

Coronary CT Angiography¹

U. Joseph Schoepf, MD
Peter L. Zwerner, MD
Giancarlo Savino, MD
Christopher Herzog, MD
J. Matthias Kerl, BS
Philip Costello, MD

Owing to ongoing technical refinements and intense scientific and clinical evaluations, computed tomography (CT) of the heart has left the research realm and matured into a clinical application that is about to fulfill its promise to replace invasive cardiac catheterization in selected patient populations. CT coronary angiography is technically more challenging than other CT applications owing to the nature of its target, the continuously moving heart. Rapid technical developments in this field require constant adaptation of acquisition protocols. These challenges, however, are in no way insurmountable for users with knowledge of the general CT technique. The intent of this communication is to provide those interested in and involved with coronary CT angiography with a step-by-step “manual” describing the authors’ approach to performing coronary CT angiography. Included are considerations regarding appropriate patient selection, patient medication, radiation protection, contrast enhancement, acquisition and reconstruction parameters, image display and analysis techniques, and the radiology report. The recommendations are based on the authors’ experience, which spans the evolution of multi-detector row CT for cardiac applications, from its beginning to the advent of the most current generations of 64-section and dual-source CT technologies, which they believe herald the entrance of this examination into routine clinical practice.

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¹ From the Department of Radiology (U.J.S., P.L.Z., G.S., C.H., J.M.K., P.C.) and Division of Cardiology, Department of Medicine (U.J.S., P.L.Z.), Medical University of South Carolina, 169 Ashley Ave, Charleston, SC 29425; Department of Radiology, Università Cattolica del Sacro Cuore, Rome, Italy (G.S.); and Department of Radiology, Johann Wolfgang Goethe University, Frankfurt, Germany (C.H.). Received December 30, 2005; revision requested February 24, 2006; revision received March 16; accepted May 2; final version accepted July 6. **Address correspondence to U.J.S.** (e-mail: schoepf@musc.edu).

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With the ongoing evolution of ever faster and more sophisticated multi-detector row computed tomography (CT) technologies, CT of the heart has evolved into an examination that is applied to a broad variety of clinical situations (1). With the advent of the latest iterations of multi-detector CT technology, both the temporal resolution and the spatial resolution of coronary CT angiography (hereafter CT angiography) have improved to a point where the threshold for routine noninvasive assessment of the coronary arteries for atherosclerotic disease may have been crossed (2–10).

Essentials

- Currently, coronary CT angiography seems to be most indicated for improving the diagnosis in patients with an intermediate risk of coronary artery disease. Screening of low-risk individuals and examination of patients with typical chest pain are probably not appropriate.
- Although the increased robustness of the more recently developed scanners allows scanning of patients with higher and more irregular heart rates, use of β -blockers improves diagnostic quality and minimizes radiation exposure at 64-section or lower-section CT.
- For coronary CT angiography, scanning parameters that represent the best possible compromise between diagnostic quality and radiation exposure for individual patients should be chosen.
- Recent developments in injector technology facilitate the use of contrast medium injection protocols that optimize coronary artery enhancement and suppress artifacts at coronary CT angiography.
- In many patients, a diagnosis can be established on the basis of the findings on transverse images and simple secondary reformations; however, the use of advanced visualization methods improves diagnostic accuracy and facilitates evaluation of more challenging cases.

Imaging of the heart has always been technically challenging because of the heart's continuous motion. The development of electrocardiographically (ECG) synchronized multidetector CT scanning and reconstruction techniques (11–13) has yielded fast volume coverage and high spatial and temporal resolution as prerequisites for successful cardiac imaging (14). The exceedingly powerful technology that enables one to perform CT angiography, however, transcends routine CT applications and thus needs to be used in a manner that facilitates optimized results with the lowest degree of invasiveness for the patient. Our experience performing contrast material-enhanced CT angiography has evolved over the years since the introduction of multidetector CT and has encompassed multiple evolutionary steps of this technology. The purpose of this communication is to share our experience with those interested in and involved with CT angiography to facilitate the beneficial application of this examination.

Patient Selection

Patients who may benefit from CT angiography for cardiac evaluations may be classified under several broad categories. These include screening of asymptomatic patients, examination of symptomatic patients, and specialized applications.

Examination of Asymptomatic Patients

The presence of coronary atherosclerosis and the subsequent manifestations of coronary disease exist on a continuum. High plaque burden may exist yet remain asymptomatic and undetectable at conventional testing. The screening of asymptomatic patients for occult coronary disease remains a substantial challenge, and the role of CT angiography in providing added value to traditional risk factors remains to be determined. Standard Framingham risk factors help in identifying groups at low, high, and intermediate risk for future cardiac events. A person with a likelihood of cardiac events of less than 10% per 10 years is considered to be at low risk, while a person with a likelihood of cardiac events of greater than 20% over a 10-year period is consid-

ered to be at high risk. Persons in the intermediate risk group have cardiac event rates between those of the high- and low-risk groups. The asymptomatic patient at low risk according to Framingham criteria is less likely to gain further benefits from additional cardiac testing. In addition, patients in the low-risk group are most likely to have false-positive examination results owing to a low pretest likelihood of disease.

The asymptomatic intermediate-risk group is most likely to benefit from further risk stratification. Forty percent of the general population belong to this group (15), and multidetector CT angiography may contribute to the evaluation of risk in asymptomatic patients. However, the relatively high effective radiation dose equivalent (about 5–20 mSv, depending on sex and acquisition technique) and the use of contrast material make multidetector CT impractical as a general screening tool. There may be a small select group of asymptomatic patients with an exceedingly high Framingham risk score who would benefit from a noninvasive evaluation of coronary plaque burden and morphology, although further research is required to determine the precise role of multidetector CT in the examination of asymptomatic patients. Preoperative screening for coronary artery disease in asymptomatic patients undergoing non-cardiac surgery has been addressed in the guidelines of the American College of Cardiology and the American Heart

Published online before print
10.1148/radiol.2441052145

Radiology 2007; 244:48–63

Abbreviations:

ECG = electrocardiography
LAD = left anterior descending
MIP = maximum intensity projection
MPR = multiplanar reformation
RCA = right coronary artery
3D = three-dimensional

U.J.S. is a medical consultant to Bayer Healthcare (Wayne, NJ), Bracco Diagnostics (Princeton, NJ), GE Medical Systems (Princeton, NJ), Siemens (Malvern, Pa), and TeraRecon (San Mateo, Calif) and receives research support from Bayer Healthcare, Bracco Diagnostics, GE Medical Systems, Medrad (Pittsburgh, Pa), and Siemens. P.C. is a medical consultant to Bracco Diagnostics.

Association. There are several class I recommendations for invasive coronary angiography as part of the preoperative examination of patients suspected or known to have coronary artery disease. Although to our knowledge there is no substantial literature addressing the use of cardiac CT angiography for preoperative screening, in the future, CT angiography could replace the recommended invasive strategies as part of the preoperative evaluation and obviate high-risk cardiac catheterizations in this population. An additional potential use of CT angiography may be the preoperative examination of high-risk patients.

Atypical Chest Pain

Patients commonly present with atypical chest pain (16,17). This results in considerable concern among physicians and patients, who are anxious to exclude a cardiac etiology. Patients identified as having low or intermediate risk on the basis of Framingham parameters who present with atypical chest pain would benefit from a noninvasive test with a high negative predictive value. Multidetector CT angiography may help to rapidly and noninvasively diagnose (Fig 1) or rule out coronary disease in this population. A normal CT angiogram and negative calcium score could obviate invasive cardiac catheterization in a substantial percentage of patients. A large number of referrals to our cardiac imaging center fall into this category, and it is our recommendation that patients who have atypical chest pain and coronary risk factors, with or without equivocal perfusion imaging abnormalities, be considered for CT angiography to aid with management.

Typical Chest Pain

Acute coronary syndromes have been stratified into high, intermediate, and low risk profiles. CT angiography is not recommended for patients presenting to the emergency department with acute coronary syndrome and high risk features, as defined in the American College of Cardiology–American Heart Association guidelines (18). These pa-

tients benefit from an early invasive strategy with expedited cardiac catheterization and revascularization (18). The low-to-intermediate-risk group needs further stratification. This stratification is resource intensive, and patients are frequently admitted to the hospital for a so-called “rule out” of a diagnosis. The use of CT angiography to help discriminate between the intermediate- and low-risk groups holds great promise. A test with a high negative predictive value theoretically would enable the triage of patients who present to the emergency department with chest pain. This would help avoid unnecessary and costly admissions for patients whose presenting symptoms do not have a cardiac etiology.

In addition, it has been documented that 4%–8% of patients who are discharged from the emergency department prove to have cardiac events (19,20). Clinical assessments of non-high-risk patients with traditional clinical parameters lack sensitivity. CT angiography may play a role in the detection of obstructive coronary disease in patients who may be inappropriately discharged from the emergency department. The high spatial resolution and high temporal resolution of multidetector CT have established the capability of this examination to reveal cardiac (Fig 2) as well as noncardiac causes of chest pain and to exclude alternative life-threatening diagnoses such as pulmonary embolus (21) and aortic dissection. The use of CT angiography as a first-line examination for the evaluation of chest pain in the emergency department is currently being explored. The so-called “triple rule out” to evaluate aortic dissection, pulmonary embolus, and acute coronary syndrome with a single test holds great promise, and we expect multidetector CT to become the test of choice for evaluating acute chest pain. We currently use multidetector CT angiography in the appropriate clinical setting to exclude these life-threatening conditions. Owing to the lack of large-scale trials that support the practice of discharging patients from the emergency department solely on the basis of negative CT angiography results, we do not recommend it.

