis, a transcatheter valve can be placed into the existing frame to overcome the structural deterioration of the bioprosthetic valve, called valve-in-valve (ViV).

3. General principles of PHV imaging assessment

The first step of PHV evaluation involves reviewing the operative report which contains information on the prosthesis brand, model type, device number labelling, implantation technique and date of implant. If the operative report is unavailable, familiarity with the CT or fluoroscopic appearance of PHVs enables a streamlined approach to confirm the specific device. Knowledge of the used PHV allows device-specific assessments, while minimizing potential confusion regarding its form and

function.^{4,8} Second, reviewing previous imaging studies, when available, adds to the narrative of the current imaging findings. Serial imaging allows for longitudinal comparison reads for early detection and serial evaluation of signs of valve degeneration. Lastly, all available imaging data from different modalities should be included in the interpretation and synthesis of available imaging sets, as different imaging modalities provide valuable information on different aspects of PHV (dys)functioning.⁴

4. Transthoracic and transesophageal echocardiography for PHV assessment

Transthoracic echocardiography (TTE) assesses the hemodynamic and anatomical function of PHVs.⁴ It is non-invasive, free of radiation and iodinated contrast agents and easily accessible, while providing both anatomical and functional information. Transesophageal echocardiography (TEE) is the preferred imaging modality to identify the mechanism of PHV dysfunction or failure. TEE offers higher spatial resolution than TTE and views unobstructed by ribs and lungs but is semi-invasive and requires sedation (which may affect general haemodynamics and hence valvular flow) prior to performing the examination. Both TTE and TEE have a higher temporal resolution than CT.

European and American guidelines recommend a baseline echocardiogram to establish baseline measurements for future comparison within 30 days or six to twelve weeks after a PHV is placed.^{9,10} Routine echocardiographic evaluation can then be performed at 1-year and annually thereafter, or at 5-year, 10-year, and then annual intervals to evaluate for valvular degeneration depending on the PHV type that was placed.^{9,10} In patients with PHV, echocardiography is the first line of investigation for new onset symptoms of heart failure.^{4,9,10} Imaging for PHVs can be divided into two primary categories of study: detection of valve degeneration or dysfunction and subsequent identification of their underlying mechanisms.

Standard of care echocardiographic assessment for PHV follows an established search profile pattern for hemodynamic evaluation.

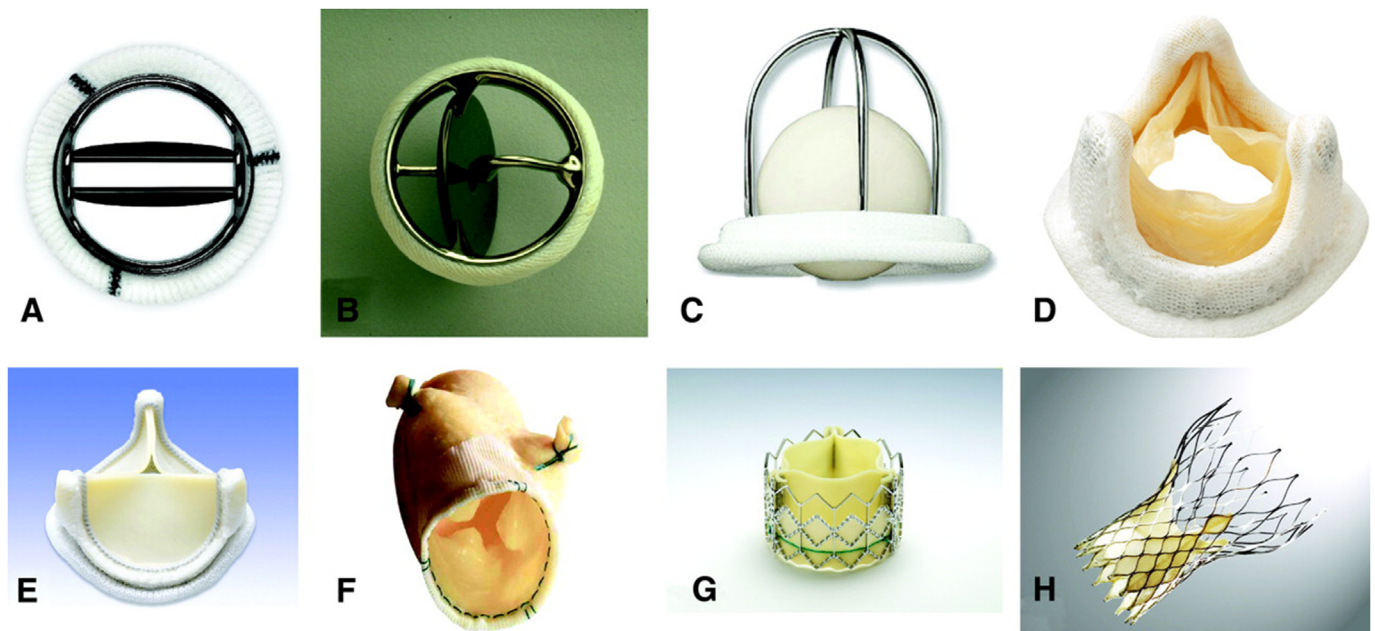


Fig. 1. Photographs of different prosthetic heart valve types. A: Mechanical bileaflet valve prosthesis. Two semilunar disks are suspended in the valve ring at the hinge points. Most contemporary mechanical valves have this design. B: Tilting disk mechanical prosthesis. The single disk is held in place by fixed struts that allow the disk to move between the open and closed position. C: Mechanical ball in cage valve. This valve type is no longer implanted but may be encountered in specific patients. D and E: Biological stented frame valves which consist of a frame in which the valve leaflets of either porcine valve tissue (D) or bovine pericardium (E) are suspended. All valve types in A-E have a fabric suture ring (white ring in the images) through which the sutures are placed to insert the valve. F: Biological non stented valve and aorta prosthesis. The valve and aorta are explanted porcine tissue. G and H: Transcatheter biological prostheses that consist of a metal stent in which leaflets made of bovine (G) or porcine (H) tissue are suspended. Reproduced with permission from Pibarot et al.⁶

Established calculated echocardiographic parameters suggesting PHV deterioration have been defined by PHV-specific velocities and gradients and Doppler velocity indices.⁴ Echocardiographic evaluation of PHV should be a comprehensive, integrative approach, utilizing multiple echo views and angulations, including off-axis angles to acquire 2-dimensional, Doppler (color, pulse, and continuous wave), M-mode, and 3-dimensional images with and without color.⁴ Using these tools, echo can often visualize the PHV leaflet motion, presence or absence of bioprosthetic leaflet thickening, calcification, or masses (thrombus and vegetation), stability of the PHV sewing ring, and flow through and around the valve.^{4,11} Color Doppler interrogation of the PHV is engaged for assessment of presence or absence of PHV regurgitation. Color Doppler imaging helps identify the presence, location (central vs. paravalvular), and severity of regurgitant jets. A complete echo assessment of PHV must also include chamber size and function, wall thickness, intracardiac pressure estimation, and assessment of adjacent valve function.^{4,11,12} Echocardiographic template reporting should include the PHV type, size, date of implant, indication for the examination, patient symptoms, height, weight, vitals (heart rate and blood pressure), and results of any prior studies.

The presence of sewing ring and stent frame shadowing artifacts limits adequate visualization of surgical and transcatheter PHV by TTE.¹³ Acoustic shadowing from the PHV may impair adequate Doppler assessment. TTE Doppler flow malalignment may lead to under-estimation of PHV velocity/gradients, and the presence of eccentric jets of regurgitation may not be appreciated by TTE.

TEE may overcome some of the limitations of TTE and can be a useful adjunct for PHV assessment, particularly with 3D and multiplanar reconstruction. TEE allows for optimal visualization of posterior structures, and transgastric views of the PHV enable thorough evaluation of PHVs for paravalvular leaks, valve dehiscence, PHV leaflet motion, and feasibility of next-generation repair/replacement strategies. The American Society of Echocardiography has described detailed information on echocardiographic assessment of PHV by.⁴

Key points

After PHV implantation, a baseline echocardiography is recommended by both European and American guidelines, to be followed by repeated echocardiography examinations at a variable time interval depending on the used device.

Transthoracic echocardiography is the first-line imaging test in case of suspected PHV dysfunction and provides both anatomical and functional information.

Transesophageal echocardiography may overcome some of the limitations of TTE and can be a useful adjunct for PHV assessment but is semi-invasive.

5. X-ray cine fluoroscopy for leaflet motion assessment of mechanical valves

Cine fluoroscopy is an easy, accessible, and non-invasive examination that provides high temporal and spatial resolution. Non-contrast exams can be used to determine the general type of prosthesis (based on appearance), relative stability of the device, and mechanical PHV leaflet mobility. Using iodinated contrast adds qualitative assessment of regurgitation of the valve, though it does not always identify the exact mechanism of regurgitation (central vs paravalvular). Furthermore,

intra-arterial contrast delivery is required and hence it is only used in very selected cases, with TTE and TEE being available as alternatives.

Cine fluoroscopy can evaluate adequate leaflet opening and closing of mechanical PHV leaflets, often complementing echocardiography in the setting of elevated gradients or significant regurgitation.^{4,9,14} Cine fluoroscopy examinations are performed with the patient in a supine position, with the operator adjusting the C-arm to align the valve in a side view “in profile” as well as “en face,” if feasible. Due to differing anatomy and post-surgical orientation, the cranial/caudal and right/left angulations are often different for each patient, and care must be taken to fully align the annular frame and leaflets each in a single side view plane to accurately measure the opening and closing angles.¹⁴ These angles are then compared to expected normal values as available from the manufacturer’s documentation. Limitations of cine fluoroscopy include lack of any hemodynamic or advanced anatomical assessment to determine the severity of PHV dysfunction or mechanism of failure. Thus, cine fluoroscopy is best when paired with clinical and hemodynamic data.^{4,14}

Key points

Cine fluoroscopy can be used to assess mechanical PHV leaflet motion and determine opening and closing angles.

Depending on the PHV orientation it may be difficult to obtain a view precisely perpendicular to the valve leaflets.

