# Cardiac CT for Coronary Imaging

Marisa Lubbers

Koen Nieman

*Cardiac CT, PET and MR, 2nd edition.*
*Edited by Vasken Dilsizian and Gerry Pohost. © 2016 Blackwell Publishing Ltd.*

## INTRODUCTION

Cardiac CT allows for practically motion-free imaging of the heart and detailed visualization of the coronary arteries. Over the past decade noninvasive coronary angiography by cardiac CT has become a valuable technique for the diagnostic triage of patients with (suspected) coronary artery disease in various settings.

### Data Acquisition and Evaluation

#### Cardiac CT scan modes

A fundamental step in the technical development of cardiac CT has been the removal of the physical connection between the rotating and stationary scanner elements. So-called slip-ring technology allows transfer of energy and data between the rotating tube-detector and the stationary unit without cables that necessitate unwinding after a few scanner rotations. Continuous rotation allows continuous data acquisition, which was crucial for the development of cardiac CT. The first widely applied scan mode for cardiac imaging using multislice CT systems was the spiral scan mode. A spiral CT scan is performed using continuous table advancement and data acquisition. From the table's perspective the path of the rotating elements has the shape of a helix or spiral, hence the name spiral or helical CT. By expanding the number of detector rows coverage speed could be improved significantly. While a 4-slice cardiac CT scan required up to 40 seconds, 64-slice CT systems and beyond can complete the acquisition in a few heart beats or less, which allows for a much more comfortable breath-hold. While the spiral scan mode with retrospective ECG synchronization is a very robust technique it has the drawback of a relatively high radiation exposure. In an effort to reduce radiation exposure the axial scan mode was re-introduced, though with continuous scanner rotation, and has by now become the default scan mode. Scanners with sufficient detector-collimation width to cover the entire heart do not require movement of the table during the examination.

#### ECG-Synchronization

For most scanners the width of the combined detector rows is insufficient to cover the heart at once. Therefore several stacks of data need to be acquired over several heart cycles to image the complete heart (figure 1). In order to create a comprehensible CT angiogram the acquisition or reconstruction of images needs to be synchronized to the heart cycle. Displacement of the coronary arteries varies throughout the cardiac cycle and is generally least during mid-diastole or end-systole. Therefore, ECG-synchronization is important both to create images without motion artifacts as well as phase consistency between images acquired during different heart cycles. There are two approaches to acquire ECG-synchronized CT images. The original spiral CT protocols used only retrograde ECG-gating, which implies that after the acquisition of CT data a recorded rhythm tracing was used to select phase-consistent data to reconstruct images. This approach requires that each table position is scanned for the duration of at least one heart cycle. The advantage is that retrospectively any cardiac phase can be reconstructed. The downside is that the radiation dose to the patient is fairly high. The alternative approach is prospective ECG-triggering, in which case the data acquisition (and radiation exposure) is limited to a pre-specified window within the heart cycle based on the live ECG trace. The axial scan mode is performed using prospective ECG triggering: each set of images is acquired in sequence, triggered by the ECG, with repositioning of the table in between scans. Nowadays, ECG-gated spiral scans can be combined with prospectively ECG-triggered variation of the roentgen tube output to lower exposure during phases that are not expected to be needed for image interpretation. Alternatively, contemporary axial scan protocols can be performed with an extended exposure window to allow for reconstruction of more cardiac phases.

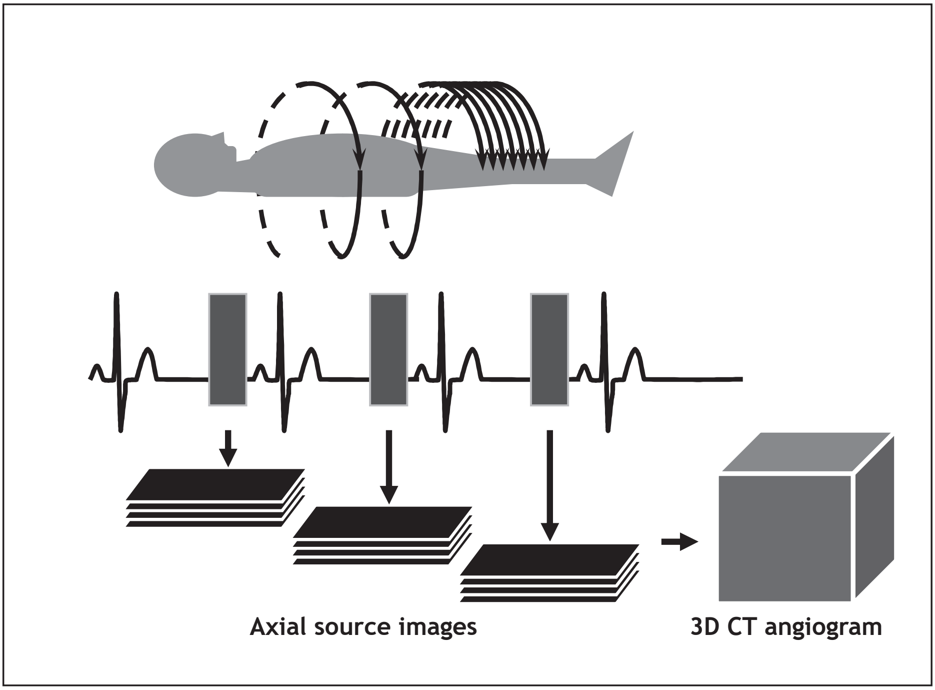


**Figure 1.** ECG-gated spiral CT image reconstruction. Overlapping data is acquired during a spiral CT scan. Using the recorded ECG, images are reconstructed from phase-consistent data acquired during each consecutive heart cycle. Together the reconstructed images from several heart cycles become a complete 3D data set of the heart during a single phase of contraction.

**Temporal Resolution**

While the scan time refers to the duration of the entire CT acquisition, the temporal resolution relates to the time needed to acquire a single image. The temporal resolution is comparable to the shutter time of a camera, and needs to be as short as possible to avoid motion blurring on the images. The fundamental temporal resolution of CT is determined by the rotation speed of the system, the image reconstruction algorithm, as well as the number of tube-detector units on the scanner. Standard partial scan reconstruction algorithms require approximately half of a rotation of projection data to create an image, so the temporal resolution is about half of the rotation time of the scanner. Alternatively, multisegmental reconstruction algorithms combine scan data from consecutive heart cycles to reconstruct images. Theoretically, the temporal resolution could be a fraction of the number of cycles combined (generally between two and four). In reality the effective temporal resolution is improved to a lesser magnitude, depending on the heart rate in relation to the scanner rotation time. Another limitation of multisegmental reconstruction algorithms is the requirement that each table position needs to be scanned during at least two or more heart cycles. For this reason these algorithms are generally only applied in case of a fast heart rate. For slower heart rates the table speed would need to be lowered, which would prolong the scan time and increase the radiation exposure. Depending on the rotation speed currently available single-source CT scanners offer a temporal resolution between 140 and 200 ms. To improve the relative temporal resolution modification of the heart rate by beta-blockers is common practice, and essential in patients with a faster heart rate. Alternatively calcium channel blockers or sinus node blockers may be used. Dual-source CT scanners are equipped with two tube-detector units mounted at an angular offset of 90°. Instead of a 180° rotation dual-source CT can acquire the same number of projections from a 90° rotation, which improves the temporal resolution by a factor of two (75-83 ms) independent of the heart rate. In the vast majority of patients with an acceptable heart rate current CT technology allows virtually motion-free imaging of the coronary arteries during phases of the heart cycle where the displacement of the heart is small, i.e., the mid-diastolic phase just before atrial contraction and/or the end-systolic phase.