Patient Preparation

Intravenous Access

Intravenous access is preferably established in a cubital vein. An access site in the right arm should be chosen to prevent streak artifacts that arise from high-attenuating contrast mate-

Figure 1

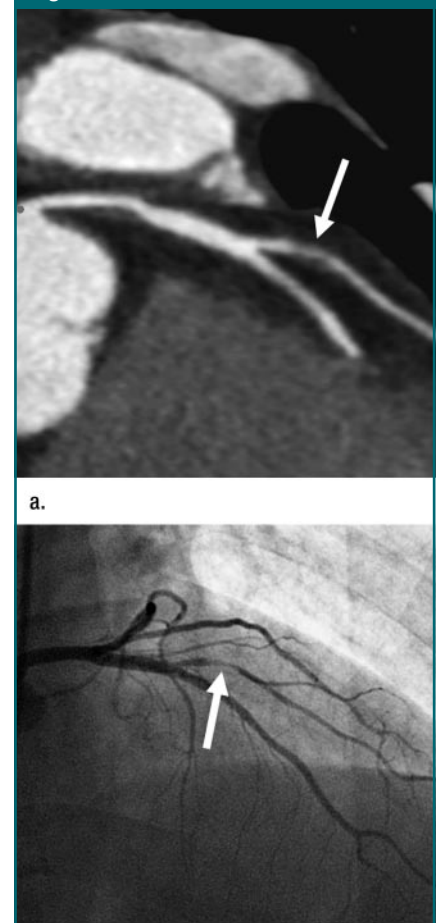
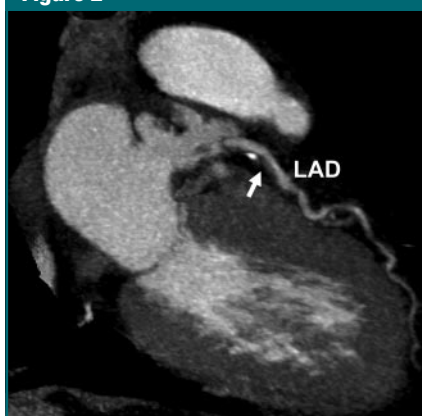


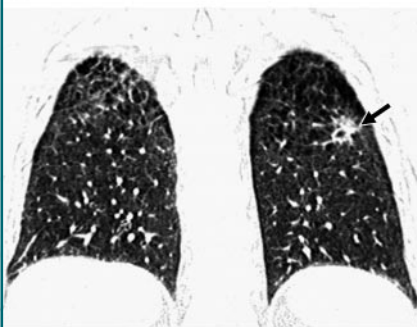
Figure 1: Contrast-enhanced retrospectively ECG-gated 64-section coronary CT angiography in 58-year-old man with dizziness at exertion and risk factors for coronary artery disease. Right anterior oblique views of left coronary artery tree are shown. **(a)** Curved multiplanar reformation (MPR) shows about 60% stenosis (arrow) of the proximal first diagonal branch caused by noncalcified plaque. **(b)** Conventional coronary angiogram findings confirm the presence of the lesion in **(a)** (arrow), which was subsequently treated with stent placement.

rial in the left subclavian vein from interfering with evaluation of the left internal mammary arterial origin—especially if a left internal mammary arterial bypass graft is to be assessed. Owing to the fairly fast injection rates of 5–6 mL/sec, an 18-gauge or larger catheter should be used whenever possible.

Figure 2



a.



b.

Figure 2: Contrast-enhanced retrospectively ECG-gated 64-section coronary CT angiography of entire thorax in 52-year-old man with smoking history of 25 pack-years who presented to the emergency department with acute chest pain. **(a)** Maximum intensity projection (MIP) in a left anterior oblique perspective of the left anterior descending (LAD) coronary artery shows atherosclerotic plaque (arrow) in the inferior anteromedial wall. The plaque causes about 50% stenosis and consists of noncalcified tissue adjacent to a calcified nodule. **(b)** Coronal lung-window reconstructions of the entire chest reveal panlobular emphysema with upper lobe predominance and incidental squamous cell carcinoma (arrow) of the left upper lobe of the lung.

Patient Positioning and ECG Lead Attachment

According to our institutional preference, we ordinarily position the patient in the supine, feet-first position in the scanner gantry. Ordinarily, a three-lead ECG is used for cardiac CT. A stable reading of the patient's ECG with clear identification of the QRS complex is a prerequisite for successful retrospective ECG gating. To establish good electrical contact and prevent lead detachment with consecutive signal loss during scan acquisition, using additional conductive gel and shaving hairy attachment sites are recommended.

Heart Rate Control

Heart rate control for improving image quality.—For a variety of reasons, slow heart rates are highly desirable for cardiac CT performed with four- to 64-section scanners. Slow heart rates relatively prolong those cardiac phases with little cardiac motion—namely, end-diastolic relaxation and end-systolic contraction—so a reconstruction window of a defined duration can be safely set within these phases without including preceding or consecutive portions of the heart cycle that involve motion. In our practice, we aim for a target heart rate of 50–65 beats per minute (22,23) for examinations performed with 64-section CT scanners. However, with dual-source CT scanners, the newest generation of CT machines (9,10), heart rate control might not be necessary anymore: In our experience, dual-source CT allows scanning of patients with high (ie, 120–140 beats per minute) and irregular heart rates and yields diagnostic results. Accordingly, we have abandoned the use of rate-controlling agents with dual-source CT.

Heart rate control for single-segment reconstruction.—As a direct consequence of improved temporal resolution, image reconstruction can be ordinarily performed by using single-segment reconstruction—that is, on the basis of the projections acquired during a single heart beat. The single-segment reconstruction enabled by slow heart rates has theoretic advantages over multisegment reconstruction algorithms,

which can be implemented on all currently available cardiac CT scanners. At multisegment reconstruction, the projections needed to form a single section are sampled over two to four consecutive heart beats (14). While this approach improves temporal resolution, which is beneficial for faster heart rates, it requires that the heart follow the exact same motion pattern for each of the two to four heart beats that occur during projection sampling for reconstruction of a single section. This is unreasonable to expect, however, given the variability of cardiac motion patterns seen under even physiologic conditions. Spatial inconsistencies within the data inevitably occur with use of multisegment reconstruction. In our practice, we strive to avoid using multisegment reconstruction algorithms by appropriately reducing the heart rate and use it exclusively in patients with heart rates higher than 80 beats per minute, above which, in our experience, the benefits of improved temporal resolution outweigh the risk of spatial inconsistency (24).

Heart rate control for radiation protection.—For generations of CT scanners up to 64-section CT units, heart rate control has been directly related to the patient's radiation exposure at cardiac CT. Substantial dose savings can be realized with ECG-gated dose modulation (ie, ECG pulsing) (14,25). With this approach, the nominal tube output is applied only during the particular phase of the cardiac cycle at which images are most likely to be reconstructed (Fig 3). During the rest of the cardiac cycle, the tube output is reduced. However, use of ECG-gated dose modulation is limited to patients with slow and steady heart rates, in whom the optimal time point for image reconstruction predictably occurs during diastole (Fig 3). At faster heart rates, ECG-gated dose modulation with use of four- to 64-section CT scanners increasingly loses its efficacy as the period of reduced tube output becomes progressively shorter relative to the cardiac cycle. It is more important that with faster heart rates, the optimal time point for image reconstruction becomes more difficult to predict and in the case of 64-section CT

frequently occurs during the end-systolic phase of total myocardial contraction (26) (Fig 4). Since with ECG-gated dose modulation the radiation level is typically reduced during systole, diagnostic quality will inevitably be compromised during image reconstruction, so the use of ECG-gated dose modulation is not recommended for patients with faster heart rates. Thus, heart rate control has become a crucial factor in the endeavor to keep the radiation exposure at 64- or lower-section CT within reasonable limits.

In our practice, we use ECG-gated dose modulation in patients with steady heart rates lower than 65 beats per minute. Until recently, we believed that for patients with faster and more irregular heart rates (Fig 4), ECG-gated dose modulation limited our options with regard to selecting the optimal reconstruction time point too much to recommend its general use. Conversely, with dual-source CT, we now routinely use ECG-gated dose modulation in every patient since—owing to the temporal resolution of 83 msec—ECG-gated dose modulation can be more aggressively and liberally applied (9,10,27) with substantial reductions in radiation dose.

