Claudio Smuclovisky
Editor

Coronary Artery CTA

A Case-Based Atlas

Second Edition

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Preface

Since the publication of the first edition, there has been continued progression in the field of cardiac CT angiography (CCTA). The CT hardware and software currently has improved the image quality with less radiation and faster workflows. Hundreds of peer-reviewed publications solidly support the use of CCTA in many clinical situations.

The book has expanded in the second edition with many outstanding colleagues contributing additional new chapters:

Drs. Alain Vlassenbroek, Mani Vembar, and Michael Grass: Innovations in Cardiac CTA
Dr. Dianna Bardo: Pediatric CCTA
Drs. Christopher Brown and Charles White: CCTA Extracardiac Findings
Dr. Constantino Peña: CCTA in the Emergency Department
Drs. Lohendran Baskaran, Christopher Zarins, and James K. Min: CT Fractional Flow Reserve (CT-FFR)
Dr. Tariq Hameed: CT for TAVR Planning
Dr. Alex Llanos: A Cardiac Interventionist Perspective to CCTA
Dr. Daniel Weitz: CCTA for Electrophysiology (EP) Planning

The chapters on coronary anatomy, coronary artery disease, coronary intervention, and surgical revascularization have been revised and updated, and additional interesting cases for review have been added to help the reader.

As in the first edition, this book has been created to be an easy to review CCTA atlas with many “Pearls and Pitfalls” in order to help the reader expand their knowledge.

In summary, this second edition is expected to be an excellent reference guide for radiology and cardiology residents, fellows, and practitioners.

Fort Lauderdale, FL, USA
Claudio Smuclovisky, MD

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Dr. Lee also worked closely with Drs. Llanos and Weitz in the development of two new chapters. He also stayed in close contact (stalking) with the chapter contributors in order to coordinate the review and submission to our editors.

I would also like to thank the outstanding people at Springer, especially Ms. Janet Foltin and Ms. Jennifer Schneider, who made this book possible.

Claudio Smuclovisky, MD

Contents

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1 Introduction

Claudio Smuclovisky

> *"More powerful than the might of all the armies on Earth is an idea whose time has come." (On résiste à l'invasion des armées; on ne résiste pas à l'invasion des idées.)*
>
> Victor Hugo-1852

Cardiac CT angiography (CCTA) has become a broadly accepted diagnostic modality in cardiac imaging by both the medical community and payers. There is an abundance of published peer review articles in worldwide journals establishing the clinical value of CCTA in the evaluation of congenital and acquired cardiac diseases.

The manufacturers of CT hardware and software have made many significant improvements in simplifying patient workflow, acquisition, postprocessing, and interpretation of images. CCTAs can now be acquired in 1–4 heartbeats with very short breath holds. Single beat whole cardiac imaging is available as well as sub-millisiviert dose scans.

3-D workstations have become faster, more automated and easier to use for image review, coronary extraction and analysis. Once the CCTA is acquired the data can automatically be uploaded to a computer server for pre-processing and thin-client remote access from a network terminal.

Image quality continues to improve through innovations in both hardware and software.

Iterative reconstruction (IR) technology that can virtually eliminate noise on the images is now available and should be a strong consideration in the upgrade or purchase of a CT scanner. The major advantage of IR is that it improves both low and high contrast, resulting in images with less noise, artifact, and better spatial resolution.

It is remarkable that in less than a decade CCTA radiation dose has been dramatically reduced mainly by the combination of using lower Kv technique, axial-prospective acquisition and IR. Also, improved CT gantry (speed), x-ray tube, collimation and detector design/sensitivity. In our CT department, when compared to the various CTs performed, CCTAs went from being the highest radiation dose study to now among the lowest. It is now possible to acquire a CCTA with the equivalent radiation dose similar to a two-view chest radiograph. This second edition includes a new chapter on "Innovations in Cardiac Multi-Slice Computed Tomography" (Chap. 2).

