Deciphering the role of cardiac computed tomography in interventional cardiology: 2012 and beyond

Cardiac computed tomography (CT) provides accurate 3D assessment of the coronary arteries and cardiac structures and serves as an important adjunctive imaging modality in the preprocedural planning of percutaneous coronary and structural interventions. Using contemporary multidetector CT scanner technology, preprocedural CT is currently particularly relevant in guiding chronic total occlusion and left main coronary artery interventions, in assessment of stent patency and in providing an accurate assessment of the aortic annulus and iliofemoral arteries before transcatheter aortic valvular replacement. Notably, its role in providing comprehensive assessment of the coronary arteries, including the detection of vulnerable plaque and myocardial ischemia, is being determined. As future technological advances in CT continue to improve its diagnostic performance and reduce required radiation exposure, further expansion of its utilization is expected across the scope of interventional cardiology.

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Transcatheter-based therapies have revolutionized the practice of cardiology and have provided significant improvements in the symptoms and survival of patients with coronary artery and structural heart disease [1–3]. Invasive and noninvasive imaging play a crucial role in choosing patients who are suitable for these therapies, guiding the procedure and identifying post-procedural complications. While invasive angiography (ICA) is the mainstay imaging modality by providing real-time iterative feedback and guidance, its main limitation predominantly stems from its 2D projection format and the lack of information it provides regarding surrounding structures. Computed tomography (CT) offers 3D volumetric assessment of the heart and its surrounding structures. Using this dataset, elaborate multiplanar reconstructions can be performed that enable cardiologists to better understand cardiac anatomy across multiple planes. In this article, we highlight how CT is being increasingly utilized in assisting both coronary and structural interventions, and its future role in interventional cardiology.

Advances in multidetector CT

The technological advances in CT have undoubtedly played an important role in its integration into the practice of interventional cardiology. Over the past decade, cardiac CT has evolved rapidly from the introduction of 4-detector row systems to those with 64 detectors, dual-source CT and, more recently, 320-detector systems. This has been accompanied by improvements in spatial and temporal resolution, extended longitudinal coverage and decreased scan times and radiation exposure (TABLE 1).

Current generation multidetector CT (MDCT) scanners have a spatial resolution that ranges from 0.3 to 0.5 mm, which is slightly lower than the 0.1 and 0.2 mm afforded by intravascular ultrasound (IVUS) and ICA, respectively. This permits accurate and consistent assessment of native coronary arteries. Prior studies evaluating the diagnostic performance of MDCT have shown high accuracy for the detection and exclusion of obstructive coronary artery disease (CAD) with sensitivity and negative predictive values both in excess of 95% [4,5]. The temporal resolution of modern scanners ranges from 75 to 175 ms which has been vastly reduced from 300 ms using 4-detector CT. As a result, image quality is improved and coronary assessment can be performed, even in patients with higher heart rates [6,7]. Furthermore, wide-detector CT offers an extended longitudinal coverage of 16 cm, This allows the entire volume of the heart to be imaged in a single heart beat, compared with the 4–8 heart beats required using narrow-detector CT. Accordingly, image acquisition

Detector/slice CT	Year	Spatial resolution (mm)	Temporal resolution (ms)	Scan time (s)	Longitudinal coverage (cm)
4	2000	1–1.25	165–330	40	0.4
16	2002	0.75	105–210	20	0.8
64	2004	0.5–0.6	82–165	10	3.2–4
First-generation DSCT (2 × 64)	2006	0.6	84	7	3.2
Second-generation DSCT (2 × 128)	2009	0.6	75	<1	7.3
HDCT	2008	0.23	175	5–7	3.5
256	2010	0.6	135	1.5	8.0
320	2008	0.5	175	0.35	16

Table 1. Advances in computed tomography.

CT: Computed tomography; DSCT: Dual source computed tomography; HDCT: High-definition computed tomography.

is less vulnerable to breathing artefacts in patients who are not fully cooperative and the occurrence of arrhythmias or ectopic beats. CT acquisition has evolved from traditional low-pitch helical scanning using retrospective ECG gating to prospective ECG-gated image acquisition, which has vastly reduced the radiation exposure required in coronary assessment from 16–20 mSv [8] down to 1–4 mSv [9,10]. Lastly, new techniques in CT image reconstruction have been introduced using adaptive statistic iterative reconstruction (ASIR). When compared with the traditional filtered back projection techniques, ASIR results in significant reductions in image noise and improved image quality while maintaining image spatial resolution [11]. This may allow for further reductions in tube current and, hence, up to 44% of the required radiation dose [11]. These reductions in radiation exposure will ultimately broaden the applicability of cardiac CT in interventional cardiology.

Role of cardiac CT in percutaneous coronary interventions
■ Cardiac CT in selection of suitable patients for percutaneous coronary intervention
While ICA is considered the gold standard for the detection of coronary artery stenosis, the decisions involved in selecting patients suitable for revascularization are complex and take into account symptoms, results of functional studies and severity of stenosis on invasive angiography. Cardiac CT in its current form, similar to ICA alone, plays a limited role in the routine selection of patients who may benefit from coronary revascularization.

Computed tomography coronary angiography (CTA) offers coronary assessment that most closely resembles invasive angiography among all other noninvasive imaging modalities. This has been demonstrated in large multicenter trials, particularly in patients with a low–intermediate risk of CAD in whom 64-detector CT identified significant coronary artery stenosis with a sensitivity of 95–99%, specificity of 64–83% and a negative predictive value of 97–99% [4,12]. As a result of the high sensitivity and negative predictive value, current guidelines recommend the use of cardiac CT to exclude significant CAD in this population [13].

However, the specificity of CTA is comparatively lower, especially in calcified stenoses. Calcific densities enhance the Hounsfield units of adjacent contrast by the partial volume effect of the denser calcium (blooming effect), which may result in an overestimation of the degree of luminal stenosis [14]. For this reason, patients who are identified to have significant stenosis on CT often require further assessment using invasive angiography or functional testing.

