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Evaluation of Coronary Artery Bypass by CT Coronary Angiography

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Abstract

Coronary computed tomography angiography (CCTA) is an accurate method for graft imaging and assessment than invasive coronary angiography (ICA). CTA has excellent sensitivity and specificity. The chapter describes the role of CTA in evaluation of coronary bypass graft. It covers the appropriate indications for performing CTA after bypass operation, patient preparation, as well as protocol and technique of CTA. The chapter describes the post-examination processing of the images and how to interpret CTA images for detection of graft patency or dysfunction as occlusion, partial thrombosis, poor blood flow, and stealing flow from native artery. According to the American College of Cardiology, the American College of Radiology, and the North American Society for Cardiovascular Imaging, graft patency assessment with CTA is an appropriate approach in symptomatic patients at risk for graft stenosis/occlusion. Cardiac CT can be used to assess the patency of coronary artery bypass graft (CABG) with high diagnostic accuracy compared with ICA and even with a better performance compared to the assessment of native coronaries.

Keywords: CT coronary angiography, coronary artery bypass graft, arterial graft, venous graft, coronary graft failure

1. Introduction

The standard of care for management of advanced coronary artery disease is coronary artery bypass graft (CABG) surgery. The long-term clinical outcome after myocardial revascularization depends on the patency of the coronary artery bypass grafts [1].

Percutaneous coronary angiography is the conventional diagnostic modality to evaluate the coronary arteries and grafts. It is considered the gold standard tool to assess bypass graft status in post-CABG surgery patients. However, invasive coronary angiography (ICA) is invasive, risky, and costly procedure [1].

Advances in technology makes multidetector computed tomography (MDCT) a reliable imaging modality for evaluation of coronary artery bypass graft. The coronary bypass grafts are superior to native coronary arteries for imaging as they are less influenced by cardiac motion, have a wider luminal diameter, and are less calcified. CT coronary angiography (CTA) is a relatively painless noninvasive procedure when compared to invasive coronary angiography, and it is well tolerated by most of the patients. All these causes make CTA a primary method in evaluation graft patency and dysfunction.

2. Evaluation of coronary artery bypass by CT coronary angiography

2.1. Types of coronary bypass grafts

Depending on the approach used for revascularization, the surgeon can utilize different types of arterial and venous grafts. The outcome of coronary artery bypass grafting is closely related to the type of graft either venous or arterial. Arterial grafts are commonly used because of a better patency rate than venous coronary artery bypass grafts [2].
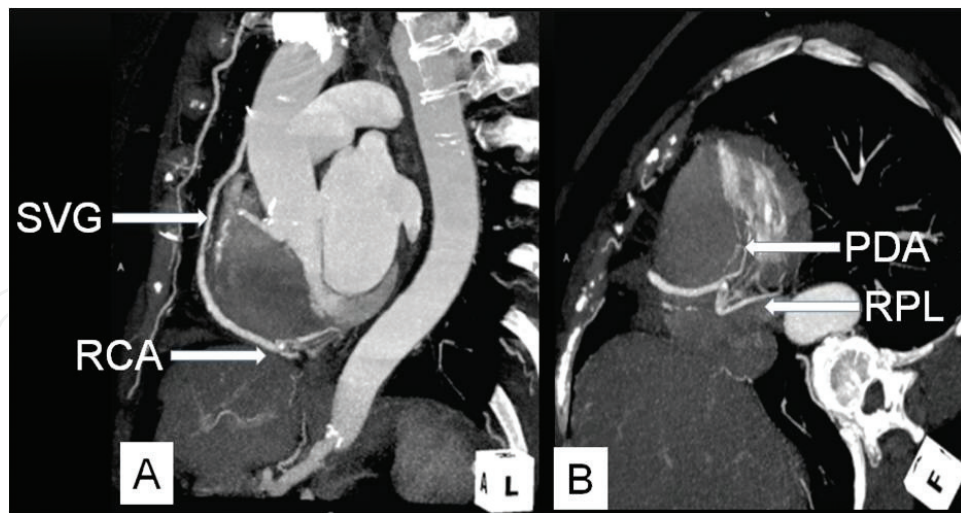
2.1.1. Venous grafts

Venous bypass grafts still represent the majority of all grafts used for bypass surgery. Venous bypass grafts are typically larger in diameter than the native large epicardial coronary arteries (approximately 4–10 mm versus 2–5 mm), and they are less subjected to cardiac motion. Although arterial grafts have better long-term patency rate and outcome, venous grafts, specifically saphenous vein grafts (SVGs), are more readily available. The great saphenous vein (GSV) is usually directly anastomosed to the aorta to revascularize any coronary artery both in a single graft (**Figure 1**) and in a sequential arrangement (**Figure 2**).

There are many causes of venous bypass graft dysfunction. According to the post-operative period, very early after surgery till few weeks after surgery, technical deficiencies and thrombotic activation lead to thrombotic occlusion in approximately 5–10% of the grafts. Then, the two major causes of graft failure within the first year after surgery are intimal hyperplasia and thrombosis, with an occlusion rate of 10–15% [3].

Finally, after the first year, atherosclerosis mechanisms predominate. After 5 years, atherothrombotic occlusion of venous grafts accounts for a reduced patency rate. It has traditionally been estimated to range between 40 and 60% at 10–12 years [2, 4].

2.1.2. Arterial grafts.

As a rule, arterial grafts are smaller in caliber than venous grafts. In the order of frequency of use, graft arteries include the internal mammary arteries (IMAs), radial arteries (RAs), right

Figure 1. An example of a patent single venous graft in a 63-year-old male patient who underwent saphenous vein graft (SVG) to distal right coronary artery (RCA) with well-opacified distal branches; the posterior descending artery (PDA) and right posterolateral branch (RPL). The figure shows maximum intensity projection images (MIP) of CTA in the sagittal (panel A) and oblique (panel B) planes.

gastroepiploic artery, and inferior epigastric artery. The left internal mammary artery (LIMA) is most often used in coronary bypass arterial grafts. The walls of the arterial graft vessels are much better adapted to the high systemic blood pressure and shear stress mechanism than the
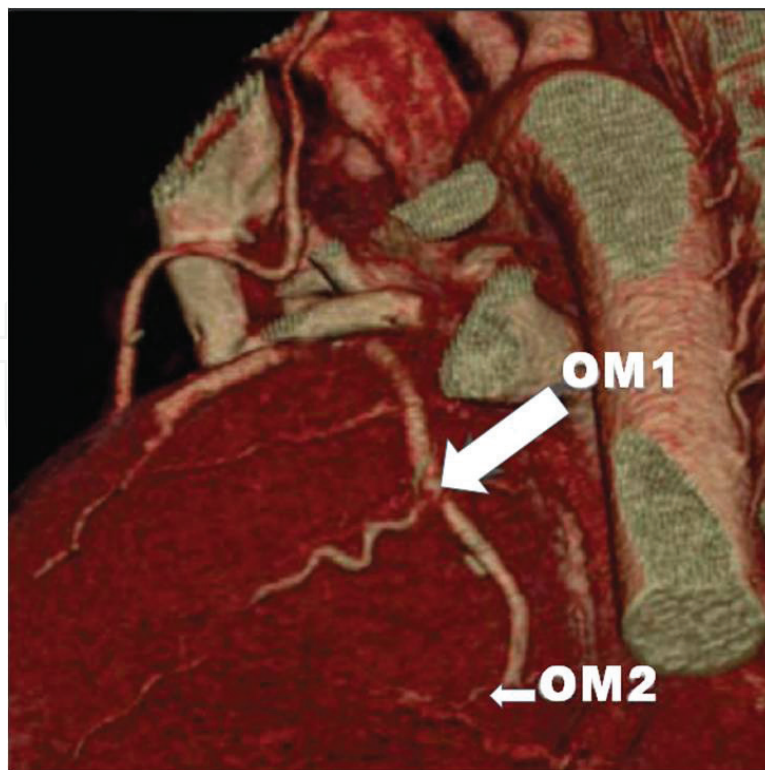
Figure 2. An example of a patent sequential venous graft in a 68-year-old male patient who underwent saphenous vein graft (SVG) to the first and second obtuse marginal arteries (OM1 and OM2). The image is a 3D volume rendering of CTA which was performed because of inconclusive stress test.

