Chapter 2

Coronary CT Angiography

After completing this chapter, the learner should be able to:

- Implement the patient preparation protocol for coronary CTA
- Explain when and how prospective and retrospective triggering should be used
- Describe the benefits of dual source CT in cardiac imaging
- Compare the benefits and disadvantages of screening CCTA to stress testing and cardiac catheterization
- Describe the types of artifact that appear on cardiac CTA and how to minimize or eliminate them
- Discuss how to reduce radiation dose for CCTA and how it compares to other cardiac testing

INTRODUCTION

In addition to calcium scoring, coronary CT **angiography** (coronary CTA or CCTA) is a reliable screening tool for the detection of coronary artery disease. Multiple studies have confirmed the high **negative predictive value** (NPV) of coronary CTA, that is, the probability that subjects who have a negative screening test truly do not have the disease. Coronary CTA used for screening may reduce the number of unnecessary follow-up procedures, especially cardiac catheterization.[1]

CORONARY CTA PROTOCOL

Patient Preparation

Because the beating heart creates motion artifact, imaging the coronary arteries with CT requires ultrafast scanning and cardiac gating. To obtain the highest quality coronary CTA, the heart rate should be within the optimal range of 50-60 beats per minute (bpm), and the coronary arteries should be dilated.

A rapid heartbeat can be safely lowered and stabilized below 65 beats per minute with the use of **beta blockers** prior to the exam. Contraindications for use of beta blockers include **sinus bradycardia**, allergy to beta blockers, and 2nd or 3rd degree **AV block**.[2]

Administration of oral nitroglycerin before scanning will dilate the coronary arteries and improve visualization of the side branches. Nitroglycerin is contraindicated in patients who are sensitive or allergic to it or who have taken medications for erectile dysfunction within the previous 48 hours.[3]

The preferred protocol for coronary CTA also requires intravenous (IV) administration of an iodinated contrast agent with a saline flush. The saline flush decreases the amount of iodinated contrast required, flushes the contrast material from the peripheral veins into the central veins, reduces **beam hardening** artifact in the right coronary artery, and aids excretion of the contrast material through the kidneys.[4]

The patient should be screened for potential contraindications to the use of iodinated contrast, including previous sensitivity or allergic reaction, asthma, renal insufficiency, and cardiac history. The American College of Radiology recommends that patients who have had a previous allergic reaction to iodinated contrast be pre-medicated with 50mL of prednisone at 13 hours and 7 hours prior to the exam, and 50mL of prednisone and Benadryl® immediately before the exam.[5]

Temporal Resolution

As CT scanner technology has advanced, coronary CTA has also improved. For many years, 16-detector-row CT scanners were the standard for cardiac imaging, but 64-, 256- and 320- detector scanners are currently available at most clinical sites. The entire heart can be imaged using 256- and 320-detector scanners in one heartbeat!

With each increase in the number of detectors, scan time is reduced, temporal resolution is improved, and the incidence of motion artifact is decreased. High temporal resolution is important because if a coronary segment is non-diagnostic due to motion artifact, the decrease in the level of confidence in the study could result in unnecessary cardiac catheterization.[6] Since scanners with a greater number of detectors provide better temporal resolution, it is obvious why they are preferred for coronary CTA.

The entire heart can be imaged using 256- and 320-detector scanners in one heartbeat!

Spatial Resolution

Recall that spatial resolution is defined as the ability to separate two structures. Slice thickness, image field of view (FOV), and image matrix are CT parameters that affect spatial resolution. A narrow FOV and slice thickness are required for coronary CTA to maximize spatial resolution to improve differentiation between the vessel and any obstruction.[6]

Postprocessing

After the patient is scanned, images are sent to a workstation for 3D postprocessing. Thin axial images are reconstructed into **volume-rendered images**, **curved multiplanar reformats** (MPR), or **maximum intensity projection** (MIP) images.