Nevertheless, upfront use of CTA in patients with low–intermediate risk of CAD may reduce unnecessary downstream ICA referrals and lower overall costs when compared with upfront use of single photon emission computed tomography-myocardial perfusion imaging (SPECT-MPI) [15] with no excess adverse events [16]. The downstream utilization of this approach is currently being investigated in the Coronary CT Angiography Evaluation for Clinical Outcomes: an International Multicenter (CONFIRM) registry [17]. Apart from stenosis assessment, CTA permits atherosclerotic plaque characterization and quantification. The latter has been demonstrated to provide incremental prognostic information beyond the analysis of conventional cardiovascular risk factors [18–21].

■ Cardiac CT in the preprocedural planning of coronary interventions

Information derived from CTA may provide the interventionist with important knowledge above and beyond that of invasive angiography to guide percutaneous coronary intervention (PCI). Lesion visualization on invasive angiography can be hampered by adjacent vessel overlap, but this problem is not encountered in CT as each vessel is tracked independently. In addition, lesion assessment on invasive angiography can be difficult when it has not been possible to selectively cannulate a vessel or bypass graft. As such, CT can be particularly useful, such as in the assessment of anomalous coronary arteries, right internal mammary grafts and vein grafts originating from unanticipated aortic locations [22]. Even after successful selective invasive angiography, unresolved questions may remain, and CTA can be invaluable in determining whether PCI is required. This includes differentiating ostial disease from coronary spasm unrelieved by intracoronary nitroglycerin, determining the potentially malignant anterior versus the benign posterior course of anomalous coronaries, and deciphering path and length of chronic total occlusions. CTA may also provide information regarding the size and angulation of the aortic root as well as the plaque burden and morphology in the ostium of the coronary arteries, which may allow better selection of guide catheters and may shorten procedural duration [22,23].

Invasive angiography is limited in its ability to inform the interventionist about the vessel wall, hence, the provision of reliable reference vessel and luminal area measurements can be challenging. This information is particularly important when PCI is considered in coronary segments with positive or negative remodeling. This can be obtained from preprocedural CT, which may aid the interventional cardiologist in the selection of the optimal size and length of stents, therefore resulting in better lesion coverage and larger post-procedural in-stent and reference diameters [22,23]. While IVUS has been traditionally used for this purpose in the assessment of proximal coronary lesions, it has been demonstrated that CT detects the presence of calcified and noncalcified plaque with comparable accuracy [24]. Furthermore, CT-derived plaque and luminal area measurements have been demonstrated to correlate with IVUS-derived measurements, although they are consistently lower than the invasive reference [24,25], which may result in the underestimation of luminal stenosis.
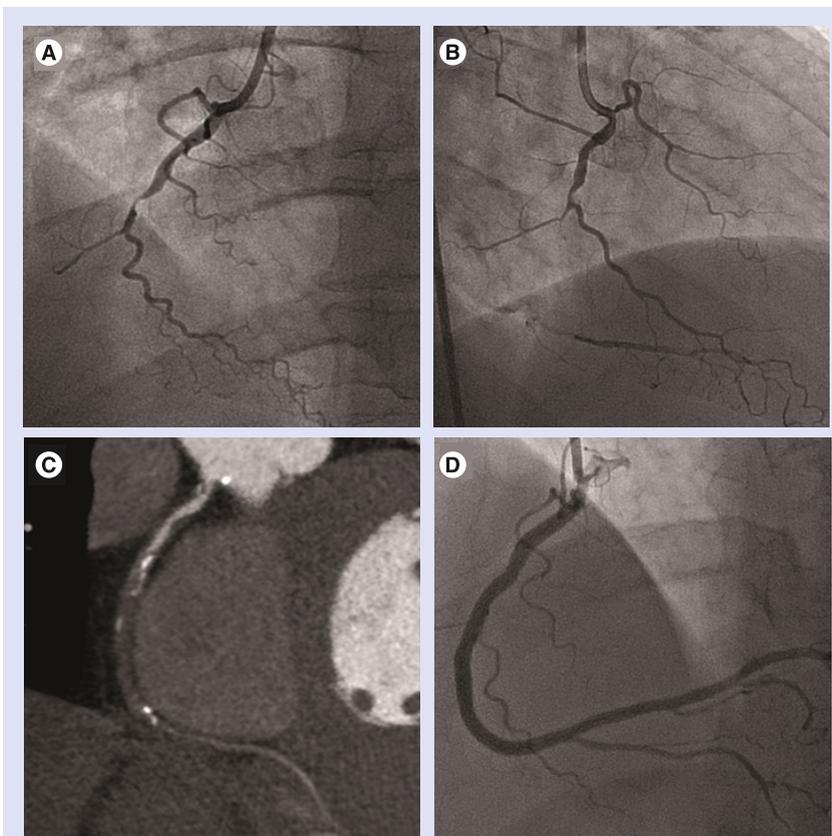
Chronic total occlusion interventions

The role of preprocedural CTA in guiding interventions has been extensively studied in chronic total occlusion (CTO) interventions. While successful recanalization of a CTO is associated with substantial improvement in symptoms, quality of life and survival [1,26], the procedure remains a challenge for interventional cardiologists due to lack of ability to visualize the occluded segment. As such, these procedures are often lengthy and complex, with elevated radiation exposure, increased contrast load and a higher risk of complications [27]. Success rates in most experienced centers range from 55 to 80% [28].