Practical aspects of heart rate control.—In our practice, we routinely use an intravenous β -blocker (metoprolol tartrate, Lopressor; Novartis, East Hanover, NJ) to control our patients' heart rate, with very satisfactory results and without complications to date. Metoprolol tartrate is commonly used and readily available. β_1 -adrenoreceptor antagonists' selectivity minimizes bronchospasm. Other β -blockers are likely to have similar effects on heart rate. Contraindications to the use of β -blockers include severe chronic obstructive pulmonary disease, asthma, sensitivity to β -blockers, second- or third-degree heart block, and hypotension (systolic blood pressure < 100 mm Hg). In the absence of contraindications, we inject an initial bolus of 5 mg of metoprolol tartrate with the patient already on the scanner table and begin preparations for scanning. If the ventricular response is unsatisfactory—that is, if the average heart rate remains

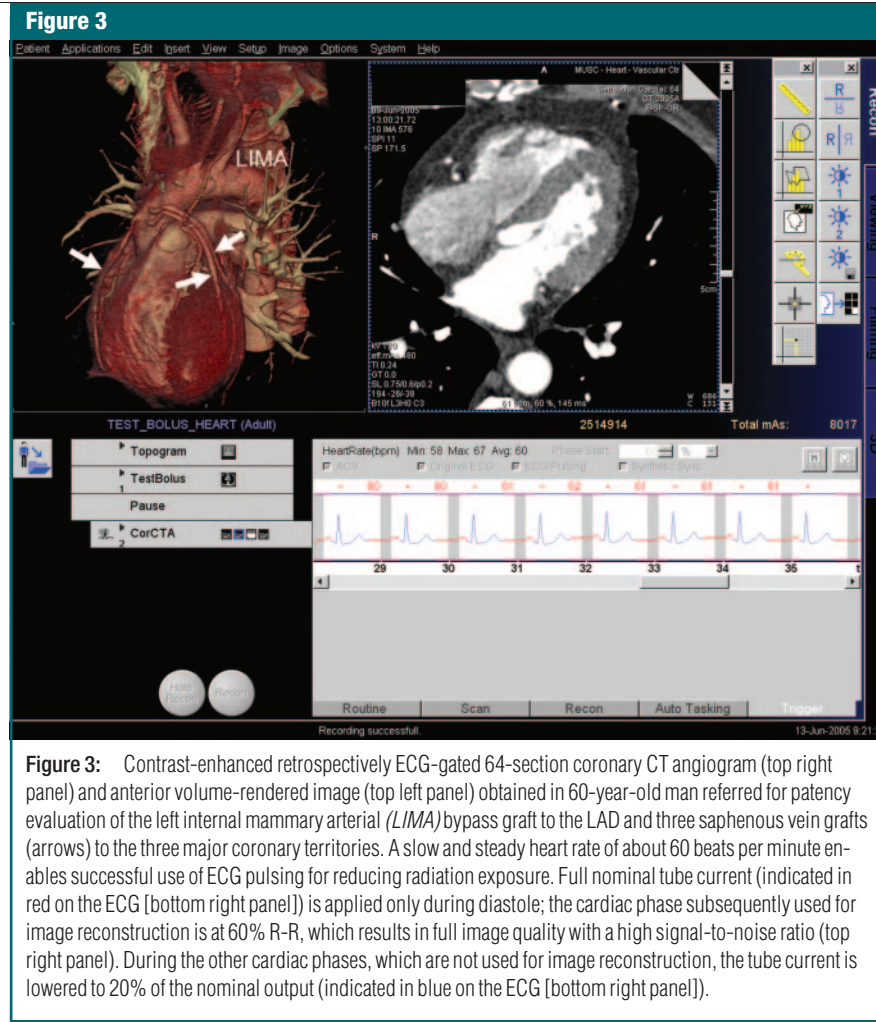


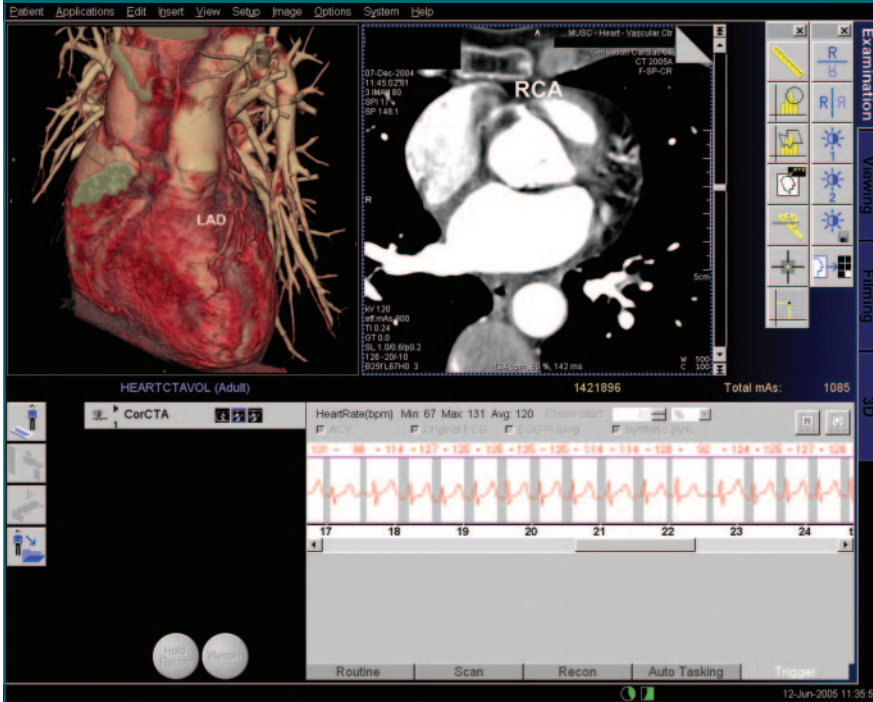
Figure 3: Contrast-enhanced retrospectively ECG-gated 64-section coronary CT angiogram (top right panel) and anterior volume-rendered image (top left panel) obtained in 60-year-old man referred for patency evaluation of the left internal mammary arterial (LIMA) bypass graft to the LAD and three saphenous vein grafts (arrows) to the three major coronary territories. A slow and steady heart rate of about 60 beats per minute enables successful use of ECG pulsing for reducing radiation exposure. Full nominal tube current (indicated in red on the ECG [bottom right panel]) is applied only during diastole; the cardiac phase subsequently used for image reconstruction is at 60% R-R, which results in full image quality with a high signal-to-noise ratio (top right panel). During the other cardiac phases, which are not used for image reconstruction, the tube current is lowered to 20% of the nominal output (indicated in blue on the ECG [bottom right panel]).

higher than 70 beats per minute—we inject up to two additional doses (maximum, 15 mg) of metoprolol tartrate. After administering three doses, we commence scanning, regardless of the heart rate, which is eventually achieved after β -blocker administration. While there are many important reasons why slow heart rates are preferable (discussed earlier), the increased robustness of the current generation of 64-section CT scanners enables the acquisition of diagnostic images even in patients with fairly fast and irregular heart rates (Fig 4).

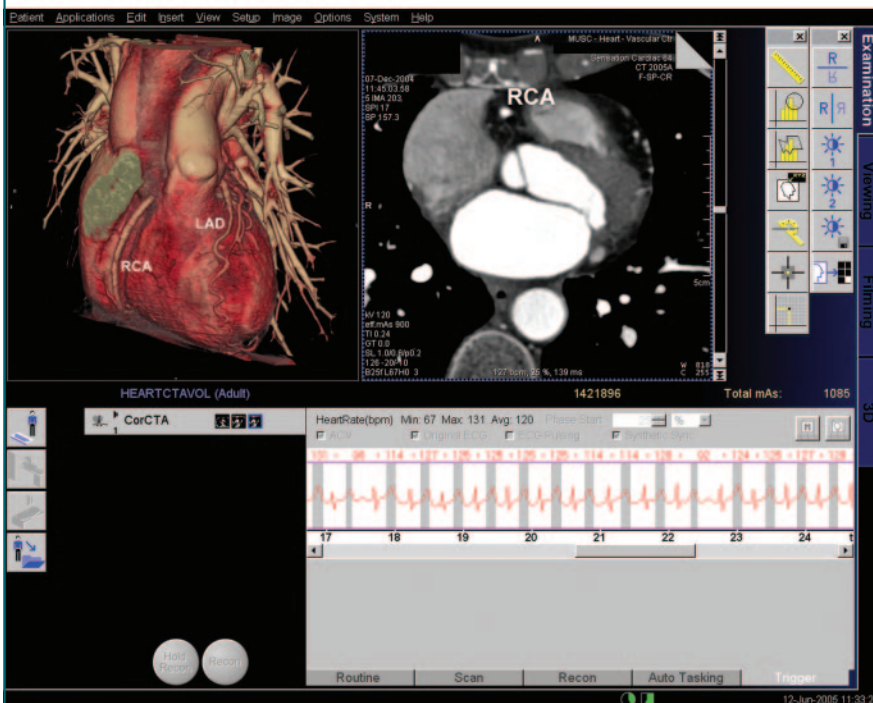
Oral administration of β -blockers—which, compared with our intravenous protocol exerts higher demands on operational logistics—is an alternative means of controlling the heart rate. If oral administration is preferred, the

regimen ideally should be commenced the night before scanning (28), with an initial dose of 50–100 mg of metoprolol tartrate. Thirty to 60 minutes before scanning, another oral dose is given and followed by a third dose in the absence of an adequate ventricular response. There is less experience with alternative rate-controlling medications. However, if there are contraindications to the use of β agonists (discussed earlier), an attempt with calcium channel blockers may be worthwhile. Calcium channel blockers can be administered intravenously (diltiazem, 0.25 mg per kilogram of body weight [up to 25 mg total], Cardizem Monovial; Hoechst Marion Roussel, Kansas City, Mo) or in an oral regimen of 30 mg of regular-release diltiazem (Cardizem; Biovail, Toronto, Ontario, Canada).

Figure 4



a.



b.