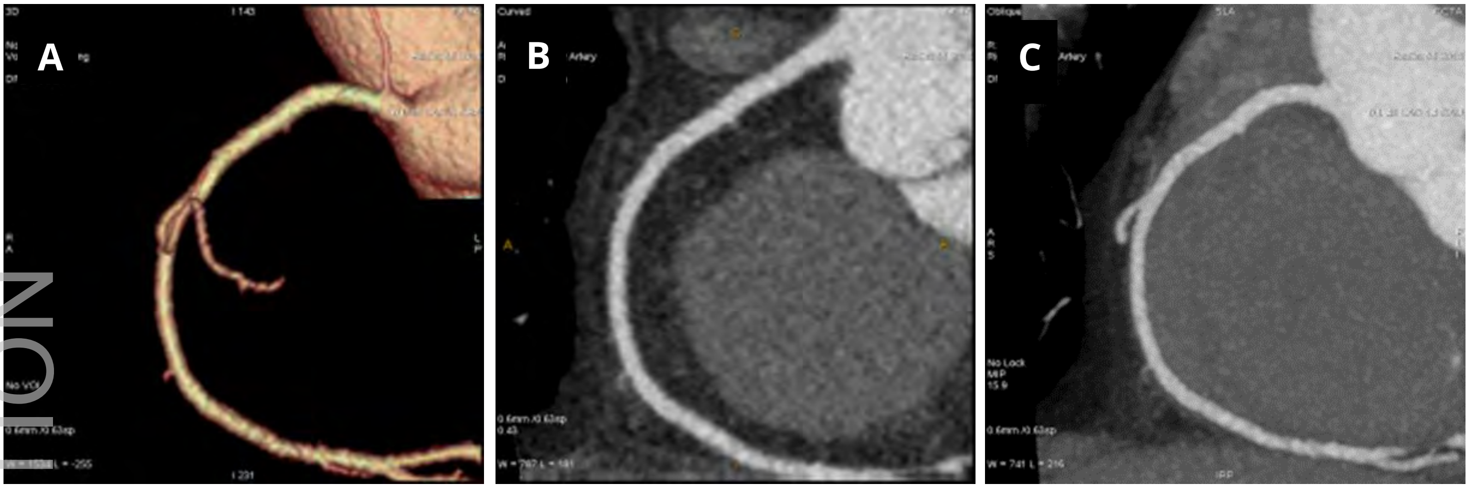

Figure 1. Postprocessing of RCA of same patient with (A) volume-rendered CT; (B) curved MPR; (C) and MIP. All images reveal no evidence of stenosis.

Volume-rendered images are helpful for showing cardiac anatomy but not useful for defining luminal narrowing. Curved multiplanar reformats allow visualization of an entire coronary artery in one view. Maximum intensity projection images are faster to process than curved MPRs but do not show arteries with as much detail. Curved MPRs are superior to MIPs for evaluating arteries with calcified plaques. **Figures 1** and **2** are examples of volume-rendered, curved MPR, and MIP images.