Angiographic features including the length, trajectory, tortuosity of the occluded segment, and the severity and distribution of calcification within the CTO, are considered to be the most important angiographic predictors for procedural failure, even in expert luminary centers with high procedural success rates [29]. All these features can be identified reliably on CTA and, by contrast, can be difficult to identify with ICA, which is largely limited by its 2D projection format (**Figure 1**) [30]. While real-time 3D reconstructions of the coronary arteries can be approximated from images acquired during rotational invasive angiography with encouraging results for CTO procedural success [31,32], these are limited by the need for a dedicated system to perform additional data processing, operator expertise to interpret the 3D reconstructions and prolonged injection into the coronary arteries to acquire the images, which poses an arrhythmic concern [31].

Multiple studies have demonstrated that the presence of CTO length >15 mm [33,34] and severe calcification, defined by the presence of calcium which occupies >50% of the luminal cross section area, are negative CT predictors of success [33–36]. Notably, the presence of severe calcification on CT has been demonstrated in multiple prospective registries to be the most significant independent predictor for procedural failure beyond conventional characteristics on ICA [34–37].

While CT may identify important features that may predict procedure failure, there are limited data on whether its use may improve procedural success. Ueno *et al.* demonstrated, in a retrospective cohort of 100 patients, that the use of cardiac CT was not associated with an increased prevalence of procedural success (80 vs 77.5%; p = 0.76) [38] and did not reduce irradiation time or contrast usage during PCI, but was associated with a significantly lower prevalence of complications (23.3 vs 7.5%; p = 0.039). This was driven

Figure 1. Computed tomography assessment of a chronic total occlusion.
A 56-year-old was investigated for chest pain. **(A)** Invasive coronary angiography demonstrated a chronic total occlusion in the mid-right coronary artery. **(B)** There were collaterals from a right ventricular branch, which filled the right posterior descending artery distal to the occluded segment. **(C)** Computed tomography coronary angiography demonstrated a long, straight segment of chronic total occlusion (44 mm), which consisted of predominantly noncalcified plaque with minor calcification within the occluded segment. **(D)** Given the latter, percutaneous coronary intervention was attempted and successfully performed.

is currently under investigation. The lack of soft tissue contrast attenuation decreases the ability to accurately delineate the luminal and vessel borders in the occluded segment. Owing to its limited spatial resolution, the visualization and characterization of the distal segment beyond the occluded segment and its collaterals can be challenging. CT is highly accurate in identifying the presence or absence of collaterals (sensitivity: 91%; specificity: 100%) [39] but is moderately accurate for detection of individual collaterals across each CTO [39,40]. Specifically, it is not possible on CT to identify bridging collaterals or septal collaterals owing to their intramyocardial location [30]. The use of helical CT increases the overall radiation exposure of CTO interventions by 8.5 to 12 mSv using 64-detector CT scanners, [35,41]. Notably, significant dose reduction in CT can be achieved using prospective ECG-gated acquisition, which allows no compromise in image quality at a minimum radiation expense (1–3 mSv) [10]. Further dose reduction to <1 msV has been reported with the use of high-pitch spiral acquisition in second-generation dual-source CT scanners [42]. Lastly, given the need for iodinated contrast, the use of CT requires caution in patients with renal impairment. Accordingly, CT is ideally performed 1 week prior to scheduled intervention.

There have been reports of the use of hybrid CTA/ICA in guiding CTO interventions. This aims to provide real-time co-registration of data obtained from the two modalities, which can be presented as a fused image to guide interventionalists during PCI [43]. This technology is currently under investigation but has the potential to reduce contrast usage and procedural time, and to improve the success rates of CTO recanalization in the future.

by a lower occurrence of coronary perforation in patients who had had preprocedural CT assessment, yet demonstrated a similar occurrence of other major adverse cardiac events. These data suggest that CT is most useful in the cases with undesirable demographic and lesion characteristics to reduce complications during CTO interventions. In our experience, preprocedural cardiac CT should be applied to assess CTO lesions that are difficult to visualize on ICA or possess angiographic features on ICA that are negative predictors for procedural success, and in lesions that have had previous failed attempts at recanalization.

CT has a number of limitations in its assessment of CTOs. It remains difficult to differentiate between calcified subtotal and total occlusions. This may be overcome by dual-energy CT, which uses two different tube voltages to generate a pair of imaging datasets and may improve tissue characterization and the ability to discriminate between calcification and iodine contrast. This

Left main coronary artery interventions

Since the introduction of drug-eluting stents, percutaneous intervention in the left main coronary artery (LMCA) using drug-eluting stents is increasingly performed with low procedural complication rates and encouraging long-term outcomes [44]. While ICA is considered the gold standard to assess the LMCA, it is often difficult and can be unreliable [45–47]. Hence, IVUS, which confers the ability to accurately assess luminal dimensions, plaque composition and vessel remodeling, is the current preferred method to assess angiographically borderline LMCA lesions [48,49].

Given the large dimensions of the left main coronary artery, there has been interest in the incremental value of preprocedural CT. CT may better identify the exact location, length

and composition of disease in the LMCA [50]. It also provides important information regarding the extent of plaque extension into the left anterior descending and left circumflex arteries, and the bifurcation angle. Dragu *et al.* compared the accuracy of CT assessment with IVUS in 20 patients with intermediate left main stenosis on invasive angiography. The study demonstrated a good correlation between CT and IVUS measurements in minimal luminal diameter (r = 0.77; p < 0.01), minimal luminal area (r = 0.93; p < 0.01), luminal area stenosis (r = 0.83; p < 0.01) and plaque burden (r = 0.94; p < 0.01) [51]. CT detected noncalcified plaque on IVUS with 100% sensitivity and calcified plaque with 75% sensitivity. While this may suggest that CT has a potential role in patient selection and procedure planning prior to LMCA intervention [52], further studies are required to further define the role of CT in LMCA interventions.

■ **Accuracy of CT to evaluate stent patency after coronary intervention**

In-stent restenosis and resultant target lesion revascularization remain prevalent after stent implantation. Binary angiographic restenosis can occur in upto 30% of patients after bare-metal stenting [53] and in 3–20% of patients after drug eluting stent implantation [54].