CT myocardial perfusion and fractional flow reserve (FFR-ct) is not yet widely used but holds great promise in evaluating myocardial ischemia and to further help determine the need for revascularization.

A key to a successful CCTA program is to be able to integrate CCTA efficiently into the average busy CT schedule in a timely manner similar to any other CT angiogram and in which greater than 95% of the studies are of high diagnostic quality. With experience, the review and interpretation of a study should, in the majority of cases, take just a few brief minutes.

Although there is undeniable broad data supporting the use of CCTA in many clinical situations, no previous imaging technology has ever

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been under such criticism and skepticism. Skeptics continue to argue that CCTA does not add clinical value, has excessive false positives, provides no myocardial physiology information, leads to additional testing, increases costs and delivers high radiation. Although the body of literature, particularly in the last 5 years, largely does not support most of the criticism, I feel compelled to answer these questions.

The high sensitivity and negative predictive value (95–99%) of CCTA does indeed add clinical value in ruling in or out coronary artery disease as the possible cause of chest pain, particularly in the emergency room setting [1]. The specificity and positive predictive value (60–80%), especially in calcified stenotic appearing coronary plaques, is currently the Achilles heel of CCTA. This is also true for invasive coronary angiography where studies (FAME Trial) [2] have shown that up to 20% of 70–90% high-grade stenotic plaques by quantitative coronary angiography (QCA) were not flow limiting by fractional flow reserve (FFR). It is well known that calcified plaques on CCTA cause blooming artifact that overestimate the degree of luminal stenosis, and there is no shame in reporting these plaques and/or coronary segments as "indeterminate" to cause high-grade stenosis. Intervention, both catheter based and surgery, focuses on revascularizing myocardial ischemic segments. Myocardial ischemia at a cellular level is known to be multifactorial with coronary stenosis being among one of several causes [3, 4].

CCTA can establish the presence of coronary artery disease and help in the risk stratification of the patient. The Courage Trial [5, 6] published in 2007 in patients with stable angina showed similar long-term results (cardiac events and death) in patients treated with optimal medical therapy (OMT) versus OMT + percutaneous coronary intervention (PCI).

In terms of CCTA not providing myocardial physiology information, FFR-ct [7] (HeartFlow, Inc.) is now FDA approved and holds great promise in the demonstration of ischemic myocardial segments on a CCTA. In Chap. 7, James Min and colleagues highlight the clinical value of FFR-ct. Myocardial perfusion is also now available and can be routinely performed [8].

Although further research is needed in patients with a low-intermediate likelihood of coronary artery disease, CCTA is a more accurate and efficient alternative noninvasive frontline diagnostic test than exercise ECG and SPECT. The increased downstream test utilization and subsequent revascularization following a coronary CTA strategy may allow for decreased myocardial infarction and mortality [9].

The argument of excessive radiation with CCTA can no longer be argued since studies can now be acquired with sub-millisiviert doses with the use of lower Kv techniques and iterative reconstruction. When compared with a Tc-99m myocardial perfusion scan with a dose of 15–25 mSv, the CCTA dose is in the range of 90% less radiation. I cannot recall reading much about the worries and concerns about the radiation from nuclear studies that are not infrequently performed yearly on patients.

On a personal note, it is interesting to reveal that my physician colleagues who have been the most vocal against the use of CCTA have been among the fastest to arrive at my office for a CCTA when "they" or close family members have any symptoms of chest pain or concern of having obstructive coronary artery disease. These even include doctors with nuclear cameras in their office! The reader can reach their own conclusions, but in my mind this is the most powerful testament of the value of CCTA.

Although many robust indications for CCTA are appropriate, such as screening patients that present to the emergency department with chest pain, it is important to remember that coronary artery atherosclerosis starts in the first or second decade of life. My main focus is cardiovascular disease prevention. An adult who presents with symptoms of coronary artery disease has undoubtedly had the disease for decades. A common first symptom of heart disease is sudden death, which occurs in one out of four patients. About half of the patients do not survive the first myocardial infarction (MI). The human tragedy and costs worldwide from cardiovascular diseases continues to rise and is staggering. There is no question that the best solution is "prevention" and I am convinced that cardiac CT can play a significant role.