6. Positron emission tomography CT

Molecular cardiovascular imaging provides complementary information on the metabolic activity of pathological processes in PHV tissue and surrounding structures, which is particularly useful in challenging cases with a diagnostic dilemma. In principle, molecular imaging is performed using a systemic injection of a ligand-specific radiotracer which colocalizes with a target of interest (GLUT1,3 receptor, nanocrystalline hydroxyapatite, glycoprotein IIb/IIIa receptor) and provides a metric of emitted photon energy detection using either a positron emission tomography (PET) or single-photon emission computerized tomography scanner. Recent advances in whole-body PET scanners enable rapid, low radiation exposure acquisitions which have a spatial resolution of less than 3mm. Infection and inflammation imaging are the main clinical applications for molecular cardiovascular imaging. 18F-fluorodeoxyglucose (18F-FDG)^{15,16} and 99mTc-Hexa-methyl-propyl-amine-oxime radiolabelled white blood cells¹⁷ have high accuracy in detecting prosthetic valve endocarditis (PVE), as well as highlighting remote sites of systemic infection by directly visualizing activated macrophages *in situ*. Discrete focal 18F-FDG uptake which colocalizes with low CT attenuation tissue provides supportive evidence to confirm a diagnosis of prosthetic valve endocarditis.^{15,16} However, one should be aware of false positive interpretation of normal perivalvular 18F-FDG uptake and other confounding factors such as the use of Bioglu.^{15,18} More recently, an expanding number of disease specific radiotracers have facilitated the assessment of non-inflammatory pathology in bioprosthetic valve dysfunction. Calcification is a key feature of deteriorating bioprosthetic valve performance and highly sensitive radiotracers such as 18F-fluoride can localize regions of hydroxyapatite deposition within dysfunctional bioprosthetic valve leaflets.¹⁹ Comparable 18F-fluoride signal intensity is seen within dysfunctional transcatheter aortic valve leaflets, thereby enabling clinicians to assess bioprosthetic leaflet integrity in challenging cases.²⁰ Additionally, the novel glycoprotein IIb/IIIa receptor radiotracer 18F-GP1 can be used to confirm the presence of thrombus formation in hypoattenuated leaflet thickening.²¹ By combining biological activity

data from PET with the high-resolution structural information from cardiac CT images, clinicians have a hybrid modality to monitor disease progression and stratify therapy more precisely.

Key points

18F-fluorodeoxyglucose PET-CT and radiolabeled white blood cells single-photon emission CT have a high accuracy in detecting prosthetic valve endocarditis (PVE), as well as highlighting remote sites of systemic infection. PET imaging has an important role in patients with an unclear diagnosis.

New radiotracers such as 18F-fluoride are being investigated to demonstrate valve degeneration and the presence of thrombus formation in hypoattenuated leaflet thickening.

7. CT acquisition protocols for PHV imaging

The role of CT in evaluation of prosthetic heart valves is rapidly expanding. CT complements echocardiography imaging, further aiding physicians to gain a comprehensive assessment of the functional and anatomic performance of the PHV. To image suspected PHV dysfunction, physicians must choose an optimal CT image acquisition protocol, which necessitates a multifaceted approach. Such a protocol should include image data acquisition in various phases of the cardiac cycle, to facilitate the assessment of PHV dynamics. Furthermore, the protocol should enable precise differentiation between the prosthetic materials and surrounding native tissue changes and be adapted to the anatomical position

of the investigated PHV (left vs. right heart). Finally, the use of a dedicated workstation enables optimal extraction of information from the acquired data set through image analysis and postprocessing.

As a general rule, tube potential and current settings used for coronary CTA provide good image quality for PHV imaging as well. Automatic tube potential and current adaptation based on the patient's size and anatomical region scanned usually provides adequate adjustments. For mechanical and transcatheter PHV it may be beneficial to use higher kV settings (120, 140 kV) to reduce PHV artifacts. Tube current modulation during the R–R interval should be used cautiously (see below).

7.1. Functional evaluation

In general, CT imaging of the heart and PHV should be performed using ECG-synchronized thin slice (<1mm) acquisition and reconstructions to optimally visualize the PHV and allow for multiplanar reconstructions^{22,23} (Fig. 2). CT scanners with at least 64 slices or equivalent are recommended although retrospective ECG-gated acquisitions may also be performed on scanners with fewer slices (e.g. 16 or 40), albeit at a longer acquisition time. Data acquisition allowing reconstructions of image datasets throughout the cardiac cycle is required for functional evaluation of leaflet motion (also called 4D-CT imaging). Typically, images are reconstructed at 5–10 % intervals across the cardiac cycle. This approach allows a dynamic assessment of both normal and abnormal leaflet motion with results comparable with conventional cinefluoroscopy for mechanical PHV and valve stability/dehiscence (i.e. rocking motion).^{24,25} CT evaluation can also replace fluoroscopic assessment when it is limited by impractical C-arm angulation.^{25,26} For most centers a retrospective electrocardiography (ECG)-gated image acquisition protocols is the preferred acquisition mode. Alternatively, perform a prospective ECG-gated sequential acquisition preferably with a wide padding window to have the required phases throughout the cardiac cycle for image analysis.²⁷ While the radiation dose of retrospective

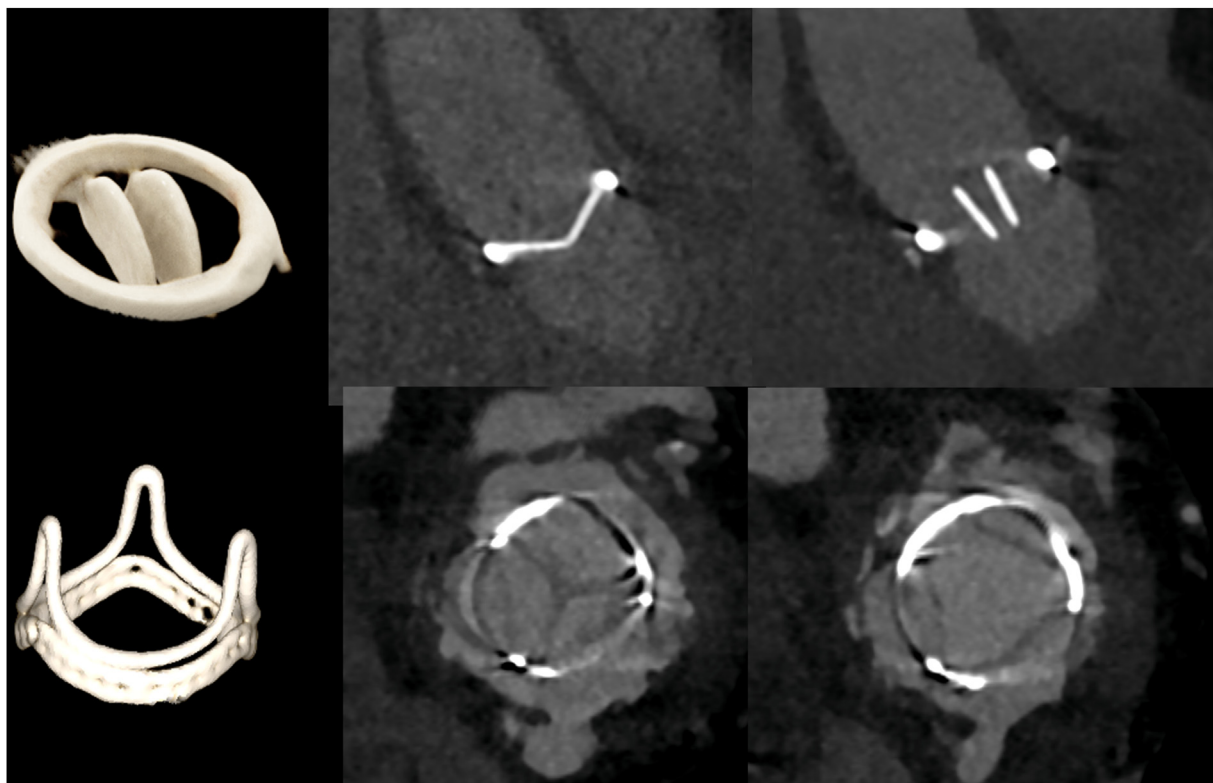


Fig. 2. Normal imaging appearance on CT images of different types of prosthetic heart valves with 3D volume rendering and valve in closed and open position. Top row: mechanical bileaflet valve, lower row: stented biological valve.

ECG-gating is higher compared with other data acquisition techniques, it offers in general the highest flexibility to correct triggering errors due to arrhythmias.^{26,28}

Keeping radiation exposure in mind, design the arterial phase acquisition with caution. Since image quality in this phase should ideally be consistent across the cardiac cycle, one can use dose modulation techniques targeted to optimize one cardiac phase over another (as often used in conventional CT-imaging of the coronary arteries) but do not lower tube current too aggressively. Cardiac arrhythmia such as atrial fibrillation or extrasystole are relatively common in patients with valvular heart disease. In such patients ECG editing²⁹ or absolute delay multiphase reconstructions³⁰ may be beneficial to improve image quality. Note that streaking and beam hardening artifacts from mechanical leaflets can limit interpretation, and it is important to identify the phases of the cardiac cycle with the least artifact.³¹

Previous studies describe the use of Beta-blocker medication for heart rate control to improve image quality which in general improves image quality.^{32,33} Nitroglycerine does not impact PHV image quality but may be beneficial if the coronaries are to be assessed as well. However, both beta-blockers and nitroglycerine may be contraindicated in patients with e.g. aortic stenosis and one should use them with care depending on the clinical status of the patient and in consultation with the referring cardiologist.

7.2. PHV material imaging and tissue characterization

PHVs can cause artifacts that may hamper image quality and lower the diagnostic yield.^{34,35} Several techniques can reduce PHV material-induced artifacts, including higher (e.g. 140 kVp) tube voltage,³⁴ reconstruction of high keV level monoenergetic images from dual-energy CT,³⁶ and acquisitions that use prospective ECG-triggering.³⁷ Iterative reconstruction techniques allow for considerable dose reduction^{38,39} and even improved overall objective image quality.³⁹ More recently, photon-counting detector CT with its high spatial resolution in combination with sharp kernels and dual energy-based reconstruction with high keV monoenergetic images has demonstrated further improvements in the quality of prosthesis depiction with fewer artifacts.⁴⁰ Iterative metal artifact reduction algorithms may reduce beam hardening artifacts but their application for PHV imaging is limited and results may be variable and may even induce secondary artifacts.³⁴

Despite these approaches, excessive streaking may make it difficult to evaluate monoleaflet valves, especially the Bjork-Shiley and Sorin monoleaflet valves.^{26,32} Fortunately, most contemporary bileaflet mechanical valve leaflets are associated with only limited artifacts on CT imaging.^{26,35}

7.3. Contrast injection

In general, a multiphase contrast injection protocol is recommended. A non-contrast enhanced scan demonstrates presence and extent of calcifications, which may help to differentiate between acute and chronic infection and show structural biological PHV dysfunction. Additionally, non-contrast images can distinguish suture pledgets and paravalvular leakage, which have similar attenuation characteristics when only contrast-enhanced images are available^{41,42} Fig. 3. Perform this non-contrast enhanced acquisition in a single phase of the cardiac cycle. A low dose multiphase acquisition can be used to evaluate mechanical PHV leaflet motion in case of contra-indications for contrast administration.²⁸ With spectral or photon counting CT scanners, a virtual non contrast reconstruction from the CTA images may substitute an additional true non-contrast scan.^{43,44} Acquire an arterial phase acquisition to evaluate valve position and leaflet dynamics as well as to search for leakage, obstruction, pannus, hypoattenuated leaflet thickening (HALT), and to search for the various features of infective endocarditis.²⁷ If required one can also evaluate the coronary arteries on these images, with prior sublingual administration of nitroglycerine recommended in this scenario if the patient's hemodynamic condition allows for this.⁴⁵ Optionally, add a delayed phase acquisition to the protocol (with image data acquisition starting 60–70 seconds after contrast injection), which can be useful for improved visualization of abscesses in infective endocarditis and to differentiate between delayed flow and thrombus in the cardiac chambers.^{27,46,47} In contrast to the arterial phase acquisition, both the non-enhanced and delayed phase acquisition usually can be acquired with a narrow ECG-pulsing window, to reduce radiation exposure.