**Radiation Exposure**

CT cannot be performed without exposure to roentgen, which is potential harmful for patients. The radiation dose of a cardiac scan generally exceeds that of non-ECG-synchronized CT scans. ECG-gated spiral CT requires multiple sampling to ensure availability of data at each table position during at least one entire heart cycle. Additional contributing factors to the relatively high radiation dose of cardiac CT are the need for fast rotation and thin detector collimation, and the location of the coronary arteries deep inside the chest. The actual radiation dose a patient receives during a given examination varies substantially, and is determined by the scanner type, patient characteristics (body size) and the scan protocol. Initially, more powerful CT scanners resulted in a gradual increase in radiation doses associated with cardiac examinations. Without dose saving measures the dose of a 64-slice CT coronary angiogram varies between 8 and 20 mSv [1–4].

General measures to reduce the radiation exposure include narrowing of the scan range, lowering of the tube voltage, and lowering of the tube current, particularly in smaller patients (table 1) [1,5]. Contemporary scanners with powerful roentgen generators allow for imaging at tube potentials as low as 70 or 80kV in smaller patients. In patients with a regular heart rhythm ECG-triggered tube modulation is an effective means to reduce total dose for spiral CT acquisitions, without sacrificing image quality [1] (figure 2).With prospectively triggered axial scanning image acquisition (and radiation exposure) is limited to the phase of interest, which significantly reduces patient dose. Iterative reconstruction techniques, which largely replaced filtered back projection over the past few years, improve image quality with effective reduction of image noise. Iterative reconstruction techniques lead to dose reductions, when usual noise levels are accepted while images are acquired at lower tube current settings. The most recent generations of dual-source CT scanners have the capability of performing a prospectively ECG-triggered high-pitch spiral CT scan. This scan mode allows for complete data acquisition covering the entire heart within a single heart cycle, despite a maximum detector collimation of 5-7 cm. This scan protocol avoids potential stack artifacts that are typically seen for scans acquired over several heart cycles, but also further decreases the radiation dose. Because only a single heart-phase can be acquired, and a longer period within the heart cycle is needed to acquire all images, a low heart rate is important for good image quality. In general practice, state-of-the-art CT scanners perform coronary CT angiography at an average radiation exposure below 5 mSv. Using more cutting-edge technology the radiation dose can be less than 1 mSv in selected patients.

**Table 1.** Dose-reduction measures.

| General tube current reduction |
|---|
| Geometry dependent (attenuation-based) tube current modulation |
| Tube voltage reduction |
| Tighter scan ranges |
| Table speed adjusted to the heart rate |
| ECG-triggered roentgen tube output modulation |
| ECG-triggered axial scan mode |
| ECG-triggered high-pitch spiral scan mode |
| Anatomic tube modulation |
| Iterative reconstruction algorithms (indirectly) |

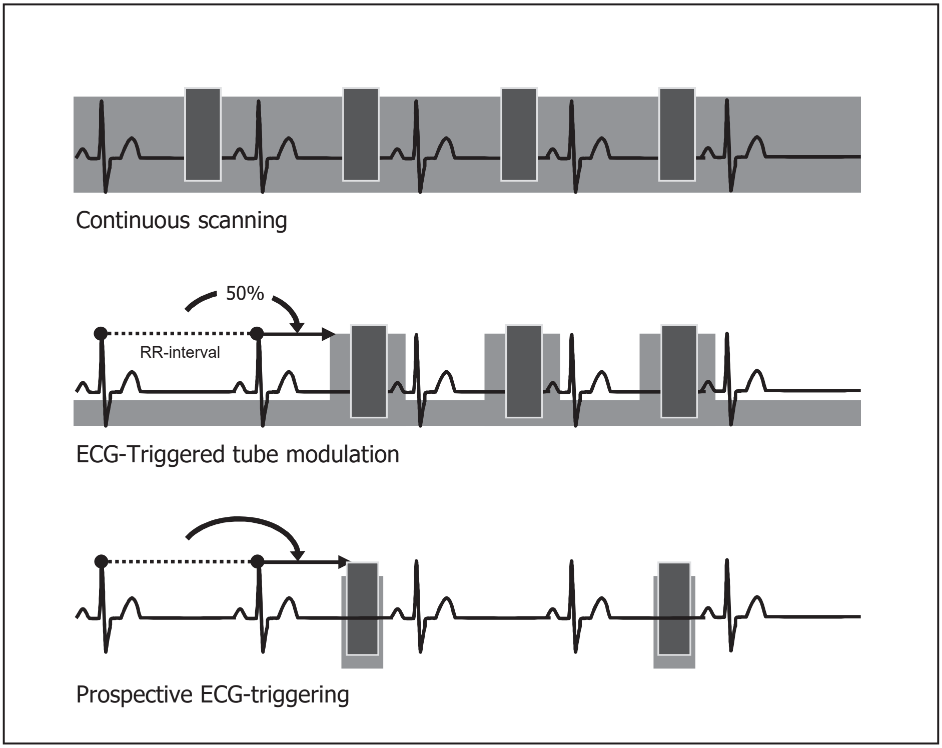


**Figure 2.** ECG-triggered tube modulation. Originally, tube output would be continuous during the data acquisition. Using ECG-triggered tube modulation the roentgen tube output can be alternated during the heart cycle. Based on the previous heart cycles the anticipated phase for reconstruction is predicted, at which time the tube output is elevated to the nominal level. For the remaining of the cycle the tube current is maintained at a very low level. For prospectively ECG-triggered, axial CT imaging the table is stationary during data acquisition. After each consecutive acquisition the table moves to the next position, which generally requires the time of two heart cycles, during which time no roentgen is emitted.

### Image Reconstruction and Post-processing

As mentioned before images are acquired or reconstructed using ECG synchronization, and depending on the scan protocol different phases can be reconstructed afterwards, which may be helpful in case of motion artifacts. Images can be reconstructed using the filtered back-projection, or using the more recently introduced iterative reconstruction algorithms, which have become more or less the current standard. The slice thickness is adjustable, but generally selected in accordance with the detector width at around 0.4-0.75 mm. Overlapping slices can be reconstructed to improve the (subjective) longitudinal spatial resolution. The smoothness or sharpness of the images can be adjusted by using different reconstruction filters (kernels). Generally the field of view for the reconstruction is planned to include the entire heart. Given the fixed image matrix dimensions, reconstruction of a larger field of view will reduce the spatial resolution of the images.

To facilitate the evaluation of the large numbers of CT images postprocessing tools have been developed (figure 3). Cross-sectional images through the CT angiogram can be created in any position or orientation. These multiplanar reformations (MPR) can be flat cross-sectional planes, or they can be created along the (tortuous) trajectory of a vessel to demonstrate the entire course of that vessel in a single image. Thin-slab maximum intensity projections (MIP) are 2D displays of the highest attenuation values, usually contrast medium, calcium or metal, within a given slab. It provides greater overview of the vessel with better contrast between the lumen and the surrounding tissues. Because of the higher attenuation of metal and calcium, MIP is less effective in case of stented or severely calcified vessels. These postprocessing tools can be very helpful in combination with the axial source images, to assess the coronary lumen and detect coronary artery disease. Although not intended for the initial coronary evaluation three-dimensional (3D) volume-rendered images are an attractive means to summarize and communicate findings. Dedicated postprocessing tools have been developed for specific applications, including quantification of stenosis, differentiation of atherosclerotic plaque components, myocardial enhancement or contractile function.

## CORONARY LUMENOGRAPHY

### Detection of Coronary Stenosis

With the introduction of 64-slice CT systems coronary CT has emerged rapidly as a reliable diagnostic modality to detect coronary artery disease. (figure 4). Multiple studies comparing CT angiography with invasive angiography have shown that for the assessment of individual coronary segments, the sensitivity to detect significant coronary artery stenosis is around 94%. Calcified coronary disease causes blooming artifacts on CT, which increases the apparent stenosis severity of a lesion. CT angiography cannot assess the hemodynamic severity of CAD. Depending on the selected stenosis threshold the reported specificity of coronary CTA for detecting hemodynamically significant stenosis is 64-90%. The negative predictive value of CT has been consistently high in all studies, with a pooled average of 98%. Because of the excellent negative predictive value, coronary CTA is very effective for ruling out obstructive coronary artery disease [6,7,8].

