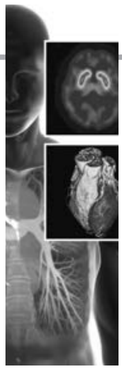

Recent developments in coronary computed tomography imaging

Cardiac computed tomography (CT) has recently emerged as a noninvasive alternative to catheter angiography for the assessment of coronary artery disease. Rapid technological advances have rendered CT coronary angiography a robust, accurate and fast imaging modality to assess coronary artery disease in selected patients. Difficulties in imaging coronary arteries are mainly due to the small vessel size, the tortuous course of the coronary arteries along the heart surface and the fact that the coronary vessels are in constant motion with varying motion velocity during the cardiac cycle. The rotation speed of modern CT systems, the increased spatial and temporal resolution and the ability to time the scan to match the cardiac cycle by means of the ECG signal all assist to minimize cardiac-motion artifacts and allow for the accurate analysis of coronary conditions. Cardiac CT has been established as a comprehensive evaluation method allowing not only assessment of coronary artery stenosis and coronary anomalies, but also permitting analysis of cardiac function, cardiac valve morphology and aortocoronary bypass grafts, and providing highly detailed information about the aorta, pulmonary arteries and veins, lung and mediastinum. This article describes the technical requirements for coronary CT imaging, traces the technical evolution of CT and diagnostic performance of CT coronary angiography, and discusses the limitations and future perspective of coronary CT imaging.

KEYWORDS: computed tomography ▪ coronary angiography ▪ coronary artery disease ▪ diagnostic accuracy ▪ multislice technology ▪ radiation dose ▪ technical improvements ▪ technological requirements

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Technical requirements for cardiac computed tomography

Visualization of the heart and the coronary arteries has been of great interest for radiologists even in the early beginning of computed tomography (CT). In his novel prize lecture in 1979, Sir Godfrey N Hounsfield hypothesized on the future of CT for cardiac imaging [1]. Another 30 years of technical developments were required to achieve the current state of modern CT systems that are sufficiently robust and accurate for coronary imaging.

Coronary imaging requires the highest technical demands of any diagnostic modality because of the small size of the coronary arteries and the continuous motion during the cardiac cycle. Three major technical parameters define the capability of a CT system for imaging the coronary arteries: spatial resolution, temporal resolution and coverage speed in z-axis direction.

■ Spatial resolution

A high spatial resolution is required for imaging and evaluation of small distal coronary artery segments and side branches. The spatial resolution depends on the physical width of the detector in a longitudinal direction. Ideally, isotropic voxel imaging should be achieved, which means that a voxel has the same size in all dimensions and is mandatory to reconstruct high-quality images in all planes. Current CT systems provide an isotropic spatial resolution of up to 0.4 mm. Further improved resolution at a level of 0.2 mm is desirable for a reliable evaluation of stent patency or severely calcified arteries [2]. However, a higher spatial resolution will require a higher radiation dose to maintain sufficient signal-to-noise ratio [2].

■ Temporal resolution

The temporal resolution depends on the gantry rotation time. A temporal resolution of less than 100 ms is desirable to allow artifact-free imaging of the coronary arteries even at elevated heart rates [2].

For reducing motion artifacts, the CT data acquisition is synchronized with the ECG signal. The most commonly used approach for synchronization is retrospective ECG gating in which images are acquired throughout the cardiac cycle and those time points depicting the coronary arteries without motion artifacts are retrospectively selected for image reconstruction.

The projection data of a half gantry rotation are than required for image reconstruction (half-scan reconstruction) and the temporal resolution is half of the rotation time. Thus, modern 64-slice CT systems with a gantry rotation time of 330 ms have a temporal resolution of 165 ms. Further improvements in gantry rotation time are mandatory to achieve a temporal resolution of more than 100 ms when using a half-scan reconstruction method. However, the mechanical forces increase with higher gantry rotation times. Current CT systems with a gantry rotation time of 330 ms are associated with a mechanical force of approximately 28 g. Rotation times of less than 200 ms required for a temporal resolution in a mono-segmental half-scan reconstruction appear to be beyond today's mechanical limits (i.e., >75 g) [2].

In addition, in order to compensate for motion artifacts at higher heart rates, two- or multisegment reconstruction algorithms are used that merge data from two or more consecutive heart beats for image reconstruction. This approach further improves temporal resolution at specific heart rates. However, its use is limited by artifacts occurring with variable heart rates, with inter-heart beat variability of the coronary artery position, and by the necessity of lower pitch factors prolonging the data acquisition time and increasing the radiation dose delivered to patients [3,4].