In patients with a need to keep the volume of iodinated contrast material as low as possible use either low kV settings to increase contrast attenuation (at the expense of more PHV induced artifacts in some mechanical and transcatheter PHV) and/or use virtual monoenergetic reconstructions at low kV for scanners allowing spectral imaging.

7.4. Anatomical location of the PHV

Contrast injection protocols also depend on the valve of interest. For left-sided valves, a triphasic protocol consisting of a bolus of contrast followed by a mixture of saline and contrast and then pure saline is recommended, similar to that used for coronary CT angiography.²⁹ For pulmonary valves, apply an injection protocol like that used for CT pulmonary embolism. Adequate visualization of the tricuspid valve with CT is more challenging, owing to the mixing effect occurring in the right atrium from high attenuation inflow from the superior vena cava and

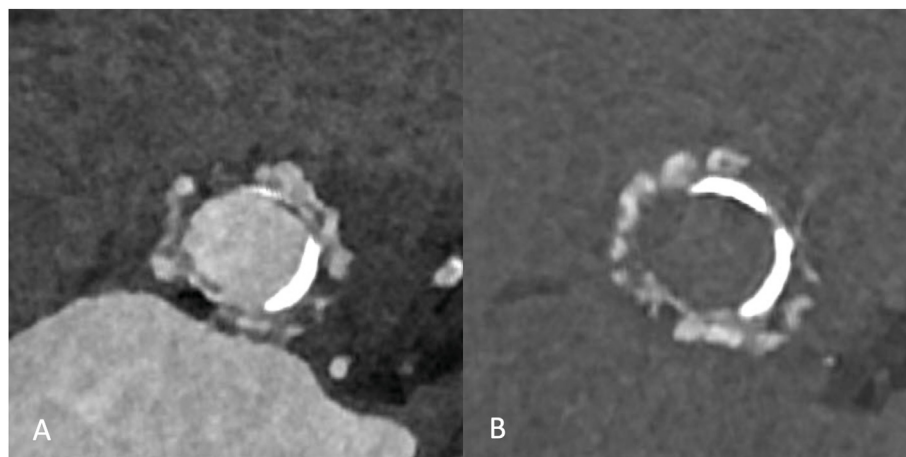


Fig. 3. Suture pledgets. CT angiography (A) and non contrast enhanced (B) images of a biological prosthetic heart valve. Notice the small hyperdense structures around the valve ring which represent pledgets.

non-enhanced attenuation inflow from the inferior vena cava. Reports describe attempts to use a two-site injection (via arms and legs).⁴⁸ Alternatively, one can use a tailored triphasic contrast media protocol that includes adapting the amount of the administered contrast media to the left ventricular ejection fraction.^{48,49} Decreased contrast flow injection speed during the last phase reduces flow artifacts in the right chambers.

7.5. Image analysis and postprocessing

Dedicated viewing software should be used for image analysis enabling both static and dynamic image reconstructions, scrolling through the images, and changing window width and level settings at the

readers' discretion. The isotropic nature of modern CT images allows high quality reformats in any plane. To obtain reformats in parallel and perpendicular to the prosthesis, rotate the axes to be in line with the valve ring and parallel to the valve leaflets.^{23,25} Set the center in the midpoint of the valve orifice in the short-axis and obtain long-axis reformations by rotating the axes while maintaining the annulus plane. This provides an optimal on-edge view of the opening and closing of the leaflet(s).^{24,50,51} Fig. 4 illustrates the specific steps. Attempts have been made to automate this process but these solutions are still in initial development stages.⁵² Assess the opening and closing angles, defined as angles between the leaflets and the orifice ring, in cine mode and measure them in the fully open and fully closed positions to evaluate leaflet motion.^{23,28,50,51} Reconstruct images in the same orientation as the

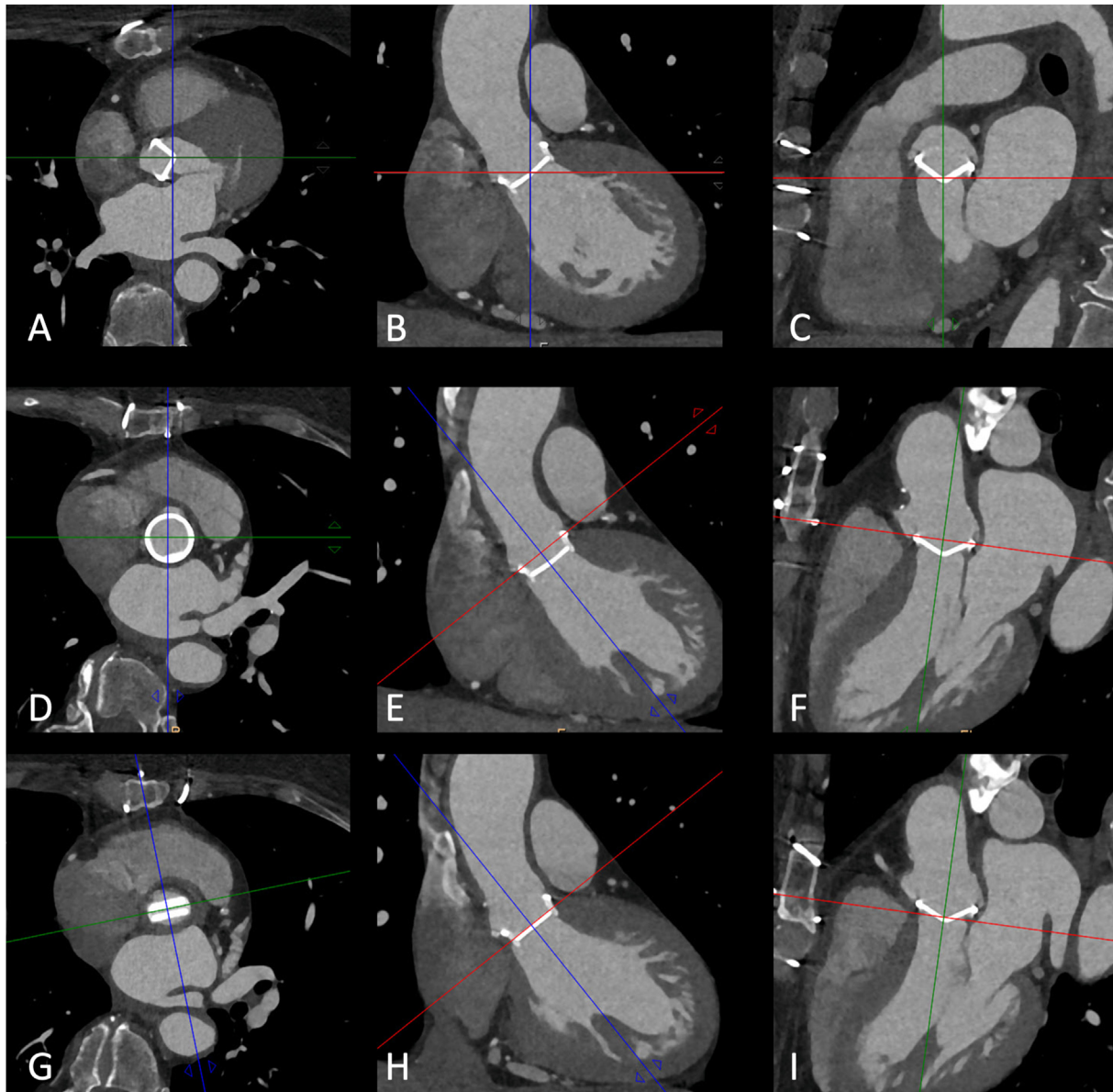


Fig. 4. How to obtain image reconstructions in plane and perpendicular to the valve. Scan of a patient with a mechanical aortic valve prosthesis. The images are loaded in a multiplanar viewer with the lines of the “crosshairs” locked (i.e. they remain in a fixed 90-degree orientation when rotating one of the axes). Panels A, B and C are the initial axial, coronal and sagittal orientations. In the coronal plane (B) the red line is rotated counterclockwise to be parallel to the valve ring. In the sagittal plane (C) the red line is then rotated to also be parallel to the valve ring. In the resulting planes (D,E and F) it is checked that the valve ring can be seen as a complete ring in the adapted axial plane (D). If the ring is not seen in one image the red axis needs to be rotated some more. Then in the adapted axial plane (D) one needs to scroll up and down until the two valve leaflets can be seen as two parallel lines inside the valve ring. If the leaflets are not parallel the red line needs to be rotated again whilst looking at the leaflets as this allows some tweaking to obtain the orientation. Then the green line in the adapted axial plane (G) is rotated so it is parallel to the valve leaflets. This results in an orientation perfectly perpendicular to the valve leaflets in the two other imaging planes (H and I).

standard TTE and TEE views to allow for direct comparison between modalities if required.⁵³

Consensus statement

Cardiac CT acquisition protocols for PHV assessment should include an arterial phase acquisition, preferably an additional (virtual) non-contrast enhanced acquisition and optionally a delayed phase.

Retrospective ECG-gated or prospective wide-window ECG-triggered arterial phase acquisition is required for the reconstructions of image datasets throughout the cardiac cycle to allow functional evaluation of leaflet motion.

Most contemporary PHV generate only limited artifacts. PHV-induced artifacts may be mitigated by using high kV acquisitions, high keV level monoenergetic reconstructions, iterative reconstruction and prospective ECG-triggering when possible.

Contrast injection should be tailored to the valve of interest with standard injection protocols used for coronary imaging often being well-suited for left sided valves.

Image analysis should be performed using dedicated viewing software that enables both static and dynamic imaging with multiplanar reconstructions in plane and perpendicular to the valve leaflets.

8. CT findings in normal functioning PHV

Each PHV type and size has a unique appearance on CT.^{35,36,54} In general, most PHV types present with only limited artifacts; with the tilting disc valves mentioned above the notable exceptions. Importantly, the PHV size as labelled by the manufacturer does not represent the actual internal orifice, stent frame, and external dimensions.⁵⁵ The implanted PHV size can be accurately determined from the CT images using a standardized measuring approach.⁵⁴ This encompasses more than simply measuring the inner diameter of the PHV and we refer the reader to the original publication for detailed instructions and reference values.⁵⁴ Lastly, not all prosthetic surgical devices are radio-opaque and visible by CT and a thorough evaluation of the patient's operative report or alternative imaging modality such as TEE will help guide assessment.