Conventional clinical risk assessment (Framingham) is largely inaccurate and stratifies incorrectly a large group of patients particularly in the low to intermediate category, which is where a large percent of cardiac events occur. A less costly calcium score has been shown to be an effective test in risk stratification. We know that risk modification and pills work to reduce cardiovascular events. Thus, it is plain common sense to identify those patients at risk as early as possible in order to have a positive impact on morbidity and mortality outcomes.

Another important goal is to help cardiologists/interventionists and cardiovascular surgeons make better clinical and surgical decisions in the care of their patients. First, it has been published [10] in a large multicenter trial that up to 60% of patients with stable angina undergoing coronary angiography have either no disease or mild non-obstructing disease. With almost 100% negative predictive value of CCTA, the majority of the patients could have avoided an invasive procedure. CCTA can also help the interventionist focus his practice more on performing intervention than diagnostic work. If we look today at peripheral vascular intervention, most of the procedures involve intervention and not diagnostic angiography. CT or MRI angiography is performed prior to diagnose obstructions and aneurysms resulting in the intervention being preplanned. With the use of CCTA, cardiac interventionists now have the opportunity to do the same.

Second, the coronary angiogram (CA) is essentially a luminogram that does not show the true extent of CAD. I have seen many CCTA studies with advanced atherosclerotic disease in which the coronary angiogram is reported as having “clean coronaries.” We have known for decades that nonstenotic “soft” plaques in the wall (positive wall remodeling) can rapidly grow, become stenotic, and in a relative short period of time rupture, causing an acute coronary event [11].

Third, when a CA is performed, the cardiologist may be essentially “guessing” the true extent of CAD. Also, there exists “blind spots” on the CA that may be very difficult to identify on standard projections, particularly short segment stenosis in the ostium of the left main, left anterior descending and right coronary arteries. CCTA can easily identify these stenotic areas and, if needed, provide the appropriate X-ray tube angle for CA visualization of the stenosis, thus avoiding additional acquisitions or runs.

Fourth, CCTA can demonstrate the location, length, and type of plaque (calcified, noncalcified, mixed) in the artery, which provides additional information for planning treatment.

Fifth, CCTA can demonstrate proximal critical coronary stenosis that may require catheter or surgical intervention as soon as possible. This is most noticeable in patients who present to the emergency department with chest pain and who were determined low to intermediate risk.

I have been teaching cardiac CT courses level 1, 2, and 3 for 10 years and about half of the participants are cardiologists. We show a wide variety of cases where CCTA correlates perfectly with CA and where it does not correlate: what I call “the good, the bad and the ugly.” What I emphasize most is to look at the CCTA to determine how to use this test as a tool to make better clinical decisions.

It is important to emphasize that CCTA is *not* only a coronary CT but rather a cardiac CT. It is a mistake to only focus on the coronary anatomy. The field of view on the study includes the lungs, pleura, pericardium, myocardium, cardiac valves, pulmonary vessels, aorta, other mediastinal structures bones, chest wall, and infradiaphragmatic organs. What I tell students is that CCTA is a high-resolution accurate study as long as it is interpreted correctly. There may be many different findings on the CCTA that may explain the patient’s symptoms: pulmonary embolism, cancer, cardiomyopathy, effusions both pleural and pericardial, aortic aneurysm/dissection, and too many others to list here. CAD is one of the many causes of chest pain.

In order to serve the best interests of patients, a cardiac CT specialist is required to be proficient in the proper interpretation of all the structures included in the field of view.

References

1. Hi L, Gatsonis C, Snyder B, et al. Ct angiography for safe discharge of patients with possible acute coronary syndromes. N Engl J Med. 2012;366:1393–403.