Another method to improve the diagnostic quality of CT coronary angiography (CTCA), although not achieved by improvements in CT technology, is demonstrated by heart rate and variability reductions using either an oral or intravenous β-receptor antagonist [5–7].

■ Coverage speed in z-axis

The coverage speed in z-axis is inversely related to the longitudinal axis covered by the detector array, the gantry rotation speed and the pitch. A higher coverage speed in z-axis reduces the acquisition time. Shortening of the scan time improves CT imaging of patients who are unable to hold their breath for a longer time. Furthermore, the shorter acquisition time has the advantages of reduced heart rate variability. Commonly, a long breath-hold is accompanied with tachycardia at the end causing a considerable variability in the length of heart cycles [8]. A shorter breath-hold in turn reduces heart rate variability making the study more robust. In addition, the need for a shorter period of coronary opacification allows a smaller volume of contrast to be used.

Chronology of technical improvements for cardiac CT

The evolution of cardiac CT to its current state is closely correlated with several developments in CT technique in the last decade. Equally, the demand for coronary imaging were the most important pacemakers of CT system improvements.

■ The precursor of modern CT systems: single-slice CT

The first step on the way to widespread use of CTCA was the introduction of single-slice helical CT into clinical practice. By providing a gantry rotation time of 0.8 s and using a half-scan reconstruction algorithm, the temporal resolution was 400 ms. Slice thickness was 3–5 mm. Although better scanning parameters had been achieved earlier with a temporal resolution of 50–100 ms with electron-beam CT in the early 1980s, single-slice helical CT was the first CT system available for coronary imaging with a wide availability among many institutions worldwide. Although at the level of temporal resolution of the early helical CT systems the coronary arteries were displayed frequently as 'dancing vessels' or 'ghosts', under optimal conditions with very slow heart rates single-slice CT could establish the diagnosis of coronary artery stenosis in large proximal vessel segments [9], cardiac thrombus [10] and congenital heart disease [11].

■ On the way to clinical robustness: multislice CT

The development of multislice CT technology coupled with decreased detector element size, faster gantry rotation speed and increased volume coverage substantially improved coronary imaging capabilities.

Four-slice CT

Four-slice CT, which was developed in 1998 and became clinically available in 1999, yielded gantry rotation times of 500–800 ms, resulting in a temporal resolution of as high as 250 ms. The spatial resolution in z-axis was 1.00–1.25 mm and z-axis coverage was approximately 2 cm. With these multislice CT systems imaging of the entire heart required approximately 40–50 s, which was longer than most patients could hold their breath. Therefore, preoxygenation was frequently essential to reduce breathing artifacts. Under optimal circumstances, imaging and evaluation of the coronary artery tree, particularly of the proximal coronary artery segments, became technically feasible without artifacts [12–20]. However, small size distal segments and side branches could often not be depicted with adequate image quality, and up to 32% of coronary segments had to been excluded from analysis in four-slice CT studies [18]. Therefore, the four-slice CT systems lacked the robustness for implementation of CTCA into clinical practice.

16-slice CT

The 16-slice CT systems introduced in 2001 featured gantry rotation times of 380–500 ms, resulting in a temporal resolution of 190–250 ms, a slice thickness of 0.5–0.75 mm and a z-axis coverage of 24 mm. With these advances, heart imaging within a single breath-hold became feasible, therefore avoiding the need for preoxygenation. Even small coronary segments and side branches could be reliably evaluated with 16-slice CT [8,21–30], however, up to 21% of coronary segments remained not evaluative in some studies. In a large multicenter trial, 29% of coronary artery segments had nondiagnostic image quality caused by insufficient contrast attenuation (52%), coronary motion artifacts (45%), small vessel caliber (31%), breathing artifacts (19%) and severe calcifications (5%) [31]. These results indicate that the 16-slice CT technique is still not robust enough for coronary imaging even in patients with low heart rate.

64-slice CT

The 64-slice CT systems introduced in 2004 further improved the technical parameters to a gantry rotation time of 330–400 ms (i.e., a temporal resolution of 165–200 ms), a spatial resolution of 0.4–0.625 mm and a detector coverage of 19.2–40 mm. This allowed imaging of the heart in less than 10 s. Improvements in temporal and spatial resolution allowed for detailed evaluation of the coronary arteries and even of small-sized side branches of a diameter of 1 mm and below. Because of the low rate of coronary segments with nondiagnostic image quality and the high diagnostic accuracy, the 64-slice CT could be considered the first truly feasible CT system capable of coronary artery evaluation in clinical practice [5–7,32–37]. The 64-slice CT also allowed for more precise characterization of morphology and function of the aortic [38–42] and mitral valve [42,43]. However, the temporal resolution of 64-slice CT still requires optimal conditions of imaging, in particular a low and stable heart rate [44]. Therefore, premedication with β-blockers prior to CTCA is frequently required when using 64-slice CT.