Figure 4: Contrast-enhanced retrospectively ECG-gated 64-section transverse CT angiograms (top right panels) and frontal volume-rendered images (top left panels) obtained in 70-year-old woman referred for equivocal perfusion abnormalities at cardiac single photon emission CT. Owing to her fast and irregular heart rate of approximately 120 beats per minute (bottom right panel), the optimal reconstruction window cannot be predicted reliably and ECG pulsing is not used. **(a)** Unlike in the patient in Figure 3, in whom the optimal reconstruction window is predictably determined during diastole, in this patient image reconstruction at 60% R-R results in considerable cardiac motion, which blurs the right coronary artery (RCA) on the transverse image (top right panel) and prevents visualization of this vessel on the frontal volume-rendered image (top left panel); the LAD is contorted. However, because the full tube current is maintained throughout scanning (indicated in red on the ECG [bottom right panel]), flexibility is maintained to reconstruct data during any phase of the cardiac cycle. **(b)** Subsequent reconstruction of the same data set during full systolic contraction at 25% R-R results in a nearly motion-free transverse image (top right panel), which enables clear display of the LAD and RCA on the frontal volume-rendered image (top left panel).

Nitroglycerin

To our knowledge, no systematic studies are available to support the use of nitroglycerin in the context of cardiac CT. In theory, however, one may be able to administer nitroglycerin to dilate the coronary vessels for better visualization and to suppress coronary artery spasms that may mimic stenosis at CT angiography, especially in younger individuals. With this rationale, we administer a 0.4-mg nitroglycerin tablet (Nitro-Quick; Ethex, St Louis, Mo) sublingually 2 minutes before scanning in patients referred for CT angiography with suspected coronary artery disease. Sublingual spray can be used alternatively. Contraindications to nitroglycerin use include hypotension, early myocardial infarction, severe anemia, increased intracranial pressure, and known hypersensitivity to nitroglycerin. We also do not give nitroglycerin to patients who have recently taken nitrate-based medication for erectile dysfunction because of the potential for hypotension-induced syncope or near-syncope episodes.

Patient Medication for Cardiac CT: Safety Aspects

In our institution, all medications used in the context of cardiac CT are routinely administered by dedicated radiol-

ogy nursing staff. Our nursing protocol mandates that in all patients who receive any type of imaging study–related medication, blood pressure measurements are performed before the administration of the first drug, as well as after scanning (inpatients) or after recovery prior to discharge (outpatients). All outpatients who receive study-related medication are monitored (ie, kept in the waiting area) for 30 minutes after scanning. Patients must not operate machinery (eg, drive) for 3 hours after the intravenous administration of 10 mg or more of metoprolol tartrate. Owing to our observance of this protocol, despite our high volume of cardiac CT examinations, we have not experienced adverse events, except in rare cases of transient hypotension that warranted observation for more than 30 minutes.

Scanning Parameters

Gantry Rotation Speed and Collimated Section Width

At CT angiography, the target anatomy is minute, tortuous, and moving rapidly. Accordingly, as a universal rule that applies to multidetector CT scanners from all manufacturers, for the optimal performance of CT angiography, one can never obtain sections that are too thin or rotate too fast. Thus, at CT angiogra-

phy, regardless of the scanner used, the thinnest possible collimation and the fastest gantry rotation time should be chosen. An exception is the rare situation in which the patient's heart rate is so slow (typically <50 beats per minute) that use of a somewhat slower gantry rotation with slower pitch is required to avoid gaps in the acquired data set (29).

Calcium Scoring

In our practice, all CT angiography examinations performed for suspicion of atherosclerotic disease, except those performed in patients with known bypasses or coronary artery stents and in patients examined in the context of ablation therapy for cardiac arrhythmia, are preceded by a nonenhanced ECG-gated calcium-scoring study. With this approach, we obtain a cursory impression of the coronary artery plaque burden; however, this information is not used to exclude patients with high amounts of coronary artery calcium from contrast-enhanced CT angiography (to be discussed). Calcium, if present, is quantified by using Agatston, volume, and mass scores (30), and the results are included in the radiology report (to be discussed). The calcium-scoring scan acquisition helps accustom the patient to the scanning procedure and breath-hold commands. This acquisition also provides the technologist with suitable landmarks for planning the z-axis extension of the scan to encompass the entire coronary tree. If no calcium scoring is performed, the level of the tracheal carina based on the scout (range-planning) view is used as the cranial landmark for determining the scanning volume. The caudal extension is more difficult to determine, and our technologists—depending on their level of experience—ordinarily include a moderate safety margin to ensure complete coverage of the heart.

Tube Current and Voltage

Issuing general recommendations for selection of tube current settings is challenging, as the appropriate tube current level depends on several scanner-specific variables, such as the collimated section width and the gantry rotation

Figure 5

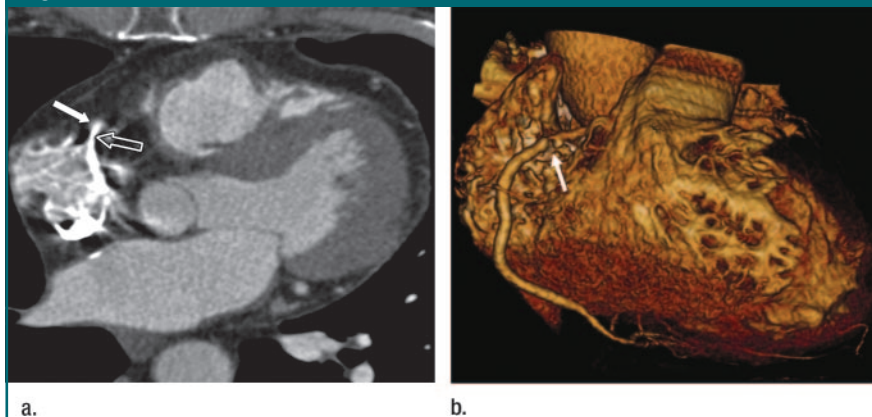


Figure 5: Contrast-enhanced retrospectively ECG-gated coronary CT angiography performed without saline chasing technique. On (a) transverse section and (b) volume-rendered image seen from left anterior oblique perspective, a streak artifact emanating from high-attenuating contrast material in the right heart (open arrow in a) overlies the RCA and causes artifactual stenosis (solid arrow) of the proximal RCA.

speed. As with all CT applications, the ALARA (as low as reasonably achievable) principle applies. This principle calls for patient-specific adjustment of scanner settings to the patient's body habitus so that the lowest possible tube current setting that still results in a diagnostic study can be chosen. When scanning normal-size adults for suspicion of coronary artery disease by using a 64-section CT scanner with 0.6-mm collimation and 330-msec gantry rotation, we ordinarily adjust the tube current to 750–800 mAs (effective) and always use all means available to reduce the patient's exposure to radiation (ie, ECG-pulsing, discussed earlier). With dual-source CT, scanning parameters of 120 kV per tube with a current of 560 mA and use of anatomic tube current modulation are ordinarily chosen. Usually the gantry rotation time is set to 330 msec and the pitch ranges from 0.20 to 0.43, depending on the heart rate.

Because the iodine absorption of x-rays is inversely proportional to the tube potential, very high tube voltage settings (ie, 140 kV) are generally not recommended for contrast-enhanced CT angiography. When we scan normal-size or larger adults for suspicion of coronary artery disease, we ordinarily use a tube voltage of 120 kV. Substantial dose savings can be realized by lowering the tube voltage to 100 or 80 kV, with increases in the level of vascular attenuation. Thus, in our experience, in slim adults, the tube voltage can be safely lowered to 100 kV with very satisfactory results. Similarly, we routinely use 100 or 80 kV, depending on the size of the patient, when performing cardiac CT in adolescent or pediatric patients for suspicion of coronary artery anomalies or other congenital cardiovascular disorders (31).

Imaging Obese Patients

Obese patients pose a substantial challenge for noninvasive CT angiography, as the high level of image noise degrades both spatial and contrast resolution such that the evaluation of small vessels and noncalcified atherosclerotic changes can be dramatically impaired. In such patients, to maximize the available tube cur-

Figure 6

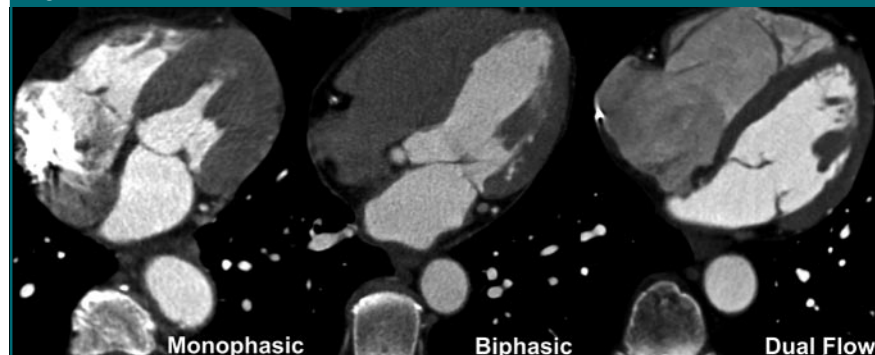


Figure 6: Contrast-enhanced retrospectively ECG-gated transverse coronary CT angiograms obtained at the level of the right atrium in three patients. Left: Monophasic injection of iodine-based contrast material results in high-attenuating streak artifacts in the right heart. Middle: With biphasic injection of the iodine-based agent performed with a saline chasing technique, residual contrast material is flushed from the right heart and artifacts are avoided; however, the right cardiac chambers can no longer be assessed. Right: With triphasic injection performed by using simultaneous dual flow from two syringes, a mixture of contrast material and saline is administered during the second injection phase. This produces sufficient enhancement for assessment of the right heart, while streak artifacts from high-attenuating contrast material generally are avoided.