walls of the veins, and this leads to improved patency rates of the arterial grafts. If IMA grafts are patent at 1 week after surgery, they will have a 10-year patency rate of 88% [5].

The location and status of the recipient coronary artery influence the graft survival rate. Better survival rate was demonstrated for LIMA bypass grafts and in the situations where the diameter of the native coronary artery is ≥2 mm. However, internal mammary grafts to a recipient vessel with <50% diameter stenosis may have a very high rate of occlusion, probably due to competing flow through the native vessel [5].

Arterial grafts pose some limitations to CTA study, as is the presence of metallic clips in mammary artery and, particularly, in radial artery grafts, which interfere with the visualization of lesions. Also, the nondynamic nature of CTA makes the assessment of competitive flow or vasospasm in the arterial graft difficult [2, 4, 6].

The arterial grafts are usually anastomosed as follows [7]:

- The left internal mammary artery is usually anastomosed to the left descending coronary artery, diagonals, and/or obtuse marginal branches both in a single graft (**Figure 3**) and in a sequential arrangement.

- The right internal mammary artery (RIMA) is usually anastomosed to the left anterior descending coronary artery crossing the midline (**Figure 4**), to the proximal right coronary artery, to obtuse marginal branches or diagonals, via the transverse sinus (behind the aorta), or to obtuse branches or diagonals.

- The radial artery is also used as free graft to all coronary arteries as a single graft or in sequential arrangement. It is more frequently attached in a Y-configuration to left or right internal mammary grafts and less commonly to the ascending aorta.

- The gastroepiploic artery is only rarely used to revascularize the posterior descending coronary artery; sometimes, it is used as a free graft to extend a left internal mammary graft anastomosed to the very distal part of left anterior descending coronary artery.

2.1.3. Planning for grafting

During CABG surgery, if multiple grafts are planned, during surgery they arranged from above downward to avoid crossover of the grafts. Grafts arising from the right side of the ascending aorta are arranged to the right coronary superiorly and posterior descending artery inferiorly. While on the left side, grafts are arranged to circumflex, obtuse marginal, diagonal, and left descending arteries from above downward, respectively.

2.2. Coronary CT angiography technical requirements and protocol

2.2.1. CT scanner

The advancement in the technology of computed tomography (CT) makes CT coronary angiography a popular diagnostic modality for evaluation of coronary arteries and bypass grafts.
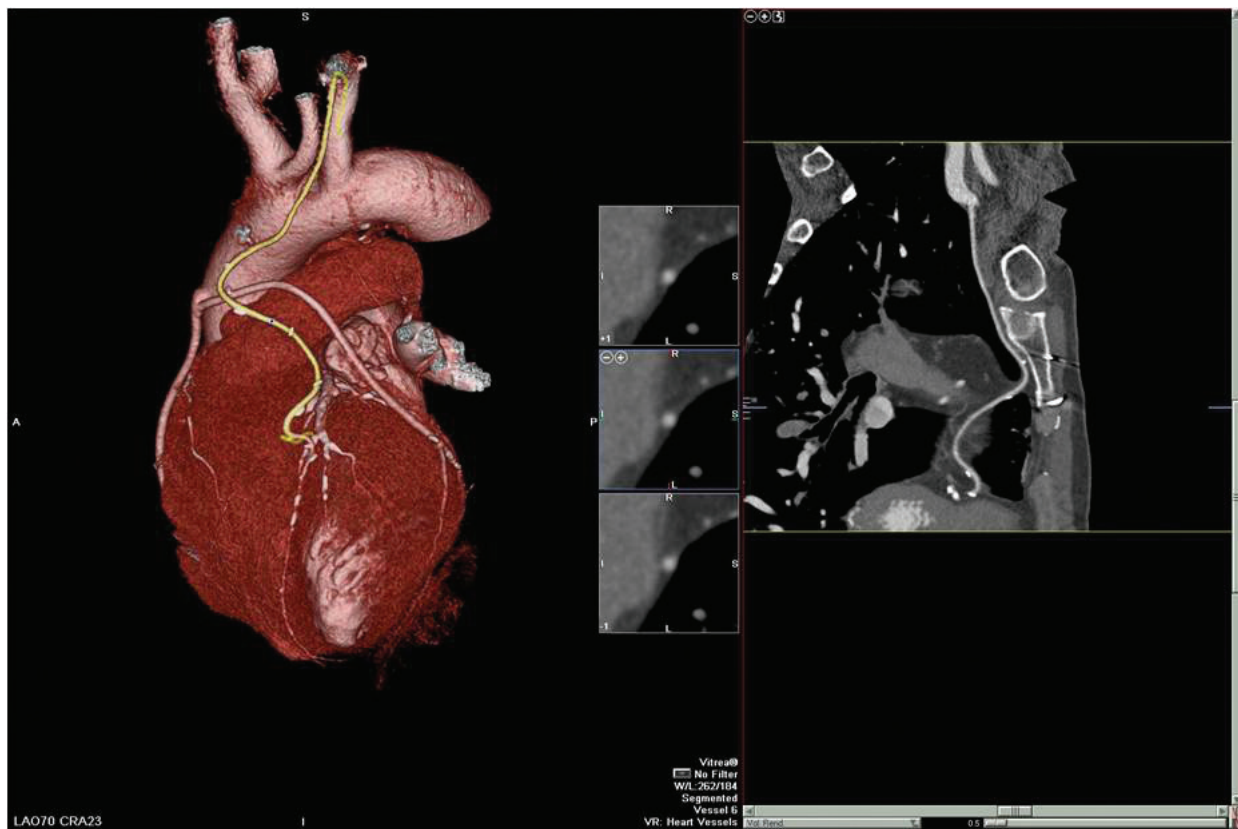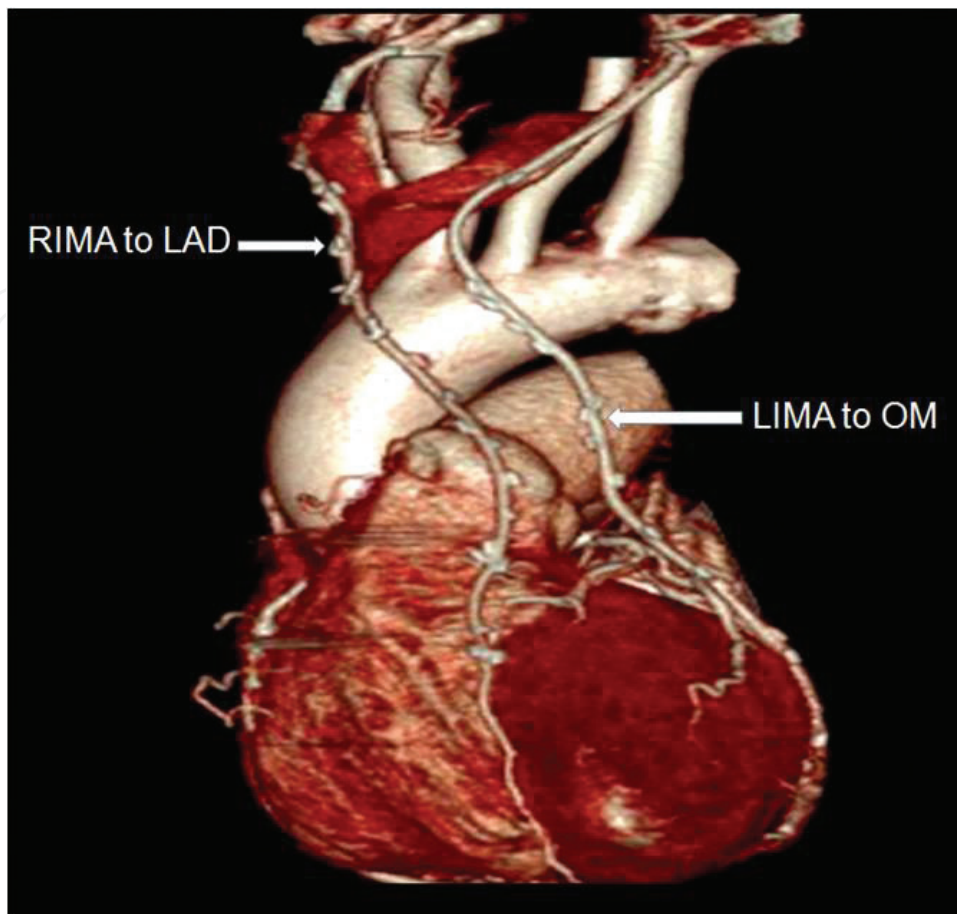
Figure 3. A patent left internal mammary artery (LIMA) graft anastomosed to the left anterior descending (LAD) coronary artery in a 62-year-old male patient who has inconclusive stress echo test.