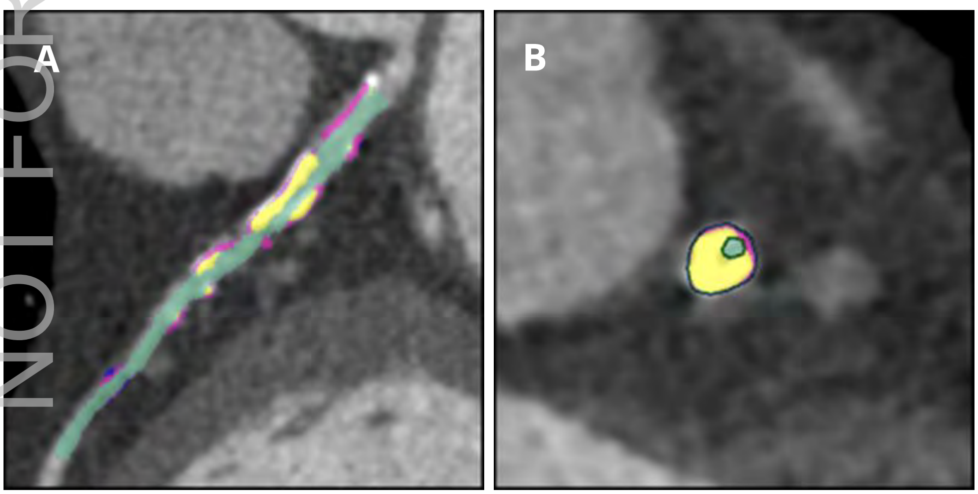

Figure 2. Color-coded (A) curved MPR and (B) cross-section of the LAD of the same patient. Green shows the contrast-filled lumen, purple reveals soft plaque, and yellow demonstrates calcified plaque.

ELECTROCARDIOGRAPHIC GATING

In order to successfully image the coronary arteries, cardiac gating must be employed to minimize imaging artifacts caused by cardiac motion. Cardiac motion is at its peak during **systole**; therefore, the highest quality images of the heart are obtained during diastole when there is the least cardiac motion.

Prospective and Retrospective Triggering

Prospective triggering is a cardiac scanning technique that reduces radiation dose to the patient during a cardiac CT exam. Studies have shown that the prospective triggering technique can reduce the radiation dose to the patient to 1-3 mSv.[7]

Prospective triggering uses the ECG to sync data acquisition with the cardiac cycle. The heart is scanned axially in a step-and-shoot format to acquire consecutive blocks of data. The first block of data is acquired during a pre-determined phase percentage of the R to R interval, usually at the 75% phase which corresponds with end-diastole. The table is then moved to the next position and when the ECG signal is again in diastole, the next block of data is acquired. Using a scanner with fewer detectors, three to four separate acquisitions are required to image the entire heart. With scanners having 256 detectors or greater, an image of the entire heart may be obtained in one block of imaging data.

Prospective triggering should not be used with patients who have rapid heart rates or **arrhythmias** as images can only be reconstructed in a limited number of phases around the acquisition phase. The narrower selection of phases may result in poor quality images due to motion artifact.[7]

Retrospective triggering is indicated for patients with rapid heart rates or arrhythmias and for functional analysis of the left ventricle, which requires imaging throughout the entire cardiac cycle. Retrospective triggering uses helical scanning to acquire images during both systole and diastole that are then reconstructed at specific phases of the cardiac cycle. This triggering technique emits a higher radiation dose to the patient of up to 14 mSv.

One technique for lowering radiation dose when using retrospective triggering is electrocardiographic gating dose modulation, which lowers mAs when the heart is in systole. In 2009, Takakuwa et al measured radiation doses of 267 patients who underwent coronary CTA exams using retrospective triggering with and without the use of ECG gating dose modulation. The exams using only retrospective triggering delivered an average dose of 18 mSv, while the exams that employed ECG gating dose modulation delivered a significantly reduced average dose of 8.75 mSv.[8]

Understanding the R to R interval

The R to R interval represents the time between one heart beat and the next (**Figure 3**). In CCTA, the time between heartbeats is expressed in phase percentages of the R to R interval. Most patients are optimally scanned at the 75% phase which corresponds with end-diastole. For patients who have heart rates >70 bpm, however, scanning during other phases may be required. If using retrospective triggering, phase percentages anywhere during the R to R interval can be reconstructed.