Figure 7

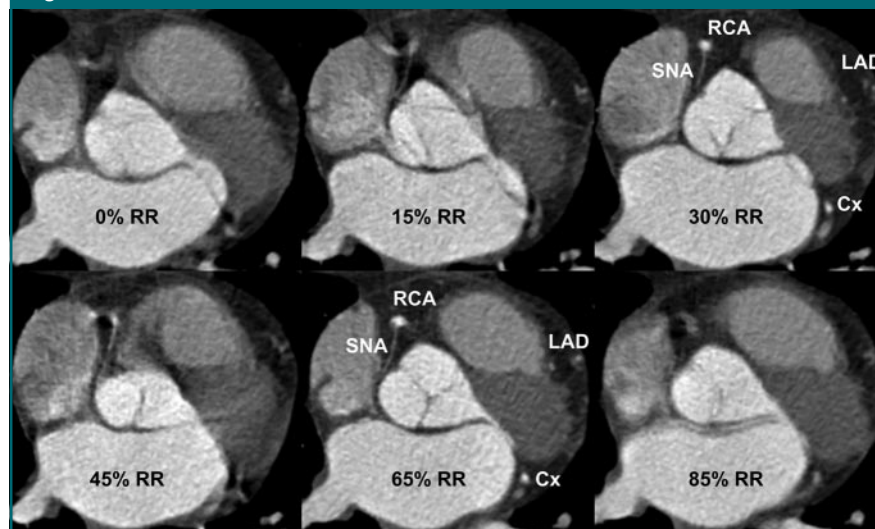


Figure 7: Contrast-enhanced retrospectively ECG-gated coronary CT angiograms. A preview function was used to identify the most suitable cardiac phase for image reconstruction. Six representative transverse sections were reconstructed, at the same z-axis position at the level of the aortic valve, from a series of 20 reconstructions at different R-R positions in 5% increments (0%–95% R-R) to encompass the entire cardiac cycle. Image reconstructions performed during full cardiac contraction at end systole (30% R-R) and during full relaxation at end diastole (65% R-R) are suitable to sufficiently suppress cardiac motion and enable clear assessment of the LAD, circumflex artery (Cx), RCA, and sinus node artery (SNA) (second branch of the RCA). These vessels are blurred during the other phases of the cardiac cycle.

rent, we use the landmarks determined by using the calcium score (discussed earlier) to keep the scanning range as short as possible. According to the consider-

ations outlined above, we do not increase the tube voltage. Another option is the use of a somewhat slower gantry rotation speed, which may be helpful in enhancing

Figure 8

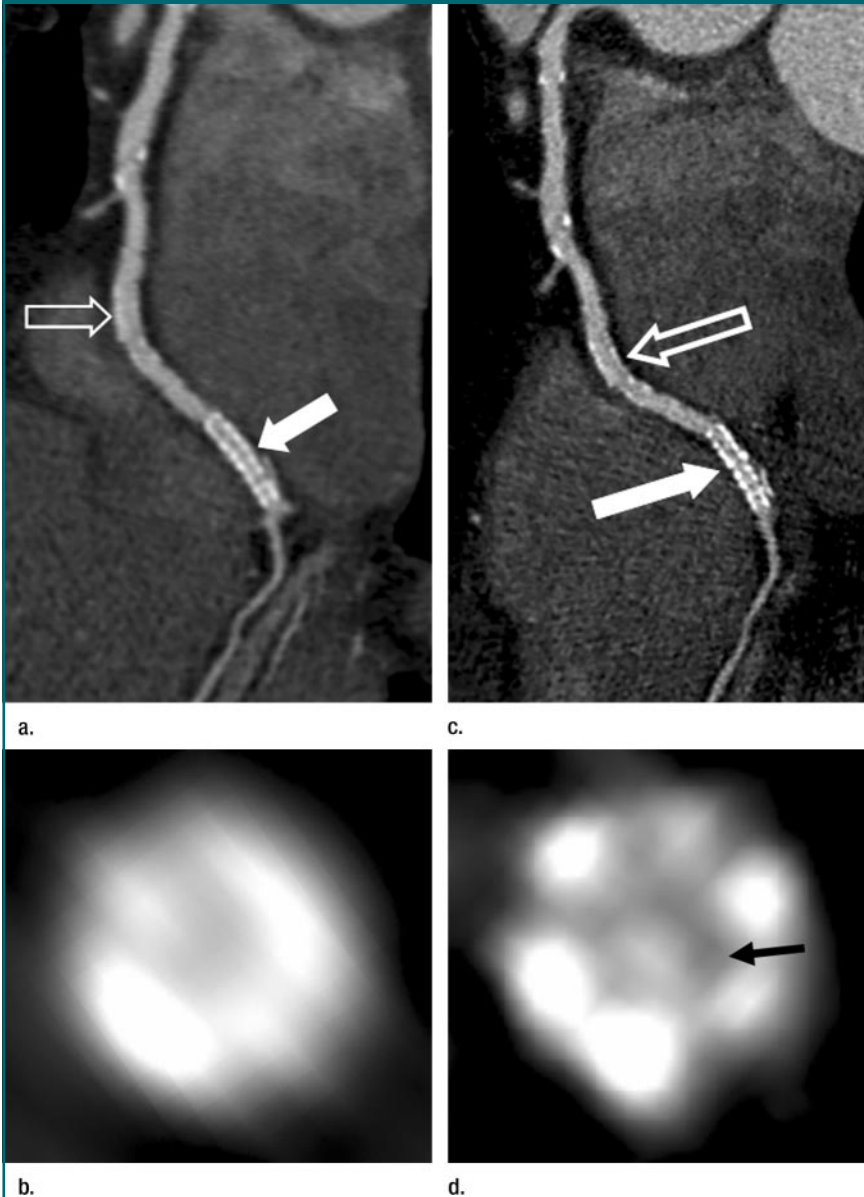


Figure 8: Contrast-enhanced retrospectively ECG-gated 64-section coronary CT angiography in 59-year-old man referred for noninvasive assessment of coronary artery stent patency. Reconstructions of the data set with (a, b) a routine coronary CT angiography algorithm and (c, d) a more edge-enhancing algorithm dedicated to assessment of the coronary artery stents and segments with severe calcification are shown.

(a, c) Curved MPRs show two coronary artery stents in the distal RCA. (b, d) Oblique MPRs perpendicular to the centerline of the vessel are reconstructed at the level of the distal stent. The proximal stent (open arrow in a and c) can be readily assessed with both reconstruction techniques owing to its filamentous strut structure. The high-attenuating struts of the more distal bare metal stent (solid arrow in a and c) cause excessive streak artifacts at routine reconstruction (a and b) such that patency and areas of intimal hyperplasia, seen as hypointense areas on the inside of the stent (arrow in d), can be appreciated only with use of the dedicated reconstruction algorithm (c and d).

the photon flux and improving the signal-to-noise ratio at CT angiography. Last, the use of contrast media with the highest available iodine concentration and faster flow rates may help to compensate for the increased levels of image noise that limit contrast resolution at thin-section CT angiography. In our initial experience, owing to the two x-ray tubes, dual-source CT is considerably better suited than single-source CT for suppressing image noise in obese patients. With dual-source CT technology, a reduction in gantry rotation speed is generally not necessary. Rather, a heart rate range that is lower than the patient's actual heart rate, which results in an artificially lower table speed and an accumulation of the radiation dose to suppress image noise, can be selected.

Contrast Enhancement

Level of Enhancement

High and consistent vascular enhancement within the vessel lumen is a prerequisite for successful CT angiography. Adequate enhancement is needed to visualize the vessel wall and the small side branches of the coronary tree. In addition, high and homogeneous enhancement serves as the basis for threshold-dependent three-dimensional (3D) visualization techniques. To achieve the desired high vascular enhancement, we use a high concentration of nonionic contrast media (7), 350–370 mg of iodine per milliliter, with a fast injection rate of 5 mL/sec (64-section CT) or 6 mL/sec (dual-source CT). It has been argued that exceedingly high intraluminal contrast may interfere with the detection of calcified atherosclerotic plaque (32). According to our experience, this pitfall can be easily avoided by appropriately adjusting the window center (to ≈ 100 HU) and window width (to ≈ 700 HU) according to the level of enhancement achieved in the individual patient.

Saline Chasing Technique

Substantial scientific effort is currently directed toward understanding and optimizing the contrast material dynamics

at CT angiography (33,34). The insights gained from ongoing investigations are continuously being implemented into commercially available automated injectors. One such implementation that has become important in CT angiography is the use of a saline chaser enabled by dual-syringe injection systems (35). The aim in using a saline chaser is to better use the injected contrast media by prolonging the plateau phase of contrast enhancement. It is more important that using a saline chaser reduces the occurrence of streak artifacts from high-attenuating contrast media in the superior vena cava and the right-sided heart chambers. At CT angiography, such streak artifacts have the potential to limit the evaluation of the RCA, and they may simulate stenosis—especially at two-dimensional and 3D image post-processing (Fig 5). However, the occurrence of streak artifacts may be reduced or entirely avoided if, at the time of image acquisition, the contrast medium is flushed from the right heart by using a saline chaser technique (Fig 6).