CT is a noninvasive procedure and well tolerated by many patients. The recent multislice or multidetector CT (MDCT) has a faster gantry rotation with high temporal and spatial resolutions. Also, MDCT has a high X-ray tube potential and wide field of scan. Therefore, MDCT gives a short scanning time, better image quality, and lower patient radiation dose. CT of coronary artery bypass grafts requires a larger scan range (12.5–22.0 cm) and consequently a longer breath hold. Sixty-four-row MDCT scanners or more make CTA of coronary artery bypasses a practical approach with a short breath-hold duration (12–15 s) and thin-slice imaging. Nowadays, for clinical routine, at least 64-row scanners are recommended for follow-up of patients after coronary bypass surgery.

2.2.2. Patient preparation

For patients with high or irregular heart rate, beta-adrenergic blockers are given prior to CT scan to prevent motion artifacts secondary to heart rate variability and tachycardia. It is better to scan patient with low heart rate ranging from 60 to 70 beats per minute. To avoid respiratory motion artifacts, patients are scanned with breath-holding (mid-inspiration period). It is better to scan patients while fasting for about 6 h before the study without dehydration. The patients must have normal renal function and are free of adverse contrast media reaction during any past radiological studies.

Figure 4. Three-dimensional reconstructions of CAA in a 65-year-old male patient who underwent right internal mammary artery (RIMA) to the left anterior descending (LAD) coronary artery and left internal mammary artery (LIMA) grafting to an obtuse marginal (OM) branch. Both grafts are patent.

2.2.3. MDCT acquisition protocols

There are a variety of protocols for image acquisition in the evaluation of patients after CABG surgery. In many respects, the protocols are similar to that for coronary CT angiography.

If the heart rate are slow and stable (less than 70 beats per minute), it is recommended to use the protocol of sequential prospective ECG triggering with padding. This protocol has the advances of reduction of the patient's total radiation dose by about 80–90% compared to retrospective scanning protocol. The drawbacks of prospective ECG-triggering acquisition are a lack of flexibility in reconstructing image data across the cardiac cycle and the impossibility to undertake functional analysis unless single-beat prospective triggering with tube current modulation is used.

On the other hand, patients with previous bypass graft surgery often have irregular and high heart rates. So, in those patients we use the retrospective spiral ECG-gating protocol which has the advantage of potential flexibility in reconstructing image data at different cardiac cycles to choose the best phase with the least cardiac motion. Also, retrospective protocol has the advantage of performing cardiac functional analysis.

2.2.4. Technical parameters of the scan

The scan range depends on both the modalities of grafting. For patients who have received an internal mammary artery bypass graft, the scan should be extended superiorly to include the origins of the internal mammary arteries from the subclavian arteries (at the middle of the clavicle). The scan usually ends at the inferior border of the heart with the exception of patients with a gastroepiploic artery graft, in whom the scan has to include the upper abdomen.

During scanning, patients are placed in the CT table in the supine feet-first position. The duration of the scan ranges from 10 to 15 s. The images are acquired in a limited field of view with axial images centered on the heart. Scanning is performed in a caudal-to-cranial direction to obtain images of the main bulk of the heart and coronary arteries during the initial phase of the acquisition when breath-holding is most effective. The tube potential is 100–120 kVp according to the patient built with tube current of 800 mAs and pitch of 0.2.

2.2.5. Contrast media

Cardiac CTA technique requires rapid injection of nonionic, iodinated, low osmolar intravenous contrast media. Right-sided injection of contrast is preferred to avoid venous contrast crossing grafts. An amount of approximately 60–100 ml of contrast agent followed by a saline flush is sufficient for bypass imaging using 64-MDCT using a dual-head injector.

To optimize the opacification of the coronary arteries, and bypass grafts, an anatomic, automatic triggering method either bolus-tracking or timing bolus technique is used with 8–10 s delay after injection. In the bolus-tracking technique, a threshold of 150 HU is preset at the region of interest (ROI) in the descending aorta. In the timing bolus technique, the ROI in the ascending aorta and scanning will be started immediately at the time of maximum density of the curve. Bolus tracking is preferred for more consistent results and more homogeneous contrast in the coronary arteries.