■ Latest improvements in CT technology: more slices, more x-ray sources

Remaining challenges of temporal resolution and detector coverage have led to the development of the latest CT systems: 256-/320-slice CT and dual-source CT.

256-slice/320-slice CT

To overcome limitations of CTCA in patients with irregular heart beats, large-detector CT systems were developed to allow coverage of the entire heart within a single heart beat. The first CT system capable of single-heart beat CTCA was introduced in 2006 by Toshiba and features a 256-slice detector array and a spatial resolution of 0.5 mm, resulting in a z-axis coverage of 128 mm, which permits coverage of the heart in a single gantry rotation. One limitation of this system is the low gantry rotation speed of 500 ms per rotation. However, preliminary results of the ability of 256-slice CT to assess coronary artery stenosis performed in small patient cohorts are promising [45,46]. Further development has led to the recently introduced 320-slice CT with a detector coverage of 160 mm and a lower gantry rotation time of 350 ms. First results indicate promising results for imaging the coronary arteries within a single heart beat [47]. Another 256-slice CT system was introduced by Philips in 2007 that yielded a lower gantry rotation time of 270 ms.

Large volume coverage CT might open the field for new cardiac imaging applications including observation of evolving processes, such as coronary contrast flow and whole heart perfusion.

Dual-source CT

The dual-source CT scanner introduced by Siemens in 2005 is characterized by two x-ray tubes and two corresponding detectors mounted onto the rotating gantry with an angular offset of 90° [48]. Therefore, a quarter rotation of each tube rather than a half rotation required with single-source CT is sufficient to acquire the required projection data for image reconstruction. The first generation of dual-source CT (Definition) provides two detector arrays each capable of acquiring 64 slices and a gantry rotation time of 330 ms, thus the first-generation dual-source CT system offers a temporal resolution of 83 ms in a mono-segment reconstruction mode that is consistent throughout various heart rates owing to individual adaptation of the table pitch. Consequently, dual-source CT provides a sufficient temporal resolution for coronary imaging even at high heart rates [48–50] and provides a high diagnostic accuracy with a low rate of not-evaluative coronary segments [51–58].

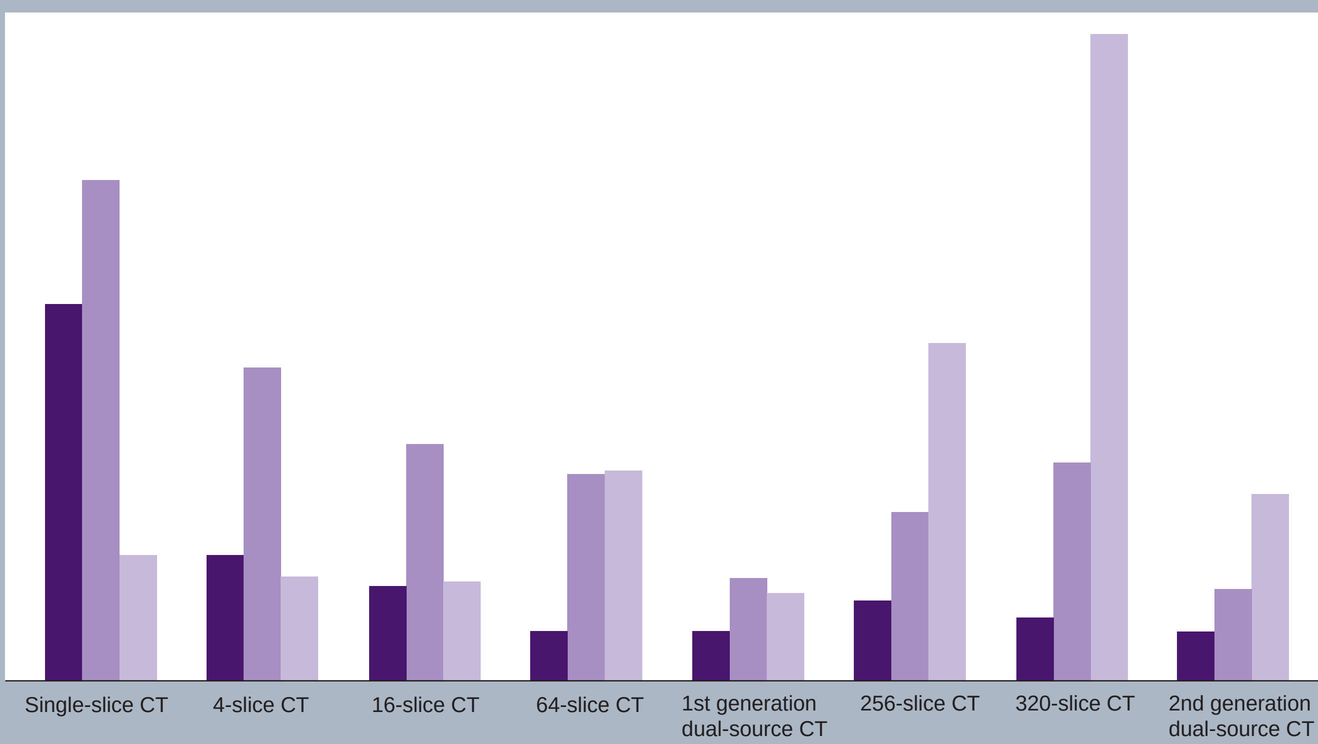
Recently, a second-generation dual-source CT (Definition Flash) has been introduced featuring 2 × 128 slices and a gantry rotation time of 280 ms, providing a temporal resolution of 75 ms. While a low pitch is needed for overlapping data acquisition in 64-slice CT, the second-generation dual-source CT can achieve gapless z-sampling even with a pitch of up to 3.2. Therefore, it enables complete coverage of the heart in a single heart beat.