Generally, the confidence and accuracy to assess stenosis is better in larger branches and in the absence of extensive coronary calcification (figure 5). Additionally, obesity decreases the signal to noise and the ability to assess coronary obstruction. An irregular heart rate, in particular atrial fibrillation, causes discontinuity between the consecutive acquisitions and negatively affects interpretation of the images, although contemporary technology does provide sufficient image quality in selected cases. As discussed previously image quality is better in patients with a low heart rate, for single-source CT preferably below 60–65/minute.

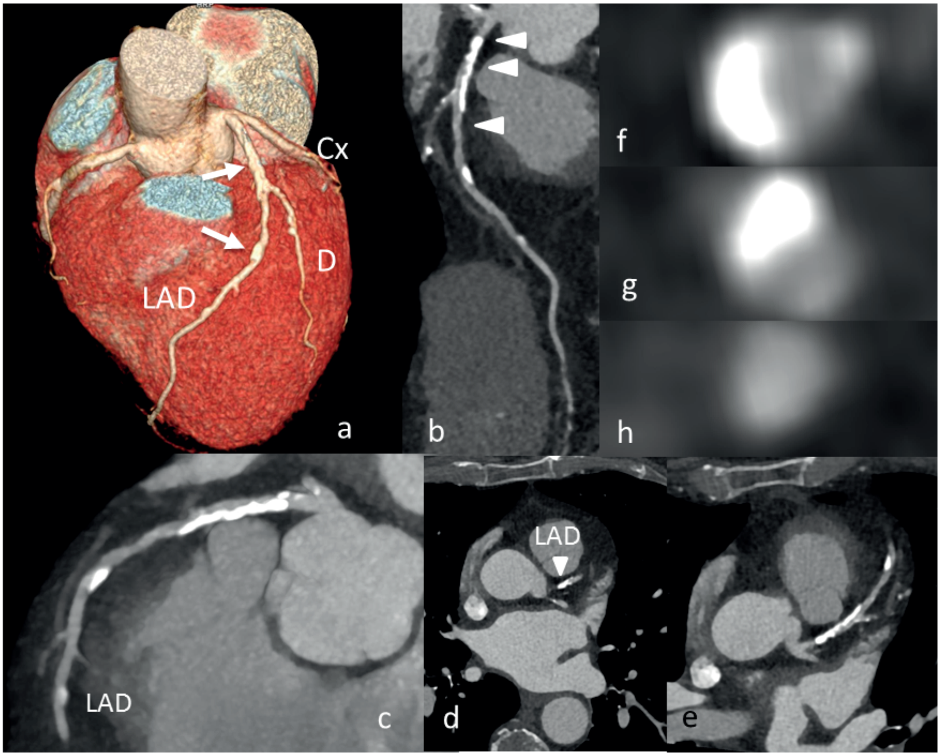


**Figure 3.** Image postprocessing. Use of different postprocessing tools in the same data set, which shows multiple calcified lesions in the left anterior descending coronary artery (LAD)(b and e). A complete 3D reconstruction of the heart (a) shows the highly calcified lesions in the LAD (arrows). Only a small section of the LAD can be visualized on a single axial slice (d), while multiplanar reformations can be created to demonstrate a longer section of the vessel (c). Curved multiplanar reformations (b) and maximum intensity projections (c) can be used to show the entire vessel in a single image. Panels (f–h) show cross-sections of the LAD at the proximal reference, the suspected stenosis and the distal reference level (arrowheads), respectively. D, diagonal branch; MO, marginal branch.

The development of contemporary CT systems with up to 320 detector rows for fast coverage, or double source-detector configuration for optimal temporal resolution, have improved the diagnostic performance of coronary CT further. However, to perform CTA with an optimal visualization of the coronary arteries it requires experienced operators, readers and sufficient preparations. Nitroglycerin expands the coronary lumen and beta-blockers improve image quality by reducing the heart rate. The challenge to rule out coronary artery disease is more difficult in patients with a high calcium burden, or otherwise higher pre-test probability of coronary artery disease. Because the spatial resolution of coronary CTA is lower than for invasive angiography, angiographic disease is classified in categories of diameter stenosis: normal in the absence of plaque, <25%, 25-49%, 50-69%, 70-99%, and occluded [9].

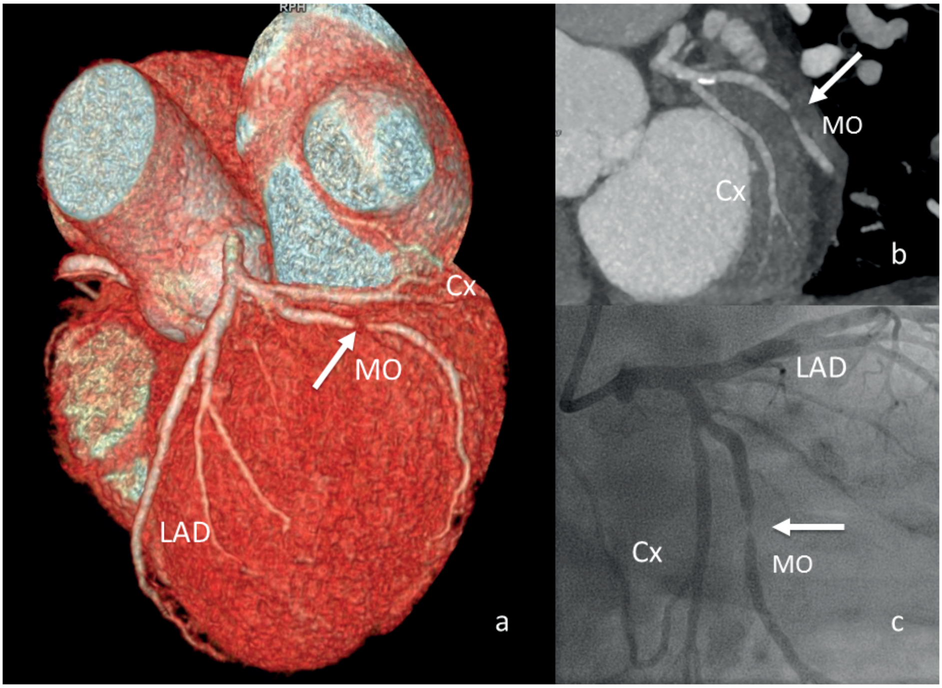


**Figure 4.** Severe coronary stenosis. CT shows a severe stenosis of a large obtuse-marginal branch (MO) of >70% (arrow). Maximum intensity projection of the circumflex artery (Cx) and the MO showing the severe stenosis (arrow) (b). Invasive angiography showing the left coronary system and stenosis (arrow)(c).

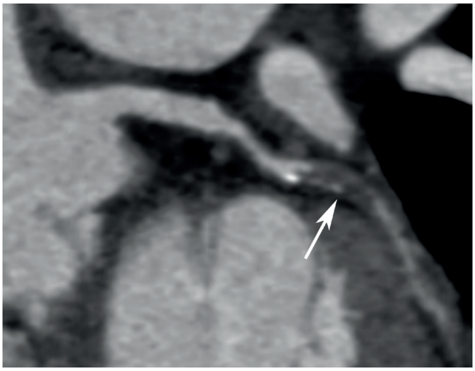

**Figure 5.** CT angiography shows an occluded left circumflex coronary artery, which appears to consist of thrombus on top of a partially calcified plaque. The plaque contains plaque with low attenuation values as well as spots of calcium. The vessel is also outwardly remodeled, all of which are features associated with rupture-prone plaque.