On the other hand, a complete void of contrast in the right side of the heart is undesirable because it will preclude right-heart analysis. We aim at improving right-sided heart visualization by using three injection phases: The initial iodine-based contrast material bolus is followed by the administration of a saline–contrast medium mixture by means of simultaneous injection from both syringes (Dual Flow Technology, Medrad, Pittsburgh, Pa) and a final saline chaser (to be discussed). This strategy yields sufficient enhancement for assessment of the right side of the heart (Fig 6) for detection of thrombo-emboli, tumors, and other anomalies, while the streak artifacts generated from high-attenuating contrast material are generally avoided (36). Should this triphasic approach prove too cumbersome, one can use a biphasic protocol in which the iodine-based contrast material is administered first and followed by the saline chaser, without injection of the contrast medium–saline mixture (to be discussed). The biphasic protocol has worked well for us in the past, although it may render the right-sided heart structures elusive.

Figure 9

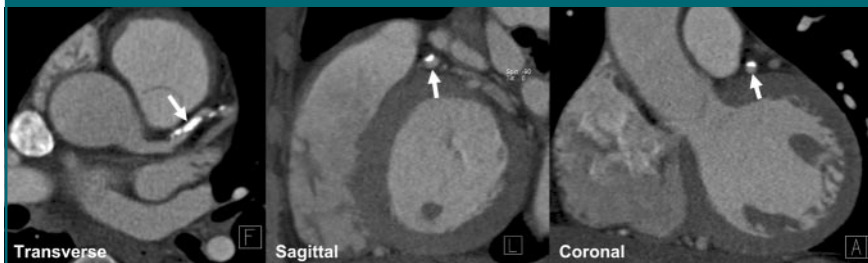


Figure 9: Contrast-enhanced retrospectively ECG-gated 64-section coronary CT angiograms obtained in 49-year-old man who presented to the emergency department with acute chest pain. Severe calcifications (arrow) are seen in the LAD, and on the transverse section they appear to obliterate the vessel lumen. However, MPRs obtained in the sagittal (middle) and coronal (right) planes enable better appreciation of the eccentric location of the calcified plaque in the anterocranial vessel wall of the LAD. The plaque is causing mild stenosis at this location, but most of the vessel lumen is patent.

Contrast Enhancement Protocol

In our practice, the individual scanning delay time is determined by using a dual-syringe injector (Stellant D, Medrad) to inject a 20-mL contrast media test bolus at 5 mL/sec (64-section CT) or 6 mL/sec (dual-source CT), followed by 50 mL of saline. Repeated scanning in 2-second intervals at the same z-axis position at the level of the aortic root is performed to monitor the arrival and passage of the test bolus. The peak time of test bolus–induced enhancement is used as the delay time. We believe that using a test bolus gives us slightly more control over the contrast material dynamics, with more consistent scan acquisition during peak enhancement. However, an approach based on automated bolus triggering at a predetermined attenuation level (eg, 150 HU) within the ascending aorta will also yield acceptable results in the majority of patients. The contrast material volume (V , in milliliters) actually used to acquire the coronary CT angiogram is individually computed according to the formula $V = s \cdot 5$ (for 64-section CT) or $s \cdot 6$ (for dual-source CT), where s is the scanning time. Thus, a typical 64-section CT angiography examination of about 12 seconds duration requires 60 mL of 350–370 mg of iodine per milliliter contrast media.

The injector is preprogrammed to deliver 50 mL of a 30% contrast medium–70% saline mixture during the second phase of injection and then a final 30–

50-mL saline chaser, all of which is injected at 5 mL/sec (for 64-section CT) or 6 mL/sec (for dual-source CT). Thus, with use of a 64-section CT scanner and a typical scanning time of 10–15 seconds, the total volume of contrast material administered at CT angiography—including the test bolus—is 85–110 mL. With dual-source CT, contrast material volumes generally are lower owing to the shorter scanning duration.

Image Reconstruction

Single-Segment versus Multisegment Reconstruction

For considerations regarding the use of single-segment versus multisegment reconstruction, one can review our discussion of heart rate control presented earlier in this article. In general, we avoid using multisegment reconstruction in patients with heart rates lower than 80 beats per minute.

Choosing the Optimal Reconstruction Window

For assessment of cardiac morphology, a phase with minimal cardiac motion is preferably chosen for placement of the image reconstruction window. To determine the starting point of the reconstruction window within the cardiac cycle, absolute and relative approaches (8) are available with most cardiac CT scanners. With an absolute approach, each image reconstruction window is

set during the cardiac cycle with a predefined temporal distance (eg, 400 msec) before or after an R peak in the ECG. With a relative approach, the starting point of the image reconstruction window is defined as a certain percentage (eg, 60%) of the duration of the cardiac cycle. We use the relative percentage-based approach for 64-section CT and the absolute approach for dual-source CT. If available, a preview function is preferably used to determine the optimal reconstruction phase with the least cardiac motion. Typically, the preview series consists of 20 images (Fig 7) reconstructed at 20 different R-R positions in 5% increments (0%–95% R-R) at the same z-axis position at the midlevel of the heart. The phase that depicts the fewest motion artifacts in both the left coronary artery and the RCA systems is chosen for image reconstruction. In cases in which the right and left coronary arteries have diverging motion patterns, more than one reconstruction is performed for optimized visualization of both arterial systems.

If a preview function is not available, a first image reconstruction of the data set can be performed at 60% R-R (Figs 3, 7). This reconstruction has been shown to yield diagnostic image quality in most patients (37), especially at slower regular heart rates. With the improved temporal resolution of the newer-generation 64-section scanners, late systole with total cardiac contraction (ie, 30% R-R) has emerged as a second suitable time point for image reconstruction (Figs 4, 7), when cardiac motion is minimal. In our experience, image reconstruction during late systole yields diagnostic results in most patients with a faster heart rate and is especially well suited for visualization of the RCA (Fig 4).

Reconstruction Parameters

Field of view.—To maximize spatial resolution, the smallest possible field of view that encompasses the entire anatomy of the heart should be chosen for image reconstruction at CT angiography. In addition, for each CT angiography examination, we perform a full-field-of-view reconstruction of the en-

Figure 10

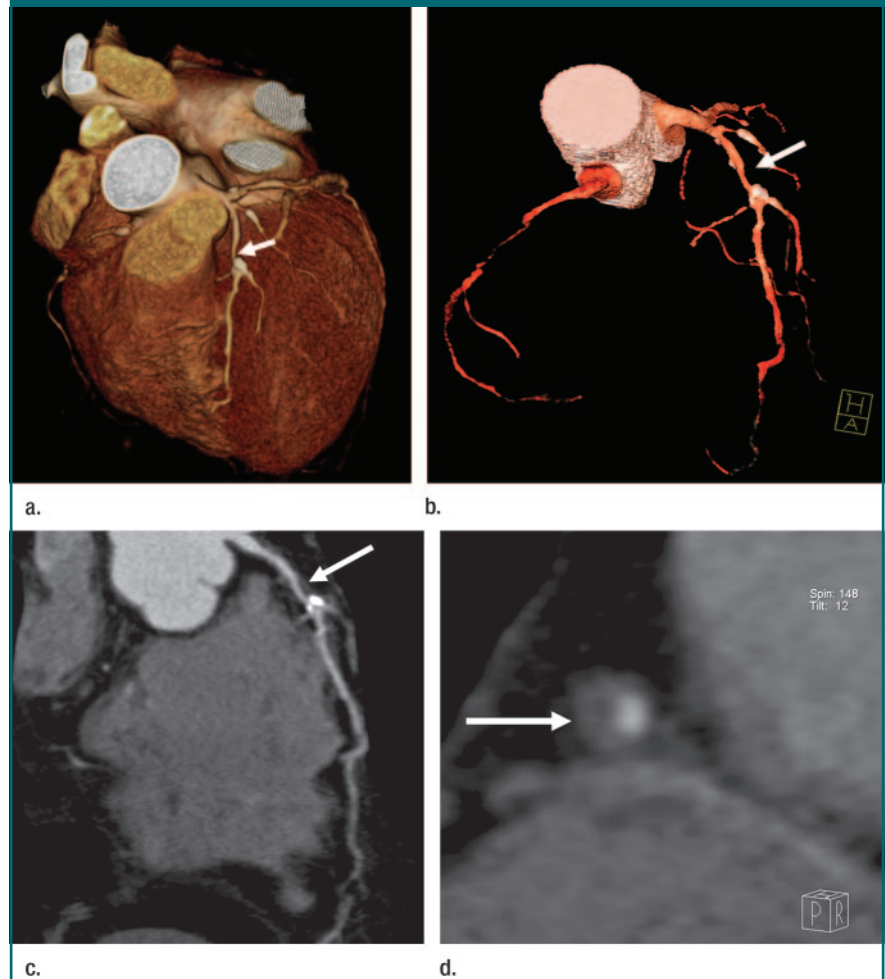


Figure 10: Contrast-enhanced retrospectively ECG-gated 64-section CT angiography in 55-year-old man with atypical chest pain and risk factors for coronary artery disease. The work flow of coronary CT angiographic analysis with dedicated visualization platforms is shown. **(a–c)** CT angiograms reveal moderate stenosis (arrow) of the proximal LAD due to a mixed, partially noncalcified plaque. **(a)** Postprocessing consists of automated sculpting of the chest wall to enable an unobstructed view of the heart, which is depicted as a volume rendering from the right anterior oblique–cranial perspective. **(b)** After placement of a seed point, extraction of the coronary arteries from the contrast-enhanced data set is performed. **(c)** The extracted coronary artery is depicted on an automatically generated MPR, which facilitates intuitive visualization of the entire vessel. **(d)** Defining the centerline of the LAD enables reconstruction of cross sections in planes orthogonal to the vessel axis, which facilitates assessment of the location and morphology of the noncalcified plaque component (arrow) (Fig 10 continues).

tire chest along the acquired z-axis volume with 3-mm section thickness and a lung algorithm to assess for concurrent lung abnormalities. For specialized applications such as triple rule out (Fig 2) scanning, we perform the two reconstructions described above and a third reconstruction by using 1-mm section thickness, a vascular algorithm,

and a field of view that encompasses the entire chest to evaluate for vascular abnormalities of the pulmonary circulation and the thoracic aorta.