2.2.6. Post-processing reconstruction

An advanced diagnostic workstation is required for post-processing reconstruction of the axial source images. Three-dimensional volume rendering (3DVRT) is particularly useful in patients who underwent surgical revascularization because it allows a quick overview of arterial and venous grafts and a quick evaluation of their anatomical condition. This should be supplemented by oblique multiplanar reformations (MPR) and curved multiplanar reformations (cMPR) which allows quantification of percent diameter stenosis on cross sections along the vessel. Significant stenoses are usually searched for by scrolling through axial images with and without maximum intensity projection (MIP).

Analysis capabilities of the machine are required in cases examined by retrospective ECG gating for assigning the cardiac anatomy and functions as well as valvular and wall motion abnormalities. Sharp kernels are used for stent imaging and in heavily calcified vessels, which are common in patients after bypass grafting.

2.3. The value of CTA in the context of cardiovascular imaging for CABG assessment

Echocardiography and MRI have recognized weaknesses in terms direct visualization of the coronary arteries or bypass grafts. CT coronary angiography is more sensitive and specific than echocardiography and MRI in imaging of coronary arteries and bypass grafts [4].

Conventional coronary angiography has so far been considered the reference standard for visualization of both native coronary arteries and bypass grafts. Evaluation by ICA in patients with prior CABG can be challenging and exposes patients to large contrast volumes in addition to rare complications such as injury to the graft vessel during catheter engagement.

With its inherent advantages and good diagnostic accuracy, noninvasive coronary angiography using CT is considered a viable alternative in symptomatic patients after coronary artery bypass grafting. Coronary artery bypass grafts are more amenable to CTA imaging, due to their larger diameter and lower pulsatile movements along the cardiac cycle than native arteries and their relative freedom from calcification. CT was first proposed for noninvasive imaging of coronary artery venous bypass grafts by Brundage et al. in 1980 [8]. However, at that time the detection of flow-limiting stenoses was not possible. Improved CT technology has since greatly improved, which has important implications for the diagnostic evaluation of bypass grafts. A relevant aspect of MDCT study of CABG is its ability to readily define the status of patency or occlusion of the graft, being in this sense equal or even superior to invasive angiography. However, applicability of CT to all patients is limited by premature atrial or ventricular contractions, which can reduce image quality when occurring during scanning. Moreover, in patients with coronary artery bypass grafts, the investigation of the native vessels can pose a challenge because of the severe coronary calcifications present.

CT coronary angiography has a very important role for CABG assessment and to avoid invasive coronary angiography. This role is termed as the potential "gatekeeper" role of CTA in the meta-analysis study performed by Barbero et al. They concluded that ICA has a higher cost compared to CTA, and it is inconvenient for most of the patients due to the need for sedation with resultant driving restrictions, as well as a low risk of stroke, infarction, dissection, arrhythmia, or death. On the other hand, CTA is a noninvasive procedure, and it is highly accepted by patients [9].

2.4. Accuracy of different generations of CT in coronary bypass graft assessment

Initial investigation of bypass grafts was done with single-slice scanners, and electron beam CT in1997 by Achenbach et al., who evaluated hemodynamically relevant stenosis, was possible in 84% of the cases with some limitation in the scan due to breathing artifacts and misplacement of the imaging volume [2].

Subsequently, the addition of electrocardiographic (ECG) gating and the improved capabilities available with 4- or 16-slice MDCT scanners for rapid scanning of the area of interest led to promising results in the imaging of bypass grafts.

Four-row CT provided an anisotropic resolution, which oftentimes did not depict the distal anastomosis, and 38% of the patent grafts could not be evaluated because of respiratory/

motion/metallic clip artifacts [10, 11]. Sixteen-row CT scanners improved assessment of occlusion/significant stenosis; however, about 20% were not assessable because of artifacts [12, 13].

The introduction of 64-slice MDCT and dual-source CT permitted improved temporal resolution (up to 83 ms), spatial resolution ($0.4 \times 0.4 \times 0.4$ mm^3), and reduction of both cardiac and respiratory motion, leading to improved assessment of arterial and venous graft stenosis and occlusion. Reports on diagnostic accuracy of MDCT in CABG have shown values of sensitivity and specificity over 95% for the presence of lesions in these vessels. However, the investigation of native vessels showed that sensitivity and specificity are significantly lower than in patients with suspected coronary artery disease [14–18].

In the meta-analysis study performed by Dr. Barbero and colleagues, they reviewed 10 different studies of 959 patients post coronary bypass operations with 1586 arterial and venous grafts. These patents were evaluated using 64-multidector CT scanners of different vendors. The overall sensitivity and specificity of CT coronary angiography in detecting complete graft occlusions were 99 and 99%, respectively, as compared to invasive coronary angiography. They also performed meta-analysis of 12 different studies of 2482 bypass grafts and found that the sensitivity and specificity of CTA in detecting significant graft stenosis (with more than 50% diameter reduction) was 98% regardless the age of patients or the post-operative period after CABG surgery [13].

The introduction of 128-, 256-, and 320-multislice CT gave high temporal and spatial resolution with a less cardiac and respiratory motion, improving assessment of bypass graft patency, stenosis, or occlusion with a promising results. This improvement in image quality allows a comprehensive assessment of the grafts and the native vessels [19–21].

2.5. The appropriate indications of CTCA in CABG assessment

One of the appropriate indications of CTA is imaging and follow-up of symptomatic patients with coronary artery bypass grafts (e.g., recurrent chest pain). In cases of suspected graft failure, post-CABG recurrent symptoms may be due to disease progression, commonly in native coronary arteries, in the venous grafts, or less commonly in an arterial grafts.

There are specific clinical conditions which may favor the use of CT angiography over invasive coronary angiography for graft evaluation as in patients with a positive cardiac test suggesting possible ischemic disease in the territory of a specific coronary bypass graft when disease distal to the graft anastomosis seems less likely. Also, CT coronary angiography is helpful in some patients where an anatomic correlation may be required following an equivocal functional cardiac test. Another clinical situation in evaluation of cases showed borderline graft stenosis or change in symptoms. CTA may be helpful in assessment of patients when the proximal grafts may be affected by other vascular diseases as vasculitis or formation of true or false aneurysms of the bypass graft [22].

Another appropriate indication is to know the course of previously grafted IMA prior to redo-CABG. CTA evaluates patients with unknown previous CABG surgical details to know the number, location, and pathways of grafts before planning management by invasive coronary angiography. CT coronary angiography before invasive coronary angiography has the potential

to the procedure faster and more efficient due to an improved understanding of topography of graft anatomy before attempting to engage graft ostia and evaluate graft body and distal coronary perfusion by percutaneous coronary catheter. However, the combined approach to evaluate CABG by both CTA and ICA results in a higher radiation and contrast dose [22, 23].

2.6. The limitations of CTCA in CABG assessment

Patients with significant obesity (e.g., body mass index >40 kg/m^2) or who have irregular heart rhythms may not be ideal candidates for CTA. In addition those with stage 4 chronic kidney disease (CKD) with glomerular filtration rate below 30 mL/min are also not good candidates for CTA. CTA has limitation in scanning individuals with a large number of metallic surgical clips as clips may interfere in assessment degree of stenosis of the graft itself and the distal anastomosis [4, 24].