The sensitivity of CTA in the detection of in-stent restenosis is lower than reported for significant native artery stenoses [55–58]. The assessment of coronary stent patency and restenosis using cardiac CT is hampered by both underlying coronary calcification beneath the stent and artificial enlargement of the metallic stent struts, resulting in blooming artefacts, which can preclude appropriate assessment of the in-stent lumen. The impact of this is inversely related to stent diameter [59].

In a large meta-analysis including 854 patients from 15 studies using 4-, 16- and 64-detector CT, CTA detected coronary in-stent restenosis (>50%) with 85% pooled sensitivity and 97% specificity when compared with invasive angiography [58]. 64-detector CT had superior visualization of stent lumen when compared with 16-detector CT, which was reflected by its superior sensitivity (87 vs 81%).

Andreini *et al.* demonstrated, in a retrospective cohort of 100 patients, that the accuracy of 64-detector CT is highly dependent on the diameter of the stent [57]. The ratio of evaluable segments and total number of segments is significantly higher in stents with a diameter of ≥3 mm than in stents with a <3-mm

diameter (99 vs 74%; p < 0.05) [57]. The corresponding accuracy of CT was 98 versus 75%, which was a result of a higher specificity (100 vs 78%; p < 0.05) and a higher positive predictive value (100 vs 57%; p < 0.05). Similar findings were reported using 320-detector CT [56] and dual-source CT [55]. Pugliese *et al.* reported on the use of dual-source CT in an evaluation of 133 patients including 178 stents, and demonstrated 100% accuracy in stents with a diameter of ≥3.5 mm (n = 78) [55]. For this reason, CTA is recommended in asymptomatic patients to assess for stent patency and in-stent restenosis in stents which are ≥3 mm in diameter, but is not recommended in <3-mm stents according to the American Heart Association/American College of Cardiology appropriate use criteria (Figure 2A & B) [13].

Given high accuracy in larger stents, the question begs as to whether it can accurately diagnose in-stent restenosis in the LMCA. Van Mieghem *et al.* demonstrated in 74 patients that 16-detector (27 patients) and 64-detector CT (43 patients) detected LMCA in-stent restenosis with a sensitivity, specificity and overall accuracy of 100, 91 and 93%, respectively, compared with invasive angiography [60]. Sub-analysis demonstrated accuracy to be higher in patients who received isolated stenting of the LMCA with or without extension into a single major side branch than in patients who had had both branches of the LMCA bifurcation stented (98 vs 83%). CT assessment of stent diameter and area was shown to have a good correlation with that of IVUS (r = 0.78 and 0.73, respectively). Accordingly, it is appropriate for CT to be used to assess LMCA stent patency in accordance with American Heart Association/American College of Cardiology appropriate use criteria (Figure 3) [13].

Recently, a high-definition CT (HDCT) scanner has been introduced, which has improved in-plane spatial resolution of 0.23 mm and possesses the ability to reconstruct images using the novel ASIR algorithm. Min *et al.* reported that HDCT yielded substantially larger luminal area visualization when compared with present-generation 64-detector CT in the *ex-vivo* assessment of stents (Figure 2C & D) [61]. Stent diameter was higher and image noise was lower with the use of HDCT and ASIR image-reconstruction techniques. Further *in-vivo* studies are needed to determine its future role and relevance in the evaluation of coronary stents. Looking ahead, the future uptake in the use of stents with a fully bioresorbable platform may remove the difficulty encountered in imaging metallic stents on CT (Figure 2E).
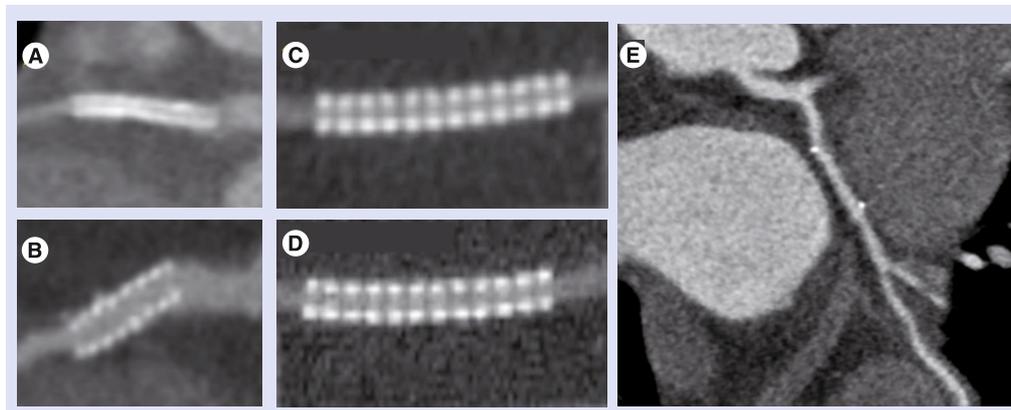
Figure 2. Stent evaluation using multidetector computed tomography. (A) Computed tomography (CT) luminal assessment of a 2.0-mm diameter stent **(B)** compared with a 3.5-mm diameter stent. **(C)** Stent visualization using standard-definition 64-detector CT with 0.63-mm spatial resolution **(D)** compared with high-definition 64-detector CT with 0.23-mm spatial resolution. CT evaluation of a bioresorbable stent. The metallic stent struts have been resorbed and are no longer seen. **(E)** Only the platinum markers at the proximal and distal ends of the stent remain and are visible on CT.
(C & D) Reproduced from [61] with permission from Elsevier.

Lastly, in-stent restenosis can occasionally be caused by the presence of stent fracture. *In vitro* studies demonstrated that the presence of stent fracture can be diagnosed on CT with higher accuracy than with IVUS or invasive angiography [62,63]. This finding is supported *in vivo* by a number of case reports [64,65].