8.1. Prosthetic heart valve positioning

Prosthetic heart valves should be well approximated to the valve annulus. Gaps/spaces between the outer wall of the prosthesis and native valve annulus may indicate paravalvular leak and dehiscence. In cases of transcatheter prosthetic heart valves, the positioning with respect to extension above and below the annular plane varies based on the valve being replaced. Surgical valves may sit intra-annular or supra-annular, based on prosthetic design. TAVR valves will demonstrate a small portion of the stent frame below the annulus. Self-expanding transcatheter PHV, and, to a lesser extent, surgical biological valves, may show a non-circular configuration at the level of the native valve annulus.^{41,56}

8.2. Leaflet motion and integrity

Use ECG-gated CT acquisitions to evaluate mechanical and bioprosthetic heart valve leaflet motion and integrity in the fully open and fully closed positions.

Mechanical bi-leaflet PHV leaflet angles can be measured in two different ways. On fluoroscopy most physicians measure the angle

between both leaflets and communicate this as a single number. On CT however, readers often measure the angle of the individual leaflets with respect to the PHV ring and report it as two separate numbers (one for each leaflet)²³ (Fig. 5). Leaflets should open and close in a symmetrical fashion.⁵⁷ Limitation of motion is likely when motion of a leaflet or leaflets is restricted and/or the opening or closing angle measured on CT deviates $>4^\circ$ compared to the manufacturer value.^{24,58}

Bioprosthetic valve leaflets can be difficult to see on CT owing to the thinness of the leaflets and the insufficient temporal resolution of CT. If seen however, the leaflets must be smooth and symmetric with complete forward excursion during systole and complete coaptation during diastole.^{33,59}

8.3. Normal early post-operative and procedural findings

The mode of PHV placement and timing of CT after surgery determine normal postprocedural findings on CT. Normal early post-operative features of surgical valves can include periaortic soft tissue stranding/edema, fluid, and air.^{60–62} Unfortunately, these early, expected post-operative findings can be difficult to differentiate from infection.⁶¹ Suture pledgets appear as small hyperdense foci in a circular pattern around the PHV.

In cases of transcatheter prosthetic heart valves, the majority of the post-procedural features seen with SAVR are not expected.⁶³

Consensus statement

Each PHV model has a distinct appearance on CT imaging.

Normal mechanical PHV leaflet opening and closing angles may show up to 4° deviation from manufacturer specifics.

Normal biological PHV leaflets are expected to be smooth and symmetric with complete forward excursion during systole and complete coaptation during diastole.

Self-expanding TAVR valves and biological surgical PHV may show a non-circular configuration at the level of the aortic annulus.

Surgical valves may demonstrate periaortic soft tissue stranding/edema, fluid, and air in the early post-operative period.

9. Types of PHV dysfunction

9.1. Obstruction

9.1.1. Thrombus and pannus

PHV obstruction may be asymptomatic or present with embolic events, decompensated heart failure, or even cardiogenic shock. Causes of PHV obstruction include thrombus, pannus, valve degeneration and infective endocarditis.⁴ Thrombus formation restricting leaflet motion is the most common cause for mechanical PHV obstruction with a reported prevalence of 0.3–1.3 % patient-years.⁶⁴ Contrary to pannus formation, mechanical valve thrombosis is commonly associated with a sub-therapeutic INR. Mechanical valve obstruction from pannus typically occurs relatively late after implantation after five or more years.⁶⁵ Importantly, pannus, which is composed of myofibroblasts and collagen fibers, can serve as a nidus for superimposed thrombus. In patients undergoing redo valve replacement for valve obstruction, nearly half demonstrate combined thrombus and pannus formation.⁶⁶ The distinction between thrombus and pannus has important clinical implications. Depending on the size and clinical presentation, PHV thrombosis may be treated with anticoagulation and possibly thrombolytics alone. However, clinically significant valve obstruction due to pannus requires redo valve replacement.^{9,10}

The initial diagnostic evaluation of suspected PHV obstruction includes TTE and TEE echocardiography (and may include cine fluoroscopy in mechanical PHV).^{4,14} Cardiac CT can provide important complementary information. Cine fluoroscopy and cardiac CT can both reliably assess restricted leaflet motion by measuring opening and closing angles relative to a reference standard^{5,67} (Table 2). However, cine fluoroscopy does not provide insights regarding the underlying cause of obstruction.⁶⁸ Accordingly, American and European guidelines both endorse cardiac CT in the evaluation of patients with suspected mechanical valve dysfunction.^{9,10}

9.1.2. Cardiac CT assessment of thrombus and pannus

PHV thrombus manifests as an abnormal hypodensity at the in- or outflow aspect of the valve leaflets or stent. The morphology of a thrombus is typically irregular, and echocardiography and cine imaging demonstrate independent mobility. Although thrombi may be small, a large hypodense mass is more commonly compatible with thrombus and less likely to be suggestive of pannus.⁶⁸

The location of the PHV abnormality helps distinguish pannus versus thrombus. Pannus is commonly located sub-valvular, with a crescentic or circular morphology as it extends along the valve sewing ring (Fig. 6). Moreover, pannus may have a higher attenuation (i.e., HU > 145) as compared to thrombus.^{31,69} Based on these characteristics, compared to other imaging modalities, cardiac CT can more readily distinguish pannus from thrombus. Cardiac CT has demonstrated higher sensitivity of 85 % for diagnosing pannus compared to TEE (sensitivity 62 %) in a meta-analysis.⁷⁰ The pooled sensitivity and specificity for diagnosing thrombus as the cause of PHV obstruction was 75 % and 75 %, respectively for TEE vs. 45 % and 90 %, respectively for CT.⁷⁰ In cases of medical management, CT can be used in follow-up to evaluate resolution of thrombus (Fig. 7).

9.1.3. Complementary value of cardiac CT in suspected PHV obstruction

Sucha et al. investigated the additional value of cardiac CT in 30 patients with suspected PHV obstruction and showed it provided incremental value to the routine evaluation with TTE and TEE (and cine

fluoroscopy in selected cases) in 26/30 (87 %) cases for detecting the specific cause of PHV obstruction, which led to a treatment strategy change in 8/30 (27 %) patients.⁷¹

9.1.4. Other causes of obstruction

Besides pannus and thrombus, CT can identify other more rare sources of obstruction of PHV, including for instance a narrowed LVOT due to a membrane or complex multifactorial anatomical obstruction following TMVR in patients with a TAVR valve in place as well.⁷²

Consensus statement

Cardiac CT provides valuable complementary information to echocardiography to determine the cause of PHV obstruction, especially by distinguishing thrombus from pannus.

Thrombus and pannus both present as a hypodense mass on CT imaging, but location and Hounsfield unit value measurements can help to differentiate between both entities.

Cardiac CT has a higher sensitivity than TEE for detecting pannus tissue as the cause of PHV obstruction.

In cases of PHV obstruction due to complex anatomical alterations, CT may provide valuable insight into the mechanism of obstruction.

10. (Para)valvular leakage

The majority of PVL (74 %) is detected in the 1st year following surgery.⁷³ Causes of PVL include early technical failures from suture loosening in surgical valves or severe (peri)annular calcifications and

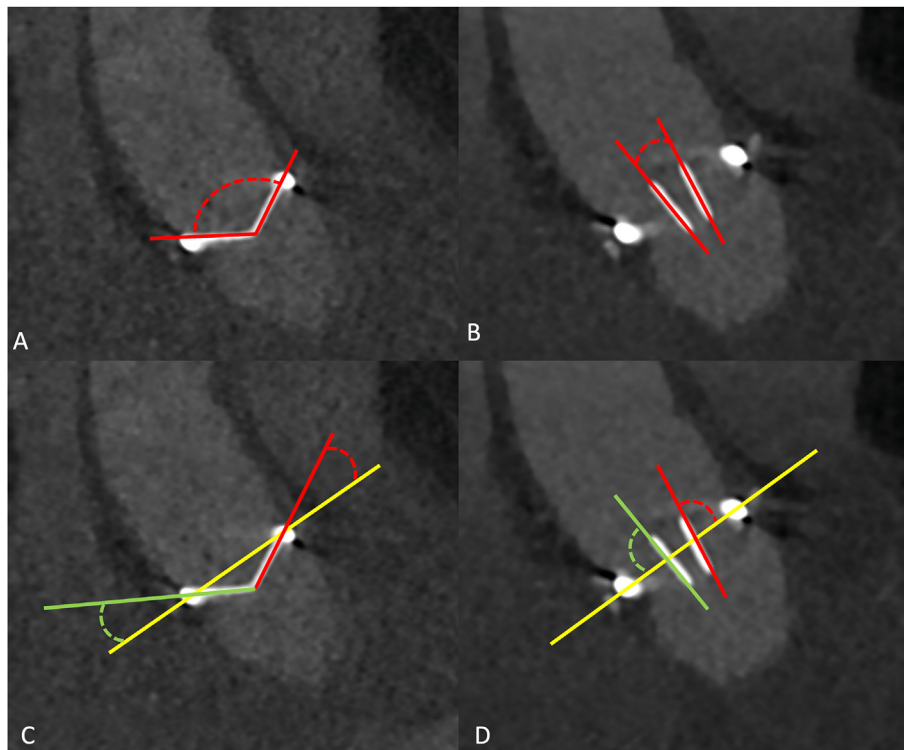


Fig. 5. How to measure valve leaflet opening and closing angles for mechanical bileaflet prosthetic heart valves. With fluoroscopy the leaflet angles are usually measured as the angle between the two leaflets. This can be done with CT as well (A and B). Using the valve ring as the reference plane (yellow line in C and D), CT also allows measurement of the opening and closing angle of each individual leaflet (green and red lines in C and D). The angles reported in Table 2 refer to measurements as seen in C and D.

Table 2
Opening and closing angles of specific PHV types. Adapted from Habets et al.^{5,21}
The list is not intended to include all mechanical PHV types. Some types are no longer available but may still be encountered in patients. Opening and closing angles refer to the angle between the leaflet and the prosthetic valve plane.

PHVs by type	Metal content	Leaflet opening angle (degrees)	Leaflet closing angle (degrees)
ATS Open Pivot	Titanium alloy ring	85 (AVR)	25 (AVR)
Carbomedics	Titanium alloy ring	78 (AVR and MVR)	25 (AVR and MVR)
Duromedics	Cobalt-chrome alloy ring	78 (AVR), 73 (MVR)	20 (AVR and MVR)
On-X	Titanium alloy ring	90 (AVR and MVR)	40 (AVR and MVR)
Bicarbon	Titanium alloy ring	80 (AVR and MVR)	20 (AVR and MVR)
St Jude/Masters/Regent	Nickel Alloy ring	85 (AVR and MVR)	30 or 25 ^a (AVR and MVR)
Björk-Shiley spherical	Cobalt-chrome alloy	60-70 [#] (AVR and MVR)	0 (AVR and MVR)
Medtronic® Hall	Titanium alloy ring	75 (AVR and MVR)	0 (AVR and MVR)
Omniscience	Titanium alloy ring	60 (AVR)	0 (AVR)
Sorin All carbon	Cobalt-chrome alloy	60 (AVR and MVR)	0 (AVR and MVR)

^a 30° for 19–25 mm valves, 25° for 27–31mm valves; [#] 60° for valves manufactured before 1981, 70° for valves manufactured after 1981.

suboptimal placement for transcatheter valves. Late PVL is most commonly related to infective endocarditis with valve dehiscence and is discussed more in detail in the endocarditis section below.