### 2.7. Systematic approach for graft assessment

Before starting CT image interpretation, the surgical report and last cardiac catheter report showed be reviewed. Then, the images are preferred to be read according to the following systemic sequences for complete and accurate image interpretation:

- Check the axial, sagittal, and coronal views of the chest wall to know if RIMA and LIMA are present or not, also the status of the surgical wires (intact or ruptured) and the sternum for dehiscence and infection (**Figure 5**).

- Volume-rendered images: for a rapid overview of graft anatomy to identify the type and course of the venous and arterial grafts as well as the presence of stumps and pledgets (**Figure 6**).

- Comprehensive graft evaluation by scrolling the axial images and MPR images to assess patency of the bypass grafts and run-off, proximal, and distal graft anastomoses. In particular, curved planar images (cMPR) with centerlines through the bypass grafts using rotation tool to attempt elimination of clip effect **(Figure 7)**.

- If possible assess the native coronary arteries.

- Examine anatomy of the thoracic aorta and left ventricle (diastolic dimensions).

- If the study is retrospective spiral CT, assess left ventricular and valve functions.

### 2.8. Imaging findings and interpretation

2.8.1. Bypass graft patency

Interpretation of CTA following CABG surgery is started first by assessing the morphology and size of the ascending aorta and the origin of the in situ vessel (in the case of an in situ vessel, such as the IMA). Then, graft patency is assessed along its whole length. Diagnosis of graft patency can be diagnosed if there is uniform homogeneous enhancement of the graft lumen by injecting contrast with smooth outline of the wall of the graft wall. For systematic
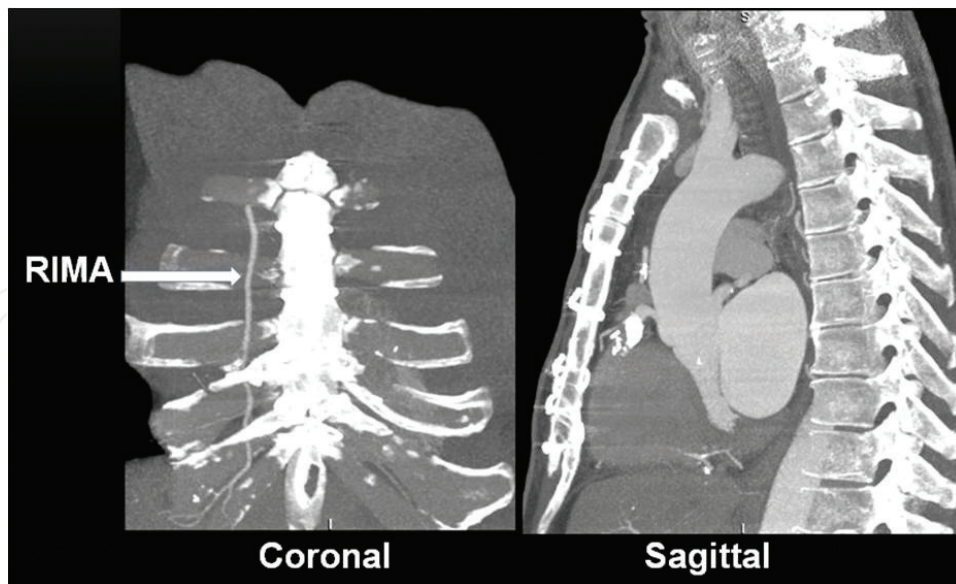
Figure 5. Coronal and sagittal reconstructed images of CTA of post-CABG surgery showing the status of the chest wall. The images show good healed sternum with intact wires. The left internal mammary artery (LIMA) is not in its normal position (repositioned for arterial graft), while the right internal mammary artery (RIMA) is present in its place.

evaluation of the graft, it is divided into three different segments: the origin or proximal anastomosis, the body, and the distal anastomosis of the graft. Usually, the proximal anastomosis of the graft is accurately assessed than the distal anastomosis due to its better visualization by CTA. In some cases where the distal anastomosis is not well visualized, the bypass graft is considered patent if there is homogeneous contrast enhancement of its lumen.
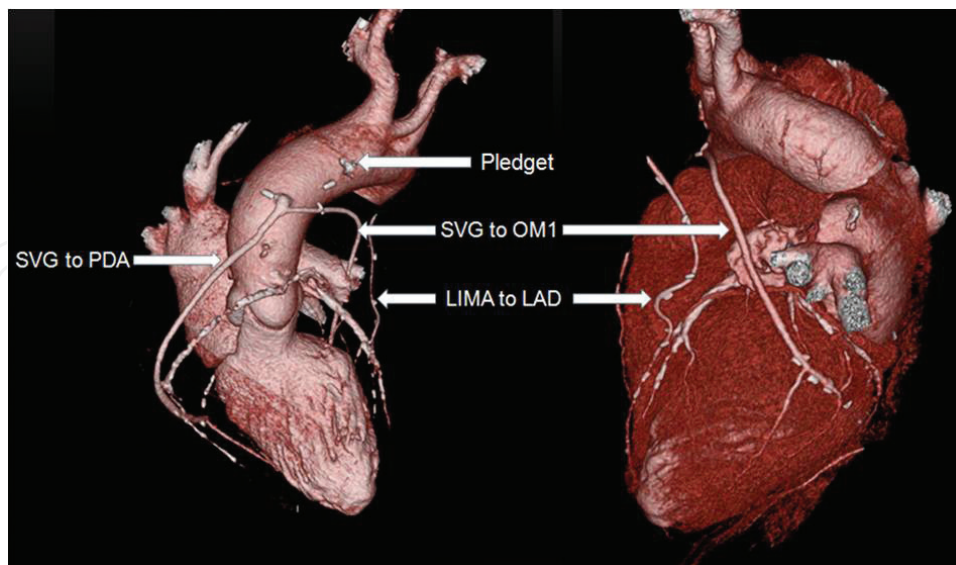
Figure 6. Volume-rendering reconstructed images of CTA of post-CABG showing the type and course of multiple different bypass grafts. The images show grafted saphenous vein graft (SVG) to posterior descending artery (PDA), left internal mammary artery (LIMA) to left anterior descending artery (LAD), and SVG to first obtuse marginal (OM1) artery. The three grafts are patent, and the native coronary arteries show different grades of stenosis. A high-attenuation felt pledget is depicted at the distal portion of the ascending aorta. Note that the high-attenuation focus is located external to the aortic wall.
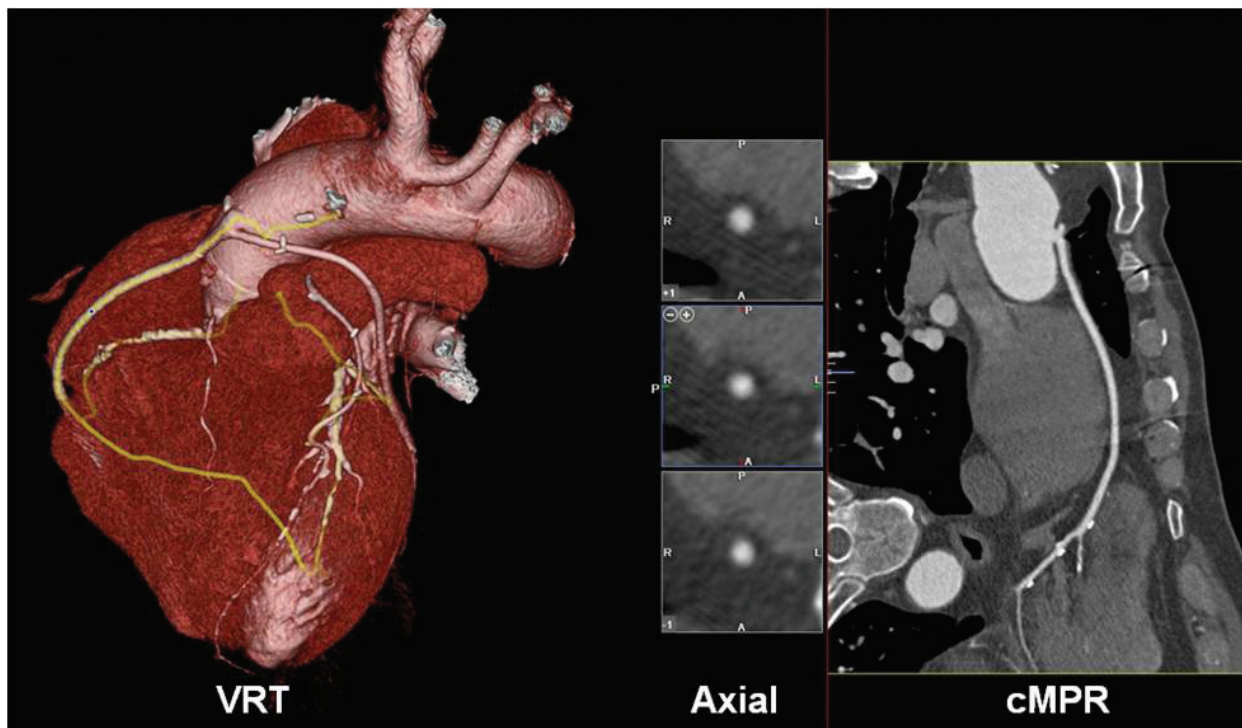
Figure 7. The comprehensive approach to track a saphenous vein graft to the posterior descending artery in 3D virtual reconstruction (VRT) and axial and curved multiplanar reconstruction images (cMPR). The tracking line in the VRT images delineates the graft from its origin to the distal anastomosis. Axial images show the cross section of the graft lumen to determine the degree of diameter reduction and status of the wall. cMPR images are rotating through the bypass graft to eliminate the blooming effect of clips. Note that the graft is patent with a normal distal anastomosis.