2. Tonino PA, Fearon WF, De Bruyne B, et al. Angiographic versus functional severity of coronary artery stenoses in the FAME study fractional flow reserve versus angiography in multivessel evaluation. J Am Coll Cardiol. 2010;55(25):2816–21.
3. Arbab-Zadeh A, Fuster V. The myth of the "vulnerable plaque": transitioning from a focus on individual lesions to atherosclerotic disease burden for coronary artery disease risk assessment. J Am Coll Cardiol. 2015;65(8):846–55.
4. Marzilli M, Merz CN, Boden WE, et al. Obstructive coronary atherosclerosis and ischemic heart disease: an elusive link! J Am Coll Cardiol. 2012;60(11):951–6.
5. Boden WE, O'rourke RA, Teo KK, et al. The evolving pattern of symptomatic coronary artery disease in the United States and Canada: baseline characteristics of the Clinical Outcomes Utilizing Revascularization and Aggressive Drug Evaluation (COURAGE) trial. Am J Cardiol. 2007;99(2):208–12.
6. Boden WE, O'Rourke RA, Teo KK, et al. COURAGE Trial Research Group Optimal medical therapy with or without PCI for stable coronary disease. N Engl J Med. 2007;356(15):1503–16.
7. Nørgaard BL, Leipsic J, Gaur S, Seneviratne S, et al. NXT Trial Study Group. Diagnostic performance of noninvasive fractional flow reserve derived from coronary computed tomography angiography in suspected coronary artery disease: the NXT trial (Analysis of Coronary Blood Flow Using CT Angiography: Next Steps). J Am Coll Cardiol. 2014;63(12):1145–55.
8. Kühl JT, George RT, Mehra VC, et al. Endocardial-epicardial distribution of myocardial perfusion reserve assessed by multidetector computed tomography in symptomatic patients without significant coronary artery disease: insights from the CORE320 multicentre study. Eur Heart J Cardiovasc Imaging. 2016;17(7):779–87.
9. Nielsen LH, Ortner N, et al. The diagnostic accuracy and outcomes after coronary computed tomography angiography vs. conventional functional testing in patients with stable angina pectoris: a systematic review and meta-analysis. Eur Heart J Cardiovasc Imaging. 2014;15(9):961–71.
10. Patel MR, Peterson ED, Dai D, Brennan JM, et al. Low diagnostic yield of elective coronary angiography. N Engl J Med. 2010;362(10):886–95.
11. Puri R, Nicholls SJ, Ellis SG, et al. High-risk coronary atheroma: the interplay between ischemia, plaque burden, and disease progression. J Am Coll Cardiol. 2014;63(12):1134–40.

2 Innovations in Cardiac CTA

Alain Vlassenbroek, Mani Vembar,
and Michael Grass

2.1 Introduction

Coronary artery disease (CAD) is one of the leading causes of death in the western world and more than half the people who die from a cardiac event have no previous symptoms. Hence, there is a clinical need for tools that enable an early and accurate diagnosis of CAD. Cardiac computed tomography (CT) angiography provides a comprehensive anatomic evaluation of the heart. Cardiac anatomy and function, coronary plaque, and coronary stenoses can be assessed in a single study that is acquired within a short breath hold over a few heart beats.