Coronary CTA is unable to directly assess the functional severity of coronary artery disease. To determine whether a lesion detected by cardiac CT causes ischemia may require a subsequent stress test or invasive FFR. Recently, CTA derived FFR (CTA-FFR) was introduced, which is a new technique that applies computational fluid dynamics to a coronary/myocardial model derived from the cardiac CT exam. Without the need for additional scans or stress medication (adenosine) aorta-coronary pressure gradients under simulated hyperemia can be calculated throughout the coronary artery tree (figure 6). The good diagnostic performance of CTA-FFR in comparison with conventional invasive FFR has been demonstrated in several trials [10,11]. On-site performed CTA-FFR have recently become available, which also shows promising performance in single center studies[12,13].

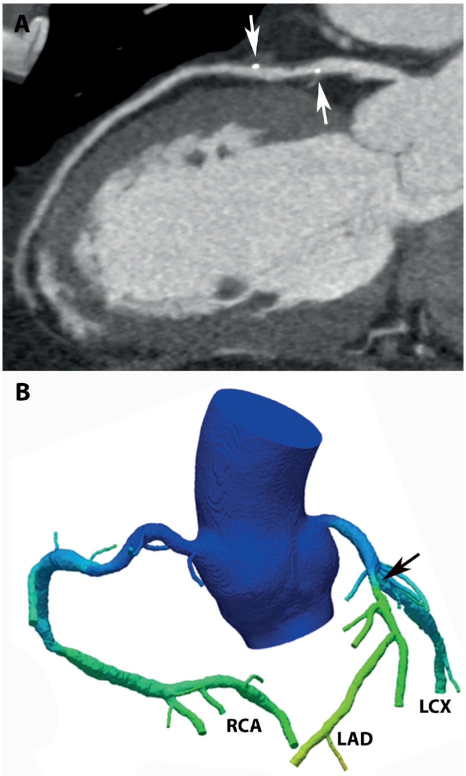


**Figure 6.** CTA shows moderate re-stenosis after placement of a bio-resorbable scaffold in the left anterior descending coronary artery (LAD) (A). The three-dimensional rendering of the CTA-derived fractional flow reserve (FFR) simulation displays calculated FFR values as a color map (B). While a change in shading from blue to green over the treated LAD indicates a change in FFR values, the distal CTA-FFR does not drop below 0.80, and is therefore not regarded as hemodynamically significant.

**Clinical Applications**

Coronary CTA is characterized by an excellent negative predictive value for confident exclusion of coronary stenosis, especially in patients with a low to intermediate probability of coronary artery disease. Based on the 2013 ESC guidelines on stable coronary artery disease coronary CTA is suitable for patients with a low to intermediate probability of disease (15-50% using the Genders prediction rule [14]) and an equal alternative compared to functional testing, under the condition that the patient is a suitable candidate for CT and if adequate technology and local expertise is available. (Class IIa, level of evidence C). [15] In addition, coronary CTA can be used for patients with inconclusive functional test results (Class IIa, level of evidence C). The ACC/AHA guidelines for stable ischemic heart disease consider coronary CTA as an alternative diagnostic option when functional testing is not possible or leads to inconclusive test results (Class IIa).

**Use of coronary CTA recommended by current ESC Guidelines**

- Coronary CTA should be considered as an alternative to stress imaging techniques for ruling out stable coronary artery disease in patients within the lower range of intermediate PTP for stable CAD in whom good image quality can be expected (class IIa, level of evidence C).
- Coronary CTA should be considered in patients within the lower range of intermediate PTP for stable coronary artery disease after a non-conclusive exercise ECG or stress imaging test, or who have contraindications to stress testing in order to avoid otherwise necessary invasive coronary angiography, if fully diagnostic image quality of coronary CTA can be expected (class IIa, level of evidence C).
- Coronary calcium detection by CT is not recommended to identify individuals with coronary artery stenosis (class III, level of evidence C).
- Coronary CTA is not recommended in patients with prior coronary revascularization. (class III, level of evidence C)
- Coronary CTA is not recommended as a 'screening' test in asymptomatic individuals without clinical suspicion of coronary artery disease (class III, level of evidence C).
- Coronary CTA should be considered as an alternative to invasive angiography to exclude ACS when there is a low to intermediate likelihood of CAD and when cardiac troponin and/or ECG are inconclusive (class IIa, level of evidence A).

After publication of these guidelines a few comparative effectiveness trials have been published (table 2). The pragmatic PROMISE trial randomized an impressive 10.003 patients with new stable chest pain between CT angiography and functional testing (mostly nuclear imaging) for evaluation of suspected coronary artery disease. The study demonstrated that there was no difference in adverse cardiac events after 2 years. [16] Although after CT more patients underwent invasive angiography and more were revascularized, the number of invasive angiograms without obstructive coronary artery disease was reduced. In the SCOT-HEART trial, the addition of coronary CTA to standard care was investigated in 4146 patients with stable angina. [17] The investigators demonstrated improved certainty of the diagnosis of angina pectoris caused by ischemic heart disease, but no effect on frequency of the diagnosis of angina due to coronary artery disease. After 1.7 years, there was a close to statistically significant 38% reduction in hard events in favor of patients in the CT group. The smaller CRESCENT trial randomized 350 patients between cardiac CT, consisting of a calcium scan and selective coronary CTA, and functional testing [18]. This study showed that after CT, more patients reported complete relief of anginal symptoms and resulted in fewer adverse events. CT was more often able to confidently rule out coronary artery disease and therefore the final diagnosis was reached faster, requiring fewer downstream noninvasive tests without a significant increase in invasive angiograms.

**Table 2.** Randomized controlled trials comparing coronary CTA and standard care in stable chest pain

| | PROMISE (2015) | | SCOT-HEART(2015) | | CRESCENT (2016) | |
|---|---|---|---|---|---|---|
| N | 10003 | | 4146 | | 350 | |
| Risk | D&F: 53 ± 21% | | ASSIGN 10-year CHD risk: 17 ± 12% | | D&F: 45 ± 29% | |
| Follow up (yrs) | 2.1 | | 1.7 | | 1.2 | |
| | USA | | Scotland | | The Netherlands | |
| | **CT** | **Standard** | **Standard+ CT** | **Standard** | **CT** | **Standard** |
| Additional testing | | | | | 25%* | 53%* |
| Cath angiography | 12.2% | 8.1% | 12% | 13% | 12% | 11% |
| Revascularizations | 8.8%* | 3.9%* | 11.2% | 9.7% | 9% | 7% |
| Adverse events** | 3.3% | 3.0% | 14% | 15.7% | 3%* | 10%* |
| Total cost (€) | | | | | 369* | 440* |
| Mean cumulative radiation dose (mSv) | 12.0* | 10.1* | | | 6.6 | 6.1 |

* Significant results ** PROMISE including all-cause death, nonfatal MI, hospitalization for unstable angina and major procedural complications. SCOT-HEART including all-cause death, non-fatal MI and stroke and hospitalizations for chest pain. CRESCENT including all-cause death, non-fatal MI and stroke, late revascularization procedures (>90days) and unplanned cardiac ED evaluations.

Besides diagnosing stable CAD, coronary CTA also has a role in suspected acute coronary syndromes in the emergency department, which has been investigated over the recent years (table 3). The CT-STAT trial compared coronary CTA with nuclear imaging as initial test in the management of patients with acute chest pain. They reported a 54% reduction in time to diagnosis and 38% lower costs of ED care with CT [19]. The ACRIN-PA trial demonstrated that low-risk patients could be safely discharged with early CT angiography twice as often, and CAD was more likely to be diagnosed with CT. [20] The ROMICAT2 trial showed a reduction in length of hospital stay and a 4-fold higher discharge rate from the ED after CT. [21] The results of these trials contributed to a class IIa recommendation (level of evidence A) for the use of coronary CTA in low-intermediate risk patients with non-conclusive ECG and biomarker results to avoid invasive angiography. [22] Since these trials were completed, the introduction of high sensitivity-troponin has changed standard care at the ED considerably and may reduce the efficiency benefits of CT substantially, as was demonstrated recently in the BEACON trial. [23] It showed that CT was safe, less expensive, with less subsequent diagnostic testing. However, CT did not identify more patients with significant CAD requiring revascularization and did not reduce the length of stay nor allowed more expedited discharge. The role of coronary CTA may shift towards the assessment of patients with low-elevated troponin levels, which become more frequent with the use of more sensitive troponin assays.