■ Development of technical parameters

The evolution from early helical CT systems to the modern dual-source and 320-slice CT scanners resulted in a substantial improvement in the technical parameters defining coronary artery imaging capabilities (Figure 1).

Development of spatial resolution

The spatial resolution has not substantially improved with dual-source CT or 256- and 320-slice CT systems compared with those achieved with 64-slice CT. However, it has been reported that blooming artifacts of severely calcified deposits are less pronounced in dual-source CTCA than in 64-slice CTCA [51]. The authors concluded that, considering the fact that the spatial resolution of dual-source CT is the same as that of a single source 64-slice CT scanner, this apparent difference in calcification dependency could indicate that the blooming artifact of severely calcified vessel walls may be sometimes superimposed by additional motion artifacts [51]. In 2008, one vendor introduced a CT system with gemstone detectors (VCT Discovery 750 HD, General Electric Healthcare), which improved photon detection by shortening the afterglow period and thereby



Year	1996	1998	2001	2004	2005	2006	2007	2008
Slice	1	4	16	64	2 × 64	256	320	2 × 128
Spatial resolution (mm)	3–5	1–1.25	0.5–0.75	0.4–0.625	0.4	0.5–0.625	0.5	0.4
Temporal resolution (ms)	400–500	250–400	190–250	165–200	83	135–200	175	75
Detector coverage (mm)	3–5	20	24	19.2–40	19.2	80–128	160	38.4

Figure 1. Chronology of CT systems from single-slice CT to large-detector CT and dual-source CT. Columns illustrate the spatial resolution (dark purple), temporal resolution (purple) and detector coverage (light purple) of each CT system.
CT: Computed tomography.

improving spatial resolution. However, it is unclear whether this new detector material will substantially improve spatial resolution and improve assessability of stent patency or coronary artery stenosis caused by severely calcified atherosclerotic plaques.

Development of temporal resolution

In order to achieve a temporal resolution better than the 100 ms at present gantry rotation times, which is considered necessary to overcome the challenge of motion artifacts at higher heart rates, two different concepts have been developed: the multisegment reconstruction algorithm and the dual-source concept.

With the multisegment reconstruction approach, small portions of projection data are selected from two or more heart cycles and all projections are combined to obtain sufficient data for image reconstruction. The maximal achievable temporal resolution could than be the gantry rotation time divided by two (half-scan reconstruction) and divided by the number of heart cycles averaged for image reconstruction. Despite effectively improving the temporal resolution, additional motion artifacts might be introduced in the images by multisegment reconstruction. Even at a steady heart rate, the cardiac position in the thoracic cage is not absolutely fixed and changes depending on the actual ventricular filling and function. Merging of data from two or more consecutive cycles results in image data that do not exactly match together and results in motion artifacts that are more pronounced in patients with variable heart rate [3,4,44]. The disadvantage of multisegment reconstruction algorithms in patients with variable heart rate has even been shown with modern CT systems [59].