■ **Accuracy of CT to evaluate graft patency after coronary artery bypass graft surgery**
While invasive angiography remains the standard of reference for detection of native coronary artery and graft stenoses after surgical revascularization, this can be cumbersome and challenging at times. As such, the engagement and visualization of venous and arterial bypass grafts can be associated with prolonged procedure time, larger contrast usage and increased radiation exposure [52]. Recently, coronary CT has emerged as an appropriate alternative investigation technique to assess for graft patency and stenosis in symptomatic patients [13]. These recommendations have been based on 93–100% and 96–100% accuracy in detection of significant graft stenosis and graft patency, respectively, using contemporary scanners [52,66,67]. Notably, the accuracy in the detection of severe stenoses in the distal runoff arteries beyond the graft anastomoses and in the ungrafted native coronary arteries is lower at 89–99% and 80–93%, respectively [52,66,67]. This lower accuracy is attributable to the smaller calibre of native arteries and the significant calcific burden in patients who have had previous surgical revascularization.

Role of coronary CT in structural interventions
■ **Transcatheter aortic valvular replacement**
Transcatheter aortic valvular replacement (TAVR) is an alternative treatment for patients with severe symptomatic aortic stenosis who are at a too-high risk for conventional aortic valve replacement [3,68] and is reported to have non-inferior outcomes when compared with surgery in high-risk surgical candidates [2]. Noninvasive imaging, including CT and echocardiography,

Figure 3. Multidetector computed tomography assessment of stent patency in the left main coronary artery. Chronic total occlusion was performed after recurrence of angina in a 52-year-old woman, 4 months after bifurcational distal left main coronary artery stenting. This was performed using the culotte technique, and two 3.5 × 18 mm zotarolimus-eluting stents were inserted into the left anterior descending and left circumflex arteries. **(A)** Chronic total occlusion demonstrated a black hypodense area at the left main coronary artery bifurcation, consistent with significant in-stent restenosis (arrow). **(B)** This was confirmed on coronary angiography, which demonstrated severe in-stent restenosis of the distal left main artery, involving the ostial and proximal portions of the left anterior descending and left circumflex artery stents.
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plays a vital role in the preoperative setting in assessing the aortic valve complex and access-site anatomy. The main role of CT is to evaluate aortic annular dimensions, root anatomy, implantation angle, distance between the annulus and coronary arteries, and iliofemoral anatomy.

Sizing of annulus

Accurate evaluation of the native aortic valve annular dimensions is critical to optimize selection of the correct bioprosthetic valve size. Incorrect valve sizing may lead to paravalvular aortic regurgitation, which is a predictor of worse long-term outcome [69], valve embolization, patient prosthesis mismatch or catastrophic annular rupture [70].

Current recommendations for prosthesis sizing are largely based on annulus measurements performed using 2D transthoracic echocardiogram or transesophageal echocardiography (TEE). However, annular assessment by 2D transthoracic echocardiogram is limited by single annular plane measurements. Hence, it is difficult to fully appreciate the elliptical nature of the annulus and its complex 3D structure. Surgical correlation demonstrated that TEE-derived diameters can underestimate the true diameter by a mean of 1.2 mm and not infrequently by more than 2 mm [71]. While the current practice of TEE-based annular determination and routine over-sizing of the valve by 1–2 mm has provided good outcomes, there remains a percentage of patients with paravalvular regurgitation after the procedure, resulting in many investigators pursuing the use of MDCT annular measurements when screening patients for TAVR [72,73].

Computed tomography assessment may better account for the 3D elliptical shape of the annulus. Measurements are typically taken as the average of the short and long dimensions of the basal ring or derived from the basal ring area **(Figure 4)**. In a recent cohort of 50 patients, Gurvitch *et al.* demonstrated these measurements to be reproducible and typically 1–1.5 mm larger than TEE measurements of the annulus [72]. Based on this information, a CT-based sizing scale has been proposed for TAVR and for current valve sizing thresholds, which are based on TEE measurements, to increase by 1–1.5 mm when CT measurements are used. Future large prospective multicenter studies will be required to gain more understanding of the optimal method for annulus sizing using CT.