**Table 3.** Randomized controlled trials comparing coronary CTA and standard care in acute chest pain

| | ACRIN (2012) | | ROMICAT II (2012) | | BEACON (2016) | |
|---|---|---|---|---|---|---|
| N | 1370 | | 985 | | 500 | |
| Risk | TIMI score 0-2 | | Low–intermediate risk | | Average GRACE 83 | |
| | USA | | USA | | The Netherlands | |
| Troponin assay | Conventional | | Conventional | | High-sensitivity | |
| | **CT Angio** | **Controls** | **CT Angio** | **Controls** | **CT Angio** | **Controls** |
| ACS diagnosis | 1% | 1% | 9% | 6% | 9% | 7% |
| ED discharge | 50%* | 23%* | 47%* | 12%* | 65% | 59% |
| Cath angiography | 5% | 4% | 12% | 8% | 17% | 13% |
| Revascularizations | 3% | 1% | 6% | 4% | 9% | 7% |
| Length of stay (hrs) | 18* | 25* | 23* | 31* | 6.3 | 6.3 |
| 1-month MACE | 0% | 0% | 0.4% | 1.2% | 10%** | 9%** |
| Total cost | | | $4026 | $3874 | €337* | €511* |

* significant results; ** including revascularizations. Acute coronary syndrome (ACS); emergency department (ED); major adverse cardiovascular events (MACE)

## Imaging of Stents

The high roentgen attenuation of the metal in standard coronary stents causes artifacts that complicate evaluation of the coronary lumen within the stent, particular close to the stent struts. The magnitude of these artifacts vary depending on the material and the stent design, i.e., the strut thickness [24]. The effect on visualization of the in-stent lumen is most severe in smaller stent [25]. Comparative studies have shown a very reasonable accuracy for in-stent stenosis in comparison to conventional angiography, although a substantial number of stent were excluded because of insufficient image quality [26–28]. Accuracy is better in larger stent and is more accurate for detection of occlusion compared to stenosis [29]. Guidelines recommend CT angiography after coronary stenting in symptomatic patients and in asymptomatic patients with a prior left main stent with a diameter ≥ 3mm [9]. On an individual basis CT can be considered to rule out severe obstruction of stents in larger proximal coronary branches of bypass grafts [30]. Even more than in nonstented patients acquisition of high-quality data, with application of dedicated filters for image reconstruction is recommended to achieve interpretable image quality (figure 7). Recently bioresorbable scaffolds have been introduced. The metal-free struts allow unrestricted coronary CT angiography both at the time of implantation, as well as after resorption (figure 8).

## Bypass Graft Imaging

Because of their large diameter, limited calcification and relative immobility bypass grafts, and particularly saphenous vein grafts, are well visualized by CT, although surgical material may cause artifacts (figure 9). Even with earlier generations of CT graft occlu-

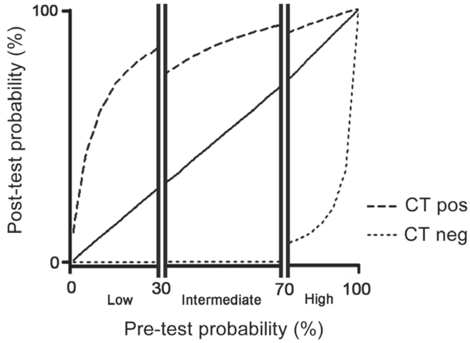


**Figure 7.** Diagnostic value of CT coronary angiography. Pretest and post-test probability of significant coronary artery disease after CT coronary angiography, confirmed by catheter coronary angiography. In the low-to-intermediate pretest probability group CT virtually excludes significant coronary artery disease, while a positive CT scan increases the probability of coronary artery disease to 68 and 88% for low and intermediate pretest probability patients. (Adapted from Meijboom *et al*. [6].)

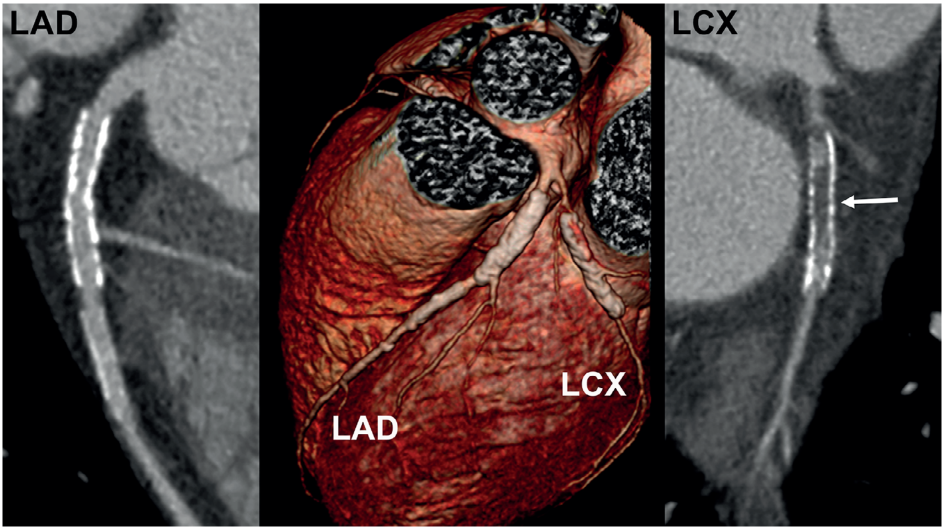


**Figure 8.** CT stent imaging. Two patent stents in the left anterior descending coronary artery (LAD). The different intensity of the stent struts on CT suggests they are stents of a different type. A septal branch is preserved after stenting. A third stent has been implanted in the left circumflex branch (LCX). The low-density material within the stent suggests occlusion (arrow). Distally the LCX is opacified, likely due by collateral supply.

sion or patency can be differentiated with very good accuracy. Current CT technology detects graft occlusion, as well as significant stenosis with an accuracy of approximately 95% (table 4) [31-35]. However, ischemic symptoms in patients after bypass surgery can be caused by obstruction of bypass grafts, or by progression of disease in the native coronary arteries. Longer after surgery obstruction of the non-grafted coronary arteries or distal coronary run-offs is in fact more likely than graft failure as the cause of recurrent complaints [36]. Therefore, evaluation cannot be limited to the bypass grafts alone, but should include the coronary arteries as well. The latter however proves to be more complicated due to often diffuse coronary disease and excessive presence of coronary calcification [37]. Although results have improved using contemporary technology: sensitivity and specificity of approximately 90%, diagnostic performance is still inferior to the published results in patients without previous bypass graft surgery [32,33,35]. Because of the chronic nature of atherosclerotic disease in these patients luminal obstruction may be diffuse and extensive. Occluded grafts may exist for years without causing symptoms because of maintained coronary flow or development of collateral vessels [38]. Even more than in nonsurgical patients, functional information concerning the presence and localization of ischemic myocardium is important to identify the culprit coronary or graft lesion. As a consequence CT is often not fully conclusive in patients presenting with symptoms late after surgery. It can be of use in specific situations when one is (exclusively) interested in the condition of the bypass grafts. CT imaging of the grafts can be performed prior to catheterization to shorten the time spent in the catheterization laboratory, particularly when the location of the grafts is challenging or unknown.