The other method introduced for improving temporal resolution is the dual-source CT concept. This approach has shown improved image quality by reducing motion artifacts without administration of β-blockers for heart-rate control [51–53,57].

Development of z-axis coverage

The z-axis coverage speed has increased tremendously with recent CT developments. Scan time for covering the entire heart is more than 40 s with four-slice CT, 16–20 s with 16-slice CT and less than 10 s with current 64-slice CT systems. Modern 320-slice CT and second-generation dual-source CT systems permit imaging of the entire heart in a single heart beat, allowing sub-second cardiac imaging. In addition, the developments in z-axis coverage resulted in a decrease in the amount of contrast media required for CTCA. While up to 160 ml of contrast media was needed when CTCA was first used [60], this amount has been reduced to 50–80 ml with dual-source and 320-slice CT [47,50,51,53,57,61].

Diagnostic performance of CTCA

■ Development of diagnostic performance of CTCA

Numerous studies have evaluated the diagnostic ability of CTCA for the assessment of coronary artery stenosis in correlation with catheter angiography for different generations of CT systems (Tables 1 & 2). The effect of improvement in CT technology on the diagnostic accuracy can be summarized in the following bullet points [62]:

- Patients with significant stenosis (>50% luminal diameter narrowing) were detected with 95% or higher sensitivity with four-slice, 16-slice and 64-slice CT;
- The negative predictive value for CTCA is near 100%;
- Average specificity for patients with significant stenosis has increased with modern CT technology;
- The number of nonevaluable segments decreased significantly with modern CT technology;
- Stenosis in proximal and mid-segments were shown with a higher sensitivity than distal segments.

Several studies have demonstrated that dual-source CT has a high diagnostic accuracy for the assessment of coronary artery stenosis coupled with a low rate of not-evaluative coronary segments [51–58]. A recently published study by Alkadhi and colleagues investigating diagnostic performance of dual-source CTCA in 150 patients reported no significant decrease in diagnostic accuracy in patients with high heart rates or overweight patients [57]. However, severe coronary calcifications increase the rate of false-positive classifications and therefore decrease the specificity and positive predictive value.

■ Comparison with alternative noninvasive coronary imaging modalities

In comparison with magnetic resonance coronary angiography (MRCA), CTCA has a superior spatial resolution, image acquisition time and signal-to-noise ratio [63]. Although MRCA has the great advantage that it does not apply

Table 1. Diagnostic performance of four-slice, 16-slice and 64-slice computed tomography coronary angiography.

Computed tomography system	n	Rate of not-evaluative segments (%)	Sensitivity (%)	Specificity (%)	Ref.
Four-slice	61	NA	77	91	[14]
Four-slice	91	18	82	96	[17]
Four-slice	53	30	82	93	[20]
Four-slice	31	27	81	97	[19]
Four-slice	25	19	95	91	[13]
Four-slice	28	5	81	90	[12]
Four-slice	42	NA	72	99	[15]
Four-slice	102	NA	86	96	[16]
Four-slice	30	32	72	99	[18]
16-slice	102	6	95	98	[22]
16-slice	33	17	63	96	[23]
16-slice	59	NA	95	86	[89]
16-slice	72	7	82	98	[24]
16-slice	61	16	89	98	[26]
16-slice	40	0	96	96	[21]
16-slice	29	4	86	99	[29]
16-slice	45	6	98	97	[30]
16-slice	51	NA	95	98	[27]
16-slice	127	7	92	95	[28]
16-slice	58	21	72	97	[25]
64-slice	67	0	94	97	[34]
64-slice	70	12	86	95	[5]
64-slice	59	4	73	97	[33]
64-slice	52	3	99	95	[7]
64-slice	35	3	99	96	[36]
64-slice	72	10	82	93	[6]
64-slice	134	6	85	98	[90]
64-slice	69	8	90	94	[32]
64-slice	84	4	93	97	[37]

NA: Not applicable.

either x-ray radiation or iodinated contrast media, the diagnostic performance and robustness of MRCA is not currently sufficient for use in clinical practice. In a recent meta-analysis including 39 studies comparing MRCA with catheter coronary angiography (CCA) as the standard of reference, the sensitivity was 73% and the specificity was 86% [64]. Compared with MRCA, CTCA currently has a significantly higher diagnostic accuracy for the assessment of coronary artery disease (CAD) [65].