Transthoracic and transesophageal, 2D and 3D echocardiography are the primary diagnostic modalities, assessing and subsequently monitoring severity, and can guide percutaneous closure procedures.¹⁴

On CT, the presence of PVL may be suspected by the presence of contrast-enhanced blood around the PHV, in continuity with the adjacent cardiac and aortic structures (Fig. 8). Although cardiac CT cannot directly assess the functional PVL severity, it can provide information about the size and shape of the orifice, as well as the location of the leakage in relation to the surrounding tissues in selected cases. Dynamic evaluation across the cardiac cycle can display abnormal mobility of the PHV (rocking valve) in case of dehiscence.

PVL sizing by CT is commonly performed through phase-by-phase CT analysis to evaluate the largest opening area of the PVL defect to the PHV. In the mitral position, the larger PVL may more commonly be identified during end-systole and for the aortic position during mid-diastole.^{74,75} Based on an observed larger regurgitant orifice size, alternatively, the mitral valve can be evaluated during mid-diastole and the aortic valve during systole.⁷⁶ Overall, as motion-augmented beam hardening artifacts generally determine and limit phase selection, readers should compare multiple phases if available. Metal artifacts can significantly affect image quality and preclude assessment of the paravalvular region. Reader must carefully set window level and width to reduce beam-hardening artifacts

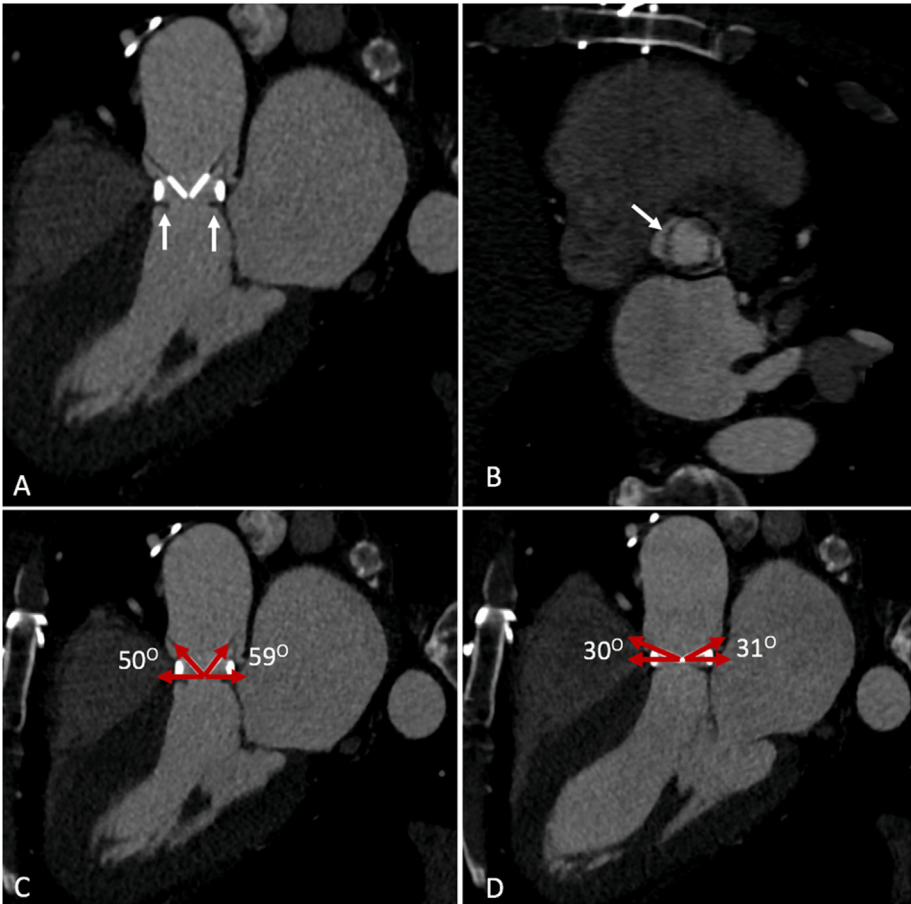


Fig. 6. Prosthetic heart valve obstruction due to pannus tissue underneath mechanical aortic valve prosthesis. Pannus tissue is seen as a thin circular hypodense rim underneath the valve ring (arrows in A and B). The valve leaflets are restricted and do not open completely (C) and do not close completely (D).

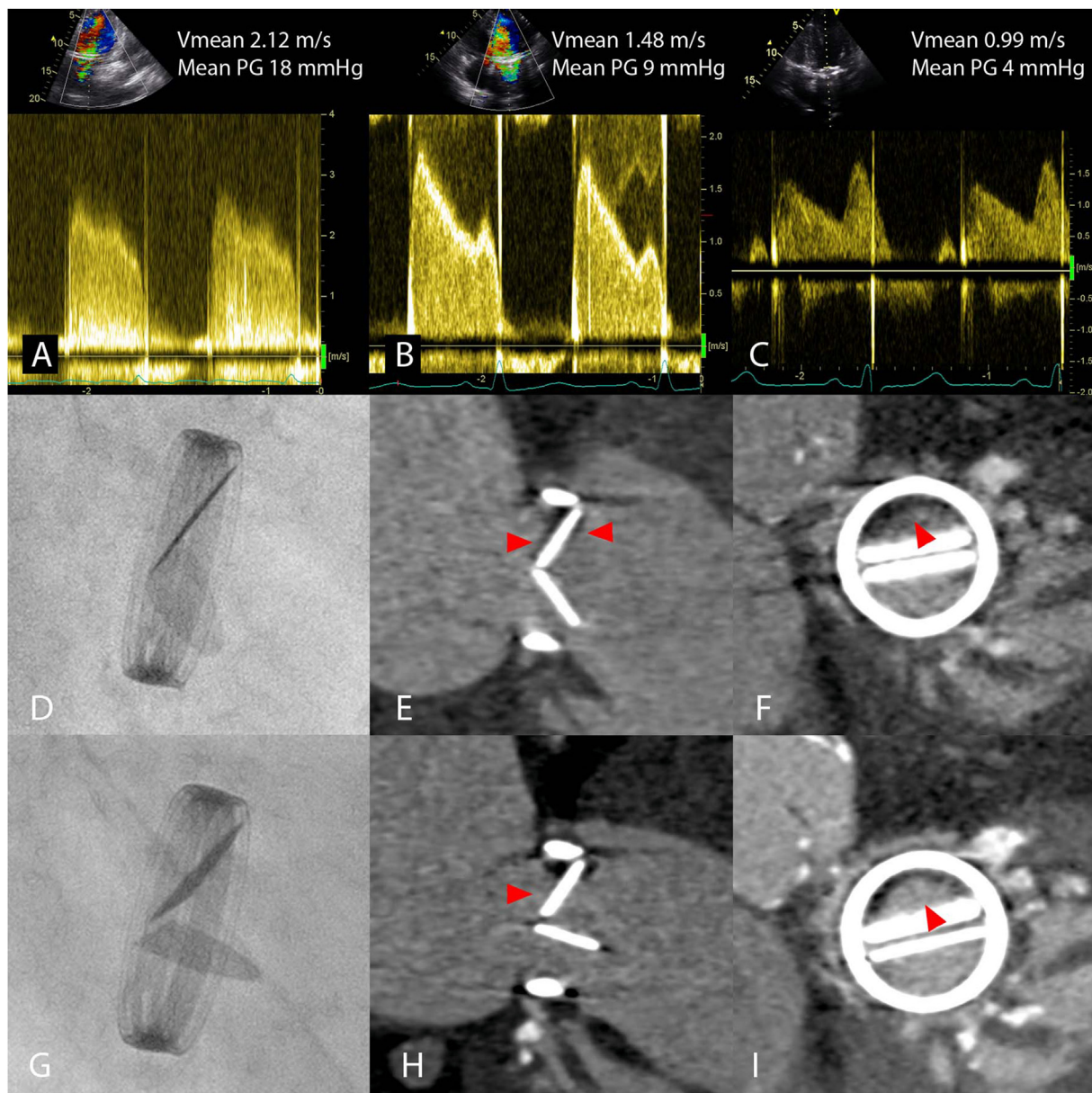


Fig. 7. Mechanical PHV thrombosis. Images of a patient with a mechanical mitral PHV (Carbomedics, size 29 mm) who developed progressive heart failure. Transthoracic echocardiography (TTE) showed severely increased pressure gradients (PG) (mean 18 mmHg; max 30 mmHg) (A) over the PHV. Fluoroscopy showed immobility of one of the valve leaflets and greatly diminished mobility of the other (D). CT reconstructions in diastole confirmed fluoroscopy findings of the restricted leaflets (E). Moreover, CT revealed a hypodense mass attached to the hinges and leaflets and on both the ventricular and atrial side, making thrombus most likely (arrowheads E and F). Two days after thrombolysis, TTE showed decreased PG (mean 9 mmHg, max 21 mmHg) (B) and fluoroscopy demonstrated improved opening of one leaflet with the other still immobilized (G). A repeat CT scan confirmed fluoroscopy findings and showed diminished thrombus load (H,I). TTE performed 6 weeks after discharge showed full mobility of both leaflets and normalized PG (mean 4 mmHg, max 9 mmHg) (C).

(wide window width) while preserving the visualization of the sometimes thin surrounding tissues.

The presence of radiopaque suture pledgets can be difficult to distinguish from small paravalvular leaks on contrast-enhanced scans. Multiple pledgets of equal size are typically placed symmetrically around the prosthesis. Comparing the CTA with a non-contrast or post-contrast scan can help differentiate small leaks from pledgets (Fig. 3).