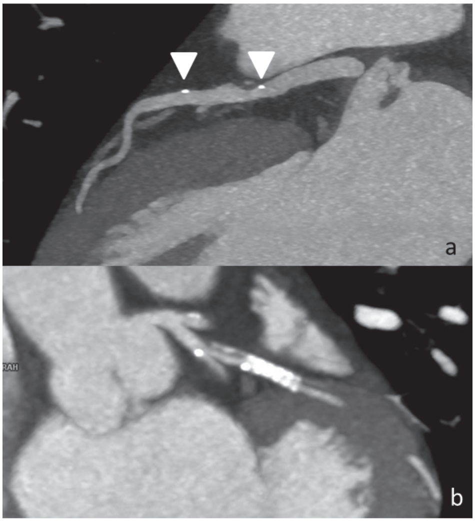


**Figure 9.** Bioresorbable scaffold in the left anterior descending artery (LAD). Remnant platinum markers (arrowheads) indicate the location of the previous scaffold placement. After the proximal marker noncalcified plaque results in a <50% stenosis (a). A patient with a previous bioresorbable scaffold placement from the proximal circumflex artery (Cx) into the marginal obtuses (MO) side branch. There is some intima hyperplasia visible causing stenosis up to 50%. A metal stent was placed distally from the bioresorbable scaffold. (b)

**Table 4.** Diagnostic performance of CT to detect significant bypass graft disease.

| | *N* | *Excl.(%)* | *Sens.(%)* | *Spec.(%)* | *PPV(%)* | *NPV(%)* |
|---|---|---|---|---|---|---|
| Pache *et al.* [24] | 31 | 6 | 98 | 89 | 90 | 98 |
| Malagutti *et al.* [25] | 52 | 0 | 99 | 96 | 95 | 99 |
| Ropers *et al.* [26] | 50 | 0 | 100 | 94 | 76 | 100 |
| Meyer *et al.* [27] | 138 | 0 | 97 | 97 | 93 | 99 |
| Onuma *et al.* [28] | 54 | 2 | 100 | 91 | 74 | 100 |

Number of patients (*N*), exclusion rate (Excl.), sensitivity (Sens.), specificity (Spec.), positive predictive value (PPV) and negative predictive value (NPV) to detect >50% luminal obstruction.

## IMAGING OF CORONARY ATHEROSCLEROSIS

### Coronary Calcium

Because of the roentgen attenuating properties of calcium in comparison to other tissues, calcium can be imaged without the need for contrast medium. While most clinical data has been gathered using electron-beam CT, calcium imaging can be performed with MSCT using either prospectively ECG-triggered scanning or retrospectively ECG-gated image reconstruction [35,36]. Finding calcium is evidence of coronary atherosclerosis. Most patients with flow-limiting disease have a positive calcium score. In symptomatic patients the positive predictive value of a positive calcium score for the presence of coronary stenosis is about 50%, and without symptoms even lower. The absence of coronary calcium does not exclude the presence of (noncalcified) atherosclerosis, although severe coronary artery disease will be unlikely in this case.

The (semi-)quantitative amount of coronary calcium is a surrogate measure for the total coronary plaque burden. Several studies have shown that the coronary calcium score [37] predicts adverse coronary events independently of conventional risk factors [38–42]. The St Francis Heart Study showed that the calcium score outperformed the Framingham Risk Score for the prediction of coronary events [39]. According to published guidelines calcium scoring is reasonable to better classify patients at an intermediate risk of cardiovascular events [43]. Patients with an Agatston score below 100 have a annular CV risk well below 1% and can be considered low-risk. Those with a score >400 have a CV risk equal to for instance diabetics and are entitled to more intensive preventive treatment. Whether this will reduce their risk, and whether calcium scoring as such improves clinical outcome still needs to be established.

The current ESC guidelines state that a "zero" calcium score cannot be used to rule out coronary artery stenosis in symptomatic individuals, especially when young and with acute symptoms (class III, level of evidence C). However, for asymptomatic adults at intermediate risk for CAD or with diabetes and 40 years of age and older, the use of coronary calcium scanning should be considered for CV risk assessment (class IIa, level of evidence B).

### Contrast-Enhanced Plaque Imaging

On contrast-enhanced CT scans noncalcified plaque can be identified in addition to calcified lesions (figure 10). In comparative studies with IVUS CT detects most of the plaque in the proximal coronary vessels, particularly when some calcium is present [44,45]. Because the outer vessel wall is poorly defined, with user-dependent measurements affected by display settings, plaque quantification remains difficult [46,47]. Measured CT attenuation (Hounsfield units) within plaques has been compared with histology and IVUS [46,48–51]. Calcified plaques have a significantly higher attenuation than noncalci-

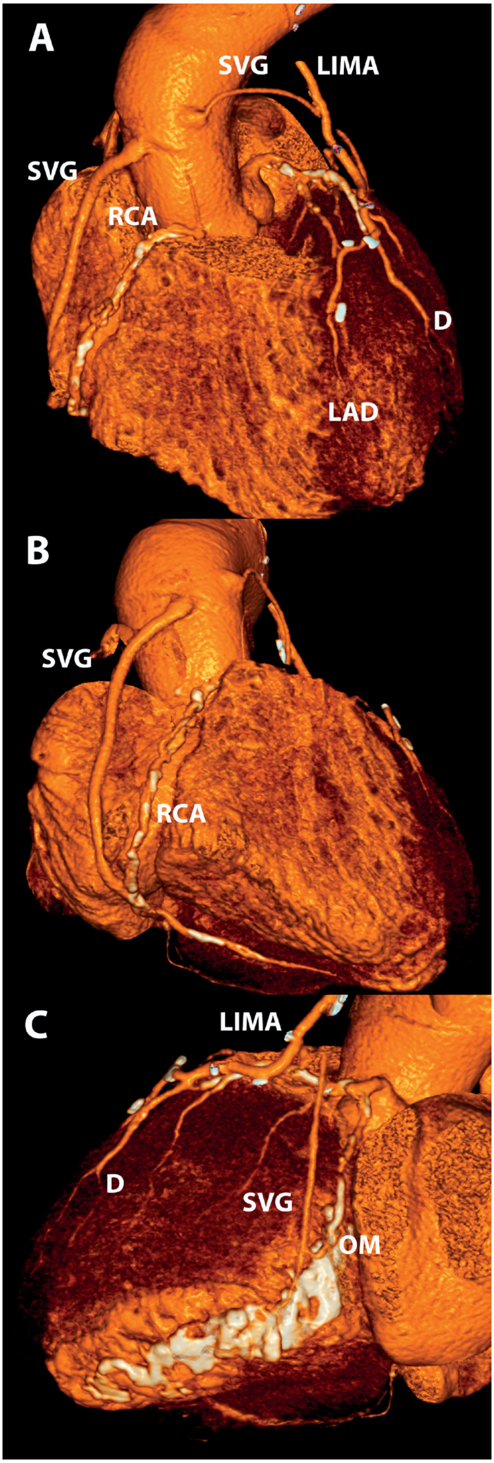


**Figure 10.** Graft imaging. Three-dimensional reconstruction of a CT angiogram of a patient with a left internal mammary artery graft (IMA) connected to the middle segment of the left anterior descending coronary artery (LAD) and a venous graft from the ascending aorta with an anastomosis to a diagonal branch (D), a posterolateral branch and a posterior descending branch (not shown). While the grafts are well visualized, assessment of the native coronary arteries, particularly the LAD, is more complicated.

fied plaques. Differentiation of lipid-rich and fibrous plaque, or hypo- and hyper-echo dense plaques has proven to be more difficult. Lipid-rich plaques have significantly lower attenuation values, but with significant overlap with measured values in fibrous plaques, particularly between studies. Similar to IVUS studies, CT has shown that culprit plaques in patients with an acute coronary syndrome tend to be larger with positive vessel remodeling. Unstable lesions contain smaller overall quantities of calcium, but with a more spotty distribution, as well as more low-density plaque in comparison to stable coronary plaques [52–56]. Recent years more research is conducted into high-risk plaques in coronary CTA. High risk plaque features are considered to be:

- low attenuation (HU) plaques, defined as <30 HU corresponding with plaques with a lipid core
- Positive remodeling, defined as a remodeling index >1.1, which is calculated as the ratio of the diameter of the plaque relative to diameters of the average proximal and distal reference diameters
- Spotty calcification, defined as calcification measuring <3mm in diameter surrounded by non-calcified plaque
- Napkin-ring sign, defined as a ring of peripheral high attenuation surrounding a low attenuation (necrotic) core

Further research and technical developments are necessary to develop CT-based plaque analysis in the future. [56,57,58].