■ Noninvasive coronary CT imaging: recent indications

The introduction of 64-slice CT has allowed the implementation of noninvasive CTCA into daily clinical practice. This was fascilitated by the higher temporal and spatial isotropic resolution. Thereby, 64-slice CT provides a high diagnostic accuracy for the assessment of the coronaries, and, in particular, its high negative predictive value allows for the exclusion of significant coronary stenoses [5–7,34].

Thus, the Task Force on the Management of Stable Angina Pectoris of the European Society of Cardiology has recently recommended in their guidelines the performance of CTCA in patients that have stable angina, a low pretest probability of CAD and a nonconclusive exercise ECG or stress imaging test [66]. Similarly, the American Heart Association states that, particularly if the symptoms, age and gender of a patient suggests a low-to-intermediate pretest probability of hemodynamically relevant stenoses, ruling out these stenoses by CTCA may be clinically useful and may help to avoid invasive catheter angiography [67].

Recently, the use of ECG-gated CTCA in the emergency department has been shown to improve the triage of patients with acute chest pain by decreasing the delay in diagnosis and treatment and, thus, morbidity and mortality [68]. In addition, appropriateness criteria for cardiac CT demonstrate the role of coronary angiography for patients with acute chest pain, but no ECG changes and negative cardiac enzymes [69]. In addition, CTCA is very well established as the imaging modality of choice in patients with suspected coronary anomalies [70].

Regarding patients after bypass graft surgery, CTCA may be useful in selected patients (e.g., failed visualization of a graft in invasive angiography), however, the inability to reliably visualize the native coronary arteries poses severe restrictions to the general use of CTCA in these patients [70].

Limitations of CTCA

■ Coronary imaging in difficult conditions

Elevated heart rates and irregular heart rates in particular have posed a challenge when using previous CT systems [4,44,71]. Single extrasystoles during CT acquisition do not commonly substantially degrade image quality when ECG editing techniques are used [72]. With the improved temporal resolution of modern CT systems, the application of CTCA has been extended to patients with atrial fibrillation, but at the price of a higher dose [61,73–75]. However, the combination of high and irregular heart rates is associated with a decrease in image quality when using CT [49].

High-density material such as calcified deposits in the arterial wall or coronary stents may cause several image artifacts that may limit accurate assessment of the coronary lumen. In particular, severe coronary calcifications may hinder inspection of the coronary lumen, and may cause overestimation of the severity of the stenosis. However, one has to bear in mind that a high coronary calcium score commonly indicates that a patient has a higher risk of CAD, and, therefore, does not constitute a proper indication for CTCA. Similarly, the evaluation of in-stent restenosis is not a recommended indication for performing CTCA according to current guidelines [66,67,69]. Therefore, both limitations are usually not encountered in clinical practice when adequate indications for performing CTCA are applied.

Another shortcoming of CTCA compared with CCA is its inability to produce time-resolved imaging. The speed and the direction of blood flow in a coronary artery and across a coronary stenosis are not obtainable on CTCA. However, large-detector CT and second-generation dual-source CT capable of cardiac imaging within a single heart beat might allow assessment of flow characteristics by acquisition of data during various heart cycles. Future research using these CT systems needs to reveal whether the clinical benefit of coronary flow assessment will outweigh the risk of the additional radiation exposure.

■ Radiation dose issues

One of the greatest barriers for CTCA becoming a standard tool in the cardiac imaging armamentarium had been the high radiation exposure of CTCA compared with that of CCA. The radiation dose from 16-slice CTCA has been estimated at approximately 9 mSv [76]. However, this radiation dose substantially increased in 64-slice CTCA to approximately 15 mSv for men and 20 mSv for women [36]. These radiation doses are significantly higher compared with that usually applied in CCA where the dose is between 2.1 and 7 mSv [7,77]. The radiation dose estimates of CTCA were achieved when using common retrospective ECG triggering for phase synchronization. Improvements in CT techniques also permit application of potential radiation dose-reduction methods. Current CT systems are capable of modulating the tube current during different phases of the cardiac cycle (ECG-based tube current modulation); the maximal tube output is applied during predefined phases likely used for image reconstruction and tube current output is reduced during the remaining phases of the cardiac cycle [50]. Using this technique, radiation doses of 6.4 mSv for 16-slice CT [78], 9.4 mSv for 64-slice CT [78] and 8.8 mSv for dual-source CT [79] have been reported. Another method to reduce the radiation dose is to reduce the tube voltage. Abara *et al.* used

Table 2. Diagnostic performance of dual-source computed tomography coronary angiography.