Section thickness.—Generally, to avoid artifacts, thin-section multidetector CT data should be reconstructed with a section width that is slightly wider than the collimated section width

Figure 10 (continued)

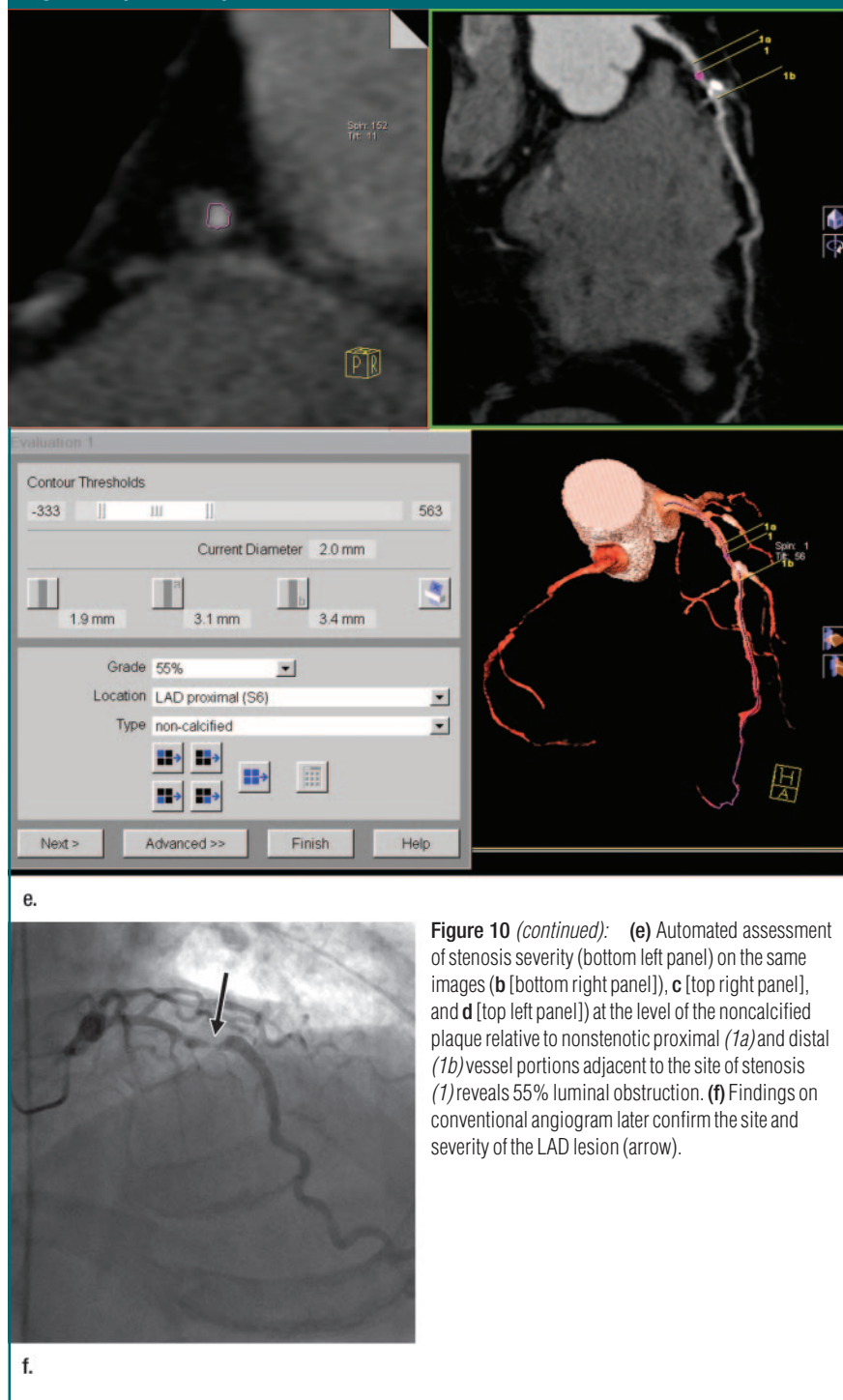


Figure 10 (continued): (e) Automated assessment of stenosis severity (bottom left panel) on the same images (b [bottom right panel], c [top right panel], and d [top left panel]) at the level of the noncalcified plaque relative to nonstenotic proximal (1a) and distal (1b) vessel portions adjacent to the site of stenosis (1) reveals 55% luminal obstruction. (f) Findings on conventional angiogram later confirm the site and severity of the LAD lesion (arrow).

with contiguous image reconstruction without overlap.

Reconstruction algorithm (kernel).—Most CT scanners used for CT angiography offer a dedicated reconstruction filter, or kernel, for image reconstruction of cardiac CT data. These kernels typically maintain a degree of edge enhancement to provide the spatial resolution necessary for visualization of small vascular detail. Ideally, the kernels are also optimized to suppress image noise as much as possible and consequently improve the visual impression and maintain the contrast resolution for evaluation of the myocardium and the vessel wall. For the evaluation of coronary artery stents, we recommend using a kernel with even stronger edge-enhancing characteristics and greater spatial resolution, compared with the algorithms routinely used at CT angiography, for better delineation of metallic stent struts (Fig 8) in the presence of beam-hardening artifacts (39). This way, the more organized linear morphology of intimal hyperplasia is easier to differentiate from hypoattenuation caused by beam-hardening artifacts; this hypoattenuation may otherwise mimic in-stent restenosis. This approach may also somewhat increase the diagnostic yield in the presence of heavy calcifications, which pose a problem similar to that posed by metallic stent struts in the evaluation of luminal integrity.

Image Display for Lesion Detection and Grading

Diagnostic Strategies

For cardiac applications, advanced dedicated image display and analysis tools have a considerably greater role than for general CT applications. Review of unprocessed source images (Fig 9), however, cannot be abandoned and must be part of the diagnostic process in each case. Unprocessed source images, viewed in the transverse plane and as MPRs, yield the richest information regarding atherosclerotic lesions of the coronary artery tree. Every postpro-

(38). For example, if the scan was acquired with a 0.6-mm collimated section width, the next highest available reconstruction thickness (eg, 0.75 mm) should be chosen for image reconstruction.

A 40%–60% increment is ordinarily used for image reconstruction at CT angiography, although this does not necessarily improve the diagnostic accuracy compared with that achieved

cessing step necessarily and by design reduces the available information for the sake of more intuitive image visualization.

For suspected coronary artery stenosis, we use the following diagnostic approach: The transverse source images (Fig 9) are initially reviewed to obtain general information about the presence, location, and composition (calcified vs noncalcified) of atherosclerotic lesions (40) and about the con-

sequences of ischemic disease, such as myocardial perfusion deficits or scarring. Once lesions are detected, stenosis severity is evaluated by using simple visualization tools that enable a more comprehensive and condensed display of the data set. MIPs (41) and MPRs (Fig 9) are easy-to-use basic tools that are available with most CT scanners. For improved detection and grading of coronary artery lesions, we use dedicated visualization and analysis tools whenever we interpret

scans obtained for suspicion of stenotic disease. There is little diagnostic value in obtaining 3D volume-rendered displays for suspicion of coronary artery disease, as lesions are frequently obscured or overestimated on these images, depending on the rendering parameters. In our practice, 3D rendering is used exclusively to intuitively communicate our findings to referring physicians and patients. Three-dimensional images are generated by the technologist and then either sent to the picture archiving and communication system for review by referring physicians in our institution or mailed in digital or hard-copy format to outside referrers and patients, if requested.

MIPs and MPRs

For visualization of the coronary artery tree at contrast-enhanced CT angiography, MIPs and MPRs are widely used and recommended as robust and easy-to-perform secondary visualization tools for data viewing (2,42,43). MIPs, MPRs, and other comparable visualization methods for diagnosis not only depict coronary artery CT data in a more intuitive format but also condense diagnostic information into a few relevant sections or views if appropriate strategies are chosen. For routine visualization of large-volume coronary CT angiographic data sets, we first analyze the transverse source images (Fig 9). Subsequently, we use MPRs in the coronal and sagittal planes (44) (Fig 9). Owing to the isotropic (equal voxel dimensions in x-, y- and z-axes) or near-isotropic nature of high-spatial-resolution CT acquisitions, image data can be rearranged in arbitrary imaging planes with image quality comparable to that of the original transverse section. An additional option is the manual creation of curved MPRs to follow the course of the coronary arteries, which in our experience is too cumbersome and operator dependent to be useful in routine practice, especially in light of the increasing availability and user friendliness of automated visualization platforms (to be discussed).