Coaxial angle of deployment prediction

Preprocedural determination of the optimal valve implantation angle is a crucial step for interventional cardiologists to increase the likelihood that the valve is deployed perpendicular to the aortic root [74]. Given the orientation of the aortic valve, the optimal coaxial angle for implantation is often a slight caudal angulation
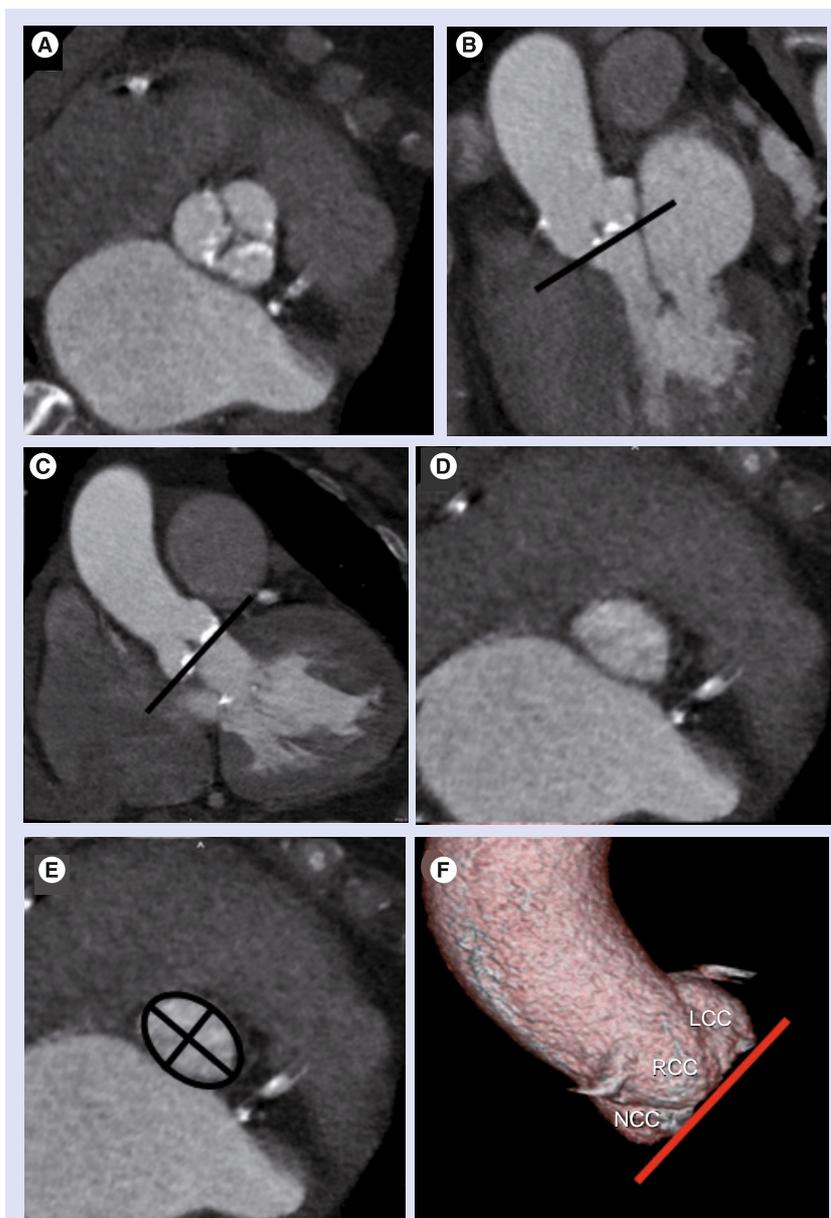
Figure 4. Assessment of the aortic annulus and coaxial angle prediction with multidetector computed tomography. Aortic annulus and angle assessment are performed using a stepwise approach. **(A)** A double oblique transverse image of the aortic root **(B)** is reconstructed from the coronal **(C)** and sagittal oblique views. The aortic annulus **(D)** is approximately 2 mm below the caudal attachments of the aortic valve. **(E)** The mean diameter, which is 23 mm in this case, is calculated by the average of the short (18.7 mm) and long (27.3 mm) dimensions. The area is 361 mm². **(F)** To predict the coaxial angle for implantation, the 3D volume-rendered image is used. The angle most suitable for implantation is one in which the inferior aspects of each coronary cusp can be aligned, with the RCC en face in view. In this case, this can be achieved using left anterior oblique 18 and cranial 3.
LCC: Left coronary cusp; NCC: Noncoronary cusp; RCC: Right coronary cusp.

when in the right anterior oblique projection and a slight cranial angulation when in the left anterior oblique projection. Traditionally, this has been determined by using repeated catheter aortograms in one or two orthogonal planes before commencing the procedure.

Preprocedural CT examinations have the potential advantage of reducing the number of aortograms required during the procedure, and hence, shortening both procedural time and contrast usage. Furthermore, they provide a dataset that can be used to determine the orientation of the aortic root and therefore in the prediction of optimal angles for valve implantation. Gurvitch *et al.* demonstrated, using data from CT, that there is a wide range of right anterior oblique or left anterior oblique projections, as long as appropriate caudal or cranial angulation is added, in each individual for which the aortic valve would be perpendicular to the aortic root [74]. This additional information is particularly useful in patients with atypical angles, which are most commonly observed in patients with musculoskeletal abnormalities and tortuous unfolded aortas.

Iliofemoral artery access assessment

Vascular complications in the iliofemoral arteries may occur as a result of the passage of the large delivery catheters required during TAVR. These constitute a major cause of mortality and morbidity. CT allows a thorough and complete 3D assessment of the iliofemoral system, including an evaluation of plaque burden and vessel tortuosity, which provides important data for procedural planning, given the common association of peripheral vascular disease and severe aortic stenosis [75]. MDCT provides more accurate luminal assessment than single-plane angiography owing to the additional data afforded by its multiplanar capabilities stemming from the isotropic voxels that are acquired. This potential allows for elaborate 3D reconstructions and accurate assessments of the minimal luminal diameter, integrating data from the coronal, sagittal and transverse axial planes.

Accurate luminal assessment on CT can be facilitated by measurements taken in a plane orthogonal to the vessel rather than in the transverse axial plane by adopting a center line approach which typically elongates the curved and tortuous iliofemoral arteries [76]. Importantly, the use of external sheaths with a larger diameter than the CT-derived minimal luminal diameter is a predictor of access complications (23 vs 5%; p = 0.01) [77].

CT can assess vessel tortuosity and the burden and pattern of calcification (**Figure 5**). Toggweiler *et al.* demonstrated, in a cohort of 82 subjects, that the presence of moderate or severe calcification on CT was a significant predictor of vascular complications (23 vs 9%; p = 0.03) [77]. This additional information also allows identification of circumferential or horseshoe calcification within small calibre vessels or stenotic segments, which may not be appreciated on screening 2D angiography [78]. The presence of circumferential calcification may preclude the safe passage of large-profile delivery catheters and, hence, be considered as a contraindication for vascular access.

■ Percutaneous mitral valve repair

Two techniques for transcatheter mitral valve repair have been studied to date, including: attempting to create a double-orifice mitral valve by using a percutaneous edge to edge technique with a clip device or stitch [79]; and remodeling of the annulus of the mitral valve with suture-based techniques, application of radiofrequency energy and device implantation [80].