Retrospective cohorts and prospective studies have reported that for the detection of PVL, the accuracy of cardiac CT is equally high as TEE compared to surgical inspection, and outperforms TTE.^{74,77,78} However, it is important to note that these publications often excluded low-quality scans so they represent only a selection of patients. Planimetry can measure the regurgitant orifice on in-plane reconstructed CT images and

these measurements correlate well with the PVL severity assessed by TEE.^{75,76}

Of note however, CT lacks flow information, and therefore, smaller PVL can be difficult to visualize, especially if CT image quality is also limited by artifacts. When excessive acoustic shadowing from metal or calcifications limits the interpretation of echocardiographic images, cardiac CT may serve as an adjunct imaging option. Cardiac CT images can provide optimal fluoroscopic angles to optimize pre-procedure planning of transcatheter treatment of PVL. Furthermore, CT imaging provides integral evaluation for precise defect measurement to select appropriate device shape and size. In a prospective study in 12 patients with suspected PHV leakage, CT provided incremental value to TTE and TEE in 7/12 (58 %) cases by visualizing pseudoaneurysms and excluding other pathology and CT information resulted in a change in management

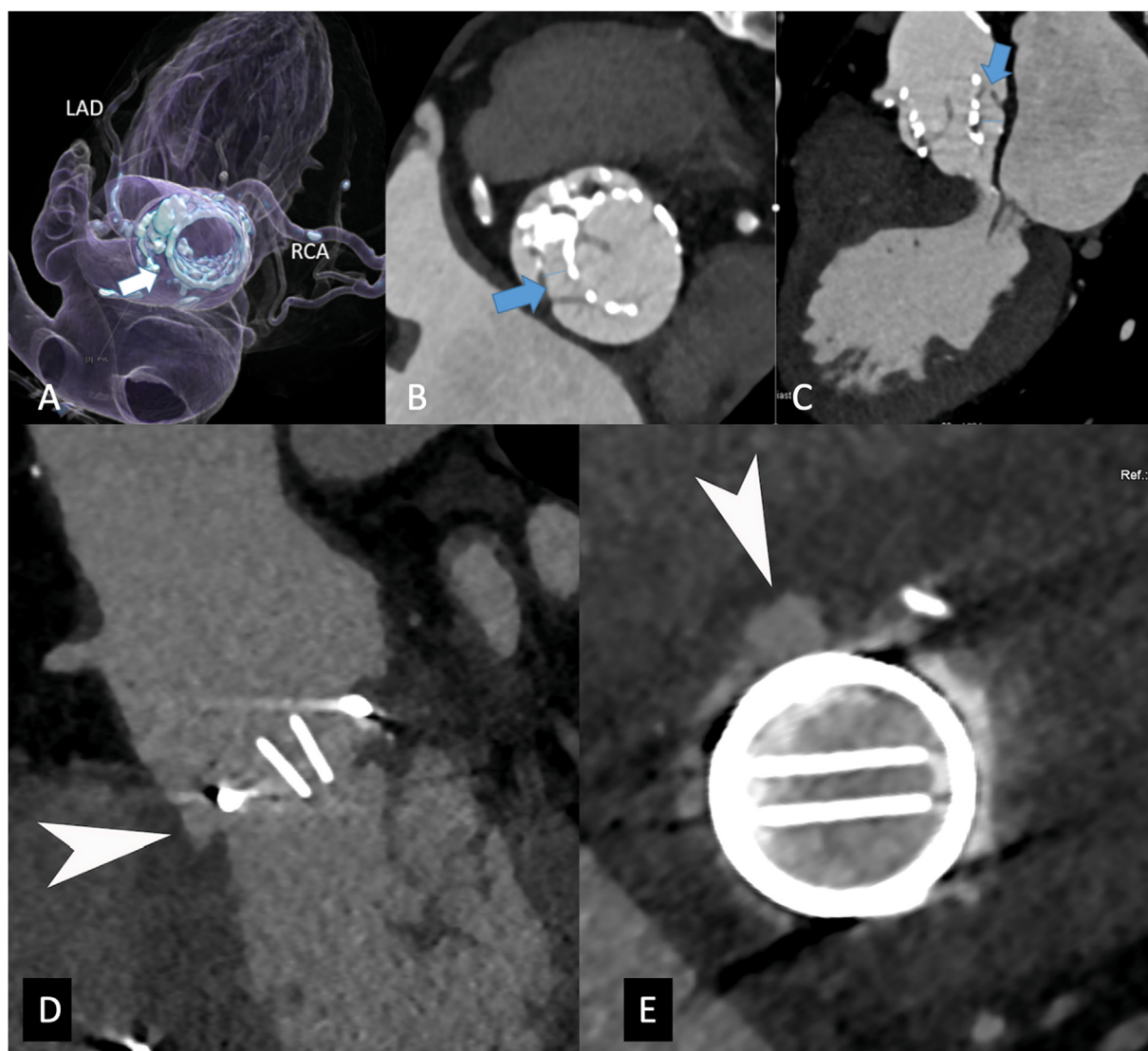


Fig. 8. Paravalvular leakage. Bioprosthetic transcatheter valve in the aortic position. Incomplete expansion of the stent due to severe annular calcification leading to severe PVL (grade 3) left-sided (arrows in A-C). 3D VRT (A), axial plane (B) and left sagittal oblique view (C). Mechanical bileaflet valve in the aortic position with a focal paravalvular leak (arrowheads in D and E) with contrast enhanced blood next to the valve ring.

in 3/12 (25 %) cases.⁷¹ Overall, however, caution is advised in using CT for PVL diagnosis and echocardiography is considered the technique of choice for PVL diagnosis and assessment.

Consensus statement

On CT images paravalvular leakage is defined as contrast-enhanced blood around the valve in continuity with the cardiac cavities on each side of the valve.

In good quality CT scans the diagnostic accuracy of CT for paravalvular leakage detection is in the same range as TEE. However, this represents data from selected populations. Echocardiography is considered superior for PVL detection and CT may easily miss PVL.

Cardiac CT images can also be used in pre-procedure planning of transcatheter treatment of PVL by providing optimal fluoroscopic angles, device sizing, and transseptal approach.

11. Patient prosthesis mismatch

Prosthesis-patient mismatch (PPM) is defined as a too small effective orifice area of the inserted PHV in relation to body size, resulting in higher-than-expected pressure gradients over the PHV.⁷⁹ There is very limited data on the use of CT to diagnose PPM. CT can determine the size of the implanted PHV if this information cannot be retrieved from the surgical report.⁵⁴ In addition, CT can rule out other causes of PHV obstruction.

Consensus statement

In suspected PPM, CT may primarily be used to rule out other causes of valve obstruction. However, there are very limited data available on the role of CT in suspected PPM.

12. Endocarditis

In PVE, microorganisms adhere to foreign material and form fibrin deposits which can result in vegetations. These microorganisms can also secrete enzymes which degrade tissue and results in leaflet perforation, though bioprosthetic valves are generally more resistant to this degradation compared to native leaflets. Similarly, the infection can lead to paravalvular leak with dehiscence at the valve ring. Invasive endocarditis occurs when infection extends beyond the prosthetic valve, and can result in abscesses and pseudoaneurysms.⁸⁰ In PVE, patients can have invasive disease even in the absence of large vegetations or leaflet destruction.

For all patients with known or suspected endocarditis, echocardiography is the first-line imaging investigation. It provides a comprehensive hemodynamic assessment as well as excellent temporal resolution to detect mobile valvular vegetations. Doppler interrogation can readily identify leaflet perforations and cardiac chamber fistulae.⁸¹ However, for patients with known or suspected PVE, the role of Cardiac CT in establishing the diagnosis is increasing. It helps to delineate local complications, identify systemic embolic phenomena, and inform pre-operative planning.^{81,82} Cardiac CT is included in the diagnostic flow-chart in both the ESC and AHA guidelines.^{9,81} Cardiac CT has a class I indication in the ESC guideline to detect valvular lesions, confirm the diagnosis in possible PVE, and to detect periprosthetic complications when echocardiography is inconclusive.⁸¹ In the 2020 ACC/AHA Valvular Heart Disease Management Guidelines, CT has a class IIa recommendation for evaluation of a suspected paravalvular abscess in cases with inadequate or non-diagnostic echocardiographic imaging.⁹

12.1. CT assessment of PVE

Cardiovascular CT can detect vegetations but is inferior to echocardiography due to lower temporal resolution. Small, erratically moving vegetations may be undetected on CT, particularly if only limited phases are acquired. However, in a systematic review with pooled analysis, the accuracy for detecting vegetations by CT (78 % sensitivity and 94 % specificity) is reported to be similar to transesophageal echocardiography (sensitivity and specificity of 89 % and 74 %).⁸³ In PVE, the strengths of cardiovascular CT are to identify and define the extent of abscesses and mycotic aneurysms around the valve (Fig. 9). With CT, abscesses may have low attenuation central necrosis with a peripheral enhancing rim on delayed images. Mycotic aneurysms appear as a contrast-filled out-pouching with a connection to the cardiovascular lumen, which is better defined on CT compared to TTE and TEE. CT provides additional diagnostic value compared to TTE and TEE in patients suspected of having endocarditis mainly by detecting mycotic aneurysms.^{84,85} CT has a reported sensitivity and specificity to detect periannular complications of 80 % and 82 %, respectively which are similar to TEE (sensitivity of 77 % and specificity of 86 %) in one systematic review.⁸³

With invasive endocarditis, complications can result as infection spreads along the fibrous skeleton of the heart, resulting in conduction abnormalities and fistulous connections between the chambers of the heart. In delineating the extent of invasive PVE, cardiovascular CT has several advantages compared to echocardiography. With ultrasound, prosthetic valves, calcification, or surgical material may cause reverberation artifacts or acoustic shadowing that limits assessment. With CTA, iodinated contrast allows for a clear distinction between abscess and pseudoaneurysm. In addition, CT provides a more complete field-of-view of the structures of interest, whereas intervening bone or air may preclude adequate assessment with echocardiography.

12.2. PET-CT in PVE

For detecting invasive complications of PVE, 18F-FDG PET-CT has demonstrated good diagnostic accuracy.^{15,86,87} Accuracy improves with appropriate preparation to suppress normal myocardial glucose utilization.^{88,89} Patients with PVE are more likely to have focal and

heterogenous increased paravalvular 18 F-FDG signal, and a quantitative assessment of uptake may also aid in the diagnosis.^{15,90} PET-CT can enhance the diagnostic work-up, but has a limited role in pre-operative planning, with CTA remaining the better image modality for this.

In difficult cases, the decision to pursue a cardiovascular CTA and/or PET-CT for PVE depends on local expertise and discussion with a multidisciplinary endocarditis team.⁸⁸ A practical consideration is whether the patient can safely receive iodinated contrast. If so, CTA may better delineate relevant anatomy. When there is an inability to give iodinated contrast and there is diagnostic uncertainty after a clinical evaluation and echocardiography, PET-CT may be more informative. Fusion of the CTA images with the PET allows for optimal co-registration of the areas with increased FDG uptake and anatomical changes.⁸⁸

12.3. Additional CT findings

CT can also help define extra-cardiac manifestations of PVE.⁸² In right-sided endocarditis, septic pulmonary emboli are a common complication. With left-sided disease, the most feared extra-cardiac manifestations include central nervous system emboli and resultant mycotic aneurysms, and infectious vasculitis. Septic emboli with occlusion of visceral or peripheral arteries can occur as well. Finally, when needed, an endocarditis-protocol CTA can delineate the coronary artery anatomy, as well as the presence and severity of coronary atherosclerosis.^{91,92} Invasive angiography may be relatively contra-indicated in patients with aortic PVE and large vegetations. In selected cases when assessment of concomitant coronary artery disease is important, pre-medication may be justified after careful assessment of the patient's status. However, even without pre-medication and with sub-optimal evaluation of the distal coronary arteries, images can be sufficient to assess the need for surgical coronary revascularization.^{91,93}

Consensus statement

Cardiac CT plays an important role in the diagnosis of PVE and is firmly included in the ESC and AHA guidelines.