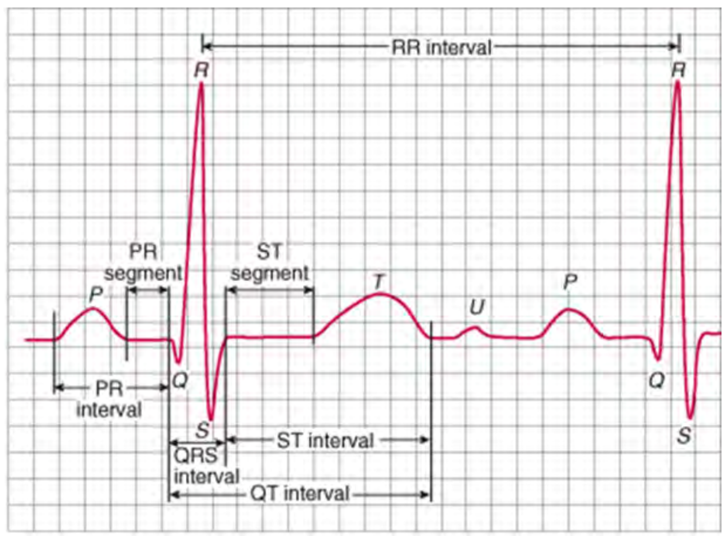

Figure 3. ECG QRS wave form illustrating the R to R interval. Available at [Life in the Fast Lane.]()

Importance of Optimal Heart Rate

We have learned that the prospective triggering technique produces diagnostic quality images with reduced radiation doses to patients with lower heart rates. On the day of the cardiac CTA exam, patients should refrain from caffeine and nicotine to ensure their heart rate remains in the optimal range of 50-60 beats per minute. For patients with rapid heart rates or arrhythmias, beta blockers may be administered to lower the heart rate to the target range during image acquisition.

Imaging a patient with a rapid heart rate

Technical advances have increased the reliability of scanning patients who have rapid heart rates. In 2010, Xu et al compared dual source cardiac imaging to MDCT with retrospective ECG gating in patients with heart rates from 70-100 bpm. Not only was image quality superior when using the dual source scanner, but radiation dose was decreased by more than 50%.[9]

A study published in 2015 by Macron et al compared images obtained using 64-detector scanners to 256-detector scanners in patients with rapid heart rates and found better image quality with lower radiation dose using the 256-detector scanner. Since temporal resolution increases as the number of detectors increase, the reliability of imaging patients with rapid heart rates also increases on higher-detector scanners.[10]

Despite these technological advances, high quality CT coronary artery imaging is ideally acquired at lower heart rates because of decreased motion artifact.

Motion artifact

A rapid heart rate during image acquisition can produce motion artifact, resulting in a blurry appearance of the coronary arteries. When image quality is diminished by motion artifact, all available phases of the R to R interval should be evaluated (**Figure 4**).

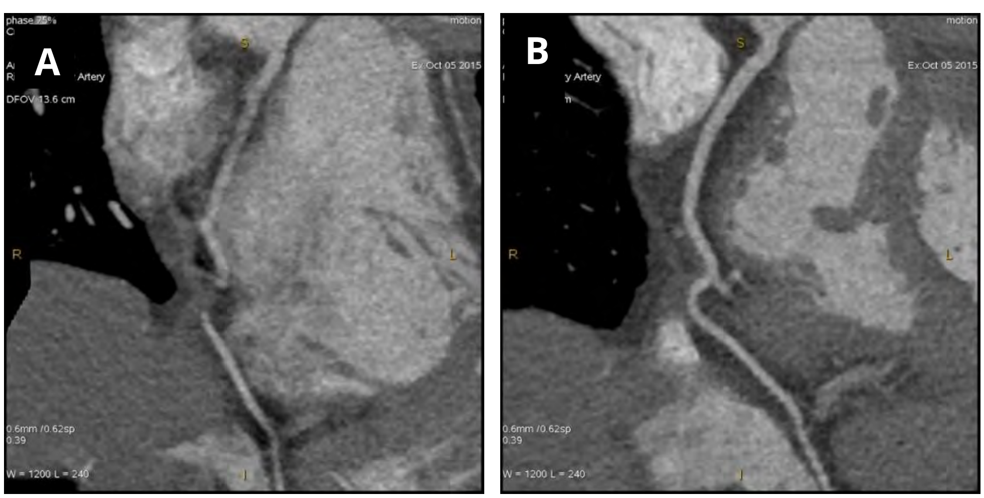

Figure 4. RCA of patient with a rapid heart rate: (A) note the blurry image due to cardiac motion artifact at 75% of the R to R interval; (B) motion artifact is corrected using images at 45% of the R to R interval.