Outcome of the graft patency differs according to its type and anastomosis. General patency of IMA grafts was better than for SVGs, and patency of SVG graft in LAD or D1 was better than its placement in PDA or OM artery. The patency of the grafts and presence of significant stenosis (>50% reduction in graft diameter at any point along its length by visual estimation) were evaluated. Recognize artifacts associated with surgical clips as blooming and beam hardening. The nonrevascularized native coronary arteries and those with incomplete revascularization were assessed by segments, following the 17-segment American College of Cardiology/American Heart Association (ACC/AHA) model 17 [25].

2.8.2. Bypass graft failure

Recognizing the appearances of graft complications is an essential part of the radiologist's interpretation of post-bypass CTA imaging.

2.8.2.1. Stenosis and occlusion of the graft

Failures of the graft can occur early or late after CABG surgery.

Early graft failure usually occurs within 1 month after surgery, and its main reason is vessel thrombosis from platelet dysfunction at the site of focal damage of the lining endothelium during surgical intervention. There are other factors that also initiate early venous graft failure

such as the hypercoagulability state of the patient and the high-pressure distension or stretching of the venous graft, with its intrinsically weaker antithrombotic features. These factors contribute for 3–12% occlusion rate within the first post-operative month [26].

The cause of delayed venous graft failure is due to progressive physiopathological changes related to the exposure of their wall to the systemic blood pressure which results in neointimal hyperplasia. By itself neointimal hyperplasia does not produce luminal occlusion or stenosis. But later on it will be the seat for development of atheroma and thrombosis of the venous graft. One year after surgery, the main cause of graft failure is atherosclerosis. The arterial grafts, specifically IMA grafts, are more resistant to formation of atheroma than the venous grafts. However, the main reason for late IMA graft failure is progression of atherosclerotic disease in the native coronary artery distal to the graft anastomosis [26].

Univariate analysis was performed in the study of Esam et al. in 2016 to find out the probable risk factors for graft occlusion such as age (>65 years), post-CABG duration >5 years, hypertension, diabetes, dyslipidemia, smoking, diffuse CAD, and LV dysfunction. Surprisingly, the statistical analysis could not demonstrate any cardiac risk factors which could significantly be associated with graft patency or occlusion [27].