There is currently no described role for the use of cardiac CT in preoperative assessment of patients prior to mitral clip device insertion, possibly as a result of the inferior temporal resolution of MDCT in comparison with echocardiography in the assessment of the dynamic nature of mitral valve dysfunction. In the case of coronary sinus annuloplasty, cardiac CT may play a role in delineating the anatomy of the mitral annulus, coronary sinus and great cardiac vein, and their relationship with the left circumflex artery [81]. This is important as earlier imaging studies have demonstrated that branches of the circumflex artery travel deep to the great cardiac vein in >50% of patients [82].

■ Other structural interventions

In adult patients with a patent ductus arteriosus, cardiac CT can be a useful adjunct to echocardiography in demonstrating the 3D ductal anatomy, ductal dimensions and complicating features such as calcification or aneurysm formation, which may guide interventional strategy [83].

Furthermore, in patients awaiting left atrial appendage (LAA) closure, preprocedural CT may exclude the presence of thrombus in the LAA, which is a contraindication for closure and provides detailed and 3D morphological assessment of the LAA, which may guide device selection for closure [84]. During follow-up, failure to achieve complete closure can be
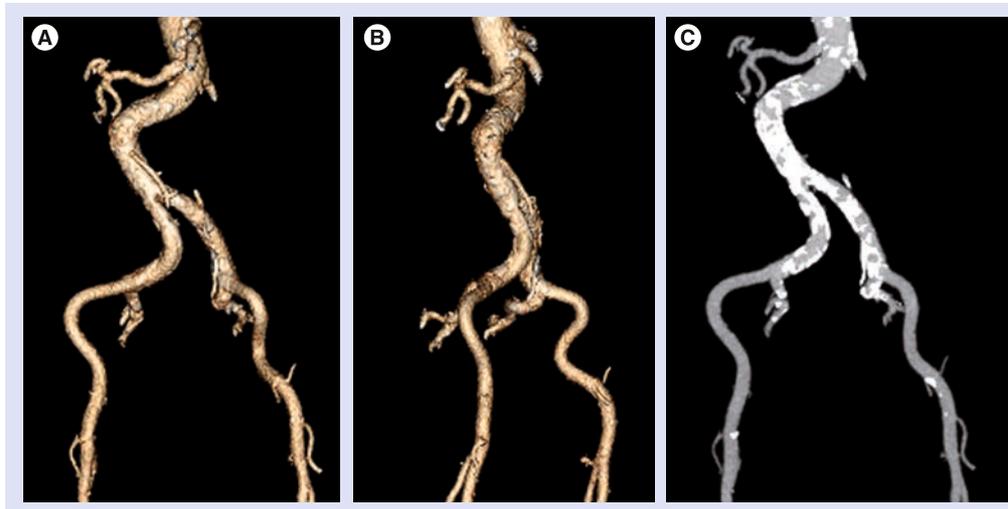
Figure 5. Iliofemoral anatomy assessment with computed tomography. Computed tomography iliofemoral assessment of a 90-year-old man. **(A)** The tortuosity of the right iliofemoral artery in this case is best appreciated in the anterior posterior projection, **(B)** while the tortuosity of the left iliofemoral artery is best seen in an oblique view. **(C)** Computed tomography can also provide detailed assessment on the distribution and degree of calcification in the iliofemoral system.

demonstrated on CT by the presence of persistent communication between the left atrium and LAA, and incomplete device endothelialization [85].

Future applications under investigation

■ Assessment for vulnerable plaque

Currently, the role of CTA in the identification of vulnerable plaques remains investigational. CTA offers the ability to identify important plaque characteristics that may be associated with acute coronary syndrome (ACS). Motoyama *et al.* demonstrated, in a retrospective cohort of 71 patients including 38 patients with ACS and 33 patients with stable angina, that the combined presence of low-attenuation plaque, positive remodeling and spotty calcification on CT had a high positive predictive value for culprit ACS plaques [86].

The question begs whether CT plaque features may be used to identify rupture-prone plaque and predict future ACS. Kashiwagi *et al.* reported that the presence of plaque that is surrounded by a ring of high contrast attenuation (<130 HU) on CT is highly specific (96%) for thin-cap fibroatheroma on OCT, which is believed to represent rupture-prone plaques [87]. This ring enhancement is speculated to represent the presence of highly active neovascularizations in vasa vasorum within a vulnerable plaque [88]. Furthermore, a prospective study including 1059 patients demonstrated that patients with positively remodeled coronary

segments and low attenuation plaques on CT were at a higher risk of ACS developing over time when compared with patients without these characteristics (22 vs 0.5%; p < 0.001) [89]. Whilst vulnerable plaque features on CT, like other imaging modalities, are associated with a higher incidence of adverse outcomes, currently, these features cannot be used to predict ACS or influence treatment.

■ Combined assessment of coronary stenoses & their hemodynamic significance

The combined evaluation of coronary stenoses and their hemodynamic significance is the holy grail of noninvasive diagnostic imaging. Cardiac CT in its current form is limited in predicting the hemodynamic significance of coronary stenoses [90]. New methods are being investigated to provide this information, including the use of CT fractional flow reserve (FFR) and CT stress myocardial perfusion imaging.