Variability in the heart rate can cause step artifact, which simulates **ectopic** or **arrhythmic** beats and distorts part or all of the images. Variations in heart rate, either increasing or decreasing, can lead to additional or missed portions of the R to R intervals. Step artifact can also occur at heart rates lower than the optimal target heart rate of 50-60 bpm (**Figure 5**).

Figure 5. Step artifact of RCA as visualized on curved MPR.

Dual Source CT

Dual source CT (DSCT) is a generation of scanner that revolutionized CT scanning by employing two tubes and two detectors to achieve ultrafast, motion-free imaging of structures while applying low-dose radiation parameters and maintaining diagnostic imaging quality (**Figure 6**).

Figure 6. Example of a dual source CT unit. *Courtesy of Siemens Healthcare*

Because the tubes act in concert, dual source CT is ideal for imaging pediatric patients as scan times can be reduced to subseconds and for cardiac imaging where increased temporal resolution is essential. Although dual source CT emits less radiation than conventional CT, power can be increased when needed, making dual source CT a good alternative for scanning obese patients, visualizing coronary stents, and identifying coronary calcifications.

The following characteristics make DSCT especially useful for cardiac CTA:

- DSCT acquires data throughout the entire cardiac cycle.
- DSCT has the ability to scan at any heart rate.
- DSCT images can be reconstructed into a 4D multiphase series.
- DSCT can be used to measure left ventricular function.
- DSCT images are acquired in subseconds.
- DSCT delivers a radiation dose of approximately 1mSv to the patient.

CORONARY CTA AS A SCREENING TOOL

Coronary CTA is used as a screening tool to help determine if a patient should proceed to cardiac catheterization.

Cardiac catheterization is an invasive procedure that carries many risks, some of which can be life-threatening. However, cardiac catheterization remains the gold standard for defining the degree of stenosis in the coronary arteries, in part because of its high spatial resolution.[11]

Given the risks associated with a cardiac catheterization, there is a need for a reliable screening exam to limit the number of patients unnecessarily undergoing the procedure. In other words, the screening exam should have a high negative predictive value.[12] Currently, stress testing and coronary CTA are the two screening exams used to determine if a patient should proceed to cardiac catheterization.

Stress Testing

Non-imaging stress testing

During a standard non-imaging stress test the patient is required to exercise while attached to an ECG, which measures changes in the heart's electrical activity.

Results are achieved by increasing oxygen demand of the heart muscle. If the coronary arteries are stenotic, oxygen demand cannot be met, and the patient may experience chest pain or shortness of breath.

Imaging stress testing:
Stress echocardiography and nuclear stress testing

In stress echocardiography or cardiac echo, ultrasound images are obtained while the patient is at rest and after exercise. If the patient is unable to exercise, a pharmacologic stress agent like dobutamine is administered to simulate exercise. Cardiac echo produces moving pictures of the heart and can detect abnormalities in blood flow and left ventricular function (**ejection fraction** [EF]).

Nuclear stress testing uses a gamma camera to obtain images during exercise or after administration a stress-producing medication. A radioactive dye such as thallium or sestamibi is administered, and images are obtained using a gamma camera to measure uptake of the isotope. A radiologist evaluates the images to assess how well blood is pumping through the heart.

A notable limitation of stress testing is its inability to detect non-obstructive plaque.

Imaging stress testing is superior to non-imaging testing for detection of coronary disease.[13] However, a notable limitation of stress testing is its inability to detect non-obstructive plaque. Although approximately 70% of stress tests are reported as normal, up to 70,000 patients suffer myocardial infarction or cardiac death each year after having had a normal stress test.[14]

Negative Predictive Value of Coronary CTA

CorE-64 trial

The CorE-64 trial was an international study of 371 patients who underwent coronary CTA, calcium scoring, and cardiac catheterization.