The imaging findings associated with graft stenosis and occlusion can be easily diagnosed by CTA as the presence of calcified, mixed, and noncalcified atherosclerotic plaques. The estimation of the extent and degree of diameter reduction can be easily performed by post-processing images of CTA. Graft occlusion can be easily diagnosed by nonvisualization of the lumen of the graft after revision of the previous grafting surgical report (**Figure 8**).
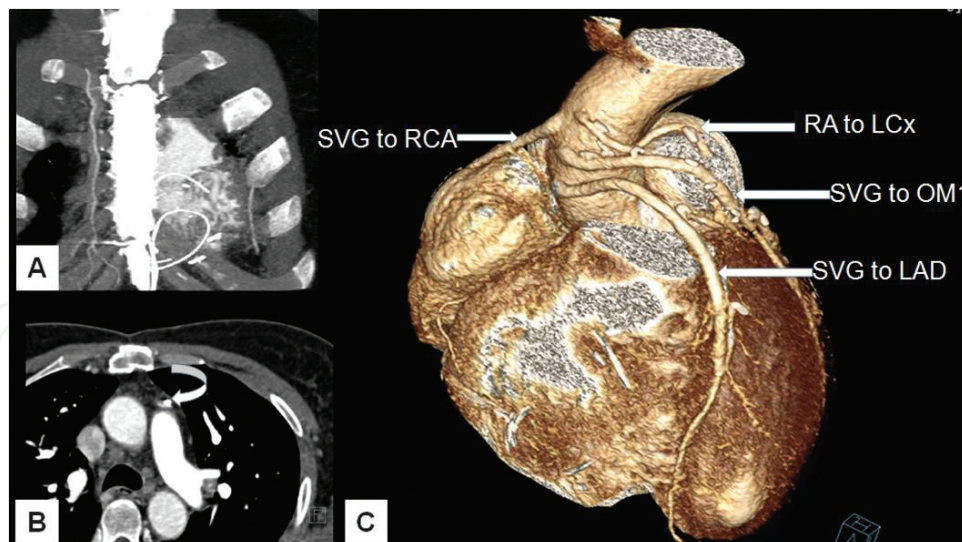
Figure 8. A 72-year-old male patient who was operated 10 years earlier with four grafts: left internal mammary artery graft to left anterior descending artery (LIMA to LAD), saphenous vein graft to right coronary artery (SVG to RCA), radial graft to left circumflex (RA to LCx), and SVG to first obtuse marginal (SVG to OM1). Because of an occlusion of LIMA to LAD graft and typical chest pain, redo-bypass graft surgery was performed 4 years ago with SVG to LAD to revascularize LAD. Post second operation CTA was performed because of atypical chest pain. Carnal (panel A) and axial (panel B) images showed absent LIMA with occlusion of the old LIMA to LAD graft (curved arrow). VRT image (panel C) showed patent all old and new venous grafts, but the arterial graft (RA to LCx) is occluded midway between its origin and distal anastomosis.
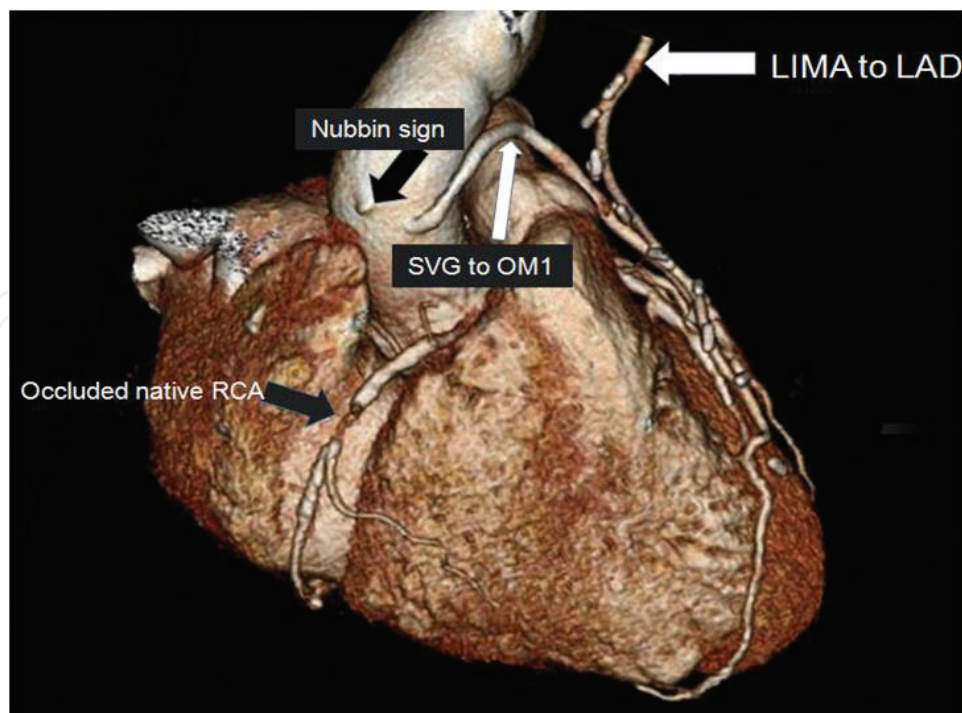
Figure 9. A 65-year-old male patient who underwent left internal mammary artery to left anterior descending artery graft (LIMA to LAD) as well as two venous grafts, saphenous vein graft to right coronary artery (SVG to RCA), and SVG to first obtuse marginal branch (SVG to OM1) 7 years ago. CTA was performed because of recurrence of atypical angina. Volume-rendering images showed that the LIMA to LAD and SVG to OM1 grafts are patent. The image showed the nubbin sign along the right anterolateral ascending aorta, indicating an occluded SVG to RCA. Additionally, occlusion of the native RCA is seen as well.

In many cases of proximal graft occlusion, the most proximal part of an occluded aortocoronary graft fills with contrast, creating a small contrast-filled outpouching from the ascending aorta known as nubbin sign (**Figure 9**). In some cases a "ghost" of the occluded part of the graft may be visible [1].

In some cases, a felt pledget can be seen in the aorta prior to cannulation sites. The holes are closed with stitching or suturing, which may then be reinforced with prosthetic material such as polytetrafluoroethylene (PTFE) sutures to reinforce suture sites and reduce the tearing of vessels. This hemostatic technique is most often used in elderly patients (>80 years old), who have fragile tissue. The use of felt pledgets increases susceptibility to local bacterial seeding. At CT, felt pledgets are depicted as high-attenuation material (**Figure 7**). It is important to distinguish this nonsignificant post-operative finding from the appearance of other significant findings as a calcified atherosclerotic plaque, a contrast leak, a calcified mediastinal lymph node, or pericardial calcification. The atherosclerotic plaques can be differentiated from the felt pledgets as the later are located on the extraluminal surface of the aorta. Differentiating between a felt pledget and a focal contrast leak can be difficult on the post-contrast CT because the CT attenuation of a felt pledget measured in Hounsfield units can be similar to that of contrast-enhanced blood. This difficulty can be resolved with examination of the nonenhanced CT images, on which the felt pledget remains hyperdense [28].

Acute or chronic graft occlusion can sometimes be differentiated by the diameter of the bypass graft. In chronic occlusion, the diameter is usually reduced from scarring, as compared with acute occlusion in which the diameter is usually enlarged. If graft occluded, carefully examine proximal vessel for severe disease or competitive flow.

2.8.2.2. Evaluation of native coronary arteries

In patients who underwent coronary artery bypass grafting, recurrence of symptoms can be due to graft failure or progression of atherosclerosis in the native vessels. While CTA offers excellent accuracy for the detection of bypass graft stenosis or graft occlusion, this test is more limited for evaluating native coronary arteries. The native coronary arteries in patients after bypass grafting are not as easily assessed as are the bypasses themselves, and only a few studies have addressed the combined reading of coronaries and bypasses. The native arteries are very difficult to assess by CT as they often have severe atherosclerosis, including pronounced calcification, and frequently are of small caliber, which makes their evaluation challenging. So if the clinical situation requires assessment of the native coronary artery system only, the value of CTA is limited. However, recent scanner with 128 and 256 MDCT has higher temporal and spatial resolution and may thus allow more reliable assessment of the native coronary system in patients with bypass grafts. There are few studies reporting accuracy of CTA to diagnose stenosis in native ungrafted coronary arteries. Using a 64-MDCT, the reported sensitivity and specificity of CTA in diagnosis of native coronaries were 86–97% and 76–92%, respectively. Despite these results, functional imaging is more practical than CTA in evaluation of the status of the native coronary arteries in patients after coronary bypass surgeries [29].

2.8.2.3. Graft malposition

Malposition of the bypass graft is one of the rare causes of early graft failure. If the graft is too long, it may twist or kink. If the graft is too short, it may stretch, a particular problem in severe chronic obstructive lung disease patients. Also, the aortic connector can also play a role in kinking the bypass graft if the vessel is not supported adequately.

2.8.2.4. Vasospasm of the radial artery graft

One of the very early post-operative radial artery bypass graft failures is vasospasm of the grafted radial artery. The appearance is similar to severe graft stenosis, although the length of the narrow segment is much longer. This can be avoided by the administration of intraoperative alpha-adrenergic blocking agents or post-operative calcium channel blockers which can overcome many cases of graft vasospasm postoperatively. Arterial spasm is not a late complication for graft failure as the patency rate for radial artery grafts is approximately 92% at 10 years, similar to IMA grafts [30].