Cardiac CT can detect valvular vegetations but is especially helpful in delineating the extent of infection and detecting periprosthetic complications such as paravalvular mycotic aneurysms.

CTA images may be fused with 18F-FDG PET images to provide optimal anatomical detail and metabolic information.

CT can also play an important role in detecting distant emboli.

In endocarditis patients the Cardiac CT acquisition to evaluate the valve can also be used to assess the status of the coronary arteries in case of a planned re-operation.

13. Structural valve deterioration/dysfunction

Structural bioprosthetic valve dysfunction (BVD) is defined by irreversible changes to the surgical or transcatheter heart valve (THV) leaflet or stent, including fibrosis, collagen disorganization, wear and leaflet injury, fibrosis, and calcification.⁹⁴ This differs from non-structural BVD which includes any changes to the bioprosthetic valve that are not related to the prosthetic valve device such as e.g. pannus formation.⁹⁴ BVD is a slow process developing over one decade and usually seen 5–8 years after implantation, with a steep incline after 10 years.^{95,96} Due to the increasing number of bioprosthetic valves implanted during the past decades, the number of patients with BVD is currently increasing, and expected to rise further. Cardiac CT is currently not used for routine screening for BVD.

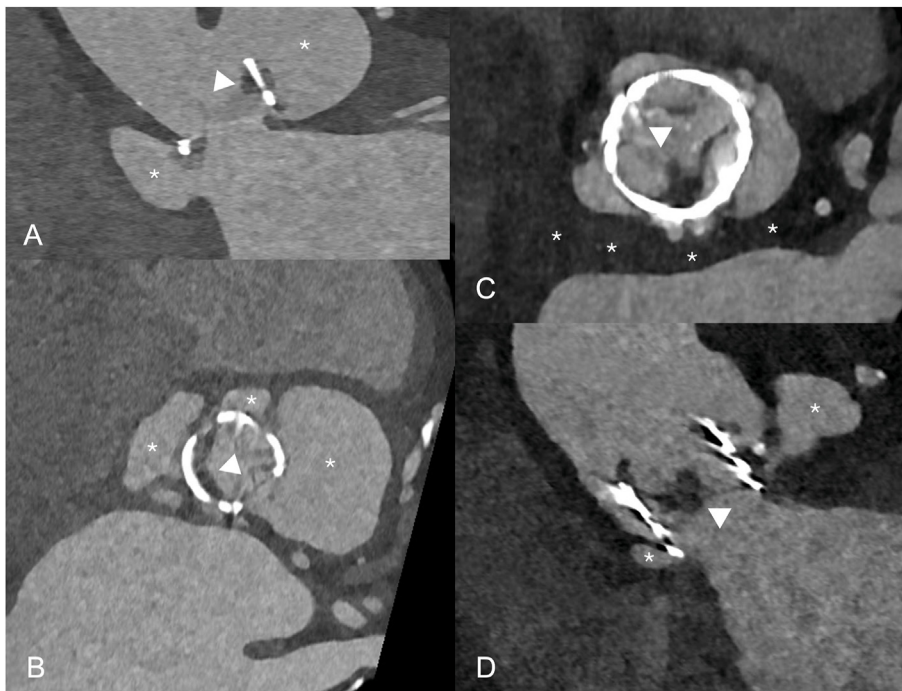


Fig. 9. Endocarditis. PHV in the aortic position (A,B) with vegetation on the valve leaflets (arrowheads in A and B) and large mycotic aneurysms (asterixis in A and B). Prosthetic valve in the aortic position (C) with infectious thickening of the fibrous continuity of the mitral and aortic valve (asterixes in C) and both leaflet calcification (arrowhead in C) as well as vegetation on the valve leaflets. Transcatheter valve in the aortic position with large vegetation (arrowhead in D) and mycotic aneurysms (asterixes in D).

Subclinical structural BVD is detected primarily through imaging by either CT and/or echocardiography, which may exhibit features of leaflet thickening or circumferential hypoattenuating material on CT at the inflow of the bioprosthetic valve with absent or mild hemodynamic changes.^{4,94} Especially once calcification is evident by CT there are typically hemodynamic changes of the bioprosthesis with rising transvalvular gradients. According to the valve academic research consortium (VARC) 3 guidance document, BVD is graded based on the extent of hemodynamic changes increasing from absent in Stage 1 to Stage 3 with a mean gradient increase of 20 mm Hg or a mean gradient of 30 mm Hg with a commensurate decrease in effective orifice area as per VARC 3 guidelines.⁹⁶ BVD transitions to bioprosthetic valve failure with the onset of end organ failure. Progression is from stage 1 with findings of LV hypertrophy or irreversible pulmonary hypertension, over Stage 2 with valve re-intervention to finally death at stage 3.

13.1. Imaging findings of BVD

Leaflet calcification can be identified on non-contrast CT, while contrast-enhanced CT can identify hypoattenuated leaflet thickening (HALT) that may affect leaflet mobility. As calcification is a common end stage feature of BVD across many etiologies, CT is helpful to aid in diagnosis (Fig. 10). During the development of BVD, microcalcifications during early stages of BVD are not visible by CT, while during later stages, calcified spots or diffuse calcification of leaflets or annular bioprosthetic material becomes visible.

Radiotracers and the role of PET imaging to assess valve degeneration has been of growing interest. 18F-sodium fluoride (18F-NaF) PET is a radiotracer that can identify areas of microcalcification (<50 µm) allowing for specific detection of developing microcalcifications and active calcific activity. Recent studies have suggested 18F-NaF uptake as a sensitive marker of leaflet degeneration following SAVR and a predictive indicator of THV dysfunction and degeneration.^{19,20,97}

Consensus statement

CT findings of structural bioprosthetic valve dysfunction include leaflet thickening and calcification of bioprosthetic valves.

Non contrast enhanced CT imaging can detect valve calcifications but lacks the resolution to detect microcalcifications in the early stages of bioprosthetic valve dysfunction.

14. Hypo-attenuated leaflet thickening

Hypo-attenuated leaflet thickening (HALT) can be seen on biological valves. The exact mechanism of bioprosthetic PHV leaflet thrombosis is unclear, but there is growing evidence that the development of leaflet thrombosis represents a complex mechanical and biological process.⁹⁸ From a mechanical perspective, incomplete leaflet expansion and reduced neo-sinus volume may play important roles in leaflet thrombosis formation.⁹⁹ From a biological perspective, stasis, endothelial injury, and hypercoagulability remain important factors.¹⁰⁰ Prosthetic valve material is thrombogenic and activates the clotting system. Non-physiological blood flow, characterized by areas of high shear stress and/or low velocity/stagnant blood promotes platelet activation and thrombosis.¹⁰¹

The incidence of HALT in the literature varies by valve type, timing of imaging and design of the study.¹⁰² In randomized trials of low-risk cohorts the incidence of HALT was similar between surgical and transcatheter bioprostheses and across the transcatheter valve designs. The prevalence of subclinical HALT following TAVR was 28 % (Sapien 3 valve) and 31 % (Evolut system) at one year and comparable to SAVR at one year, at 20 % in the PARTNER 3 and 28 % in the Evolut Low Risk studies, suggesting this phenomenon equally affects both surgical and transcatheter aortic bioprosthetic valves.^{103,104} While HALT may result in valve stenosis and increased pressure gradients there is ongoing debate

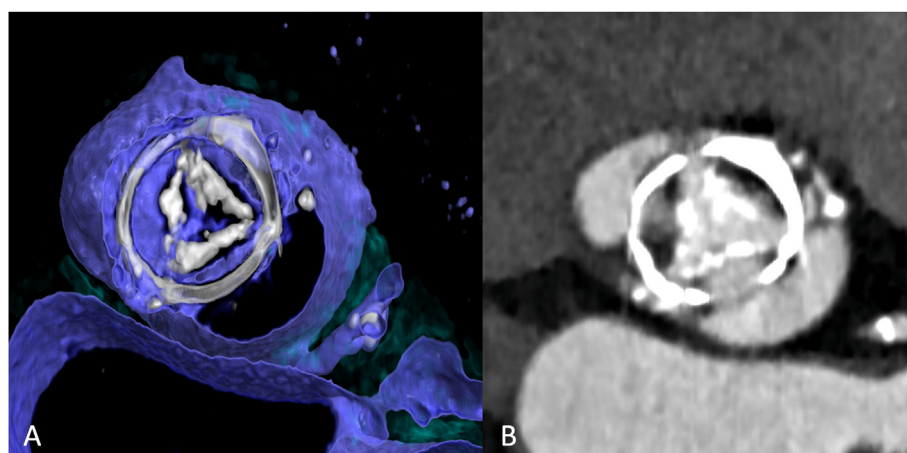


Fig. 10. Structural valve deterioration. Biological prosthetic heart valve in the aortic position. There is severe calcification and thickening of the leaflets compatible with structural valve deterioration. 3D VRT (A) and in-plane reconstructions (B).

on the relation between HALT and thromboembolic events as well as structural valve deterioration.^{105,106}

14.1. CT findings

The hallmark feature of leaflet thrombosis on CT, i.e. HALT, is meniscoid thickening of the bioprosthetic leaflet(s) thickest at the base and thinnest at the tip, with a relative aortic-sided distribution (Fig. 11). Importantly, according to the VARC 3 criteria, subclinical HALT is defined as CT imaging findings in the absence of an elevated echocardiographic gradient or clinical symptoms.^{96,107,108} Thrombi characteristically form at the leaflet insertion point and may extend towards the leaflet tip to varying extent.^{109–111} HALT is best visualized during the phase when the leaflets coapt (diastolic for aortic valves) and there are minimal artifacts from leaflet motion. The extent of leaflet thickening should be graded on a 4-tier grading score along the curvilinear orientation of the leaflet: $\leq 25\%$, 25–50%, 50–75%, $>75\%$.^{96,112} HALT can then be scored using a 12-point scale summing-up the scores of up to four assigned to each leaflet depending on the extent of thickening as outlined above.⁹⁶

14.2. Reduction in leaflet motion

As the thrombotic burden increases, leaflet opening may be restricted. Varying nomenclatures have been applied to this phenomenon such as reduced leaflet motion and hypo-attenuation affecting motion.^{110,113–115} Both terms describe a degree of quantifiable leaflet restriction caused by HALT.^{96,109,111} Reduction in leaflet motion is assessed during maximal leaflet excursion, and the degree of leaflet restriction is hence best evaluated in the systolic phase for aortic valves and diastolic phase for mitral valves.¹¹² For scans with reconstructions during the entire R–R interval evaluating the other phases and cine reconstructions aids in diagnosing reduced leaflet motion.¹⁰⁹ According to SCCT guidelines and overall consensus, once HALT is identified, the presence of reduced leaflet motion should be evaluated.¹¹²

Consensus statement

On CT, hypo-attenuated leaflet thickening (HALT) is characterized by hypodense meniscoid thickening of the bioprosthetic leaflet(s) thickest at the base and thinnest at the leaflet tip.