The results of CorE-64 showed that the negative predictive value of coronary CTA decreased for patients with higher calcium scores. CCTA showed a negative predictive value of 93% in patients with calcium scores <100, meaning that 93% of the study group was accurately diagnosed by CCTA as having mild or no coronary artery disease. However, for patients with calcium scores >100, the negative predictive value dropped to 75%. The range of calcium scores and their correlation to coronary artery disease are listed in **Table 1**.

Total Calcium Score	Evidence of CAD
1	No evidence of CAD
1-10	Minimal evidence of CAD
11-100	Mild evidence of CAD
101-400	Moderate evidence of CAD
Over 400	Extensive evidence of CAD

Table 1. Extent of coronary artery disease (CAD) based on calcium score.

Source: www.radiologyinfo.org

CCTA was found to be less effective for patients having calcium scores >600 due to the presence of **blooming artifact,** which can cause calcified plaque to appear larger than it actually is and result in overestimation of the degree of stenosis. In a 2012 study, Arbab-Zadeh et al reported that, "Because of the perceived limitation of CTA in patients with severe coronary calcification, many investigators have favored obtaining a coronary calcium score to inform the decision of proceeding or not with CCTA. However, the utilization of a coronary calcium score threshold for deciding to perform CTA remains controversial." The study also revealed that coronary CTA was less effective for diagnosing patients who were considered at high risk for CAD; however, the study did demonstrate a 90% negative predictive value for patients considered to be at intermediate risk for CAD.[15]

The ACCURACY study

The purpose of the ACCURACY study was to evaluate the diagnostic accuracy of coronary CTA at thresholds of both ≥50% and ≥70% stenosis. This prospective study enrolled 230 chest pain patients with no known coronary artery disease who underwent both coronary CCTA and cardiac catheterization.[16]

The ACCURACY study found the negative predictive value of CCTA in patients with ≥50% and ≥70% stenosis was 99%. Additionally, over 85% of the patients included in the ACCURACY study did not have obstructive coronary artery disease and likely would have avoided cardiac catheterization had a screening CCTA had been performed.[17]

The authors concluded that CCTA has high diagnostic accuracy and is an effective screening tool for measuring stenosis, making it a viable alternative to cardiac catheterization.[16, 17]

Advantages of CCTA over Stress Testing

Coronary CTA and stress testing are both non-invasive studies used to determine if a patient should undergo an invasive cardiac catheterization.

While stress testing only identifies obstructive coronary artery disease, CCTA visualizes all of the coronary anatomy.

In a large study published in 2012 of almost 400,000 subjects, researchers attempted to quantify the effectiveness of stress testing as a gatekeeper to cardiac catheterization. The registry was comprised exclusively of patients without prior history of coronary artery disease, 89% of whom underwent stress testing prior to catheterization. Despite the large percentage of study participants who had undergone a stress test prior to catheterization, obstructive coronary artery disease was diagnosed in just 38% of the patients, leading the authors to conclude that better strategies for risk stratification are needed to prevent unnecessary invasive procedures.[14]

Similarly, PROMISE was a multicenter study of more than 10,000 symptomatic patients randomly assigned to evaluation by stress testing or CCTA. Results showed that patients in the CCTA group underwent fewer cardiac catheterizations than patients who were evaluated by stress testing alone.[18]

The greatest advantage of coronary CTA over stress testing may be its ability to improve long-term outcomes for patients. While stress testing identifies only obstructive coronary artery disease, CCTA can visualize most if not all of the coronary anatomy. Coronary CTA combines a high negative predictive value with the ability to visualize non-obstructive CAD, which may prevent unnecessary cardiac catheterization.[18]

Blooming and Beam Hardening Artifacts

Blooming artifact is a result of **partial volume averaging** and can cause high-density structures like calcified plaque to appear larger than it is, often resulting in overestimation of the degree of stenosis and false positive findings (**Figure 7**). Edge-enhancing filters may be used to decrease the appearance of blooming artifacts, although image noise will increase.[19]

Beam hardening artifact is produced when the mean energy of the x-ray beam increases as it passes through the patient, affecting visualization of the lumen adjacent to dense calcification. This occurs most often when a **polychromatic** beam is used and low energy photons in the beam **attenuate** first, leaving the high energy photons to pass through the patient and strike the detectors.