## SUMMARY

- ECG-synchronized cardiac CT allows noninvasive visualization of the heart and coronary arteries. Beta-blockers are often used to lower the heart rate and minimize motion artifacts.
- Contemporary scanner technology and scan protocols, combined with operator awareness, can reduce the radiation dose of cardiac CT considerably.
- The diagnostic accuracy of coronary angiography using the latest generation CT is good in comparison to conventional catheter angiography, and permits exclusion of significant coronary obstruction in the majority of patients. Challenges in coronary CT imaging include calcified vessels, stents, small vessel pathology, arrhythmia, tachycardia, and obese patients.
- Coronary CT is considered a diagnostic option in patients with chest pain, a low-intermediate probability for coronary artery disease, particularly when exercise tests are unavailable or nonconclusive. Other applications include the triage of patients

with recent/acute chest pain at low to intermediate risk without ECG changes or elevated blood markers.

- Coronary calcium scoring can improve risk stratification, and may be considered for individuals at intermediate risk. Imaging of noncalcified plaque by CTA is a field of intensive research and expectations.

## REFERENCES


1. Hausleiter J, Meyer T, Hadamitzky M, et al. Radiation dose estimates from cardiac multislice computed tomography in daily practice: impact of different scanning protocols on effective dose estimates. Circulation. 2006;113:1305–1310.
2. Leber AW, Knez A, von Ziegler F, et al. Quantification of obstructive and nonobstructive coronary lesions by 64-slice computed tomography: a comparative study with quantitative coronary angiography and intravascular ultrasound. J Am Coll Cardiol. 2005;46:147–154.
3. Mollet NR, Cademartiri F, van Mieghem CA, et al. High-resolution spiral computed tomography coronary angiography in patients referred for diagnostic conventional coronary angiography. Circulation. 2005;112:2318–2323.
4. Ropers D, Rixe J, Anders K, et al. Usefulness of multidetector row spiral computed tomography with 64- × 0.6-mm collimation and 330-ms rotation for the noninvasive detection of significant coronary artery stenoses. Am J Cardiol. 2006;97:343–348.
5. McCollough C, Bruesewitz M, Kofler J. CT dose reduction and dose management tools: overview of available options. RadioGraphics. 2006;26:503–512.
6. Meijboom WB, Meijs MF, Schuijf JD et al. Diagnostic accuracy of 64-slice computed tomography coronary angiography: a prospective, multicenter, multivendor study. J Am Coll Cardiol. 2008 Dec 16;52(25):2135-44.
7. Budoff MJ, Dowe D, Jollis JG . Diagnostic performance of 64-multidetector row coronary computed tomographic angiography for evaluation of coronary artery stenosis in individuals without known coronary artery disease: results from the prospective multicenter ACCURACY (Assessment by Coronary Computed Tomographic Angiography of Individuals Undergoing Invasive Coronary Angiography) trial. J Am Coll Cardiol. 2008 Nov 18;52(21):1724-32.
8. Miller JM, Rochitte CE, Dewey M et al. Diagnostic performance of coronary angiography by 64-row CT. N Engl J Med. 2008 Nov 27;359(22):2324-36.
9. Raff GL, Abidov A, Achenbach S, et al. SCCT Guidelines for the interpretation and reporting of coronary computed tomography angiography. SCCT
10. Min J, Leipsic J, Pencina M, et al. Diagnostic Accuracy of Fractional Flow Reserve From Anatomic CT Angiography. JAMA. 2012;308(12):1237-1245.
11. Norgaard B, Leipsic J, Gaur S, et al. Diagnostic Performance of Noninvasive Fractional Flow Reserve Derived From Coronary COmputed Tomography Angiography in Suspected Coronary Artery Disease. The NXT Trial. J Am Coll Cardiol. 2014;63(12):1145-1155.
12. Coenen A, Lubbers M, Kurata A, et al. Coronary CT angiography derived fractional flow reserve: methodology and evaluation of a point of care algorithm. J Cardiovasc Comput Tomogr. 2016 Mar-Apr;10(2):105-13.
13. Schoepf J. Diagnostic value of quantitative stenosis predictors with coronary CT angiography compared to invasive fractional flow reserve. 2015 Eur J Radiol.
14. Genders TS, Steyerberg EW, Alkadhi H, et al. A clinical prediction rule for the diagnosis of coronary artery disease: validation, updating and extension. Eur Heart J. 2011;Jun;32(11):1316-30.
15. Task Force M, Montalescot G, Sechtem U, Achenbach S, et al. 2013 ESC guidelines on the management of stable coronary artery disease: the Task Force on the management of stable coronary artery disease of the European Society of Cardiology. Eur Heart J 2013; 34(38):2949-3003.
16. Douglas PS, Hoffmann U, Patel MR, et al. Outcomes of Anatomical versus Functional Testing for Coronary Artery Disease. N Engl J Med 2015.

17. investigators S-H. CT coronary angiography in patients with suspected angina due to coronary heart disease (SCOT-HEART): an open-label, parallel-group, multicentre trial. Lancet 2015.
18. Lubbers M, Dedic A, Coenen A, et al. Calcium imaging and selective computed tomography angiography in comparison to functional testing for suspected coronary artery disease: the multicentre, randomized CRESCENT trial. Eur Heart J. epub Jan 2016.
19. Goldstein JA, Chinnaiyan KM, Abidov A, et al. The CT-STAT (Coronary Computed Tomographic Angiography for Systematic Triage of Acute Chest Pain Patients to Treatment) Trial. Journal of the American College of Cardiology 2011;58:1414-22.
20. Litt HI, Gatsonis C, Snyder B, et al. CT Angiography for Safe Discharge of Patients with Possible Acute Coronary Syndromes. N Engl J Med 2012.
21. Hoffmann U, Truong QA, Schoenfeld DA, et al. Coronary CT angiography versus standard evaluation in acute chest pain. N Engl J Med 2012;367:299-308.
22. Hamm CW, Bassand JP, Agewall S, et al. ESC Guidelines for the management of acute coronary syndromes in patients presenting without persistent ST-segment elevation: The Task Force for the management of acute coronary syndromes (ACS) in patients presenting without persistent ST-segment elevation of the European Society of Cardiology (ESC). Eur Heart J 2011;32:2999-3054.
23. Dedic A, Lubbers M, Schaap J, et al. Coronary CT angiography for suspected ACS in the Era of high-sensitivity troponins. J Am Coll Cardiol. 2016;67(1):16-26.
24. Maintz D, Seifarth H, Raupach R, et al. 64-slice multidetector coronary CT angiography: in vitro evaluation of 68 different stents. Eur Radiol. 2006;16:818–826.
25. Nieman K, Cademartiri F, Raaijmakers R, Pattynama P, de Feyter P. Noninvasive angiographic evaluation of coronary stents with multi-slice spiral computed tomography. Herz. 2003;28:136–142.
26. Gilard M, Cornily JC, Pennec PY, et al. Assessment of coronary artery stents by 16 slice computed tomography. Heart. 2006;92:58–61.
27. Cademartiri F, Schuijf JD, Pugliese F, et al. Usefulness of 64-slice multislice computed tomography coronary angiography to assess in-stent restenosis. J Am Coll Cardiol. 2007;49:2204–2210.
28. Rixe J, Achenbach S, Ropers D, et al. Assessment of coronary artery stent restenosis by 64-slice multi-detector computed tomography. Eur Heart J. 2006;27:2567–2572.
29. Pugliese F, Weustink AC, Van Mieghem C, et al. Dual-source coronary computed tomography angiography for detecting in-stent restenosis. Heart. 2008;94:848–854.
30. Van Mieghem CA, Cademartiri F, Mollet NR, et al. Multislice spiral computed tomography for the evaluation of stent patency after left main coronary artery stenting: a comparison with conventional coronary angiography and intravascular ultrasound. Circulation. 2006;114:645–653.
31. Pache G, Saueressig U, Frydrychowicz A, et al. Initial experience with 64-slice cardiac CT: noninvasive visualization of coronary artery bypass grafts. Eur Heart J. 2006;27:976–980.
32. Malagutti P, Nieman K, Meijboom WB, et al. Use of 64-slice CT in symptomatic patients after coronary bypass surgery: evaluation of grafts and coronary arteries. Eur Heart J. 2007;28:1879–1885.
33. Ropers D, Pohle FK, Kuettner A, et al. Diagnostic accuracy of noninvasive coronary angiography in patients after bypass surgery using 64-slice spiral computed tomography with 330-ms gantry rotation. Circulation. 2006;114:2334–2341.
34. Meyer TS, Martinoff S, Hadamitzky M, et al. Improved noninvasive assessment of coronary artery bypass grafts with 64-slice computed tomographic angiography in an unselected patient population. J Am Coll Cardiol. 2007;49:946–950.
35. Onuma Y, Tanabe K, Chihara R, et al. Evaluation of coronary artery bypass grafts and native coronary arteries using 64-slice multidetector computed tomography. Am Heart J. 2007;154:519–526.