HALT may be associated with a reduction in leaflet motion, which can be assessed on cine CT reconstructions.

15. Role of CT in preoperative planning for reoperation

CT provides important additional information in case of a planned reoperation. Since the acquisition for valve assessment is ECG synchronized and contrast injection protocols often resemble those for dedicated CCTA, the coronary arteries and bypass grafts can be assessed for stenosis and patency.

CT findings can change the re-entry plan and cannulation strategy for cardiopulmonary bypass.¹¹⁶ In patients with previous coronary artery bypass grafting, CT can identify the course and patency of previous coronary bypass grafts to help the surgeon avoid injury. Also, assessing the distance between the posterior sternum and the heart, particularly the right ventricle, can help reduce life-threatening injuries during re-do sternotomy. The aorta can be evaluated for calcifications and iatrogenic aortic dissection as well as aortic root and ascending dilatation that merits concomitant replacement during re-operation, especially in patients with a history of aortic valve replacement for bicuspid aortic valve.¹¹⁷ Including CT of the abdomen and pelvis can help identify peripheral artery disease that can affect peripheral cannulation via femoral vessels. If surgical risk during re-entry is prohibitively high based on CT scan, a transcatheter valve-in-valve approach may be considered.

In case of a planned valve-in-valve percutaneous re-intervention CT provides important information on the risk of coronary occlusion, aortic root and PHV anatomy for sizing and procedural planning. This is discussed in detail in another SCCT consensus document.²

Consensus statement

CT provides valuable information in preoperative planning for reoperation after valve surgery.

16. Reporting

Assessment of PHV (dys)function is best done by incorporating all available imaging and other clinical information. To achieve optimal complementary value, the CT report should follow a structured format to ensure all available information is included.

First, the clinical context and diagnostic question should be noted including the type and size of the implanted PHV. Second, procedural features are mentioned including the type of acquisition and ECG synchronization, which phases of the R–R interval have been reconstructed, the amount of contrast medium, and the premedication that has been administered.



Fig. 11. Transcatheter prosthetic heart valve with hypoattenuated leaflet thickening (grading >75 %). Notice the hypodense leaflet thickening which is thicker at the base than at the tip of the leaflet.

Then, studies for comparison are considered; any prior CT or other studies that could be useful such as echocardiography, MRI or PET/CT and to which the current imaging findings are specifically compared, should be mentioned. Image quality of the scan and specific artifacts should be reported, especially if this hinders assessment. Location and type of PHV should be described, as well as the structural integrity of the valve. The presence of specific material such as for example suture pledgets should be mentioned. For mechanical valves, leaflet or disk motion and opening/closing angles should be described and compared to manufacturer specifics. For bioprosthetic valves, leaflet thickening and leaflet motion should be evaluated, as well as signs of PHV degeneration. For all PHV types any complication such as thrombus, pannus tissue ingrowth, paravalvular leak, fistula, abscess or periprosthetic mycotic aneurysm should be reported in terms of size, location and relationship with adjacent structures. Further, cardiac dimensions, coronary arteries and aortic dimensions should be assessed, and extra-cardiac anatomy is evaluated. The report should be concluded with a concise statement of the most relevant findings and should include an answer to the clinical question which integrates the CT findings with those of other available imaging modalities. [Table 3](#) provides a template for a structured report.

In addition to this comprehensive report, we believe it is especially important to discuss imaging findings in a multidisciplinary meeting with the specialties involved in the care of the patient to optimize diagnosis and treatment decisions.

Consensus statement

CT scans performed for PHV dysfunction assessment are preferably reported using a structured template and findings discussed in a multidisciplinary meeting.

Table 3
Comprehensive template for structured reporting of CT of PHVs. The template can be adapted to the local situation by adding or leaving out specific parts.

Report of cardiac CT for PHV assessment		
Patient data and clinical context		
Diagnostic question		
CT acquisition		
Scan protocol		
Contrast protocol and amount		
Drug administration (incl. Dose)		
Quality of the scan (incl. Specific artifacts)		
PHV		
Location		
Type of PHV		
Structural integrity		
Other specific features		
Dynamic PHV assessment		
Opening and closing of the valve	Normal/Abnormal	
Mechanical valves	Opening angle(s) (incl. Ref value)	
	Closing angle(s) (incl. Ref value)	
Anatomic PHV assessment		
Abnormal masses around PHV	Most likely thrombus	Yes/No
	Most likely pannus	Yes/No
	Indeterminate	Yes/No
	If Yes: Location	
PHV angulation	Normal/Abnormal	
Signs of endocarditis	If abnormal: Describe	
	Presence of vegetations	Yes/No
	If Yes: Location and size	
	Presence of mycotic aneurysm	Yes/No
Paravalvular leakage	If Yes: Location	
	Other such as:	
	Abscess (periprosthetic fluid? Encapsulated?	
	Tissue enhancement?)	
	Yes/No	

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Table 3 (continued)

Report of cardiac CT for PHV assessment		
LVOT narrowing	If Yes: Location Yes/No	
Specific for biological PHV	If Yes: Location Systolic valve leaflet opening orifice area PHV degeneration Presence of HALT If Yes: Grading	Yes/no Yes/No Mild/Moderate/Severe, or as a numerical value of 1-12 Yes/No Mild/Moderate/Severe
Other cardiac findings	Presence of hypo-attenuation affecting motion If Yes: Grading	
Atria and ventricles		
Coronary arteries		
Prior cardiac surgery/bypass grafts		
Proximal aorta	Dimension Calcifications	None/Mild/Moderate/Severe
Relevant extra-cardiac findings		

17. Emerging technologies

Recently, photon-counting detector CT has emerged as a promising new technology in CT imaging and is expected to overcome some of the limitations of conventional CT for cardiac and PHV imaging. It represents the next generation of CT hardware technology that delivers ultra-high spatial resolution, and spectral based reconstruction with mono-energetic images.^{118,119} Both techniques can reduce blooming and metallic artifacts, which can aid in visualization of valve leaflets. In addition spectral imaging improves the contrast between different tissues and contrast agents.^{40,119} Other new developments include the assessment of intracardiac flow patterns using 4D-CT that may provide insight in the development of PHV dysfunction and the influence of PHV orientation.^{120,121} However, these potential improvements are still in very early stages and need to be developed further.

18. Conclusion

Echocardiography is the imaging modality of first choice to evaluate PHV function. However, in the last 15 years CT has proven to be a

valuable complementary technique to assess PHVs, especially in determining the cause of PHV dysfunction, the diagnosis of PVE and for providing important information in case of a planned re-operation to replace the dysfunctional PHV. In addition, along with the tremendous increase in TAVR procedures that are performed and the ability of CT to accurately detect HALT and restricted leaflet motion, the role of CT is expected to only grow in the future. Accordingly, CT is already included in the ESC and AHA guidelines on valvular disease and endocarditis. Moreover, CT has a Class I recommendation in ESC endocarditis guidelines to diagnose both native and prosthetic valve and is a major criterion for the Duke criteria. There is however a relatively limited number of studies available that have investigated cardiac CT in the diagnosis of PHV (dys)function. With this consensus document we have aimed to provide guidance on how to use cardiac CT for PHV assessment based on this available data as well as expert opinion.

Declaration of competing interest

Conflict of interest statements included in [Appendix 1](#).

Appendix 1. Relationships with Industry of Writing Group Members for Cardiac Computed Tomography for Prosthetic Heart Valve Assessment.

Writing Group Member	Formal representative of external organization	Employment	Consultant /Honoraria	Speakers Bureau	Stock and stock options	Grants and research support	Patents	Royalties
Ricardo PJ Budde (chair)		Erasmus Medical Center, Rotterdam		Bayer; Siemens		Heartflow; Siemens; Bracco		
Marguerite E Faure		Erasmus Medical Center, Rotterdam						
Suhny Abbara		Mayo Clinic, Jacksonville, USA						Elsevier
Hatem Alkadhi		University Hospital Zurich, Switzerland		Siemens Healthineers		Bayer, Canon, Guerbet, Siemens Healthineers		
Paul C Cremer		Northwestern University, Chicago, USA						
Gudrun M Feuchtnr		Medical University, Innsbruck, Austria						
Holly M Gonzales	American College of Cardiology (ACC)	Sanger Heart and Vascular at Atrium Health, Charlotte, USA	Abbott					

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(continued)

Writing Group Member	Formal representative of external organization	Employment	Consultant /Honoraria	Speakers Bureau	Stock and stock options	Grants and research support	Patents	Royalties
Todd L Kiefer		Duke University, Durham, USA						
Jonathan Leipsic		University of British Columbia, Vancouver, Canada	Circle CVI, Heartflow	Philips	Circle CVI, Heartflow	Abbott, Boston Scientific, Edwards, GE Healthcare, Medtronic		
Koen Nieman		Stanford University, Stanford, USA	Artrya; Cleerly; Novartis; RapidAI			Novartis, Siemens		
Jonathan Revels	North American Society for Cardiovascular Imaging (NASCI)	New York University Langone Health, New York, USA						
Dee Dee Wang	Society for Cardiovascular Angiography and Interventions (SCAI)	Henry Ford Health System, Detroit, USA	Abbott, Boston Scientific; Edwards LifeSciences, Materialise					
Eric Williamson	Radiological Society of North American (RSNA)	Mayo Clinic, Rochester, USA						
Moritz C Wyler von Ballmoos	Society of Thoracic Surgeons (STS)	Texas Health Harris Methodist Hospital, Fort Worth, USA.						
Brittany A Zwischenberger		Duke University						
Rodrigo Salgado	European Society of Cardiovascular Radiology (ESCR)	Antwerp University Hospital, Antwerp, Belgium						

Appendix 2. Relationships with Industry of Reviewers for Cardiac Computed Tomography for Prosthetic Heart Valve Assessment.

Reviewer	Formal representative of external organization	Employment	Consultant/honoraria	Speakers bureau	Stock and stock options	Grants and research support	Patents	Royalties
Ashraf Hamdan		Rabin Medical Center, Tel Aviv University				Nanox		
Hashrul Rashid	Monash University							
Rhanderson N. Cardoso	American College of Cardiology (ACC)	Brigham and Women's Hospital, Harvard Medical School				Cleerly		
Jean-Nicolas Dacher	European Society of Cardiovascular Radiology (ESCR)	University of Rouen Normandy, France	Sanofi; Bayer; Pfizer			Takeda		
Laura Jimenez-Juan	North American Society for Cardiovascular Imaging (NASCI)	St Michael's Hospital						
Cristina Fuss	Radiological Society of North America (RSNA)	Yale New Haven Hospital	Elsevier; Siemens					Elsevier
Triston Smith	Society for Cardiovascular Angiography & Interventions (SCAI)	Trinity Health System	Edwards Lifesciences	Zoll Life Vest				
Karen M. Kim	Society of Thoracic Surgeons (STS)	UT Health Austin/Dell Medical School						

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