2.8.2.5. Formation of bypass graft aneurysm

One of the rare complications that can occur after bypass graft surgery is the formation of pseudo or true graft aneurysm.

In the early post-operative period, pseudoaneurysm may be occurred at the anastomosis secondary to infection or tension at these sites, resulting in suture rupture. Late-onset graft aneurysms can be either true or pseudoaneurysms. They are found 5–7 years after surgery and are related to atherosclerotic changes. Graft aneurysms can lead to various complications, including compression on adjacent structures, thrombosis of their lumens, distal embolization of the bypass graft, or the coronaries leading to an acute coronary event and formation of the right atrium or ventricle. One of the risky complications is rupture of the aneurysm leading to massive hemothorax, hemopericardium, or sudden death. Management of graft aneurysm is by surgery however there is no a clear guideline for the critical size of the graft aneurysm before surgical intervention, but a size more than 2 cm has been a cause for concern [4].

2.8.2.6. Formation of pericardial and pleural effusions

Pericardial effusion is a common post-operative complication and can be occurred in about 75% of the patients after CABG surgery. Risk factors for formation of pericardial effusions are post-operative coagulopathy or the use of anticoagulation agents. Pericardial effusions are early complications and occur between 5 and 10 days postoperatively. Most of pericardial effusions are mild and resolve within a month. But in 0.3% of the patients may develop massive pericardial effusion which progresses to cardiac tamponade. Post-CABG surgery pleural effusions are even more common than pericardial effusion and occurred in 89% of the patients in the first week after surgery. These pleural effusions are usually unilateral, mainly left-sided, small in amount, and with no clinical significance [4].

2.8.2.7. Sternal dehiscence and infection

Disruption and infection of median sternotomy wounds are grave complications. It occurs in 0.3–5% of the cases. This problem is associated with a high mortality rate between 14 and 47%.

Diagnosis of sterna dehiscence is usually made clinically; imaging plays an important role to confirm diagnosis. A midline vertical lucency over the sternum of greater than 3 mm is usually abnormal and should raise the suspicion for dehiscence. X-ray examination of the sternum can demonstrate ruptured wires and sternal dehiscence, wire malposition, fracture, and pseudoarthrosis. Displacement of sternal wires can be seen in about 85% of the cases of dehiscence. CT can diagnose normally united sternum by the presence of new bone formation at the sternotomy site without definite bone remodeling in both the anterior and posterior plates. On the other hand, complete sterna nonunion can appear as definite visible sternal separation of both the anterior and posterior plates of the sternum, while incomplete sterna fusion was defined as fusion of one plate and separation of the other.

Risk factors for post-coronary artery bypass graft infection include diabetes mellitus, obesity, complexity of surgery, length of surgical time, and blood transfusion. Three different compartments may be affected by sterna infection: the presternal (cellulitis, sinus tracts, abscess), sternal (osteomyelitis, dehiscence), and retrosternal (mediastinitis, hematoma, abscess). MDCT allows multiplanar reconstruction and windowing, contributing particularly to the evaluation of the sternum. The sagittal plane is useful for determining the disease extent. Sternal wire abnormalities precede clinical detection of dehiscence by a mean of 3 days in 70% of the cases.

CT scan delineates changes in bone configuration, distinguishes insignificant from major infection, and accurately depicts extent of infection. If there is any persistent or recurrent collection, CT-guided needle aspiration can help determine whether a fluid collection is infected or not.

Post-contrast CT scan is important in diagnosis of the extension of infection and help in guidance of treatment. The detection of clear fat planes of the mediastinal structures in CT scan excludes the presence of infection. Mediastinitis can be diagnosed by the presence of diffuse soft tissue infiltrations with or without gas loculi, obliteration of mediastinal fat planes, and formation of hypodense fluid collections. CT is a useful prognostic tool as it can be used for follow-up of patients after medical and surgical management. CT can also help in guidance of percutaneous drainage of intrathoracic abscess or significant fluid collections [31].

2.8.2.8. Noncardiac complications and incidental findings

Although the intent of CTA after CABG surgery is to assess bypass graft patency and surgical complications, incidental findings are also frequently detected. 13.1% of the patients in the immediate post-operative period had unsuspected noncardiac findings, including pulmonary embolism, pulmonary nodules, pneumonia, mucous plugging, and pneumothorax. Therefore, radiologists need to be aware of clinically significant findings with possible life-threatening consequences [32].

2.9. Future researches

CT coronary angiography has high sensitivity and specificity for diagnosis of significant stenosis or occlusion of coronary bypass grafts. However, the functional and clinical significance of these lesions needs further cardiac tests. Further studies are needed to determine which CABG patient may be a suitable candidate for CTA to get the best benefits of coronary revascularization. These functional information could be derived in the future from CTA using mathematically modeled Fractional Flow Reserve CT (FFRCT) which still has not undergone validation among patients after CABG surgery. The current limitations of this technology are the cost nonavailability in most cardiac imaging centers and complexity of the post-processing modeling techniques of coronary physiology to get FFRCT. The added value of FFRCT can make CTA a stand-alone test for evaluation of post-CABG patients and to avoid unnecessary invasive diagnostic tests.

Future studies are also needed to address the cost-effectiveness of different cardiac diagnostic tests and resulting coronary intervention to improve post-operative chest pain and reduce future risk of myocardial infarction and death.

It will take long-term follow-up studies with CTA versus invasive angiography to demonstrate net cost savings in terms of total healthcare expenditures and quality of life years saved as a result of making such interventions.

Future researches may also be needed to explore the potential use of CTA to screen patients for early graft failure immediately following CABG or at different time intervals as identifying candidates for intervention earlier may improve longer-term outcomes. This would require further investigation via a prospective trial that would need to assess patient outcomes in addition to downstream costs and resource utilization.

Subclinical occlusion of the bypass graft may exist for years, because of competitive antegrade or collateral flow; however, CTA does not have the ability to determine the hemodynamic significance of such lesions, which may be unpredictable in the presence of collateral perfusion of the myocardium. So, the assessment of the significance of subclinical occlusion of the graft may require some kind of stress myocardial perfusion by CTA alone or combined with other stress tests.

2.10. Conclusions

CT angiography has a high accuracy for the detection of bypass graft stenosis and occlusion. In recent years, advanced technology of CTA allows cardiovascular imaging physician to evaluate bypass graft patency and malfunction noninvasively with greater confidence. In addition, bypass grafts themselves have a larger caliber than native coronary arteries, and they are subjected to less motion artifacts which favorably influences image quality. Post-contrast CT can also help in diagnosis of other noncoronary complications that may cause post-operative chest pain. Thus, it is very important that every cardiovascular imaging radiologist or cardiologist must be familiar with the different types of coronary bypass grafts, possible early and late post-operative complications, and other incidental imaging findings to maximize the effectiveness of CTA in evaluation of patients after CABG surgery.

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