CT system	n	Rate of not-evaluative segments (%)	Sensitivity (%)	Specificity (%)	Ref.
Dual-source CT	30	1	94	99	[51]
Dual-source CT	90	1	86	93	[52]
Dual-source CT	35	2	89	100	[53]
Dual-source CT	100	4	94	98	[54]
Dual-source CT	100	2	82	100	[55]
Dual-source CT	74	2	87	97	[56]
Dual-source CT	150	2	87	98	[57]
Dual-source CT	170	0	92	93	[58]

CT: Computed tomography.

a 80 kVp tube voltage in slim patients with a bodyweight under 60 kg and reported a dose-saving potential of 88% [80]. Tube voltages of 100 kVp have been successfully used for 16-slice CT [78], 64-slice CT [78] and dual-source CT [81,82], with a dose-saving potential of up to 40% reported. This benefit is independent and incremental to radiation dose savings by using ECG pulsing.

One of the most effective methods for radiation dose reduction in CTCA is the use of prospective ECG gating, also known as sequential cardiac scanning. This technique was first used in electron beam CTCA in 1995 and has been used for calcium scoring by CT since 1998 [83]. Despite irradiating during the entire cardiac cycle, x-ray is turned on during a short exposure period and turned off during the rest of the cardiac cycle. Sequential cardiac scanning is recommended for patients with heart rates below 70 bpm. Several studies have reported excellent image quality [84–86] and diagnostic accuracy [87,88] of prospectively ECG-gated CTCA at radiation doses of between 1 and 3 mSv (Figure 2) [84–88].

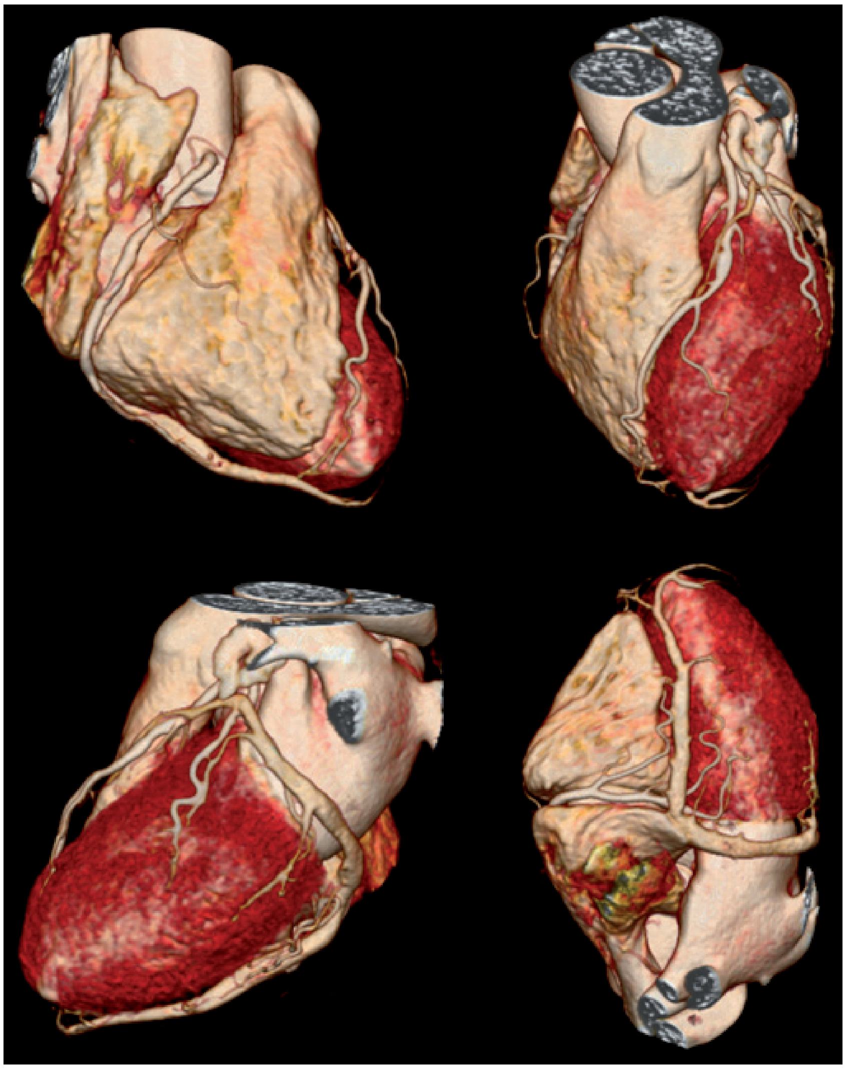


Figure 2. Volume rendered images using the sequential CT coronary angiography acquisition technique with a first-generation dual-source CT system of a 51-year-old man (heart rate: 59 bpm, BMI: 1.2 kg/m²). Applying a tube voltage of 100 kVp and a tube current time product of 190 mAs provides an excellent depiction of the coronary arteries. The radiation dose exposure was 1.4 mSv in this patient.
CT: Computed tomography.