36. Alderman EL, Kip KE, Whitlow PL, et al. Bypass angioplasty revascularization investigation. Native coronary disease progression exceeds failed revascularization as cause of angina after five years in the bypass angioplasty revascularization investigation (BARI). J Am Coll Cardiol. 2004;44:766–774.
37. Nieman K, Pattynama PM, Rensing BJ, Van Geuns RJ, De Feyter PJ. Evaluation of patients after coronary artery bypass surgery: CT angiographic assessment of grafts and coronary arteries, Radiology. 2003;229:749–756.
38. Bryan AJ, Angelini GD. The biology of saphenous vein occlusion: etiology and strategies for prevention. Curr Opin Cardiol. 1994;9:641–649.
39. Becker CR, Kleffel T, Crispin A, et al. Coronary artery calcium measurement: agreement of multirow detector and electron beam CT. AJR Am J Roentgenol. 2001;176:1295–1298.
40. Horiguchi J, Nakanishi T, Ito K. Quantification of coronary artery calcium using multidetector CT and a retrospective ECG-gating reconstruction algorithm. AJR Am J Roentgenol. 2001;177:1429–1435.
41. Agatston AS, Janowitz WR, Hildner FJ, Zusmer NR, Viamonte M, Jr, Detrano R. Quantification of coronary artery calcium using ultrafast computed tomography. J Am Coll Cardiol. 1990;15:827–832.
42. Taylor AJ, Bindeman J, Feuerstein I, Cao F, Brazaitis M, O'Malley PG. Coronary calcium independently predicts incident premature coronary heart disease over measured cardiovascular risk factors: mean three-year outcomes in the prospective army coronary calcium (PACC) project. J Am Coll Cardiol. 2005;46:807–814.
43. Arad Y, Goodman KJ, Roth M, Newstein D, Guerci AD. Coronary calcification, coronary disease risk factors, C-reactive protein, and atherosclerotic cardiovascular disease events: the St. Francis Heart Study. J Am Coll Cardiol. 2005;46:158–165.
44. Greenland P, LaBree L, Azen SP, Doherty TM, Detrano RC. Coronary artery calcium score combined with Framingham score for risk prediction in asymptomatic individuals. JAMA. 2004;291:210–215.
45. Kondos GT, Hoff JA, Sevrukov A, et al. Electron-beam tomography coronary artery calcium and cardiac events: a 37-month follow-up of 5635 initially asymptomatic low- to intermediate-risk adults. Circulation. 2003;107:2571–2576.
46. Vliegenthart R, Oudkerk M, Hofman A, et al. Coronary calcification improves cardiovascular risk prediction in the elderly. Circulation. 2005;112:572–577.
47. Greenland P, Bonow RO, Brundage BH, et al. ACCF/AHA 2007 clinical expert consensus document on coronary artery calcium scoring by computed tomography in global cardiovascular risk assessment and in evaluation of patients with chest pain: a report of the American college of cardiology foundation clinical expert consensus task force (ACCF/AHA Writing Committee to Update the 2000 Expert Consensus Document on Electron Beam Computed Tomography). Circulation. 2007;115:402–426.
48. Achenbach S, Moselewski F, Ropers D, et al. Detection of calcified and noncalcified coronary atherosclerotic plaque by contrast-enhanced, submillimeter multidetector spiral computed tomography: a segment-based comparison with intravascular ultrasound. Circulation. 2004;109:14–17.
49. Leber AW, Knez A, Becker A, et al. Accuracy of multidetector spiral computed tomography in identifying and differentiating the composition of coronary atherosclerotic plaques: a comparative study with intracoronary ultrasound. J Am Coll Cardiol. 2004;43:1241–1247.
50. Leber AW, Becker A, Knez A, et al. Accuracy of 64-slice computed tomography to classify and quantify plaque volumes in the proximal coronary system: a comparative study using intravascular ultrasound. J Am Coll Cardiol. 2006;47:672–677.

51. Moselewski F, Ropers D, Pohle K, et al. Comparison of measurement of cross-sectional coronary atherosclerotic plaque and vessel areas by 16-slice multidetector computed tomography versus intravascular ultrasound. Am J Cardiol. 2004;94:1294–1297.
52. Schroeder S, Kopp AF, Baumbach A, et al. Imaging of noncalcified coronary plaques using helical CT with retrospective ECG gating. AJR Am J Roentgenol. 2000;175:423–424.
53. Schroeder S, Kopp AF, Baumbach A, et al. Noninvasive detection and evaluation of atherosclerotic coronary plaques with multislice computed tomography. J Am Coll Cardiol. 2001;37:1430–1435.
54. Schroeder S, Kuettner A, Leitritz M, et al. Reliability of differentiating human coronary plaque morphology using contrast-enhanced multislice spiral computed tomography: a comparison with histology. J Comput Assist Tomogr. 2004;28:449–454.
55. Pohle K, Achenbach S, MacNeill B, et al. Characterization of non-calcified coronary atherosclerotic plaque by multi-detector row CT: comparison to IVUS. Atherosclerosis. 2007;190:174–180.
56. Leber AW, Knez A, White CW, et al. Composition of coronary atherosclerotic plaques in patients with acute myocardial infarction and stable angina pectoris determined by contrast-enhanced multislice computed tomography. Am J Cardiol. 2003;91:714–718.
53. Inoue F, Sato Y, Matsumoto N, Tani S, Uchiyama T. Evaluation of plaque texture by means of multislice computed tomography in patients with acute coronary syndrome and stable angina. Circ J. 2004;68:840–844.
54. Hoffmann U, Moselewski F, Nieman K, et al. Noninvasive assessment of plaque morphology and composition in culprit and stable lesions in acute coronary syndrome and stable lesions in stable angina by multidetector computed tomography. J Am Coll Cardiol. 2006;47:1655–1662.
55. Schuijf JD, Beck T, Burgstahler C, et al. Differences in plaque composition and distribution in stable coronary artery disease versus acute coronary syndromes; non-invasive evaluation with multi-slice computed tomography. Acute Card Care. 2007;9:48–53.
56. Motoyama S, Kondo T, Sarai M, et al. Multislice computed tomographic characteristics of coronary lesions in acute coronary syndromes. J Am Coll Cardiol. 2007;50:319–326.
57. Min JK, Shaw LJ, Devereux RB, et al. Prognostic value of multidetector coronary computed tomographic angiography for prediction of all-cause mortality. J Am Coll Cardiol. 2007;50:1161–1170.
58. Hecht H, Achenbach S, Kondo T, et al. High-risk plaque features on coronary CT angiography. 2015 Nov;8(11):1336-9. doi: 10.1016/j.jcmg.2014.11.018.