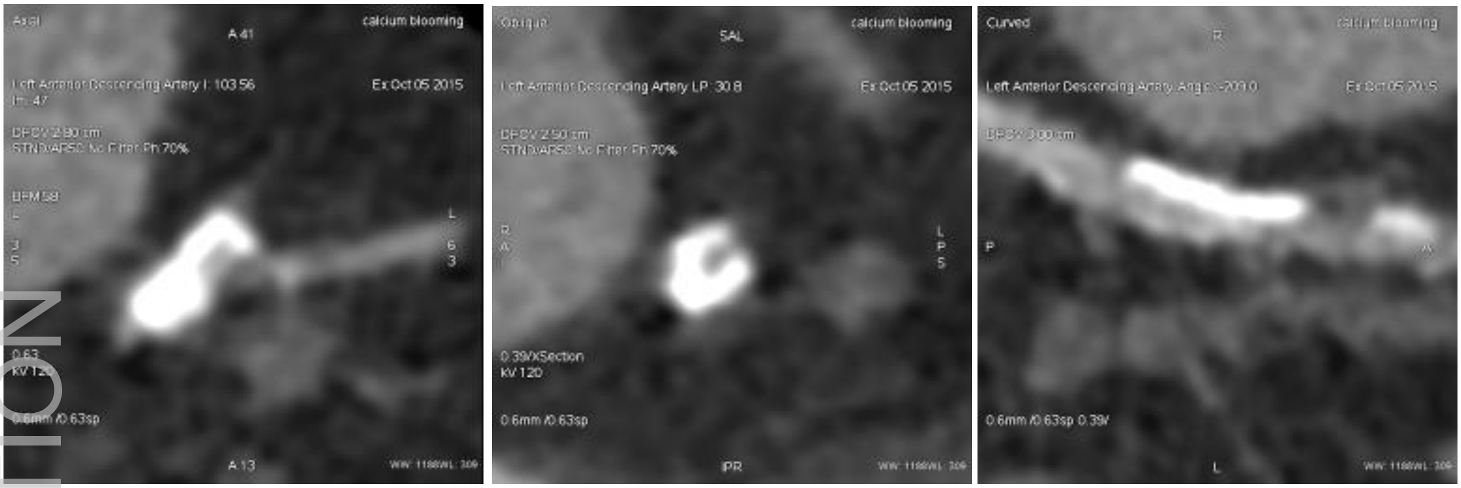

Figure 7. Blooming artifact: (A) axial (B) cross-sectional (C) curved MPR.

Beam hardening artifacts can also occur when the length of the beam varies as it passes through and around the object of interest — a longer path will further "harden" the beam. The hardening of the beam results in displacement of the HU value of the tissue and is more likely to appear on images of bone, dense calcium, or coronary stents than on fat or less dense tissue (**Figure 8**).

Beam hardening artifacts can also be reduced by using correction filters on polychromatic beams or by using dual source CT.

A study published in 2011 by Voros et al showed that in the presence of blooming artifact, radiologists overestimated the volume of calcified plaque by 104%, underestimated the luminal diameter by 21%, and overestimated luminal narrowing by 39% compared to conventional non-invasive angiography.[20]

A 2012 study addressed this challenge by utilizing dual energy CT angiography (DECTA). The authors found that using high monochromatic energies decreased the volume of the blooming artifact to a more representative size of the calcified plaque.

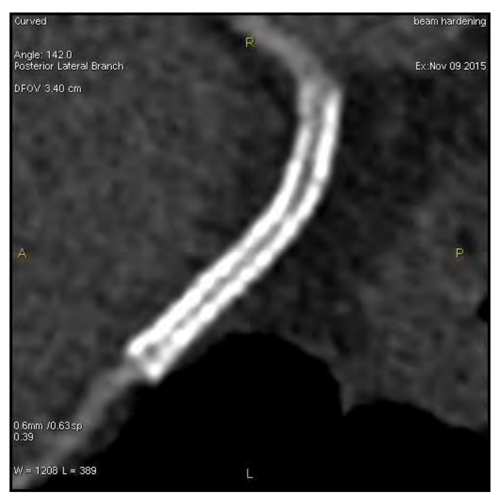

Figure 8. Stent placed in the posterior lateral branch of the RCA showing beam hardening artifact as seen on curved MPR.