Conclusion

Owing to rapid technical developments over the last 10 years, CTCA has progressively advanced from a new imaging modality applied only for research purposes to that of an increasingly used diagnostic tool in clinical practice. Although 64-slice CT is considered the first truly feasible CT system capable of coronary artery evaluation, even with 64-slice CT physical limitations still exist in cardiac imaging. Key issues in cardiac CT are spatial and, in particular, include temporal resolution as well as radiation dose and volume coverage. The current state-of-the art CT systems, including dual-source CT and 256-/320-slice CT, provide solutions for the remaining challenges encountered with previous scanner types at reduced radiation dose levels by improved spatiotemporal resolutions. These CT systems also open the field for potential new cardiac applications, such as assessment of coronary contrast flow, whole heart perfusion and dual-energy cardiac imaging. In the future, it is likely that technical developments will combine the benefits of extended z-axis coverage with temporal resolution gains of dual-source CT. This future CT system might allow the combination of a perfusion study with precise coronary artery evaluation in a single heart beat that would likely be a valuable mode for the evaluation of CAD by providing both anatomic and physiologic data in one study.

Future perspective

Although cardiac CT has evolved into a robust and accurate tool for diagnosis of CAD in clinical practice, new technologies and applications are likely to be developed that may allow more certain and rapid analysis and further cardiac pathologies to be diagnosed with CT. Advantages of the 320-slice CT (large-detector coverage) and that of dual-source CT (high temporal resolution, dual-energy information) might be combined in future CT systems. Variations of this design with even more slices and more than two x-ray tubes might permit imaging of the entire heart within one heart beat irrespective of the heart rate and without any detectable motion artifacts. Further applications to be refined for cardiac CT might include myocardial perfusion kinetics as well as precise analysis of coronary atherosclerotic plaque morphology by the means of dual-energy material decomposition. Future CT systems may combine all currently used modalities in the cardiological armamentarium into one cardiac CT acquisition that provides comprehensive evaluation of the heart and thoracic structures.

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The authors have no relevant affiliations or financial involvement with any organization or entity with a financial interest in or financial conflict with the subject matter or materials discussed in the manuscript. This includes employment, consultancies, honoraria, stock ownership or options, expert testimony, grants or patents received or pending, or royalties.

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Executive summary

- Coronary computed tomography (CT) imaging requires the highest technical demands because of the small size of coronary arteries and continuous motion during the cardiac cycle.
- The development of multislice CT technology coupled with decreased detector element size, faster gantry rotation speed and increased volume coverage substantially improved coronary imaging capabilities.
- Owing to the low rate of coronary segments with nondiagnostic image quality and the high diagnostic accuracy, the 64-slice CT could be considered the first truly feasible CT system capable of coronary artery evaluation in clinical practice, but premedication with β-blockers prior to CT coronary angiography has frequently been required when using 64-slice CT.
- Dual-source CT is characterized by two x-ray tubes and two corresponding detectors mounted, therefore, providing a sufficient temporal resolution for coronary imaging even at high heart rates.
- To overcome the limitations of CT coronary angiography in patients with irregular heart beats, large-detector CT systems were developed to allow coverage of the entire heart within a single heart beat.
- While a low pitch is needed for overlapping data acquisition in 64-slice CT, latest dual-source CT technology can achieve gapless z-sampling even with a pitch of up to 3.4, enabling complete coverage of the heart in a single heart beat.
- The evolution from early helical CT systems to the modern dual-source and 320-slice CT scanners resulted in a substantial improvement of the technical parameters defining coronary artery imaging capabilities enabling robust noninvasive coronary imaging.
- A high sensitivity and specificity in combination with a negative predictive value near 100% for the detection or exclusion of relevant coronary artery stenoses can be achieved by recent generations of CT scanners.
- Modern CT systems allow coronary CT imaging at low radiation dose values by using several dose-reduction techniques including ECG-based tube current modulation, tube voltage reduction and prospective ECG gating.

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