The 4-slice CT scanners started an unprecedented technological evolution in 1998 but it is only with the advent of the 64-slice CT systems in 2004 that the realm of noninvasive coronary imaging became an integrative part of the clinical routine. Although image quality and robustness had significantly improved compared to the early days, several challenges still remained, such as radiation dose and limited low contrast resolution, motion artifacts, and the evaluation of coronary segments with severe calcifications or coronary stents. Today, reduction of radiation exposure is still at the forefront of the developments. With the introduction of large coverage multi-slice CT scanners, prospectively ECG-triggered step-and-shoot acquisition has become a robust scanning mode, with effective doses ranging from 2.7 to 4.5 mSv [1]. Further significant dose reductions have been achieved recently with the introduction of advanced iterative reconstruction techniques enabling effective patient doses going below 1.0 mSv with improvements in spatial and contrast resolutions [2]. With an increased spatial resolution, the evaluation of calcified plaques and stents can be significantly improved due to the reduced blooming artifacts. An improved low contrast enables a better intra-plaque attenuation assessment and may help to better identify the plaques with the highest risk to rupture. In addition, new developments have recently taken place in the field of cardiac CT image reconstructions to improve the temporal resolution and the image quality. Motion compensated cardiac reconstruction incorporates the knowledge of the calculated motion vector field within the iterative reconstruction process to reduce the motion artifacts [3–5].

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With all these significant improvements in CT technology over the past 17 years, cardiac computed tomography angiography (cardiac CTA) has become the preferred noninvasive modality for the detection and rule-out of coronary artery disease (CAD), with various multicenter studies demonstrating robust diagnostic accuracy and negative predictive value (NPV) [6–8]. However, the hemodynamic significance of CAD is unknown [9]. New advanced computational developments including flow simulations and noninvasive fractional flow reserve (FFR-CT) assessment have recently been introduced and are currently evaluated in clinical studies. The promising results, combined with the new developments in first-pass and dynamic CT myocardial perfusion imaging indicate that multi-slice CT (MSCT) has a great potential to provide comprehensive information regarding the hemodynamic relevance of coronary artery stenosis. Finally, further improvements in myocardial perfusion, delayed enhancement imaging, and vulnerable plaque detection might be anticipated with the new spectral MSCT detectors enabling dual-energy imaging.

Experimental CT designs and applications which were proposed a few years ago are now part of the current clinical reality. So we can anticipate that the current innovations in cardiac CT could facilitate early, and comprehensive diagnosis of cardiovascular disease in the near future.

2.2 Cardiac CT: Requirements and CT Technology

Noninvasive cardiac imaging is an extremely demanding field and presents a number of clinical challenges. The most critical and challenging requirement for successful cardiac CT imaging is the minimization of motion artifacts because the coronary arteries undergo complex 3D motion during the cardiac cycle. These arteries are extremely small, with diameters ranging from 5 mm in the proximal sections to less than 1 mm distally. As a consequence, excellent spatial and temporal resolution requirements are prerequisites for CT scanners to assess the coronary arteries. In addition, they must have adequate and uniform contrast enhancement for proper visualization. As the scans are performed under a single breath-hold condition, the acquisition has to be completed in the shortest possible time to avoid any respiratory motion artifacts. Patients are exposed to radiation dose and hence dose-reduction techniques need to be employed. The large volume of image data generated also presents the user with visualization and workflow challenges. Lastly, the presence of plaques poses unique challenges. Calcified plaques often make it difficult to visualize the lumen whereas noncalcified plaques demand superior spatial and temporal resolution. Cardiac imaging is thus a demanding application for CT requiring multiparameter optimization.

In the early days, CT scanners were limited to scanning the patients in axial (or “step-and-shoot”) mode with a one-dimensional detection system and with a patient translation occurring in sequential steps between the scans. A complete set of X-ray attenuation data was acquired during an X-ray tube rotation around the stationary patient, and these projections were used to reconstruct cross-sectional images of the patient anatomy. The patient table was then subsequently positioned to the next axial location and the data acquisition repeated. In this fan-beam CT configuration, axial slices of the object were sequentially acquired and reconstructed using a well-known mathematical technique (2D filtered back projection (2D-FBP)) [10] and subsequently assembled to build the volume. The introduction of spiral scanning in 1990 [11, 12] enabled continuous data acquisition with simultaneous patient translation at a constant speed. Spiral scanning provided volumetric acquisitions and enabled the reconstruction of overlapping slices leading to high-resolution imaging without the need to increase the patient dose. The time to cover a