The study examined the degree of artifact by comparing monochromatic single-energy projection-based DECTA to single-energy CT and conventional angiography. Varying energies from 40 keV to 140 keV were reconstructed, and calcified plaques were evaluated at different energy levels. The results showed that blooming artifact was decreased by 26% in images reconstructed at 140 keV, concluding that the use of DECTA decreased overestimation of stenosis caused by blooming artifact.[21]

Incidental Findings on CCTA

An additional benefit of CCTA as compared to stress testing and cardiac catheterization is the ability to diagnosis extra-cardiac pathology. The mediastinum, lungs, and axilla should be seen within the field of view on CCTA and always be evaluated by the interpreting radiologist. If the display field of view includes only the heart, an axial reconstruction using a larger field of view should be used to view extra-cardiac structures.

Aortic aneurysms and dissections, pulmonary embolisms, lung masses, and enlarged lymph nodes are examples of potentially serious incidental findings found on CCTA. A 2007 study of 100 consecutive patients who underwent CCTA revealed 145 extra-cardiac findings (ECF). Of these, 107 were considered benign, 22 were of indeterminate significance, and 16 were clinically significant. Because incidental findings are not an uncommon discovery on CCTA, all organs should be carefully evaluated.[22]

CORONARY CTA IN THE EMERGENCY ROOM SETTING

Every year in the United States more than 6 million patients are rushed to the emergency room (ER) with chest pain, the second most common reason for an ER visit. Effective **triage** is critical for quickly identifying the presence of **acute coronary syndrome** (ACS). ACS refers to any group of clinical symptoms compatible with acute myocardial infarction (MI). Only 10-15% of ER these patients are actually diagnosed with ACS, but a majority are admitted to the hospital at an estimated cost of $3 billion a year.[23]

Test	Radiation Dose
Calcium scoring	**Below 1-2 mSv**
Cardiac catheterization	**7 mSv**
Coronary CTA	**3-14 mSv**
Radionuclide sestamibi stress test	**10-12 mSv**
Radionuclide dual isotope myocardial perfusion imaging	**25 mSv**

Table 2. Radiation dose for common cardiac imaging

In a recent multicenter study by Litt et al, 1,370 emergency room patients presenting with possible ACS were classified as low-to-intermediate risk and divided into two groups: 908 patients underwent CCTA and 462 patients received traditional care, meaning their healthcare provider decided what testing, if any, to order. 64% of the patients who received traditional care group went on to receive diagnostic testing, usually a stress test. Study results showed that the CCTA group was twice as likely to be discharged from the ER as the traditional care group, and the average hospital stay was on average 6 hours less than the traditional care group.[23]

The authors concluded that CCTA was a safe and efficient means for discharging patients home who would otherwise have been admitted.[23]

RADIATION DOSE

In past years, patients often received an effective radiation dose of 20 mSv or more when undergoing coronary CTA. However, use of prospective triggering and iterative reconstruction techniques has reduced the average radiation dose of CCTA to between 3-14 mSv, with some CT scanners capable of doses less than 1 mSv per exam.[24, 25] The lower radiation dose has made CCTA a more desirable screening exam when compared to nuclear stress testing[25] (**Table 2**).

SUMMARY

The high negative predictive value of coronary CTA makes it an effective screening tool for determining if a patient should proceed to cardiac catheterization. Like calcium scoring, wide implementation of CCTA screening for low-risk asymptomatic patients is not recommended. However, CCTA is an excellent screening exam for both asymptomatic intermediate-risk patients and for symptomatic patients in the emergency room setting.

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