Regardless of whether MIPs or MPRs are used, secondary reformations enable views of coronary artery lesions from different angles and perspectives,

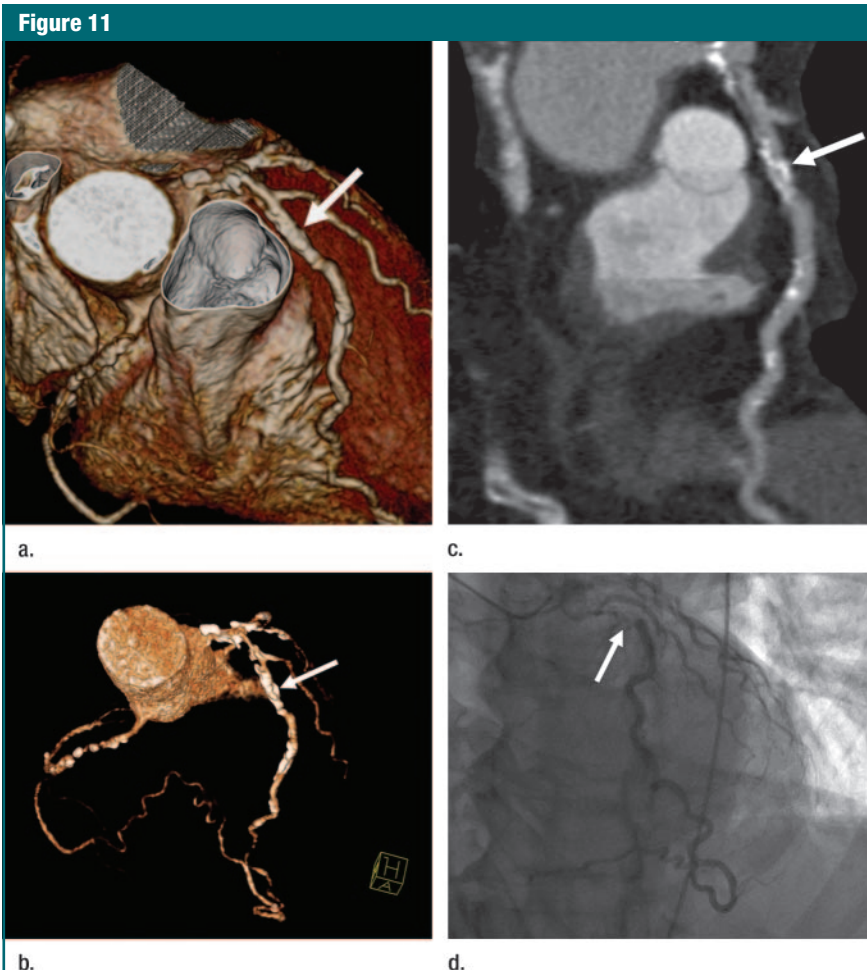


Figure 11: Contrast-enhanced retrospectively ECG-gated 64-section CT angiography in 63-year-old man with atypical chest pain and risk factors for coronary artery disease. **(a, b)** Volume-rendered images from right anterior oblique–cranial perspective obtained after automated extraction of the heart from the thoracic anatomy **(a)** and after selection of the coronary artery tree **(b)**, as well as **(c)** automatically generated MPR, reveal extensive atherosclerotic changes throughout the coronary artery tree, with particularly severe calcifications (arrow) in the proximal LAD. **(c)** Only automated unraveling of the tortuous course of the diseased vessel on the curved MPR enables reliable identification of a short-segment stenosis in the calcified proximal LAD. **(d)** Findings on the conventional catheter angiogram confirm the presence of the stenosis (arrow). Other segments of the LAD are largely patent.

which enable better assessment of stenosis severity and the residual perfused lumen than do single projections (Fig 9).

Advanced Visualization Tools

Advanced software tools that facilitate viewing and analysis of large-volume data sets have become available and are being continuously refined. The common objective of most of these software platforms is to provide a means of rapid analysis of the coronary artery tree for detection and grading of stenosis. In patients with mild or moderate atherosclerosis, we ordinarily base our diagnosis on findings seen on the transverse sections combined with sagittal and coronal MPRs. However, in more complicated cases, especially in the presence of heavy calcifications (to be discussed), we routinely use dedicated analysis platforms to enhance the diagnosis. The first step of postprocessing typically consists of automated sculpting of the chest wall to enable an unobstructed view of the heart (Fig 10a). After placement of a seed point, threshold- or contour-dependent extraction of the coronary arteries from the contrast-enhanced data set is performed (Fig 10b). Most software applications enable unraveling of the tortuous course of the extracted coronary artery, which facilitates intuitive visualization of the entire vessel, typically on an automatically generated MPR (Fig 10c). Definition of the centerline of the vessel during segmentation and extraction enables the reconstruction of sections in planes orthogonal to the vessel axis at each location of the artery (Fig 10d). Combining these two latter visualization methods is advantageous for rapid and intuitive detection of atherosclerotic wall changes and for visual grading of stenosis severity.

Finally, most available software platforms provide quantitative evaluation of stenosis severity (Fig 10e) based on cross-sectional measurements of vessel diameter or area. Naturally, the accuracy of such stenosis-grading tools is directly related to the image quality and

spatial resolution of the original acquisition and is subject to the inherent limitations of CT angiography in assessing stenosis severity. Therefore, as with any automated assessment algorithm in medicine, the measurements obtained by using vessel analysis tools should not be trusted blindly; the experience and acumen of the physician are still required to validate the results in the appropriate clinical context. While we are capable of establishing a diagnosis on the basis of transverse source image and simple MPR findings alone, in our experience, the use of advanced visualization methods is particularly important in the presence of severe calcifications (Fig 11). Advanced visualization tools combined with high-spatial-resolution acquisition and dedicated reconstruction algorithms facilitate more accurate assessment of problematic calcified vessel segments to the extent that we consider the common practice of using a calcium score cutoff threshold, above which CT angiography is not performed in many institutions, obsolete.

The Report

We use a standardized template for reporting CT angiography findings. Our CT angiography reports are not fundamentally different from general radiology reports, with the exception that they include a more detailed discussion of the coronary arteries and other cardiac structures. These reports describe all abnormalities, variations, and changes that are visible on the different reconstruction series. In the procedure section of the report, we include the items that are pertinent to appropriate billing in our local health care environment. These items may be different in other geographic areas but generally include section thickness, use of retrospective ECG gating, contrast material volume and injection speed, medications used, and image postprocessing methods such as MPR and 3D reconstruction.

In the findings section, we begin by describing the general cardiac and great vessel anatomy. We comment on the myocardium (thickness, areas of

infarction, scars, etc), cardiac chambers, valves, pericardium, pulmonary veins, pulmonary arteries, and aorta. A section is dedicated to incidental findings of the chest wall, mediastinum, and lung—for example, a description and classification of lung nodules, with recommendations for follow-up based on standard clinical practice (45). In the cardiac section, we report on the presence and location of cardiac devices, catheters, and related devices. When coronary artery bypass grafts are present, we describe the type, origin, course, and site of anastomosis; the presence, location, and degree of graft stenosis; and the quality of the runoff within the grafted vessel distal to the anastomosis. The presence and course of anomalous coronary arteries, as well as the coronary supply type (right-, left-, or co-dominant), are noted. Finally, each coronary artery (left main, LAD, circumflex, RCA) is commented on separately with regard to the presence and type of atherosclerotic plaque burden (calcified vs noncalcified).

For reporting the site of stenosis, use of the American Heart Association–American College of Cardiology segmental model, which is widely used for research purposes, has proved less useful for routine clinical interpretations. Instead, we use the common terminology found in routine catheter reports, which describe lesions as being located in the proximal, middle, or distal portion of the respective main coronary arteries or their side branches (diagonal and septal branches of LAD; obtuse marginal branches of circumflex artery, acute marginal branches of RCA). We use the described visualization methods to determine the severity of stenosis, in terms of the percentage of luminal obstruction, on the basis of cross-sectional measurements of vessel diameter or area. It is important to comment on the size and distribution of the various coronary segments to provide important information for clinical decision making. In addition, the results (Agatston, volume, and mass scores) of calcium scoring, if performed, are included in the report.

CT of the Heart: Plus ça Change, Plus C'est La Même Chose (The More Things Change, the More Things Stay the Same)

Our intent in this review was to provide a practical step-by-step manual for successfully performing coronary CT angiography. Although dual-source CT is currently the technical benchmark for CT angiography, in the near term, 64-section CT will be the most widely used modality owing to its more widespread availability. Because of the importance of heart diseases, further technical developments dedicated to this application are ongoing; however, most of the fundamental principles discussed herein will remain applicable. It is anticipated that future refinements in CT angiography will further increase the scan acquisition speed and temporal resolution and decrease the radiation exposure. It is more important, however, that these refinements will further narrow the gap between CT and invasive catheter angiography for accurate interrogation of the coronary arteries.

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