CT FFR can be derived by using computational fluid dynamics with CTA vessel data. Indeed, computational fluid dynamics enables derivation of other important hemodynamic data including flow velocity, wall shear stress and wall shear stress gradients, which may be play a role in atherogenesis [91,92]. Its major advantage is that these parameters can be derived without additional image reconstruction, acquisition or administration of medications. In a retrospective cohort of 159 vessels in 103 patients, Koo *et al.* demonstrated that CT FFR, using
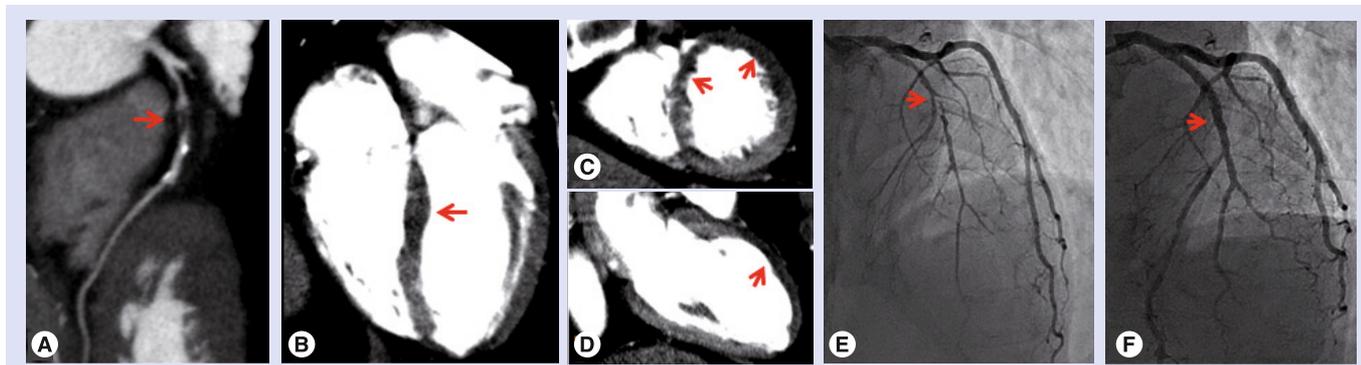
Figure 6. Combined computed tomography coronary angiography and computed tomography stress myocardial perfusion imaging. A 66-year-old male presents with stable angina. **(A)** Computed tomography coronary angiography demonstrated severe stenosis in the left anterior descending artery secondary to mixed noncalcified and calcified atherosclerotic plaque (arrow). **(B & C)** This was associated with the presence of perfusion defects identified on computed tomography stress myocardial perfusion imaging in the anterior septum (arrows) **(C & D)** and mid and distal anterior walls (arrows). **(E)** Invasive angiography confirmed the presence of a critical stenosis in the mid left anterior descending artery (arrow), **(F)** which was successfully revascularized using percutaneous coronary intervention (arrow).

a threshold of ≤0.8, detected FFR-significant (≤0.8) stenoses with a sensitivity of 84% and specificity of 82% [93]. Overall there was a good correlation between CT FFR and FFR (r = 0.72; p < 0.001) and area under the receiver operator curve was 0.90. Further studies evaluating its diagnostic performance are underway, including the Determination of Fractional Flow Reserve by Anatomic Computed Tomographic Angiography (DeFACTO) study, which will be the first prospective multicenter study [94]. An alternative approach currently under investigation is to measure the gradient of intraluminal attenuation along the course of a coronary artery in an attempt to extract flow-related information within the coronary vessel [95,96].

CT stress myocardial perfusion imaging (CTP) is an emerging technique to detect myocardial ischemia (**Figure 6**). Images are typically acquired during first pass of iodinated contrast and vasodilator stress (adenosine), using prospective ECG gating or dynamic imaging. Myocardial perfusion analysis can be performed qualitatively by visual assessment or quantified using various techniques. In patients with known CAD, the added use of CTP may improve the accuracy of CTA in the detection of myocardial ischemia on SPECT-MPI [97] and magnetic resonance perfusion imaging [98], and, importantly, of occlusive disease on ICA [99] and hemodynamically significant stenoses on FFR [100,101]. A recent study demonstrated, in 40 patients (120 vessels) with suspected CAD, combined CTA and CTP identified FFR significant stenosis with 87% sensitivity and 95% specificity, and can be achieved with a short on-CT–table duration (43 mins) and an acceptable radiation dose (9.2 mSv) [102]. The Core 320 is a multicenter international study currently recruiting participants with suspected and known CAD, and is designed to determine the diagnostic accuracy of 320-detector CT in the combined assessment of coronary arteries and perfusion when compared against invasive angiography and SPECT-MPI [103].

Future perspective

In the near future, technological advances in MDCT systems will undoubtedly allow prospective scanners to combine longitudinal coverage, multiple x-ray tubes, faster gantry speed to further enhance diagnostic performance and image quality, and decrease scan time and radiation exposure. For this reason, as the scope of transcatheter interventions in cardiology broadens, there is little doubt that cardiac CT will be increasingly utilized in the selection of patients suitable for intervention and as an adjunctive imaging tool in guiding interventions. Prospective studies exploring the clinical benefits in the use of CT will continue to be much needed to clarify its role in coronary and structural interventions.

Executive summary

Advances in multidetector computed tomography
- The improved spatial and temporal resolution inherent in current-generation computed tomography (CT) scanners permits accurate and convenient assessment of coronary arteries.
- The use of prospective ECG gating has vastly reduced the radiation dose required for coronary assessment.

Cardiac CT in percutaneous coronary interventions
- CT coronary angiography in its current form plays a minimal role in selecting patients who may benefit from coronary revascularization.
- In chronic total occlusion interventions, CT coronary angiography can identify features that may predict procedural failure. Its use may reduce complication rates but it has not been demonstrated to enhance procedural success.
- CT can reliably assess stent patency in stents that have a ≥3 mm diameter, including left main stents.

Cardiac CT in percutaneous structural interventions
- In transcatheter aortic valvular replacement, CT plays an important role in the assessment of iliofemoral anatomy, the prediction of optimal angle for valve implantation and annular sizing. The latter is traditionally guided using a transesophageal echocardiogram, hence, sizing thresholds based on CT measurements will need to be developed before wider adaptation.
- In percutaneous mitral interventions, CT is utilized to delineate the anatomy of the coronary sinus and its relationship with the left circumflex artery.

Future applications under investigation
- While the presence of certain CT plaque features is associated with a higher prevalence of acute coronary syndromes, CT may not be used to predict acute coronary syndromes or to influence management.
- CT fractional flow reserve and CT stress myocardial perfusion imaging represent promising techniques to allow the combined assessment of coronary stenoses and their hemodynamic significance.

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